Transverse Spin Physics at HERMES

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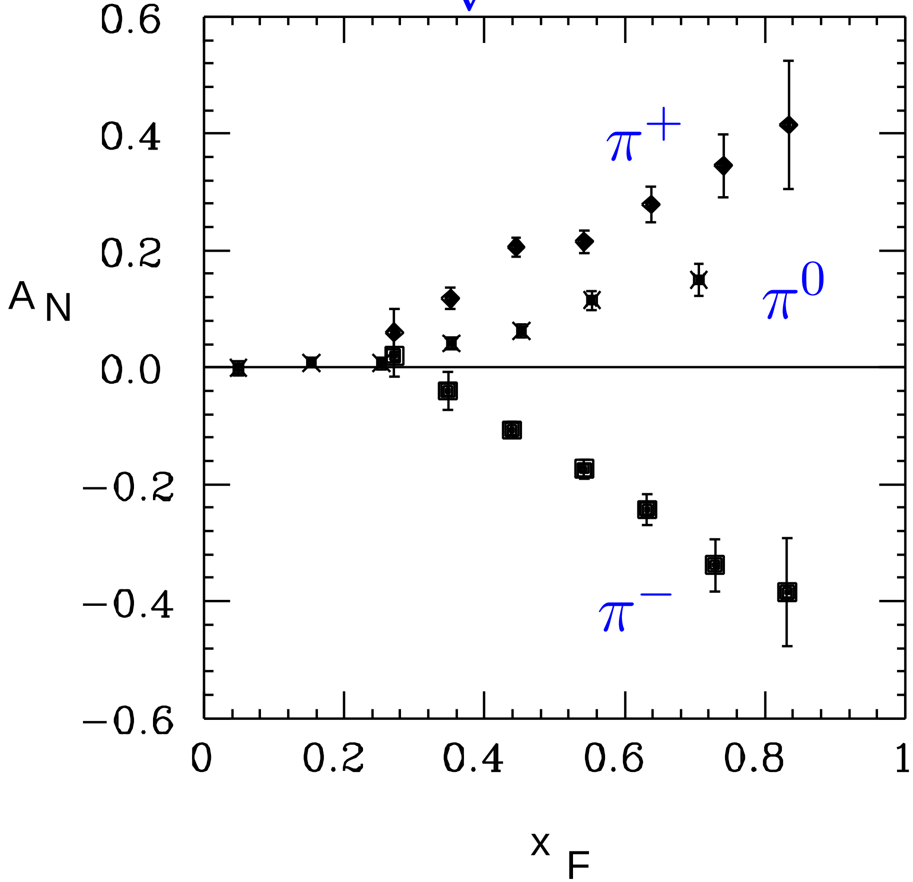
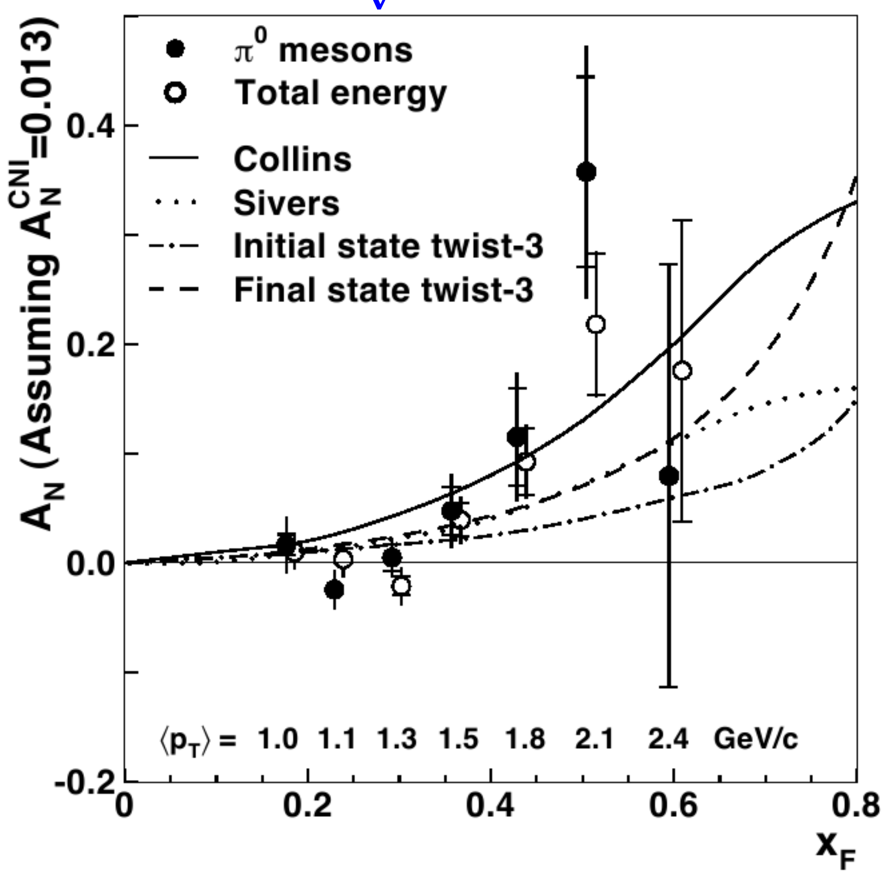
Transverse Single-Spin Asymmetries in pp Collisions

$$p^{\uparrow}p \rightarrow \pi X$$

E704 $\sqrt{s} = 20$ GeV



STAR $\sqrt{s} = 200$ GeV



left-right-asymmetry w.r.t. incoming proton's spin

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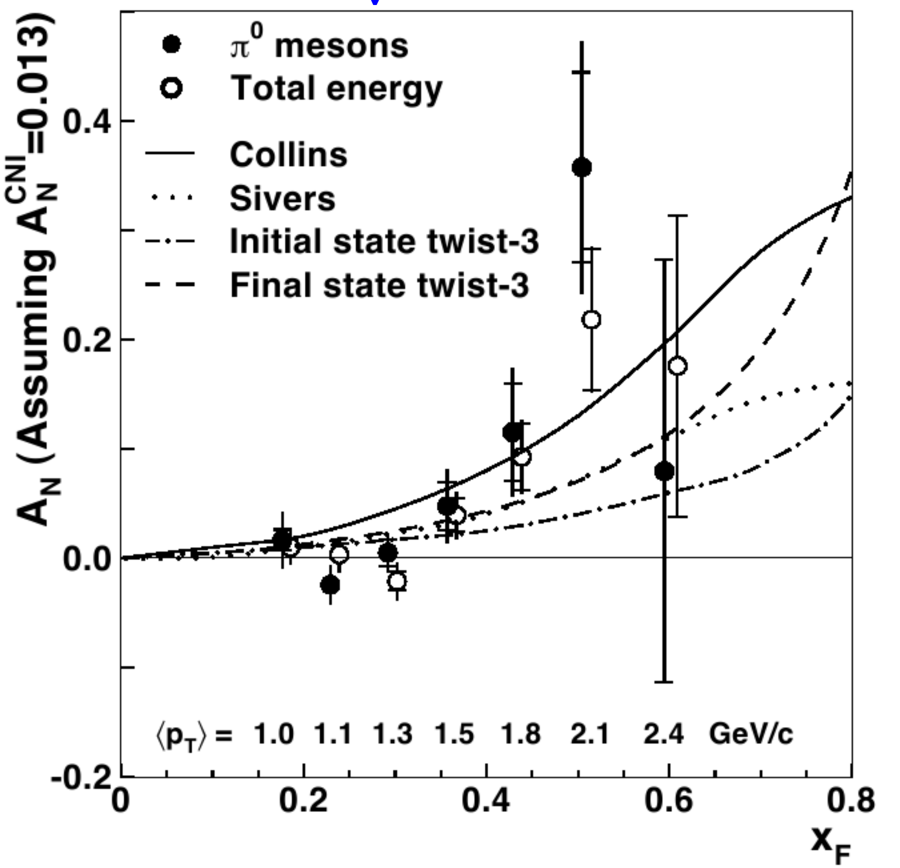


SSAs persist even at high energies! (despite being suppressed in pQCD)

- asymmetry in quark fragmentation (Collins)
- asymmetry in quark distribution (Sivers)
- subleading-twist effects

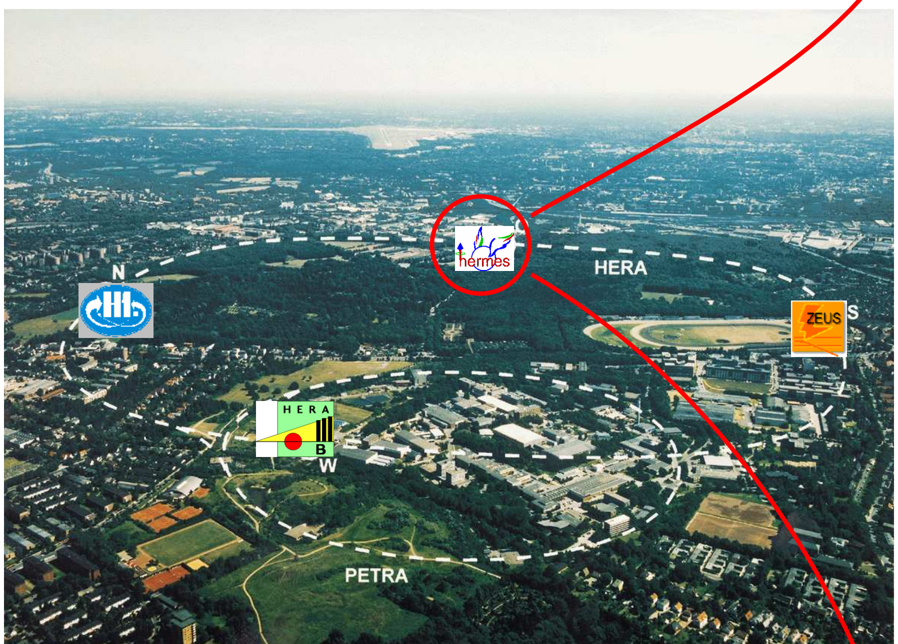
hermes

HERa MEasurement of Spin

a DIS experiment to study the nucleon structure

HERMES at DESY

27.5 GeV e^+/e^- beam of HERA

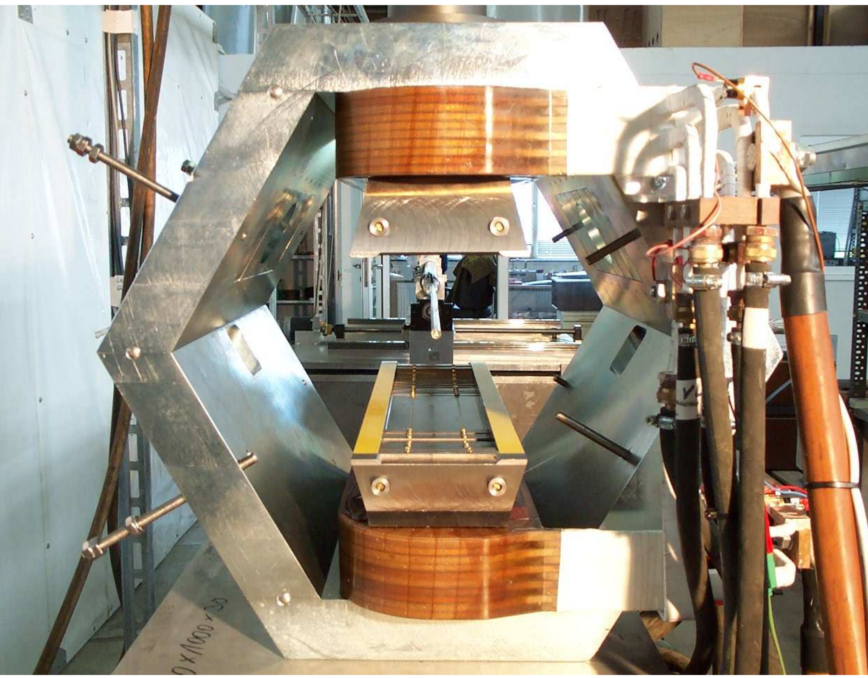


- **forward-acceptance spectrometer**

$\Rightarrow$ **40mrad$<\theta<$220mrad**

- **high lepton ID efficiency and purity**
- **excellent hadron ID thanks to dual-radiator RICH**

HERMES at DESY



- **atomic beam source**

⇒ **pure gas target, no dilution**

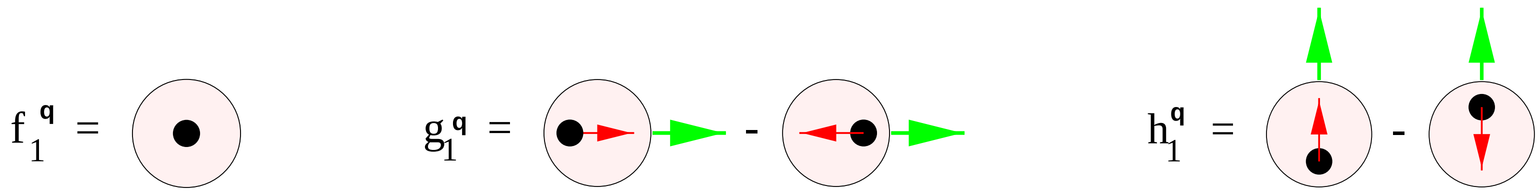
- **transversely pol. hydrogen**

  polarization $\sim 75\%$

- **90s flipping time** ⇒ **small systematics**

Transverse Spin of the Nucleon

Quark Distribution Functions



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

Unpolarized quarks and nucleons

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

$\Rightarrow$ Vector Charge

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

Longitudinally polarized quarks and nucleons

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

$\Rightarrow$ Axial Charge

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

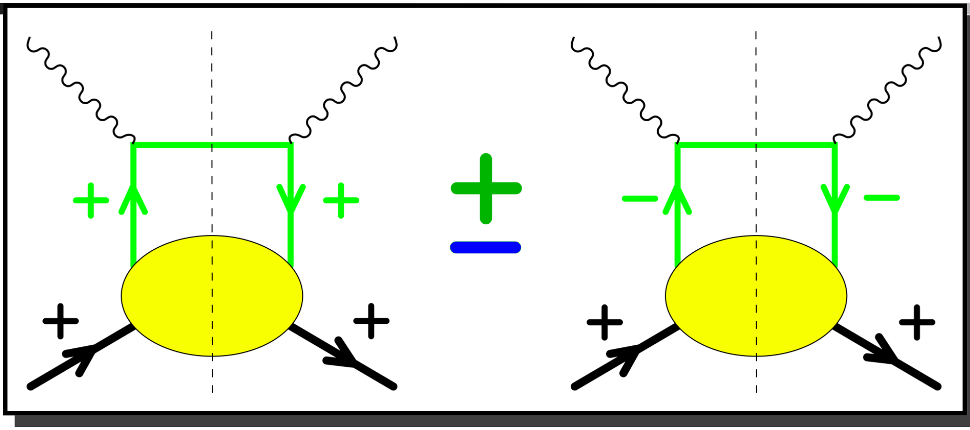
Transversely polarized quarks and nucleons

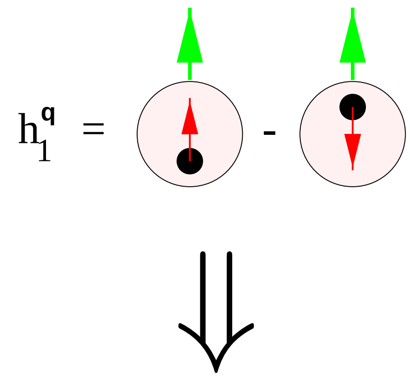
$h_1^q(x)$: transversity (hardly known!)

$\Rightarrow$ Tensor Charge

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

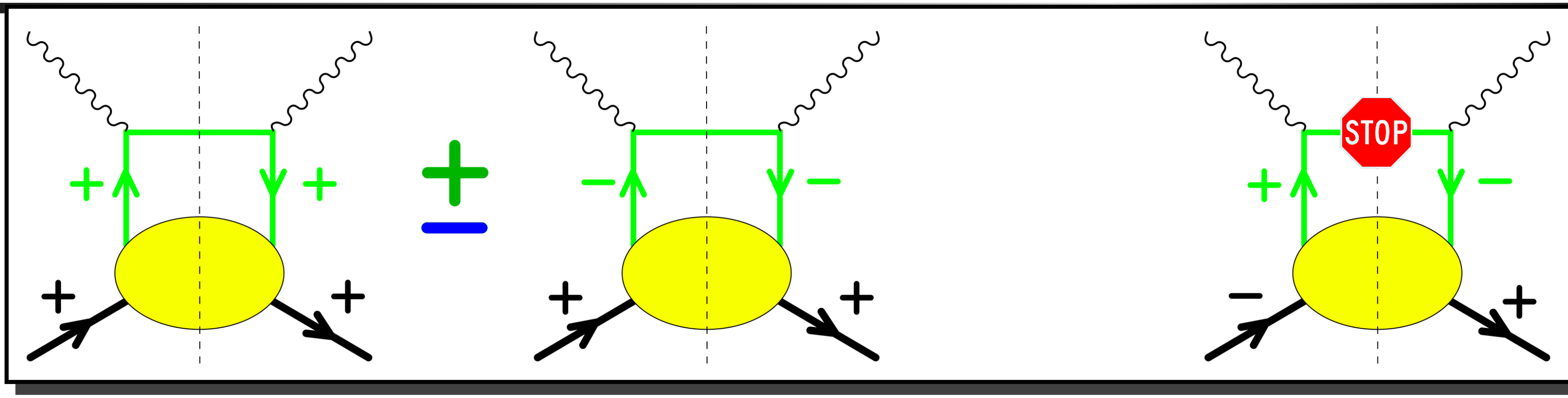
Quark Distribution Functions





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	$\Rightarrow$ Axial Charge	$\Rightarrow$ Tensor Charge
$\langle PS\vert\bar{\Psi}\gamma^\mu\Psi\vert PS\rangle$= $\int dx(f_1^q(x) - f_1^{\bar{q}}(x))$	$\langle PS\vert\bar{\Psi}\gamma^\mu\gamma_5\Psi\vert PS\rangle$= $\int dx(g_1^q(x) + g_1^{\bar{q}}(x))$	$\langle PS\vert\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi\vert PS\rangle$= $\int dx(h_1^q(x) - h_1^{\bar{q}}(x))$

Quark Distribution Functions



Unpolarized quarks and nucleons

Longitudinally polarized quarks and nucleons

Transverse polarized q s and nuc s

CHIRAL-ODD!

