Transversity and Transverse Momentum Dependent Distribution and Fragmentation Functions

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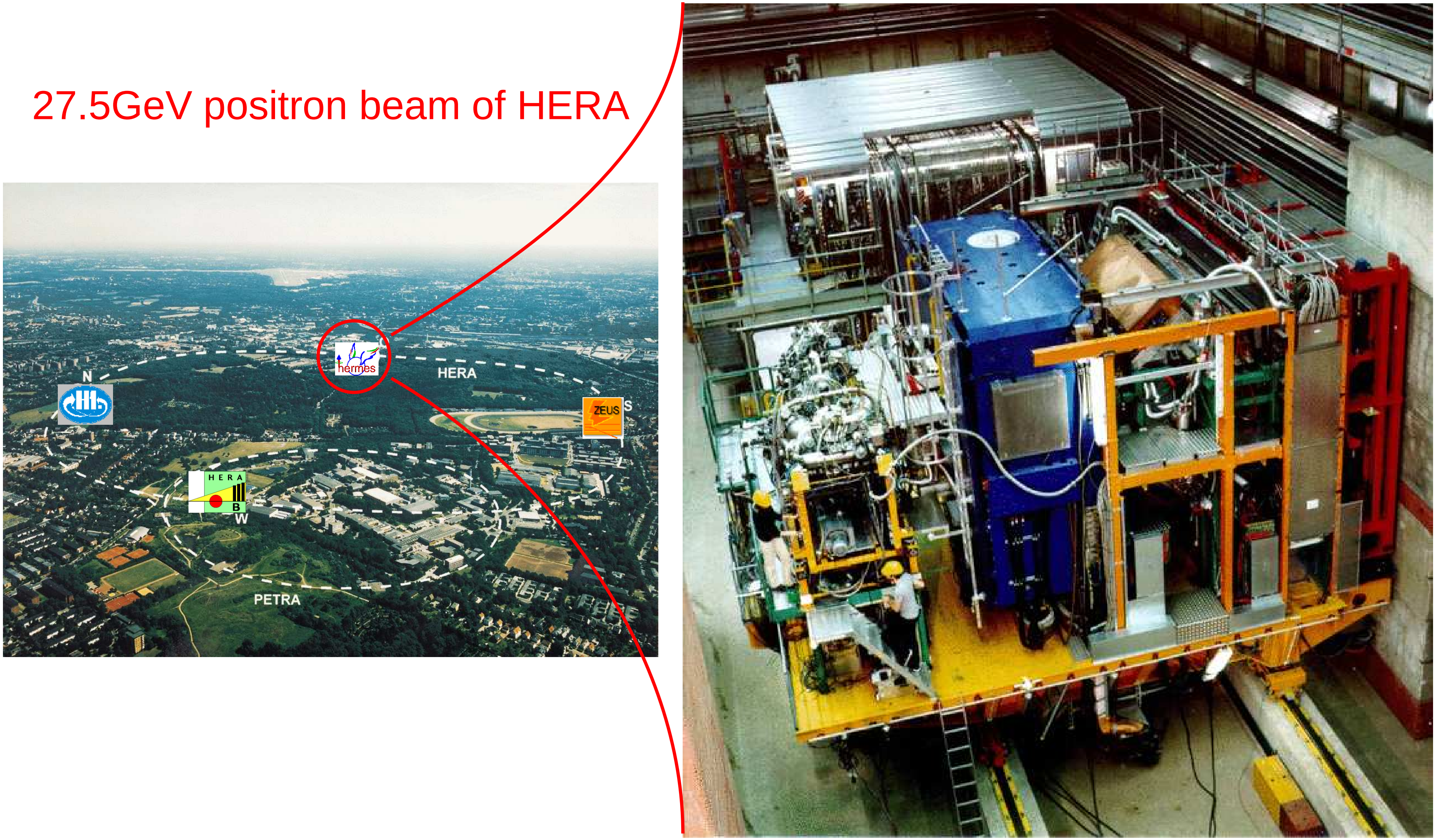
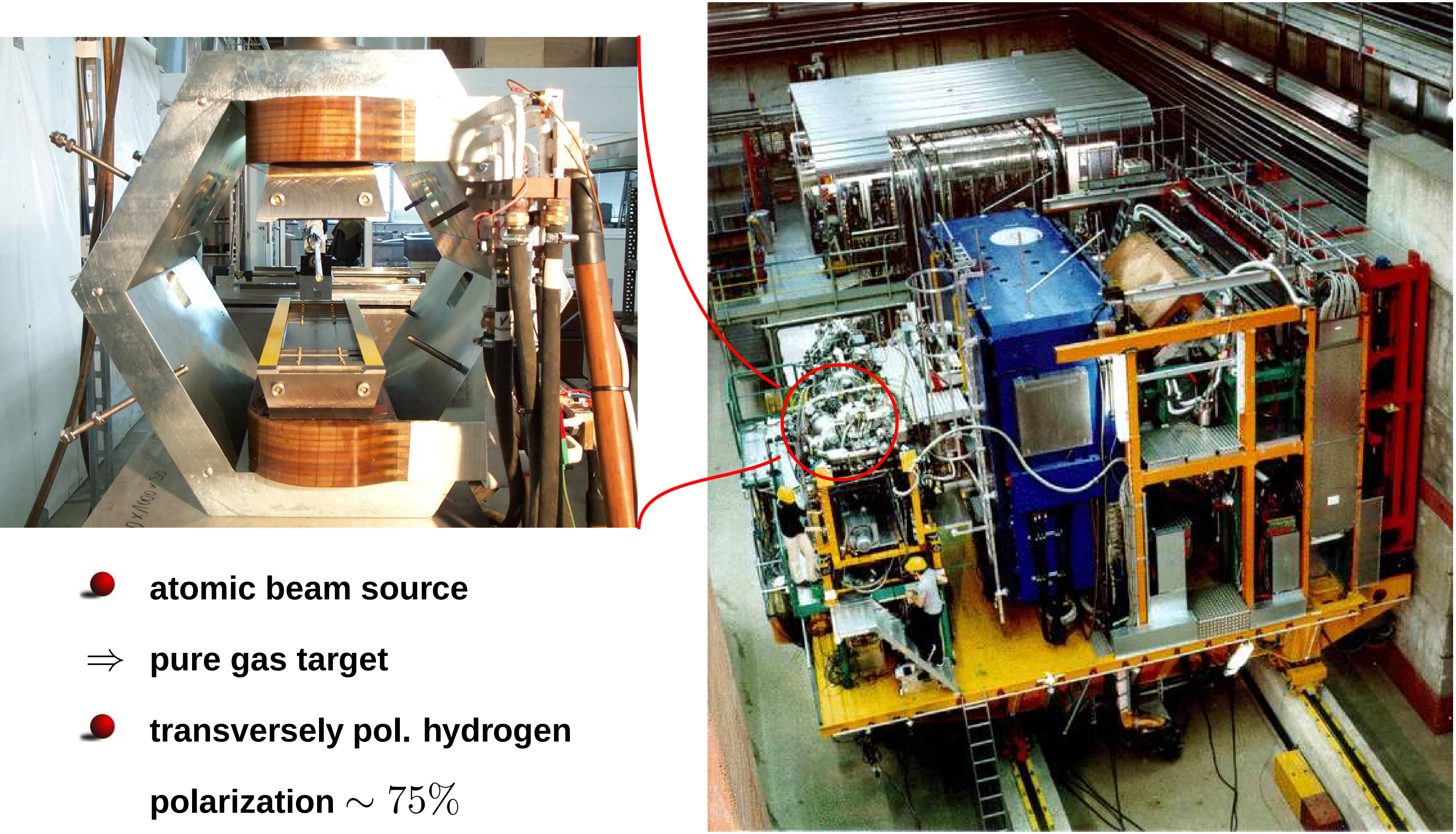
For the hermes Collaboration

HERMES at DESY

27.5GeV positron beam of HERA



HERMES at DESY



- atomic beam source

$\Rightarrow$ **pure gas target**

- **transversely pol. hydrogen**

  polarization $\sim 75\%$

- **other targets possible**

Transversity Measurements

How can one measure the chiral-odd transversity?

Need another chiral-odd object!

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Need another chiral-odd object!

⇒ Semi-Inclusive DIS

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

$\Downarrow$ $\Downarrow$

chiral-odd **chiral-odd**

DF FF

CHIRAL EVEN

Transversity Measurements

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Need another chiral-odd object!

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⇓ ⇓

chiral-odd **chiral-odd**

DF FF

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

→ chiral-odd FF as a polarimeter of transv. quark polarization

Semi-Inclusive 2-Hadron Production

2-Hadron Fragmentation

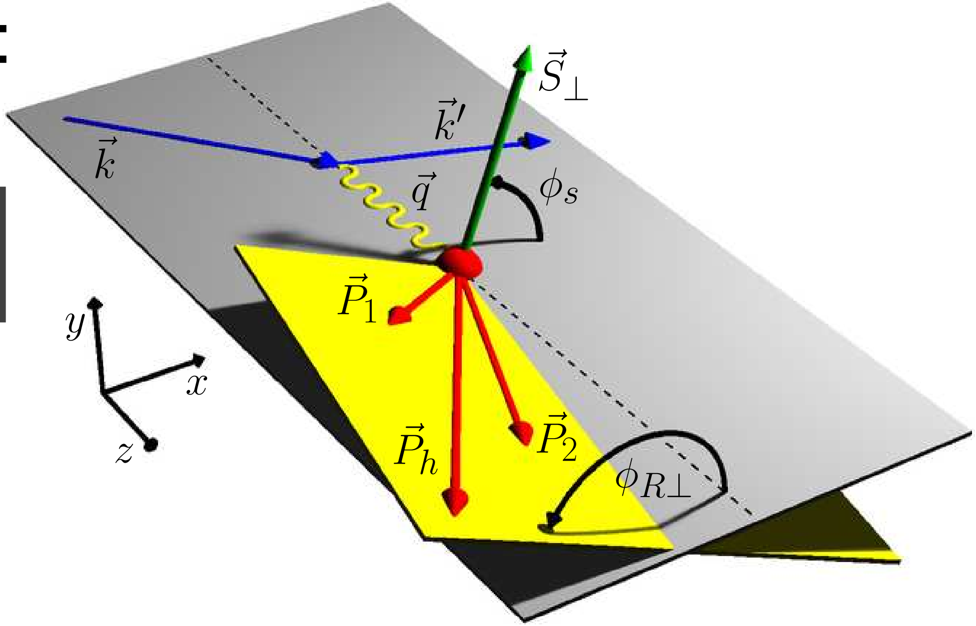
polarized 2-hadron cross section:

(Unpolarized beam, Transversely pol. target)

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

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

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



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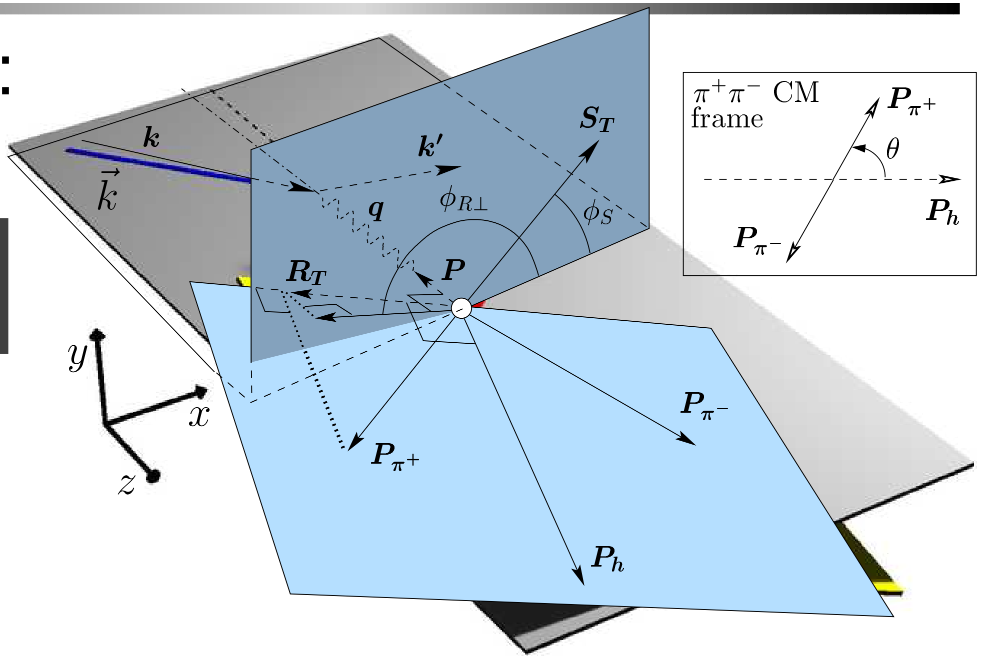

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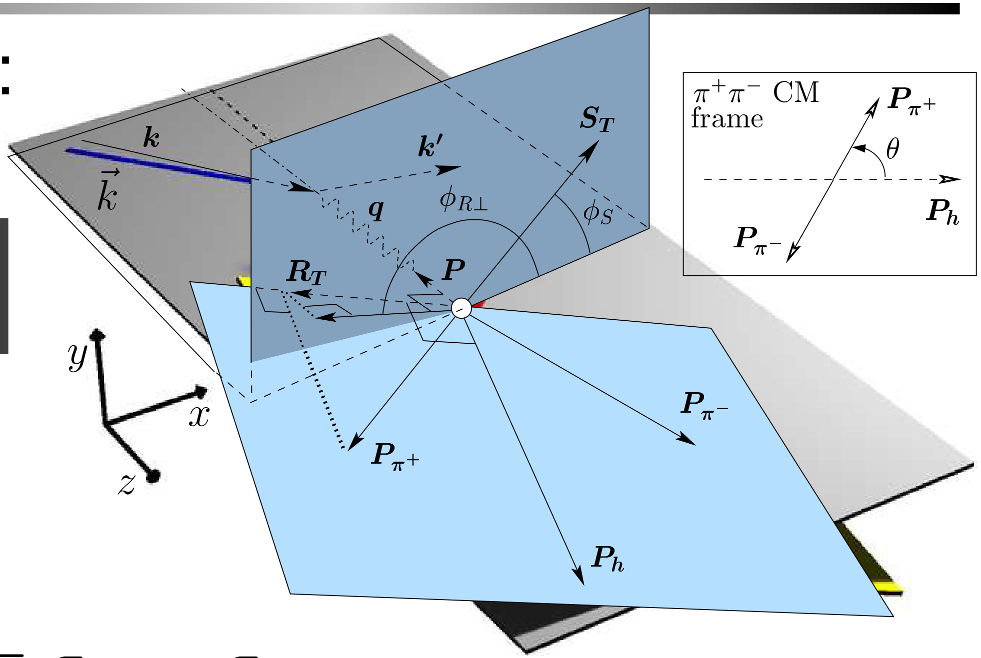

difficult to measure directly $\sigma_{UT} \equiv \sigma_{U\uparrow} - \sigma_{U\downarrow}$

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

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

$\uparrow\downarrow$ . . . **target spin states**

$N_{2\pi}$ . . . **(norm.) 2π yield**

S_T . . . **target polarization**

2-Hadron Fragmentation

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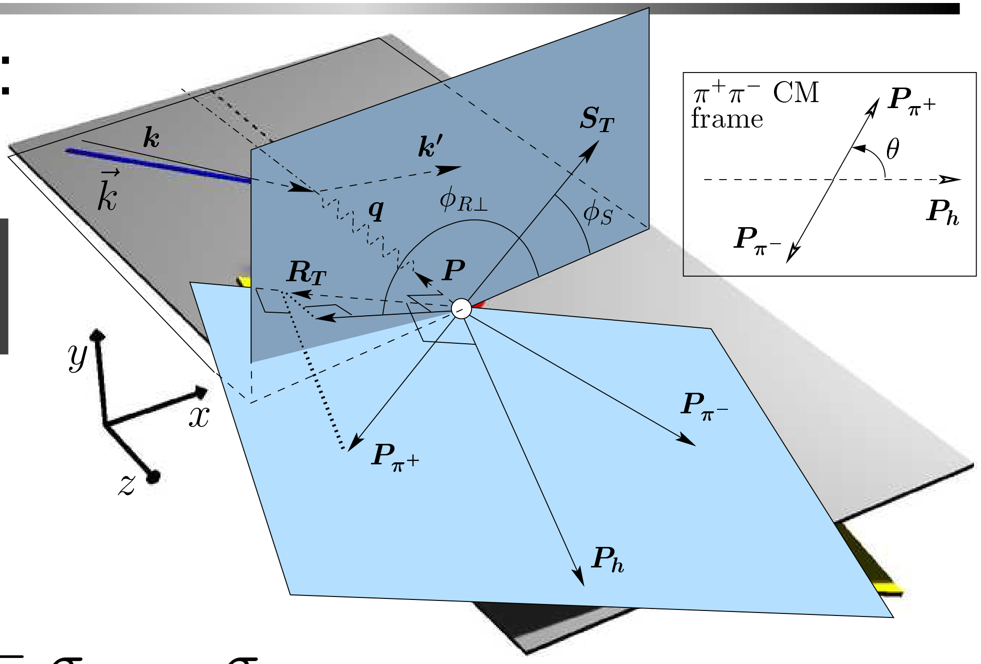

<u>difficult</u> to measure <u>directly</u> $\sigma_{UT} \equiv \sigma_{U\uparrow} - \sigma_{U\downarrow}$

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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

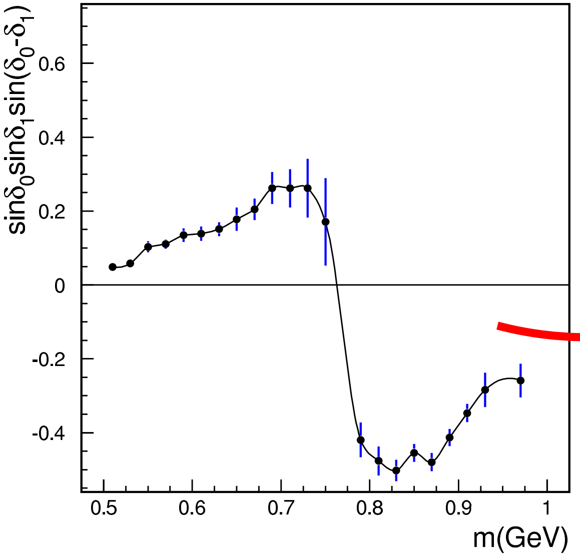
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\sin\theta\, h_1 H_1^{\sphericalangle}$$

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**]:

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

δ_0 (δ_1) → S(P)-wave phase shifts

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

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

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:

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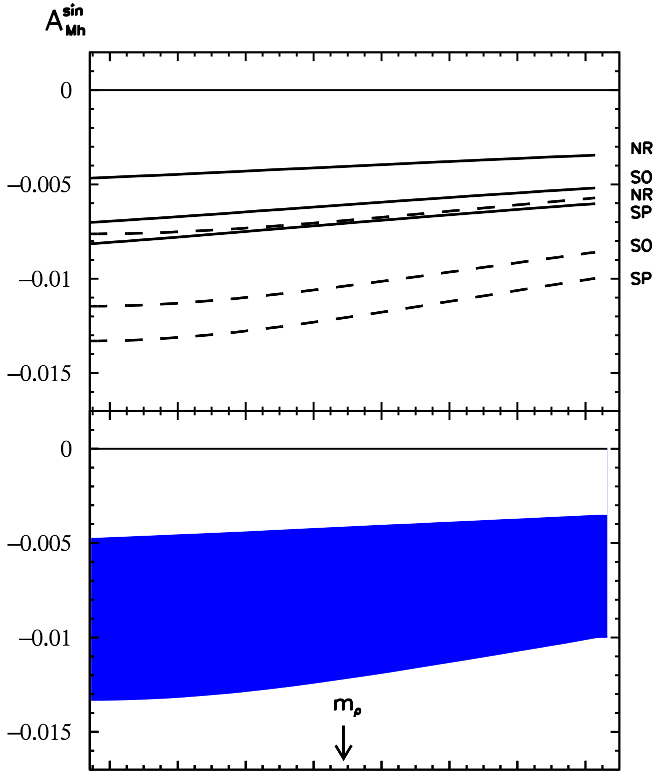
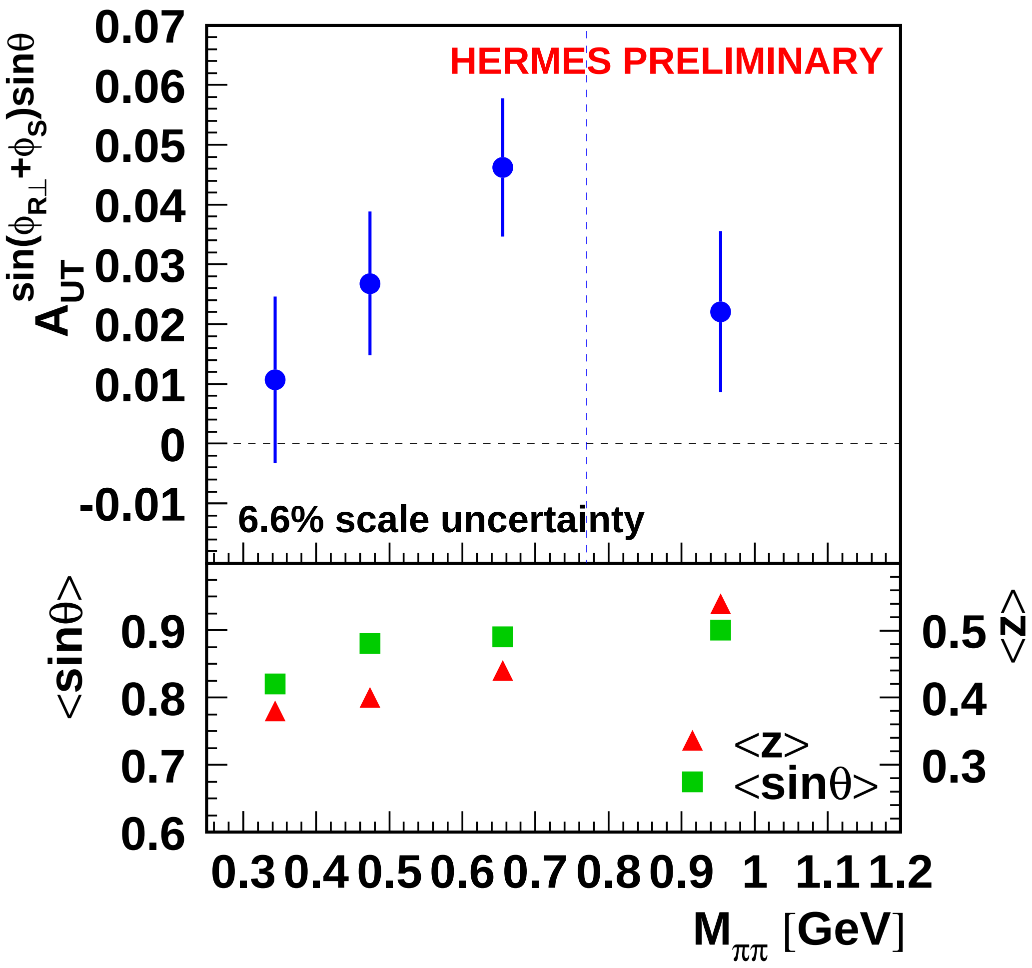


Radici et al. [**hep-ph/0110252**]:

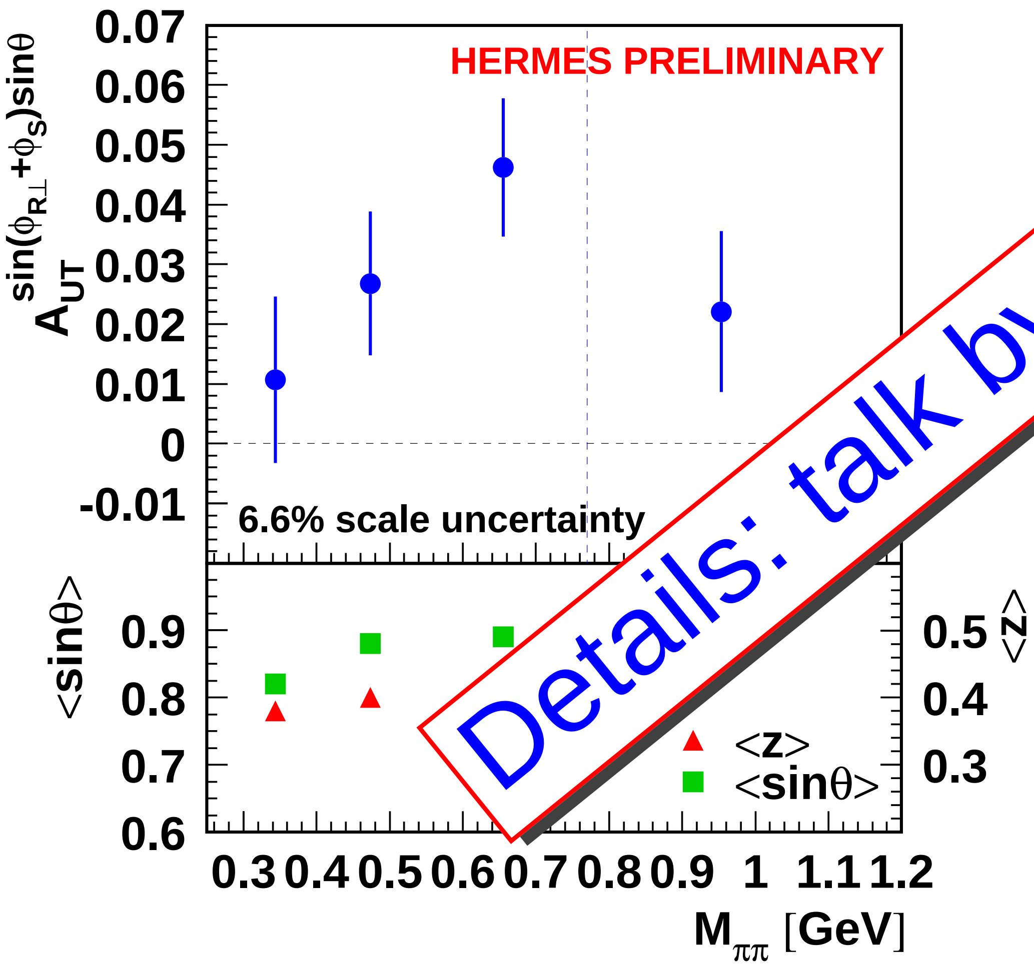
- completely different model, not predicting a sign change of the asymmetry

Mass Dependence of A_{UT}



- **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 Interference FF from Belle (or BaBar etc.)**

Mass Dependence of A_{UT}



Details: talk by F. Giordano

- 2-h interference) FF is not
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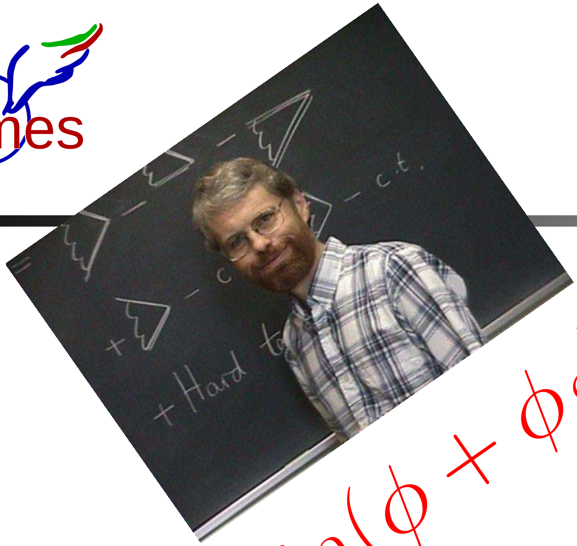


$\sin(\phi + \phi_S)$

$\sin(\phi - \phi_S)$

Semi-Inclusive 1-Hadron Production

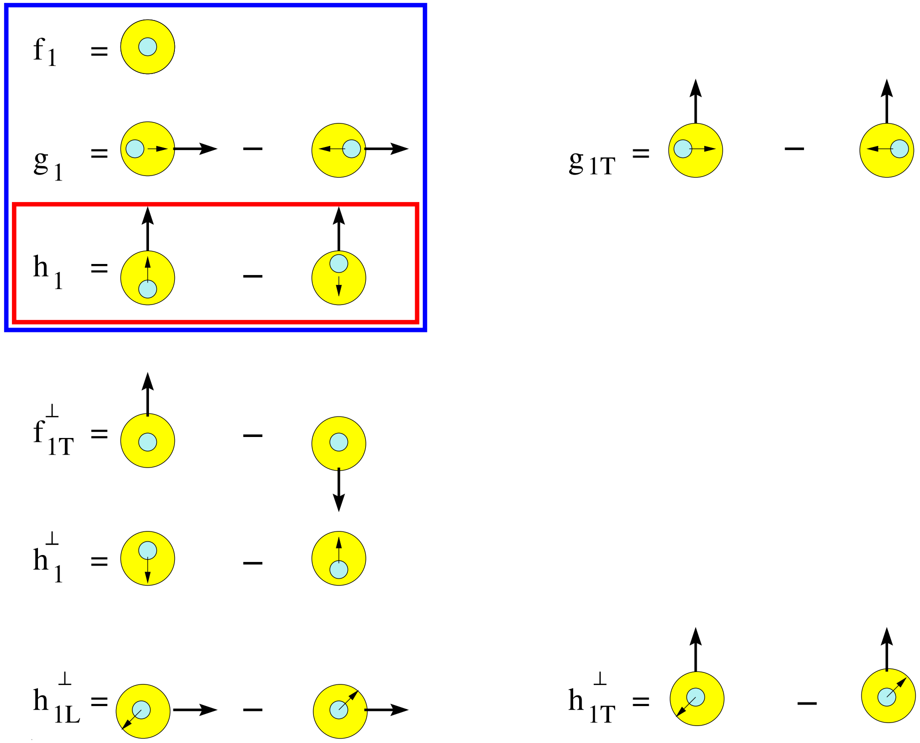
−

$\cos 2\phi$

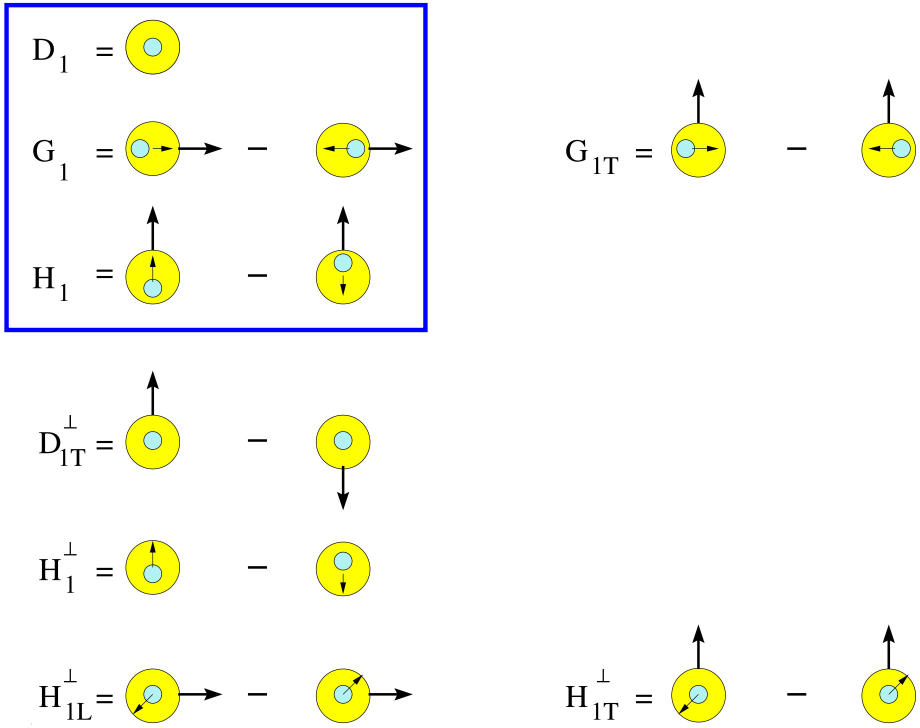
SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions



Fragmentation Functions



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

SSA & Unintegrated Distribution and Fragmentation Functions

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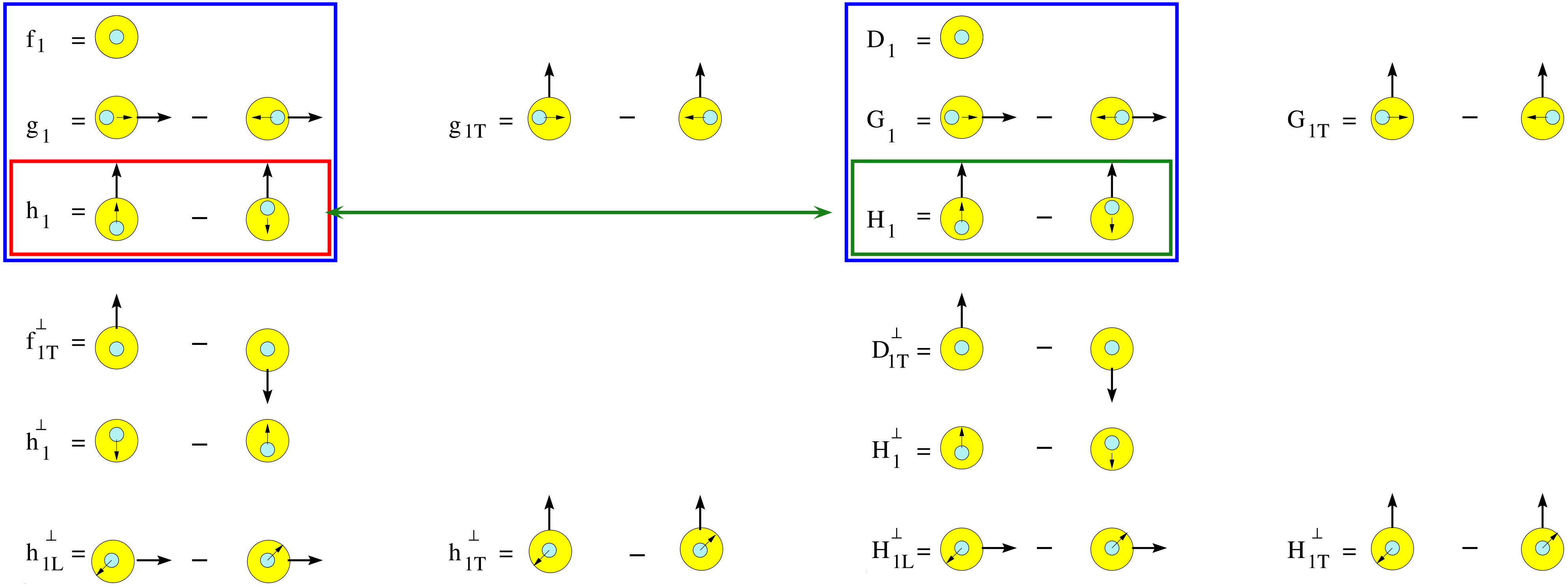

Chiral-odd transversity h_1 must couple to chiral-odd FF

$\Rightarrow$ 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

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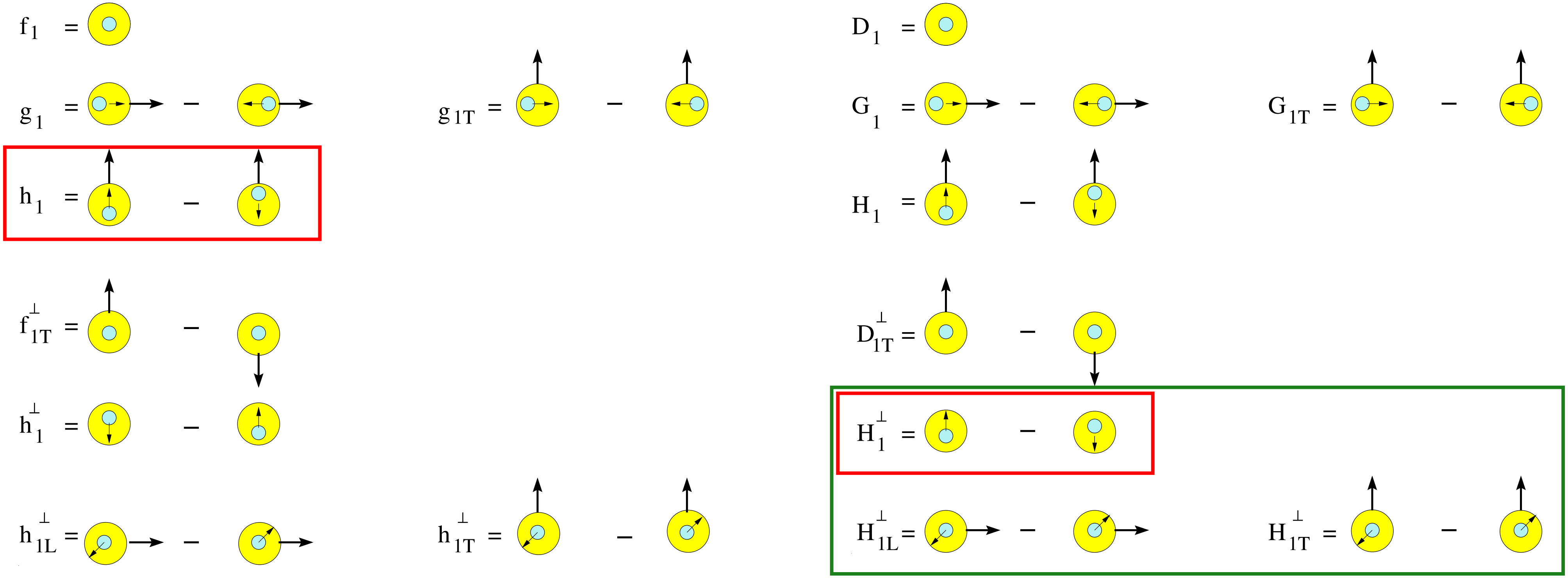


Chiral-odd transversity h_1 must couple to chiral-odd FF

can use k_T-unintegrated chiral-odd FF ⇒ T-odd Collins FF

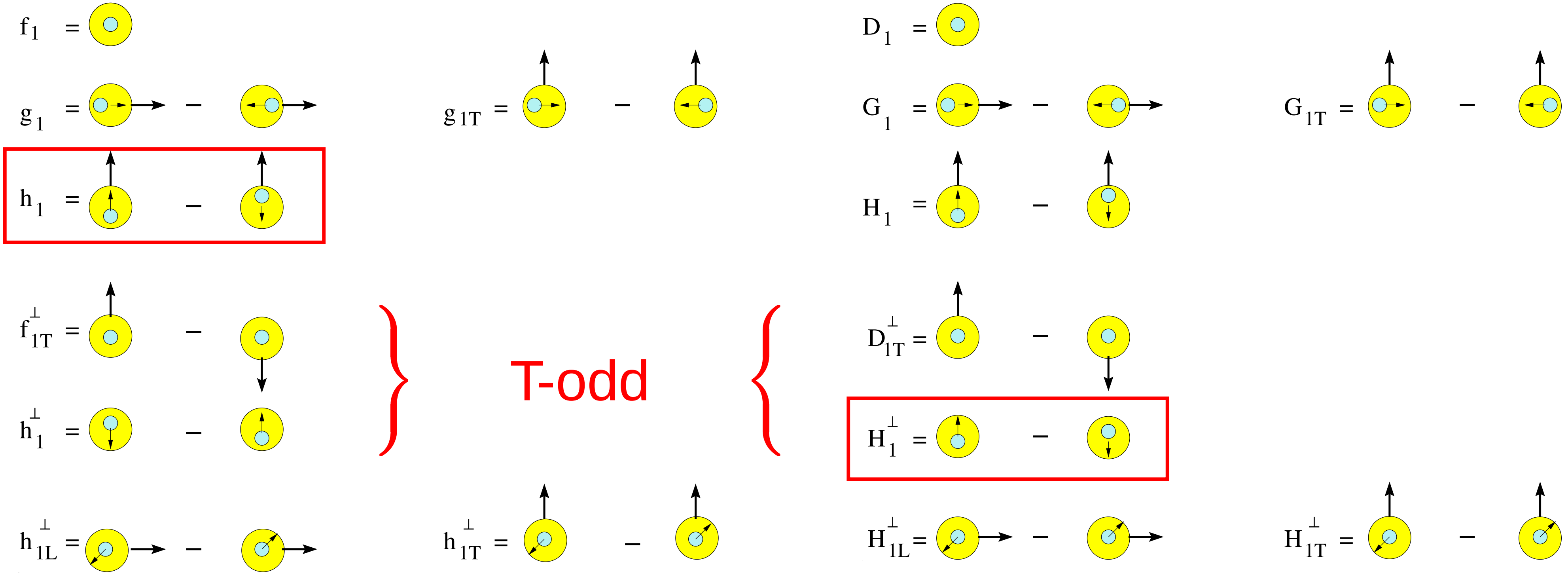
⇒ leads to Single-Spin Asymmetrie (SSA)

