Probing the transverse spin structure of the proton and TMDs at HERMES

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on behalf of the HERMES collaboration

RHIC & AGS Annual Users´ Meeting 2009

hermes

Overview

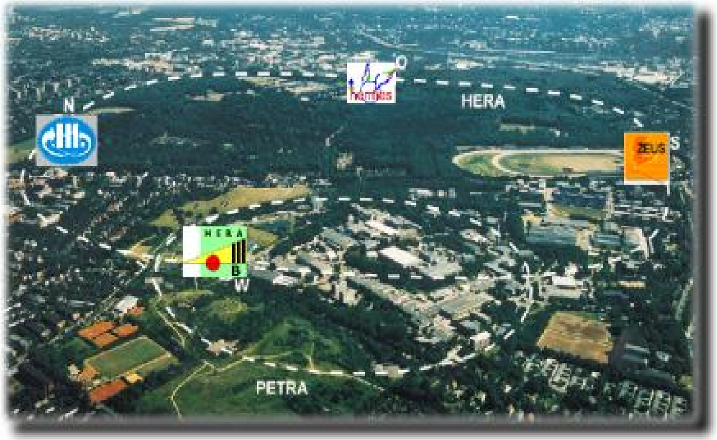
- single-spin asymmetries in DIS off transversely polarized protons:

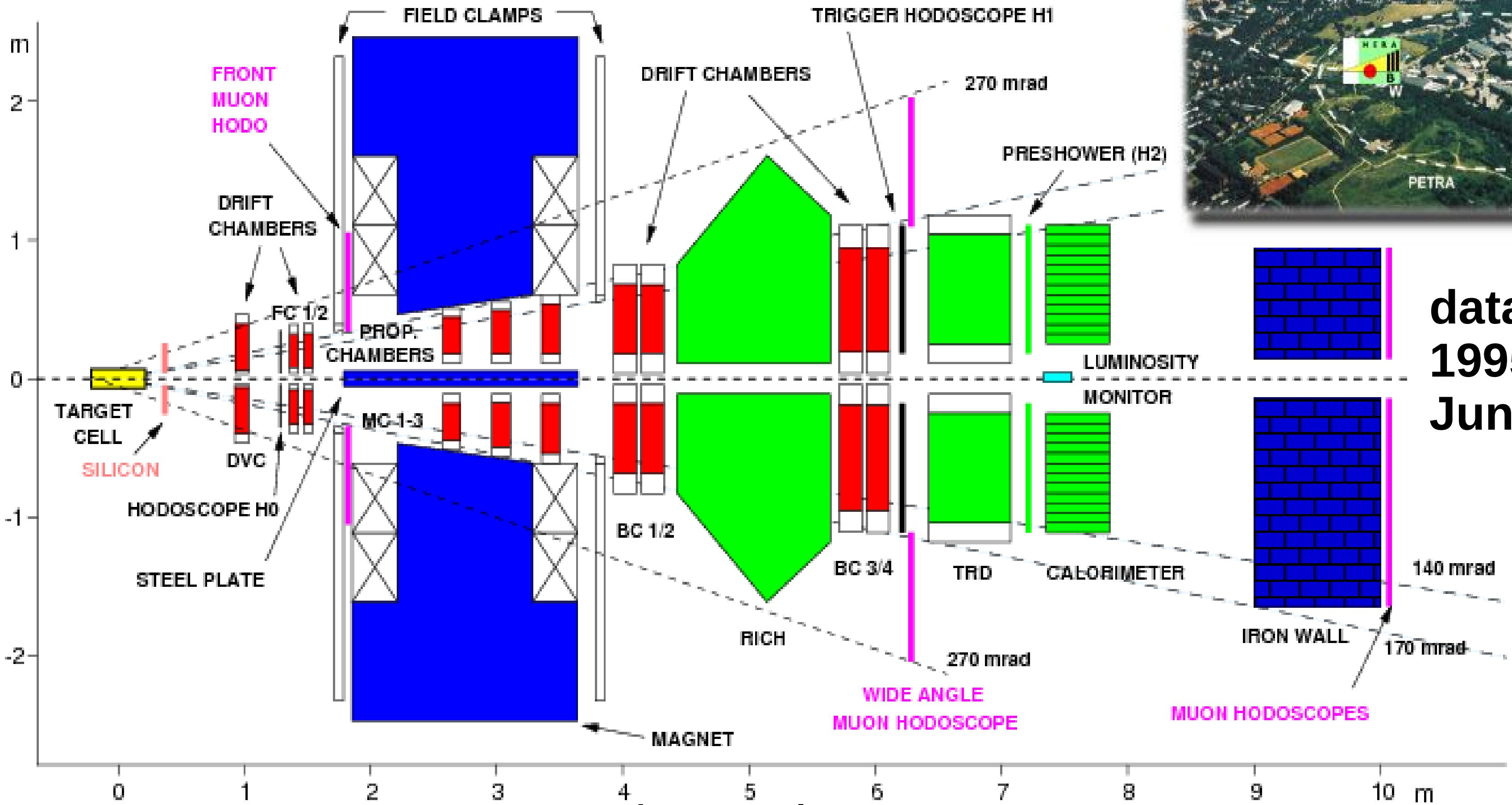
  one-hadron production

  hadron-pair production

- non-collinear spin-independent cross-section

HERMES: HERA MEASUREMENT of SPIN





data taking from 1995 until June, 30 2007

<u>Beam</u>
longitudinally pol.
e^+ & e^-
E= 27.6 GeV

<u>Gaseous internal target</u>
transversely pol. H (~75%)
unpol. H,D,Ne,Kr,..
longitudinally pol. H,D,He (~85%)

- **lepton-hadron PID: high efficiency (~98%) & low contamination (<2%)**
- **hadron PID: RICH 2-15 GeV**

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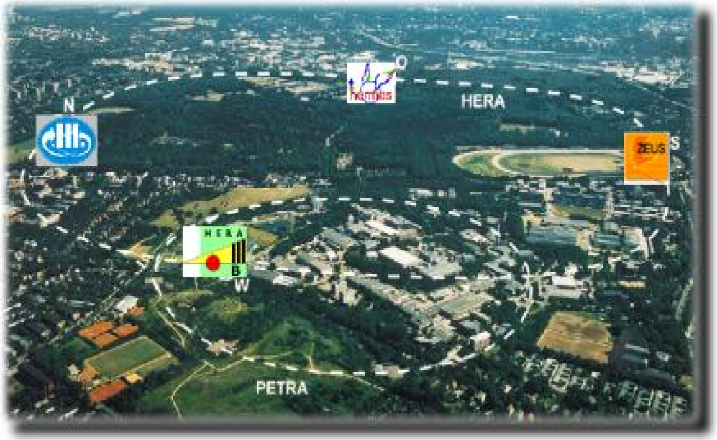
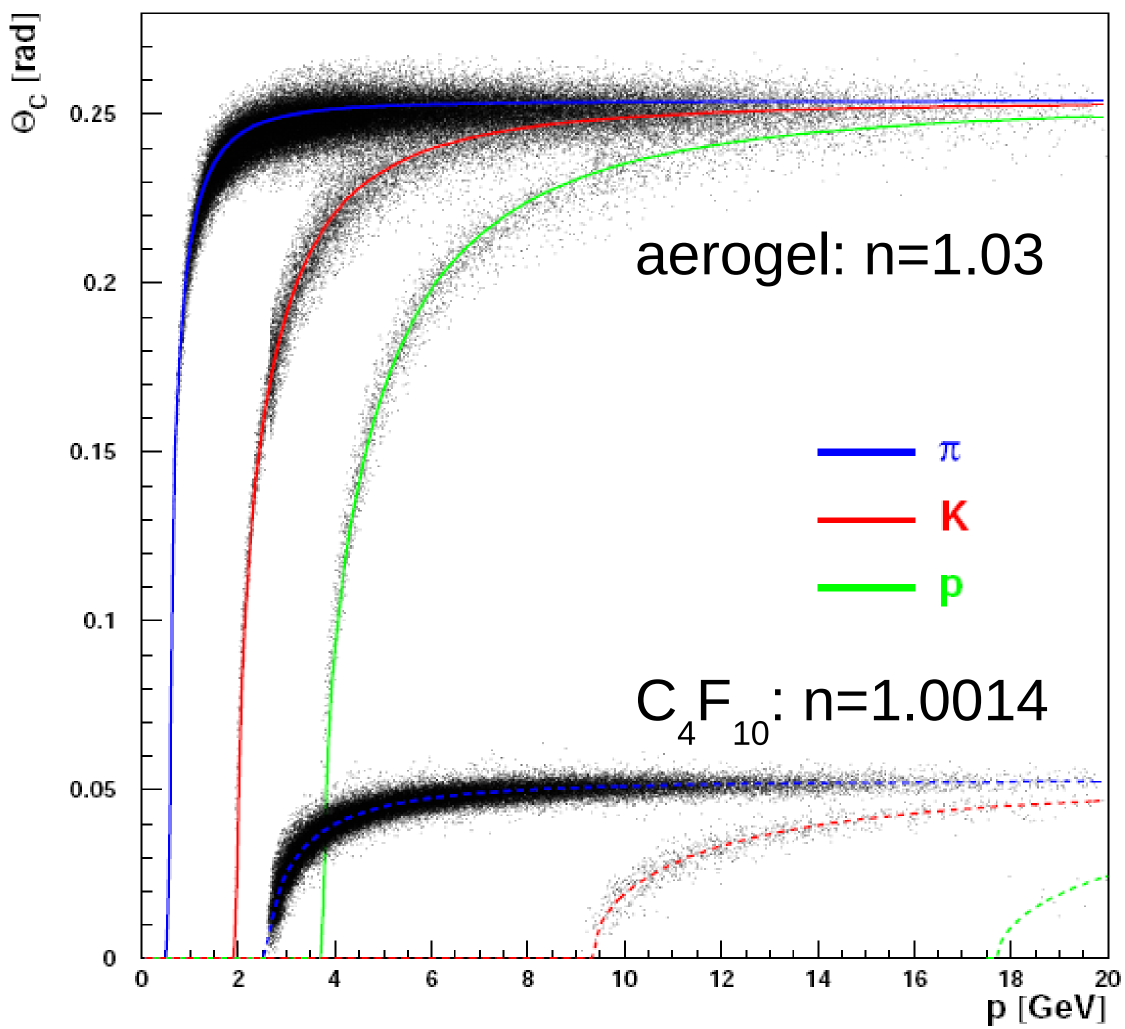
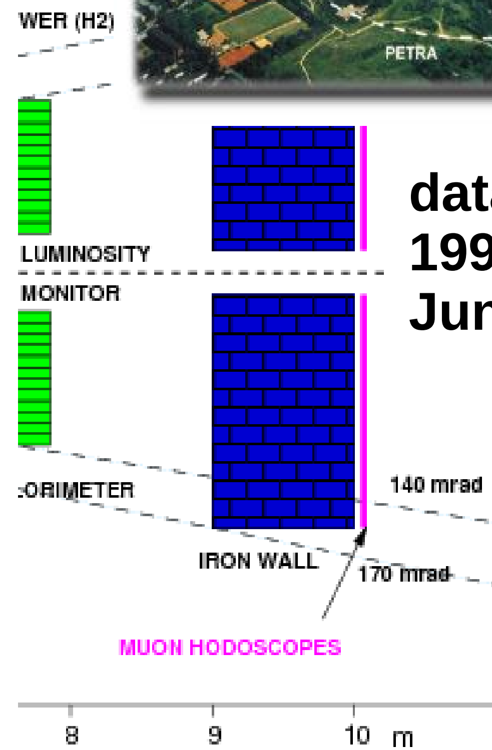


