2nd Workshop on the QCD Structure of the Nucleon, Villa Mondragone, 12. – 16. June 2006

Azimuthal asymmetries in SIDIS & electron-positron annihilation

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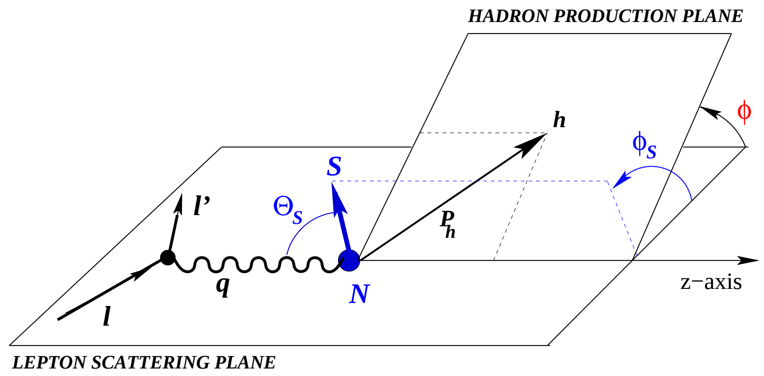
based mainly on :

A. V. Efremov, K. Goeke and PS, Phys. Rev. D 73, 094025 (2006), hep-ph/0603054

Overview:

- What is Collins effect?
- Collins effect in SIDIS & e^+e^--annihilation
- emerging picture of Collins function & transversity
- application: use of emerging picture, subleading-twist beam SSA
- summary & conclusions

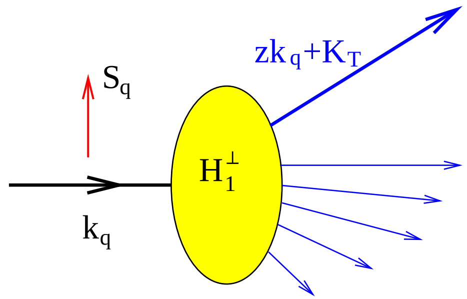
Collins effect in SIDIS



- **transversely polarized target**
- expressions in LO $1/Q$ Boer, Mulders, ... 1990s
- k_T–factorization Ji, Ma, Yuan & Collins, Metz 2004

$$\frac{\mathrm{d}^3\sigma_{UT}}{\mathrm{d}x\mathrm{d}z\mathrm{d}\phi} = \frac{\mathrm{d}^3\sigma_{\text{unp}}}{\mathrm{d}x\mathrm{d}z\mathrm{d}\phi}\left\{1 + S_T\left[\underbrace{\sin(\phi-\phi_S)\,A_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers effect}} + \underbrace{\sin(\phi+\phi_S)\,A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}}\right]\right\}$$

- $H_1^\perp(z, \mathrm{K}_T^2)$ **"twist-2", chirally odd & "naively T-odd"**
  Collins 1992, Efremov, Mankiewicz, Tornquist 1992, ...



- $h_1^a(x)$ **twist-2, chirally odd** Ralston & Soper 1979, ...

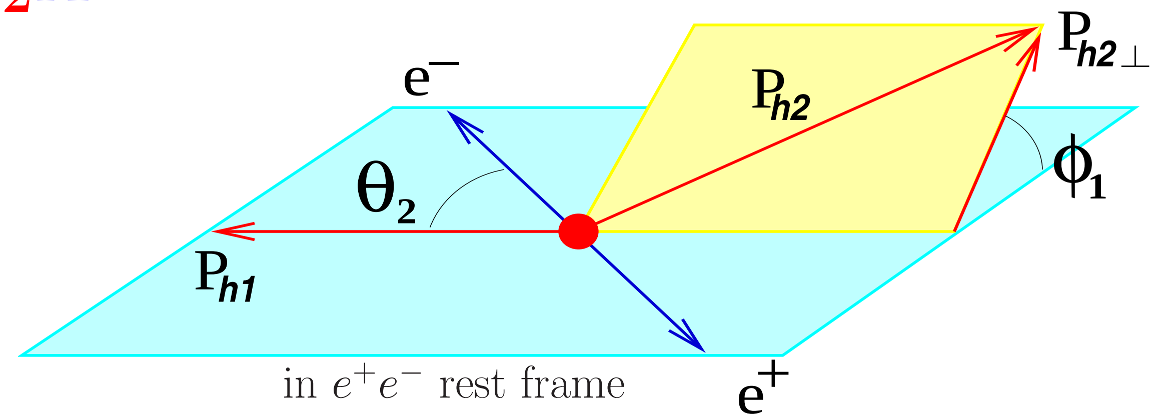
$$\Rightarrow \textbf{Collins SSA :} \quad A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{h_1^a(x, \mathrm{p}_T^2)\,H_1^{\perp a}(z, \mathrm{K}_T^2)}{f_1^a(x)\,D_1^a(z)}$$