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions

Fragmentation Functions



T-odd

SSAs require one and only one T-odd function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions

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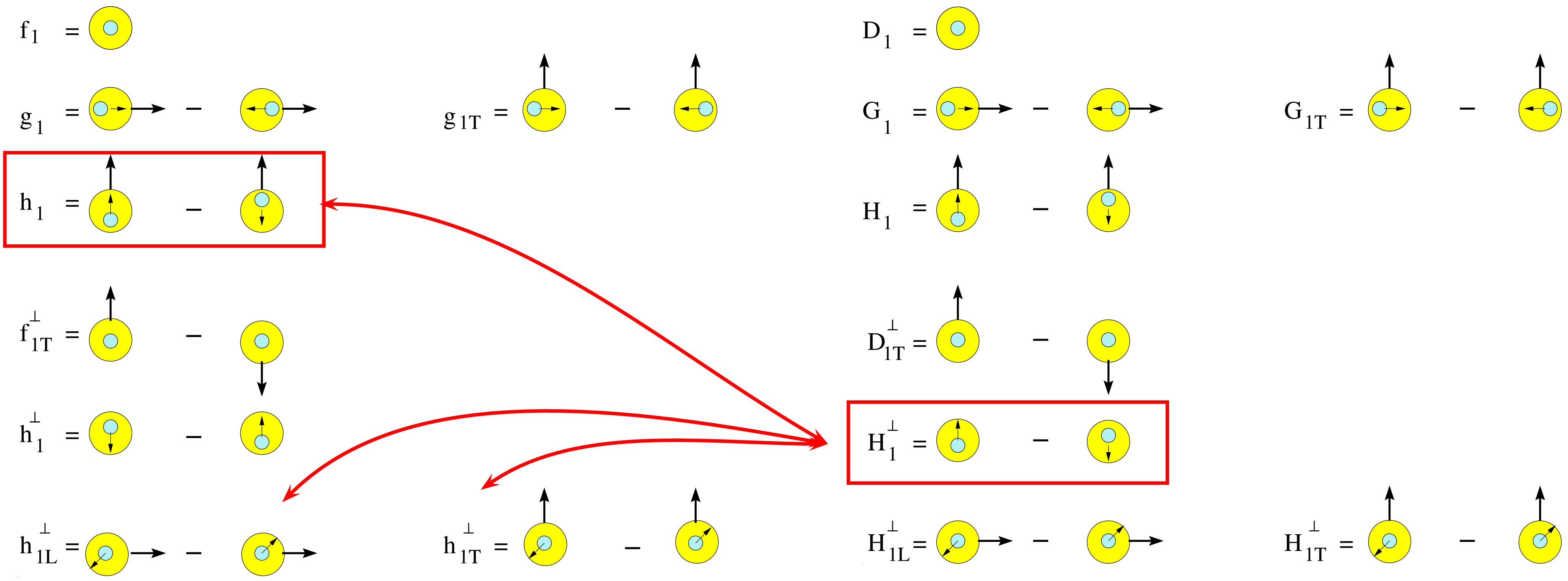

SSAs require one and only one T-odd function

⇒ SSAs through Collins function

SSA & Unintegrated Distribution and Fragmentation Functions

Leading-Twist

Distribution Functions

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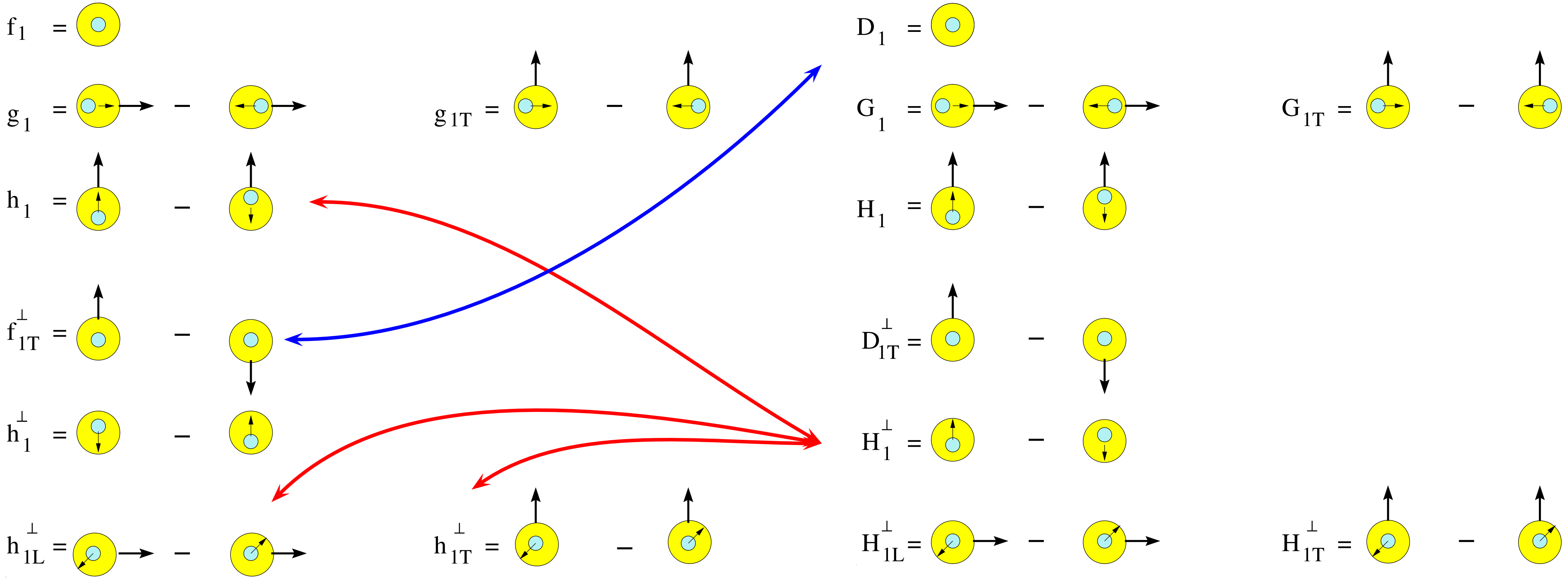


SSAs require one and only one T-odd function

$\Rightarrow$ 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)

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

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

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

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

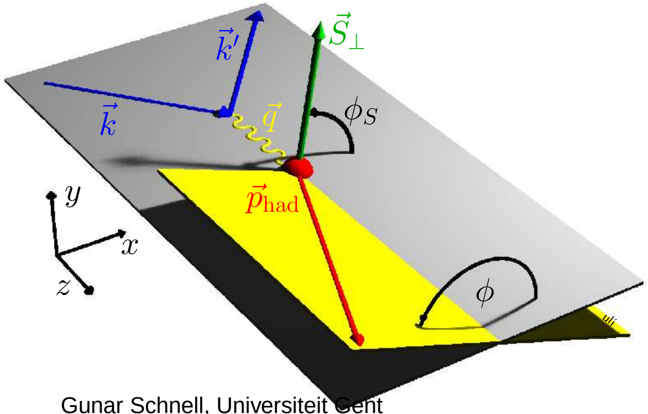
$$\left. +\lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}$$

σ_{XY}

$\swarrow \quad \searrow$

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

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

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

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

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

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

$$
\begin{tikzcd}[column sep=tiny]
& \sigma_{XY} \arrow[dl] \arrow[dr] & \\
\text{Beam} & & \text{Target}
\end{tikzcd}
$$

Beam Target
Polarization

Also Interesting:

(and under study!)

$\sin\phi_S \; d\sigma^{12}_{UT}$, $\cos\phi_S \; d\sigma^{14}_{LT} \ldots$ ⇒ Transversity, g_2

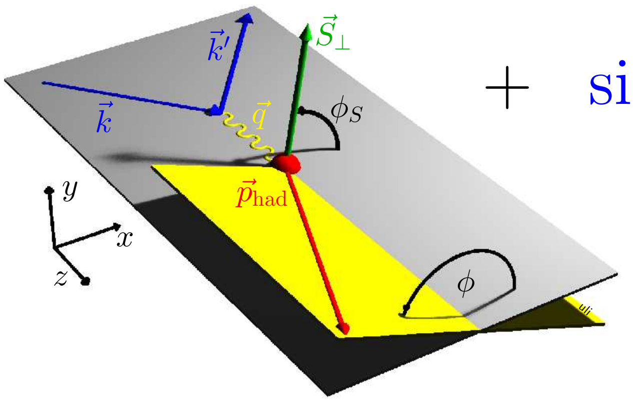
$\cos\phi \; d\sigma^{2}_{UU}$ ... Cahn Effect

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

Azimuthal Single-Spin Asymmetries

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

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



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

$$+ \quad \cdots$$

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

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

$$\boxed{A_{UT}(\phi,\phi_S) = 2\Big\langle \sin(\phi-\phi_S)\Big\rangle_{UT}\sin(\phi-\phi_s) + 2\Big\langle \sin(\phi+\phi_S)\Big\rangle_{UT}\sin(\phi+\phi_s)}$$

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

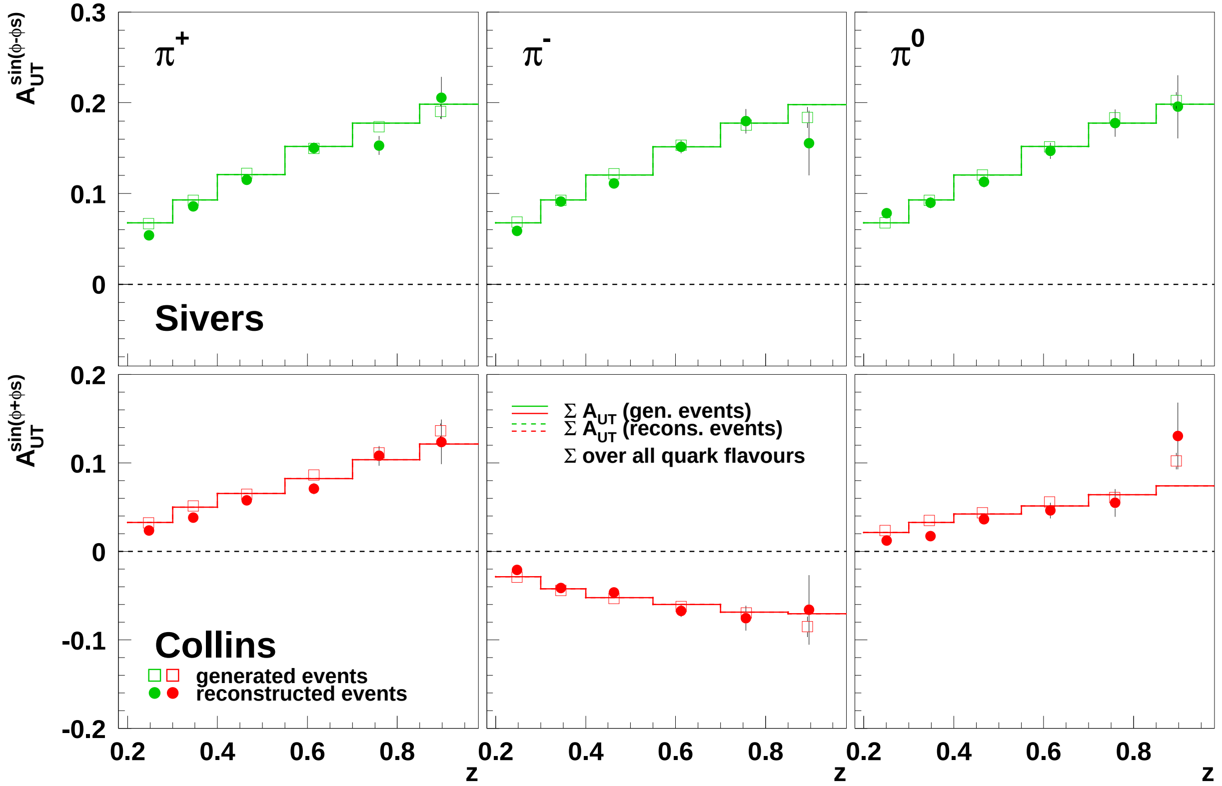
$\Rightarrow$ 2D-fit of $\tilde{A}_{UT}$ to get Collins and Sivers asymmetries:

$$\tilde{A}_{UT}(\phi,\phi_S) = M_\pi \, 2\left\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi+\phi_S) \right\rangle_{UT}(x,z) \quad \sin(\phi+\phi_s)$$

$$+ M_p \, 2\left\langle \frac{P_{h\perp}}{M_p} \sin(\phi-\phi_S) \right\rangle_{UT}(x,z) \quad \sin(\phi-\phi_s)$$

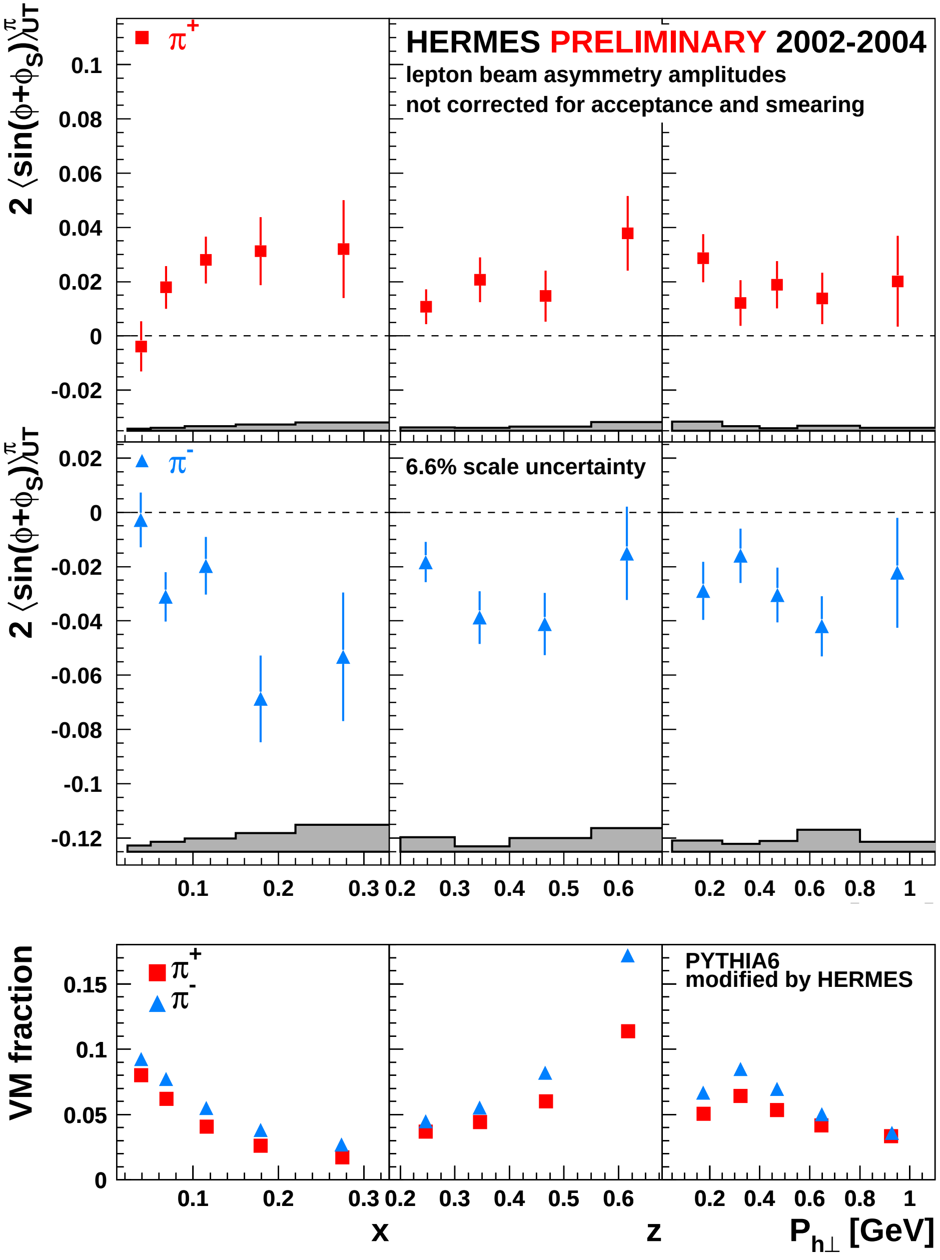
Monte Carlo Test of the Extraction Method