RICH:Cerenkov angle versus momentum





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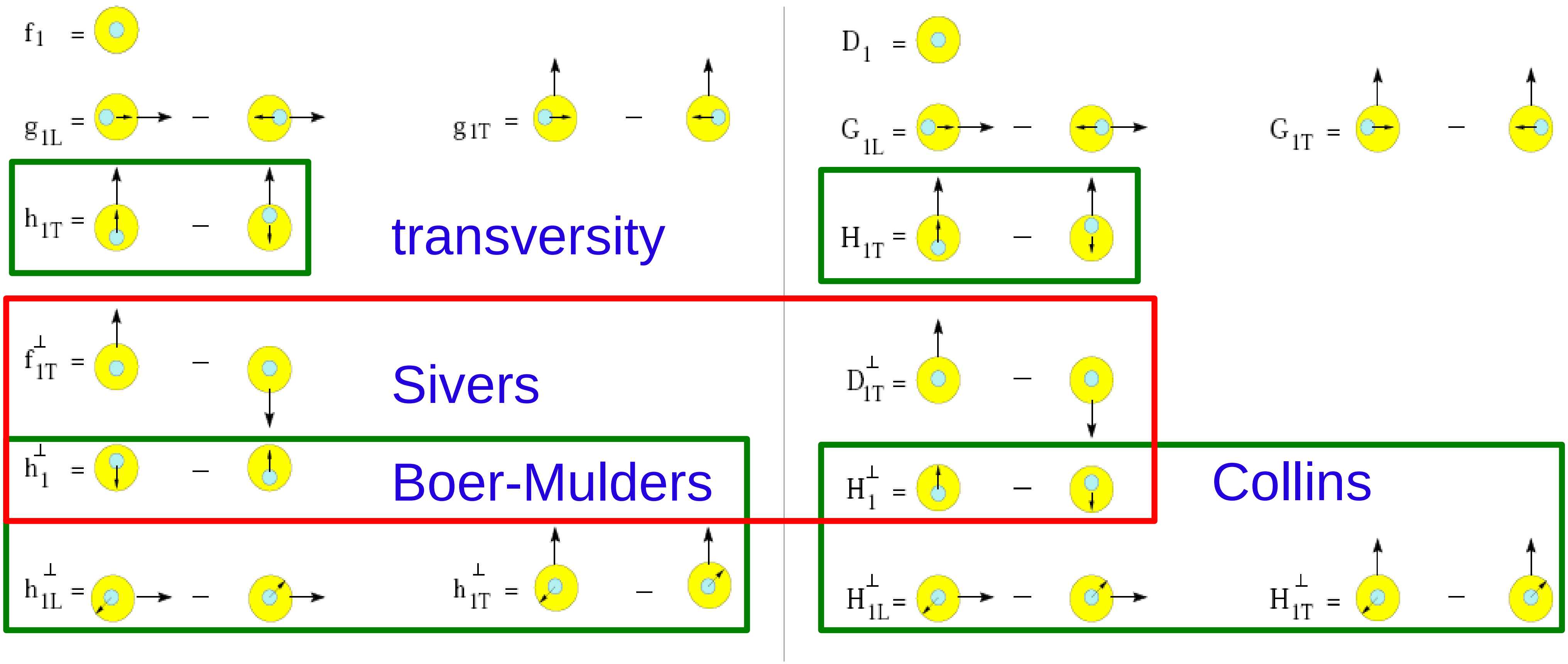
Transverse momentum dependent distributions (TMDs)

Distribution functions

leading twist

Fragmentation functions



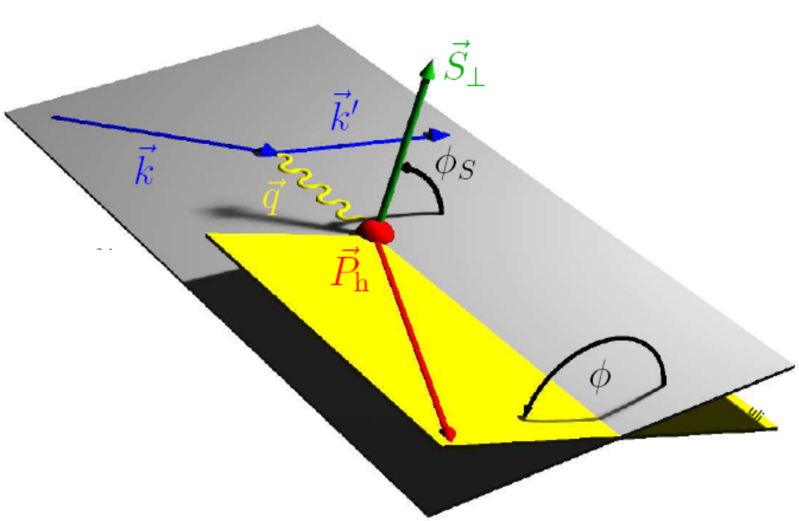
chiral odd: involve helicity flip of quark

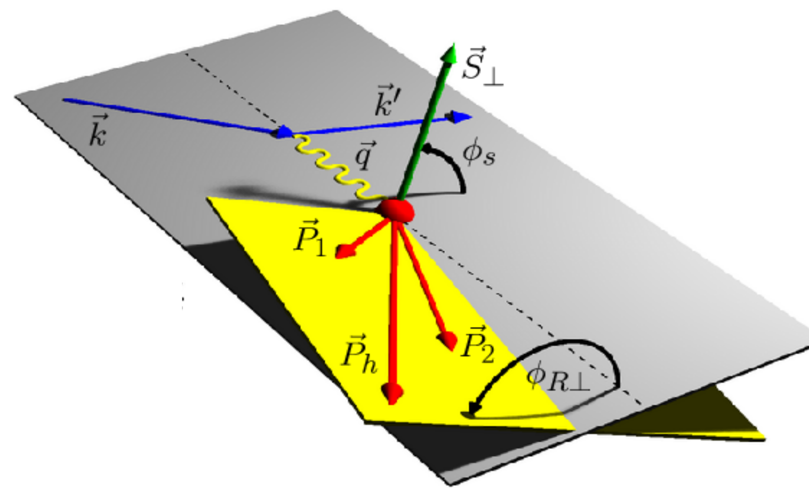
T-odd : appear in pairs in spin-independent x-section & double-spin asymmetries
single in single-spin asymmetries

Single-spin asymmetries

in semi-inclusive deep-inelastic scattering on transversely polarized target

$$\sigma_{UT} = \frac{1}{2}(\sigma_{U\uparrow} - \sigma_{U\downarrow})$$





ep ⟶ ehX

$$\sim \sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I}[\frac{\vec{p}_T.\hat{P}_{h\perp}}{M_h} h_{1T}^q \otimes H_1^{\perp,q}]$$

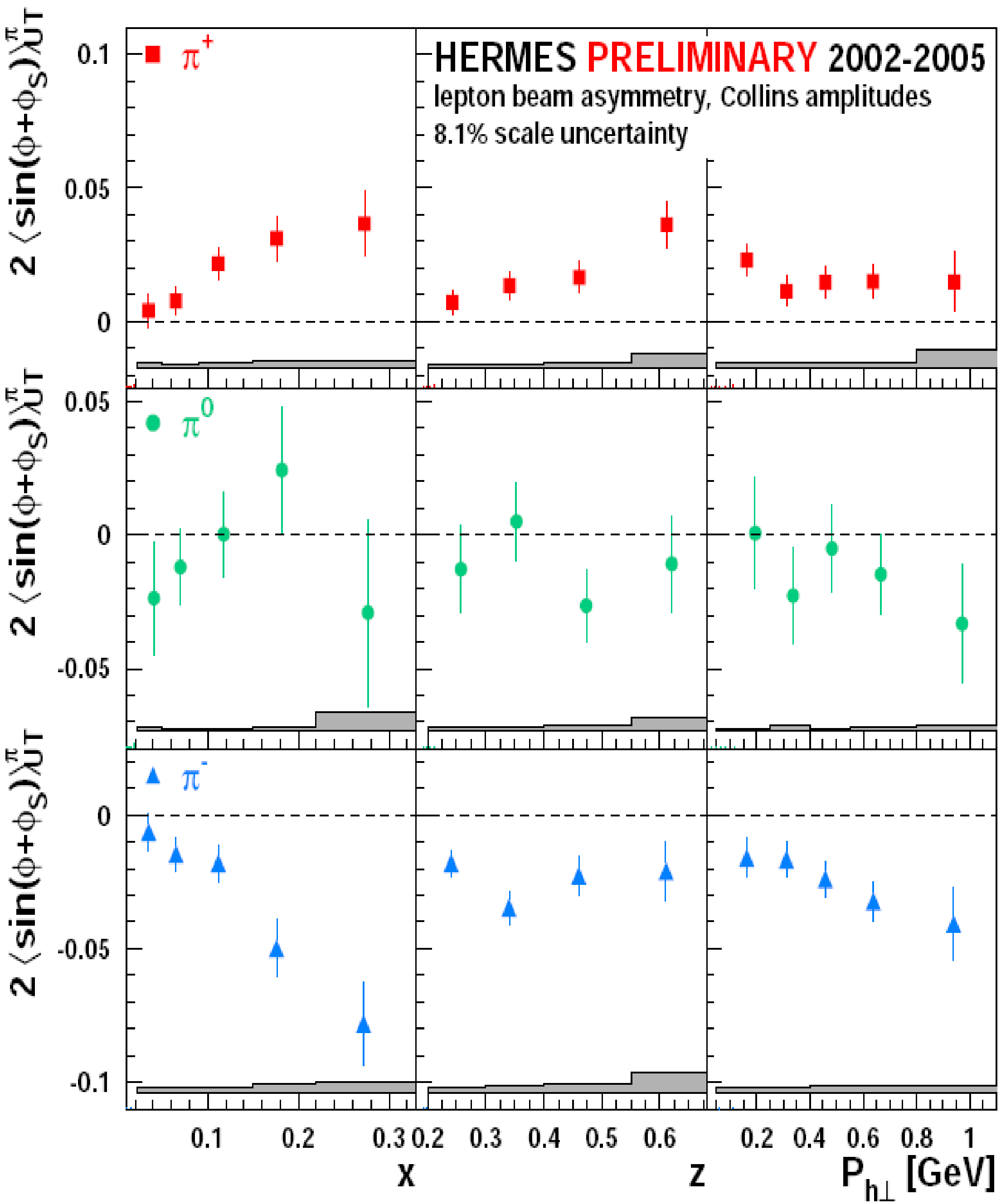
$$+ \sin(\phi - \phi_S) \sum_q e_q^2 \mathcal{I}[\frac{\vec{k}_T.\hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q} \otimes D_1^q]$$

ep ⟶ eh_1h_2X

$$\sim \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 h_{1T}^q H_1^{\measuredangle,q}$$

Single-spin asymmetry: one-hadron production

Collins amplitudes for pions



- results from 2002-2005 data
- positive for π^+
- large & negative for π^-

$$\longrightarrow \quad H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled

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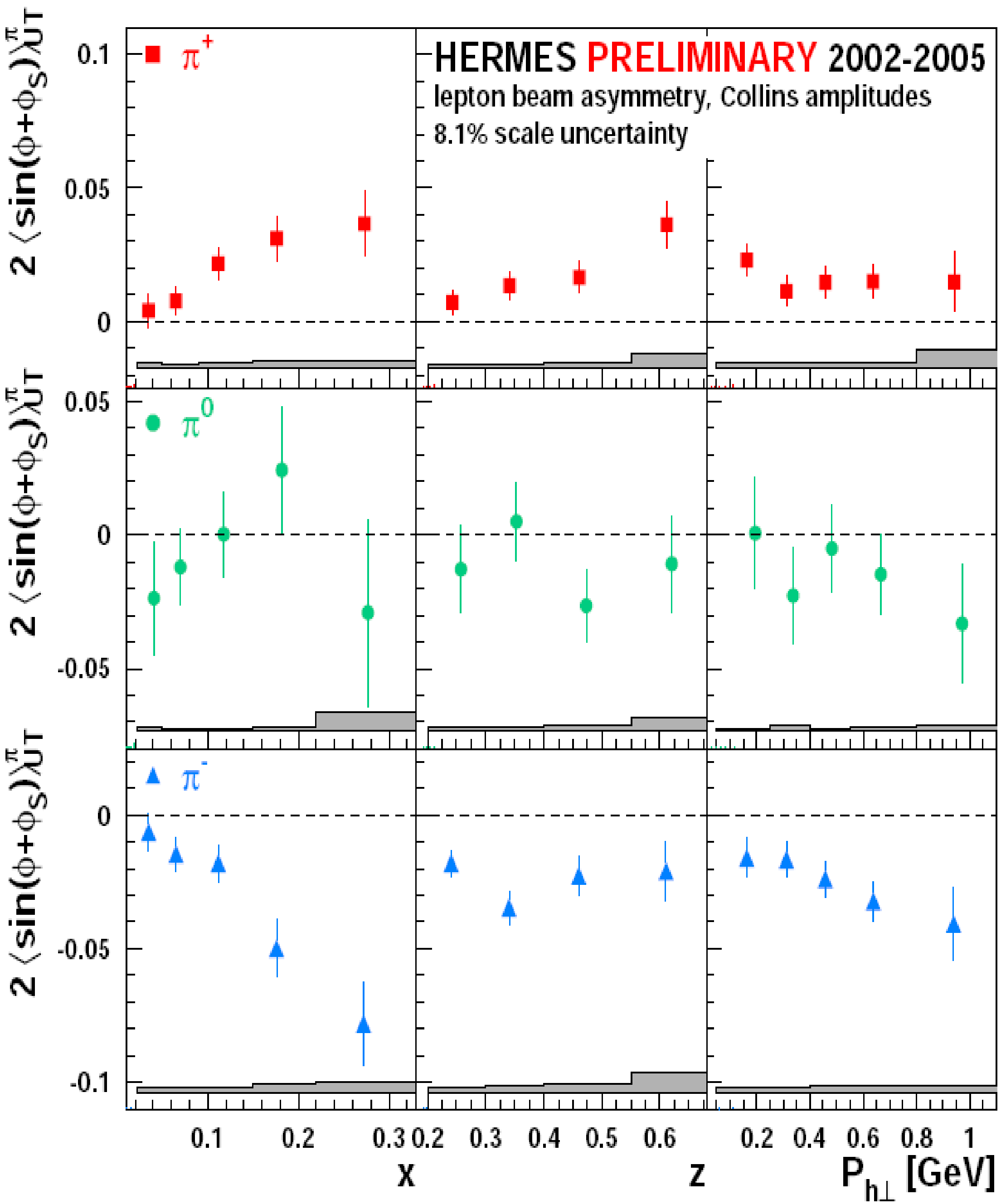