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

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

$h_1^q(x)$: tr ersity (hard own!)

$\Rightarrow$ Vector Charge

$\Rightarrow$ Axial Charge

$\Rightarrow$ T r Charge

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

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

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

Transversity Distribution

- transverse spin eigenstates related to helicity eigenstates via $|\perp\top\rangle = \frac{1}{2}(|+\rangle \pm \imath|-\rangle) \Longrightarrow$ transversity ($\langle\perp|\hat{O}|\perp\rangle - \langle\top|\hat{O}|\top\rangle$) flips helicity of quark and nucleon $\Rightarrow$ $\boldsymbol{h_1^q}$ chiral odd

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  $\Rightarrow$ different Q^2-evolution than for $f_1^q(x)$ and $g_1^q(x)$

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  $\Rightarrow$ $\boldsymbol{h_1^q}$ probes relativistic nature of quark dynamics

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- positivity bounds: $|h_1^q(x)| \leq f_1^q(x)$
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- first moment $\rightarrow$ tensor charge calculable in lattice QCD

Transversity Measurements

How can one measure transversity?

Need another chiral-odd object!

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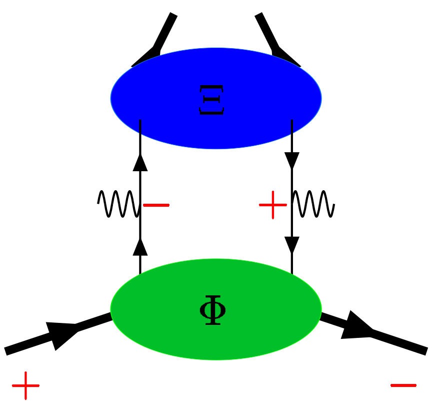
Need another chiral-odd object!

$\Rightarrow$ Semi-Inclusive DIS

$$\sigma^{ep\rightarrow ehX} = \sum_q h_1^q \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}$$



$\Downarrow$ **chiral-odd** DF

$\Downarrow$ **chiral-odd** FF

CHIRAL EVEN

hermes

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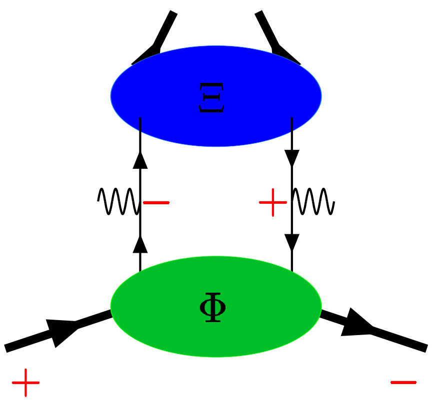


h_1^q $\Downarrow$ **chiral-odd** DF

$FF^{q\rightarrow h}$ $\Downarrow$ **chiral-odd** FF

CHIRAL EVEN

$\longrightarrow$ chiral-odd FF as a polarimeter of transv. quark polarization

Semi-Inclusive 2-Hadron Production

2-Hadron Fragmentation in Semi-Inclusive DIS

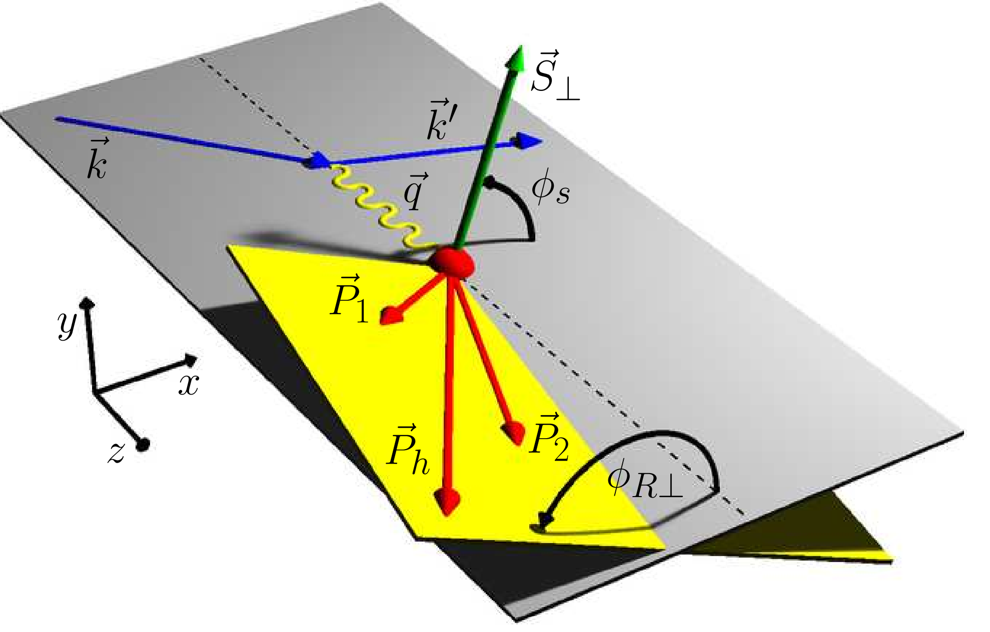
polarized 2-hadron cross section:

(Unpolarized beam, Transversely pol. target)

$$\sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 \, h_1^q \, H_1^{\sphericalangle}$$

$$H_1^{\sphericalangle} = H_1^{\sphericalangle}(z, \zeta, M_{\pi\pi}^2)$$

$$(\zeta \sim z_1/(z_1 + z_2))$$



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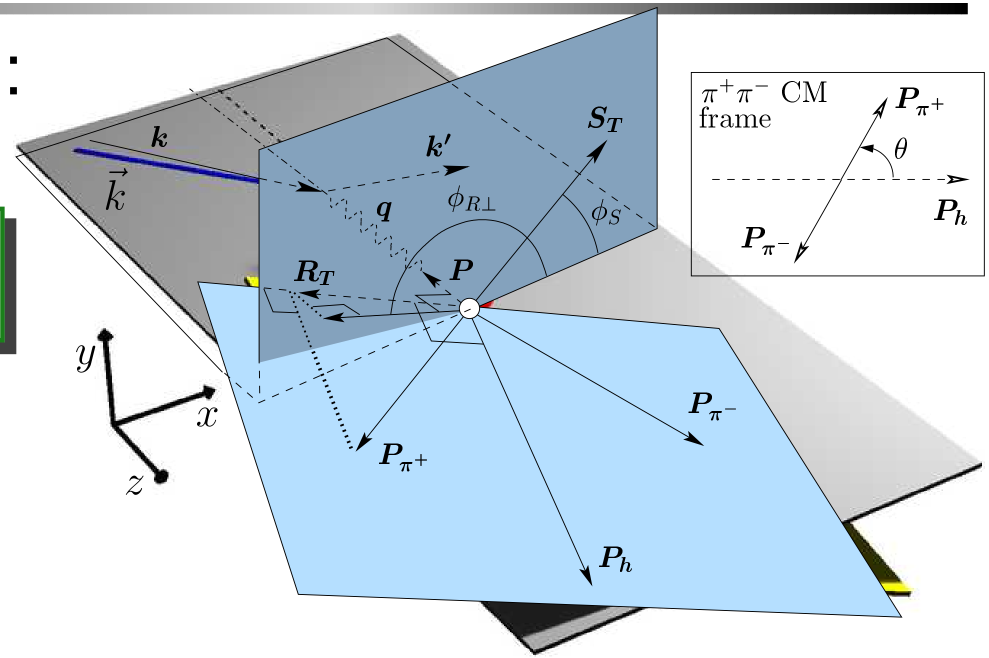

- only *relative* momentum of hadron pair relevant

⇒ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

- however, cross section becomes more complex (differential in 9 variables)

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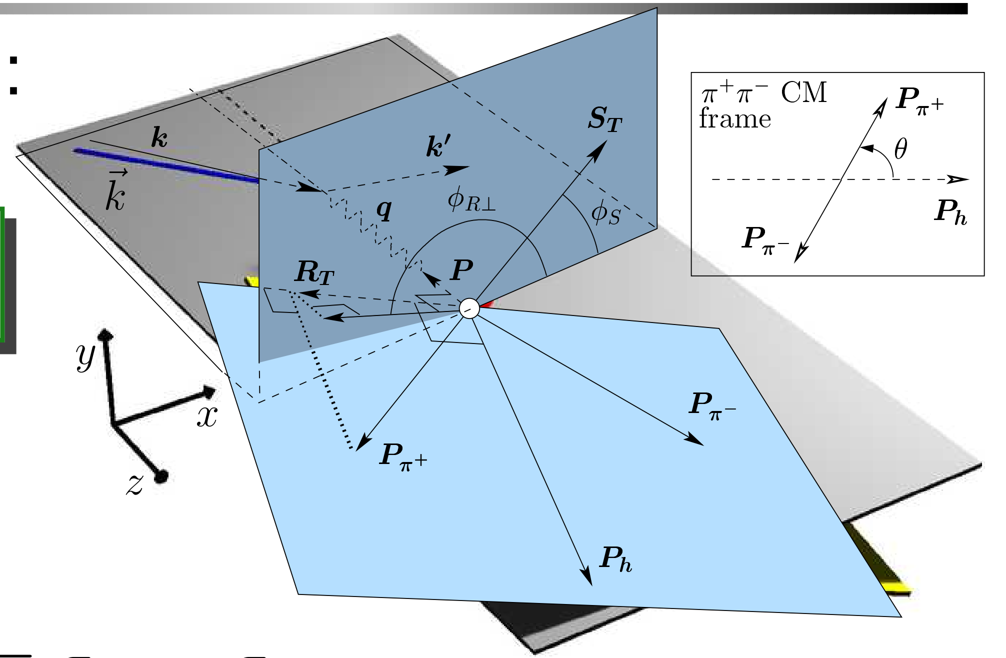

difficult to measure directly $\sigma_{UT} \equiv \sigma_{U\uparrow} - \sigma_{U\downarrow}$

$\Rightarrow$ measure cross section asymmetry A_{UT}:

$$A_{UT} \equiv \frac{1}{\langle |S_T| \rangle} \frac{N_{2\pi}^{\uparrow}(\phi_{R\perp}, \phi_S, \theta) - N_{2\pi}^{\downarrow}(\phi_{R\perp}, \phi_S, \theta)}{N_{2\pi}^{\uparrow}(\phi_{R\perp}, \phi_S, \theta) + N_{2\pi}^{\downarrow}(\phi_{R\perp}, \phi_S, \theta)}$$

$\uparrow\downarrow$ ... **target spin states**
$N_{2\pi}$ ... **(norm.) 2π yield**
S_T... **target polarization**

2-Hadron Fragmentation in Semi-Inclusive DIS

polarized 2-hadron cross section:

(**U**npolarized beam, **T**ransversely pol. target)

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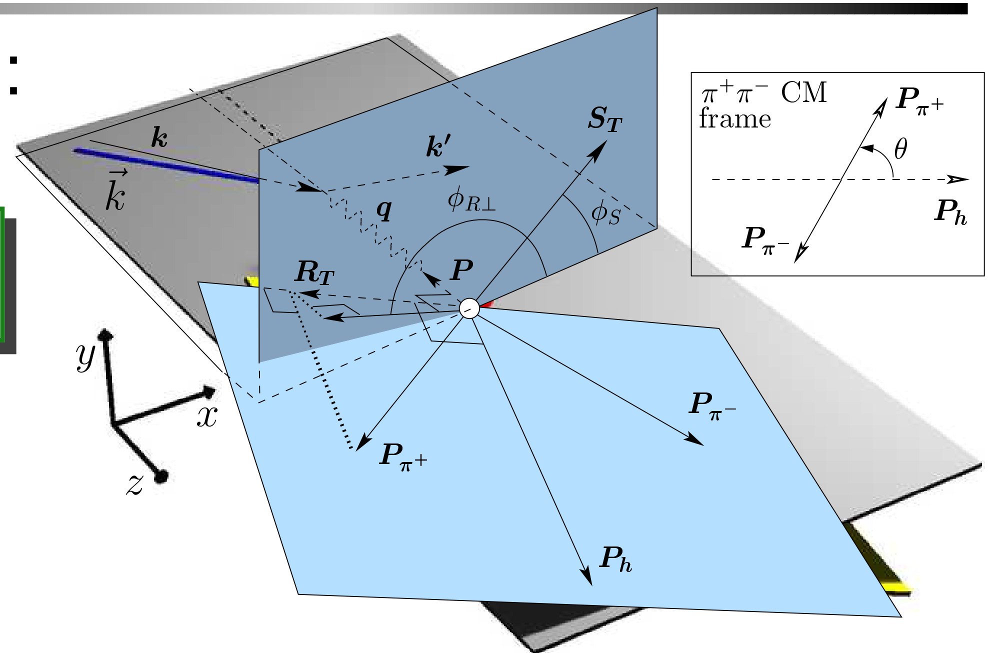

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$\uparrow\downarrow$ . . . **target spin states**
$N_{2\pi}$ . . . **(norm.) 2π yield**
S_T . . . **target polarization**

But: asymmetry involves unknown unpolarized 2π cross section

Interference Fragmentation – Models

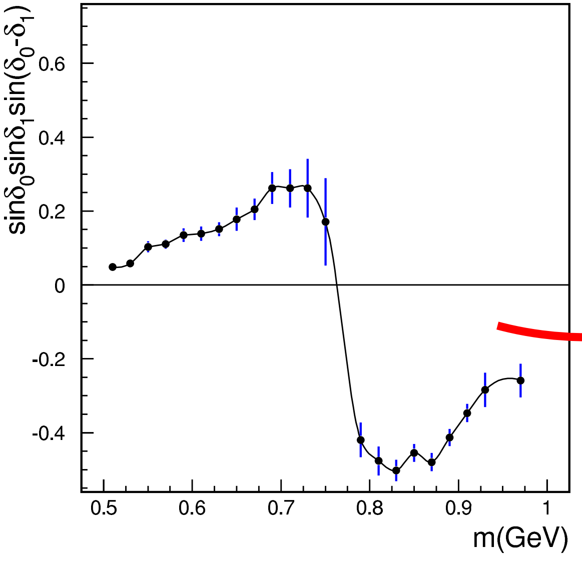
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

Expansion of $H_1^{\sphericalangle}$ in Legendre moments:

$$H_1^{\sphericalangle}(z, \cos\theta, M_{\pi\pi}^2) = H_1{}^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\theta H_1{}^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$

describe interference between 2 pion pairs coming from different production channels.

about $H_1^{\sphericalangle,sp}$:



Jaffe et al. [**hep-ph/9709322**]:

$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) H_1^{\sphericalangle,sp'}(z)$$

δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

$$= \mathcal{P}(M_{\pi\pi}^2) H_1^{\sphericalangle,sp'}(z)$$

$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

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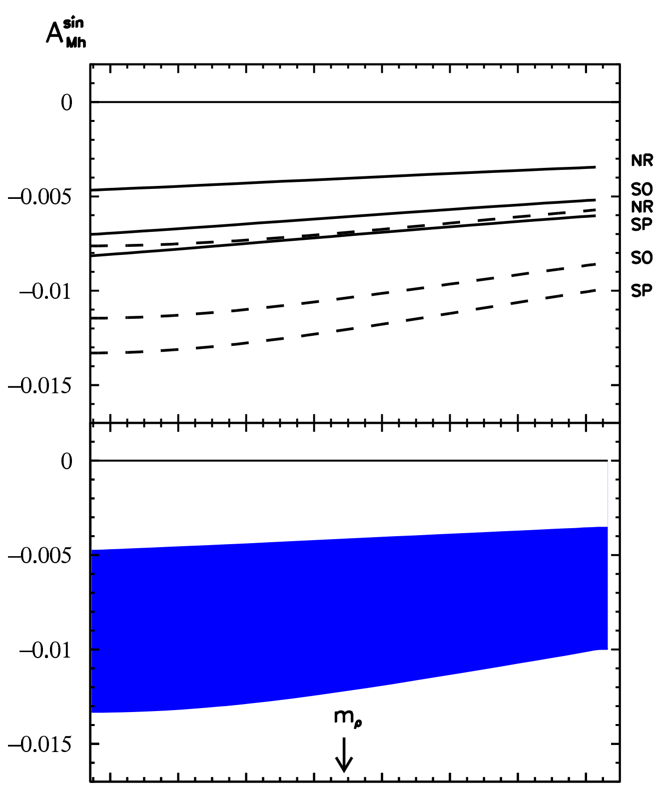
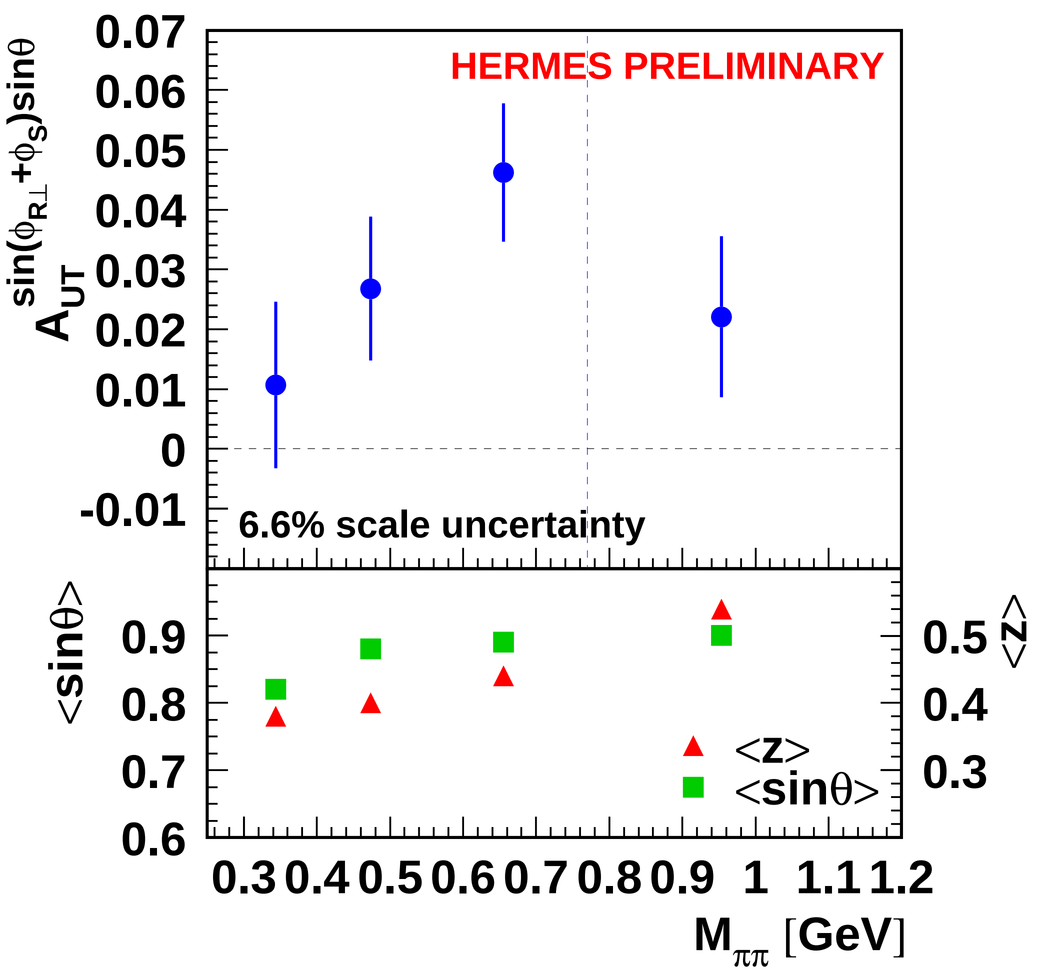