- **long. polarized target**: $A_{UL}^{\sin 2\phi} \propto H_1^\perp$ at HERMES ~ 0; promising preliminary CLAS data

Collins effect in $e^+e^- \to h_1 h_2 X$

$\mathbf{h_1} \in \text{jet}_1$, $\mathbf{h_2} \in \text{jet}_2$

Boer, Jakob, Mulders, 1997



$$\frac{d^2\sigma^{e^+e^-\to h_1 h_2 X}}{d\phi_1 d\cos\theta_2} = \frac{d^2\sigma_{\text{unp}}}{d\phi_1 d\cos\theta_2} \underbrace{\left[1 + \cos(2\phi_1)\,\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,\frac{\sum_a e_a^2 H_1^{\perp a}\; H_1^{\perp \bar{a}}}{\sum_a e_a^2 D_1^a\; D_1^{\bar{a}}}\right]}_{\equiv A_1}$$

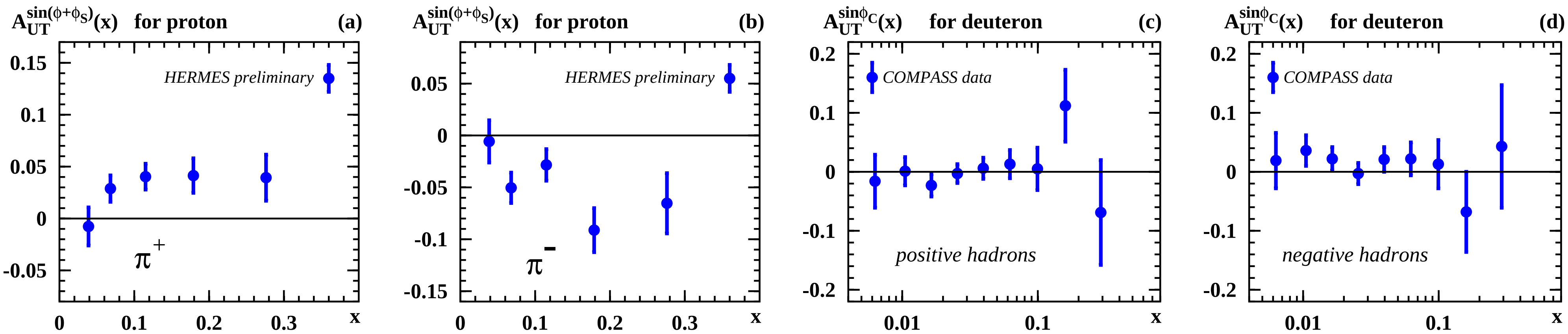
Actually same angular dependence from radiative effects, acceptance effects