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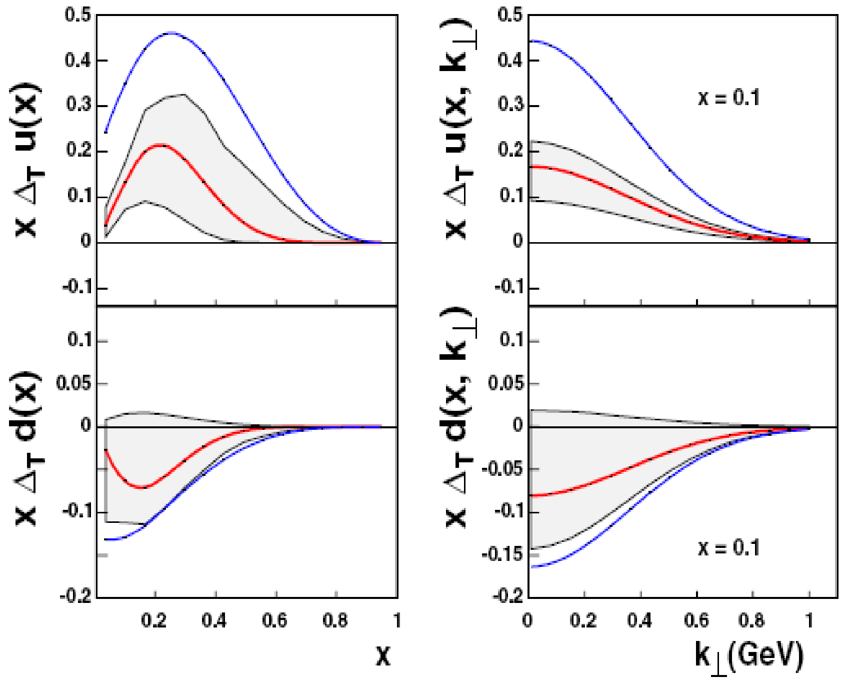
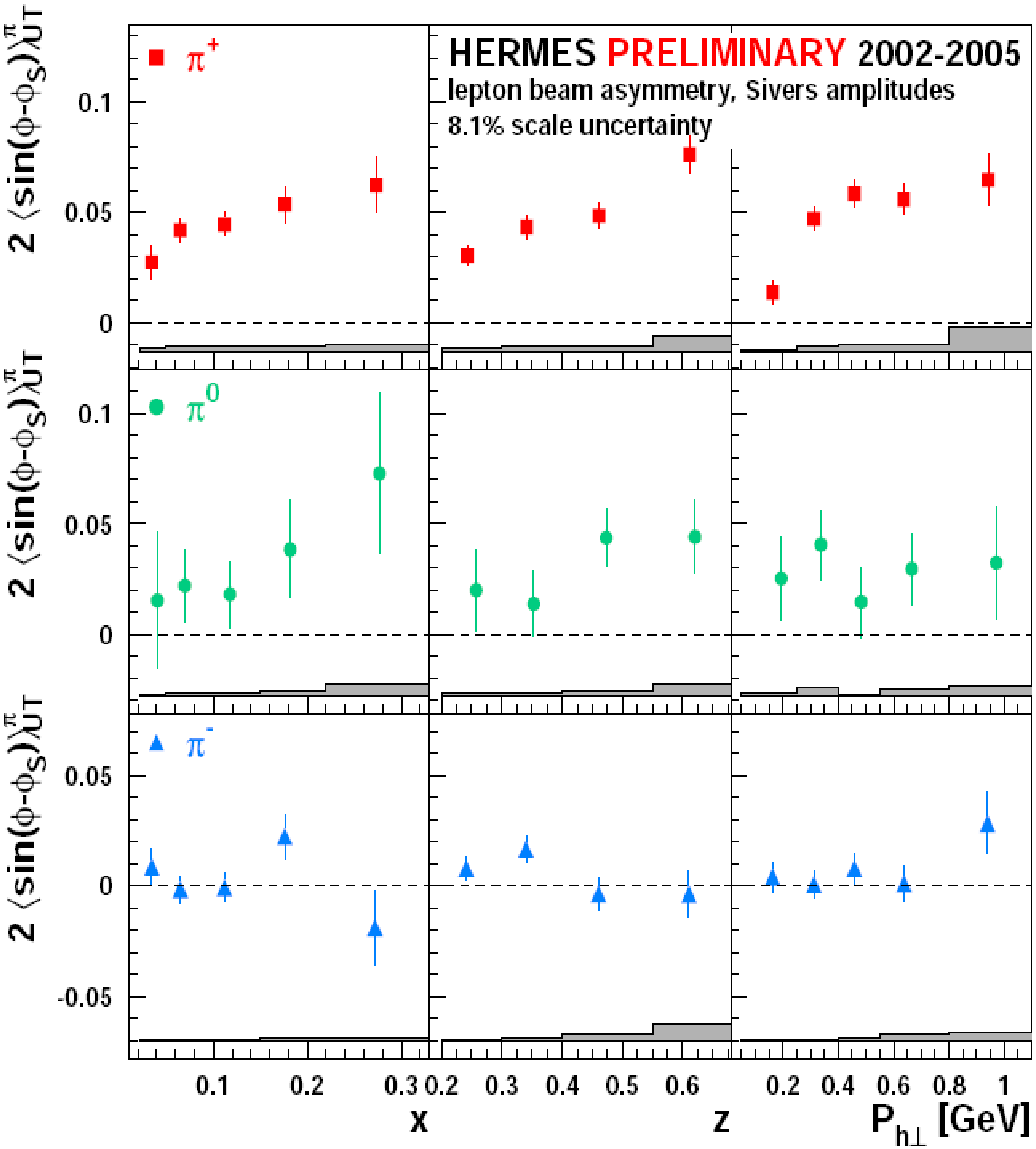
- isospin symmetry fulfilled
- extraction by Anselmino et al. (Phys. Rev. D75: 054032, 2007) based on data from BELLE, COMPASS & HERMES

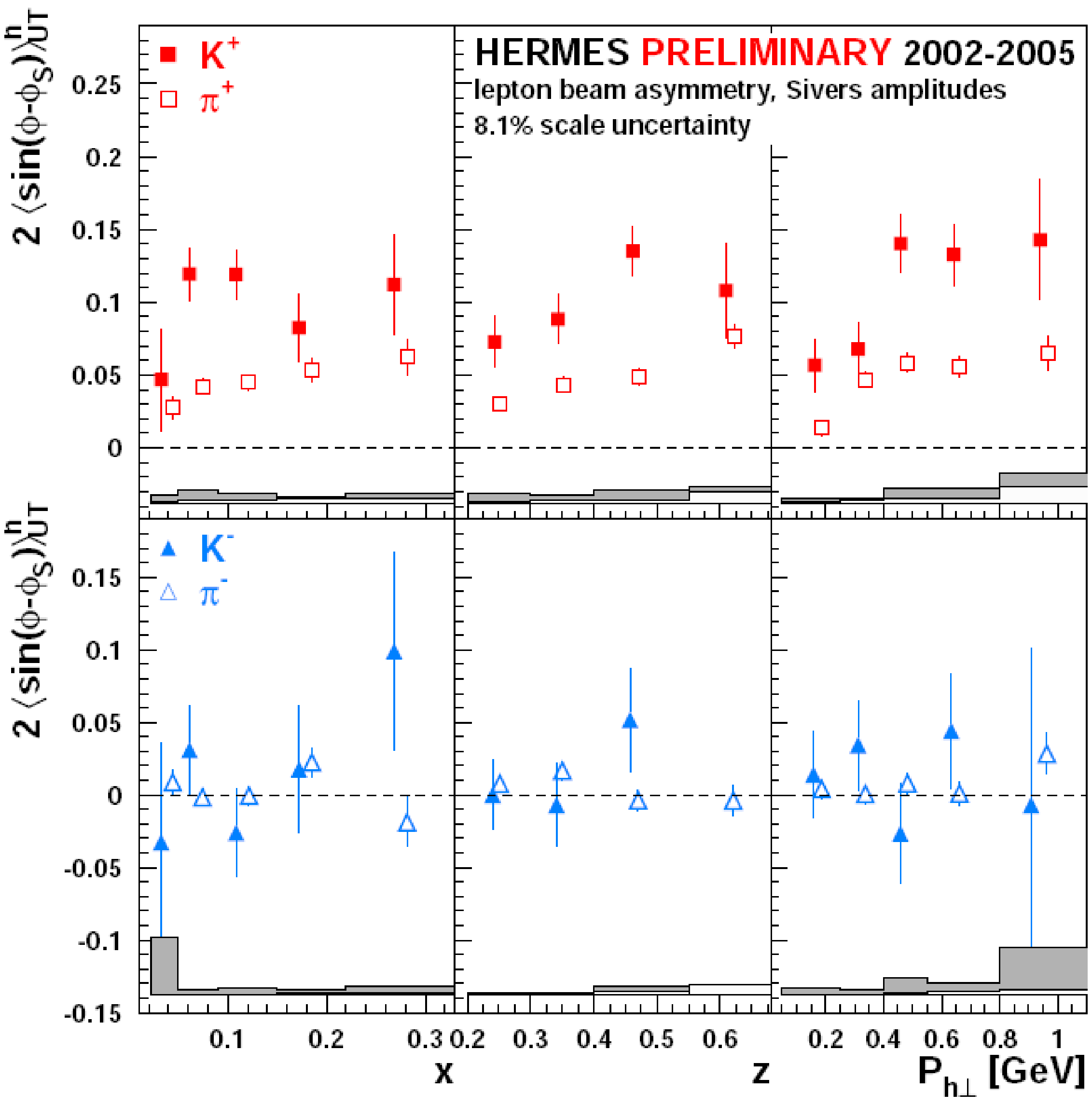


Sivers amplitudes for pions



- results from 2002-2005 data
- positive for π^+
  → non-zero orbital angular momentum!
- consistent with 0 for π^-
- isospin symmetry fulfilled