Radici et al. [**hep-ph/0110252**]:

- completely different model, not predicting a sign change of the asymmetry

Mass Dependence of A_{UT}
2002-04 Data



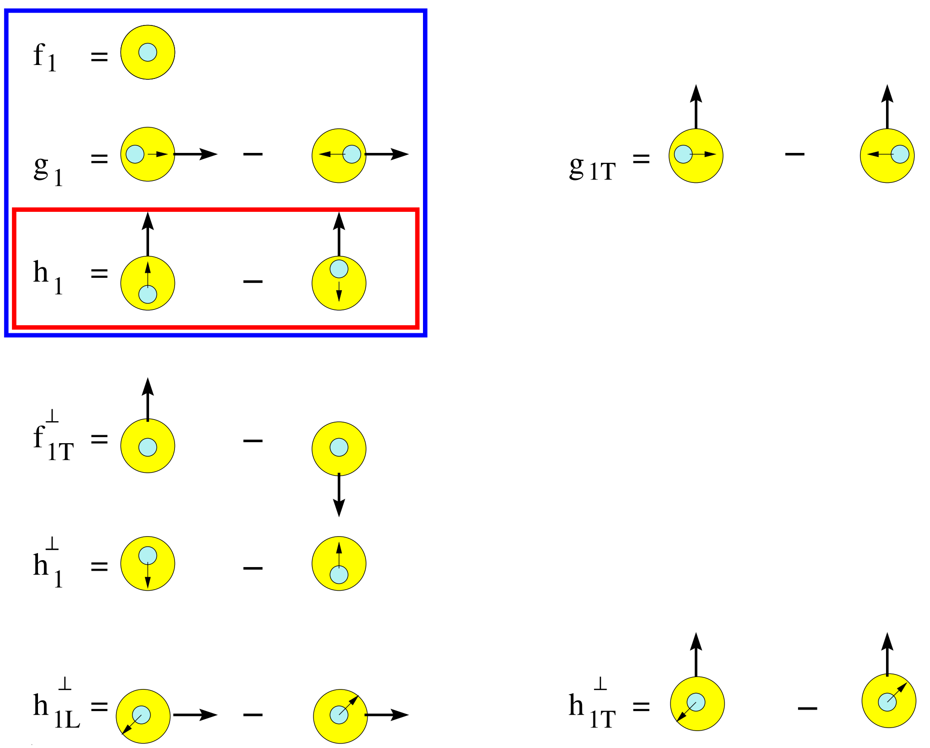
- 2-hadron (aka Interference) FF is not zero!
- asymmetry grows with $M_{\pi\pi}$ below ρ^0 mass
- positive asymmetries in all invariant mass bins
- rules out predicted sign change at ρ^0 mass (Jaffe et al.)
- to extract transversity (h_1) need IFF from Belle (or BaBar etc.)
- non-zero IFF shows feasibility of using it at, e.g., RHIC for transversity measurements

Semi-Inclusive 1-Hadron Production

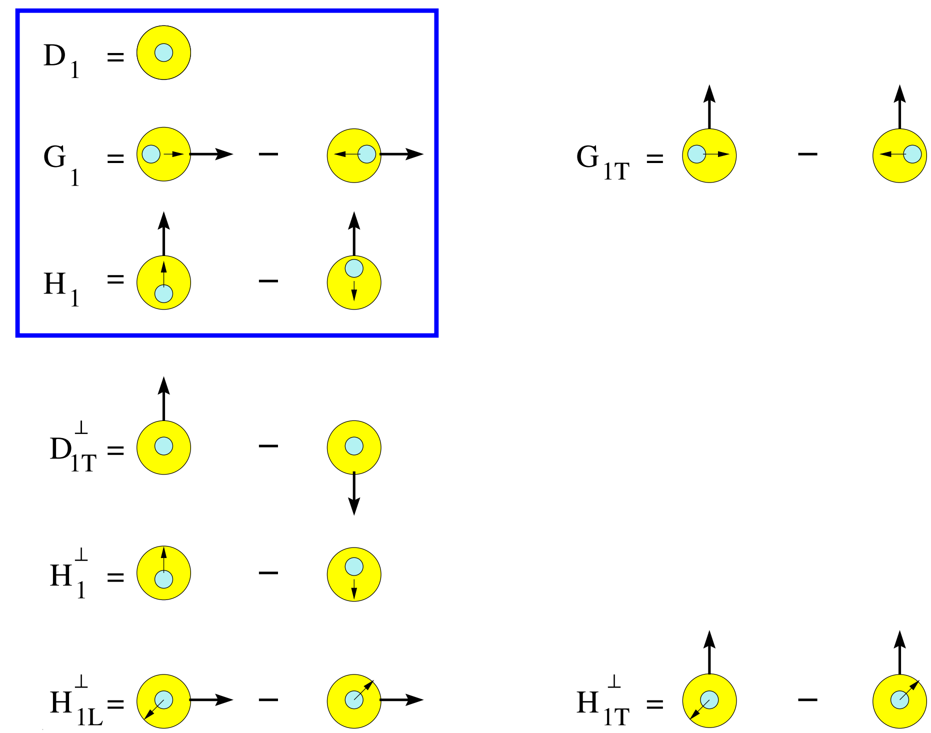
SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions



Fragmentation Functions

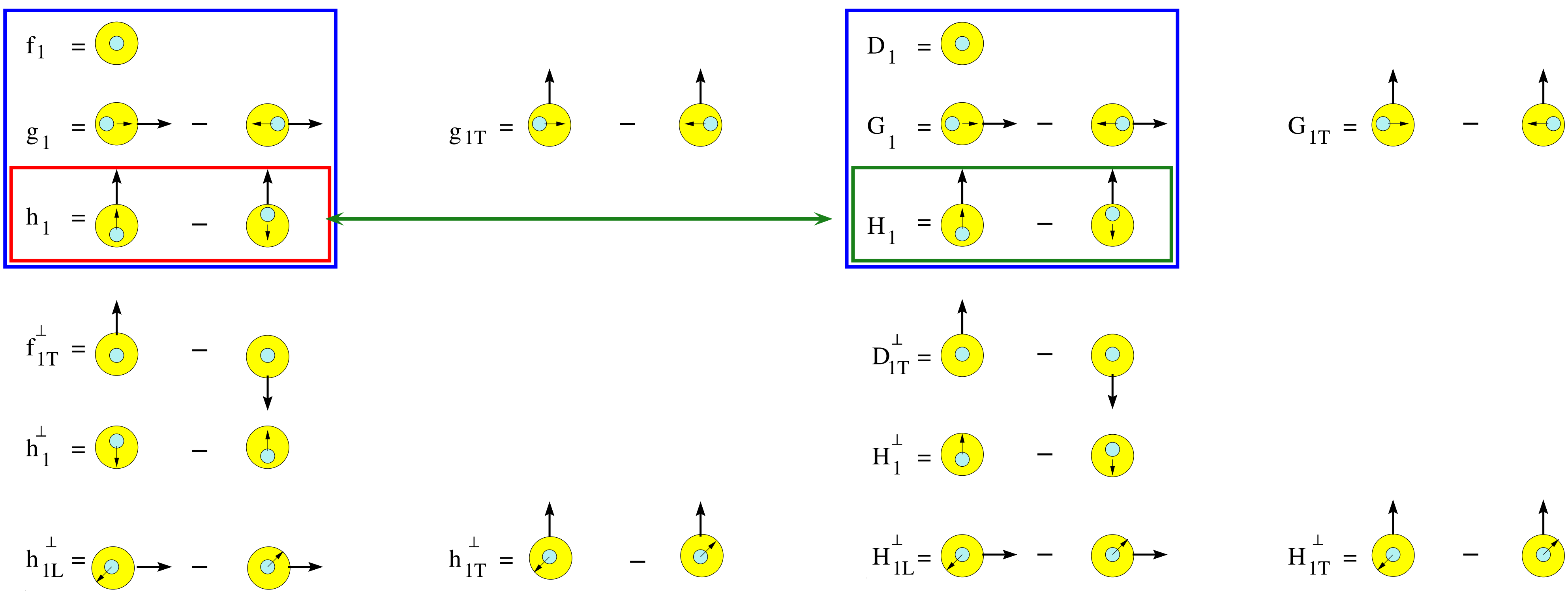


Chiral-odd transversity h_1 must couple to chiral-odd FF

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions — Fragmentation Functions



Chiral-odd transversity h_1 must couple to chiral-odd FF

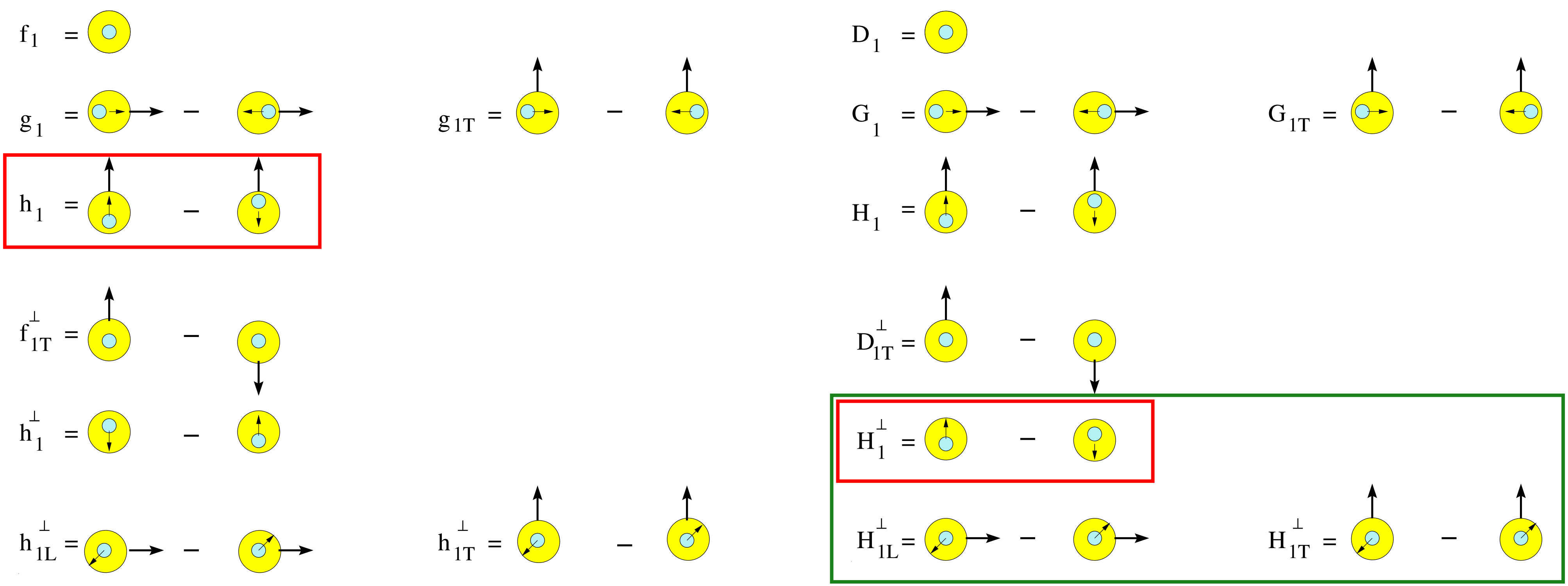
$\Rightarrow$ H_1 is the only k_T-integrated chiral-odd FF $\Rightarrow$ DSA

(Example: transverse-spin transfer in Λ-production)

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions | **Fragmentation Functions**



Chiral-odd transversity h_1 must couple to chiral-odd FF

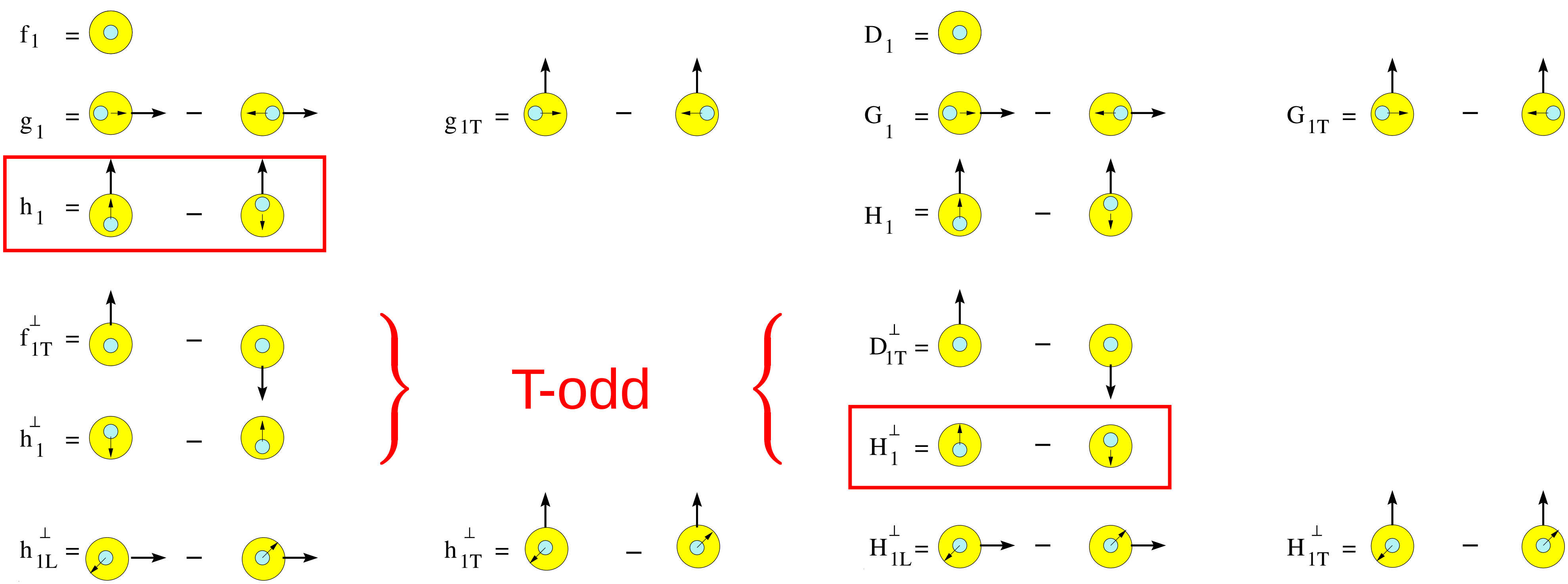
can use k_T-unintegrated chiral-odd FF $\Rightarrow$ T-odd Collins FF

$\Rightarrow$ leads to Single-Spin Asymmetrie (SSA)

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions | Fragmentation Functions