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

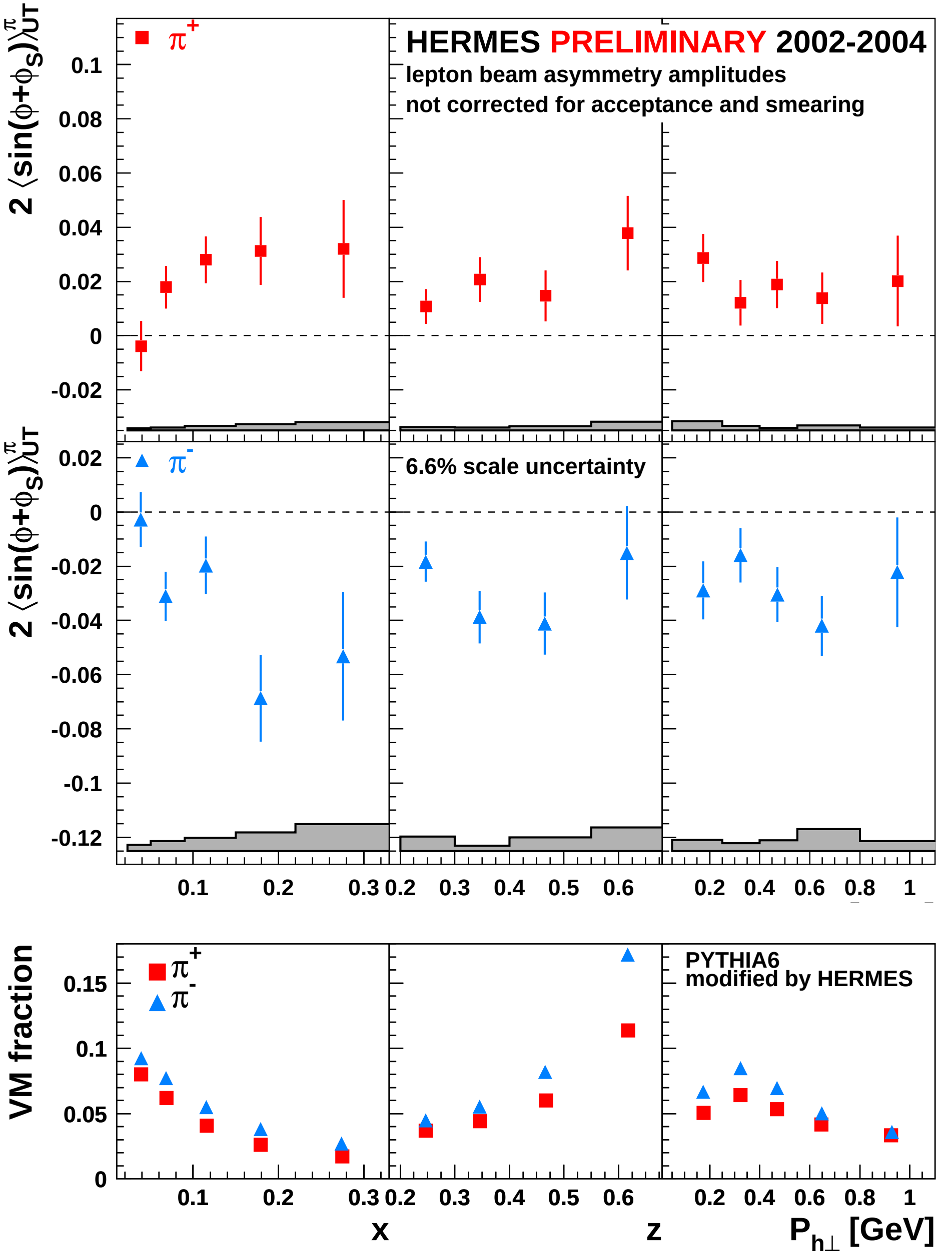
Collins Asymmetries 2002-2004

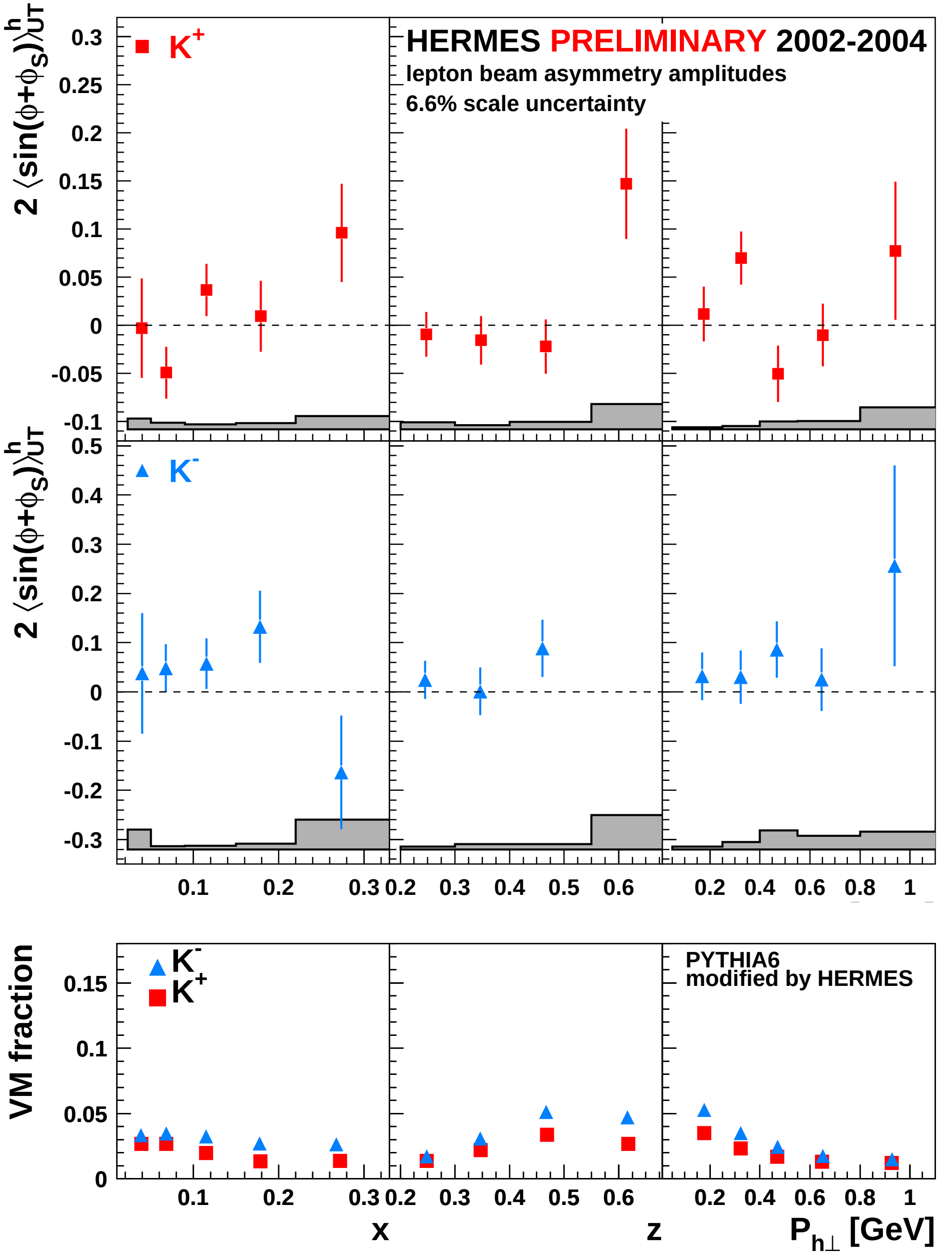


- **published**[†] **results** **confirmed** **with much higher statistical precission**
- **overall scale uncertainty of 6.6%**
- **positive for π^+ and negative for π^- as maybe expected ($\delta u > 0$**
  $\delta d < 0$)
- **unexpected large π^- asymmetry**
  ⇒ role of disfavored Collins FF
  most likely: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- **partially large contribution from decay of exclusively produced vector mesons**

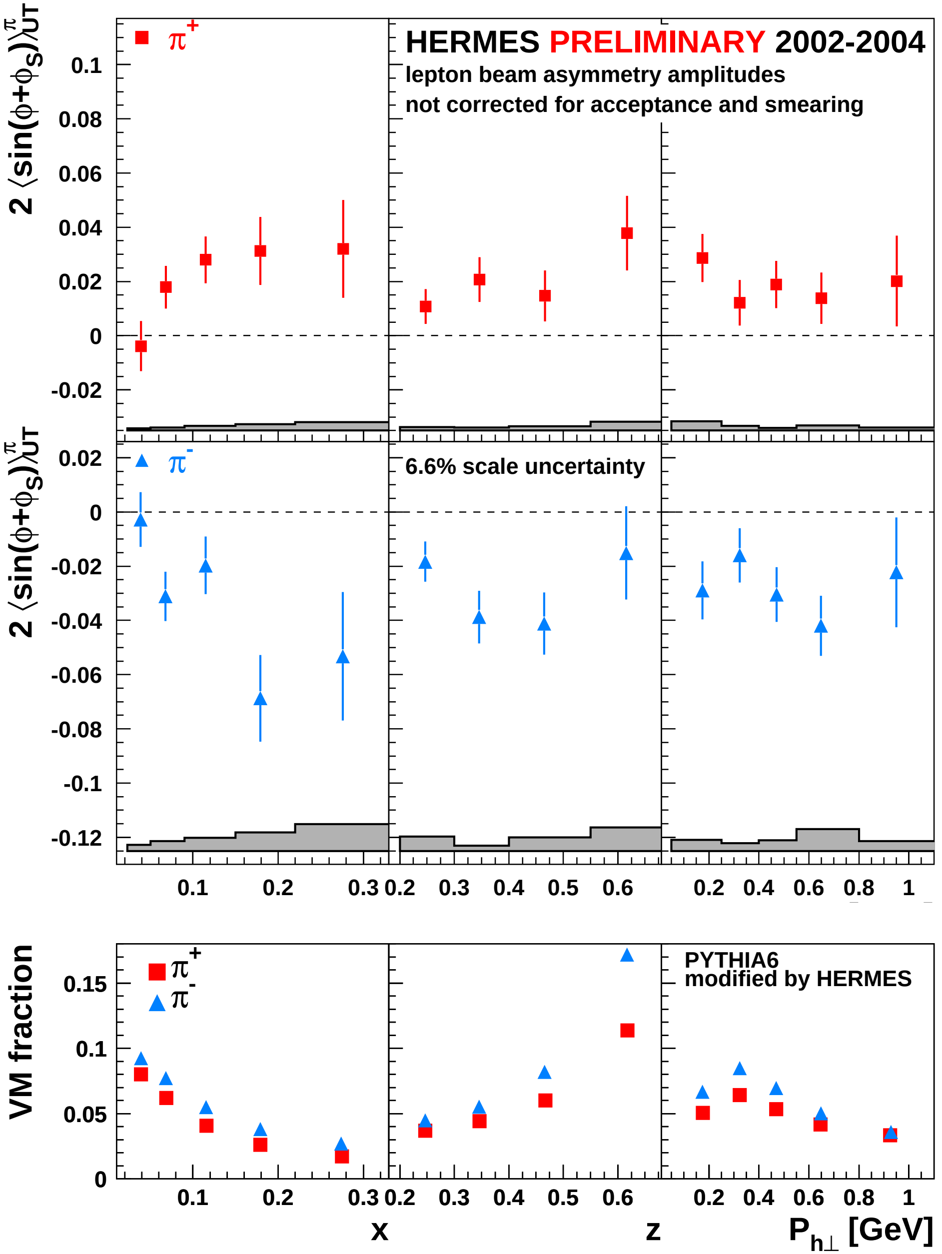
[†] [*A. Airapetian et al*, **Phys. Rev. Lett. 94 (2005) 012002]**

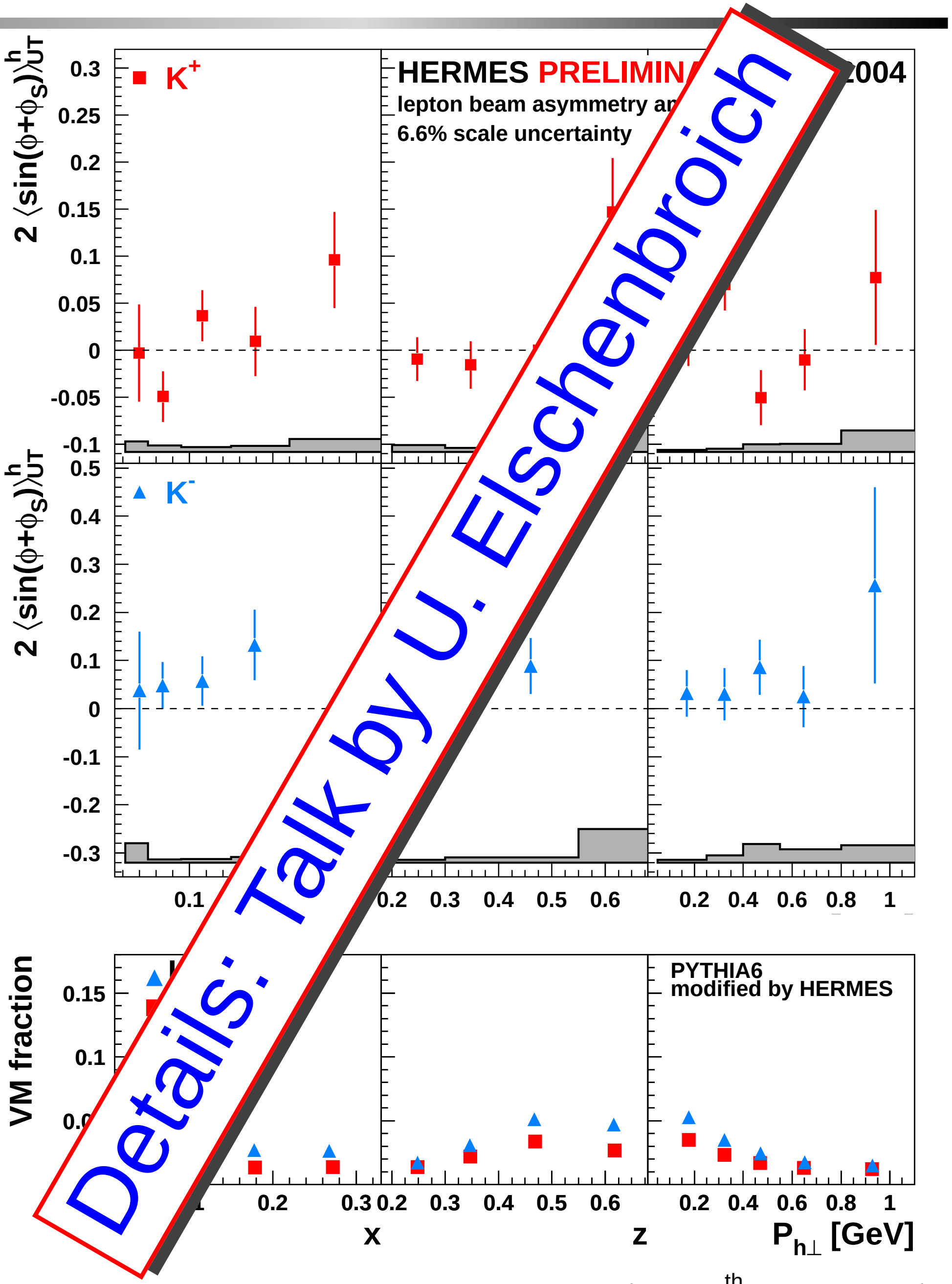
Collins Asymmetries 2002-2004





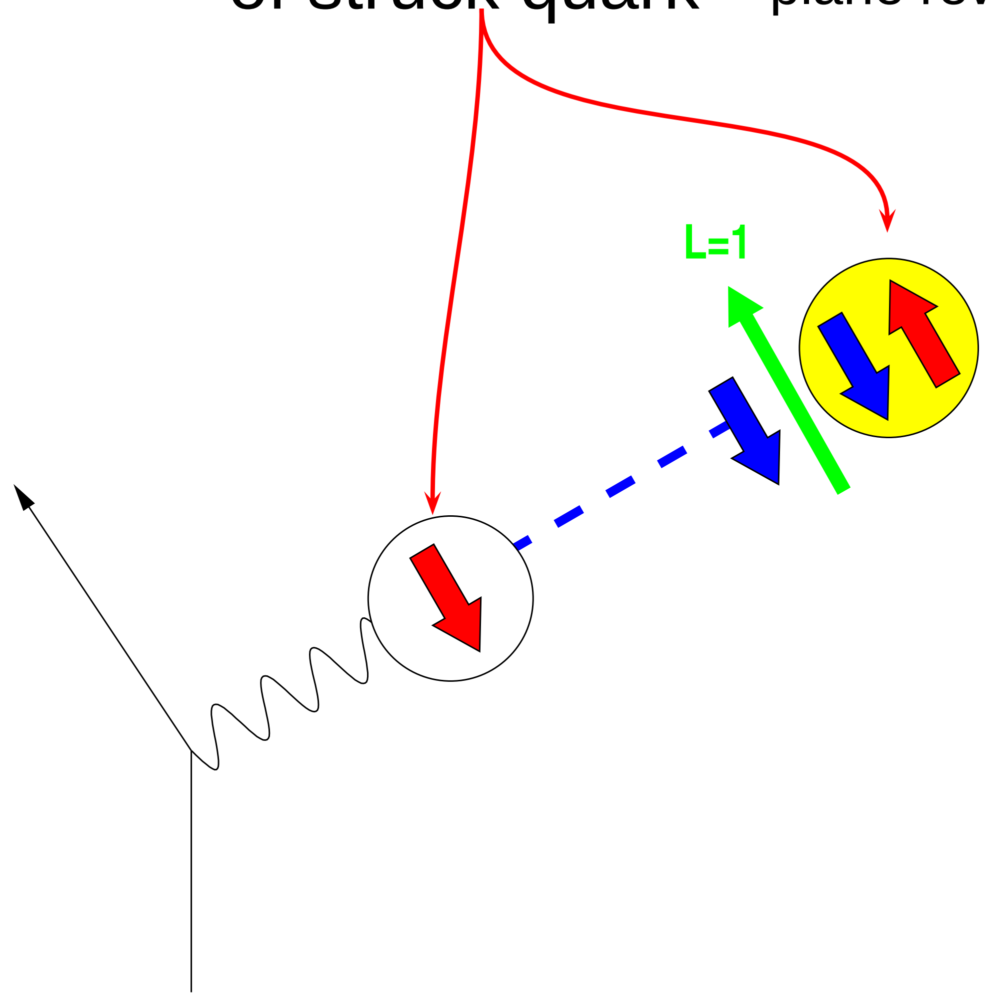
Collins Asymmetries 2002-2004





Details: Talk by U. Elschenbroich

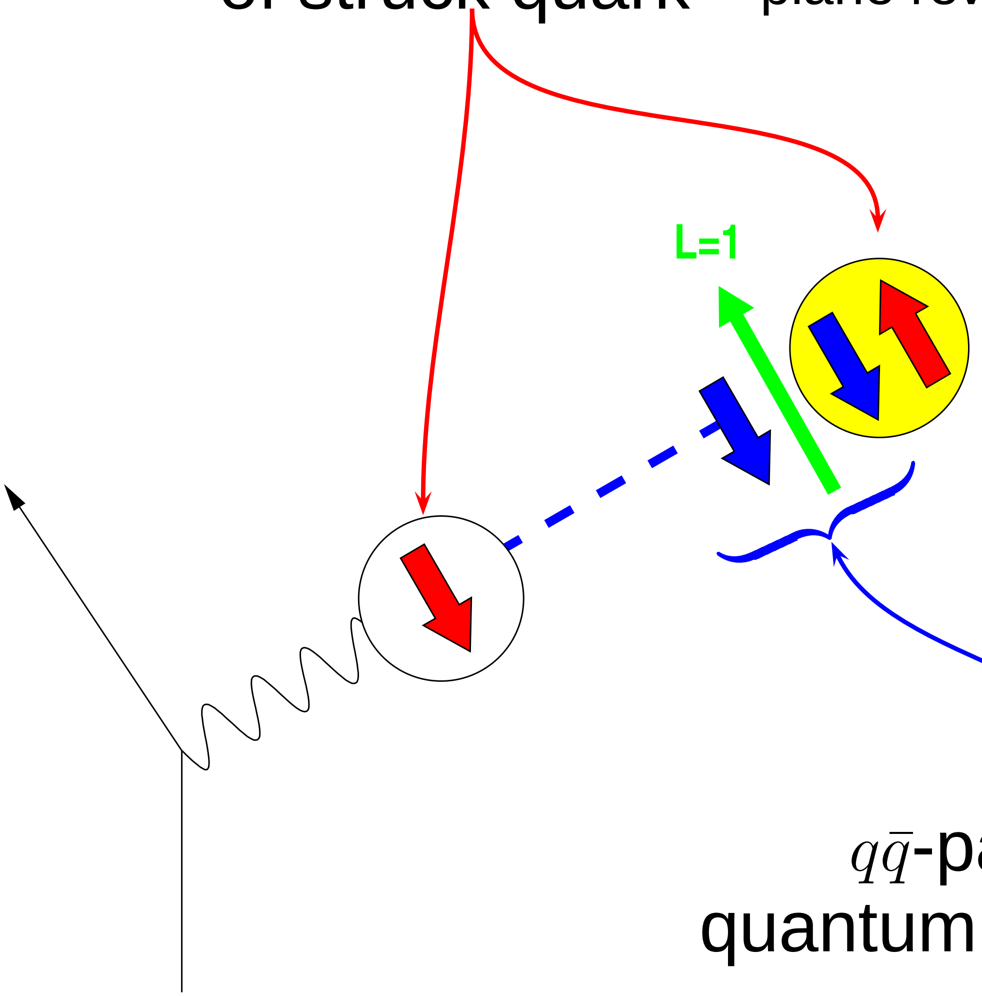
Understanding the Collins FF - String Model Interpretation (Artru)



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)

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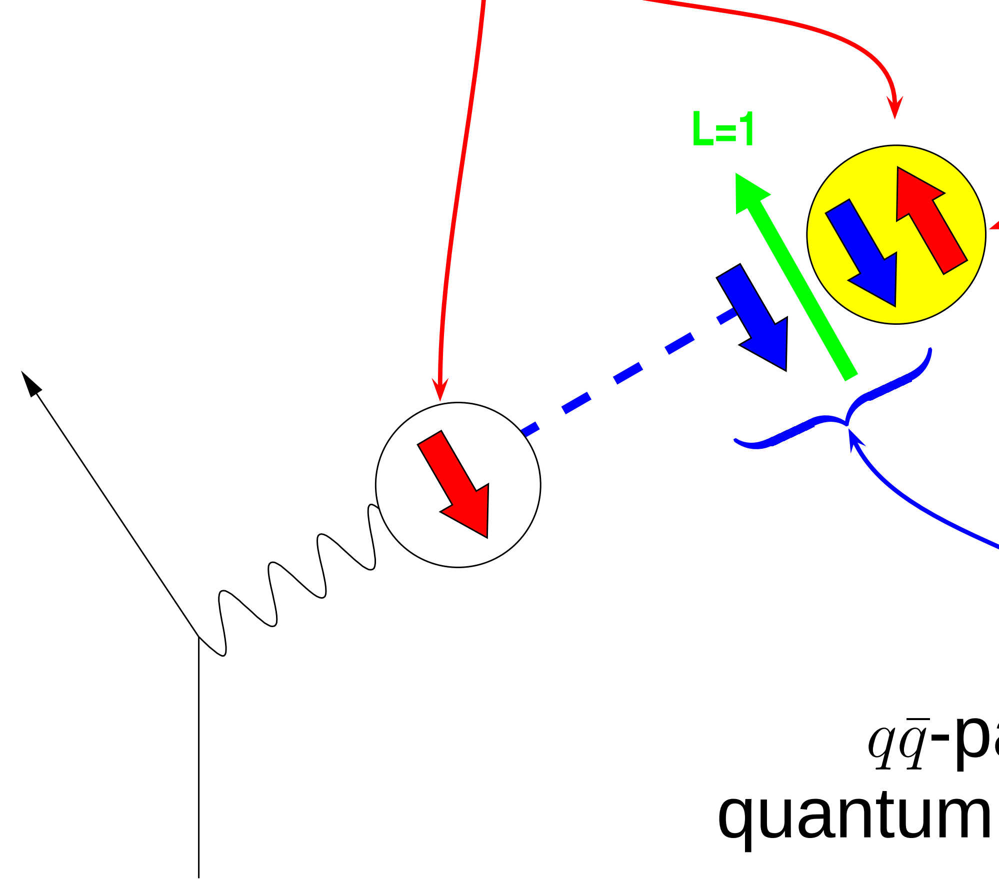
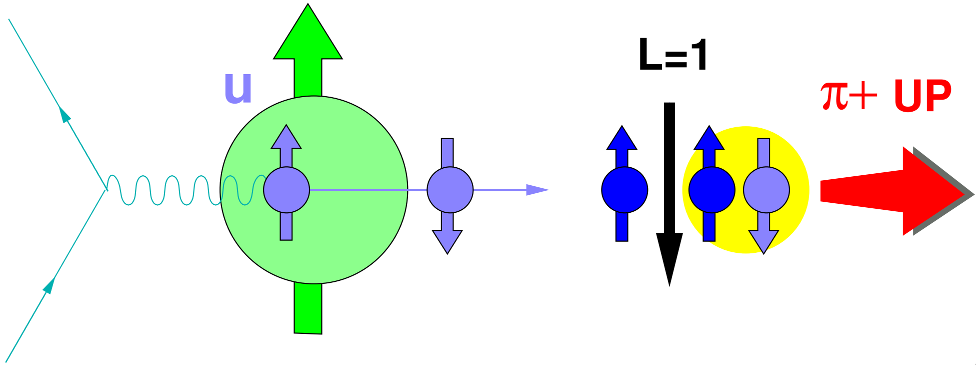


outgoing pion
deflected into page
(positive Collins FF)