Sivers amplitudes for kaons



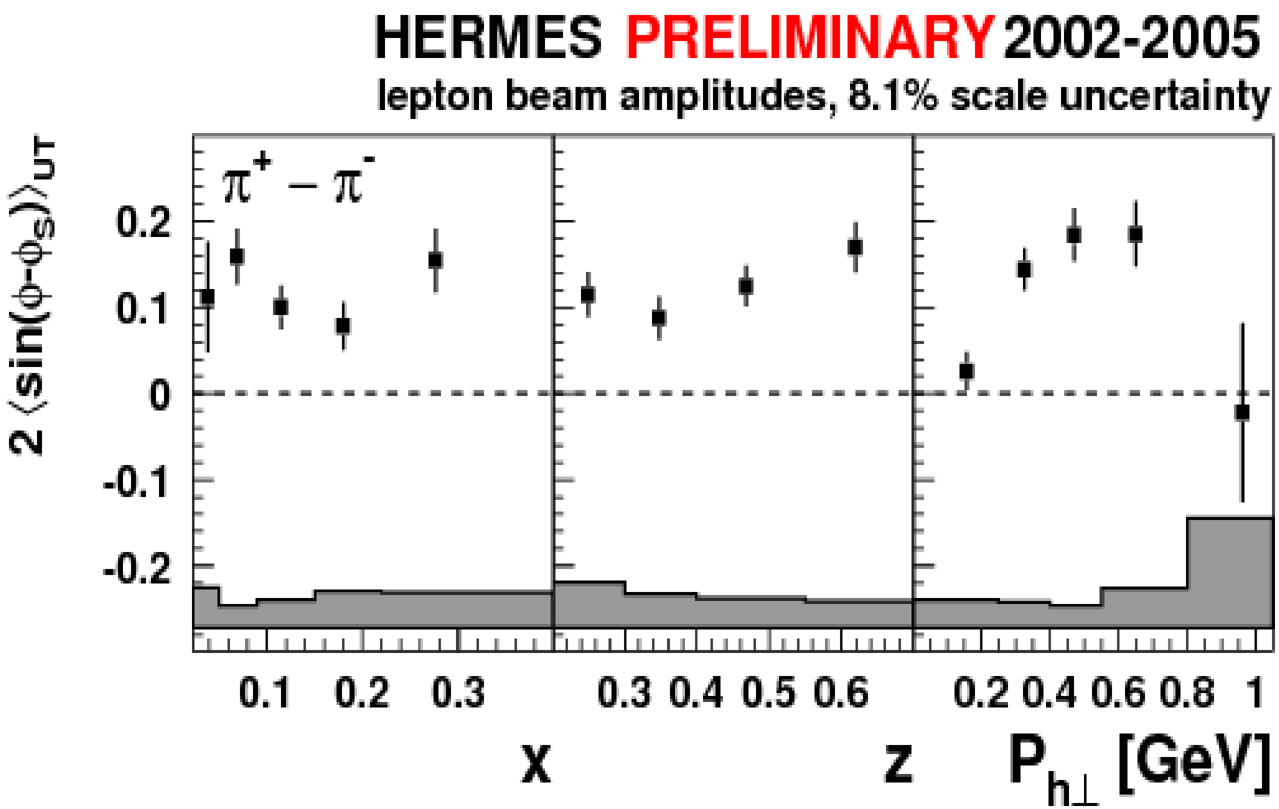
- results from 2002-2005 data
- K^+ larger than π^+
  → non-trivial role of sea-quarks
- K^-, like π^-, consistent with zero

Sivers distribution for valence quarks

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle|S_T|\rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$

→ suppressed exclusive ρ^0 contribution

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



- Sivers distribution for d-valence >> u-valence

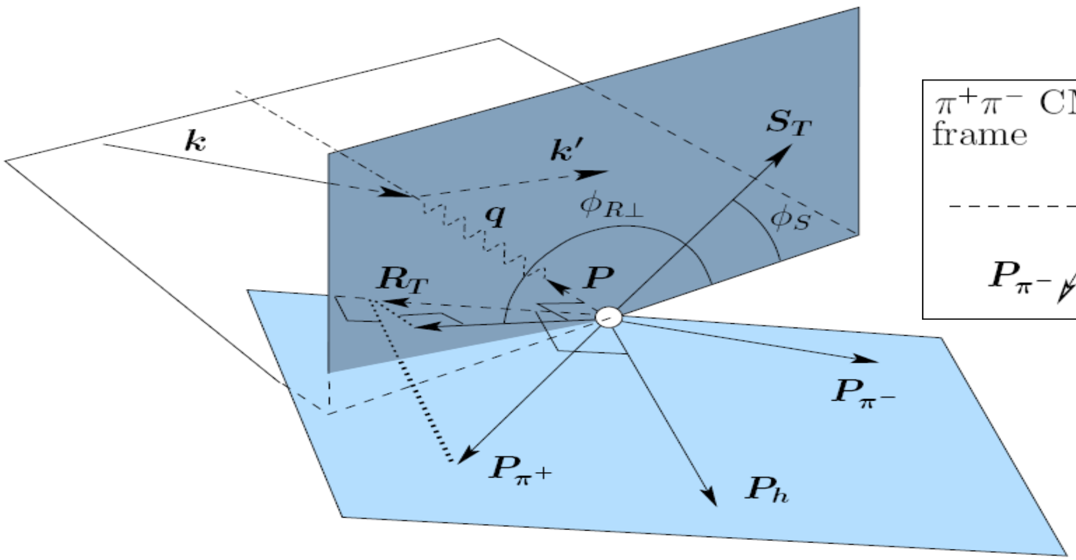
  or
- Sivers distribution for u-valence is large & <0 (more likely)

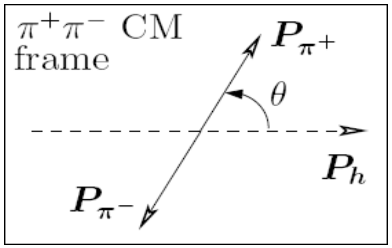
Single-spin asymmetry: hadron-pair production

Single-spin asymmetry: $\pi^+\pi^-$ production

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

$H_1^{\measuredangle,q}$: T-odd and chiral-odd dihadron fragmentation function





$$\vec{R} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2)$$

$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

$$\vec{R}_T = \vec{R} - (\vec{R}.\hat{P}_h)\hat{P}_h$$

- independent method to probe transversity: transverse spin of fragmenting quark transferred to relative orbital angular momentum of hadron pair
- integration over hadron momenta → direct product
  but
- more complex cross section (9 variables)
- less statistics

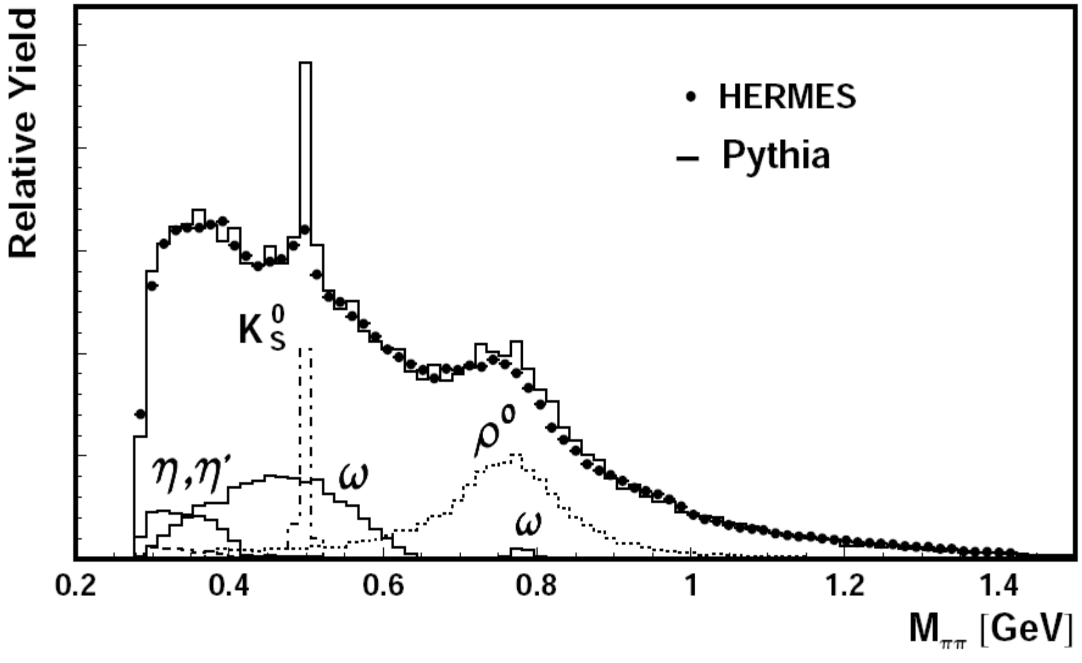
Extraction of $\pi^+\pi^-$ asymmetry

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\sin\theta \frac{\sum_q e_q^2 h_{1T}^q(x) H_1^{\measuredangle,q}(z, M_{\pi\pi}, \cos\theta)}{\sum_q e_q^2 f_1^q(x) D_1^q(z, M_{\pi\pi}, \cos\theta)}$$

- Legendre expansion ($M_{\pi\pi}$<1.5 GeV):

$$H_1^{\measuredangle} = H_1^{\measuredangle,sp} + H_1^{\measuredangle,pp}\cos\theta$$

$$D_1 = D_1 + D_1^{sp}\cos\theta + D_1^{pp}\frac{1}{4}(3\cos^2\theta - 1)$$



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$$D_1 = D_1 + D_1^{sp}\cos\theta + D_1^{pp}\frac{1}{4}(3\cos^2\theta - 1)$$

- symmetrization around θ = π/2

$$H_1^{\measuredangle,pp}\cos\theta \quad \text{and} \quad D_1^{sp}\cos\theta$$

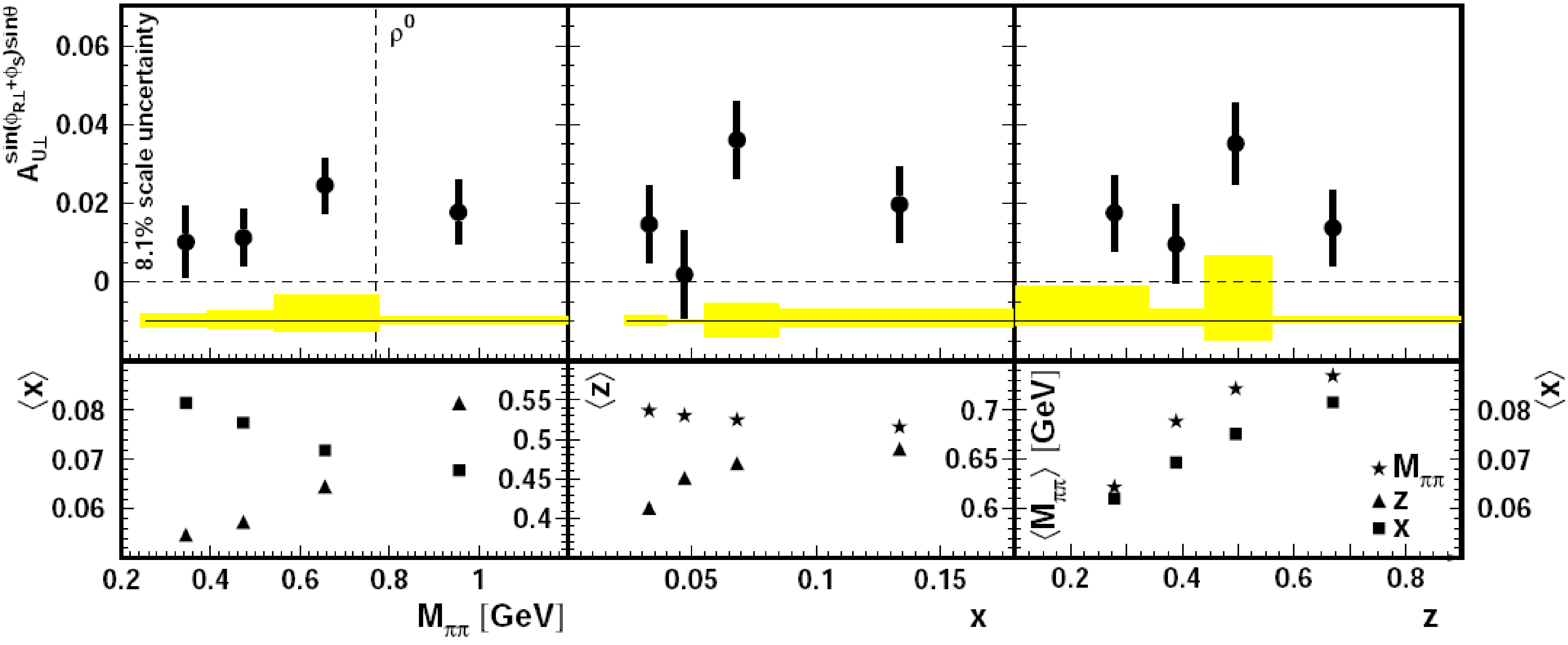
fit

$$\frac{a}{1+\frac{b}{4}(3\cos^2\theta - 1)}\sin(\phi_{R\perp}+\phi_S)\sin\theta$$

$$a \equiv A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \sim \frac{\sum_q e_q^2 h_{1T}(x) H_1^{\measuredangle,sp}(z, M_{\pi\pi})}{\sum_q e_q^2 f_1(x) D_1(z, M_{\pi\pi})}$$