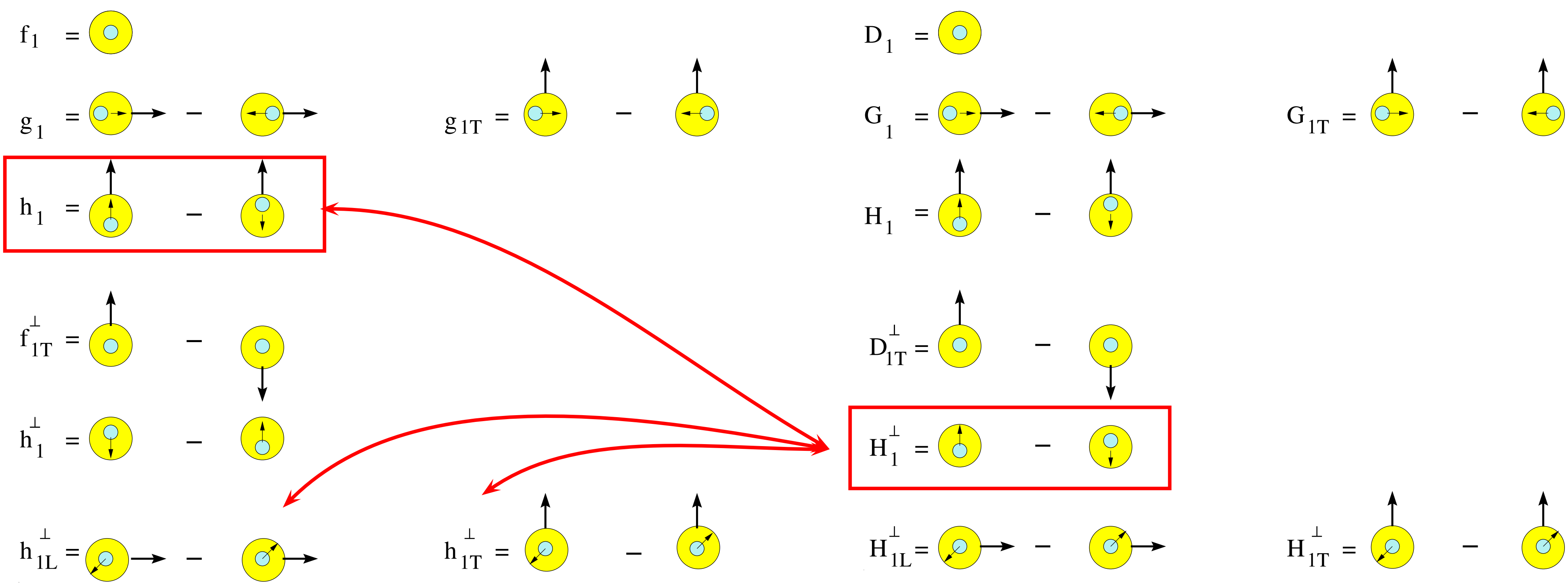


SSAs require one and only one T-odd function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions | **Fragmentation Functions**



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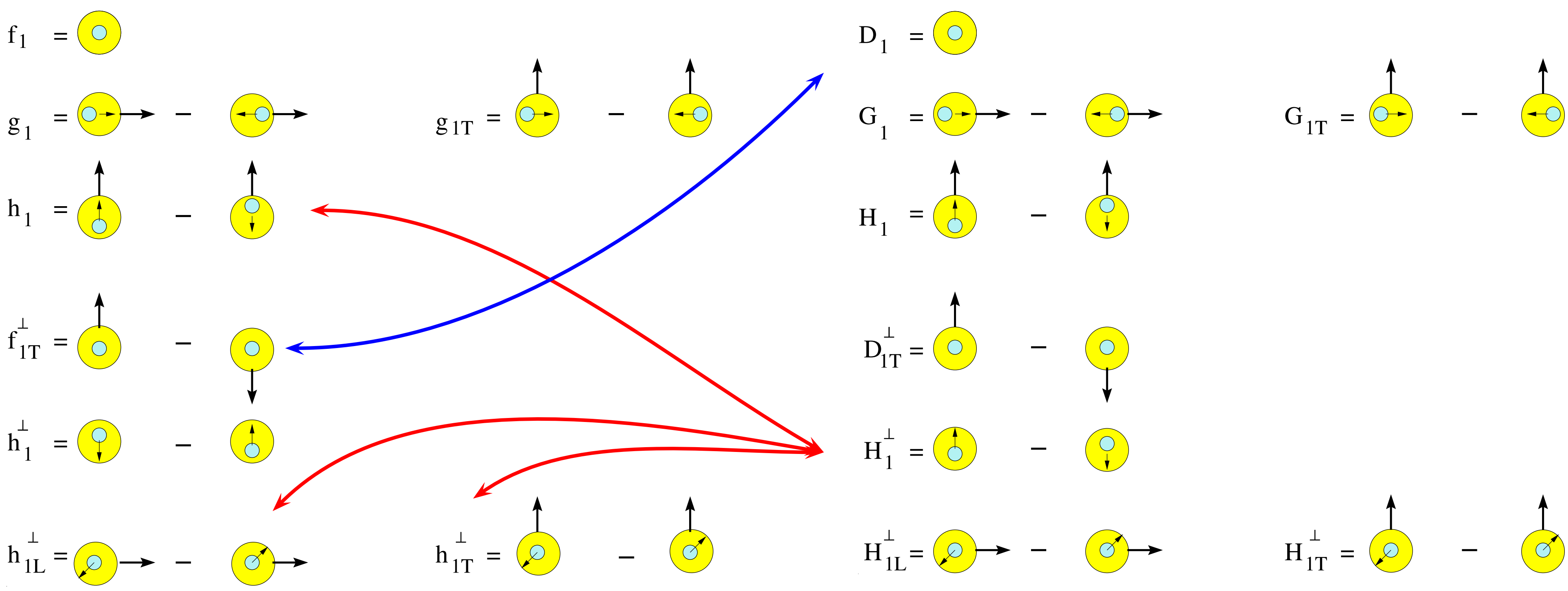
$\Rightarrow$ SSAs through Collins function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions | Fragmentation Functions



SSAs require one and only one T-odd function

$\Rightarrow$ SSAs through Collins function or Sivers function

(Boer-Mulders DF couples to H_1, but SSA requires polarization of final state!)

SIDIS Cross Section (up to subleading order in 1/Q)

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

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

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

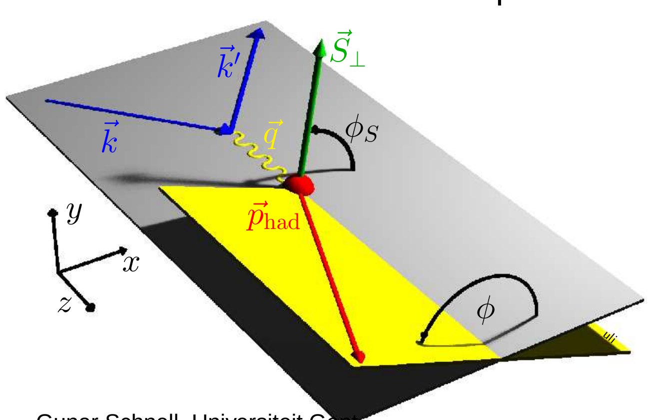
$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right)$$

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

σ_{XY}

Beam (X) **Target** (Y)

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

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

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

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

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

σ_{XY}: X → **Beam**, Y → **Target**
Polarization

This talk:

$\sin\phi \, d\sigma_{UL}^{5}$	...	Subleading Twist
$\sin(\phi-\phi_S) \, d\sigma_{UT}^{8}$	...	Sivers Effect
$\sin(\phi+\phi_S) \, d\sigma_{UT}^{9}$	...	Collins Effect

SIDIS Cross Section
(up to subleading order in 1/Q)

$$
\begin{aligned}
d\sigma =\ & d\sigma^0_{UU} + \cos 2\phi\, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^3_{LU} \\
& + S_L \left\{ \sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL} \right] \right\} \\
& + S_T \left\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \right. \\
& \quad + \frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT} \right) \\
& \quad \left. + \lambda_e \left[\cos(\phi-\phi_S)\, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S\, d\sigma^{14}_{LT} + \cos(2\phi-\phi_S)\, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

σ_{XY}: X → **Beam**, Y → **Target** **Polarization**

Also Interesting:

(and under study!)

$\sin\phi_S\, d\sigma^{12}_{UT}$, $\cos\phi_S\, d\sigma^{14}_{LT}$ ... $\Rightarrow$ Transversity, g_2

$\cos\phi\, d\sigma^2_{UU}$ ... Cahn Effect

$\cos 2\phi\, d\sigma^1_{UU}$ ... Boer-Mulders Effect

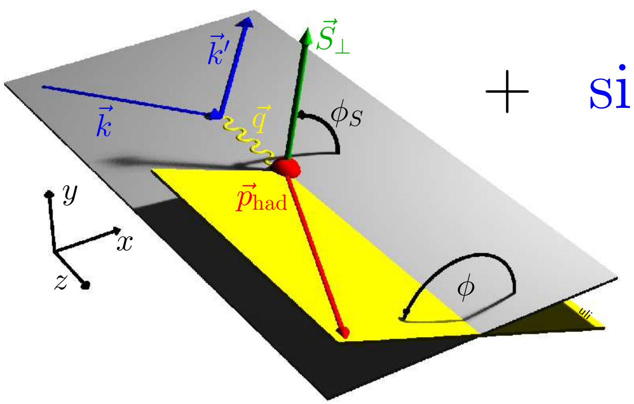
Azimuthal Single-Spin Asymmetries

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

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h\perp}}}{M_h} h_1^q(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$

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

$$+ \quad \cdots$$



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

$\Rightarrow$ 2D Max.Likelihd. fit of 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:

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

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

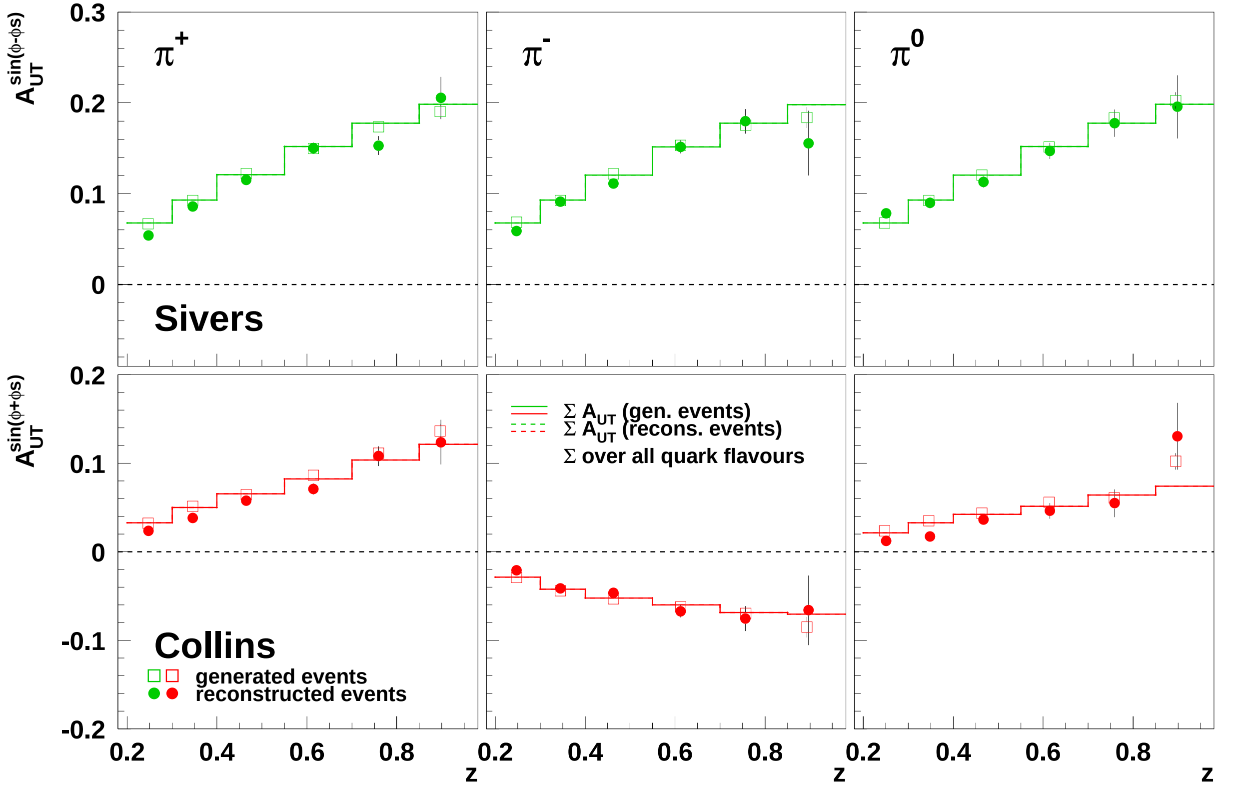
$$- \sin(\phi - \phi_S) \cdot \sum_q e_q^2 \, f_{1T}^{\perp(1),q}(x) \, z \, D_1^q(z)$$

$$+ \ldots$$

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

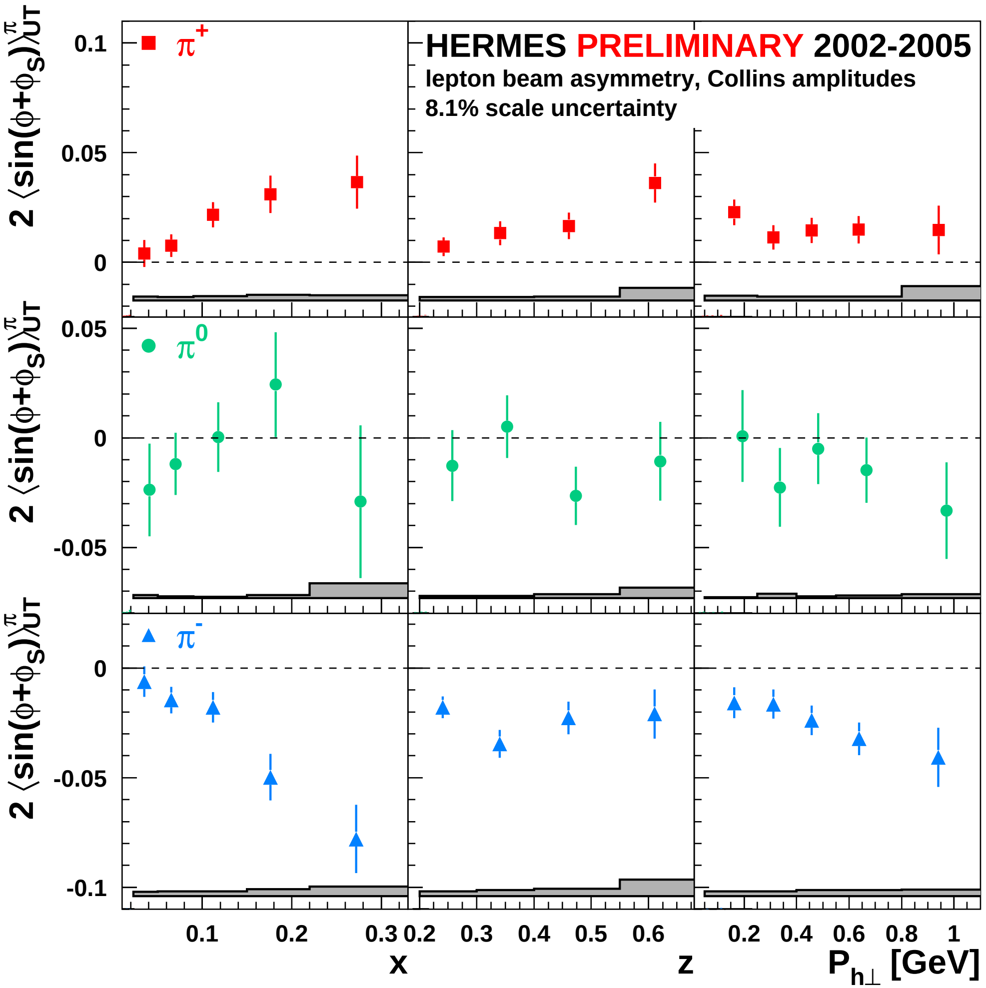
Monte Carlo Test of the Extraction Method

- generate Collins and Sivers asymmetries (Gaussian Ansatz in p_T^2)
- analyze MC data like experimental data and extract amplitudes:



- Collins-Sivers cross contamination negligible
- insensitive to $\cos(2\phi)$ moments in unpolarized cross section
- insensitive to transverse target tracking corrections

Collins Amplitudes 2002-2005

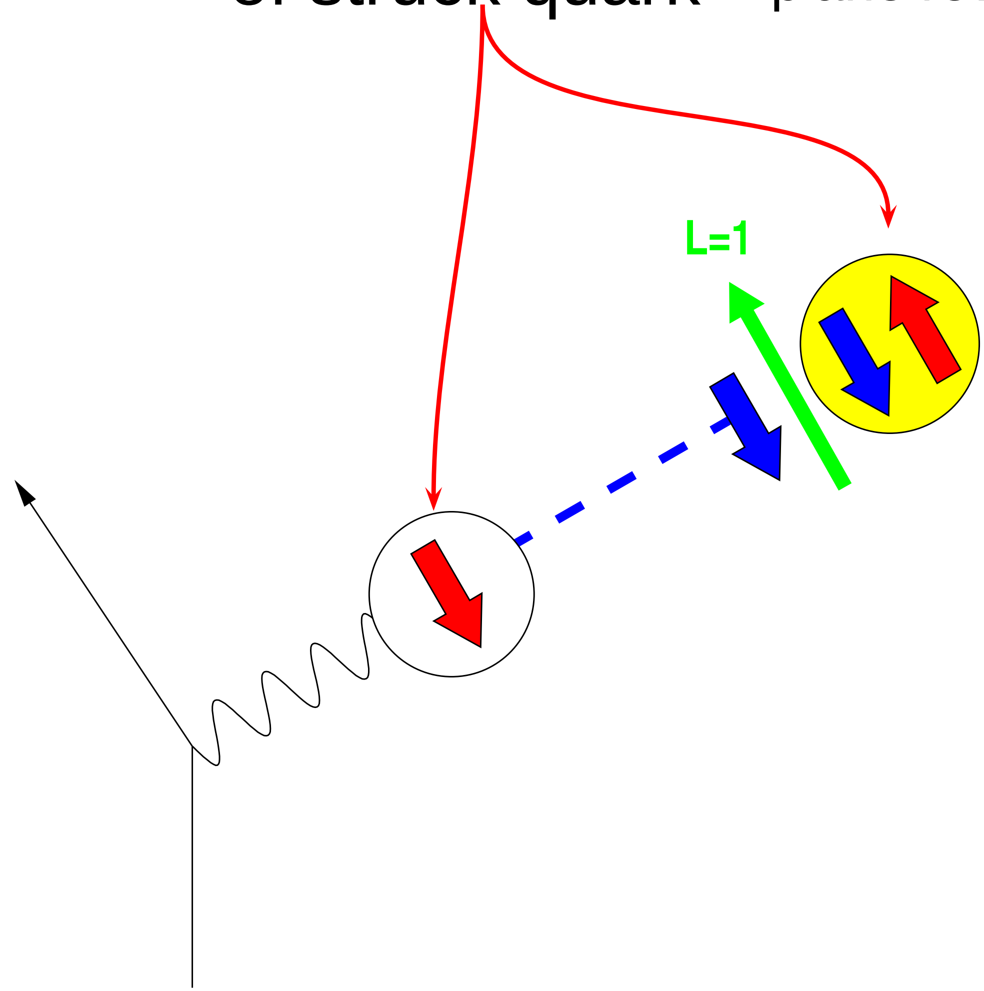


- published† results confirmed with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u > 0$
  $\delta d < 0$)
- unexpected large π^- asymmetry
  $\Rightarrow$ role of disfavored Collins FF
  most likely: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- isospin symmetry among charged and neutral pions fulfilled