Trick used at BELLE: $\dfrac{A_1^U}{A_1^L} \equiv 1 + \cos(2\phi_1)\; P_1$

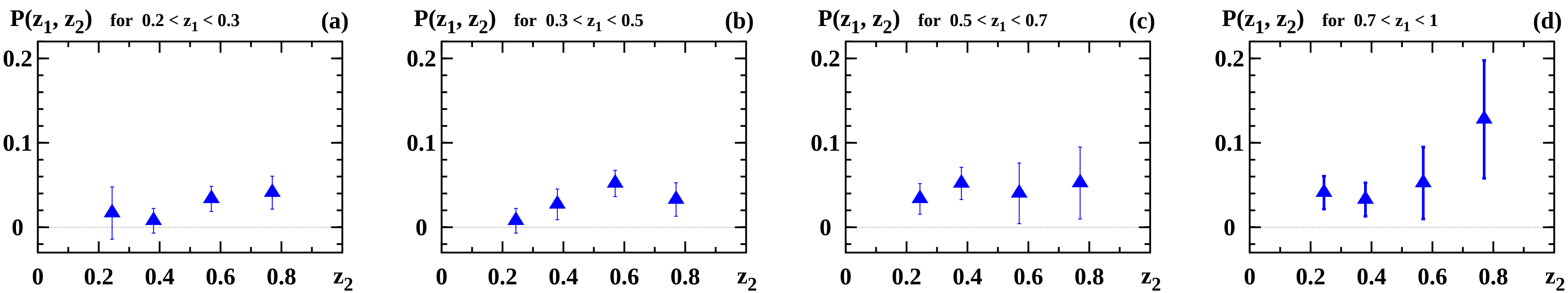
Universality expect the same Collins function in e^+e^- and SIDIS Metz 2002, Collins & Metz 2005
though . . . Amsterdam group

Available data

- SIDIS: HERMES PRL 94, 012002 (2005), hep-ex/0408013 & AIP Conf.Proc.792, 933 (2005), hep-ex/0507013
- SIDIS: COMPASS PRL 94, 202002 (2005), hep-ex/0503002



- e^+e^- BELLE hep-ex/0507063

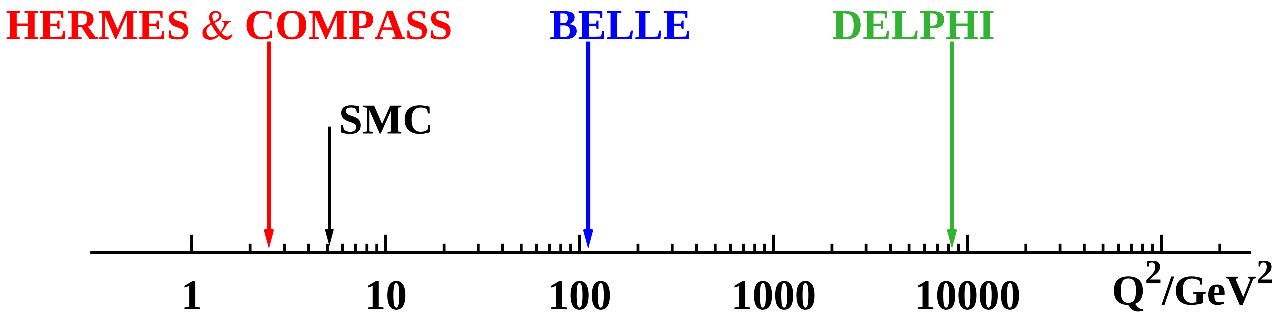


and:

- SIDIS: SMC preliminary Bravar, Nucl. Phys. Proc. Suppl. **79** (1999) 520
- e^+e^- DELPHI preliminary Efremov, Smirnova and Tkachev, Nucl. Phys. Proc. Suppl. **79** (1999) 554

Question : Are all these data due to the same Collins effect ?

