Single-Spin Asymmetries in One-Hadron Production at HERMES

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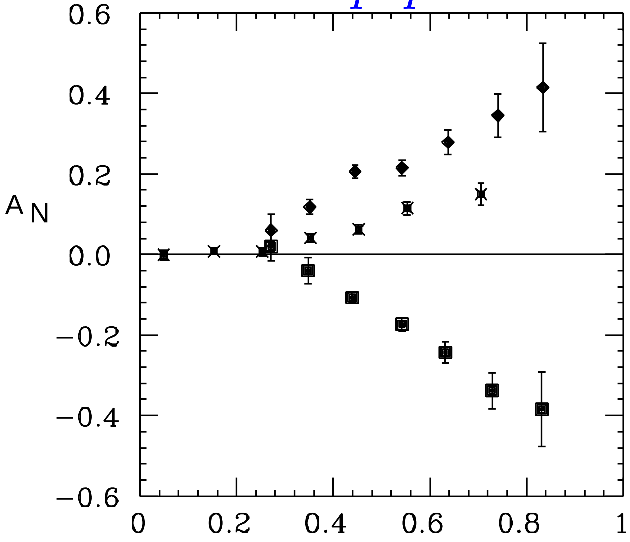
For the hermes Collaboration

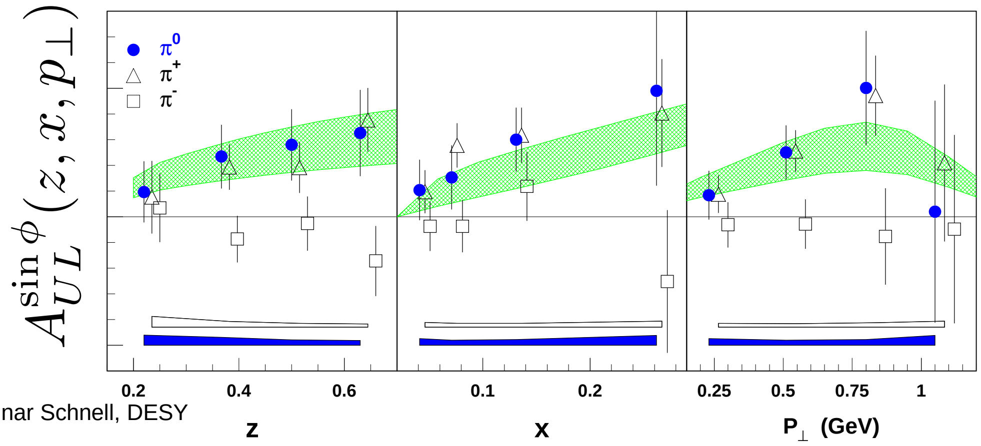
Single-Spin Asymmetries

SSA suppressed in pQCD ⇒ originate from soft physics, i.e, DF and FF

E704: $p^{\uparrow} p \to \pi X$



HERMES: $e\vec{p} \to e'\pi X$



Possible mechanisms:

- **Collins effect – struck quark polarization correlated to transverse momentum in fragmentation**

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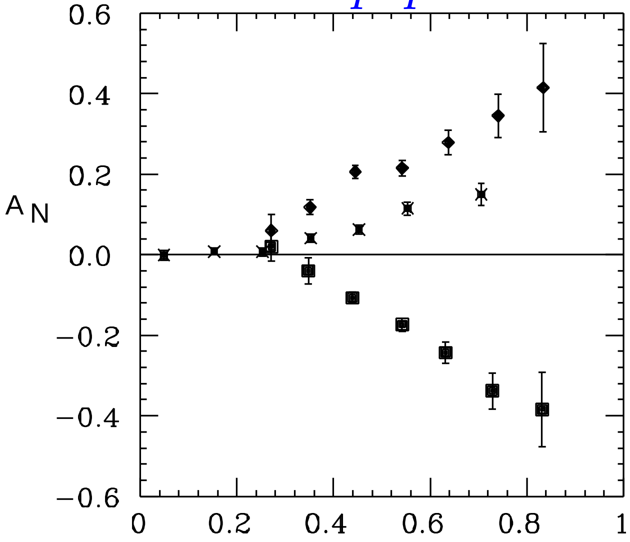

Possible mechanisms:

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- **Sivers effect – struck quark transverse momentum correlated to spin of nucleon**

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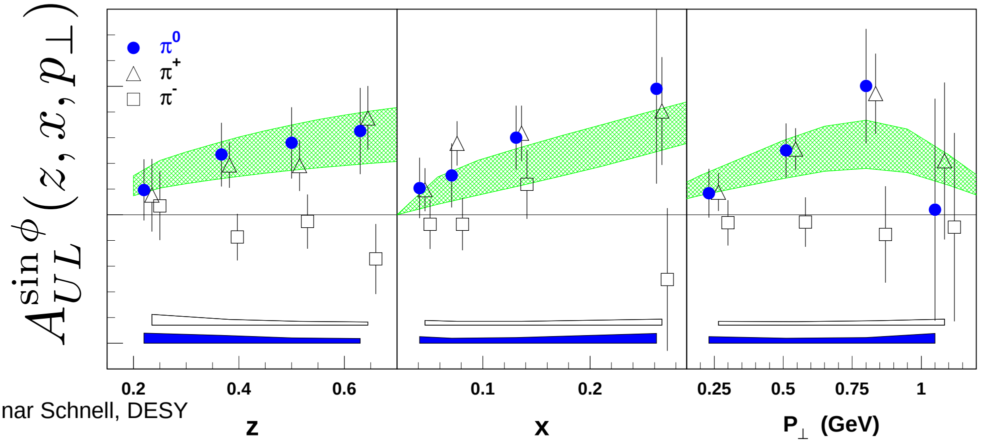

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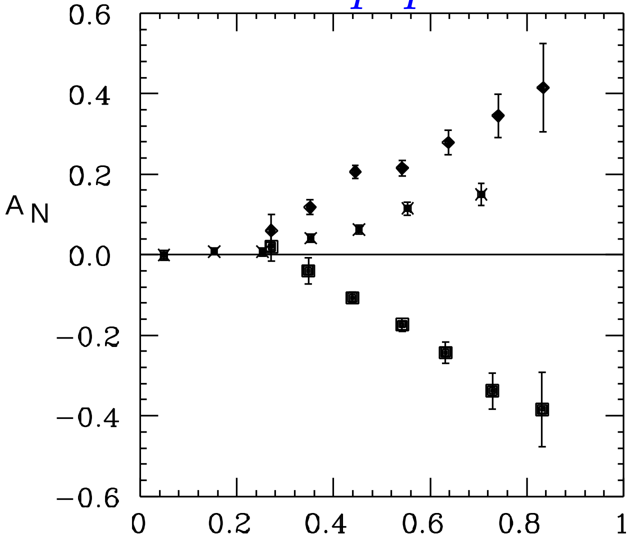

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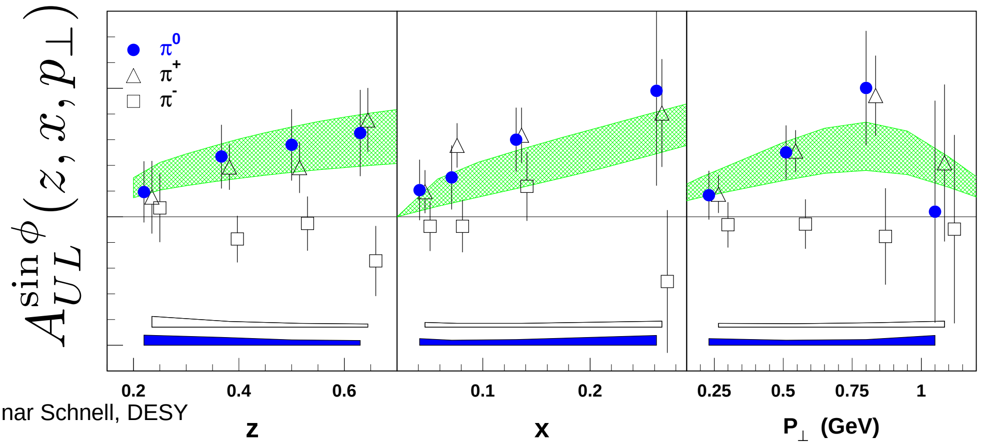

Possible mechanisms:

- **Collins effect – struck quark polarization correlated to transverse momentum in fragmentation**
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- **subleading-twist effects**

Single-Spin Asymmetries

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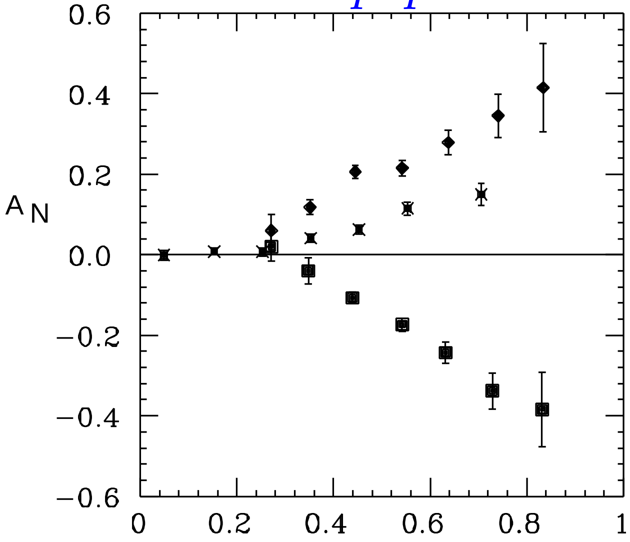

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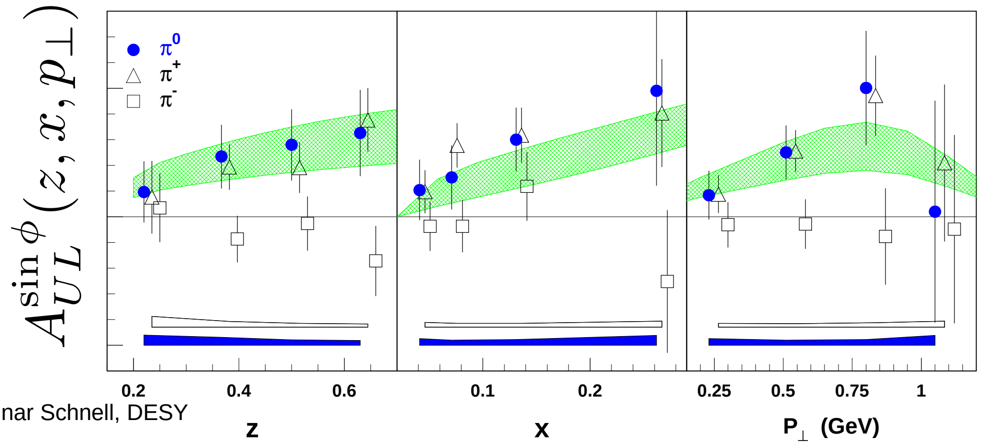


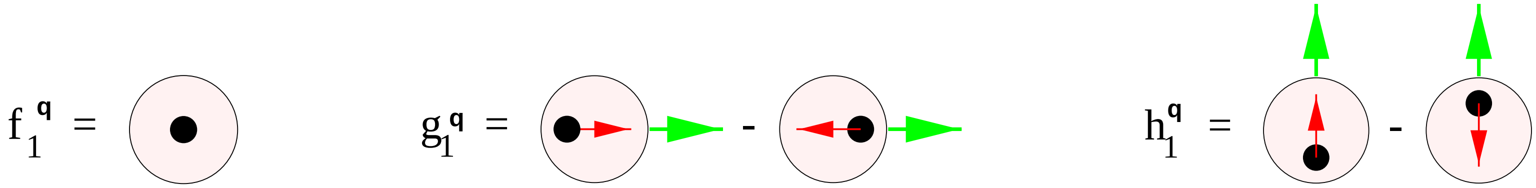
Possible mechanisms:

- **Collins effect – struck quark polarization correlated to transverse momentum in fragmentation**
- **Sivers effect – struck quark transverse momentum correlated to spin of nucleon**
- **subleading-twist effects**

$\Rightarrow$ **meachnisms indistinguishable at E704 (and alike) and HERMES A_{UL}**

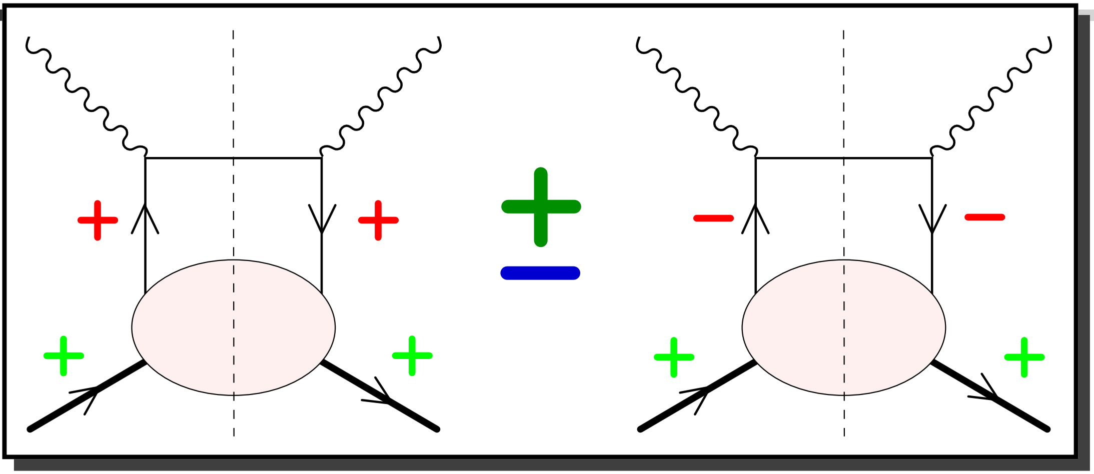
$\Rightarrow$ **can be disentangled in SIDIS with transversely polarized target**

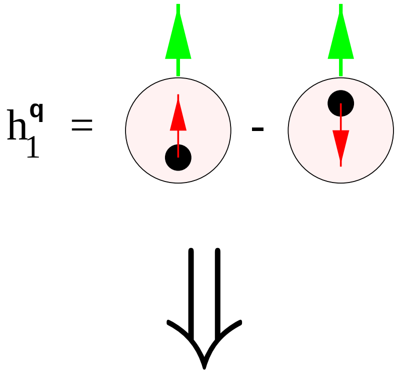
Forward Quark Distributions



⇓	⇓	⇓
Unpolarized quarks and nucleons	Longitudinally polarized quarks and nucleons	Transversely polarized quarks and nucleons
q(x): spin averaged (well known)	Δq(x): helicity difference (known)	δq(x): helicity flip (unmeasured!)
⇒ Vector Charge	⇒ Axial Charge	⇒ Tensor Charge
$\langle PS\|\bar{\Psi}\gamma^{\mu}\Psi\|PS\rangle$= $\int dx(q(x)-\bar{q}(x))$	$\langle PS\|\bar{\Psi}\gamma^{\mu}\gamma_5\Psi\|PS\rangle$= $\int dx(\Delta q(x)+\Delta\bar{q}(x))$	$\langle PS\|\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi\|PS\rangle$= $\int dx(\delta q(x)-\delta\bar{q}(x))$

Forward Quark Distributions





Unpolarized quarks and nucleons

q(x): spin averaged (well known)

⇒ Vector Charge

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

Longitudinally polarized quarks and nucleons

Δq(x): helicity difference (known)

⇒ Axial Charge

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

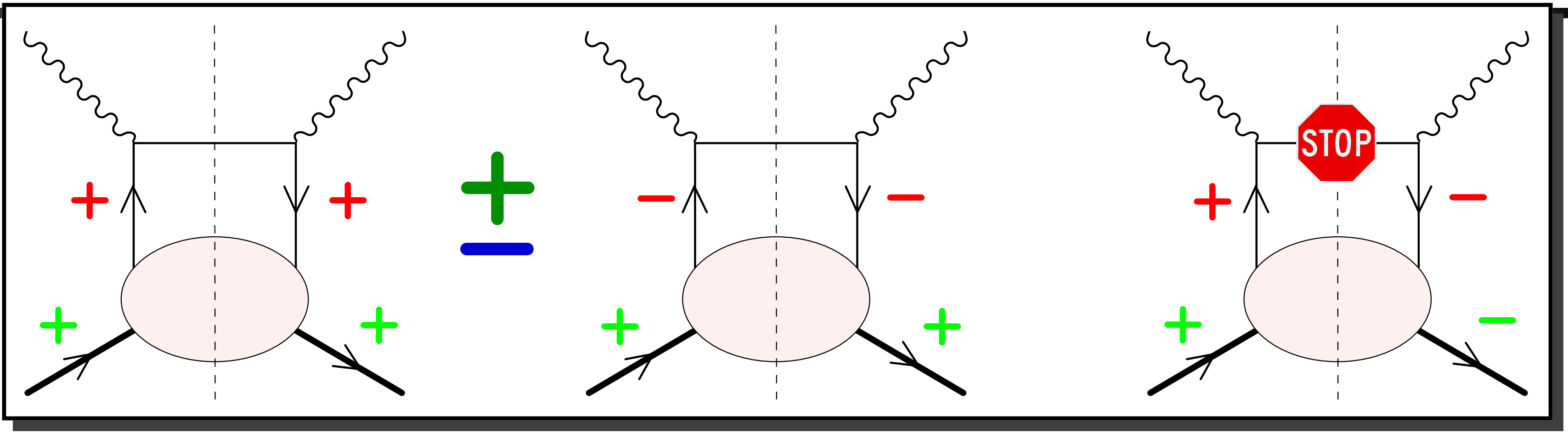
Transversely polarized quarks and nucleons

δq(x): helicity flip (unmeasured!)

⇒ Tensor Charge

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

Forward Quark Distributions



Unpolarized quarks and nucleons	Longitudinally polarized quarks and nucleons	Transverse polarized q s and nuc s
q(x): spin averaged (well known)	Δq(x): helicity difference (known)	δq(x): h y flip (unm red!)
⇒ Vector Charge	⇒ Axial Charge	⇒ T r Charge
$\langle PS\vert\bar{\Psi}\gamma^{\mu}\Psi\vert PS\rangle$= $\int dx(q(x)-\bar{q}(x))$	$\langle PS\vert\bar{\Psi}\gamma^{\mu}\gamma_5\Psi\vert PS\rangle$= $\int dx(\Delta q(x)+\Delta\bar{q}(x))$	$\langle$ $^{\mu\nu}\gamma_5\Psi\vert PS\rangle$= $\int dx(\delta q(x)-\delta\bar{q}(x))$

CHIRAL-ODD!

Transversity Measurements

How can one measure transversity?

Need another chiral-odd object!

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Need another chiral-odd object! ⇒ Semi-Inclusive DIS

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

$\Downarrow$ $\Downarrow$

chiral-odd **chiral-odd**

DF FF

$$\underbrace{\text{DF} \qquad\qquad \text{FF}}_{\text{CHIRAL EVEN}}$$

Transversity Measurements

How can one measure transversity?

Need another chiral-odd object! ⇒ Semi-Inclusive DIS

$$\sigma^{ep\rightarrow ehX} = \sum_q \underbrace{\underset{\substack{\Downarrow \\ \textbf{chiral-odd} \\ \text{DF}}}{\delta q} \otimes \sigma^{eq\rightarrow eq} \otimes \underset{\substack{\Downarrow \\ \textbf{chiral-odd} \\ \text{FF}}}{FF^{q\rightarrow h}}}_{\text{CHIRAL EVEN}}$$

⟶ use T-even transverse polarization transfer FF

Transversity Measurements

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

$$\underbrace{\begin{array}{ccc} \Downarrow & \qquad\qquad & \Downarrow \\ \textbf{chiral-odd} & & \textbf{chiral-odd} \\ \text{DF} & & \text{FF} \end{array}}_{\text{CHIRAL EVEN}}$$

⟶ use T-even transverse polarization transfer FF

⟶ use T-odd Collins FF ⇐ 1-hadron SSA

Transversity Measurements

How can one measure transversity?