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

The Collins Effect

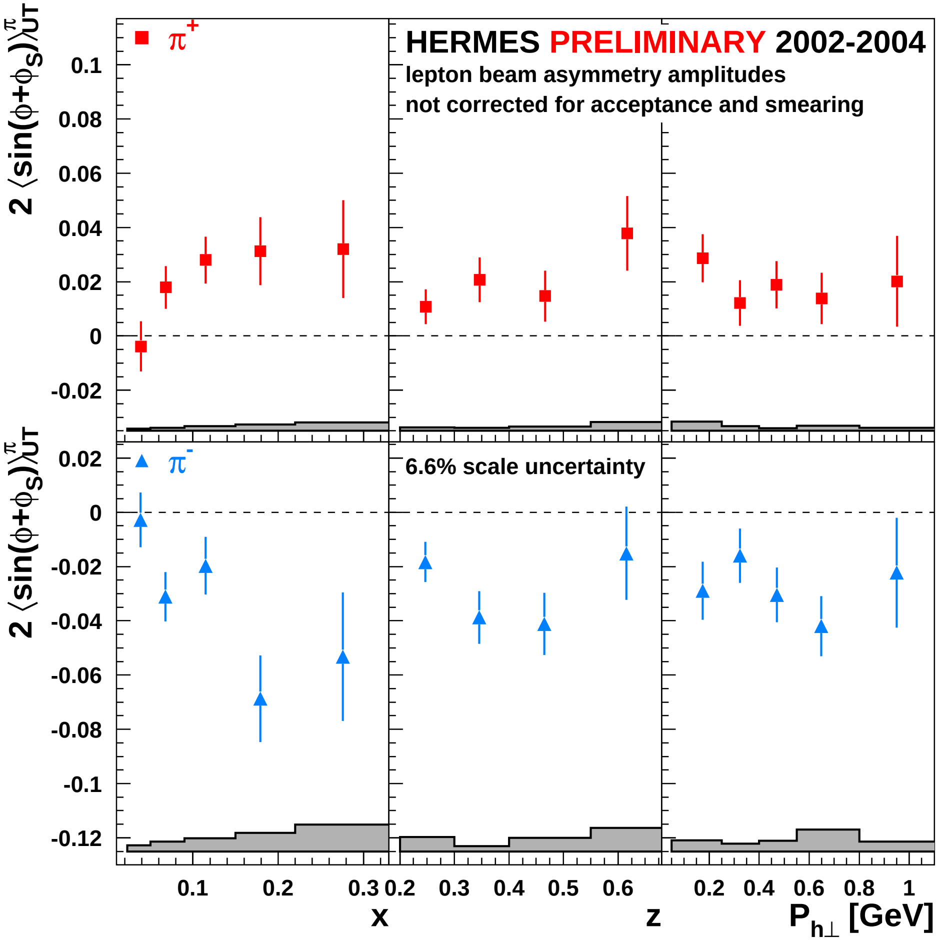
Artru Model vs. HERMES



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

The Collins Effect

Artru Model vs. HERMES

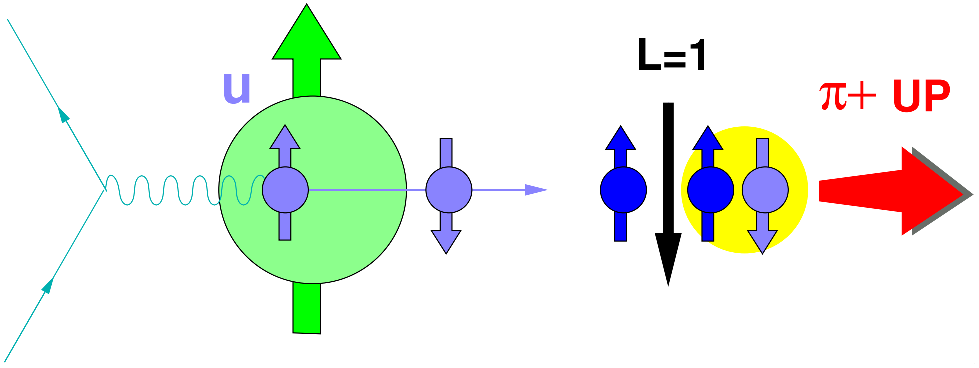


$$\left.\begin{aligned} \phi_S &= 0 \\ \phi &= \pi/2 \end{aligned}\right\} \sin(\phi + \phi_S) > 0$$

✓

The Collins Effect

Artru Model vs. HERMES



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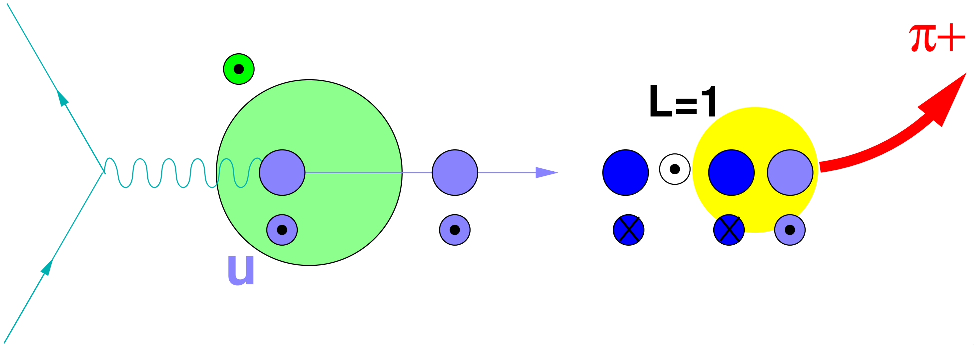

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The Collins Effect

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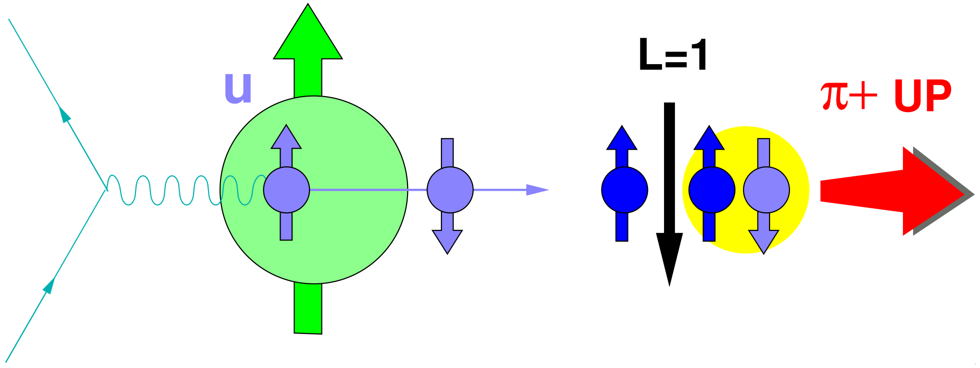

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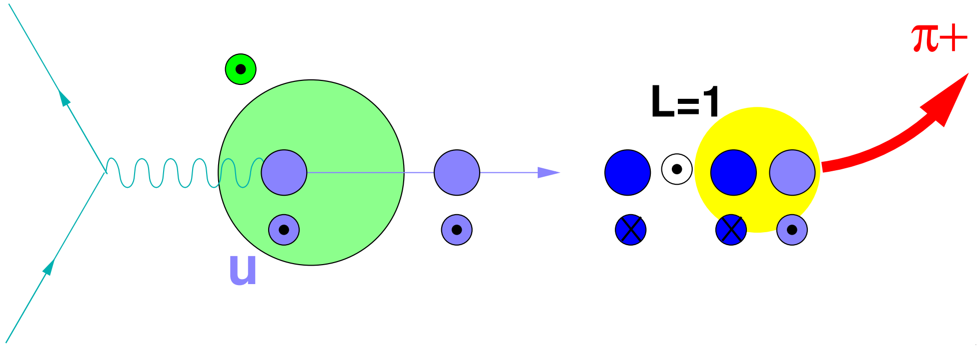

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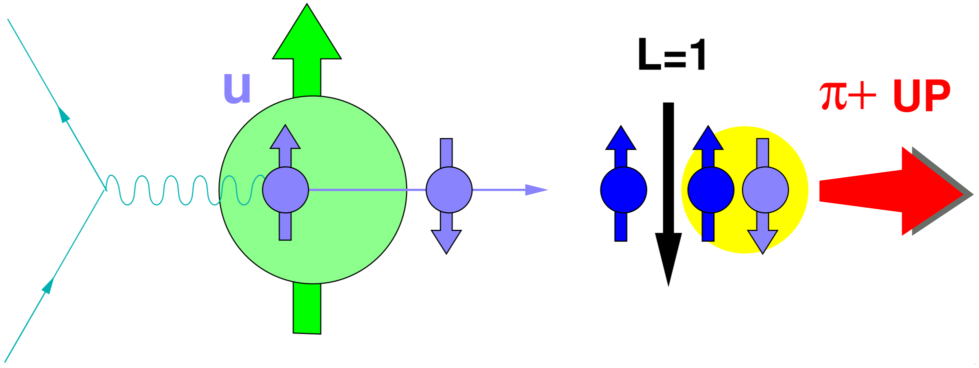

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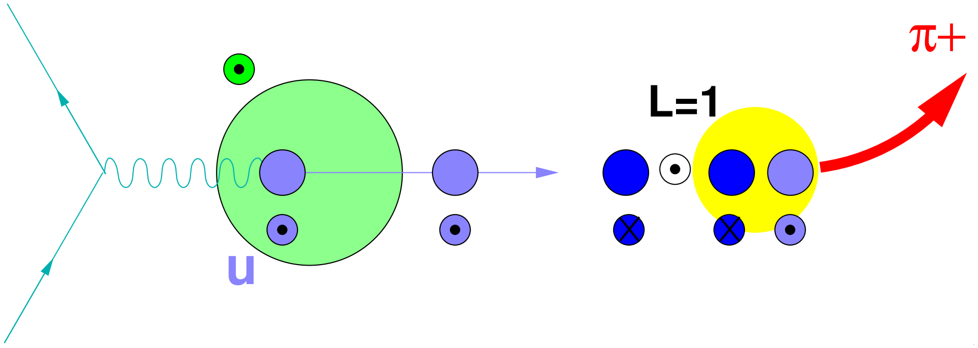


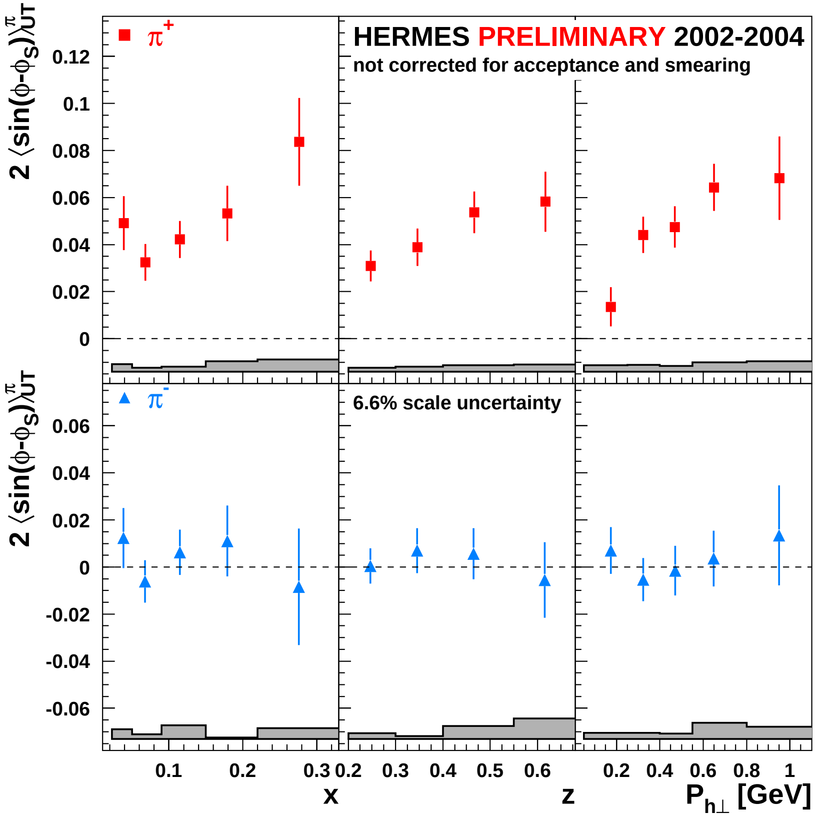
$$\left.\begin{array}{rl}\phi_S = & \pi/2\\ \phi = & 0\end{array}\right\}\sin(\phi+\phi_S) > 0$$

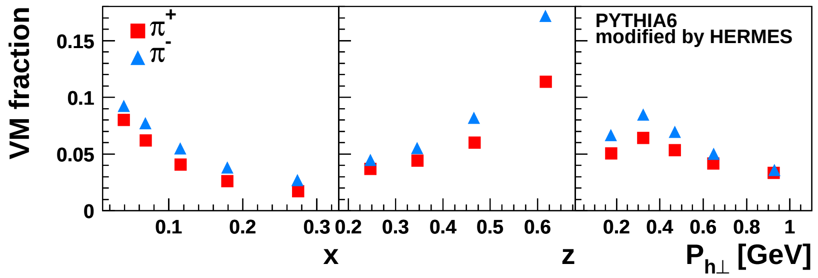
✓

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

Results on Sivers Amplitudes from 2002-2004 data

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

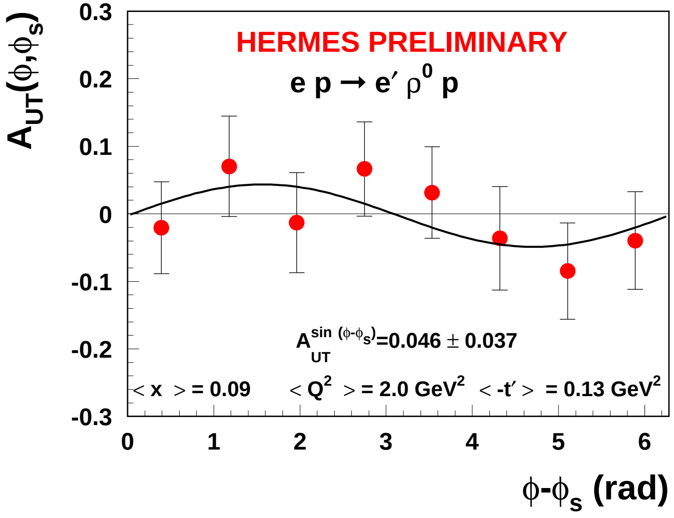




- π^+: positive; π^-: consistent with zero

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

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



⇒ small syst. error from vector mesons

Results on Sivers Amplitudes from 2002-2004 data

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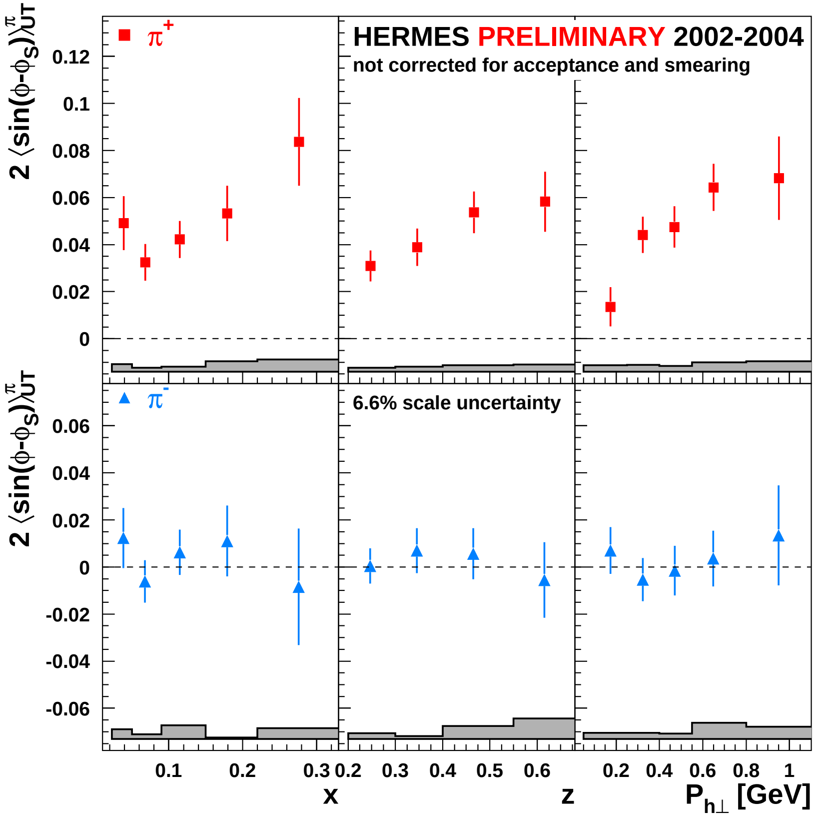
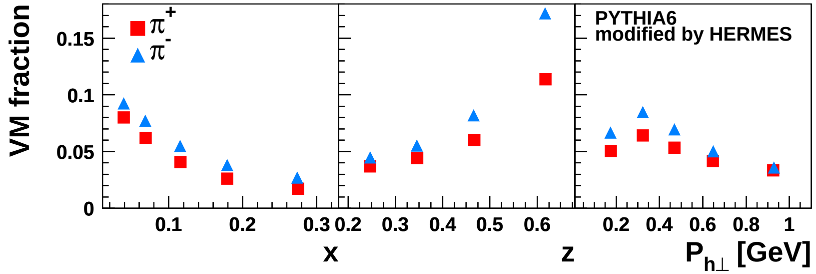
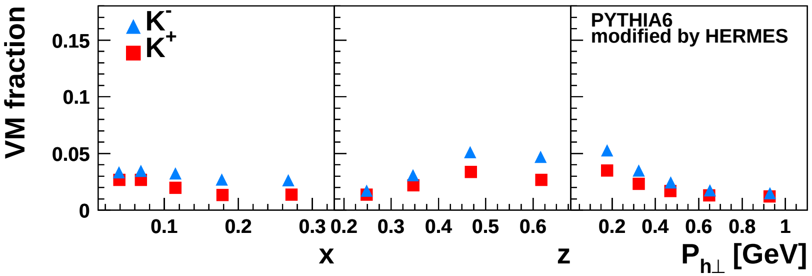




smaller VM contribution to kaon sample



Results on Sivers Amplitudes from 2002-2004 data

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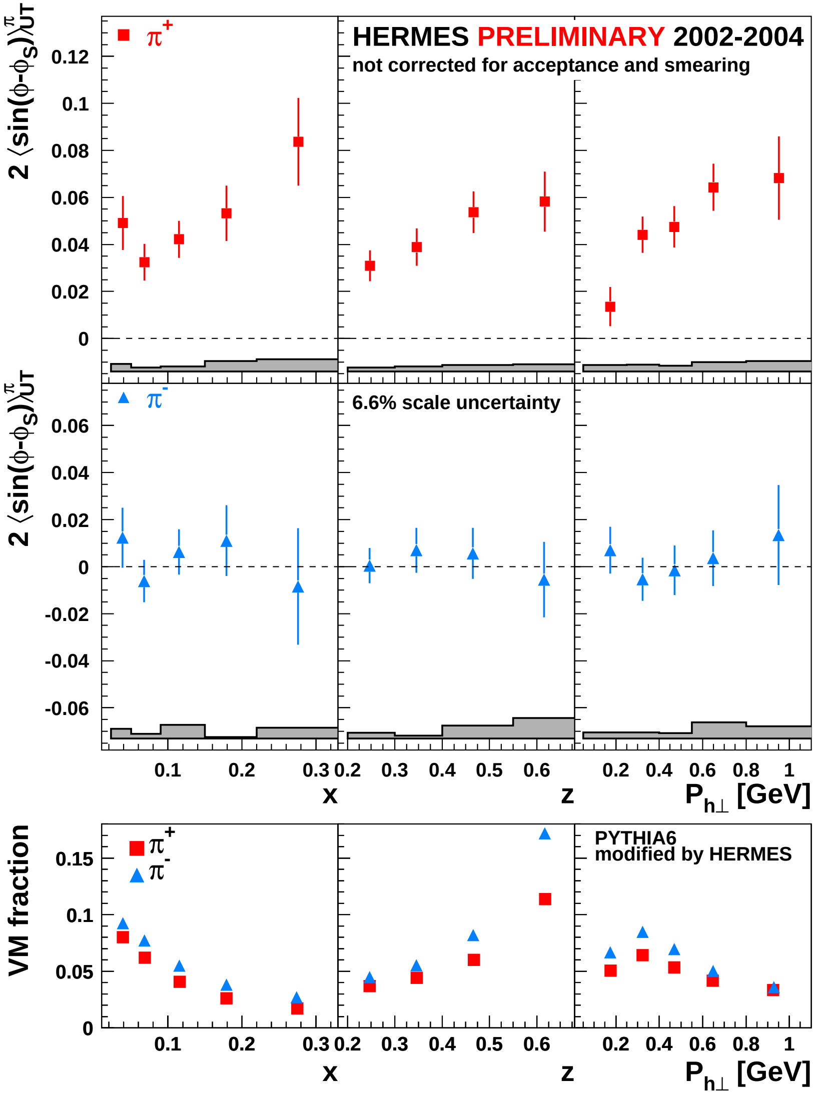