Final HERMES results

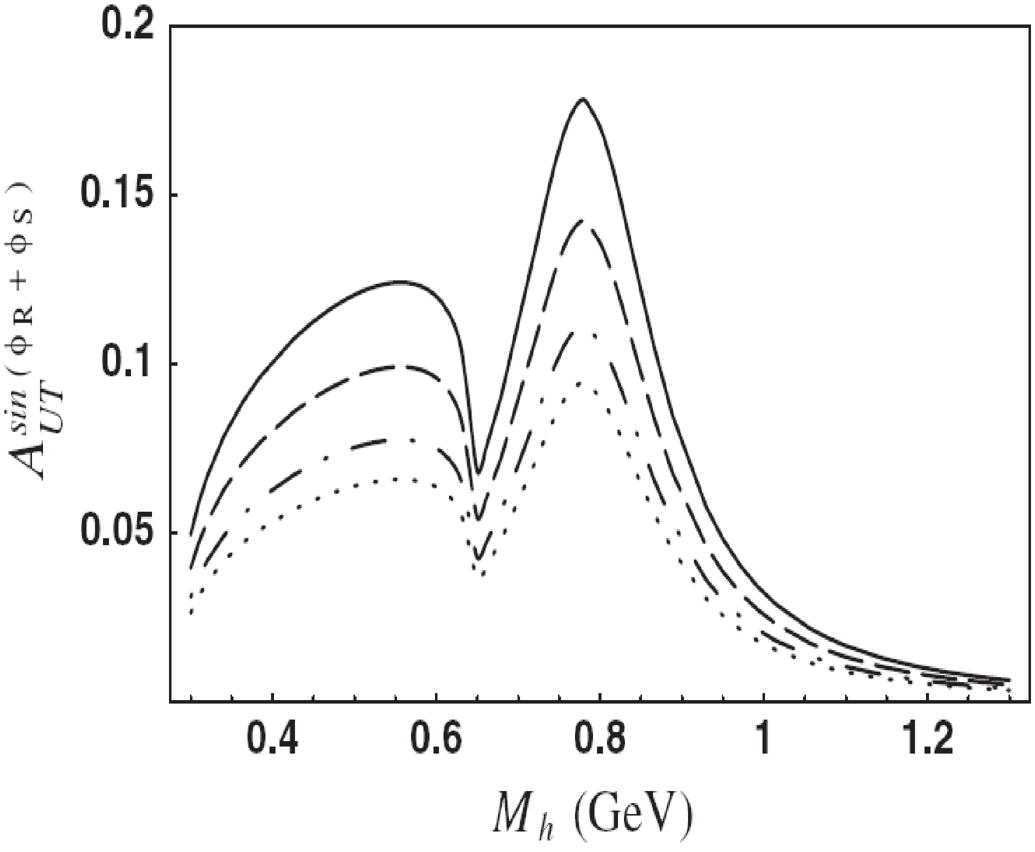
A. Airapetian et al., JHEP 0806:017,2008

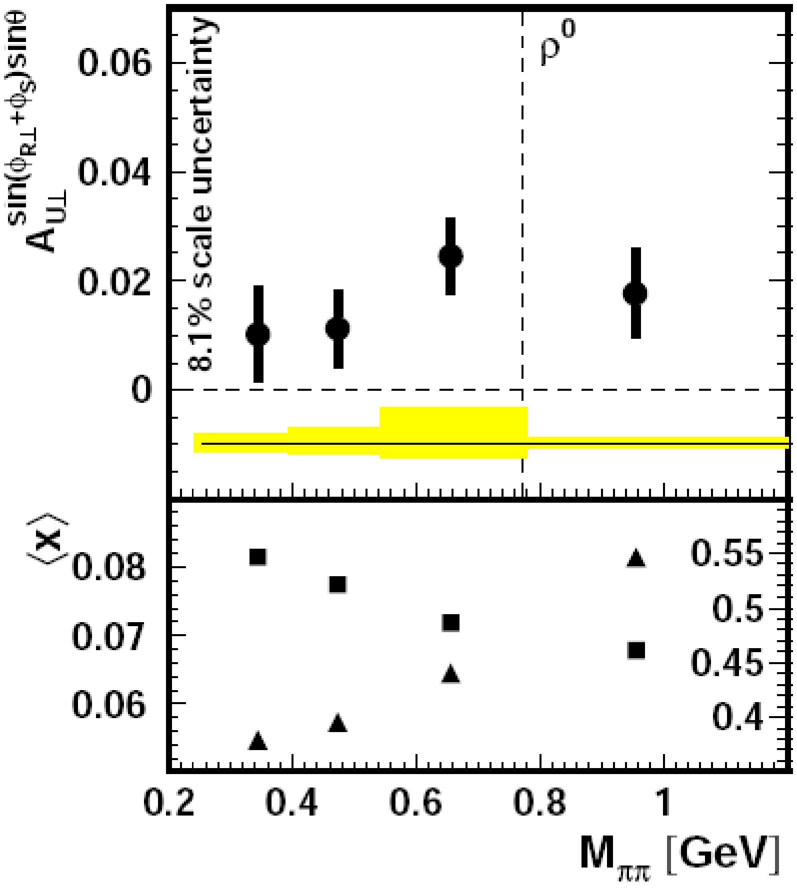


- first evidence for non-zero T-odd and chiral-odd dihadron fragmentation function!

Comparison with model

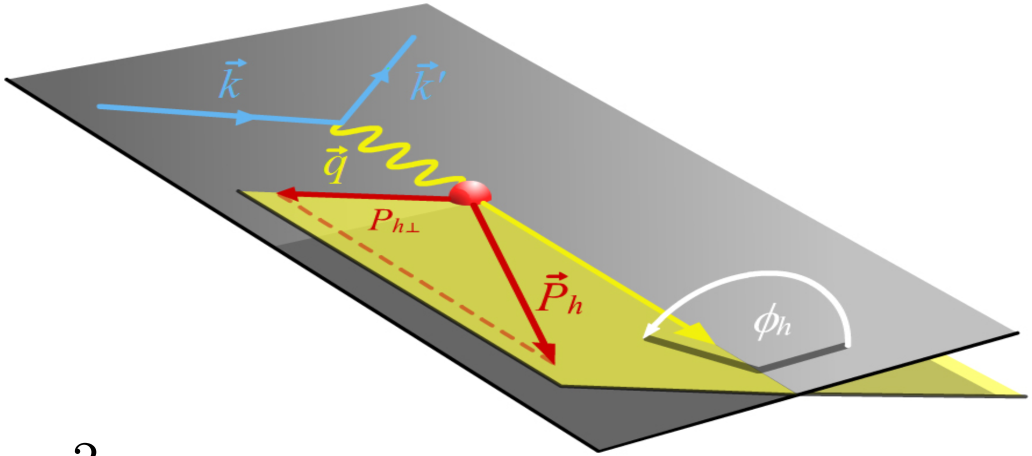
A. Bacchetta, M. Radici, Phys. Rev. D74:114007,2006





Spin-independent semi-inclusive deep-inelastic cross section

Spin-independent semi-inclusive DIS cross section

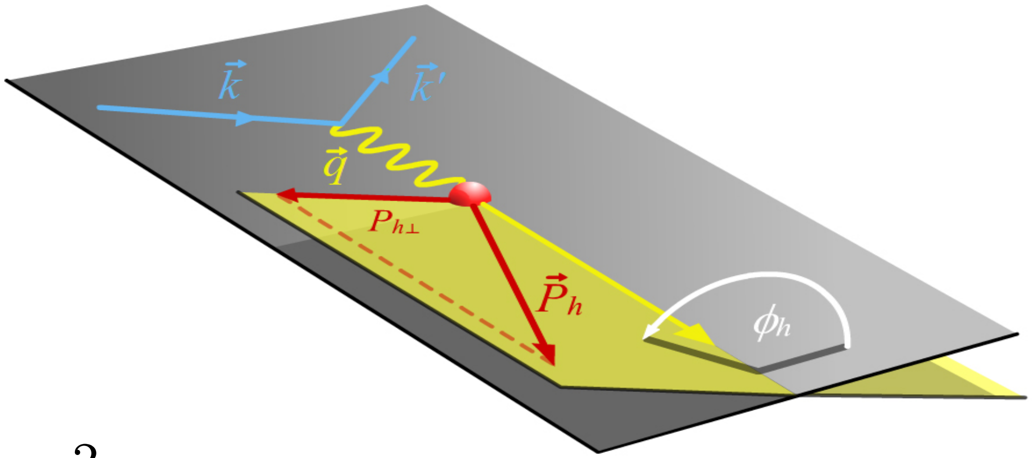


<u>Non-collinear cross section</u>

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)F_{UU,T} + B(y)F_{UU,L} + C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

$$\gamma = \frac{2Mx}{Q},\ \ F = F(x, Q, z, \vec{P_{h\perp}})$$

Spin-independent semi-inclusive DIS cross section



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$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

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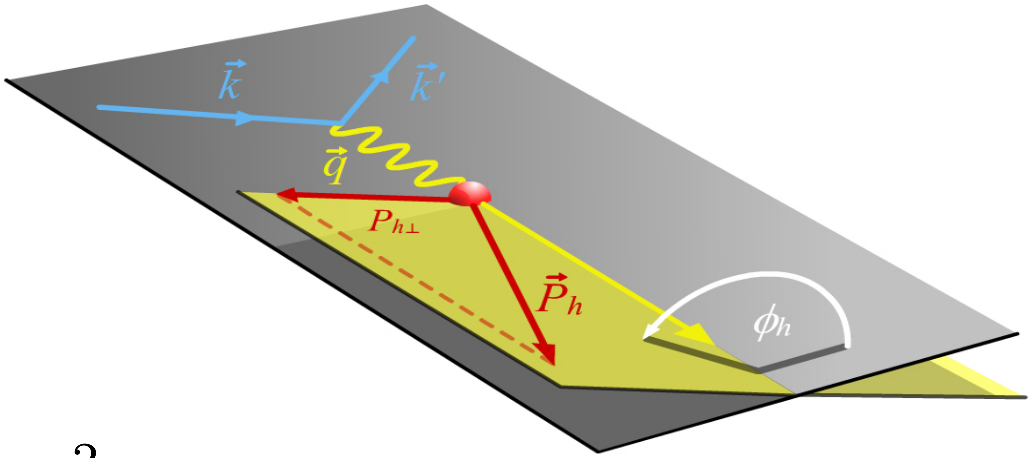
leading twist

$$F_{UU}^{\cos 2\phi_h} = \mathcal{I}\left[-\frac{2(\hat{P}_{h\perp}.\vec{k}_T)(\hat{P}_{h\perp}.\vec{p}_T) - \vec{k}_T.\vec{p}_T}{M_h M} h_1^\perp H_1^\perp\right]$$

Boer-Mulders DF — Collins FF

Spin-independent semi-inclusive DIS cross section



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$$\gamma = \frac{2Mx}{Q},\ \ F = F(x, Q, z, \vec{P_{h\perp}})$$

sub-leading twist

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{k}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{p}_T}{M_h}\frac{k_T^2}{M^2} h_1^\perp H_1^\perp + \ldots]$$

Cahn effect

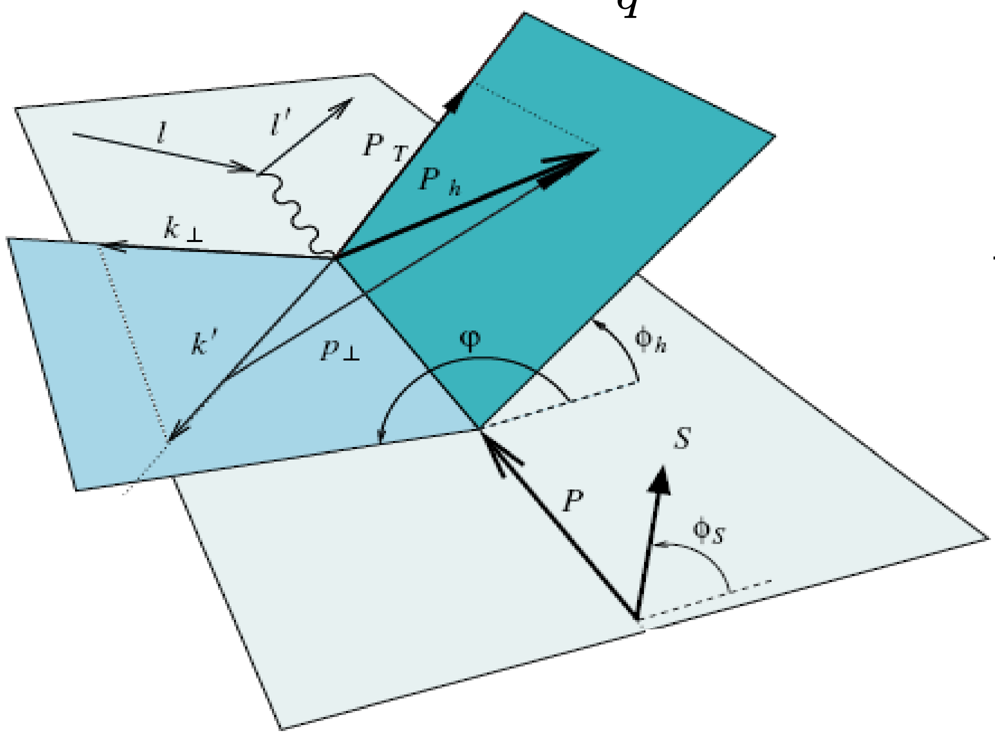
quark-gluon-quark correlations

Cahn effect

R. N. Cahn, Phys. Lett. B78:269, 1978
Phys. Rev. D40: 3107, 1989

M. Anselmino et al., Phys. Rev. D71:074006, 2005

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP^2_{h\perp}} \sim \sum_q \int d^2k_T\, f_1^q(x,k_T)\, \frac{d\hat{\sigma}^{lq\to lq}}{dQ^2}\, D_1^q(z,p_\perp)\ldots.$$



$$\frac{2\pi\alpha^2}{x^2s^2}\,\frac{\hat{s}^2+\hat{u}^2}{Q^4} \sim \vec{l}.\vec{k}_T \sim \cos\varphi$$

and

$$\vec{P}_{h\perp} \simeq z\vec{k}_T + \vec{p}_T$$

after integration over k_T azimuthal dependence remains, reflected in $\cos\phi_h$