Need another chiral-odd object! ⇒ Semi-Inclusive DIS

$$\sigma^{ep\to ehX} = \sum_q \delta q \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$

$$\Downarrow \qquad\qquad\qquad \Downarrow$$

chiral-odd **chiral-odd**

$$\underbrace{\text{DF} \qquad\qquad \text{FF}}_{\text{CHIRAL EVEN}}$$

⟶ use T-even transverse polarization transfer FF

⟶ use T-odd Collins FF ⇐ 1-hadron SSA

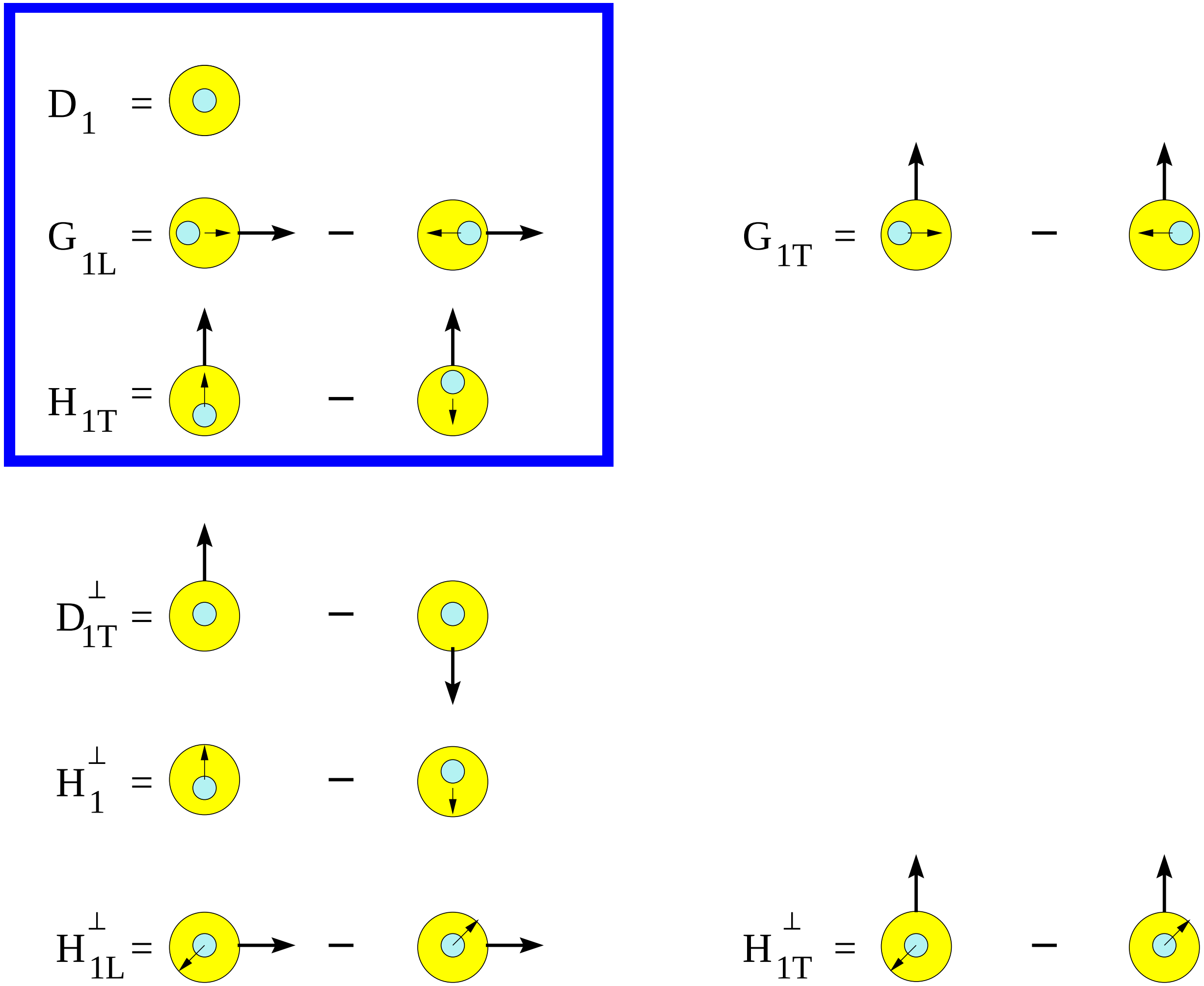
⟶ use T-odd Interference FF ⇐ 2-hadron SSA

(see e.g. talk by P. van der Nat)

Leading Twist

Unintegrated Fragmentation Functions

Functions surviving integration over intrinsic transverse momentum



Leading Twist

Unintegrated Fragmentation Functions

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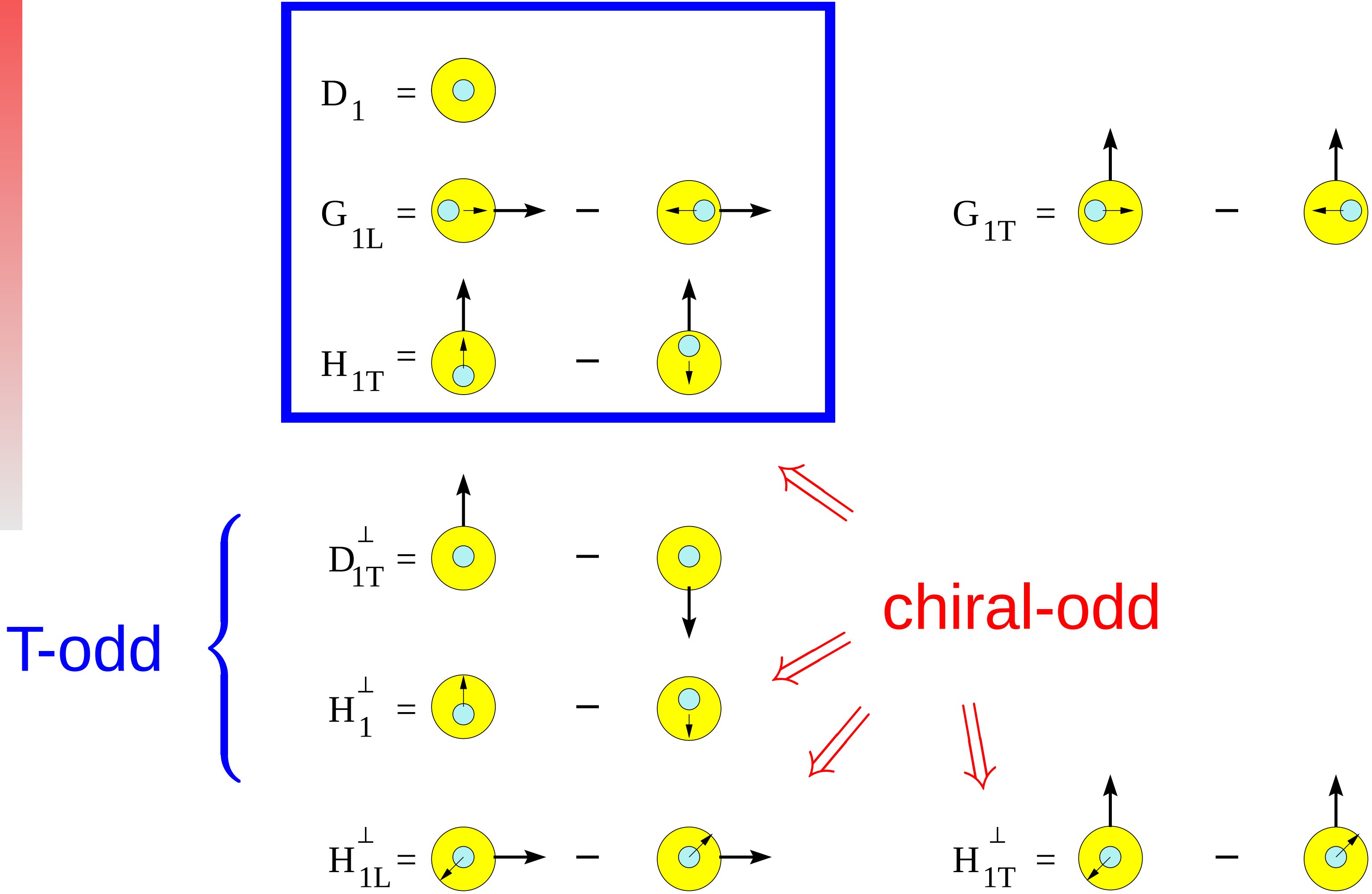

$D_1 =$

$G_{1L} =$ −

$H_{1T} =$ −

$G_{1T} =$ −

chiral-odd

T-odd

$D_{1T}^{\perp} =$ −

$H_1^{\perp} =$ −

$H_{1L}^{\perp} =$ −

$H_{1T}^{\perp} =$ −

Leading Twist

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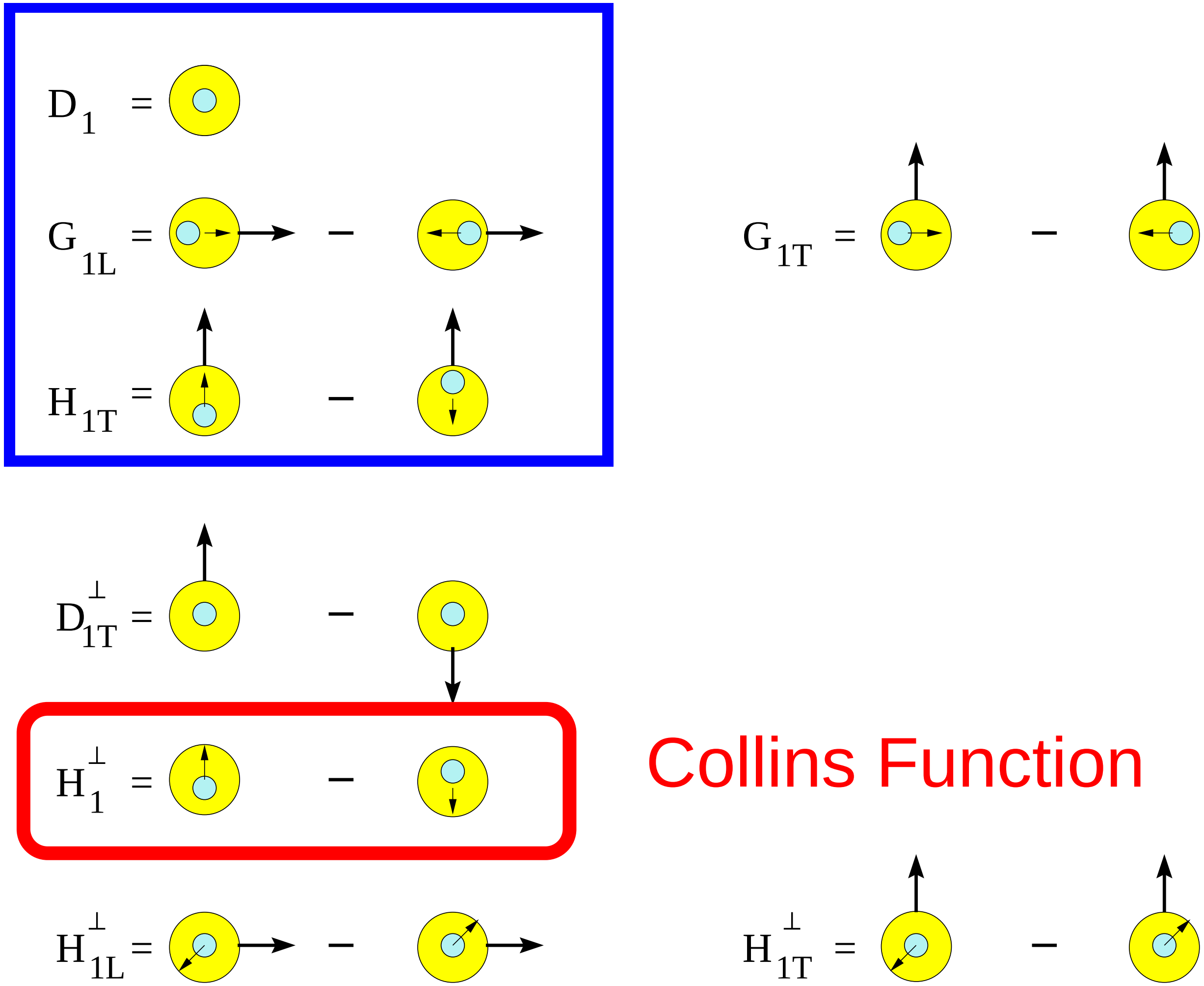
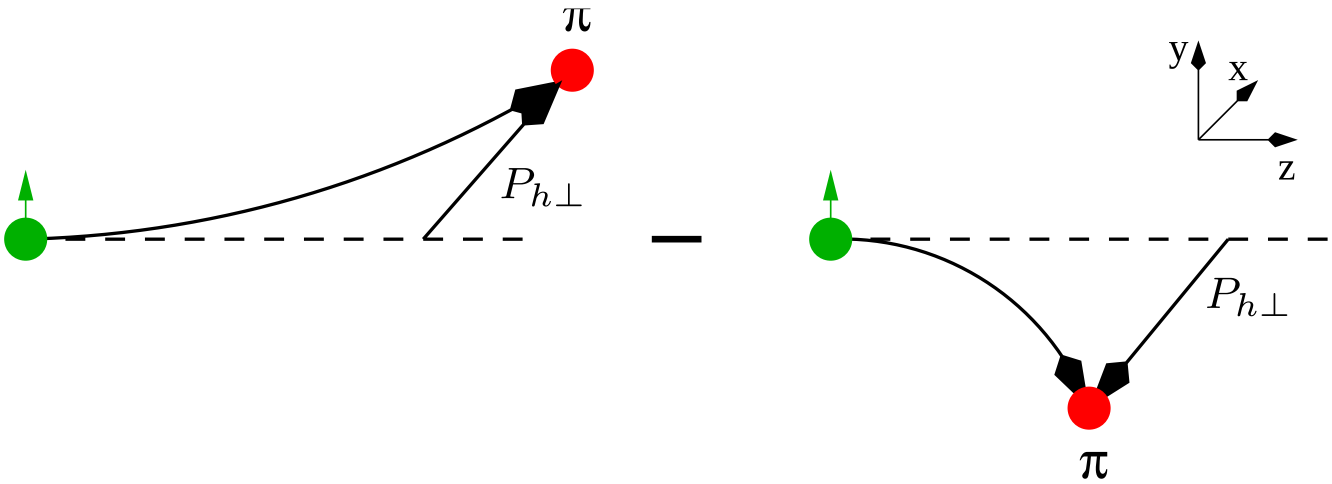


T-odd

Collins Function

Collins Fragmentation Function



- Collins function $H_1^\perp$ describes left-right asymmetry in the direction of outgoing hadron
- Originally proposed by Collins (& Heppelman)
- T-odd $\Rightarrow$ need interference of amplitudes
- basically unknown, but first fits to available data become available
- first data from Belle supports non-zero $H_1^\perp$

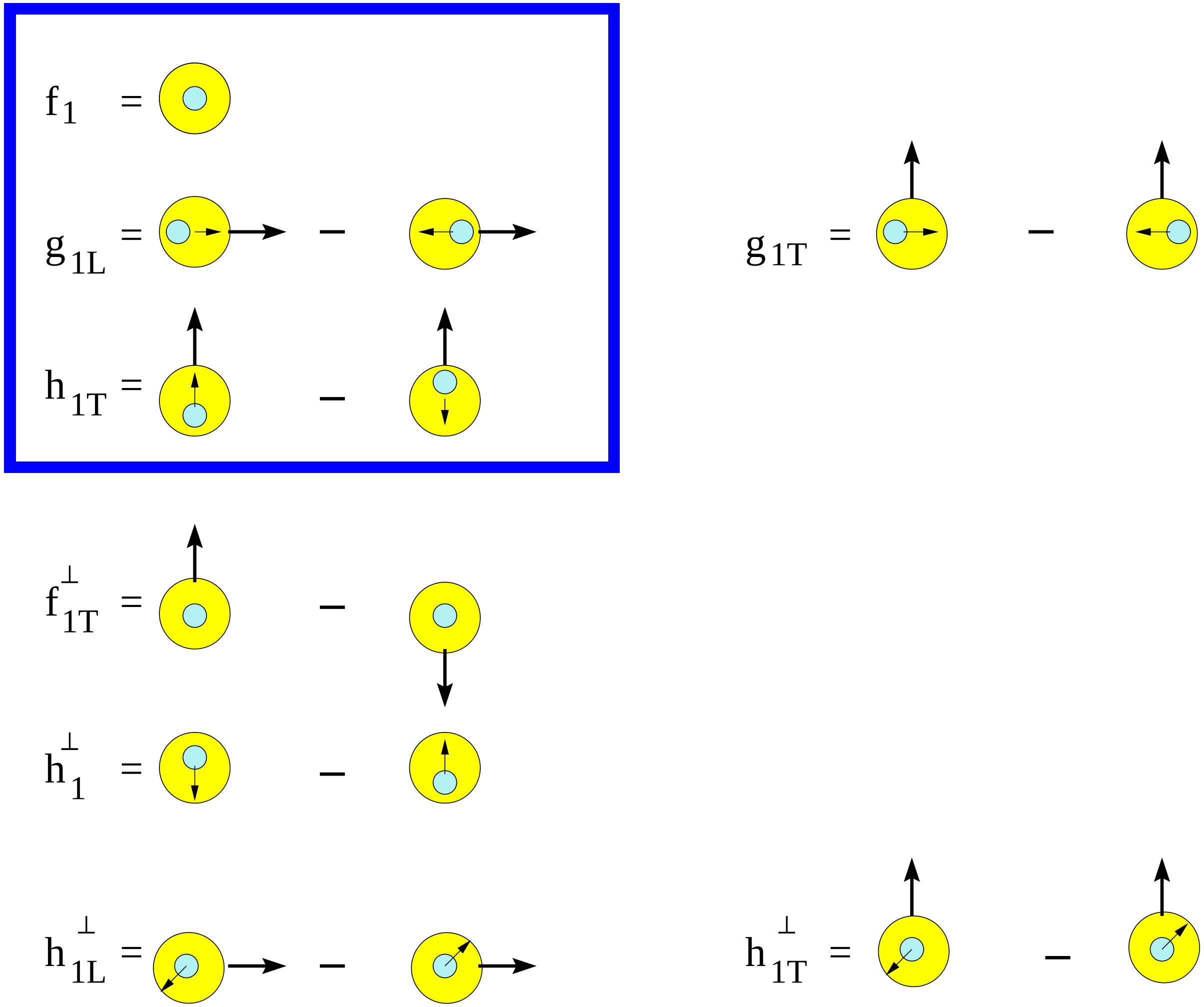
Caution!

Other Spin-Momentum-Correlations exist!