† [*A. Airapetian et al*, **Phys. Rev. Lett. 94 (2005) 012002**]

Understanding the Collins FF - String Model Interpretation (Artru)

transverse spin of struck quark (polarization component in lepton scattering plane reversed by photoabsorption)



Understanding the Collins FF - String Model Interpretation (Artru)

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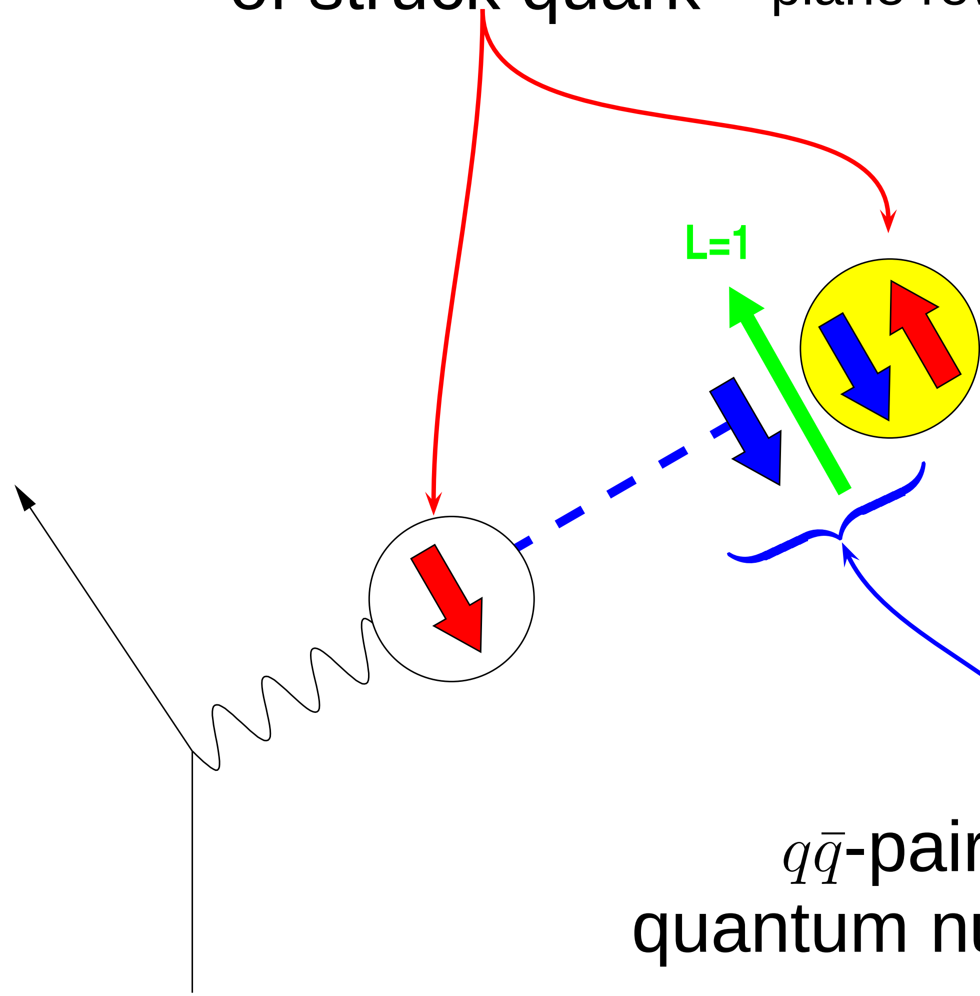
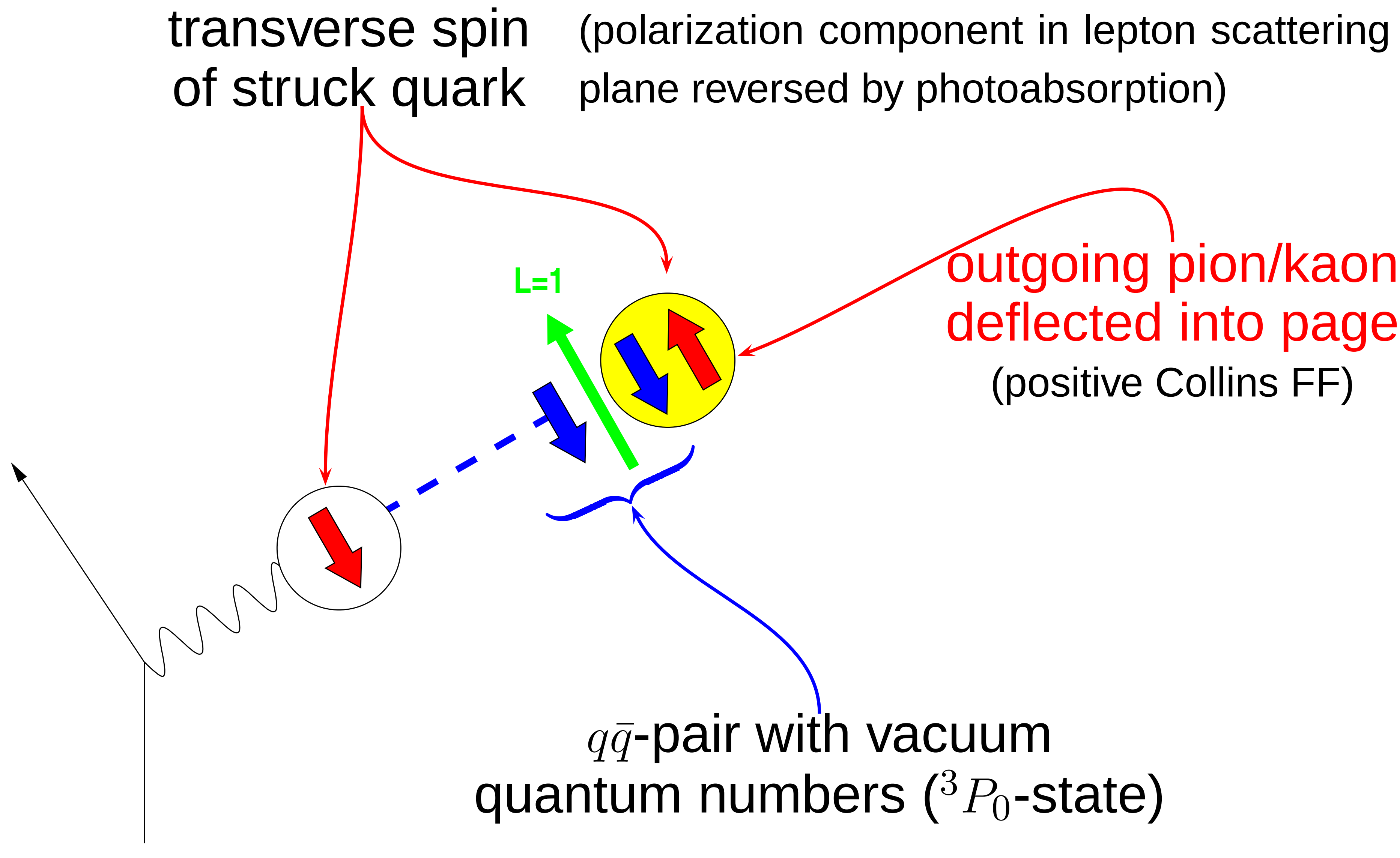


$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

Understanding the Collins FF - String Model Interpretation (Artru)



Understanding the Collins FF - String Model Interpretation (Artru)

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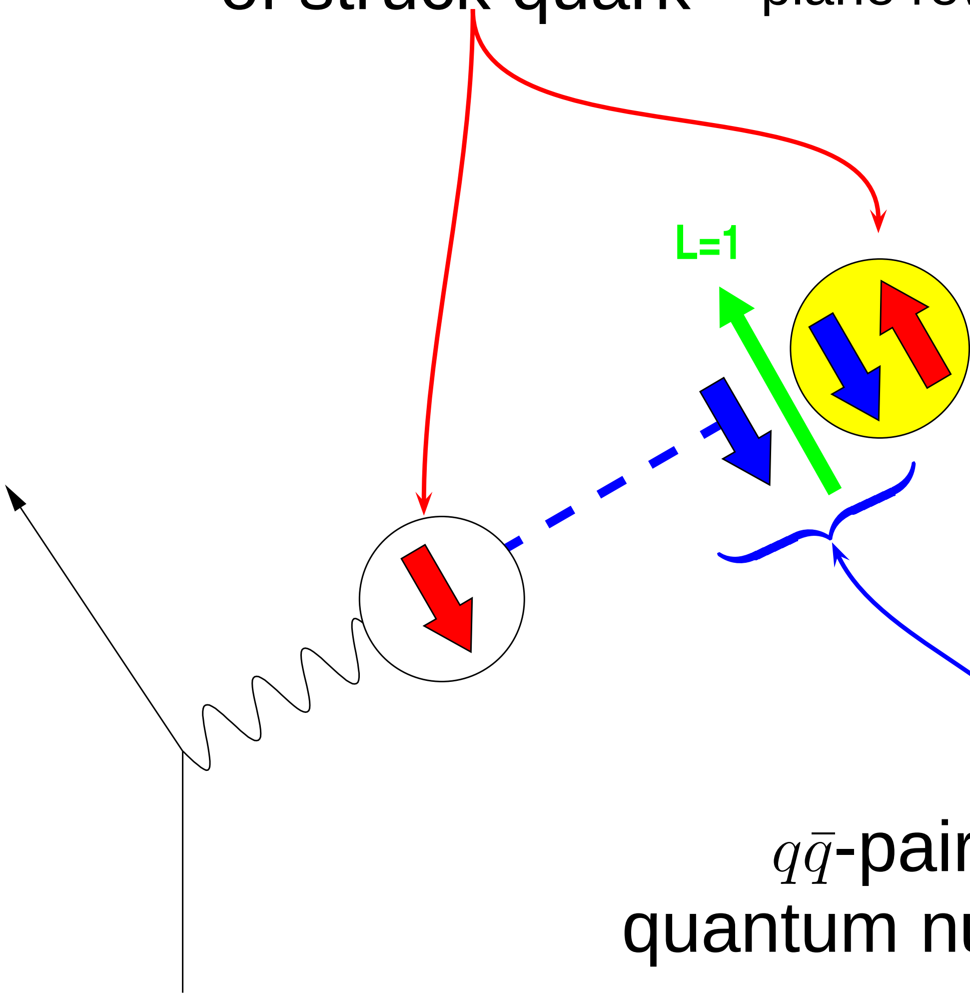
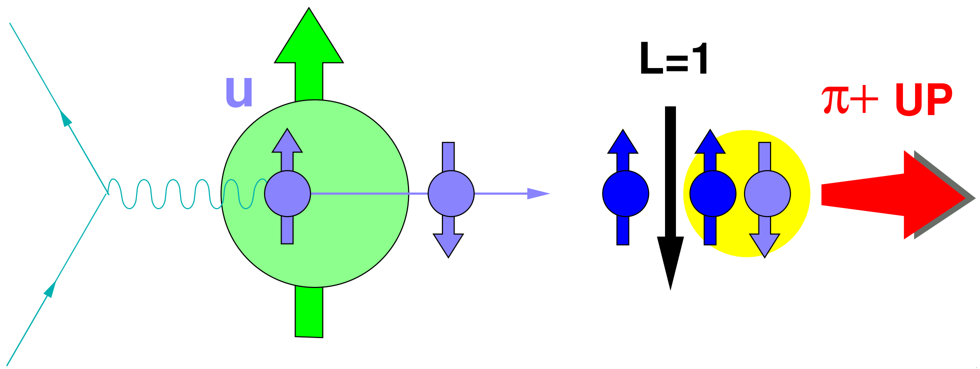


outgoing pion/kaon deflected into page
(positive Collins FF)

pion from next string break deflected out of page
(negative Collins FF)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

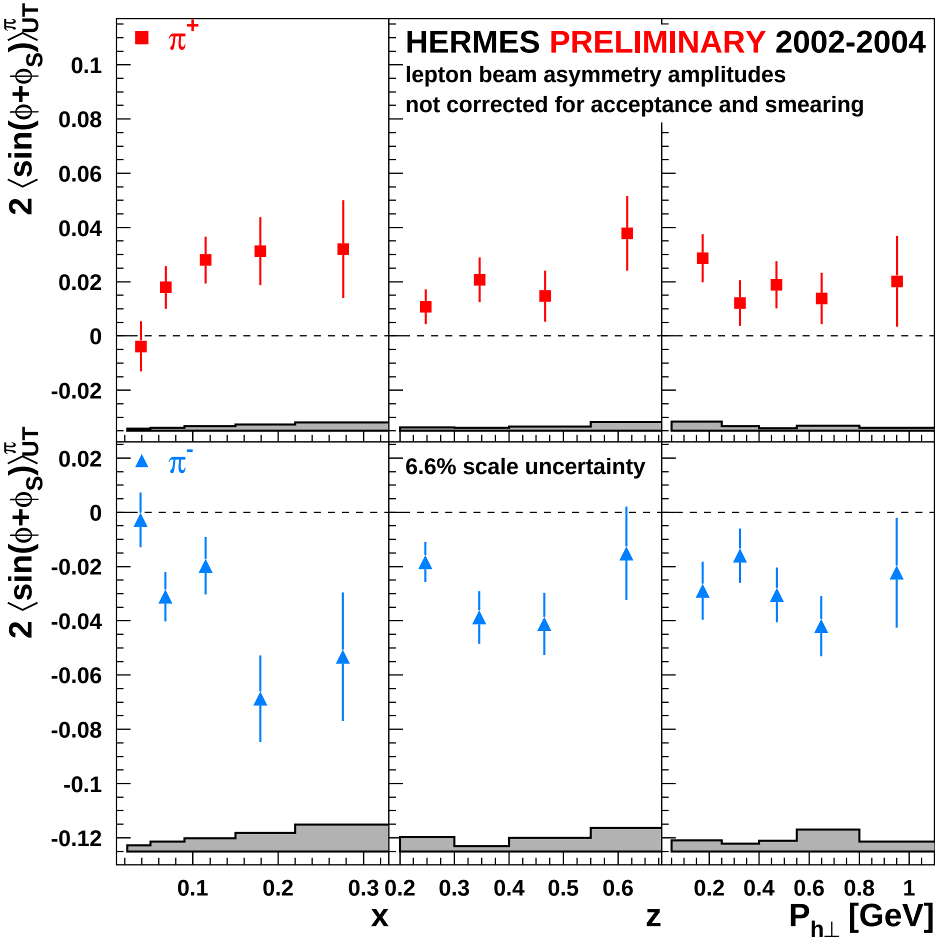
Artru Model vs. HERMES



$$\left.\begin{array}{rl}\phi_S = & 0 \\ \phi & = \pi/2\end{array}\right\} \sin(\phi + \phi_S) > 0$$

The Collins Effect

Artru Model vs. HERMES

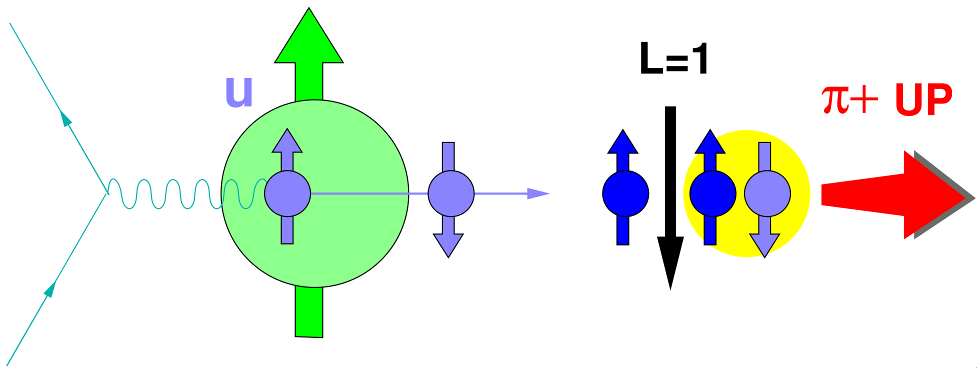


$$\left.\begin{aligned} \phi_S &= \ \ 0 \\ \phi \ &= \pi/2 \end{aligned}\right\} \sin(\phi + \phi_S) > 0$$