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \stackrel{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

$$\updownarrow$$

$$\langle \cos(n\phi_h) \rangle \stackrel{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}$$

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extraction is challenging!

azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

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fully differential analysis needed
unfolding procedure with 400 x 12 bins *

BINNING
400 kinematic bins x 12 ϕ -bins

Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

(*)see F. Giordano, R. Lamb
Proceedings of SPIN 2008,
Oct. 6-11 2008, Charlottesville, VA, USA
hep-ex 0901.2438

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$$\omega = (x, y, z, P^2_{h\perp})$$

$$\langle\cos(n\phi_h)\rangle \stackrel{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h)\epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}$$

extraction is challenging!
azimuthal modulations also possible due to
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unfolding

fully differential analysis needed
unfolding procedure with 400 x 12 bins *

$$\langle\cos(n\phi_h)\rangle\Big|_{\text{bin i}} \approx \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \sigma_{UU}(\omega,\phi_h)}\Bigg|_{\text{bin i}}$$

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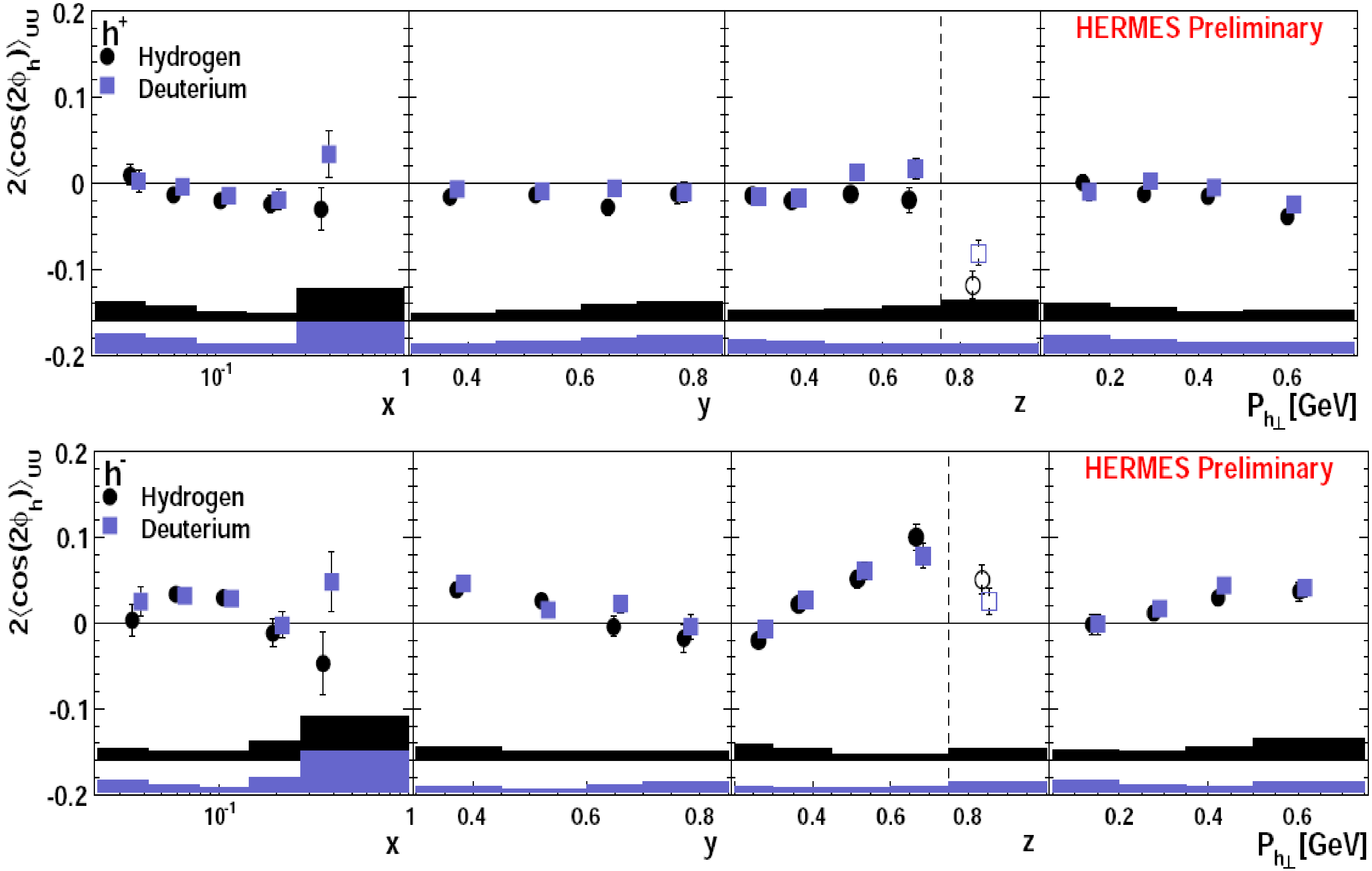
Results for <cos 2ϕ_h>

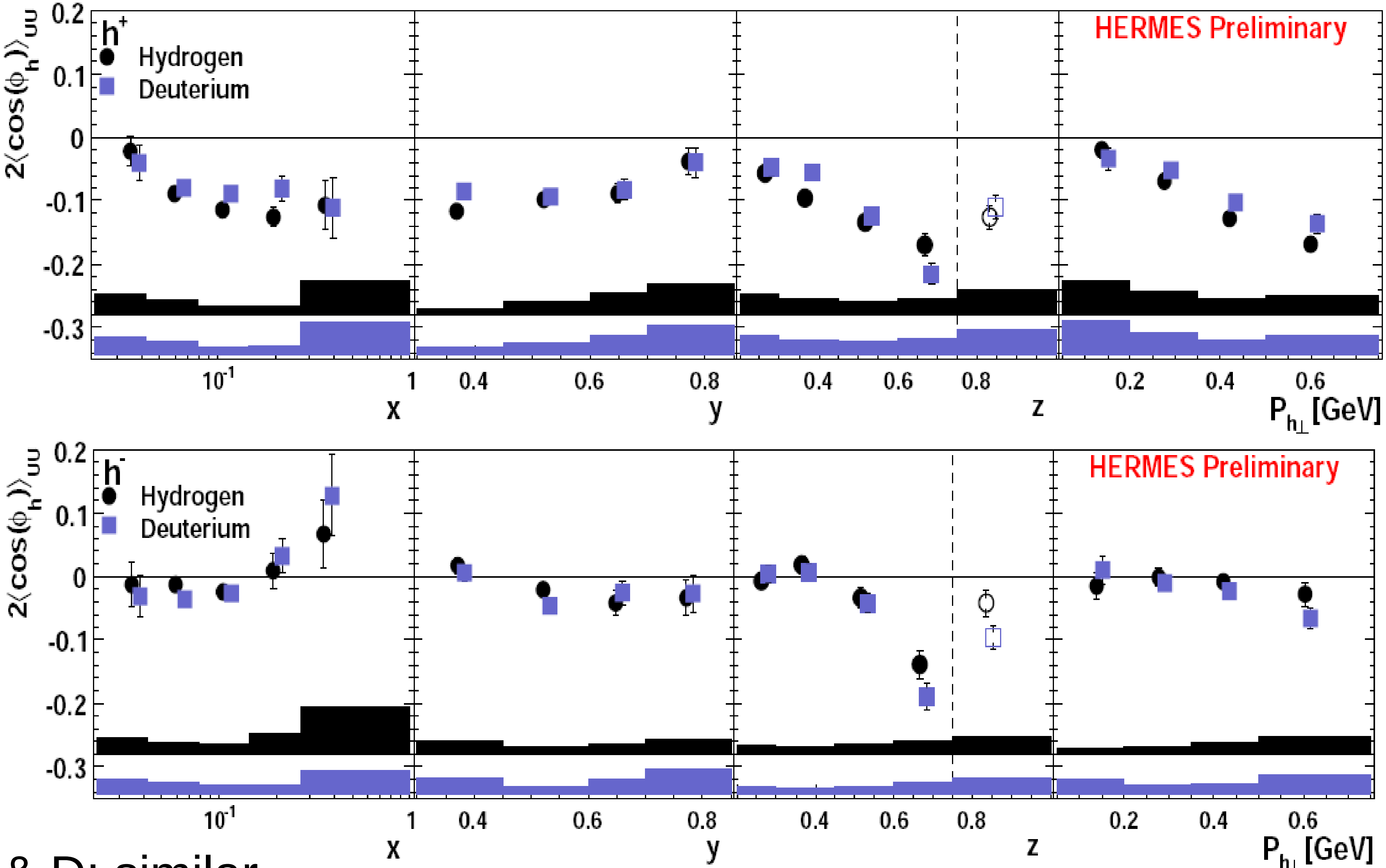
Boer-Mulders



- evidence for transversely polarized quarks in unpolarized nucleon
- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$

Results for <cos ϕ_h>

Cahn+Boer-Mulders+...