Leading Twist

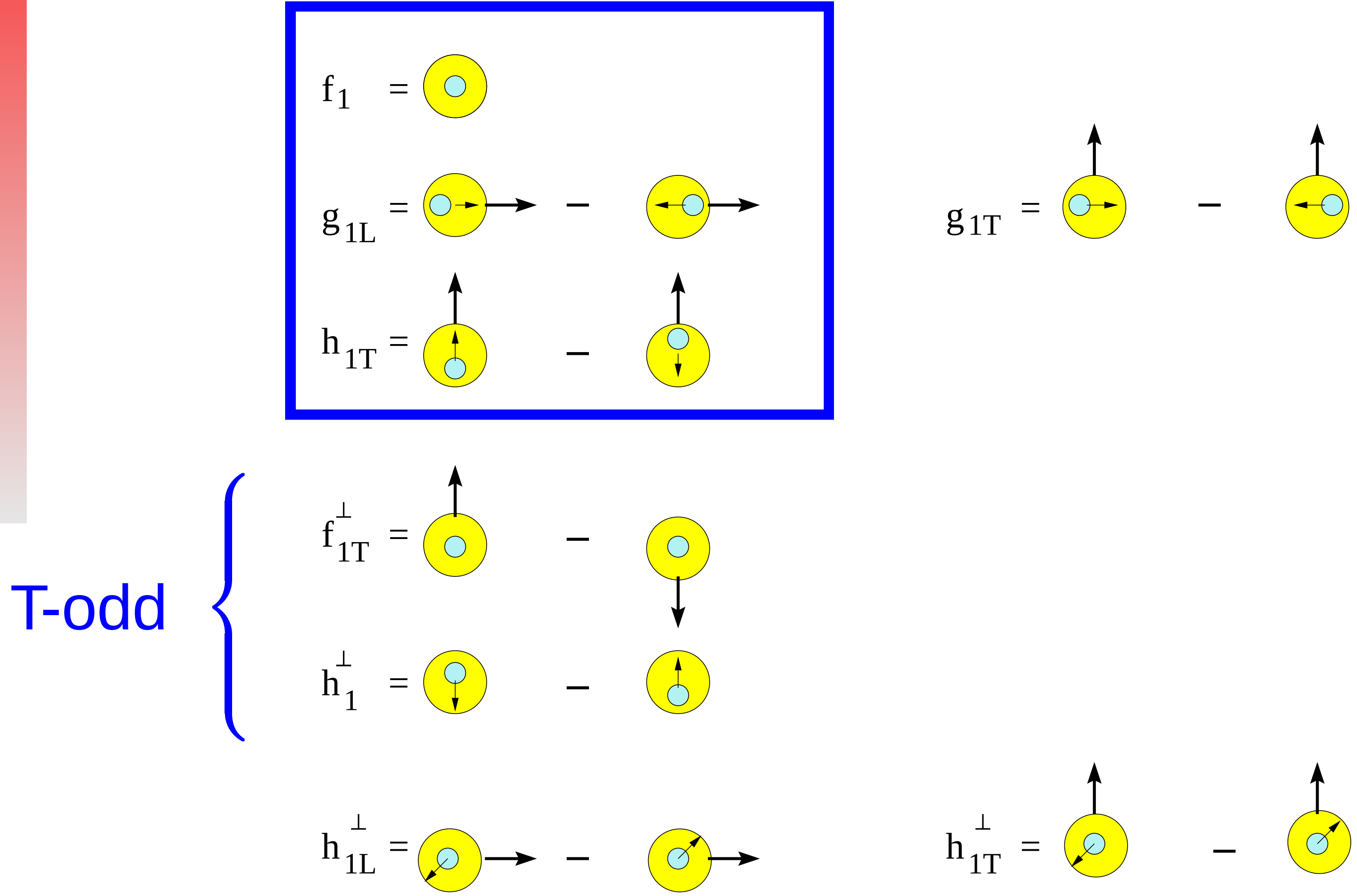
Unintegrated Quark Distributions

Functions surviving integration over intrinsic transverse momentum



Leading Twist
Unintegrated Quark Distributions

Functions surviving integration over intrinsic transverse momentum



Leading Twist

Unintegrated Quark Distributions

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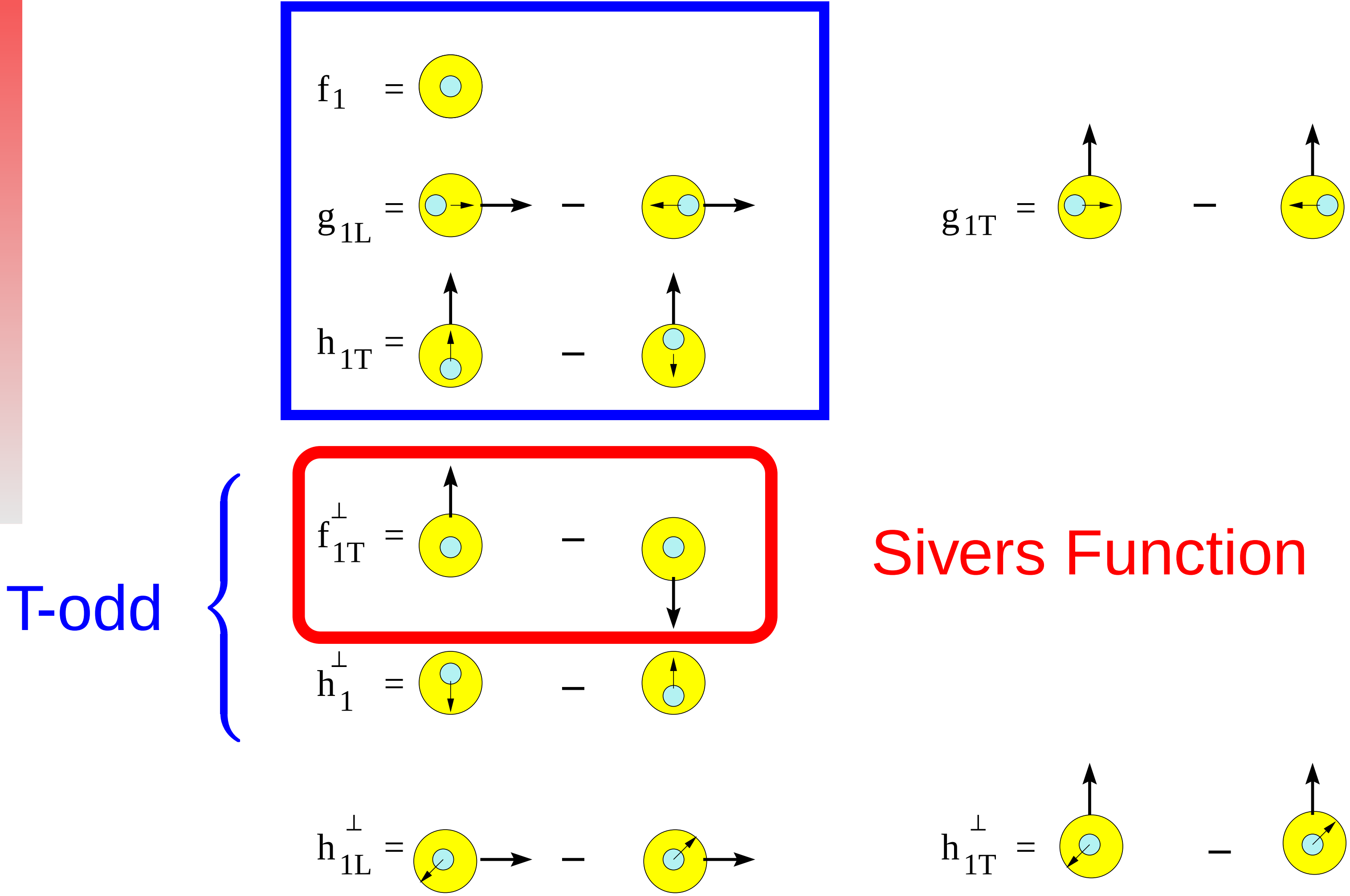
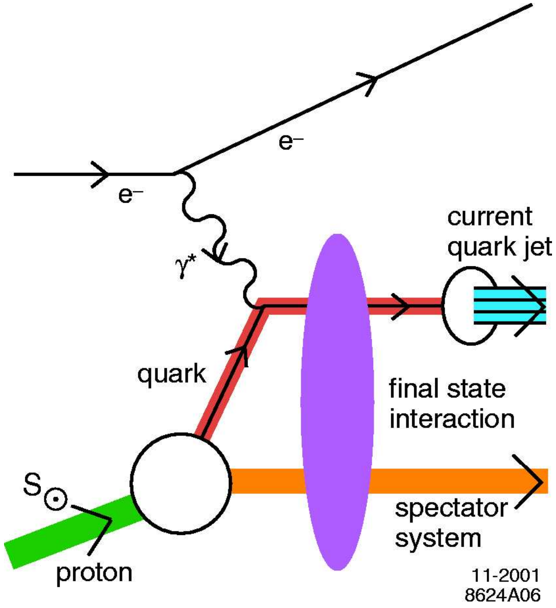


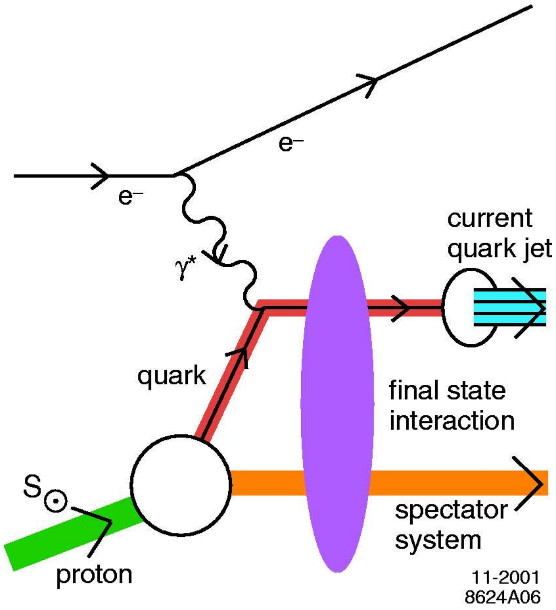
Some words about Sivers Effect



Thanks to Brodsky, Hwang, Schmidt:

- quark rescattering via soft gluon exchange
- correlates transverse spin with direction of outgoing hadron
- requires L_z of quarks

Some words about Sivers Effect



Thanks to Brodsky, Hwang, Schmidt:

- quark rescattering via soft gluon exchange
- correlates transverse spin with direction of outgoing hadron
- requires L_z of quarks

Thanks to Collins, Ji, Yuan, Belitzky ...:

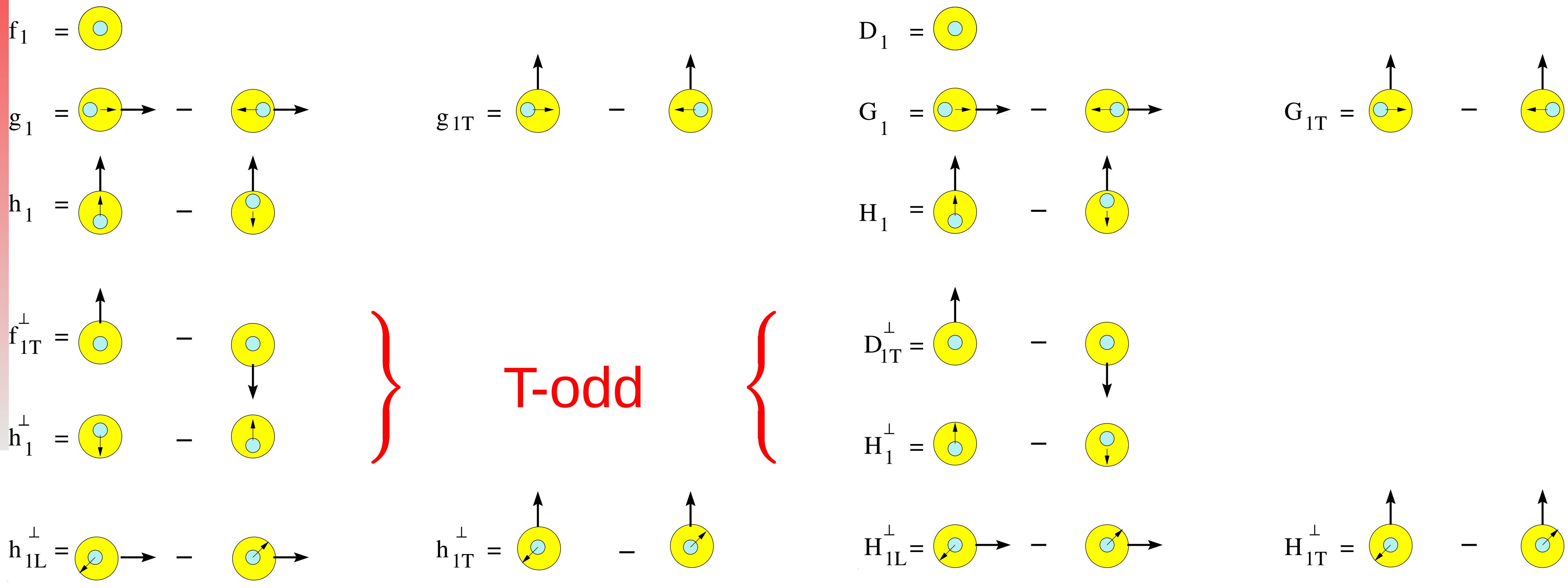
- Soft gluon is model for gauge link needed for gauge invariance
- Gauge links provide necessary complex phase for interference
- T-Symmetry of QCD requires opposite sign of Sivers function in DIS and DY
- slightly different approach by Burkardt using impact parameter dependent PDF's ("chromodynamic lensing")

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions

Fragmentation Functions



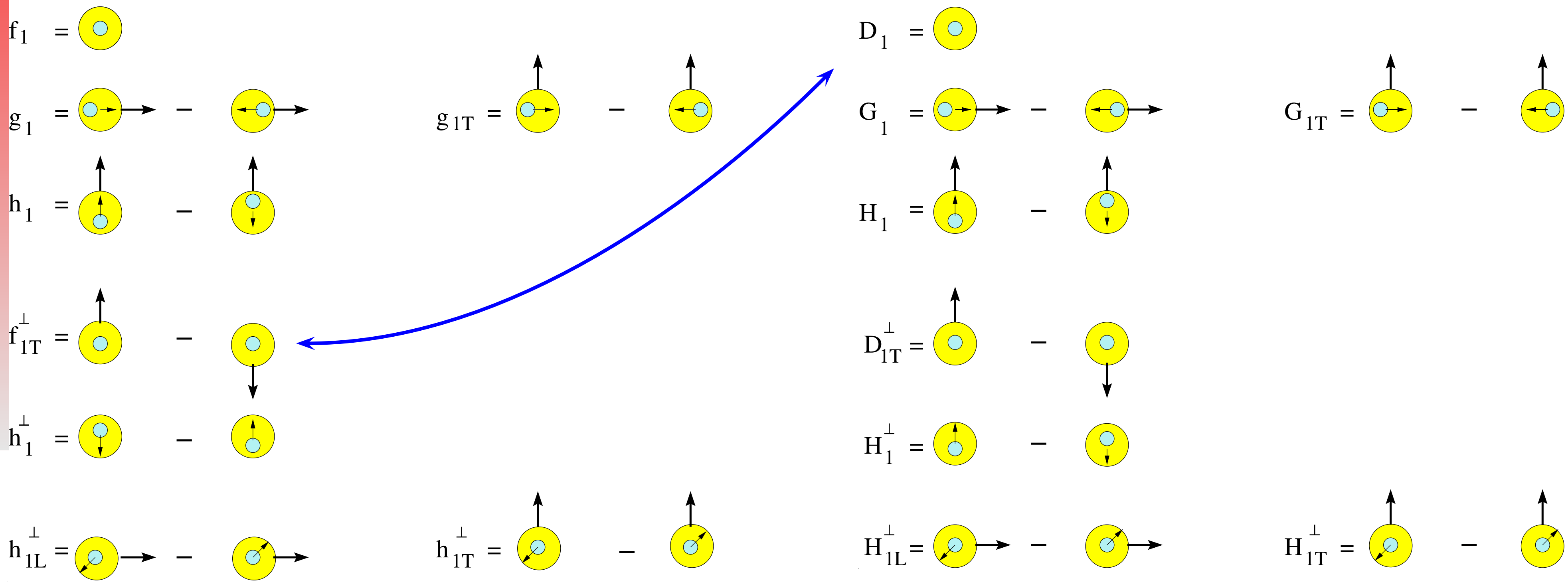
SSA require one and only one T-odd function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions

Fragmentation Functions



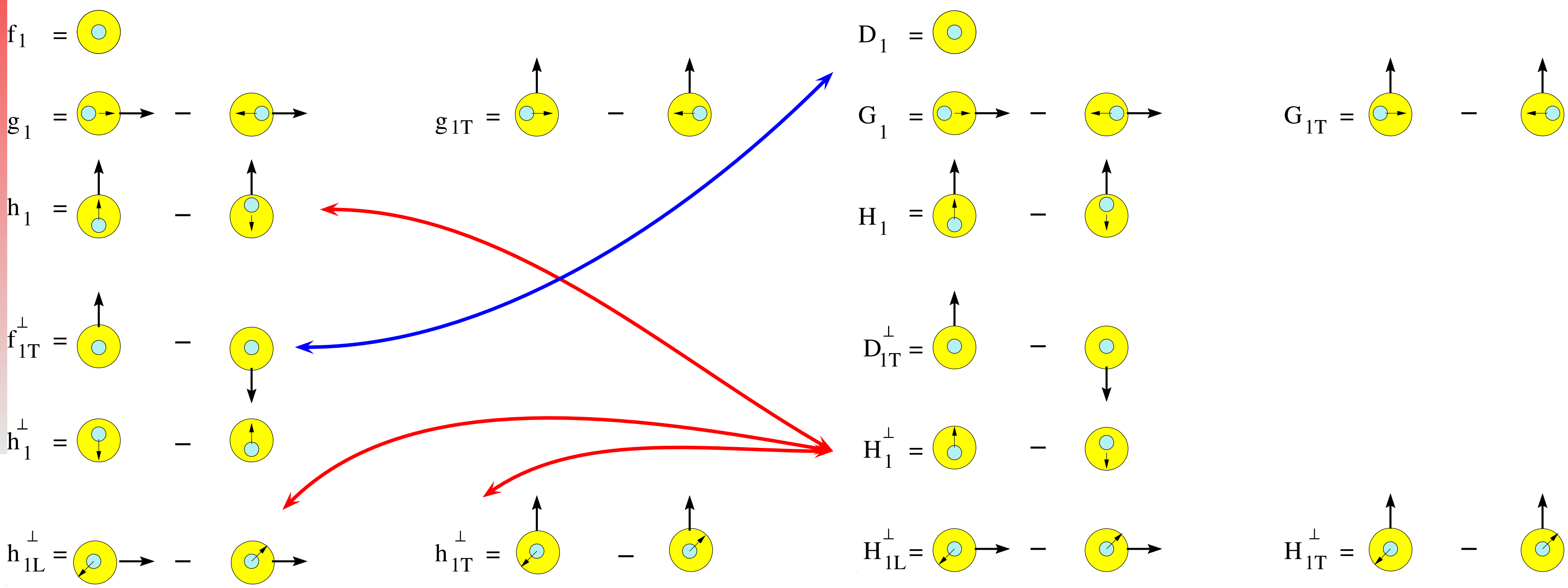
SSA require one and only one T-odd function

⇒ SSA through Sivers function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions **Fragmentation Functions**



SSA require one and only one T-odd function

$\Rightarrow$ SSA through Sivers function or Collins function

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

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

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

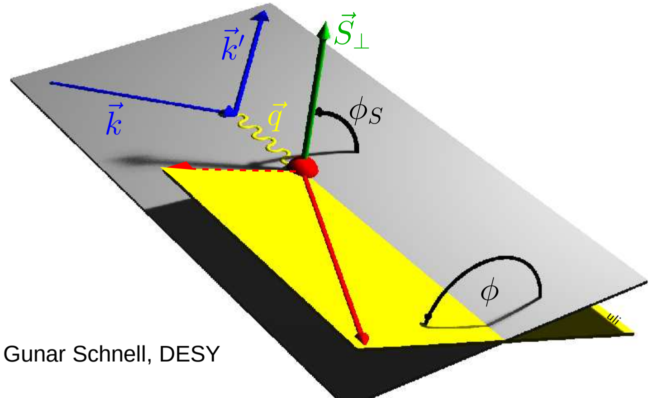
$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \right.$$

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

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

σ_{XY}

Beam **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

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

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

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σ_{XY}

Beam Target
Polarization

Terms with 1/Q are 'subleading twist'

(Factorization for SIDIS (including transverse momentum) not yet proven)