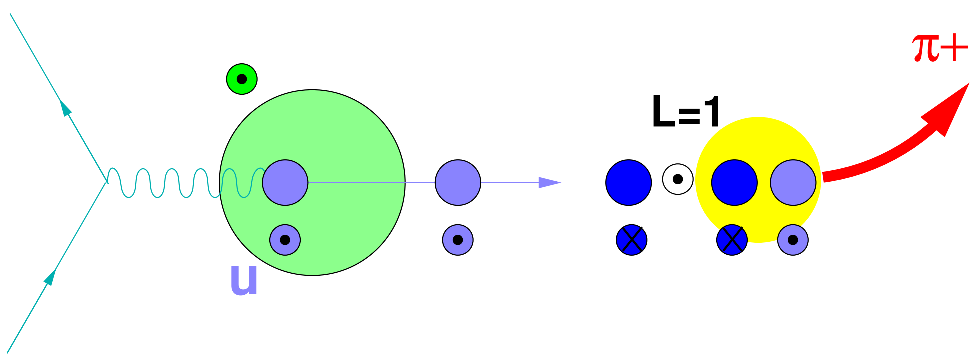
✓

The Collins Effect

Artru Model vs. HERMES



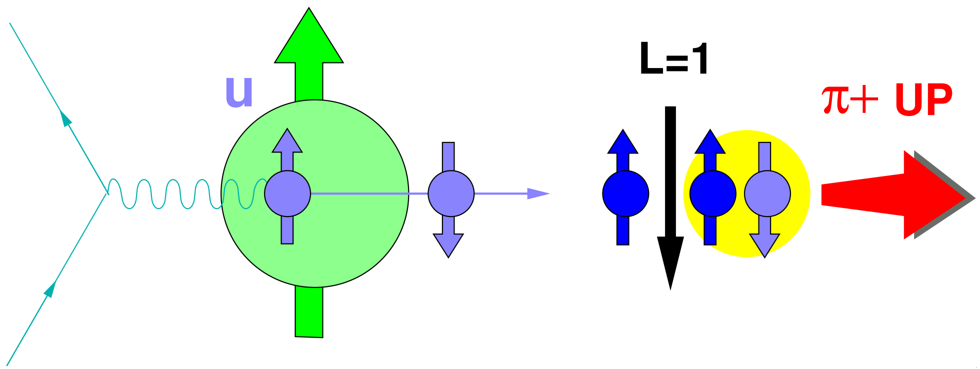
$$\left.\begin{array}{l}\phi_S = \ \ 0\\ \phi \ = \pi/2\end{array}\right\} \sin(\phi+\phi_S) > 0$$



$$\left.\begin{array}{l}\phi_S = \pi/2\\ \phi \ = \ \ 0\end{array}\right\} \sin(\phi+\phi_S) > 0$$

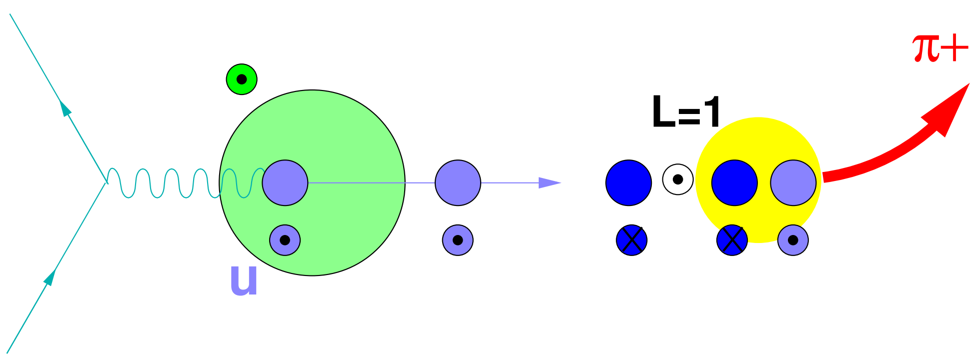
The Collins Effect

Artru Model vs. HERMES



$$\left.\begin{aligned}\phi_S &= \ 0 \\ \phi &= \pi/2\end{aligned}\right\} \sin(\phi+\phi_S) > 0$$

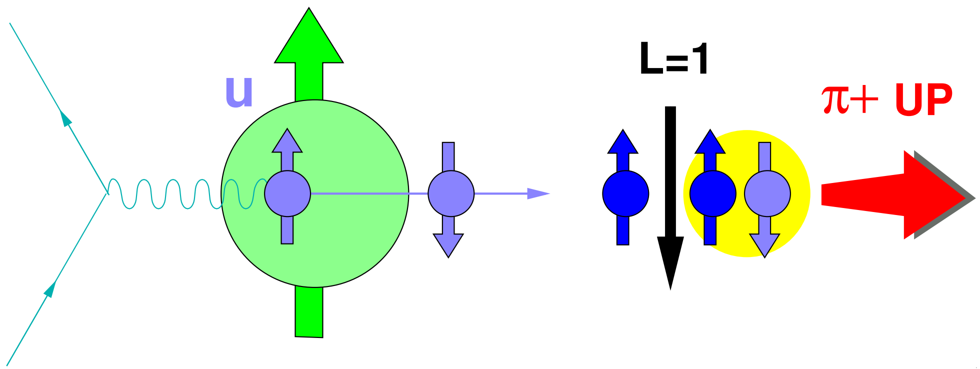
✓



$$\left.\begin{aligned}\phi_S &= \pi/2 \\ \phi &= \ 0\end{aligned}\right\} \sin(\phi+\phi_S) > 0$$

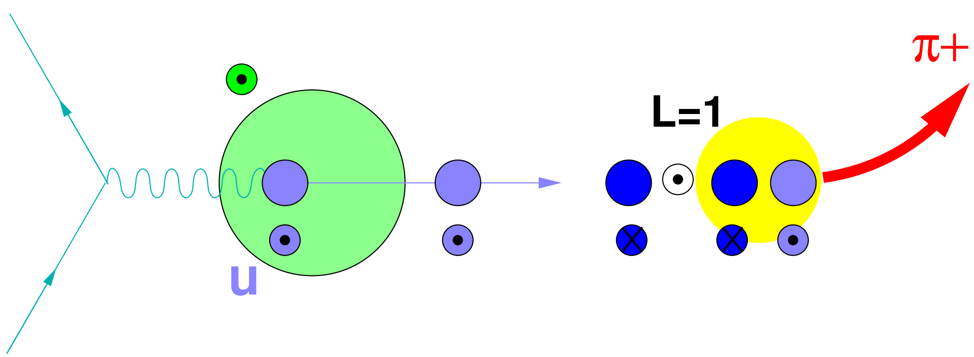
✓

Artru Model vs. HERMES



$$\left.\begin{array}{rl}\phi_S = & 0 \\ \phi = & \pi/2\end{array}\right\} \sin(\phi+\phi_S) > 0$$

✓

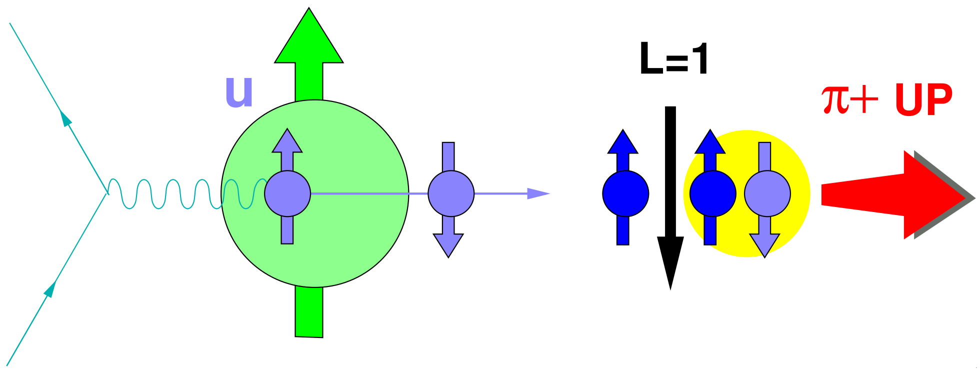


$$\left.\begin{array}{rl}\phi_S = & \pi/2 \\ \phi = & 0\end{array}\right\} \sin(\phi+\phi_S) > 0$$

✓

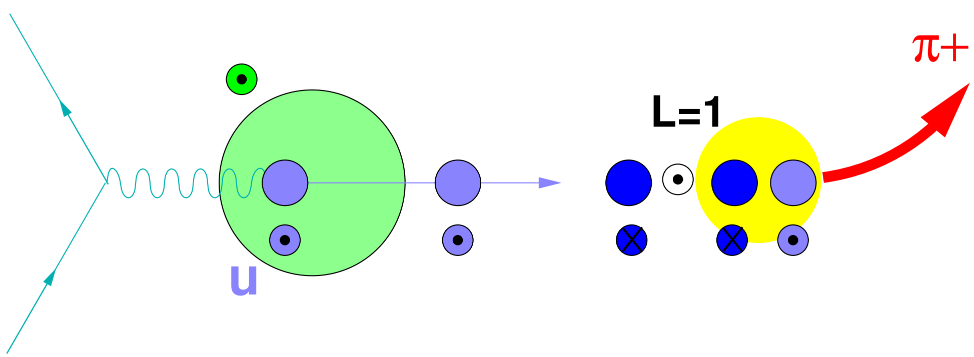
Artru model and HERMES results in agreement!
(assuming u-quark transversity positive)

Artru Model vs. HERMES



$$\left.\begin{array}{rl}\phi_S = & 0 \\ \phi = & \pi/2\end{array}\right\} \sin(\phi + \phi_S) > 0$$

✓

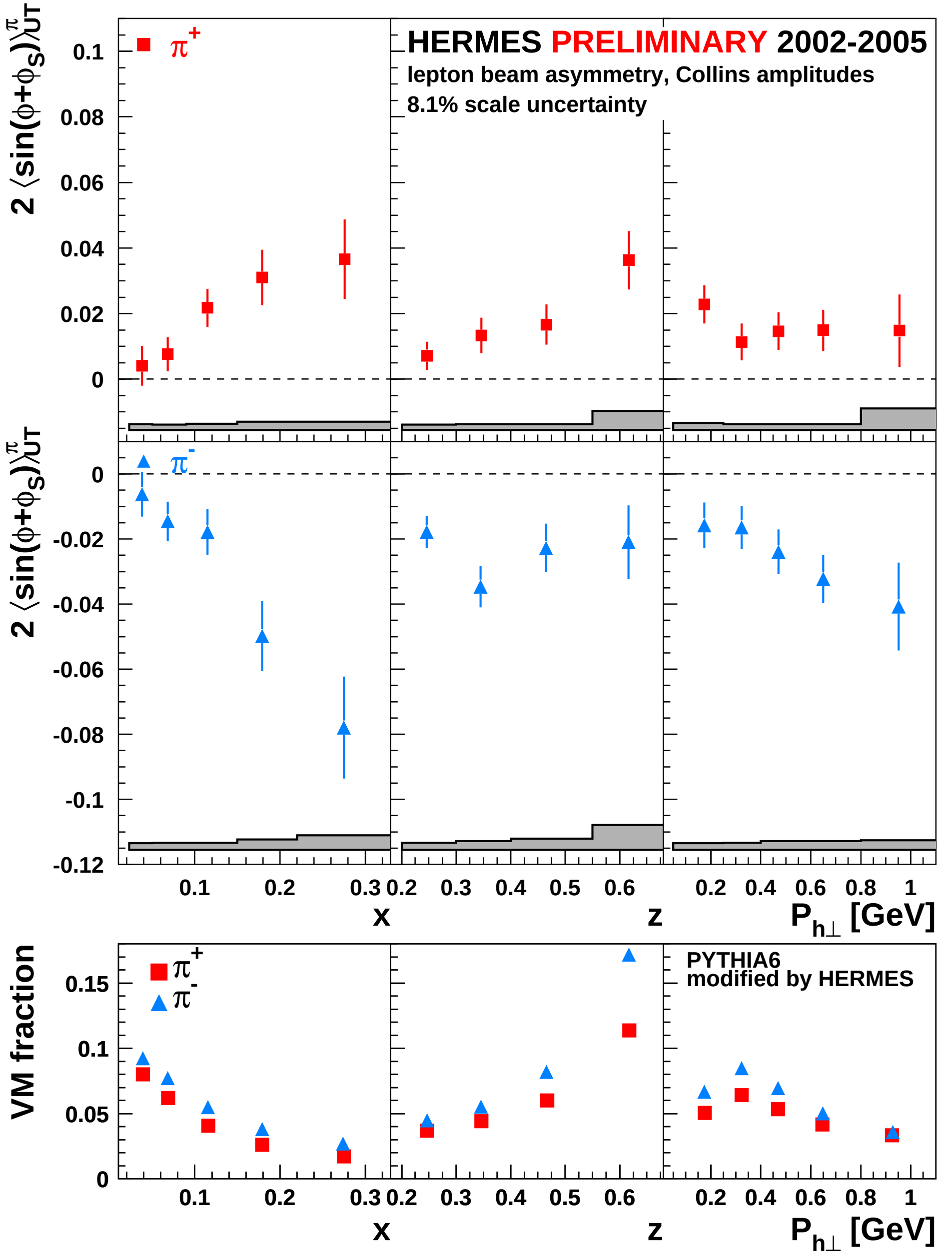


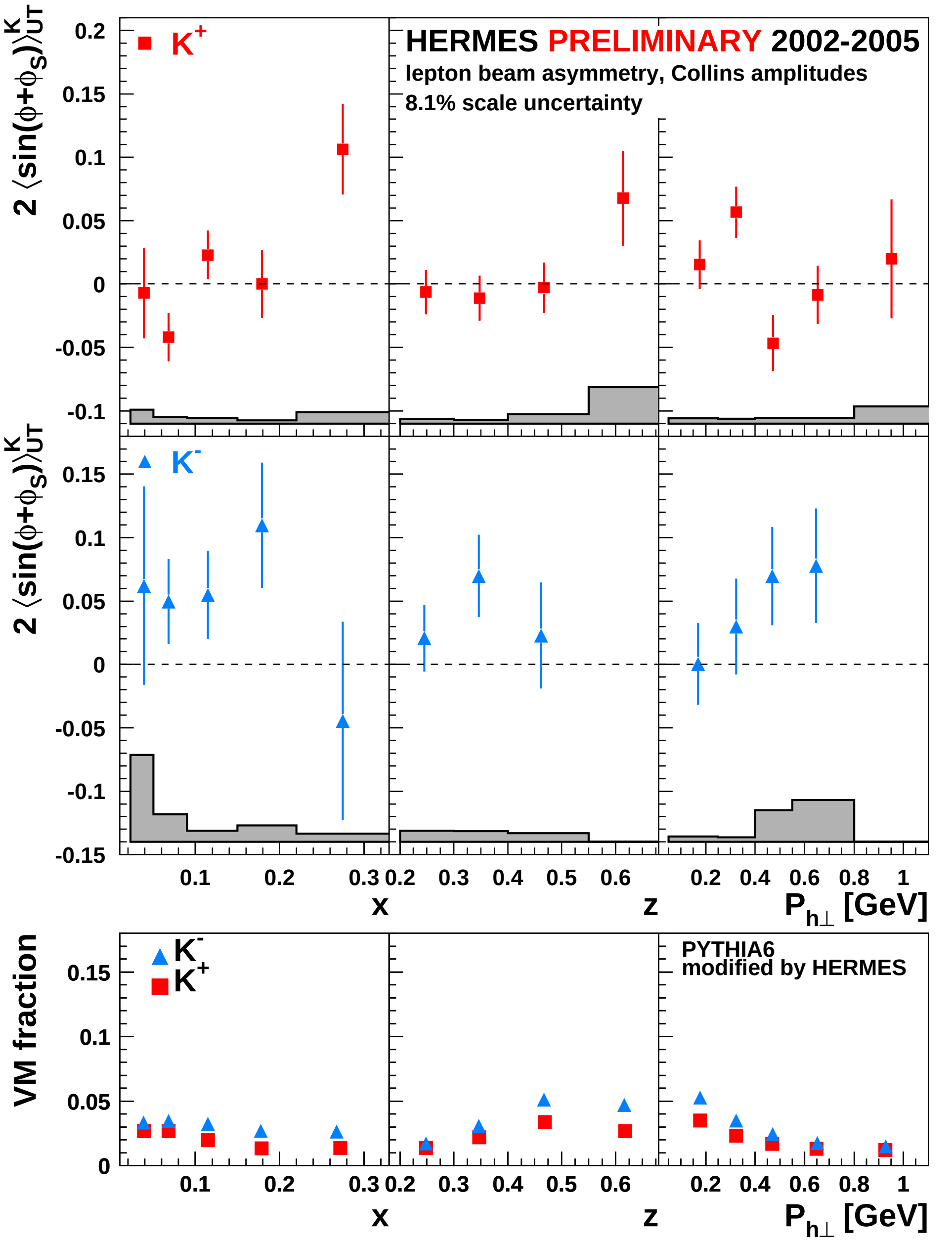
$$\left.\begin{array}{rl}\phi_S = & \pi/2 \\ \phi = & 0\end{array}\right\} \sin(\phi + \phi_S) > 0$$

✓

Artru model and HERMES results in agreement also for π^-!
(e.g., assuming $h_1^u h_1^d < 0$ and using $H_1^{u\to\pi^-} H_1^{d\to\pi^-} < 0$)

Collins Amplitudes (2002-2005 data)