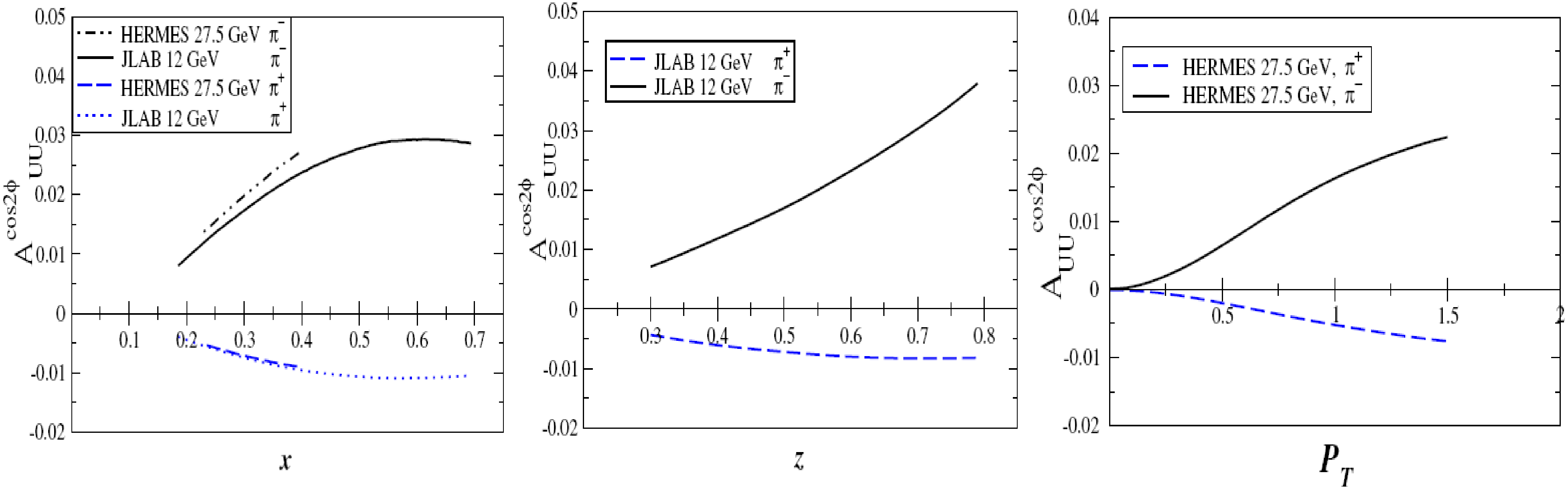


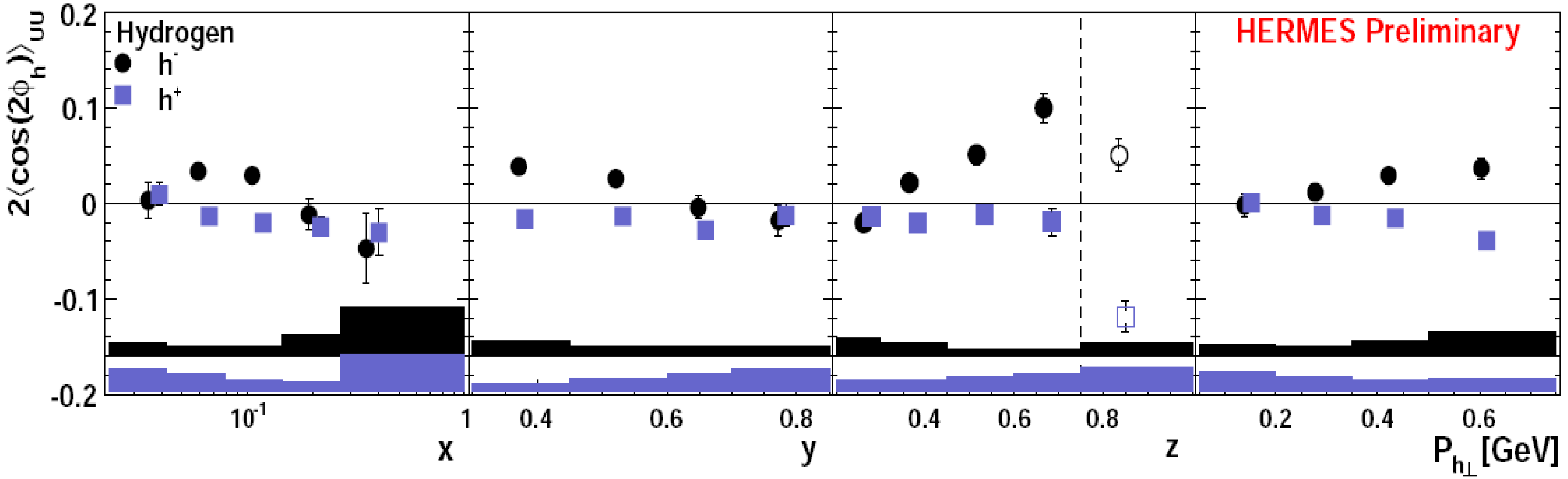
- H & D: similar
- predictions for Cahn effect: similar for h^+ and h^-

  ⟶ also other effects have to be taken into account

Comparison with model calculations: $\langle \cos 2\phi_h \rangle$

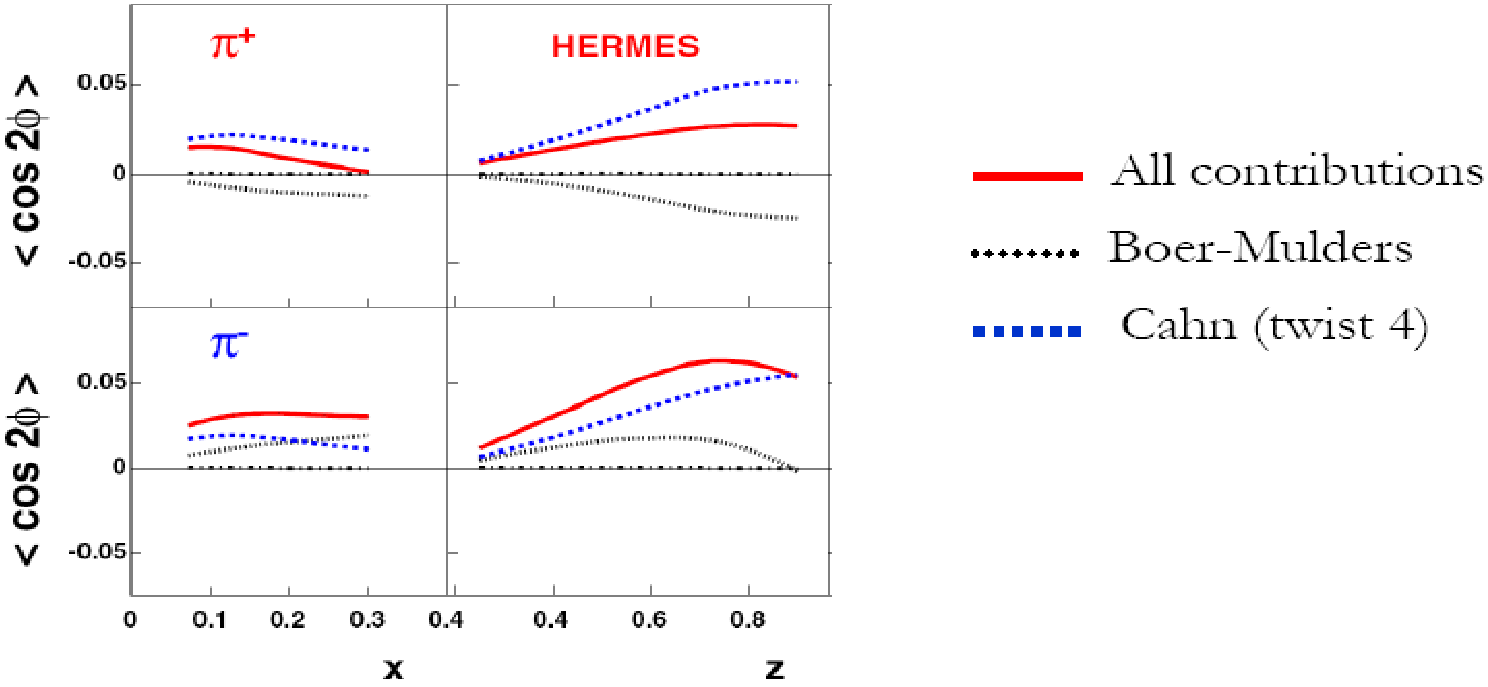
L.P. Gamberg et al. Phys. Rev. D77: 094016, 2008

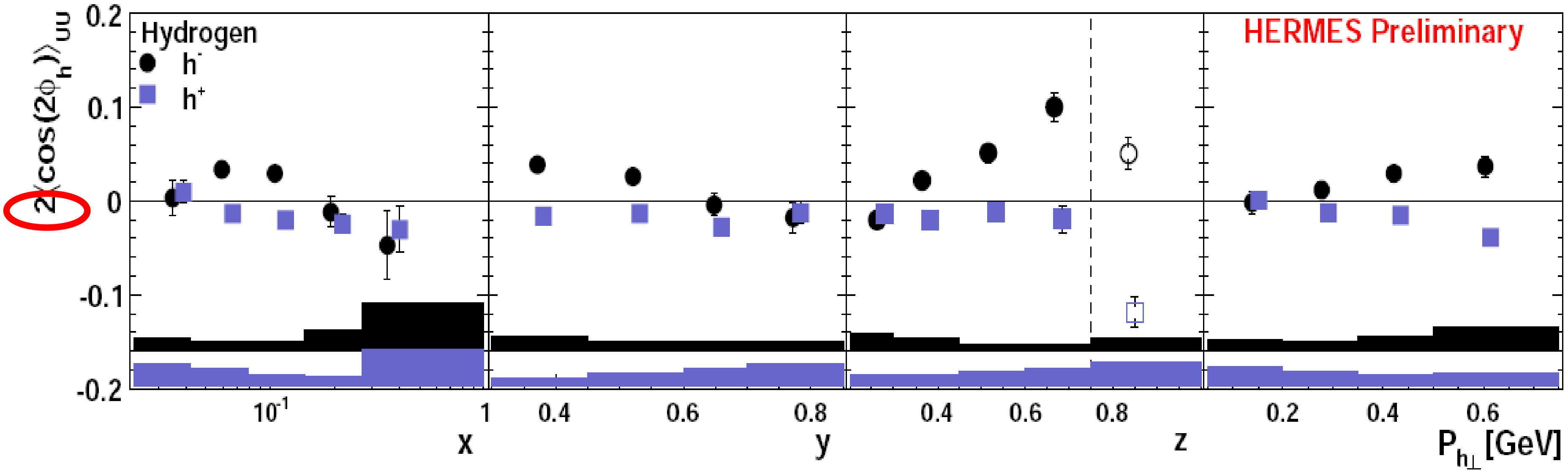




Comparison with model calculations: $\langle \cos 2\phi_h \rangle$

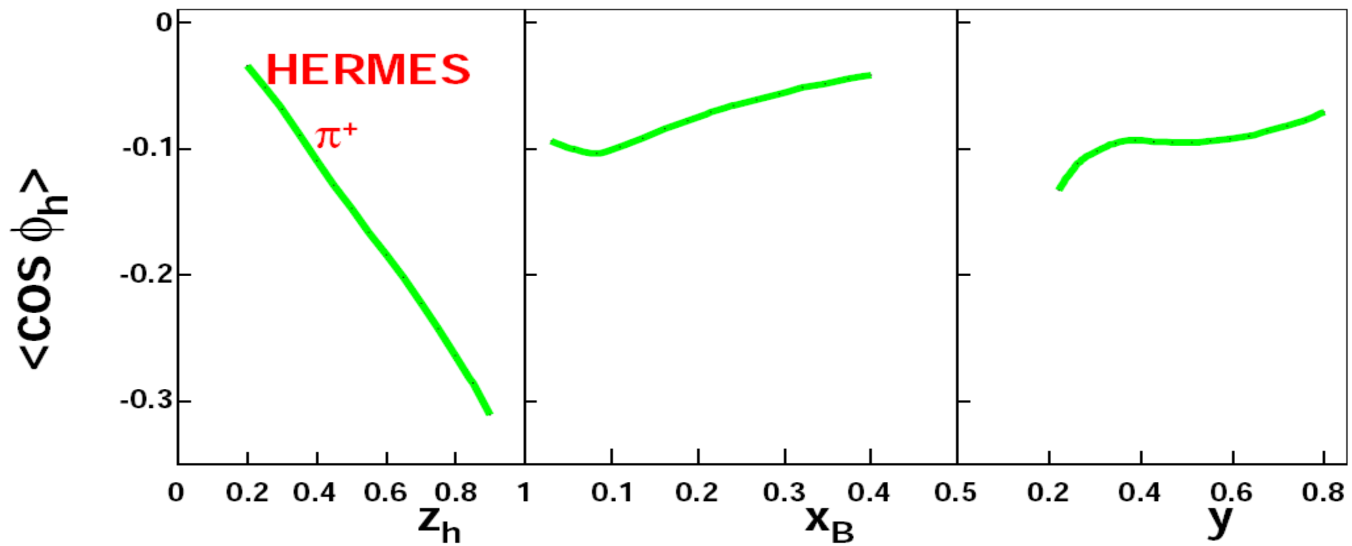
V. Barone et al., Phys. Rev. D78:045022, 2008

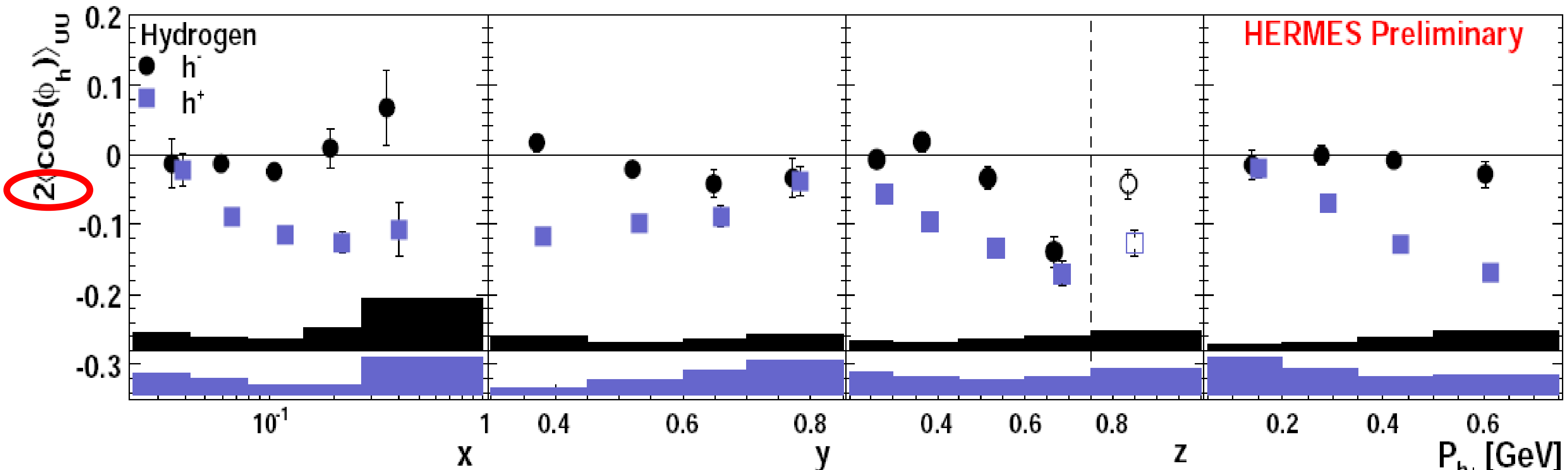




Comparison with model calculations: $\langle\cos\phi_h\rangle$

M. Anselmino et al., Phys. Rev. D71:074006, 2005
M. Anselmino et al., Eur. Phys. J. A31:373, 2007





Summary

- significant Collins amplitudes for charged pions

  → access to transversity with knowledge of Collins FF

- significant Sivers amplitudes for π^+ and K^+ (role of sea quarks)