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 **Target**
Polarization

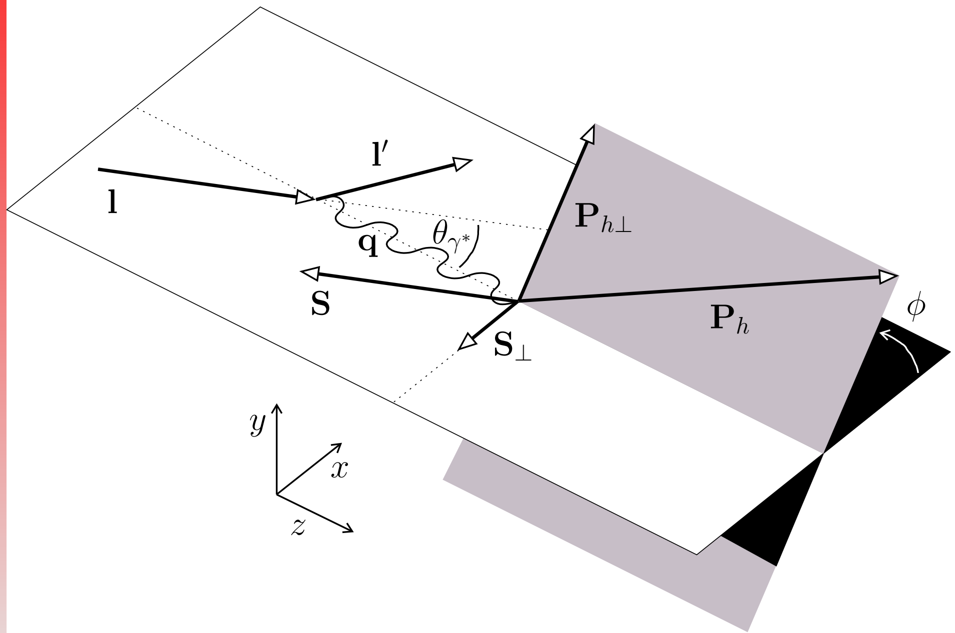
This talk:

$\sin\phi\, d\sigma^3_{LU}$, $\sin\phi\, d\sigma^5_{UL}$ . . . Subleading Twist

$\sin(\phi-\phi_S)\, d\sigma^8_{UT}$ . . . Sivers Effect

$\sin(\phi+\phi_S)\, d\sigma^9_{UT}$ . . . Collins Effect

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)]

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

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

Mixing of Azimuthal Moments II

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

solve for photon-axis moments:

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

Mixing of Azimuthal Moments II

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

solve for photon-axis moments:

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

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

correction

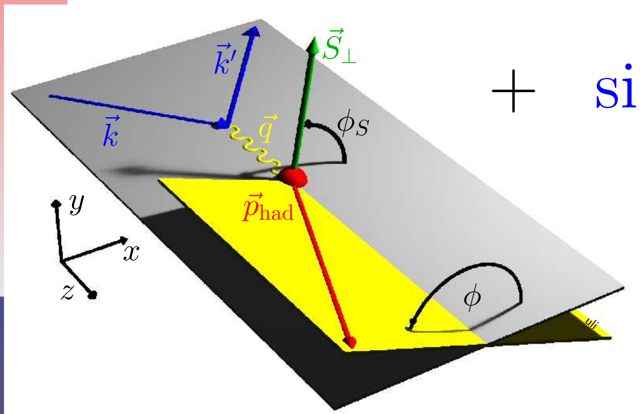
Azimuthal Single-Spin Asymmetries

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

$$\sim \quad \sin(\phi+\phi_S) \sum_q e_q^2\, \mathcal{I}\left[\frac{\boldsymbol{k_T \hat{P}_{h\perp}}}{M_h} h_{1T}^q(x,p_T^2) H_1^{\perp,q}(z,k_T^2) \right]$$

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

$$+ \quad \cdots$$

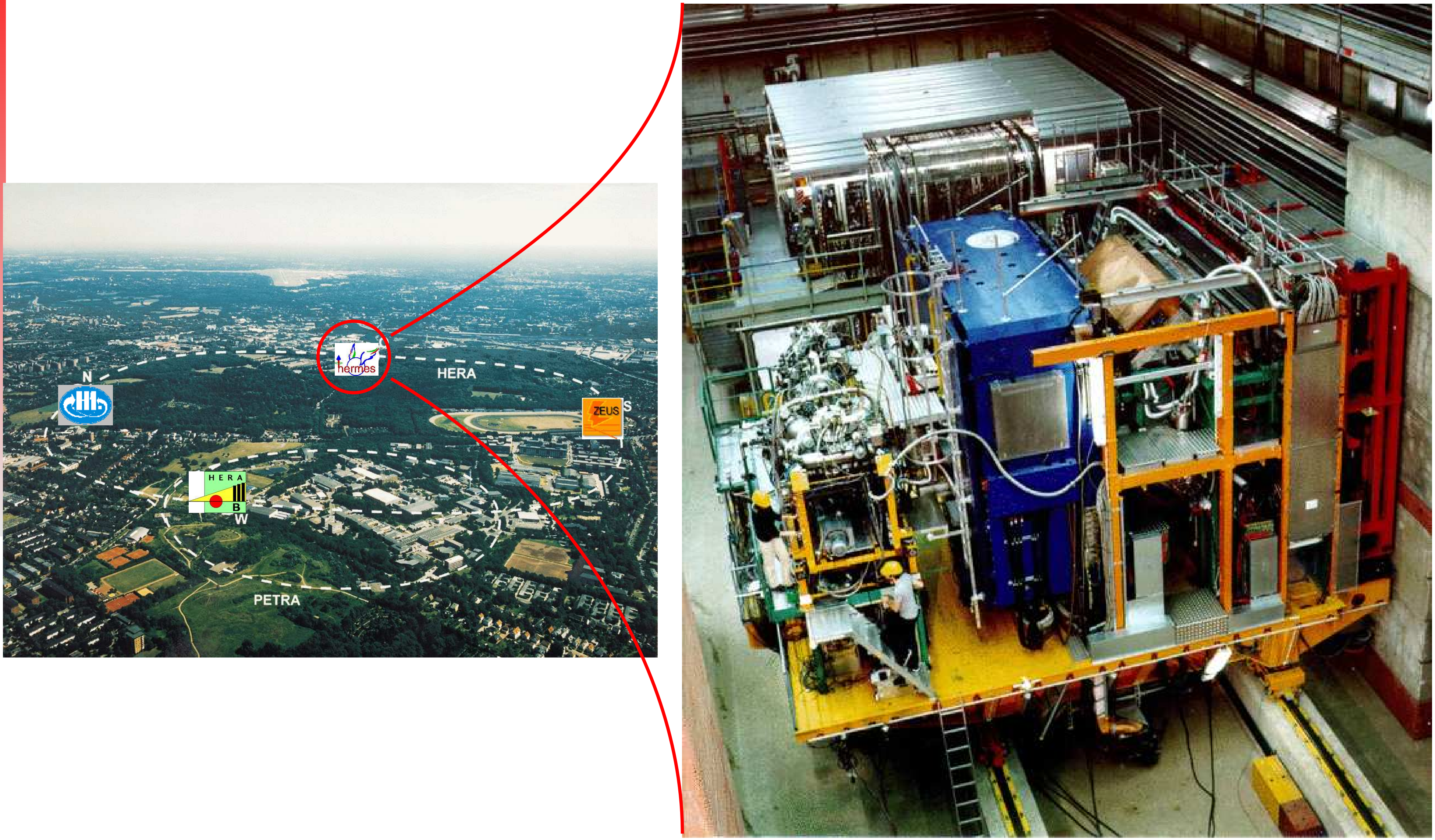


$\mathcal{I}[\ldots]$: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

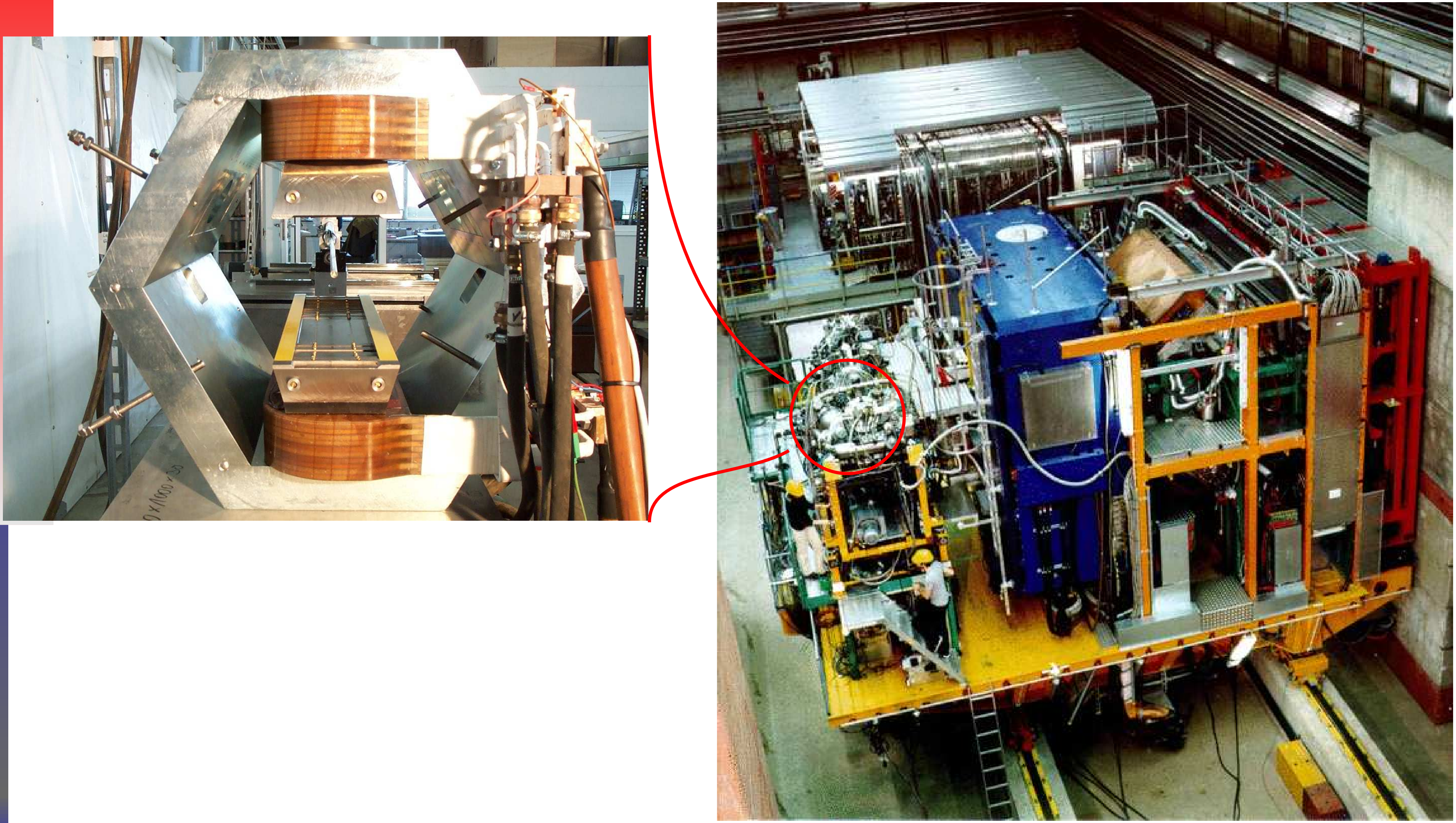
$\Rightarrow$ 2D-fit of A_{UT} to get Collins and Sivers asymmetries:

$$\boxed{A_{UT}(\phi,\phi_S) = 2\left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\mathsf{l}} \sin(\phi-\phi_s) + 2\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\mathsf{l}} \sin(\phi+\phi_s)}$$

HERMES at DESY

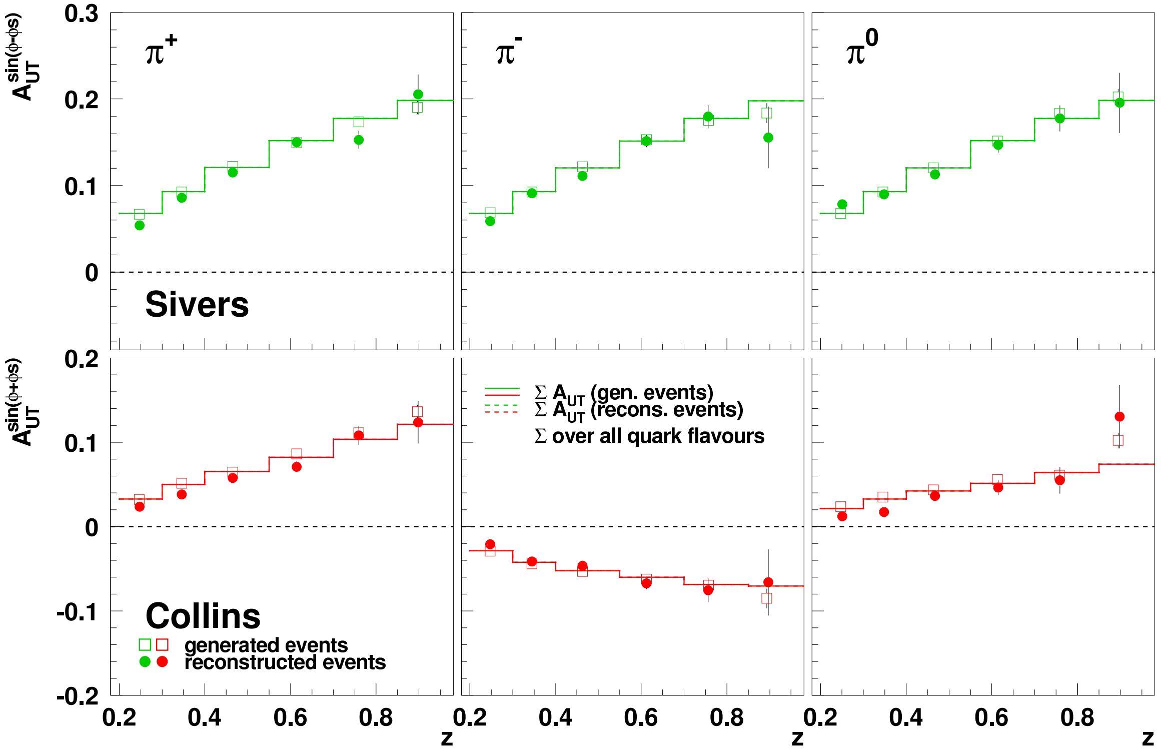


HERMES at DESY



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 asymmetries:

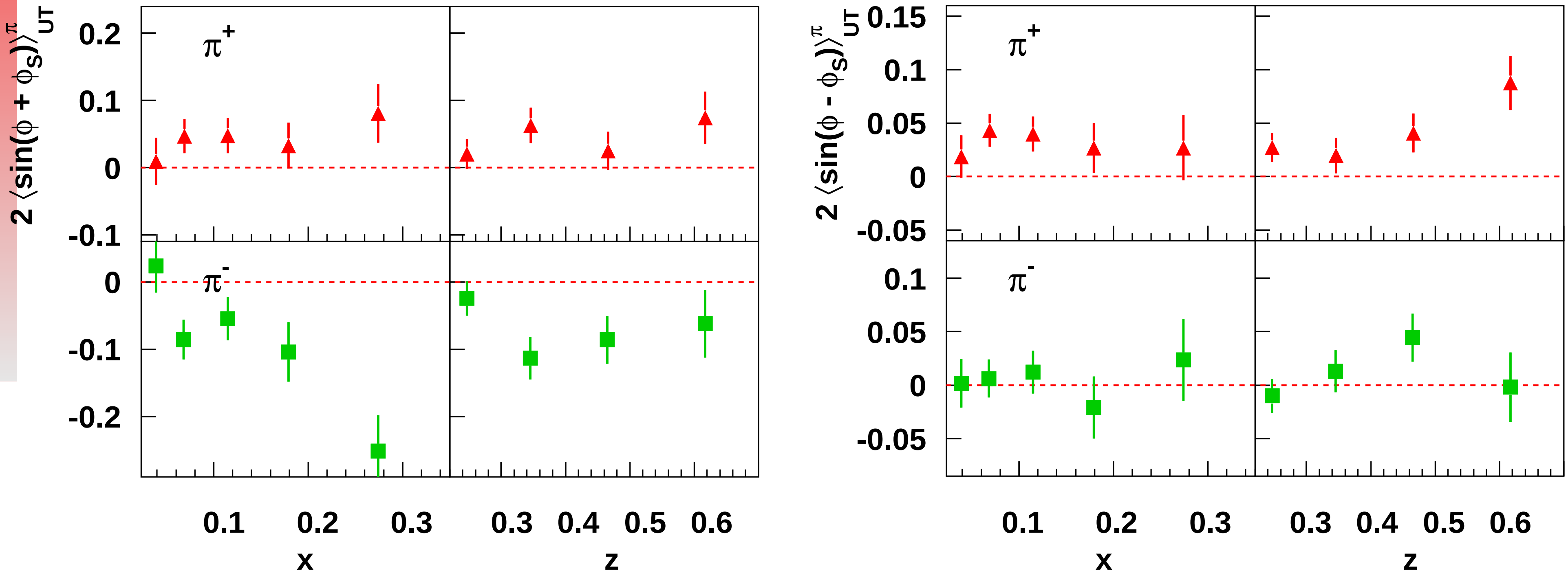


- Collins-Sivers cross contamination negligible
- insensitive to transverse target tracking corrections

2002/03 Data Taking – First Look at Sivers & Collins Moments

Fit $A(\phi, \phi_S) = A_C \frac{B(<y>)}{A(<x>,<y>)} \sin(\phi + \phi_S) + A_S \sin(\phi - \phi_S)$

("Virtual Photon Asymmetries")

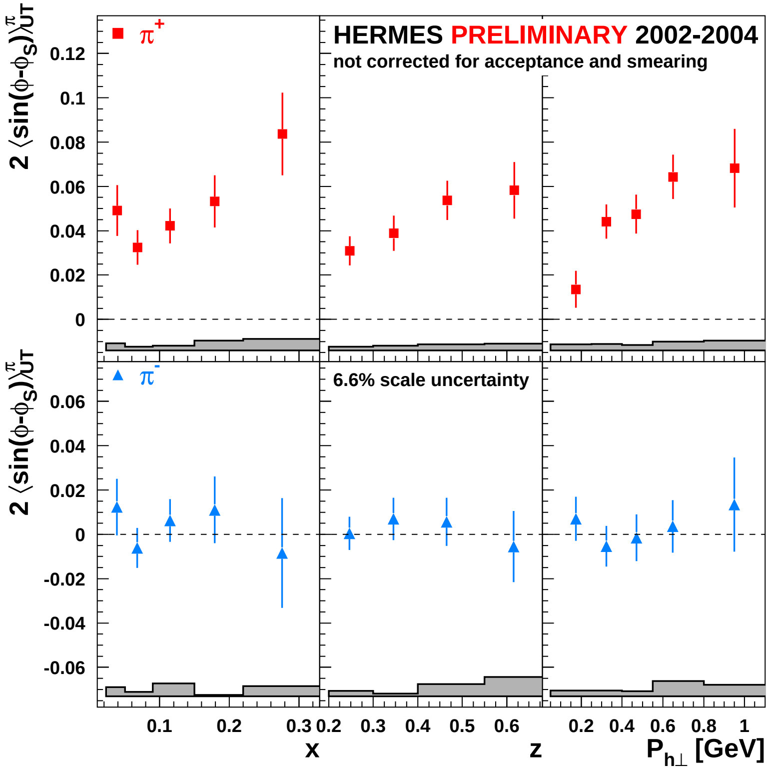


Clear signal of Collins and Sivers effect

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

Results on Sivers Moments from 2002-2004 data

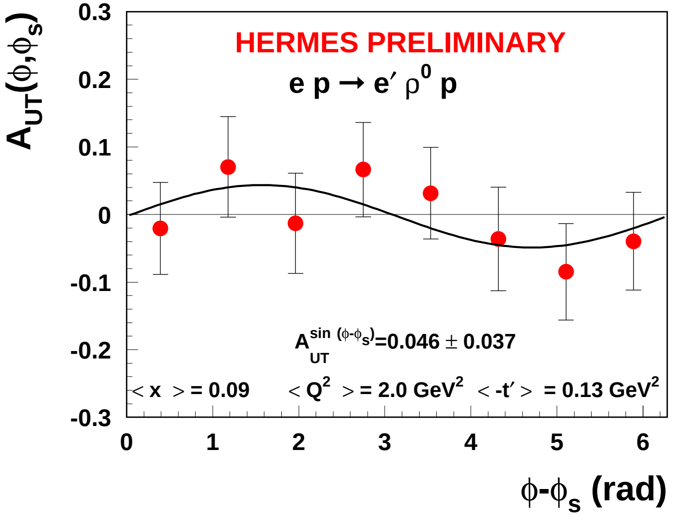
$$2\left\langle \sin(\phi-\phi_S)\right\rangle^{l}_{UT} \simeq 2\left\langle \sin(\phi-\phi_S)\right\rangle^{q}_{UT} \propto -\sum_q e_q^2\,\mathcal{I}\left[w_{Siv}\; f_{1T}^{\perp,q}(x,p_T^2)\; D_1^q(z)\right]$$