Problems :



- different scales
- Sudakov suppression
- soft factors
- unknown functions $H_1^{\perp}(z, K_T)$, $h_1^a(x, p_T)$
- unknown k_T-dependence

Way out :

- neglect soft factors, disregard Sudakov suppression
- different scales $\Rightarrow$ **compare** $\dfrac{\boldsymbol{H_1^{\perp}}}{\boldsymbol{D_1}}$ presumably less scale-dependent
- $f_1^a(x)$ from GRV 98, $D_1^a(z)$ from Kretzer 2000; Kretzer, Leader, Christova 2001
- $h_1^a(x)$ from chiral quark-soliton model PRD 64 (2001) 034013 — about (10–30)% accuracy
- $\boldsymbol{F(x, k_T) = F(x) \cdot G(k_T)}$ & Gaussian k_T-dependence. If $\langle P_{h\perp} \rangle \ll \langle Q \rangle$ ✓ & at HERMES ✓
  D'Alesio & Murgia 2004

$\Rightarrow$ **Basically one unknown** $H_1^{\perp}$ can be extracted — modulo uncertainties due to our assumptions

$$A_{UT}^{\sin(\phi+\phi_S)} = 2\,\frac{\sum_a e_a^2\, x h_1^a(x)\, B_{\rm Gauss} H_1^{\perp(1/2)a}(z)}{\sum_a e_a^2\, x f_1^a(x)\, D_1^a(z)}$$

$$H_1^{\perp(1/2)a}(z) = \int \mathrm{d}^2\mathbf{K}_T\, \frac{|\mathbf{K}_T|}{2zm_\pi} H_1^{\perp a}(z,\mathbf{K}_T) \le \tfrac{1}{2}\, D_1^a(z)$$

$$B_{\rm Gauss}(z) = \frac{1}{\sqrt{1+z^2\,\langle \mathbf{p}_{h_1}^2\rangle/\langle \mathbf{K}_{H_1}^2\rangle}} \le 1$$

for pions, two functions : $H_1^{\perp\rm fav} = H_1^{\perp u/\pi^+} = H_1^{\perp d/\pi^-} = \dots$ $\Rightarrow$ $\langle B_{\rm Gauss} H_1^{\perp(1/2)\rm fav}\rangle = (3.5\pm0.8)\cdot10^{-2}$

$H_1^{\perp\rm unf} = H_1^{\perp u/\pi^-} = H_1^{\perp d/\pi^+} = \dots$ $\qquad\langle B_{\rm Gauss} H_1^{\perp(1/2)\rm unf}\rangle = -(3.8\pm0.7)\cdot10^{-2}$

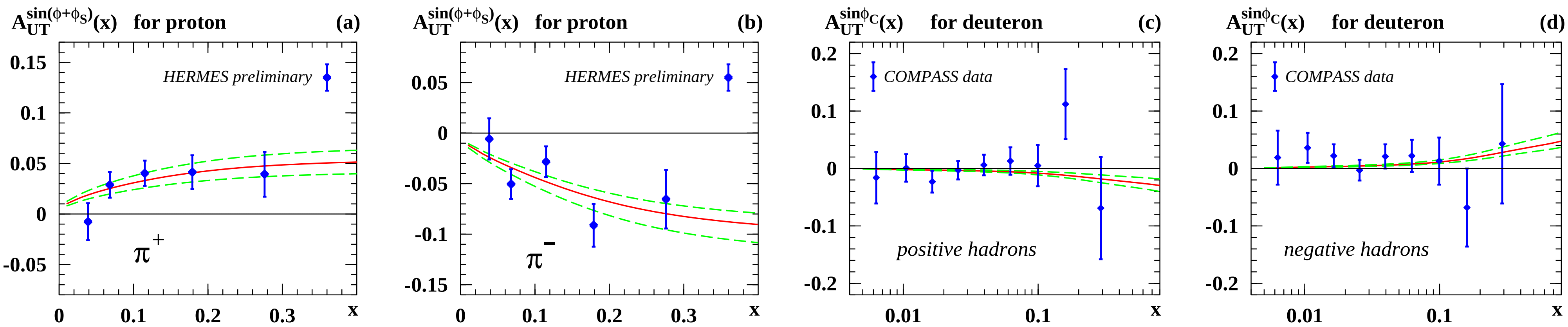
natural (?) to expect $|H_1^{\perp\rm fav}| \gg |H_1^{\perp\rm unf}|$