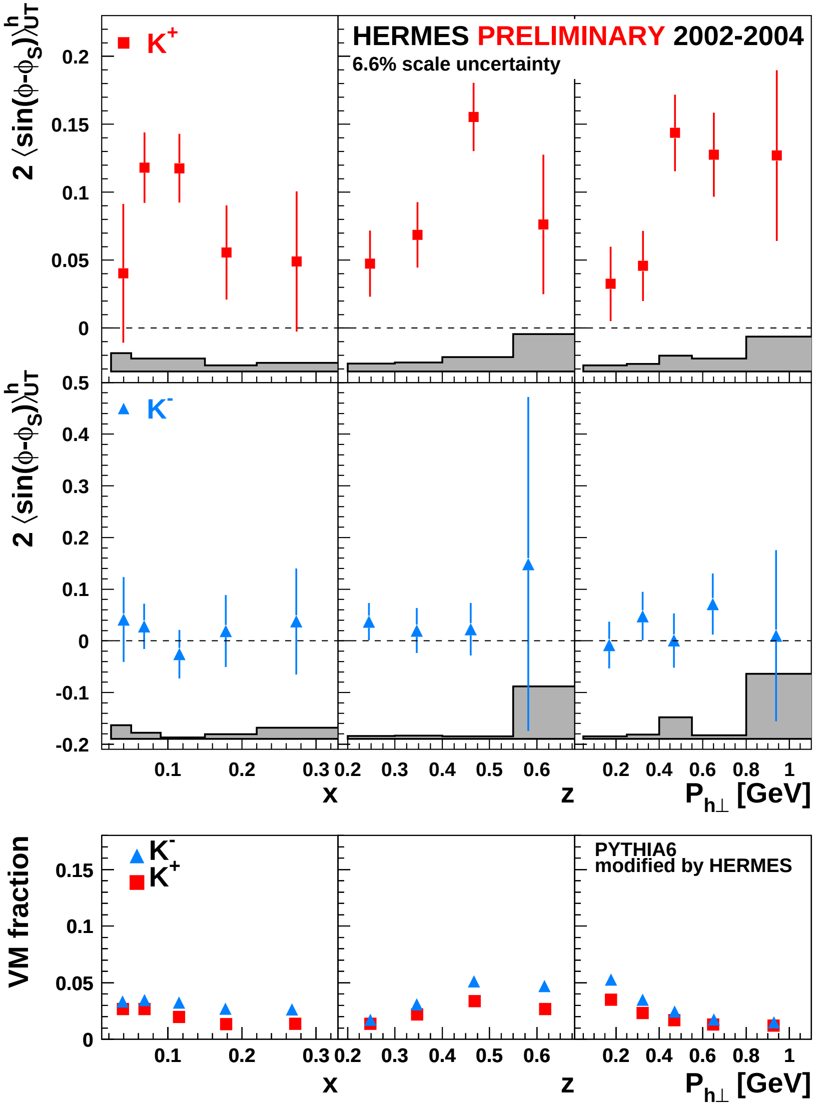

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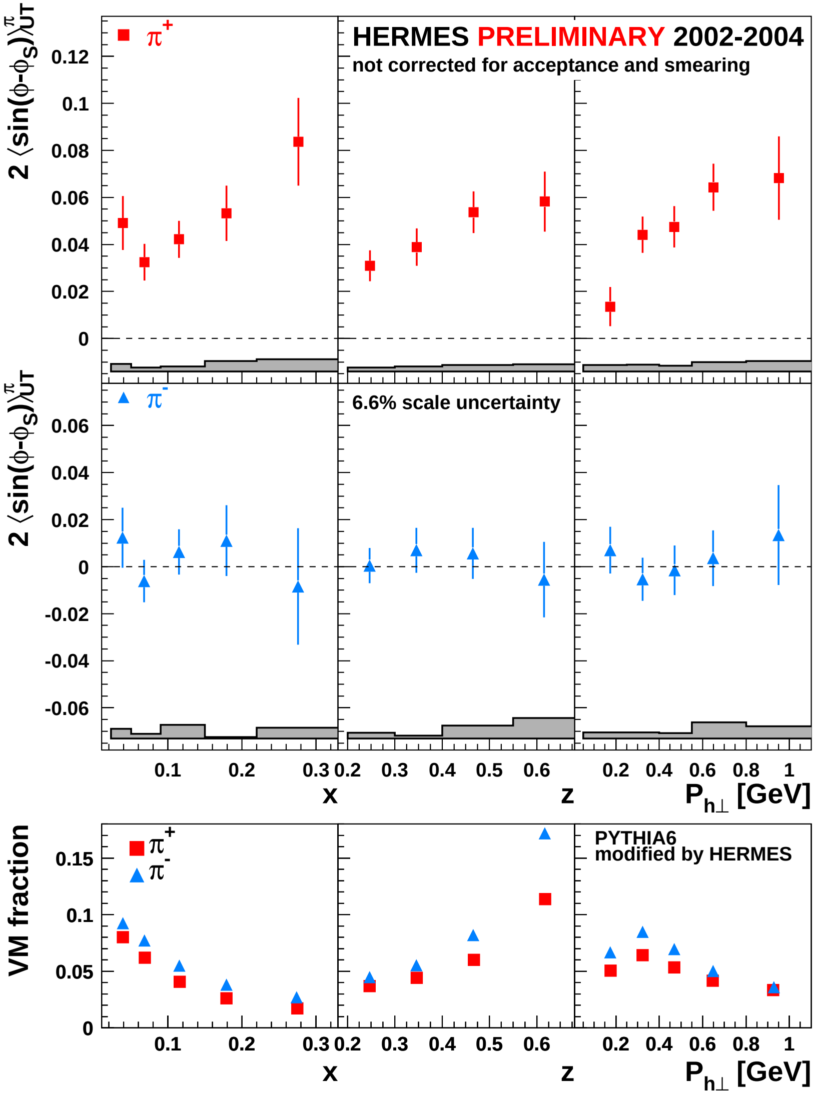
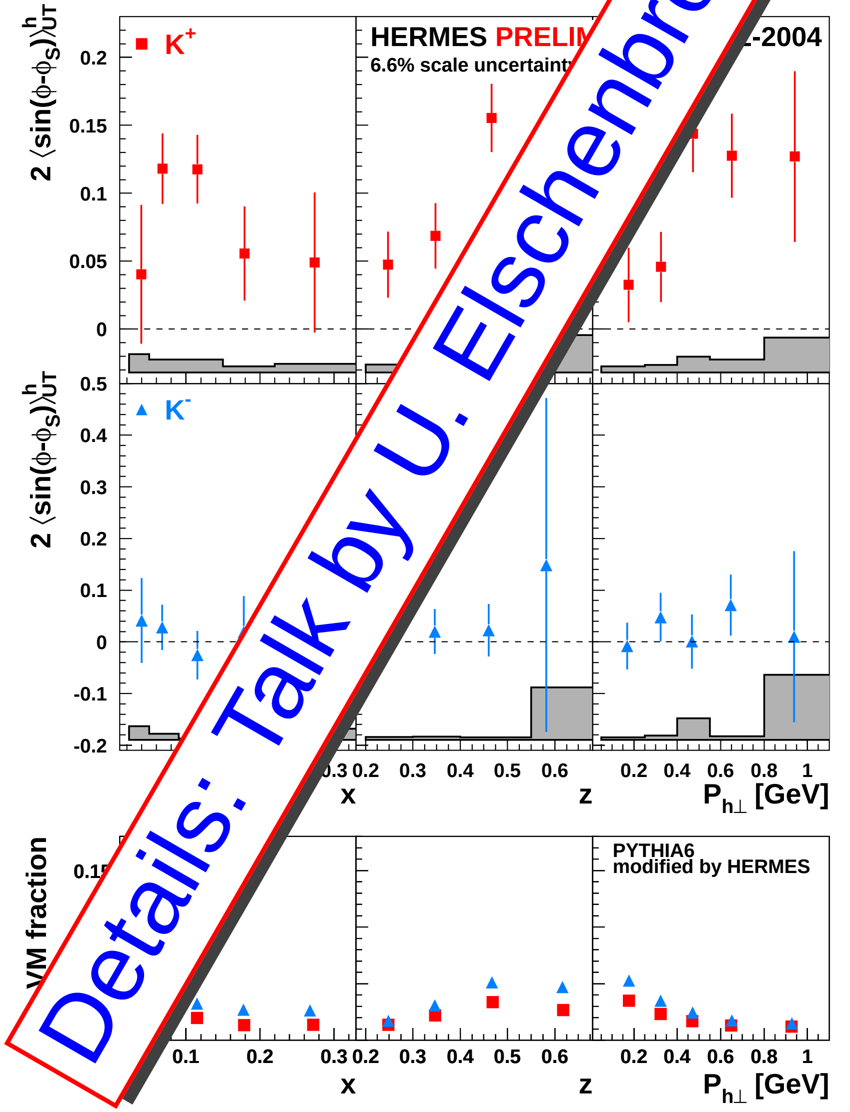




Details: Talk by U. Elschenbroich

Chromodynamic Lensing

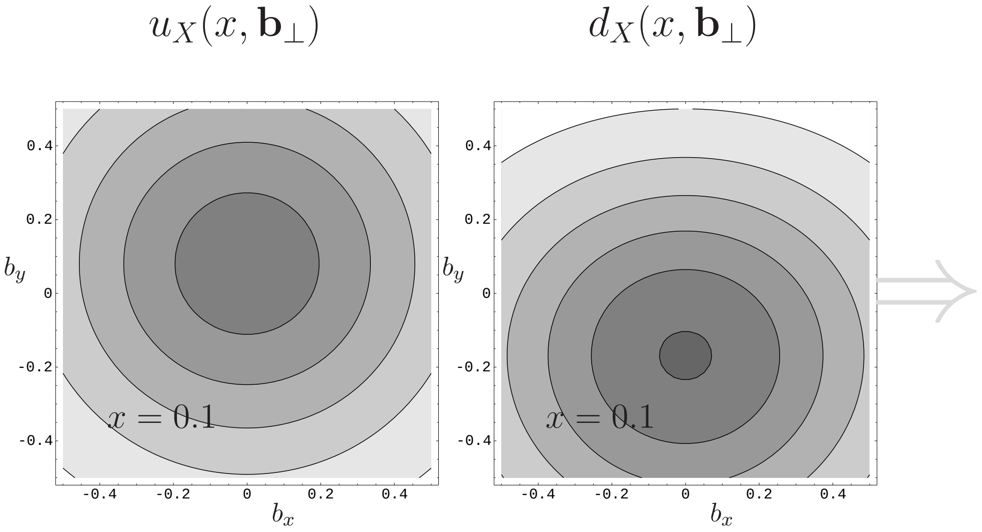
Understanding the Sivers Moments

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

spatial distortion of q-distribution

(obtained using anom. magn. moments

& impact parameter dependent PDFs)



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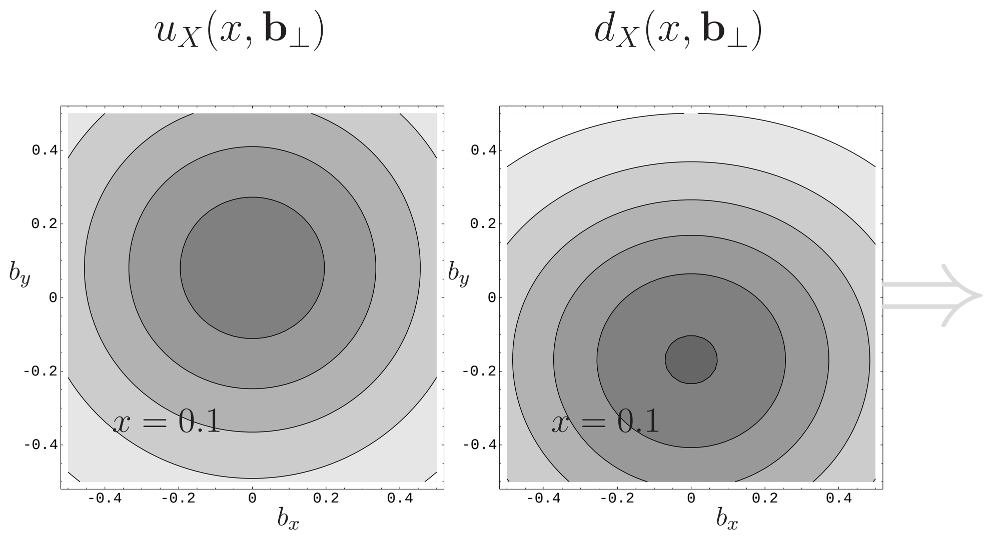
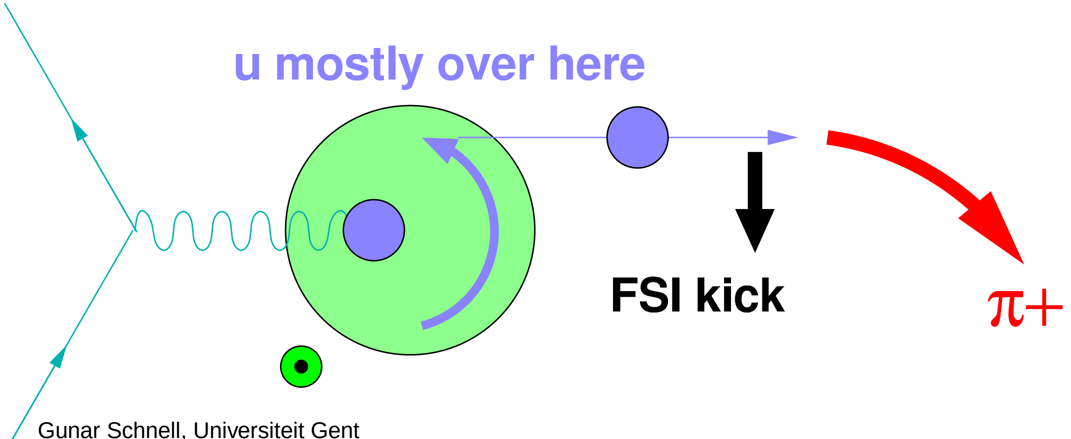


+ attractive QCD potential

(gluon exchange)

⇒ transverse asymmetries



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

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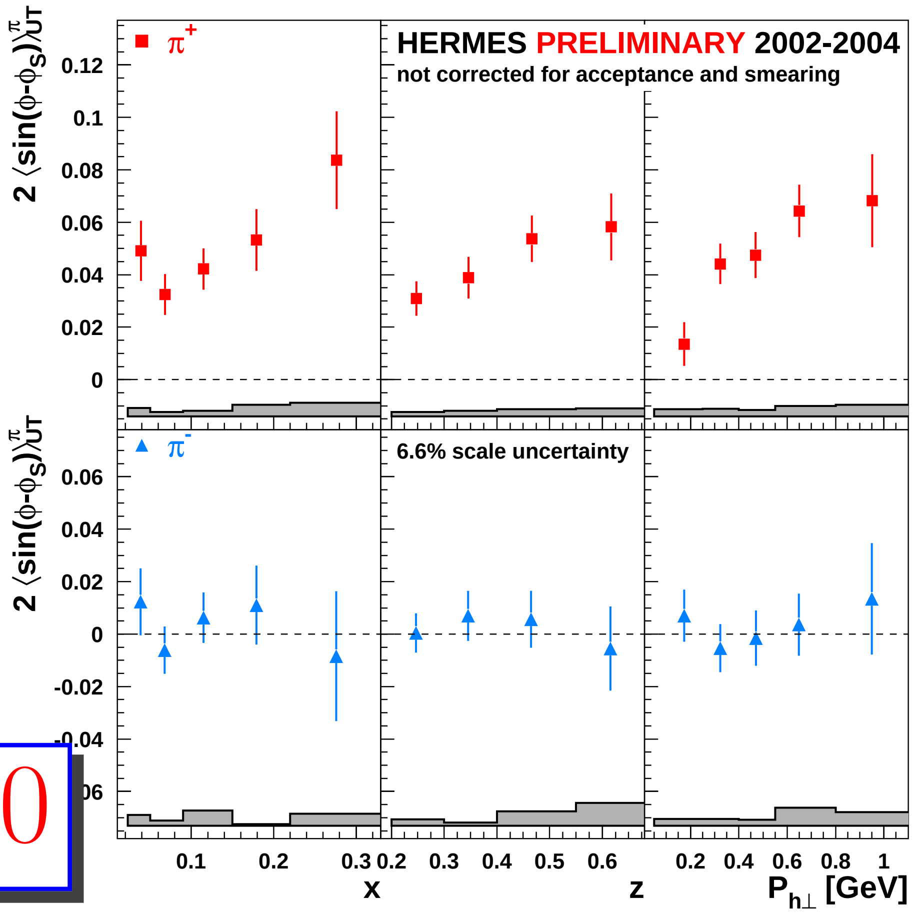

+ attractive QCD potential

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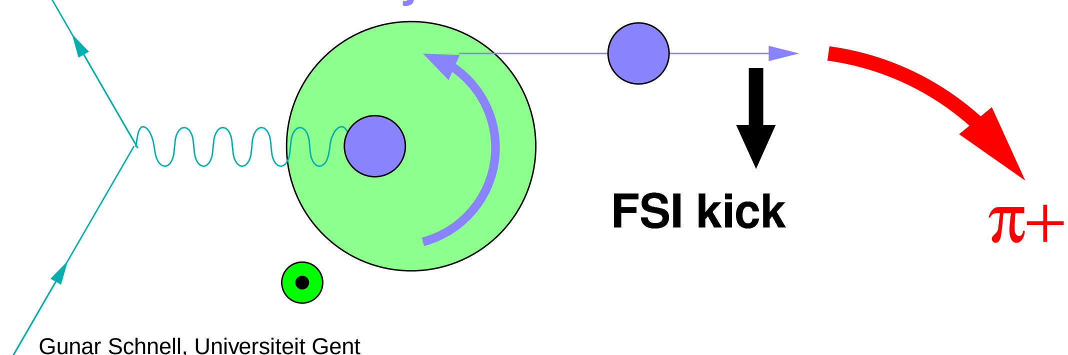
⇒ transverse asymmetries

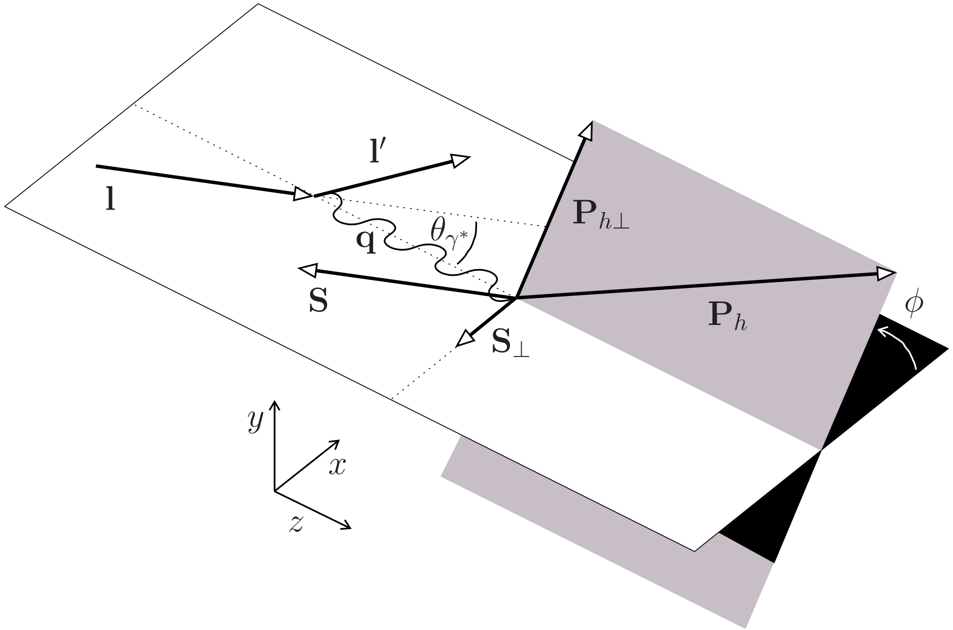
$$\boxed{L_z^u > 0}$$



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

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)]

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

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

Mixing of Azimuthal Moments II

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

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

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

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$$\left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\mathsf{q}} \simeq \left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\mathsf{l}}$$

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

correction

What About Longitudinally Polarized Targets?