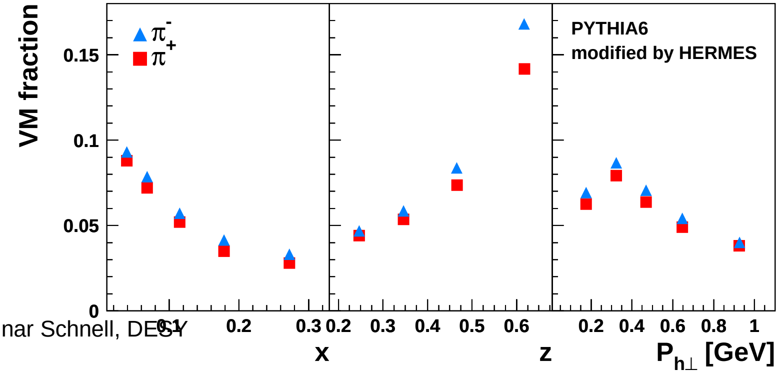


- π^+: positive; π^-: consistent with zero

⇒ first indication for non-zero Sivers fct.: $f_{1T}^{\perp,u}$ negative (u-quark dominance)

- Exclusive ρ^0 asymmetry (2005 prel.):





⇒ small syst. error from vector mesons

Chromodynamic Lensing

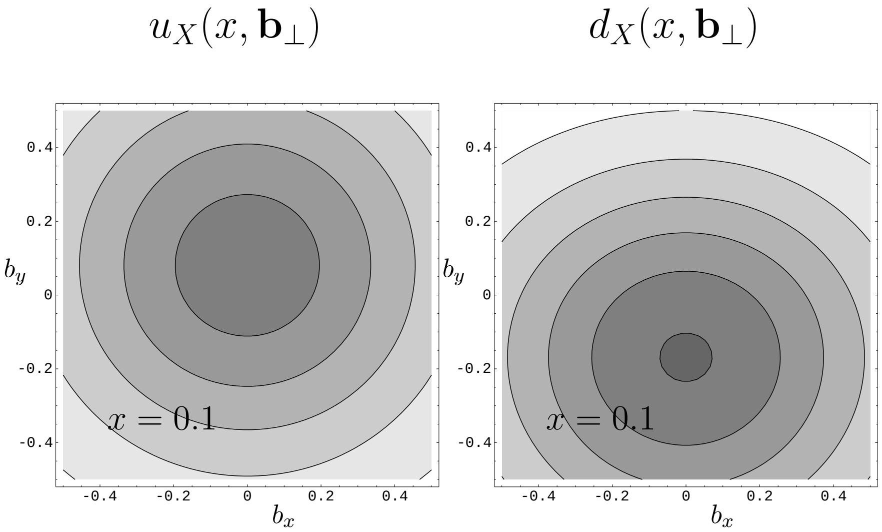
Understanding the Sivers Moments

approach by M. Burkardt:

spatial distortion of q-distribution

(consequence of anom. magn. moments

& impact parameter dependent PDFs)



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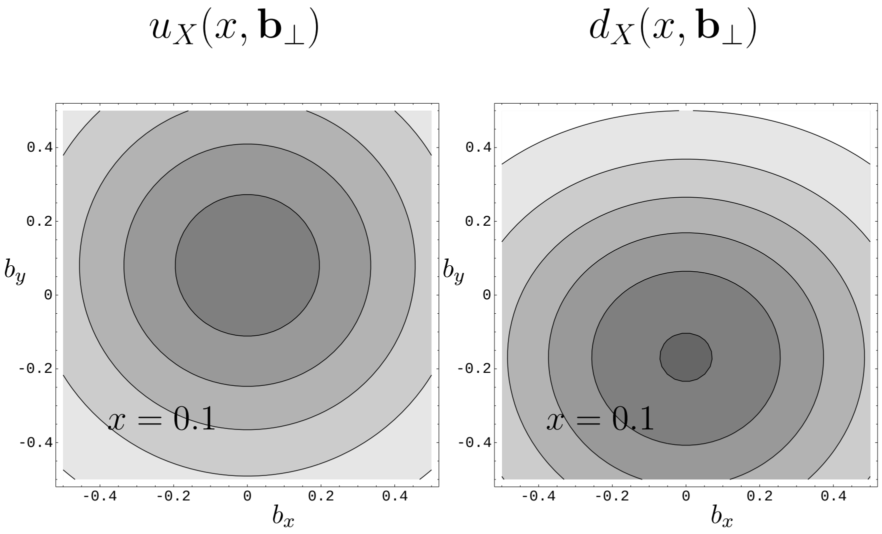


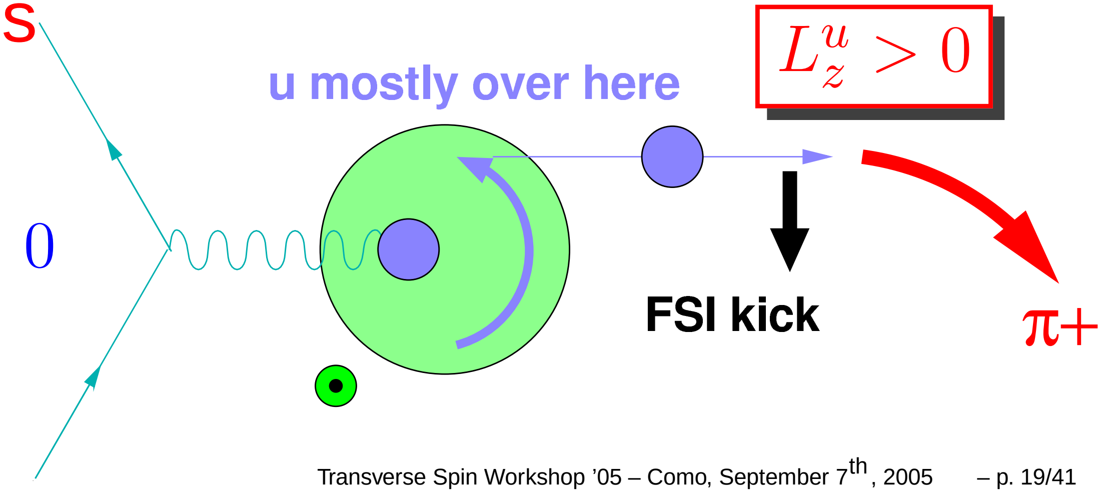
+ attractive QCD potential

(gluon exchange)

$\Rightarrow$ transverse asymmetries

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

✓



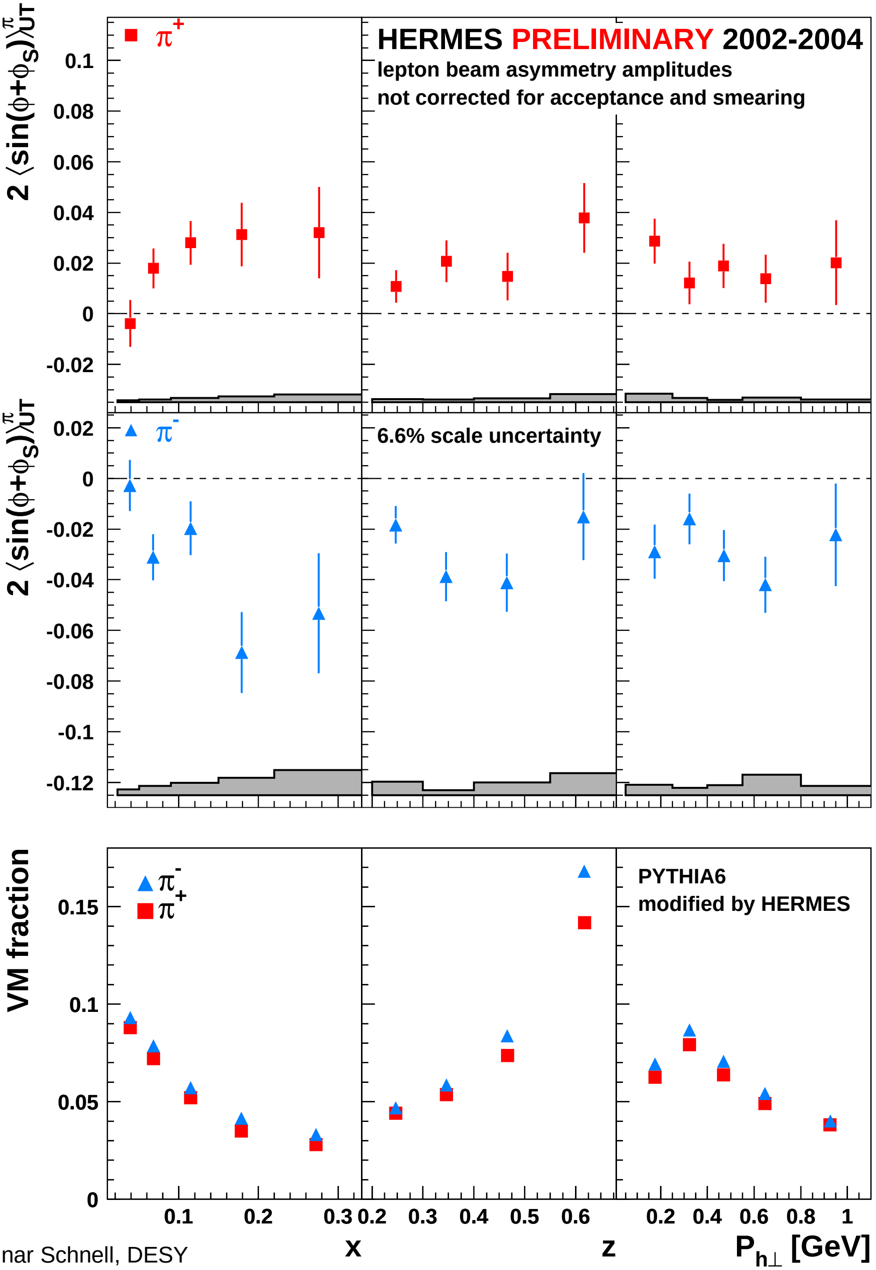
u mostly over here

$\boxed{L_z^u > 0}$

FSI kick

$\pi+$

Collins Asymmetries 2002-2004
(Lepton-Beam Asymmetries)



- positive for π^+ and negative for π^- as maybe expected (expectation: $\delta u > 0$
  $\delta d < 0$)
- unexpected **large π^- asymmetry** $\Rightarrow$ role of **unfavored** Collins FF
- lepton-beam asymmetries (vs. virtual-photon SSA in publication) $\hookrightarrow$ kin. prefactors (“depolarization factors”) still included
- overall scale uncertainty of 6.6%
- published results **confirmed** with much higher statistical precission

A Closer Look at Collins Asymmetries I

rewrite asymmetries in terms of favored and disfavored fragmentation:

- neglect strange quarks
- assume Gaussian k_T dependence of Collins FF → can resolve convolution
- employ isospin symmetry among fragmentation functions, i.e.

$$\begin{aligned} D_f &\equiv D(u \to \pi^+) \simeq D(d \to \pi^-) \simeq D(\bar{d} \to \pi^+) \simeq D(\bar{u} \to \pi^-) \\ D_d &\equiv D(d \to \pi^+) \simeq D(u \to \pi^-) \simeq D(\bar{u} \to \pi^+) \simeq D(\bar{d} \to \pi^-) \\ \frac{1}{2}(D_f + D_d) &\simeq D(u \to \pi^0) \simeq D(d \to \pi^0) \simeq D(\bar{d} \to \pi^0) \simeq D(\bar{u} \to \pi^0) \end{aligned}$$

$$\hookrightarrow \tilde{A}_C^{\pi^+/\pi^-}(x,z) \propto \frac{(4\delta u + \delta\bar{d})H_{f/d} + (4\delta\bar{u} + \delta d)H_{d/f}}{(4u + \bar{d})D_{f/d} + (4\bar{u} + d)D_{d/f}}$$

$$\tilde{A}_C^{\pi^0}(x,z) \propto \frac{\left[4(\delta u + \delta\bar{u}) + \delta d + \delta\bar{d}\right](H_f + H_d)}{\left[4(u + \bar{u}) + d + \bar{d}\right](D_f + D_d)}$$

A Closer Look at Collins Asymmetries II

express asymmetries in terms of flavor ratios:

$$\tilde{A}_C^{\pi^+} = \mathcal{K}(x,z)\frac{4+\delta r\mathcal{H}}{4+r\mathcal{D}}$$

$$\tilde{A}_C^{\pi^-} = \mathcal{K}(x,z)\frac{4\mathcal{H}+\delta r}{4\mathcal{D}+r}$$

$$\tilde{A}_C^{\pi^0} = \mathcal{K}(x,z)\frac{(4+\delta r)(1+\mathcal{H})}{(4+r)(1+\mathcal{D})}$$

Polarized Objects

$$\mathcal{H} = \frac{H_d}{H_f}$$

$$\delta r = \frac{\delta d + 4\delta\bar{u}}{\delta u + \frac{1}{4}\delta\bar{d}}$$

Unpolarized Objects

$$\mathcal{D} = \frac{D_d}{D_f}$$

$$r = \frac{d + 4\bar{u}}{u + \frac{1}{4}\bar{d}}$$

e.g., CTEQ6,R1990 and Kretzer et al.

Mixed

$$\mathcal{K} = \frac{(\delta u + \frac{1}{4}\delta\bar{d})zH_f}{(u + \frac{1}{4}\bar{d})D_f}$$

$\Rightarrow$ 3 constraints and 3 unknowns!

A Closer Look at Collins Asymmetries II

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$$\tilde{A}_C^{\pi^-} = \mathcal{K}(x,z)\,\frac{4\mathcal{H}+\delta r}{4\mathcal{D}+r}$$

$$\tilde{A}_C^{\pi^0} = \mathcal{K}(x,z)\,\frac{(4+\delta r)(1+\mathcal{H})}{(4+r)(1+\mathcal{D})}$$

Polarized Objects Unpolarized Objects Mixed

The three asymmetries are not independent ($C(x,z) \equiv \frac{r(x)+4\mathcal{D}(z)}{r(x)\mathcal{D}(z)+4}$):

$$\tilde{A}_C^{\pi^+}(x,z) + C(x,z)\tilde{A}_C^{\pi^-}(x,z) - (1+C(x,z))\tilde{A}_C^{\pi^0}(x,z) = 0$$

al.

$\Rightarrow$ 3 constraints and 3 unknowns!

A Closer Look at Collins Asymmetries II

express asymmetries in terms of flavor ratios:

$$\begin{aligned}
\tilde{A}_C^{\pi^+} &= \mathcal{K}(x,z)\,\frac{4+\delta r\mathcal{H}}{4+r\mathcal{D}} \\
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\end{aligned}$$

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Unpolarized Objects

$$\mathcal{D} = \frac{D_d}{D_f}$$

$$r = \frac{d + 4\bar{u}}{u + \frac{1}{4}\bar{d}}$$

e.g., CTEQ6,R1990 and Kretzer et al.

Mixed

$$\mathcal{K} = \frac{(\delta u + \frac{1}{4}\delta\bar{d})\,z H_f}{(u + \frac{1}{4}\bar{d})\,D_f}$$

⇒ ~~3~~ constraints and 3 unknowns!

2

A Closer Look at Collins Asymmetries III

eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to δr

$\Rightarrow$ scan solution space for $\mathcal{H}$ and δr by sampling set of $(\tilde{A}_C^{\pi^+}, \tilde{A}_C^{\pi^-}, \tilde{A}_C^{\pi^0})$

(around measured values according to statistical uncertainty)

A Closer Look at Collins Asymmetries III

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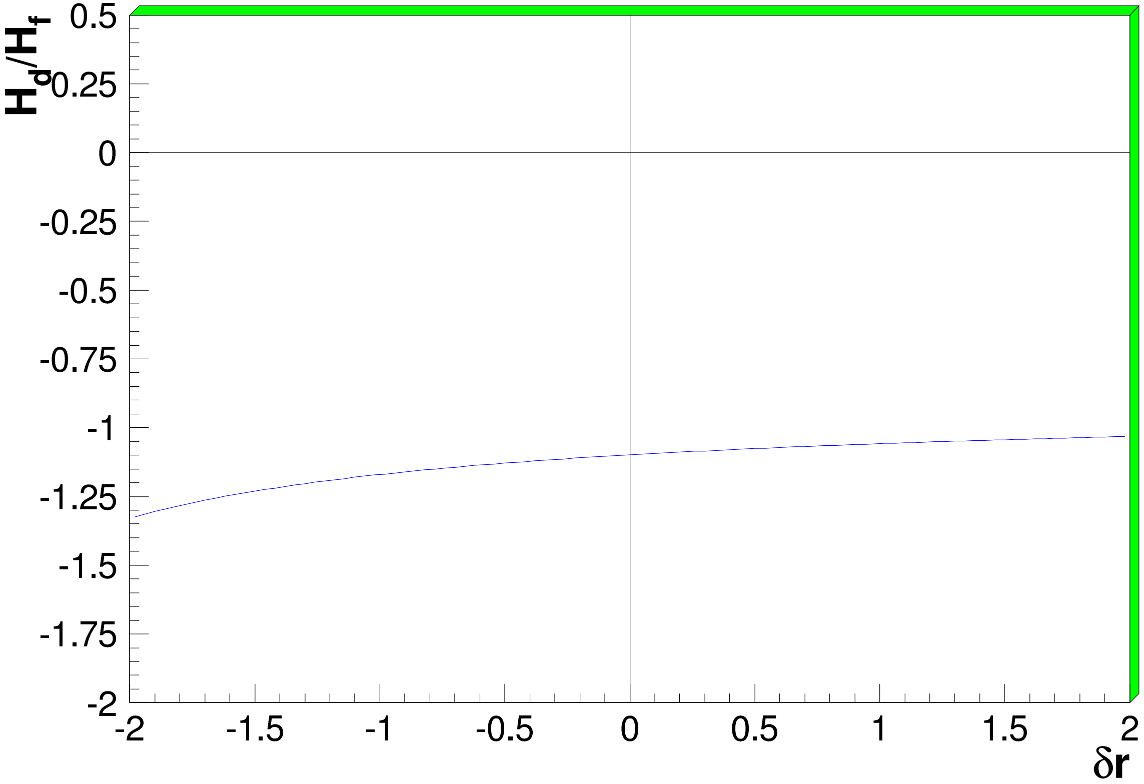