  → non-zero orbital angular momentum

- single-spin asymmetries for hadron-pair production:

  → first evidence for

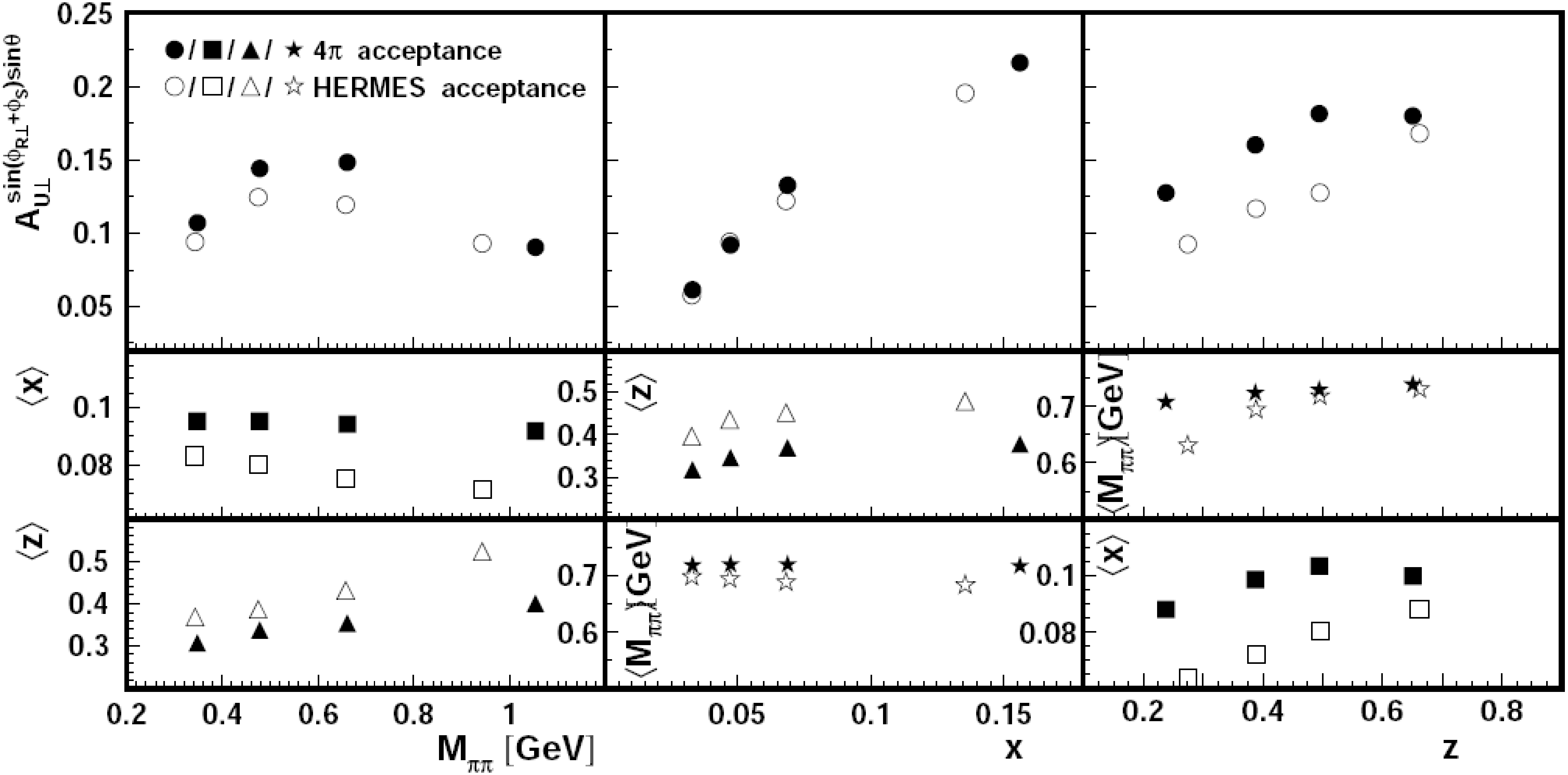
  naive-T-odd and chiral-odd dihadron fragmentation function

- spin-independent non-collinear cross section:

  → evidence for non-zero Boer-Mulders distribution function

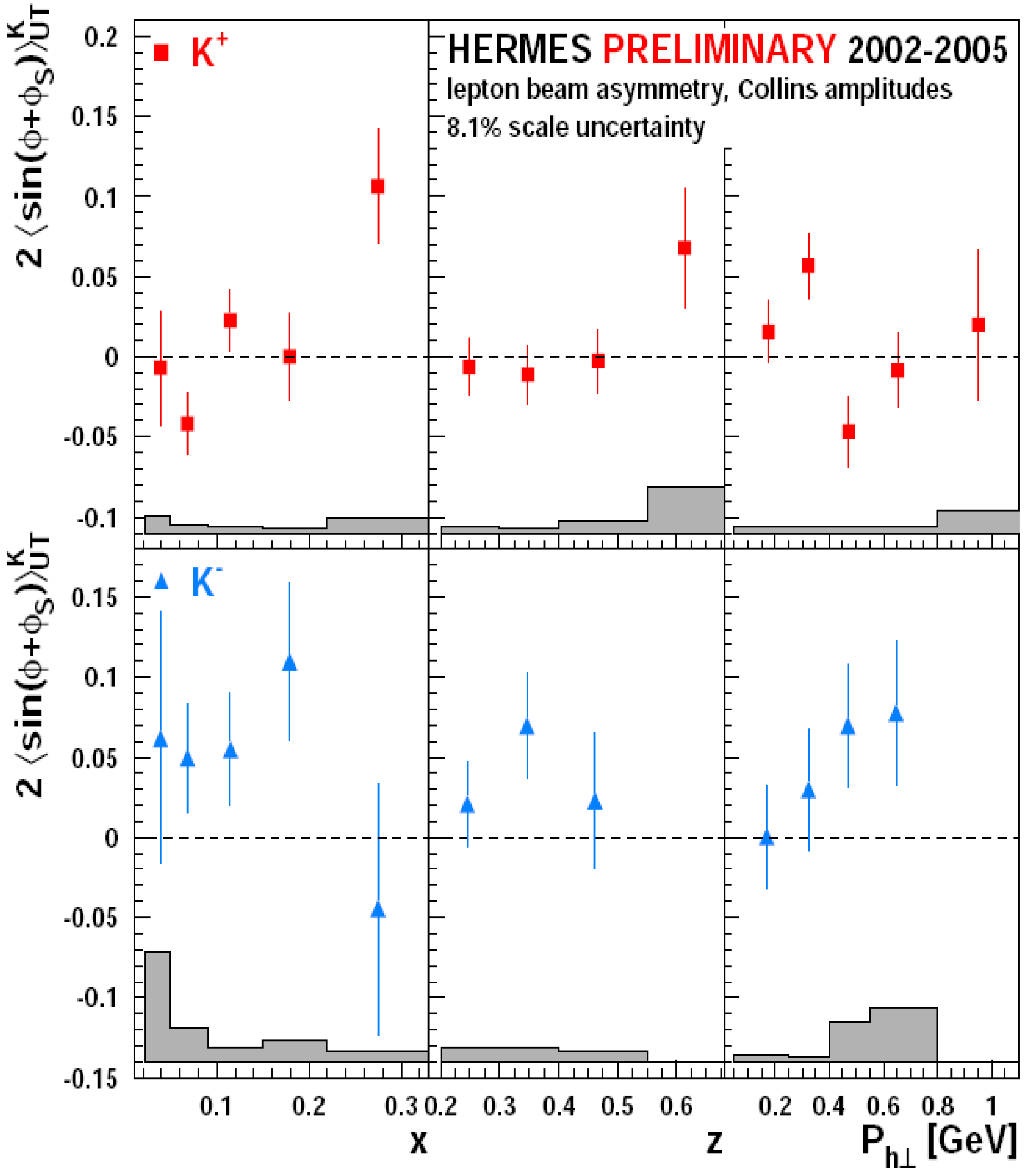
  correlation quark orbital angular momentum and its spin

Backup

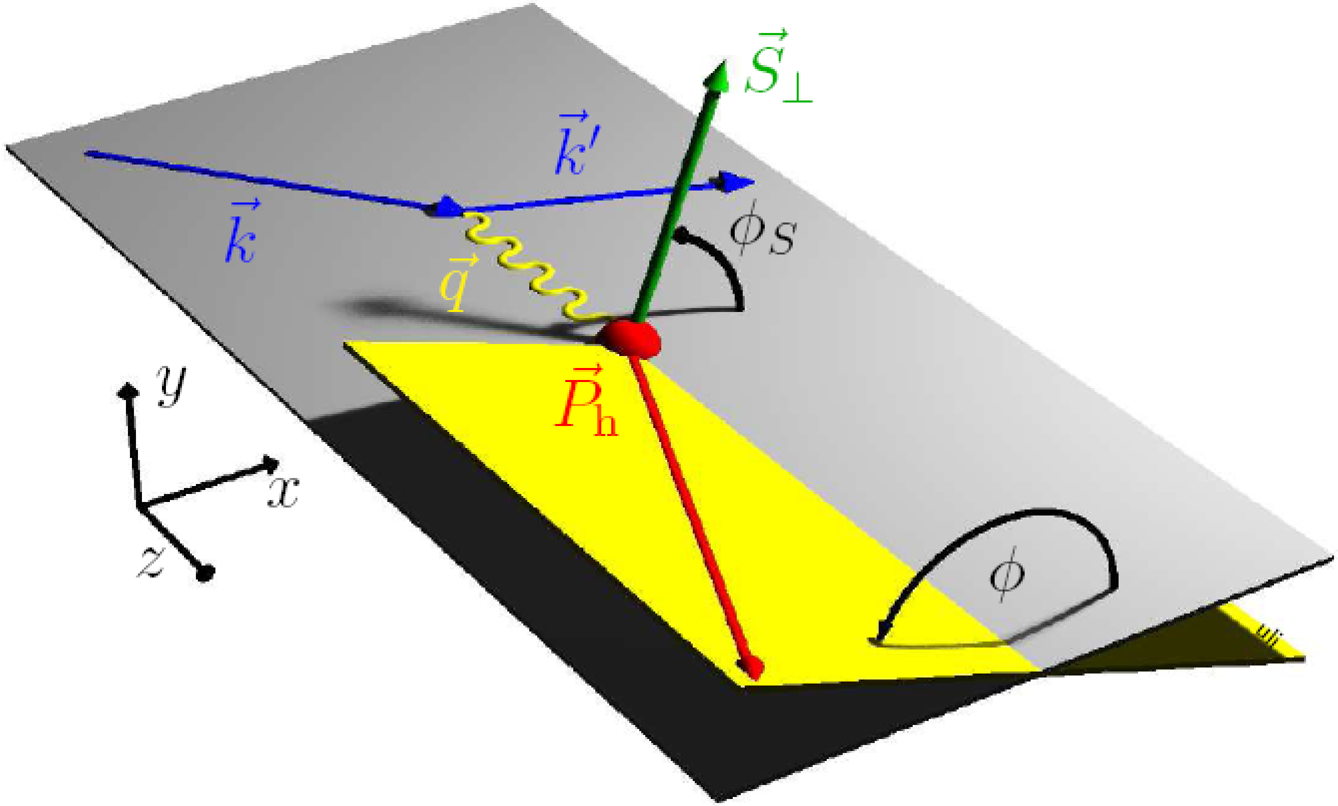


●/■/▲/★ 4π acceptance
○/□/△/☆ HERMES acceptance
$A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
⟨x⟩
⟨z⟩
⟨$M_{\pi\pi}$⟩ GeV
$M_{\pi\pi}$ [GeV]
x
z

Collins amplitudes for kaons



- results from 2002-2005 data
- no Kaon amplitudes significantly ≠ from zero.
- K^+ consistent with π^+ (u-quark dominance)
- K^- opposite to π^-
  K^- is pure sea object


$\vec{S}_\perp$
$\vec{k}'$
$\vec{k}$
ϕ_S
$\vec{q}$
$\vec{P}_\mathrm{h}$
y
x
z
ϕ