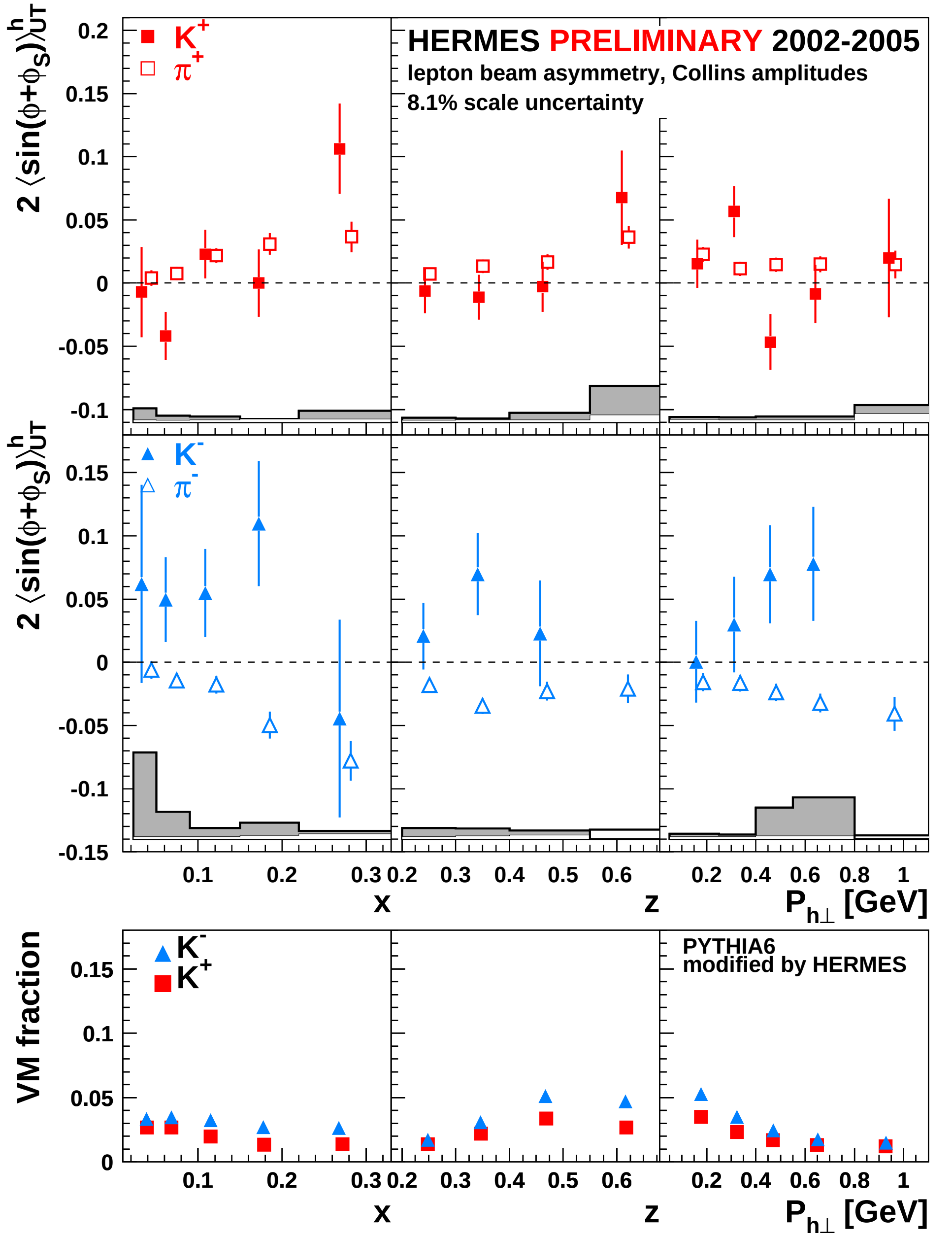




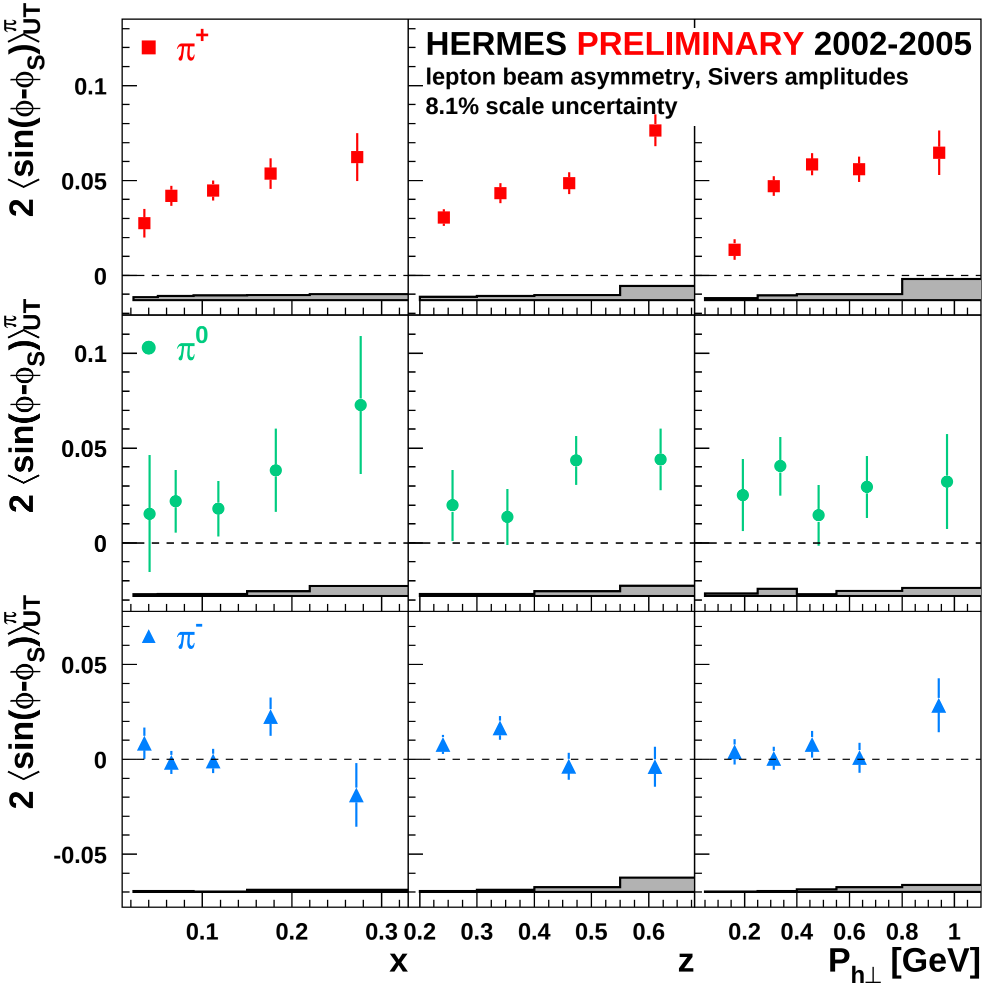
Collins Amplitudes (2002-2005 data)

- none of the kaon amplitudes significantly non-zero
- however, K^+ amplitudes not different from π^+ amplitudes
- K^- amplitudes slightly positive, contrary to large negative π^- amplitudes
- K^- pure sea object

$\Rightarrow$ production dominated by u-quark scattering



Sivers *Amplitudes (2002-2005 data)*



- published† results **confirmed** with much higher statistical precission
- overall scale uncertainty of 8.1%
- π^+: positive; π^-: consistent with zero

$\Rightarrow$ **first evidence for non-zero Sivers fct.:** $f_{1T}^{\perp,u} < 0$ (u-quark dominance)

$\Rightarrow$ **non-zero orbital angular momentum**

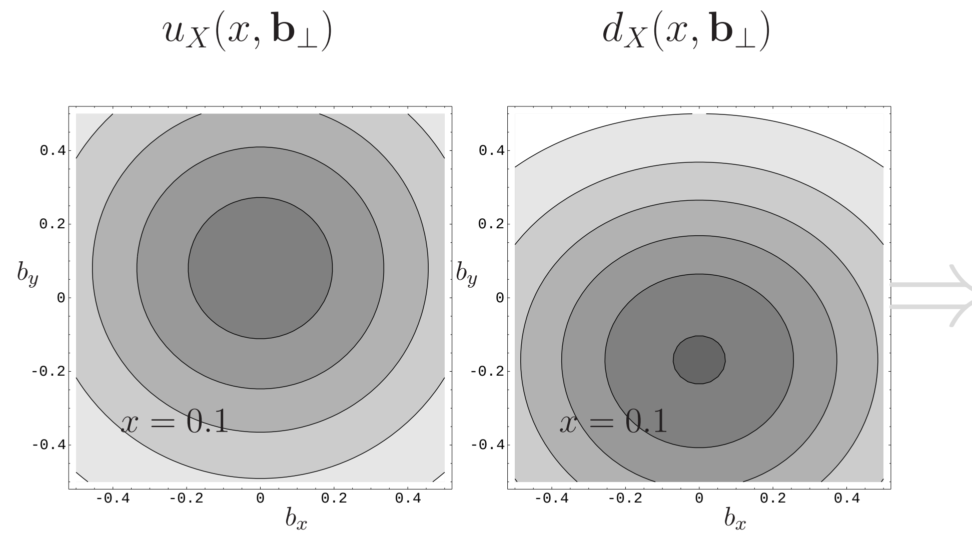
- Isospin symmetry for Sivers amplitudes fulfilled

† [*A. Airapetian et al*, Phys. Rev. Lett. 94 (2005) 012002]

approach by M. Burkardt: **[hep-ph/0309269]**

spatial distortion of q-distribution

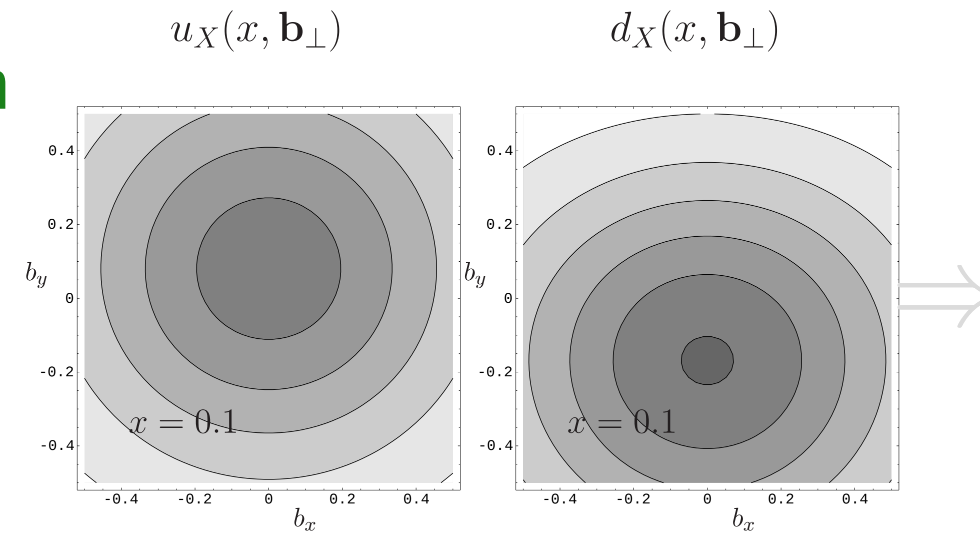
(obtained using anom. magn. moments & impact parameter dependent PDFs)



Chromodynamic Lensing
Understanding the Sivers Moments

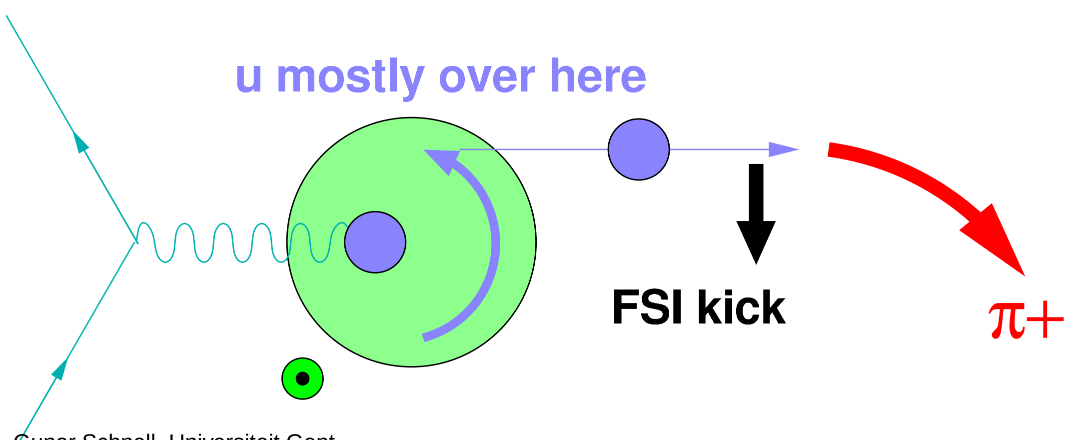
approach by M. Burkardt: [hep-ph/0309269]

spatial distortion of q-distribution
(obtained using anom. magn. moments
& impact parameter dependent PDFs)



+ attractive QCD potential
(gluon exchange)

$\Rightarrow$ transverse asymmetries



$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi \;=\; \pi\end{array}\right\} \sin(\phi - \phi_S) > 0$$

Chromodynamic Lensing

Understanding the Sivers Moments

approach by M. Burkardt:

spatial distortion of q-distribution

(obtained using anom. magn. moments

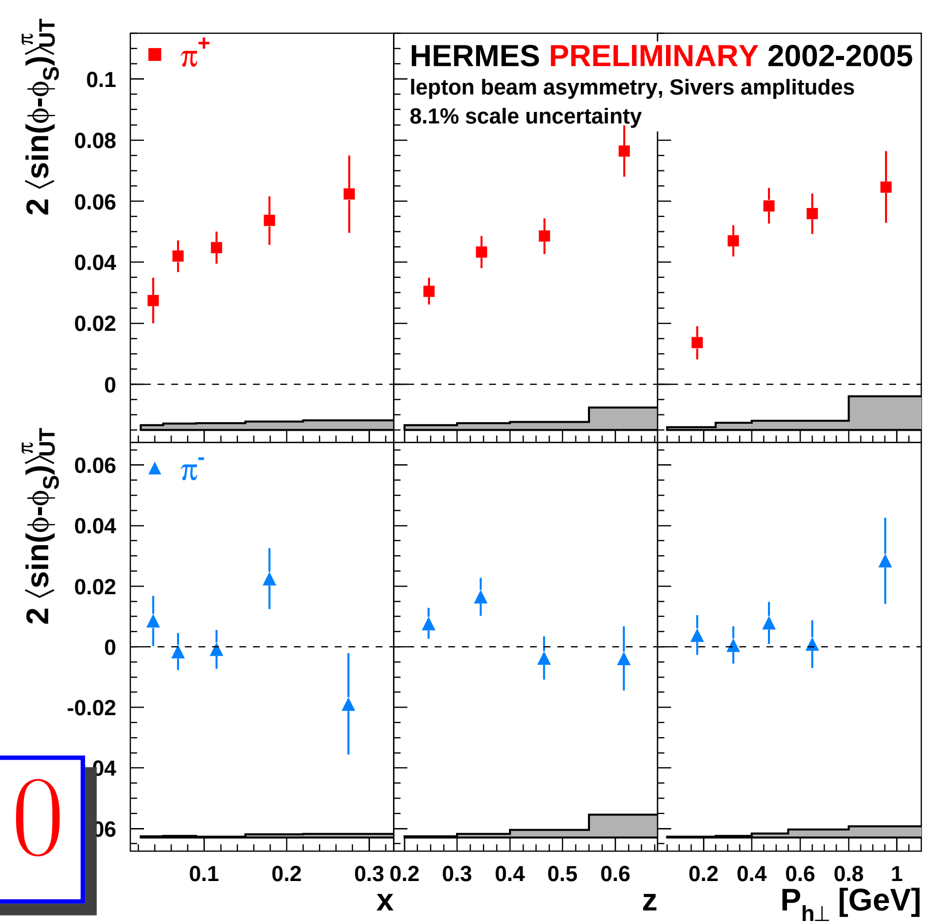
& impact parameter dependent PDFs)

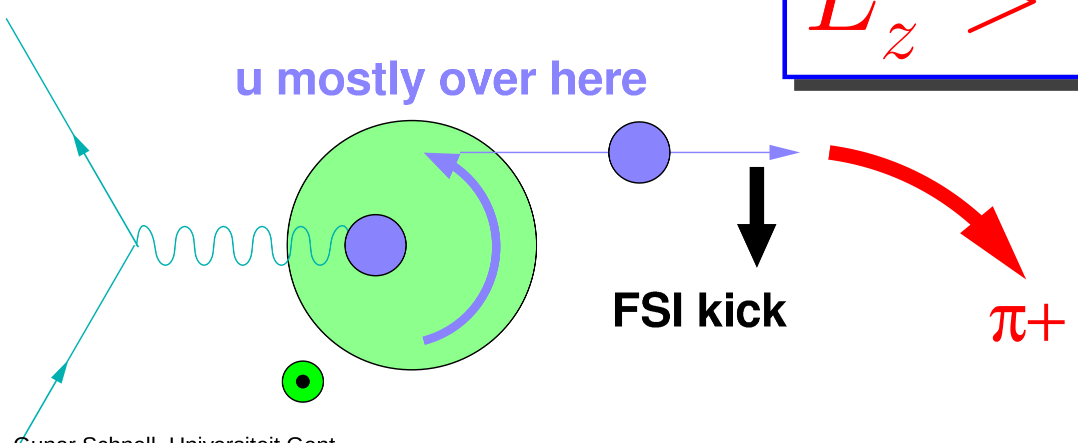
+ attractive QCD potential

(gluon exchange)