A Closer Look at Collins Asymmetries III

eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to δr

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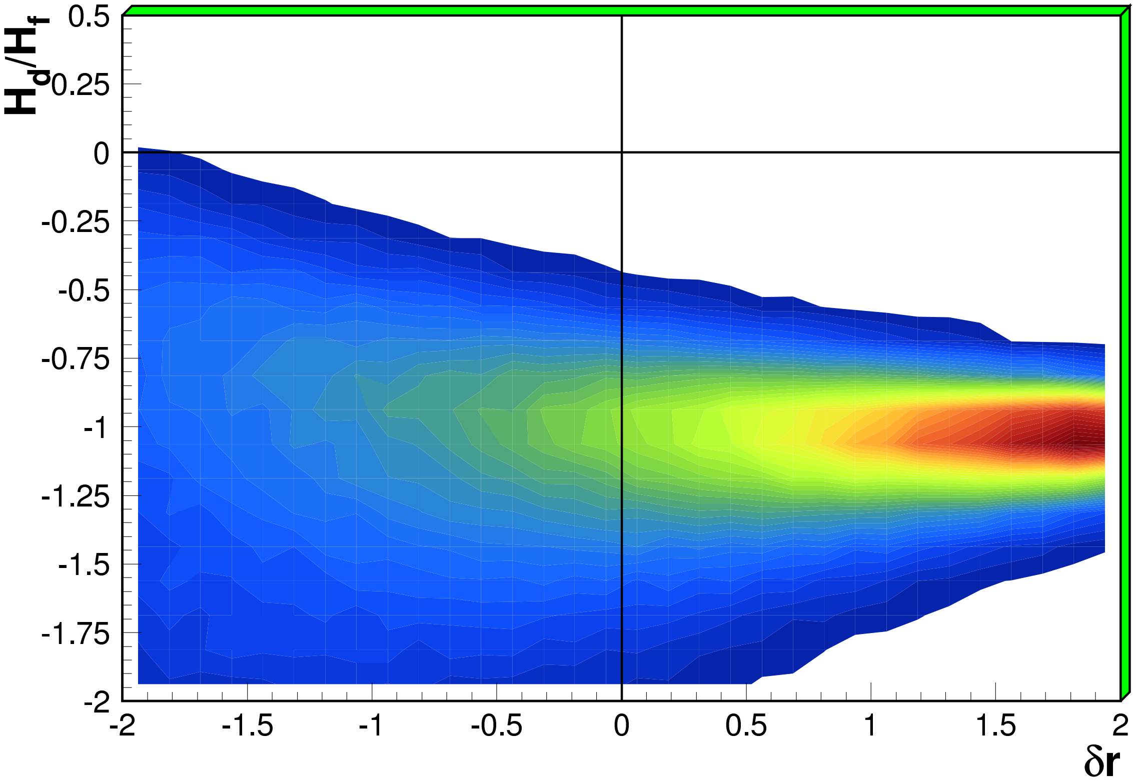
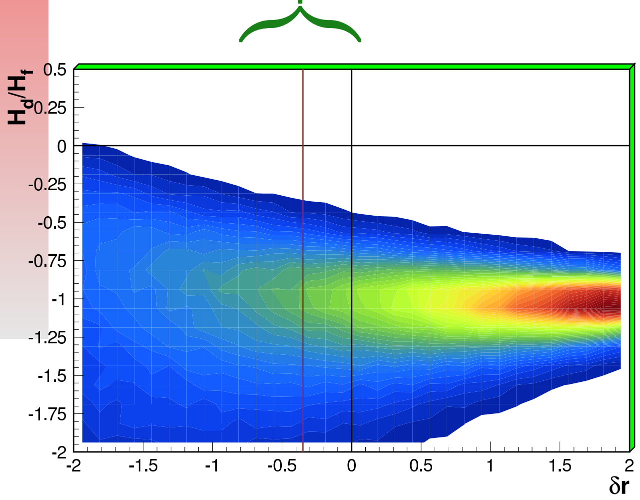
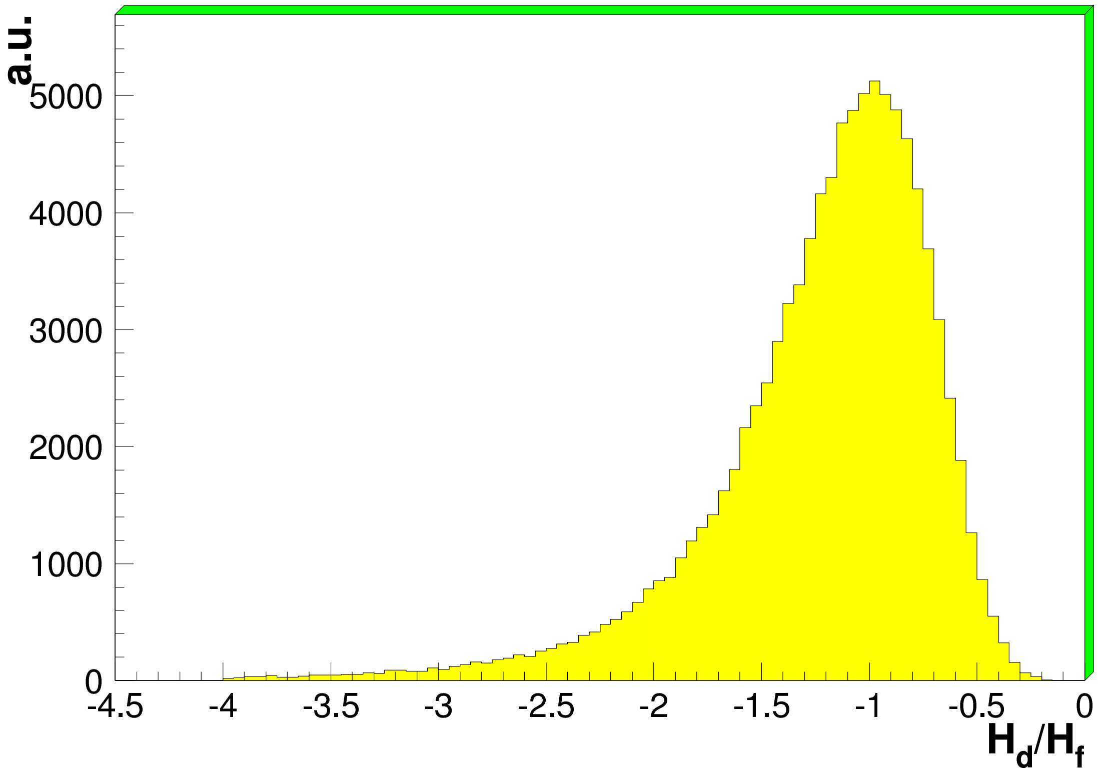


Limits on Transversity and Collins FF

$\delta r \approx \delta d/\delta u$ from χQSM

look at slice of distribution:



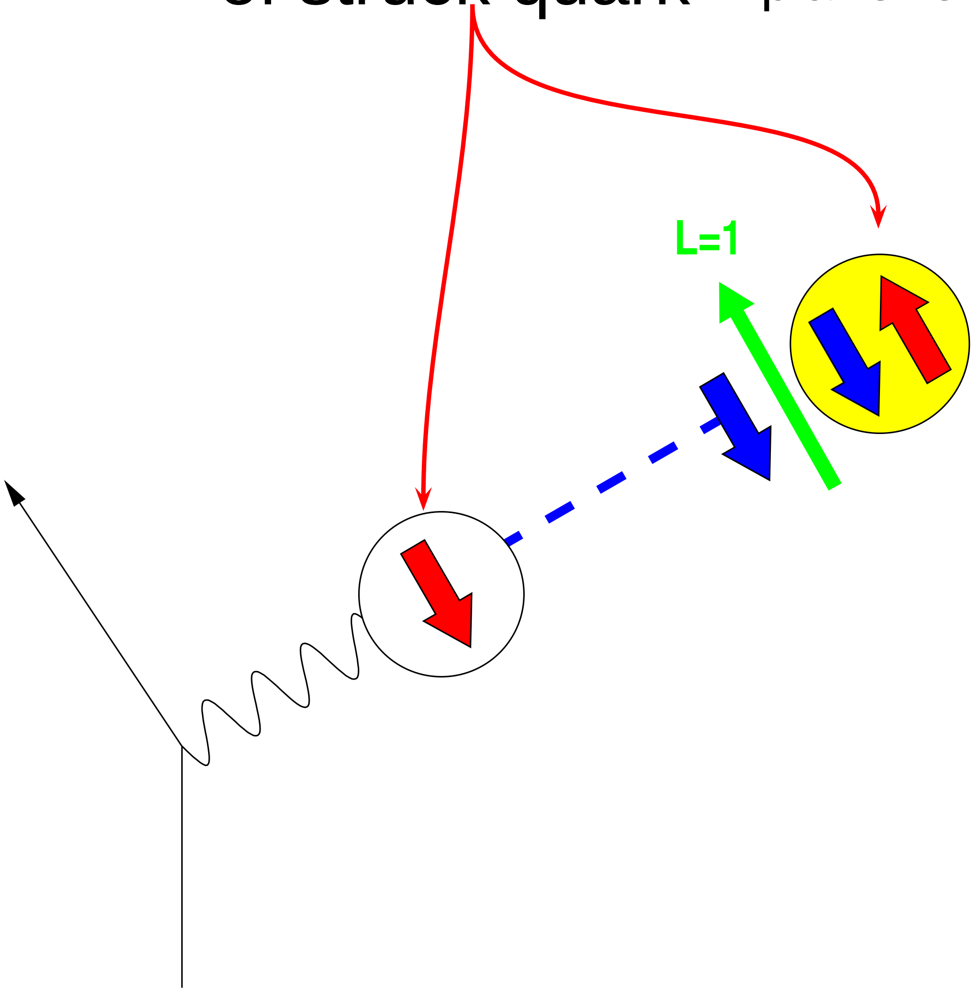


strong hint for H_d/H_f negative

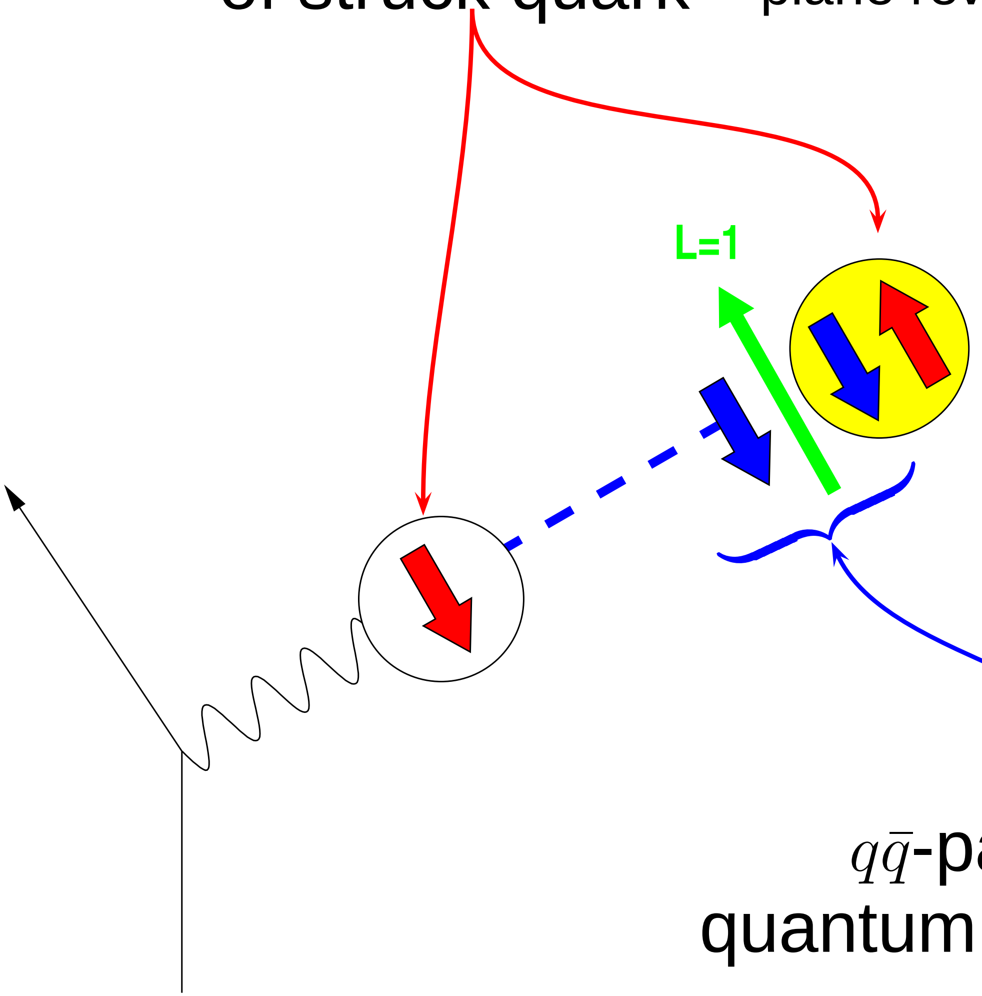
Understanding the Collins FF - String Model Interpretation (Artru)

transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)



Understanding the Collins FF - String Model Interpretation (Artru)

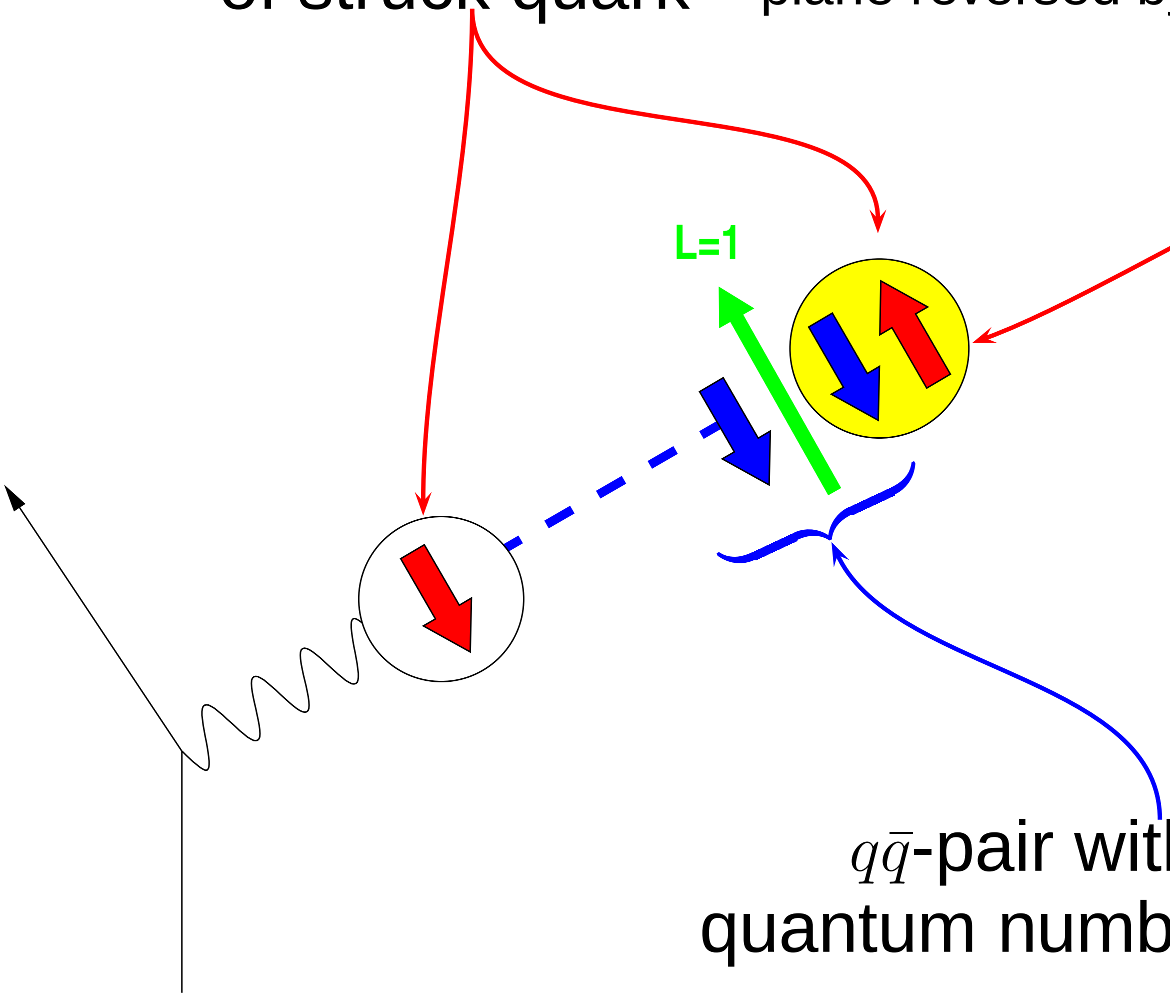


transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)

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

Understanding the Collins FF - String Model Interpretation (Artru)



transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)

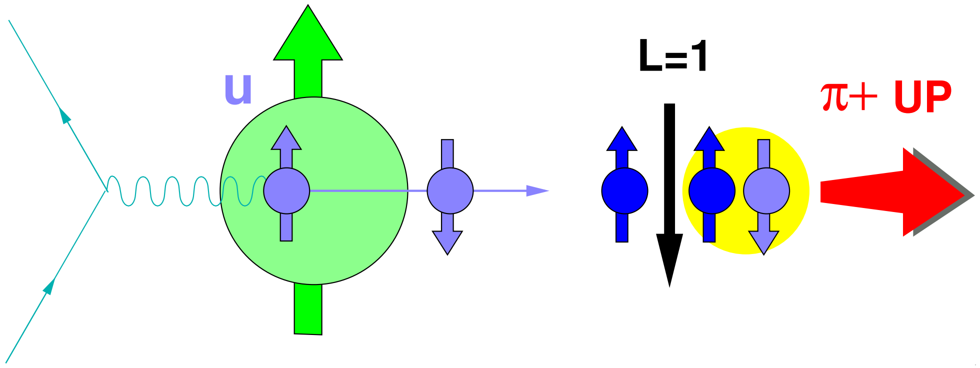
outgoing pion deflected into page

(positive Collins FF)

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

Artru Model vs. HERMES

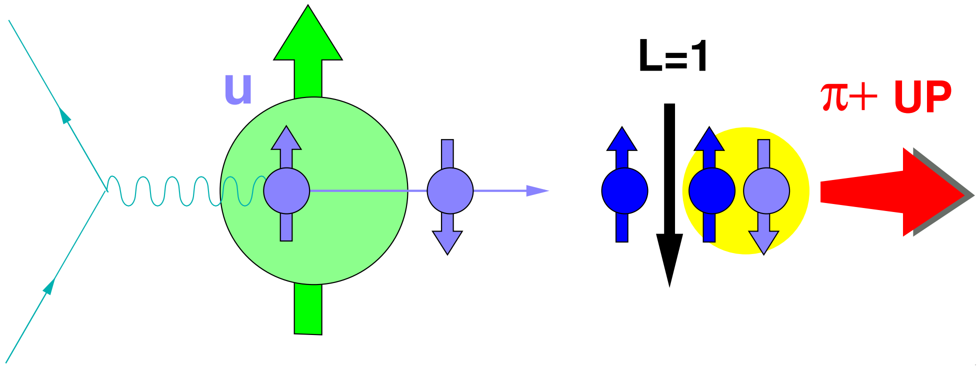
[courtesy of N. Makins]



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

Artru Model vs. HERMES

[courtesy of N. Makins]



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✓

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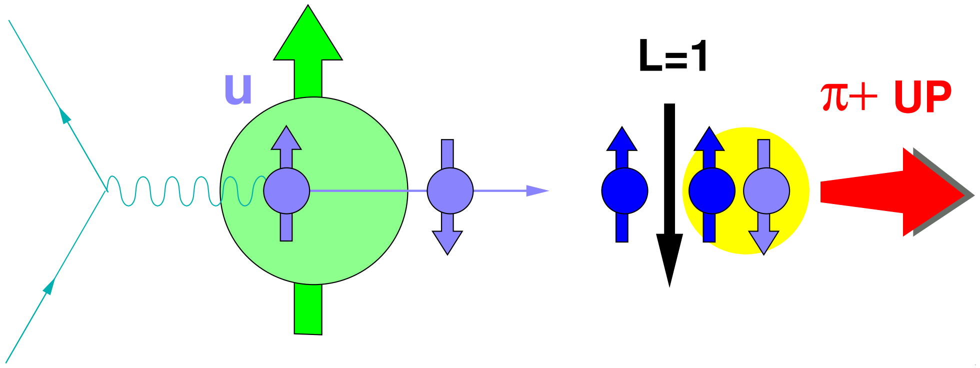

$$\left.\begin{array}{rl}\phi_S = & 0\\ \phi = & \pi/2\end{array}\right\} \sin(\phi+\phi_S) > 0$$