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

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

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

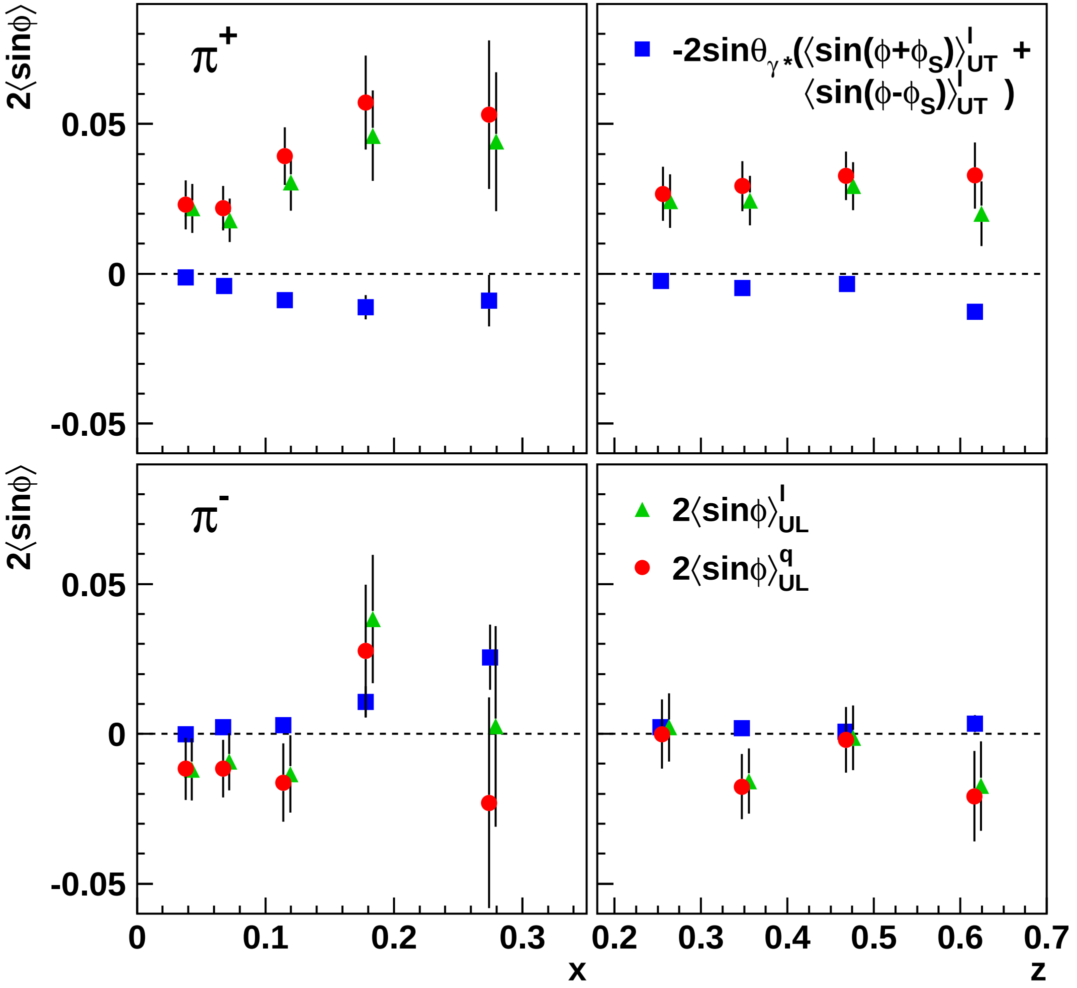
⇒ they are all subleading-twist expressions!

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

$\left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\mathrm{l}}$ . . . **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^-

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

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

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

$$+ \frac{M_h}{zM} f_1(x) G^{\perp}(z) - x g^{\perp}(x) D_1(z)$$

quark-mass suppressed ⇒

$$+ \frac{m_q}{M} h_1^{\perp}(x) D_1(z) - \frac{m_q}{M} f_1(x) H_1^{\perp}(z) \Big]$$

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

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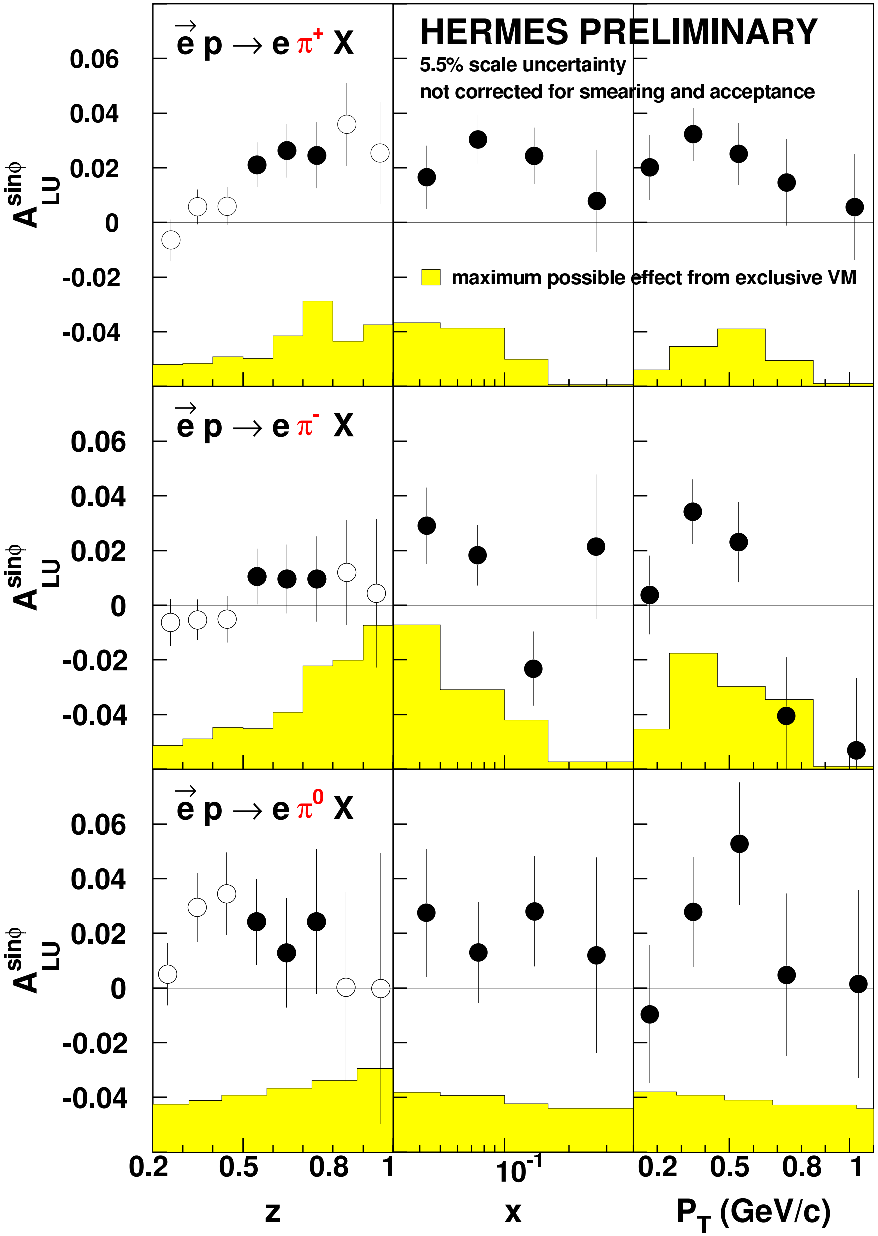
- many terms contributing – difficult to separate
- maybe some terms small?

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

Longitudinal Beam-Spin Asymmetries



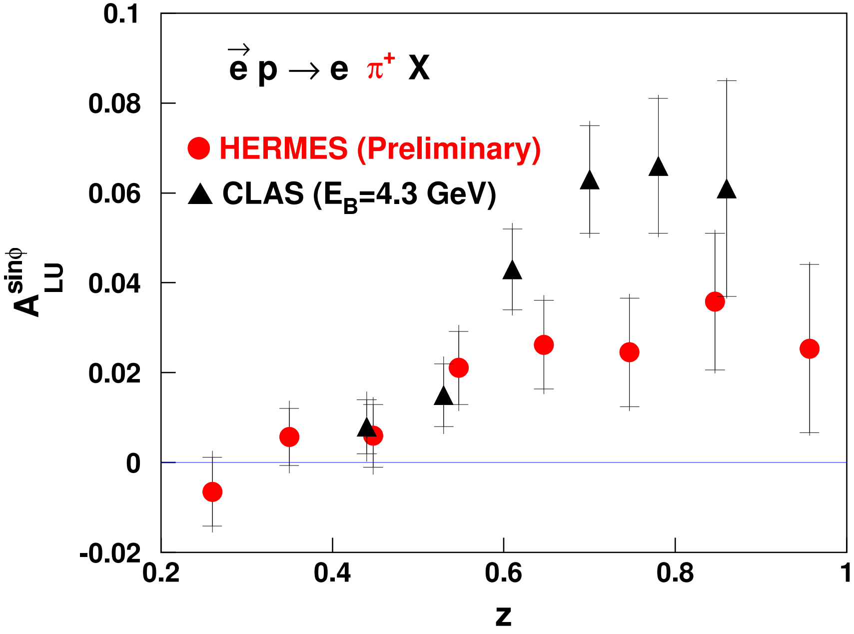
Extraction:

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

Vector Meson Contribution:

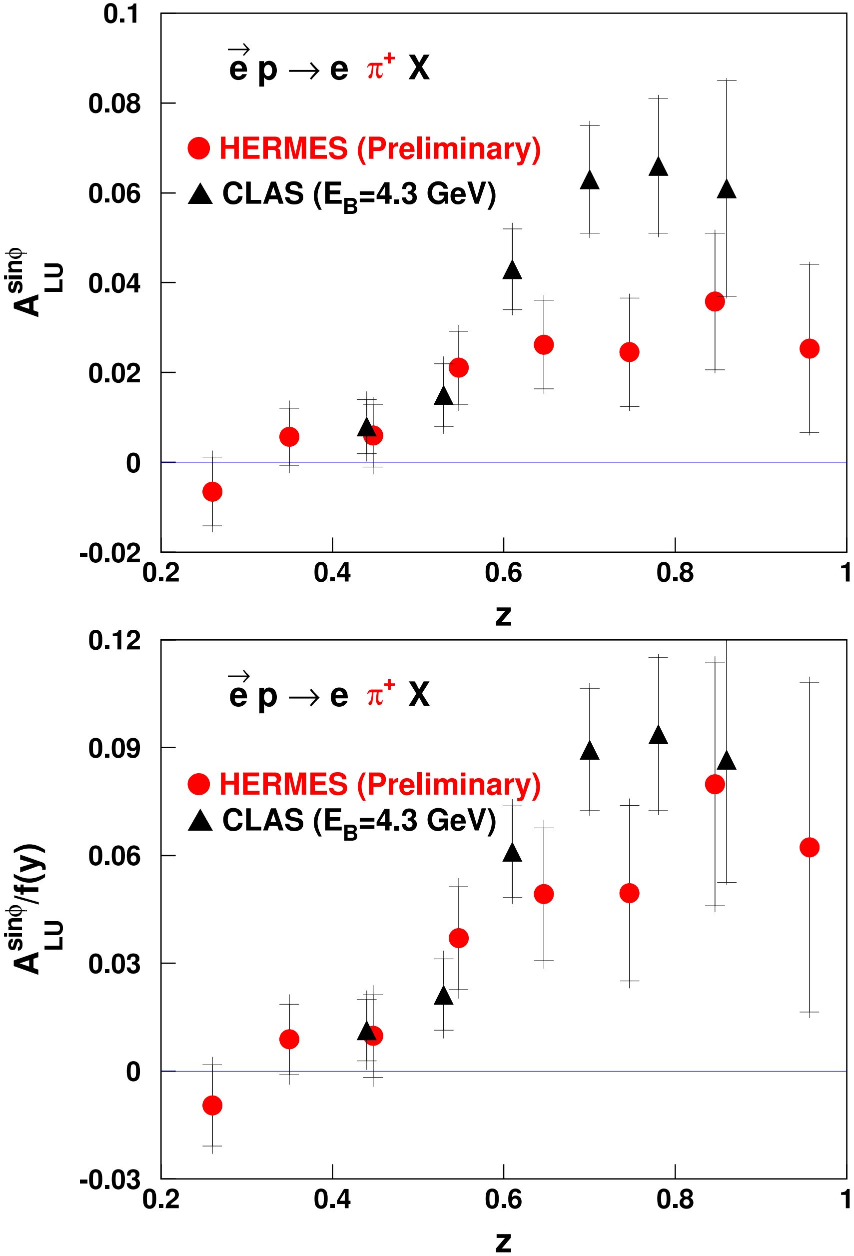
Max. possible contribution to systematic uncertainty estimated using PYTHIA MC (tuned for HERMES)

Comparisons with CLAS Results



- not so good agreement at high z

Comparisons with CLAS Results



- 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

What can we learn from A_{UL}

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

any help from other observables to separate contributions?

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- *jet SIDIS* ⇒ only $g^{\perp}$-term survives

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$$\left. - x g^{\perp}(x) D_1(z) + \frac{M_h}{zM} f_1(x) G^{\perp}(z) \right]$$

any help from other observables to separate contributions?

- *jet SIDIS* ⇒ only $g^{\perp}$-term survives
- 2-hadron production:

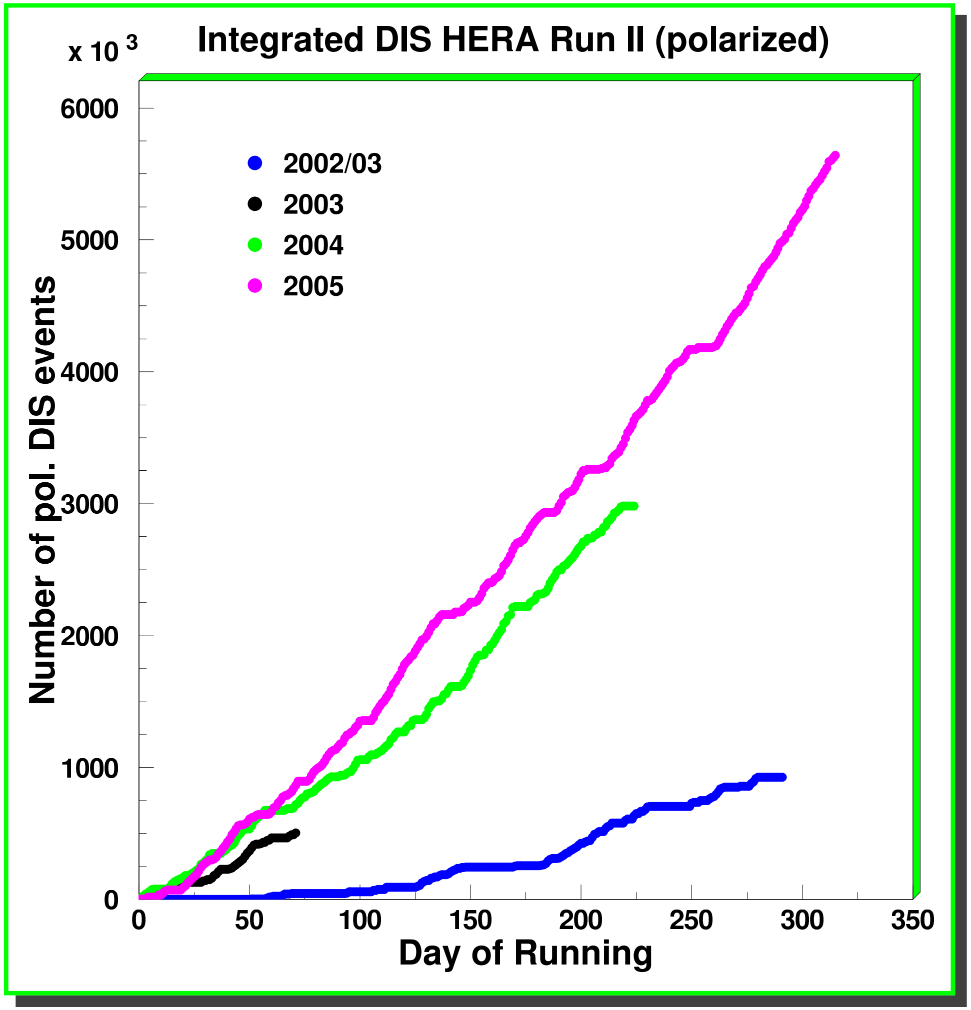
$$\sigma_{LU} \propto \sin\phi_{R\perp} \left[x e(x) H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z,\zeta,M_h^2) \right]$$

Summary

- First evidence for non-zero Interference FF
- Non-vanishing Collins effect observed for $\pi^{\pm}$
- Most likely scenario: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- First evidence of T-odd Sivers distribution in DIS
- Significant positive Sivers asymmetries for positive pions and kaons $\overset{?}{\Rightarrow} L_z^u > 0$
- $\sin\phi$ amplitudes on long. polar. target dominated by twist-3
- Observation of significant non-zero beam-spin asymmetries

Outlook

- More data taking in 2005
  ⇒ doubled statistics



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- Flavour decomposition of Sivers function

Extracting Quark Distributions

Purity Formalism

$$
\begin{aligned}
A_{UT}^{\sin(\phi-\phi_S),h}(x) = \quad & \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)} \\
= \quad & \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) \\
= \quad & \mathcal{C} \cdot \sum_q \mathcal{P}_q^h(x) \cdot \frac{f_{1T}^{\perp(1),q}}{f_1^q}(x)
\end{aligned}
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- purities are completely unpolarized objects → present Monte Carlo-tunes can be used
- probabilistic interpretation of purities possible
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Extracting Quark Distributions

Purity Formalism

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

Backup Slides

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.

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

$$\begin{aligned} \hookrightarrow \tilde{A}_C^{\pi^+/\pi^-}(x,z) &\propto \frac{(4\delta u + \delta\bar{d})H_{f/d} + (4\delta\bar{u} + \delta d)H_{d/f}}{(4u + \bar{d})D_{f/d} + (4\bar{u} + d)D_{d/f}} \\ \tilde{A}_C^{\pi^0}(x,z) &\propto \frac{\left[4(\delta u + \delta\bar{u}) + \delta d + \delta\bar{d}\right](H_f + H_d)}{\left[4(u + \bar{u}) + d + \bar{d}\right](D_f + D_d)} \end{aligned}$$

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!