$\Rightarrow$ transverse asymmetries

$$L_z^u > 0$$

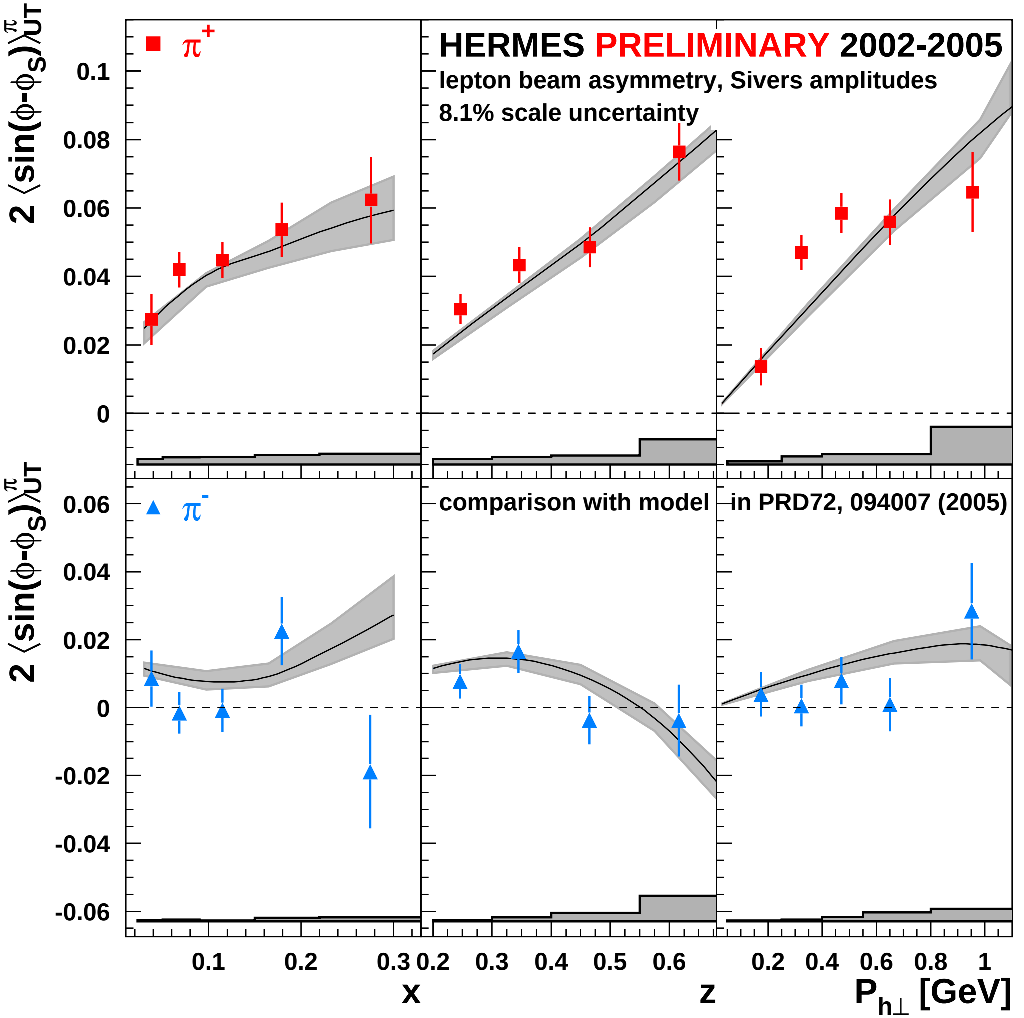




$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi = \pi\end{array}\right\} \sin(\phi - \phi_S) > 0$$

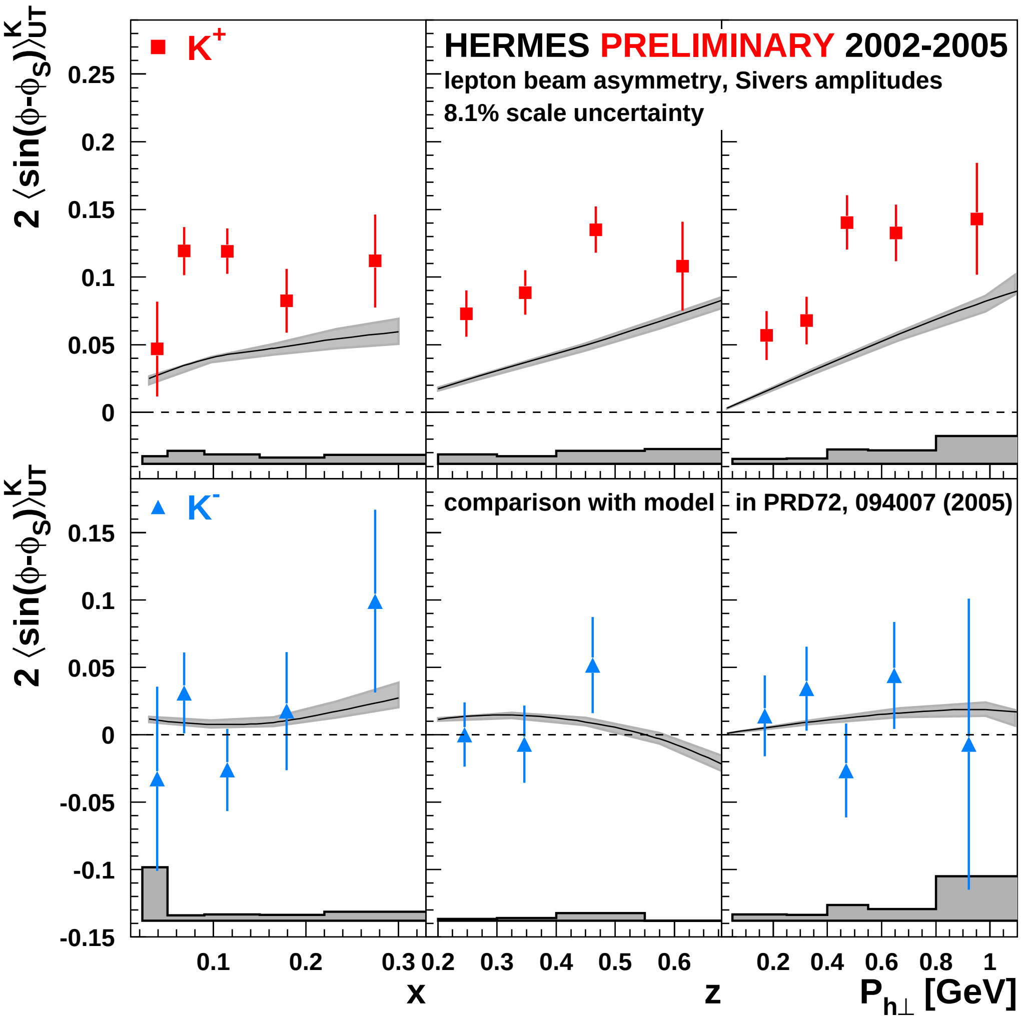
✓

Sivers Amplitudes 2002-2005



- **comparison with model calculation by Anselmino et al., based on:**
  - **Gaussian Ansatz for Sivers fctn.**
  - **average transverse momenta from unpolarized $\cos\phi$ amplitudes**
  - **non-zero Sivers fctn. only for valence quarks**
- **excellent description of pion amplitudes from 2002-05 data**

Sivers Amplitudes 2002-2005



- comparison with model calculation by Anselmino et al., based on:
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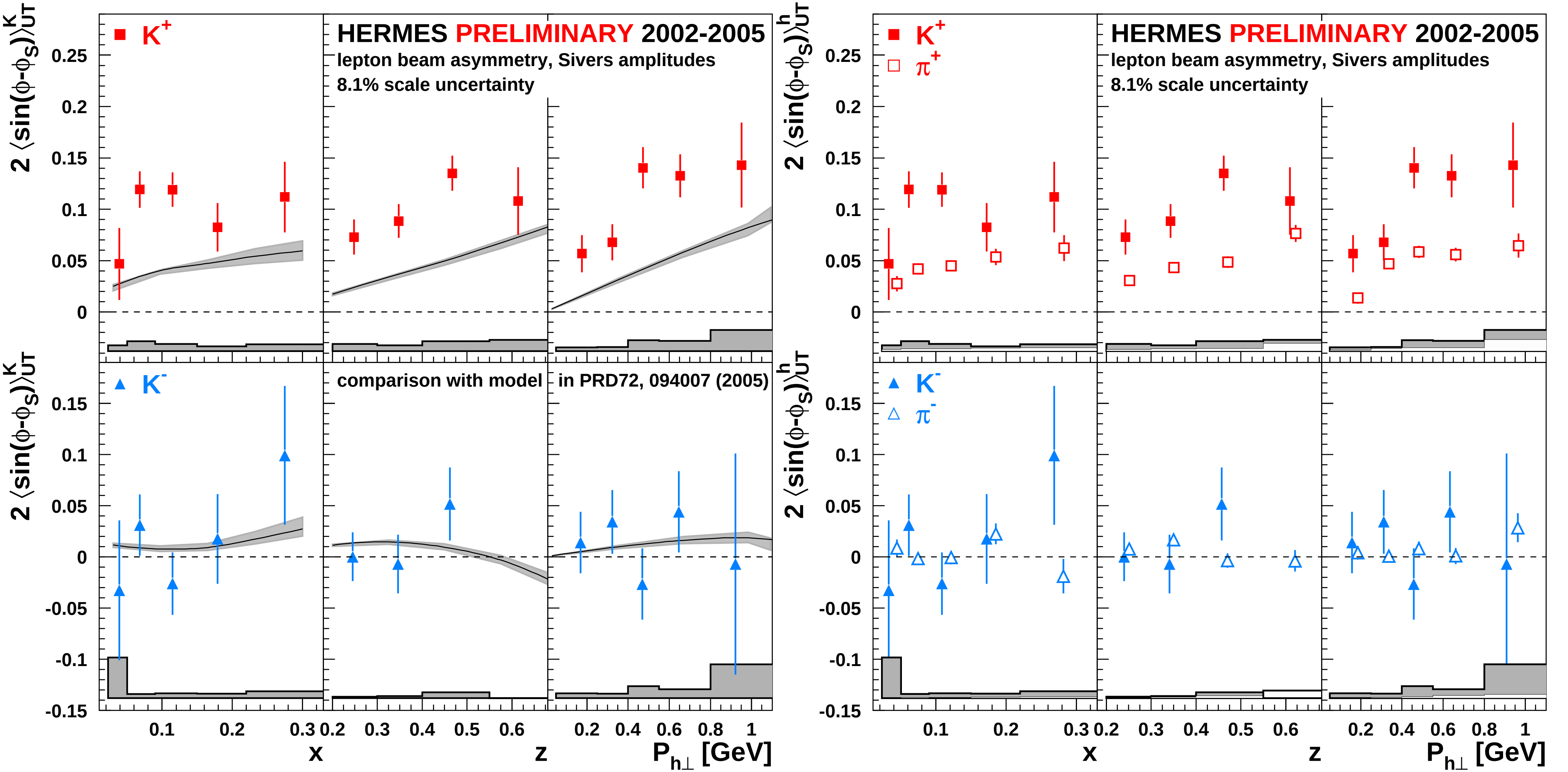
  - average transverse momenta from unpolarized $\cos\phi$ amplitudes
  - non-zero Sivers fctn. only for valence quarks
- excellent description of pion amplitudes from 2002-05 data
- fails to describe kaon amplitudes

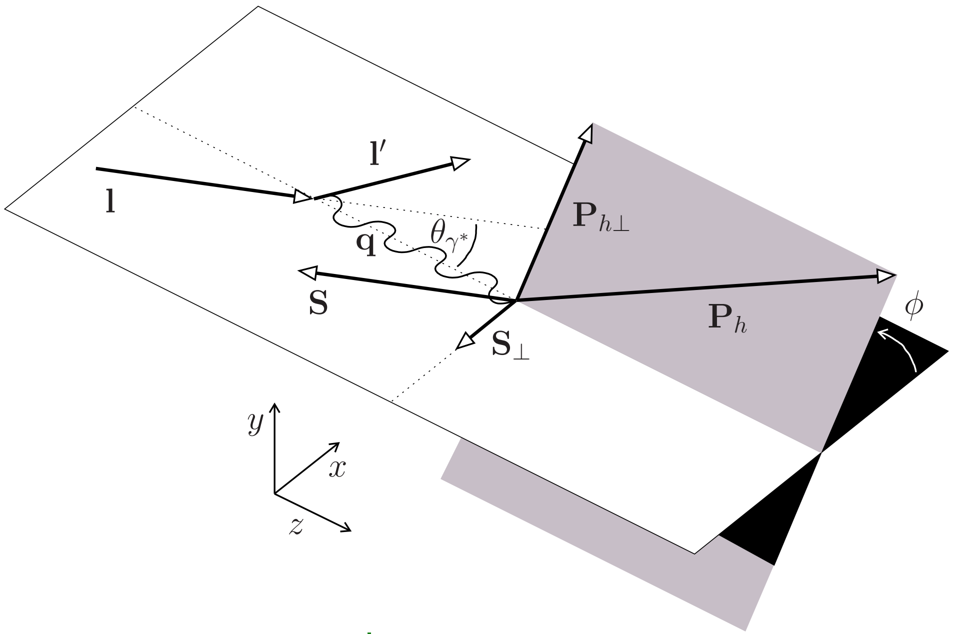
Sivers Amplitudes 2002-2005



Non-trivial role of sea quarks!

"Longitudinal" SSAs

Mixing of Azimuthal Moments



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

Theory: Polarization along virtual photon direction (q)

$\Rightarrow$ mixing of "experimental" and "theory" asymmetries via:

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

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

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

Mixing of Azimuthal Moments II

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

solve for photon-axis moments:

$$\left\langle \sin\phi \right\rangle^{\mathrm{q}}_{UL} \simeq \left\langle \sin\phi \right\rangle^{\mathrm{l}}_{UL} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle^{\mathrm{l}}_{UT} + \left\langle \sin(\phi-\phi_S) \right\rangle^{\mathrm{l}}_{UT} \right)$$

Mixing of Azimuthal Moments II

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

solve for photon-axis moments:

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

$$\left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\mathrm{q}} \simeq \left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\mathrm{l}} - \underbrace{\frac{1}{2}\sin\theta_{\gamma^*} \left(\left\langle \sin\phi \right\rangle_{UL}^{\mathrm{l}}\right.}_{\text{max. 0.4\% absolute}} + \underbrace{\left.\tan\theta_{\gamma^*} \left\langle \sin(\phi\mp\phi_S) \right\rangle_{UT}^{\mathrm{l}} \right)}_{\text{max. 1\% relative}}$$

max. 0.4% absolute max. 1% relative

correction

What About Longitudinally Polarized Targets?

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

$$\left\langle \sin\phi \right\rangle^{\mathrm{q}}_{UL} \propto \frac{M}{Q} \mathcal{I}\left[\frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{k_T}}{M_h} \left(\frac{M_h}{zM} g_1 G^{\perp} + x h_L H_1^{\perp} \right) + \frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{p_T}}{M} \left(\frac{M_h}{zM} h_{1L}^{\perp} \tilde{H} - x f_L^{\perp} D_1 \right) \right]$$

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

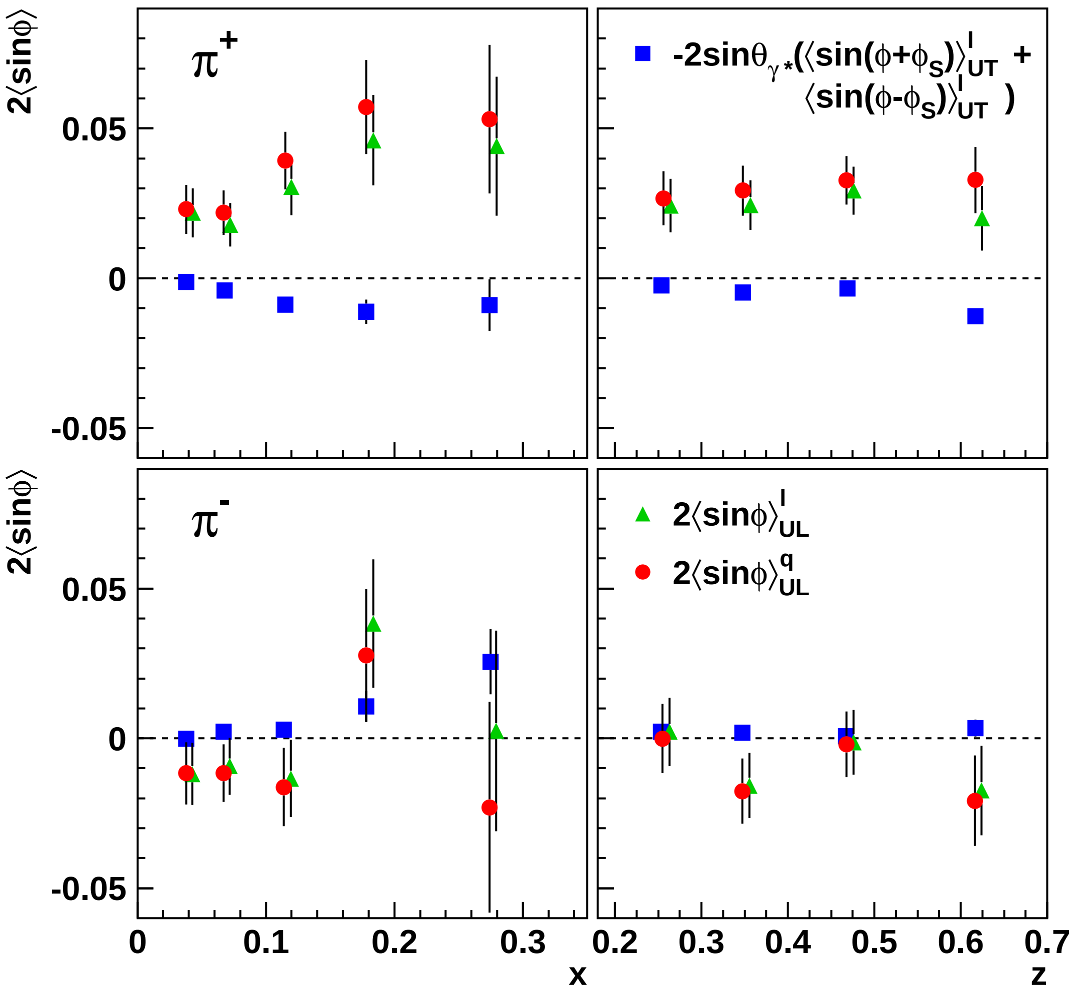
$\Rightarrow$ they are all subleading-twist expressions!

$\left\langle \sin\phi \right\rangle^{\mathrm{l}}_{UL}$ . . . **Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047**

$\left\langle \sin(\phi\pm\phi_S) \right\rangle^{\mathrm{l}}_{UT}$ . . . **Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002**

What About Longitudinally Polarized Targets?

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



- 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

Conclusions

Summary

- Most precise data on transversely polarized hydrogen presented

Summary

- Most precise data on transversely polarized hydrogen presented
- First evidence for non-zero "Interference" FF

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- $\sin\phi$ amplitudes on long. polar. target dominated by twist-3

Outlook

- polarized beam

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$\Rightarrow$ A_{LT} inclusive DIS: g_2

hermes

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- Measurement of pp-interference in 2-hadron fragmentation

Backup Slides

Extracting Quark Distributions

Purity Formalism

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

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- Collins: these purities still depend on parametrization of Collins FF function