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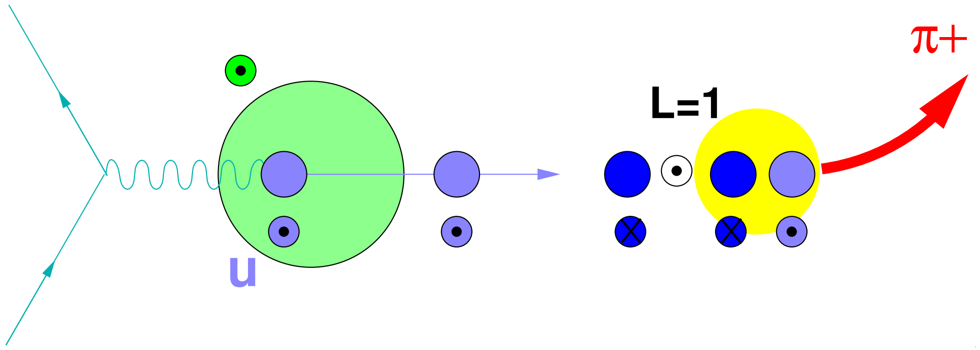

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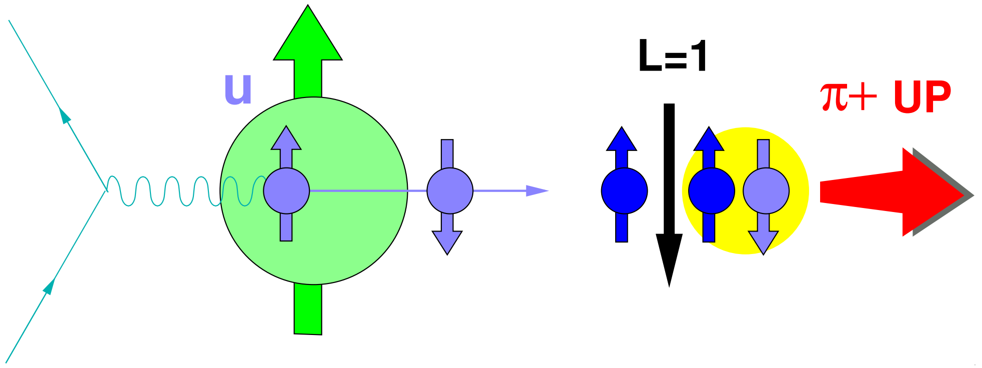

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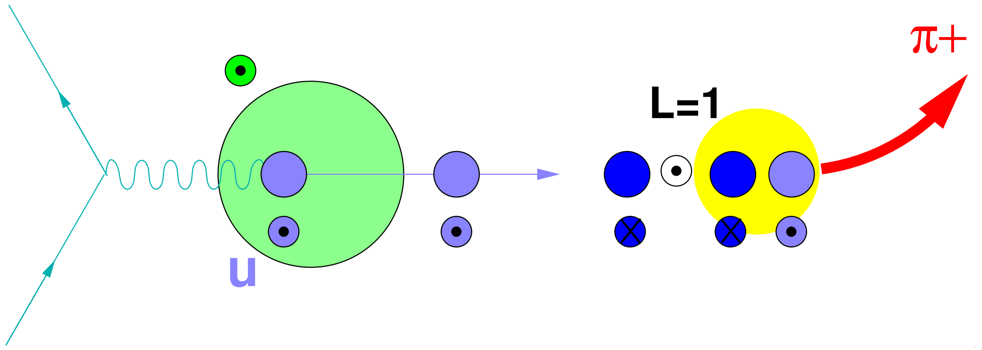
✓



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Artru Model vs. HERMES

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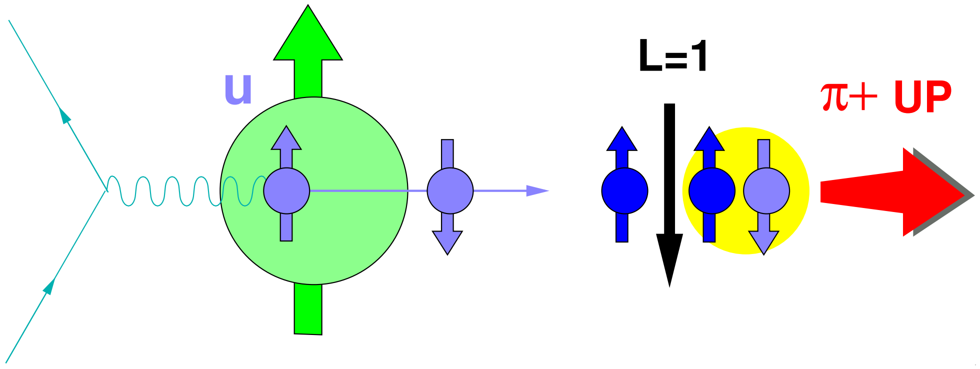

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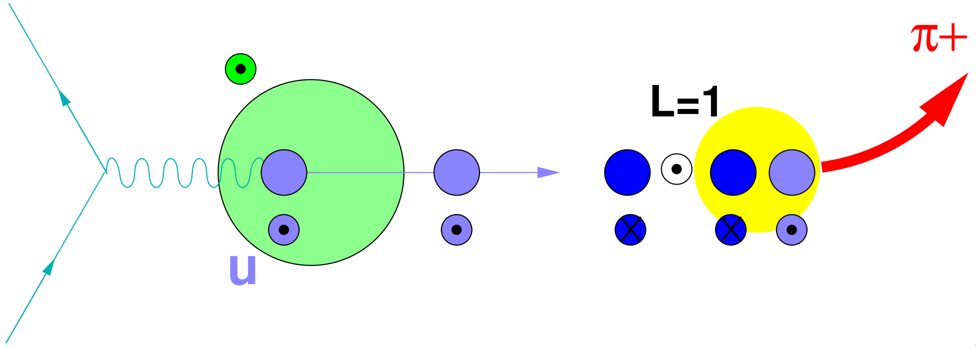

$$\left.\begin{array}{rl}\phi_S = & \pi/2\\ \phi = & 0\end{array}\right\} \sin(\phi+\phi_S) > 0$$

✓

Artru model and HERMES results in agreement!

A Small Caveat

- at HERMES energies $R^{DIS} = \sigma_L/\sigma_T$ not small! (up to 35%)
- how to incorporate in asymmetry extraction?
- can correct unpolazized cross section in asymmetry

$$A(y) \equiv 1 - y + y^2/2 \quad \rightsquigarrow \quad \frac{(1-y)(1+R(x,y))}{1+\gamma^2} + y^2/2$$

BUT: only know inclusive $R \Longrightarrow$ need SIDIS R

$\Rightarrow$ stay with cross section asymmetries (lepton-beam asymmetries), i.e., leave in kinematic prefactors?!?

What About Longitudinally Polarized Targets?

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

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

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

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

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

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

What About Longitudinally Polarized Targets?

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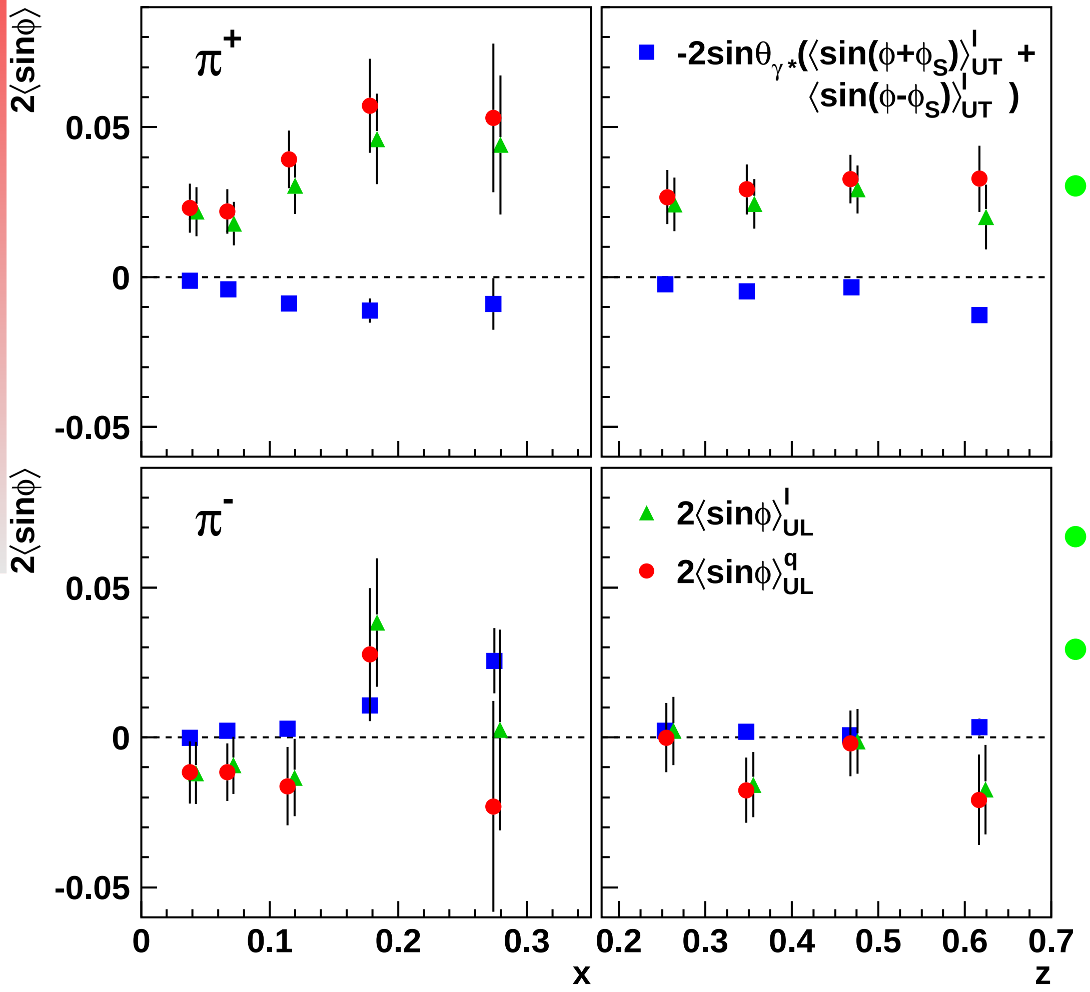


- twist-3 dominates measured asymmetries on longitudinally polarized targets!
- significantly positive for π^+
- consistent with zero for π^-

[Airapetian et al., hep-ex/0505042]

The Other Longitudinal SSA

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

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

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

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

The Other Longitudinal SSA

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

The Other Longitudinal SSA

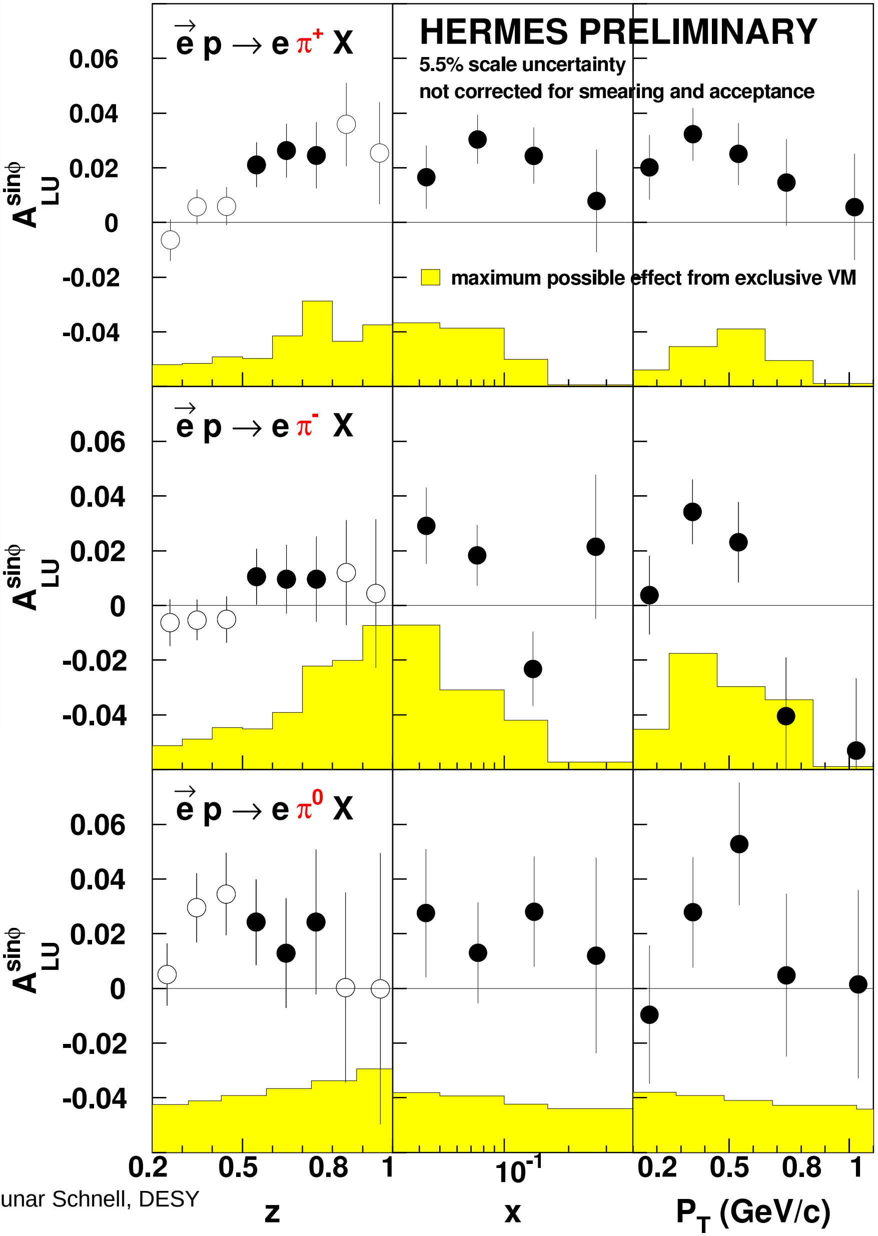
longitudinally pol. beam & unpol. target ⇒ subleading-twist

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

- many terms contributing – difficult to separate
- maybe some terms small?

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

Longitudinal Beam-Spin Asymmetries



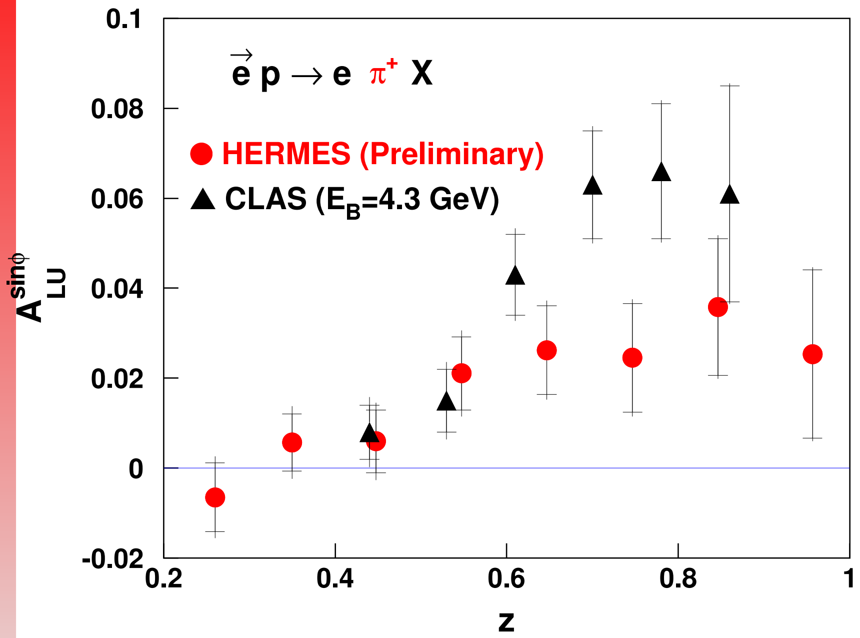
Extraction:

$$2\left\langle \sin\phi \right\rangle_{LU} = \frac{\sum^{+} \frac{\sin\phi_i}{|P_e^{+}|} - \sum^{-} \frac{\sin\phi_i}{|P_e^{-}|}}{\frac{1}{2}(N^{+} + N^{-})}$$

Vector Meson Contribution:

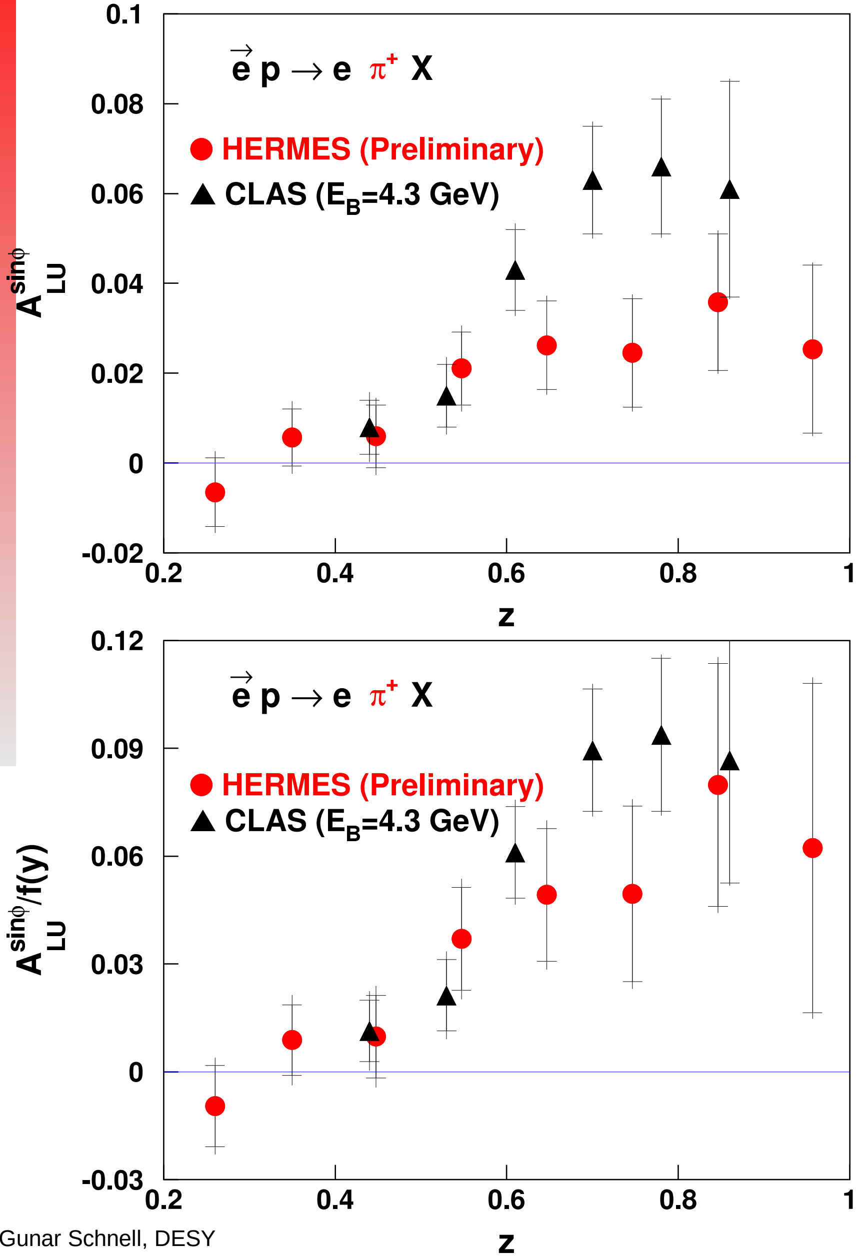
Max. possible contribution to systematic uncertainty estimated using PYTHIA MC (tuned for HERMES)