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\end{aligned}$$

Pola

$\mathcal{H}$

δr

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

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

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

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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)

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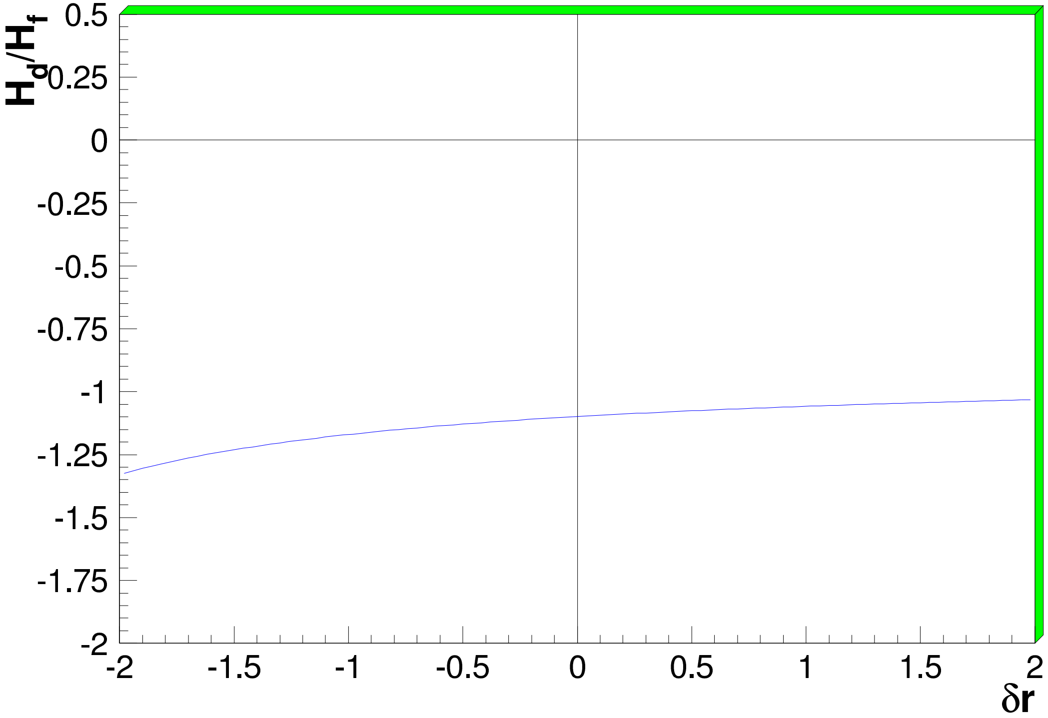

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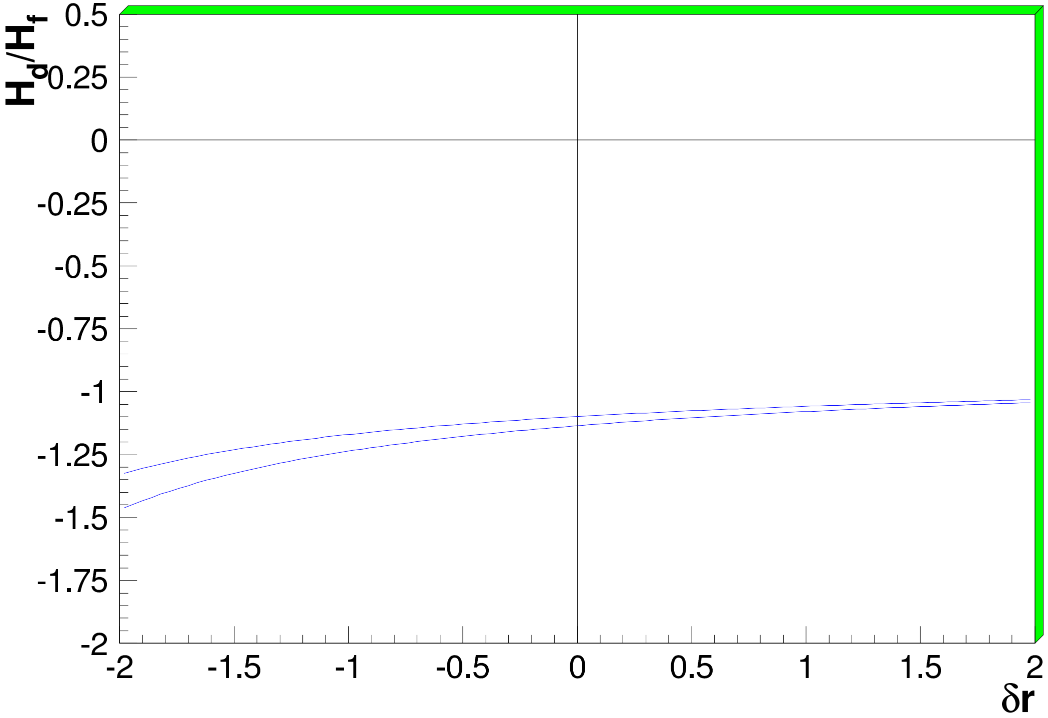

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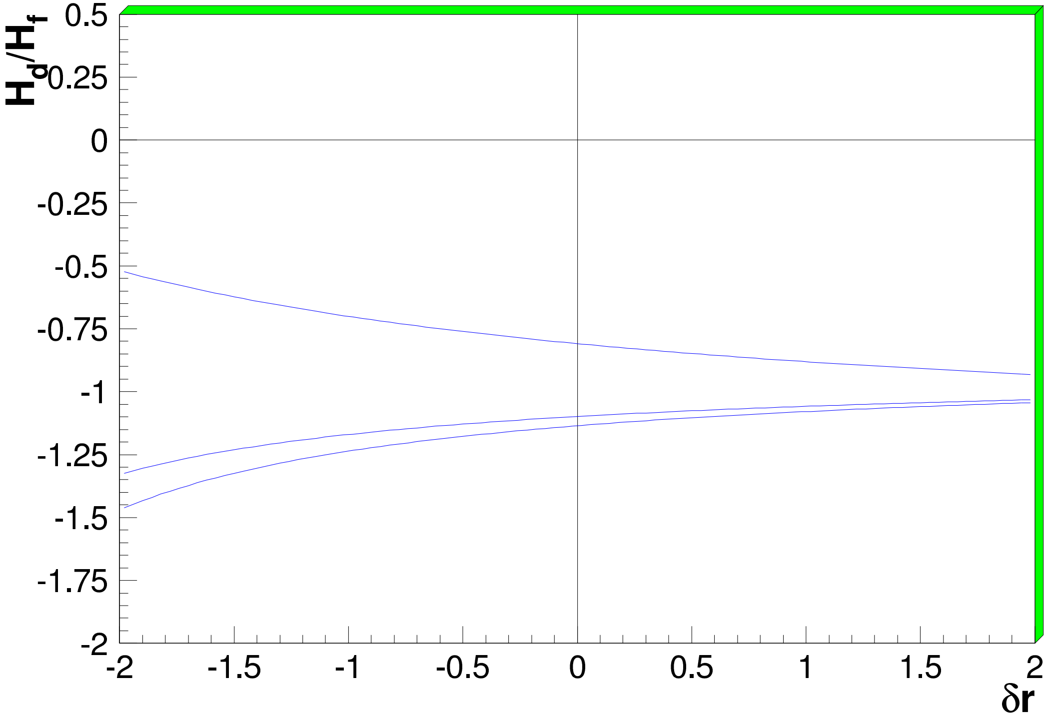

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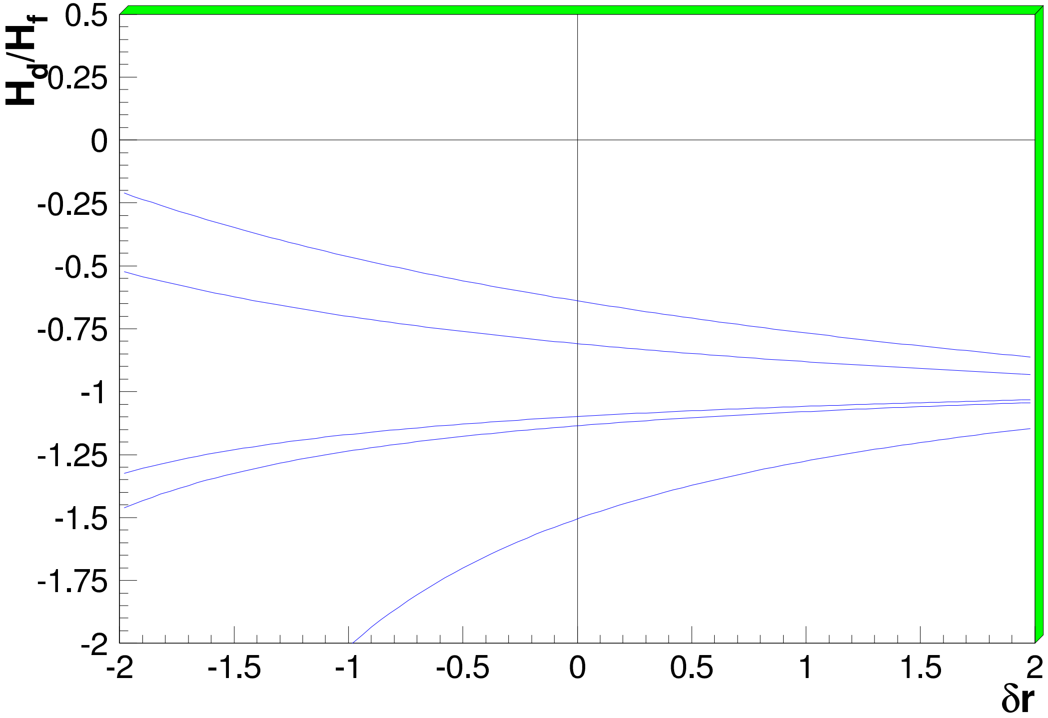

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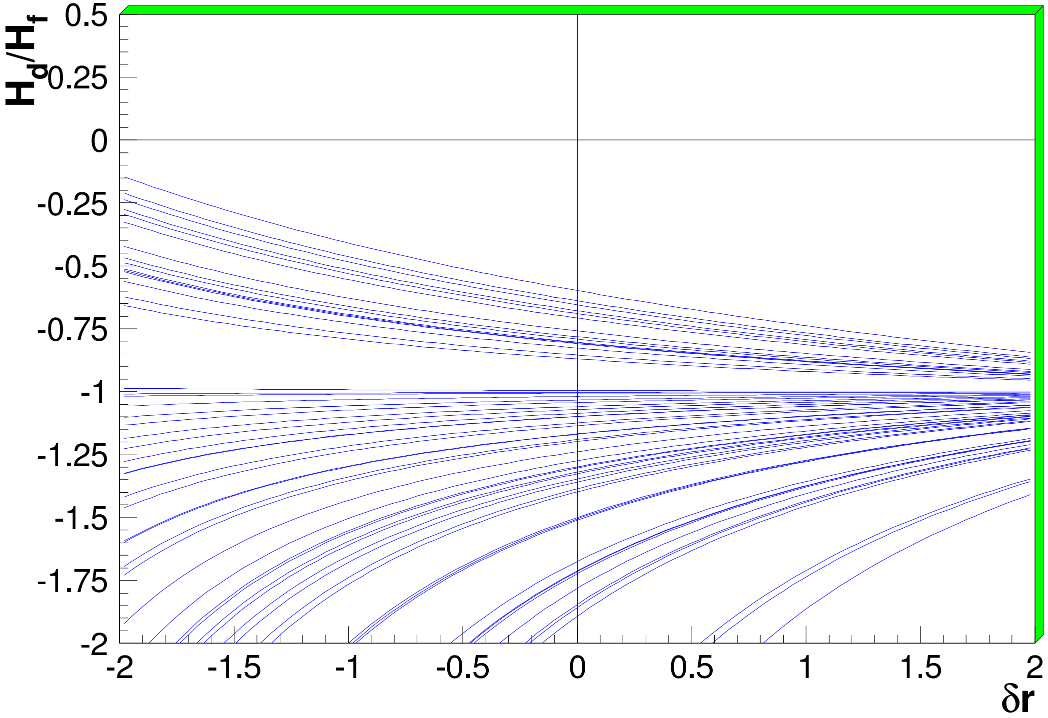
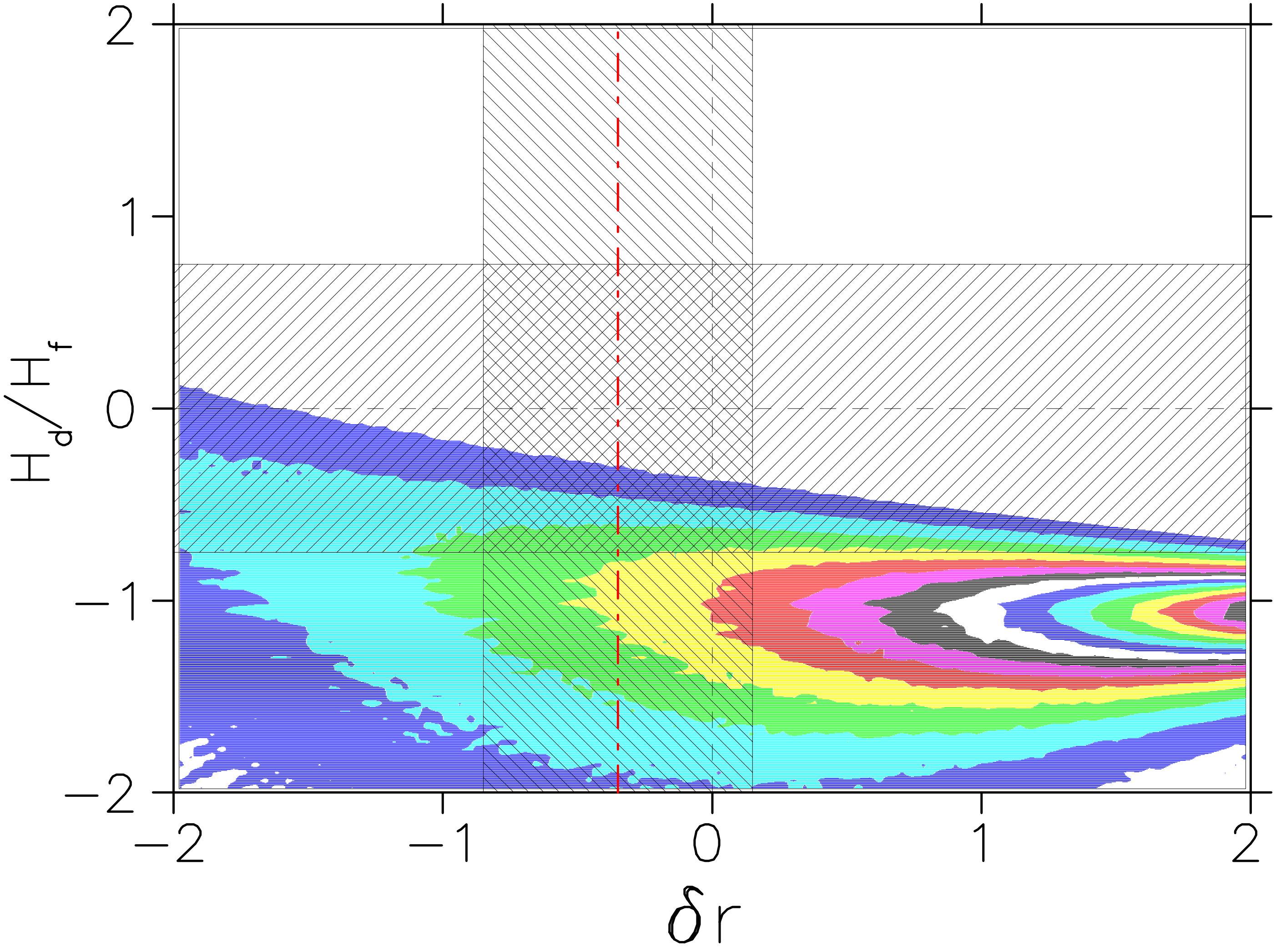


Limits on Transversity and Collins FF

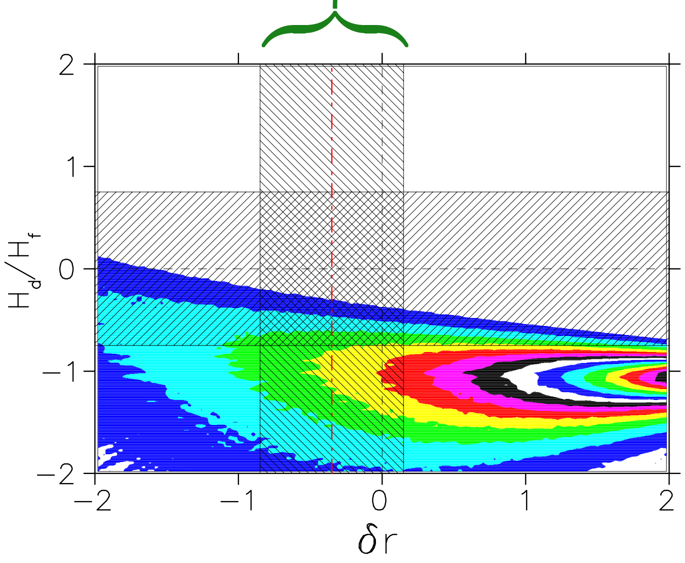
probability distribution for H_d/H_f vs. δr:

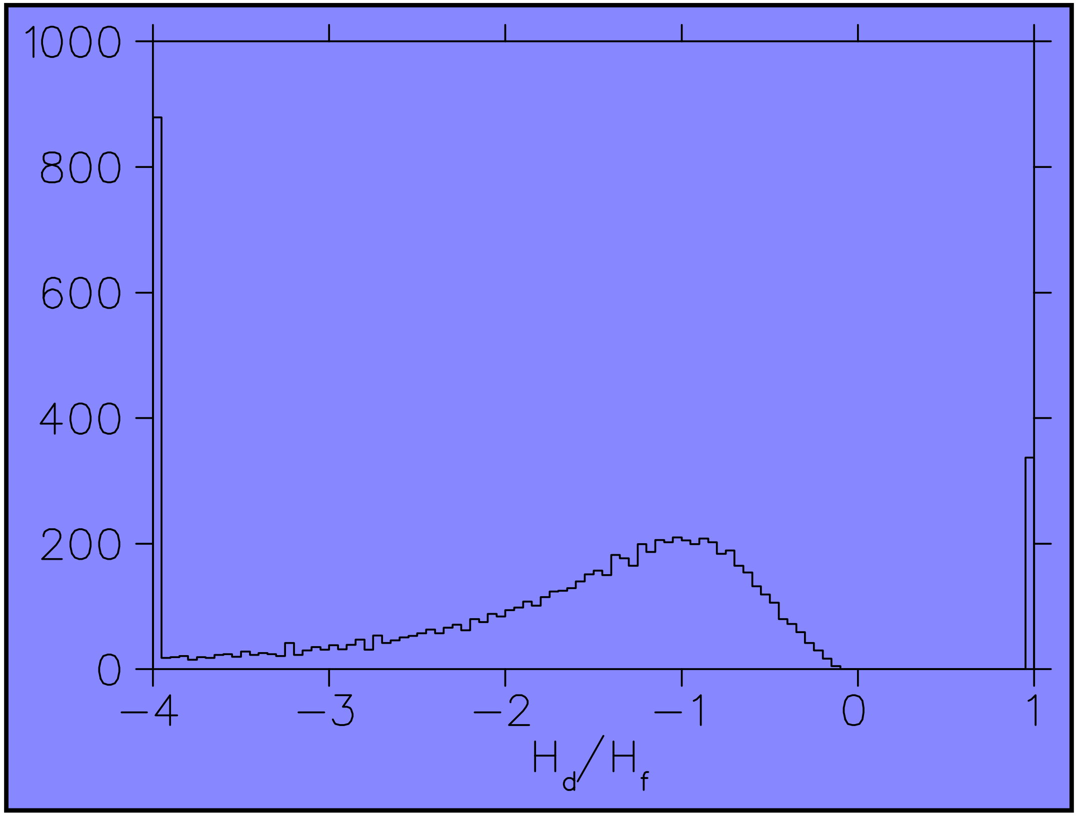


Limits on Transversity and Collins FF

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

look at slice of distribution in δr:





strong hint for H_d/H_f negative