Comparisons with CLAS Experiment



- not so good agreement at high z

Comparisons with CLAS Experiment



- not so good agreement at high z
- have to correct for different y range at CLAS and HERMES:

$$\left\langle \sin\phi \right\rangle_{LU} \propto f(y) \equiv \frac{2y\sqrt{(1-y)}}{1-y+y^2/2}$$

strong suppression at HERMES for high z compared to CLAS

$\Rightarrow$ rescaling of asymmetries leads to good agreement

Summary and Outlook

- Non-vanishing Collins effect observed for $\pi^{\pm}$
- First evidence of T-odd Sivers distribution in DIS
- $\left\langle \sin\phi \right\rangle_{UL}^{l}$ dominated by subleading twist
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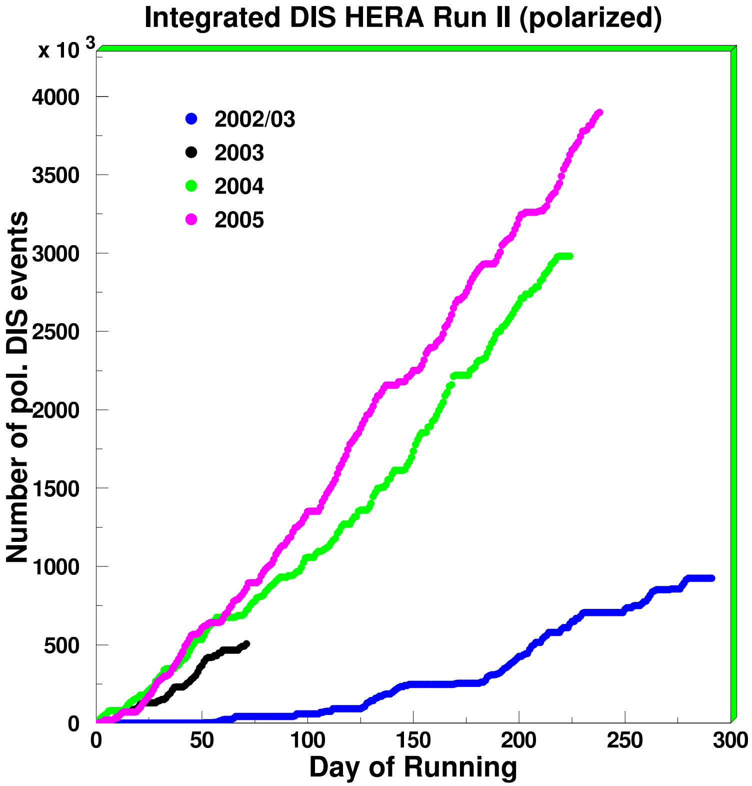

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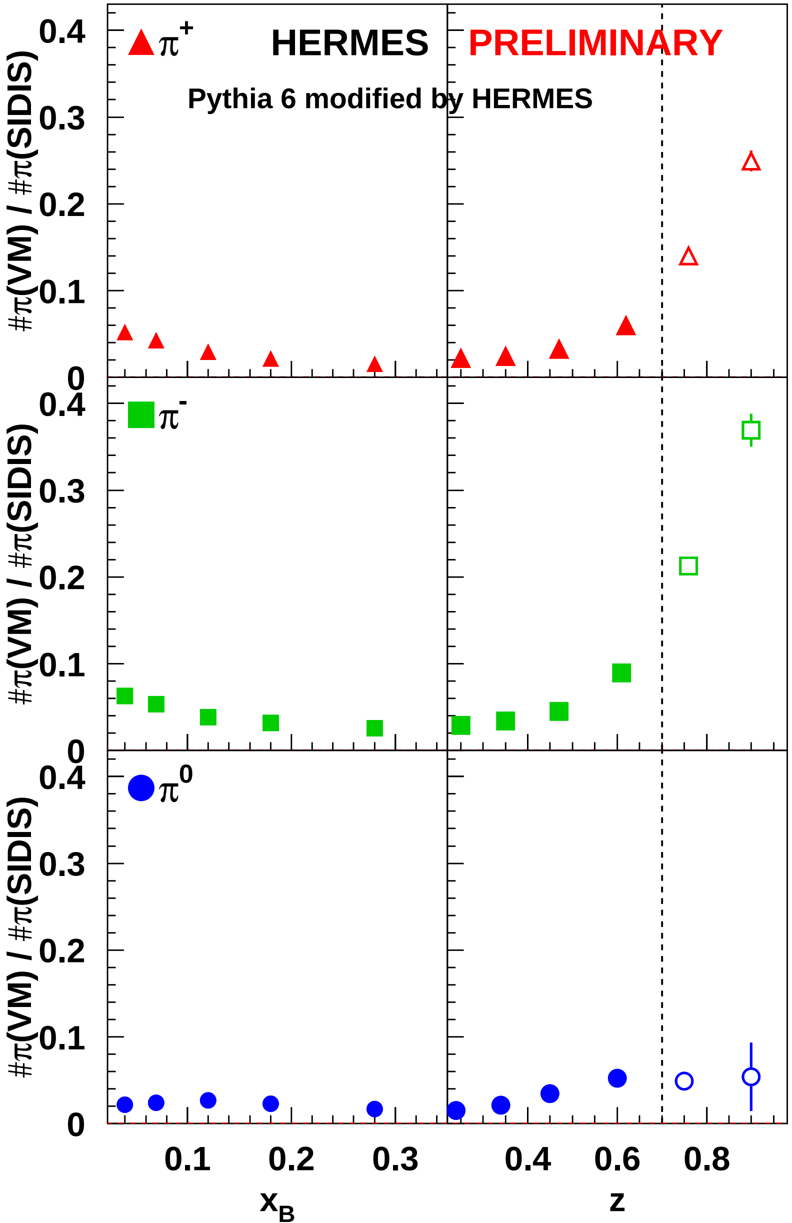
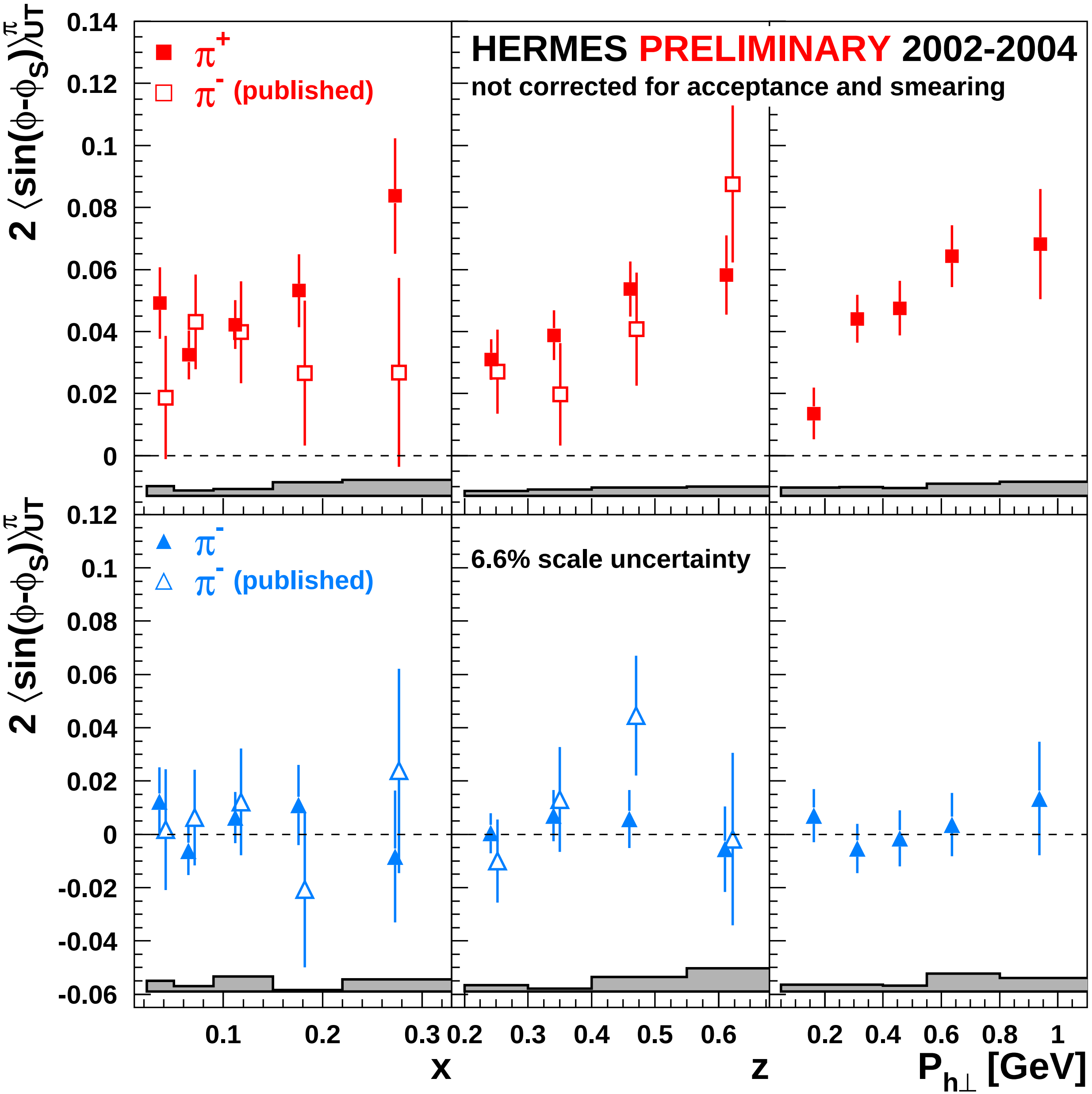
Backup Slides

Contamination of SIDIS Sample

- misidentified π's from decay of exclusive vector mesons
- VM usually can't be reconstructed (too small acceptance)
- use PYTHIA physics generator tuned for HERMES
- identify π's from exclusive processes (ρ^0, ω) to get contribution to π yield
- small contribution to π yield for $z < 0.7$
- asymmetry of these π's not (yet) known



Sivers Asymmetries 2002-2004
Comparison with Publication



Collins Asymmetries 2002-2004

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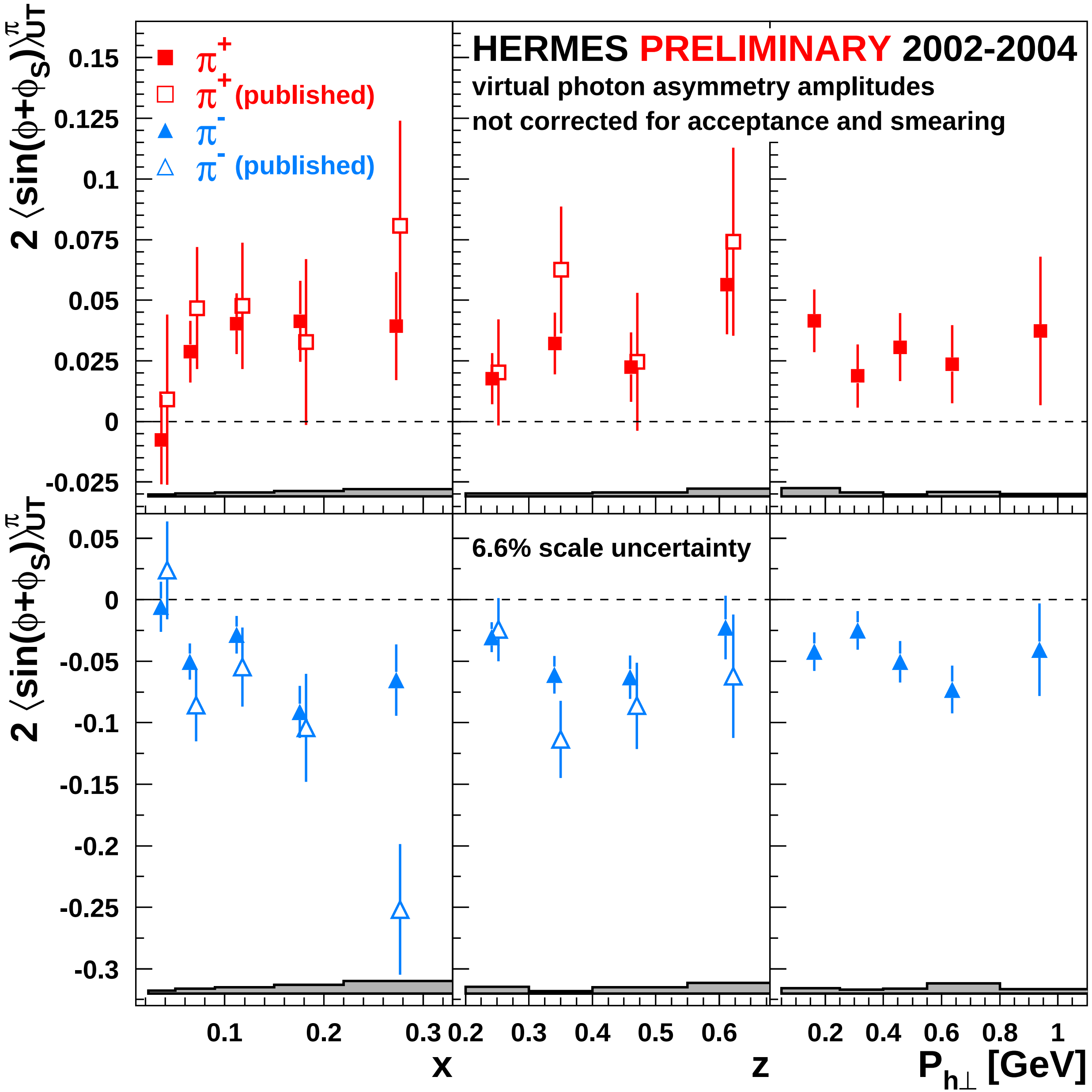


Resolving the Convolution Integral

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

$$\begin{aligned}
\tilde{A}_{UT}(\phi,\phi_S) &= \frac{1}{\langle S_\perp \rangle} \frac{\sum_{i=1}^{N^+} P_{h\perp,i} - \sum_{i=1}^{N^-} P_{h\perp,i}}{N^+ + N^-} \\
&\sim \sin(\phi+\phi_C) \cdot \sum_q e_q^2 \, \delta q(x) \; z \; H_1^{\perp(1),q}(z) \\
&- \sin(\phi-\phi_S) \cdot \sum_q e_q^2 \, f_{1T}^{\perp(1),q}(x) \; z \; D_1^q(z) \\
&+ \ldots
\end{aligned}$$

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

$\Rightarrow$ 2D-fit of $\tilde{A}_{UT}$ to get Collins and Sivers asymmetries:

$$\tilde{A}_{UT}(\phi,\phi_S) = M_\pi \tilde{A}_C(x,z) \sin(\phi+\phi_s) + M_p \tilde{A}_S(x,z) \sin(\phi-\phi_s)$$

Kinematic Cuts

$$\begin{aligned}
1\ \text{GeV}^2 &< \quad Q^2 \\
0.1 &< \quad y \quad < 0.85 \\
0.023 &< \quad x \quad < 0.4 \\
10\ \text{GeV}^2 &< \quad W^2 \\
0.2 &< \quad z \quad < 0.7 \\
2\ \text{GeV} &< \quad P_h \quad < 15\ \text{GeV} \\
0.02\ \text{rad} &< \quad \theta_{\gamma^* h}
\end{aligned}$$

Extracting Transversity

$$\tilde{A}_C(x,y) = D(y)\frac{\sum e_q^2 \delta q(x) z H_1^{\perp(1)}(z)}{\frac{1}{2}\sum e_q^2 q(x) D_1(z)}$$

- measure $H_1^{\perp(1)}(z)$ in different process or
- get from different experiment or
- get from theory
- enough statistics $\Rightarrow$ 2D analysis of $A_C(x,z)$ to get both $\delta q(x)$ and $H_1^{\perp(1)}(z)$
- use different channels to access transversity

Extracting Quark Distributions

Purity Formalism

$$
\begin{aligned}
A_{UT}^{\sin(\phi-\phi_S),h}(x) &= \mathcal{C}\cdot\frac{\sum_q e_q^2\, f_{1T}^{\perp(1),q}(x)\int dz\, D_1^{q,h}(z)\mathcal{A}(x,z)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x)\int dz\, D_1^{q',h}(z)\mathcal{A}(x,z)} \\
&= \mathcal{C}\cdot\sum_q \frac{e_q^2\, f_1^q(x)\, \mathcal{D}_1^{q,h}(x)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x)\, \mathcal{D}_1^{q',h}(x)}\cdot\frac{f_{1T}^{\perp(1),q}}{f_1^q}(x) \\
&= \mathcal{C}\cdot\sum_q \mathcal{P}_q^h(x)\cdot\frac{f_{1T}^{\perp(1),q}}{f_1^q}(x)
\end{aligned}
$$

- purities are completely unpolarized objects → present Monte Carlo-tunes can be used
- probabilistic interpretation of purities possible
- “easy”: Sivers ← fragmentation function (D_1) known

Extracting Quark Distributions

Purity Formalism

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

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

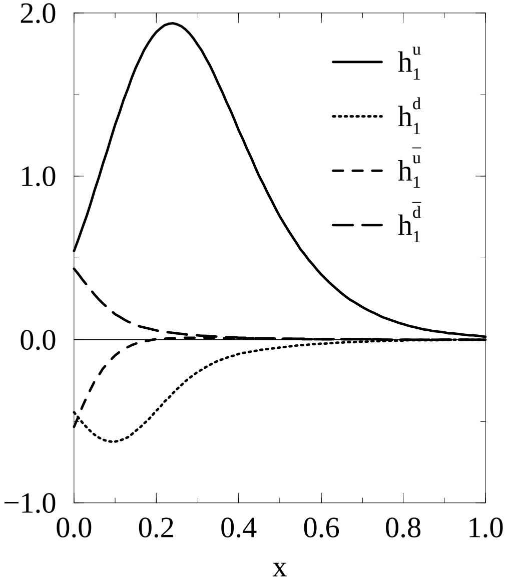
$$= \mathcal{C} \cdot \sum_q \mathcal{P}_q^h(x) \cdot \frac{h_1^q}{f_1^q}(x)$$

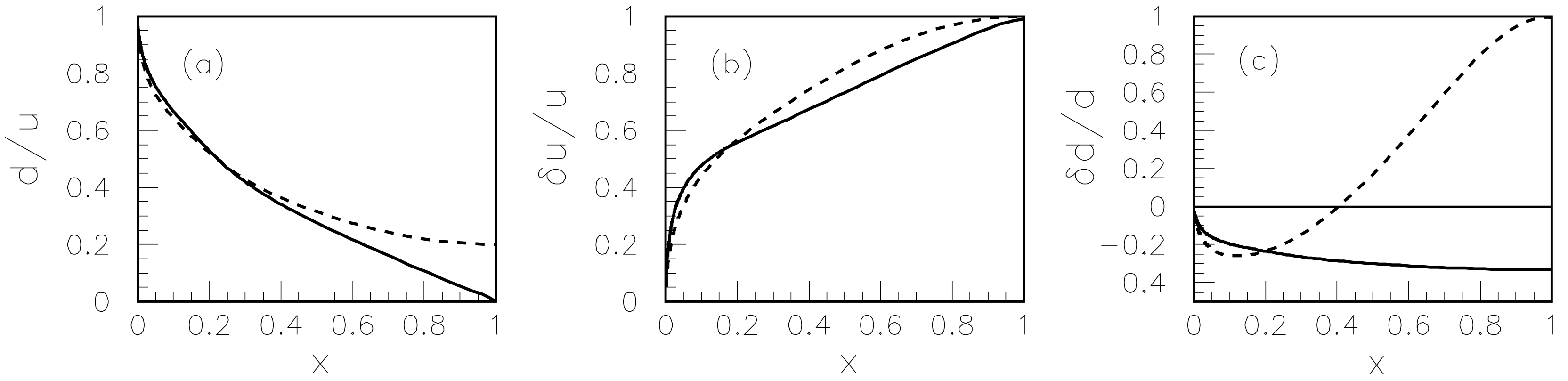
- purities are completely unpolarized objects → present Monte Carlo-tunes can be used
- probabilistic interpretation of purities possible
- “easy”: Sivers ← fragmentation function (D_1) known
- Collins: these purities still depend on parametrization of Collins FF function

Transversity Phenomenology

- ∃ a number of model calculation (facing a lack of experimental data)
- h_1 must satisfy Soffer inequality
- in common: h_1 behaves more valence-like

χQSM (A.V. Efremov et al)





Quark-Diquark (solid), pQCD based model (dashed) (B.Q. Ma et al.)