$$H_1^{\perp\rm unf} \approx -H_1^{\perp\rm fav}$$

$\to$ string fragmentation

Artru, Czyżewski and Yabuki, Z.Phys.C 73 (1997) 527

$\Rightarrow$

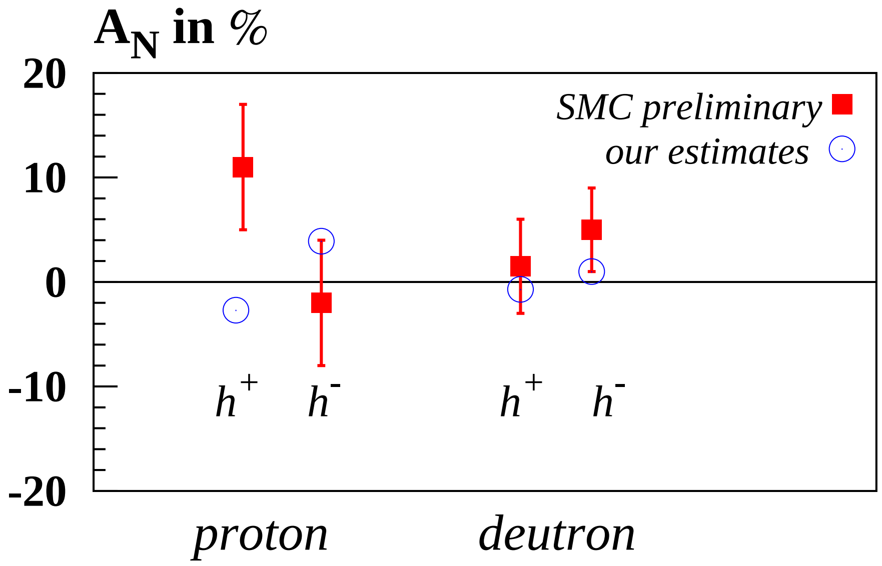


- good description of HERMES
- compatible with COMPASS

- **grain of salt: preliminary SMC**

charged hadrons
$\langle Q^2\rangle \sim 5\,\mathrm{GeV}^2, \quad \langle x\rangle \sim 0.08$
$\langle z\rangle \sim 0.45$ and $\langle P_{h\perp}\rangle \sim (0.5-0.8)\,\mathrm{GeV}$

Reason to worry? Data are preliminary ...

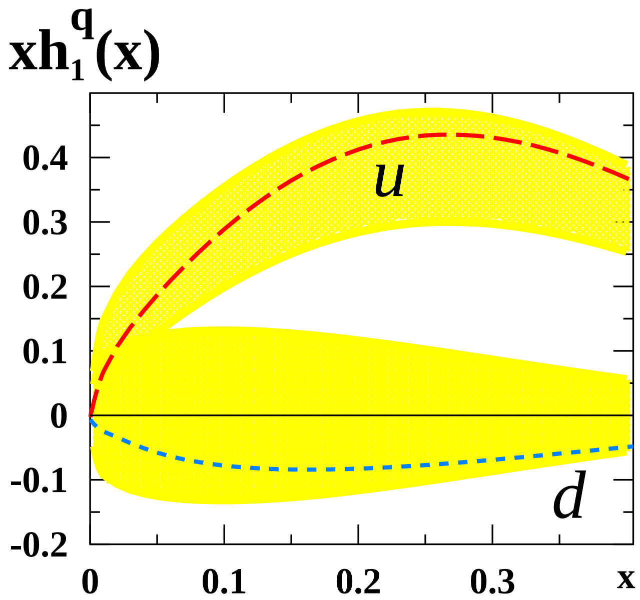


- **Emerging picture of transversity from SIDIS**

How model dependent is our result?

Compare to Vogelsang & Yuan, PRD 72, 054028 (2005)
same $\langle B_{\rm Gauss} H_1^{\perp a}\rangle$ (within different ansatz for p_T-dependence)
but assume saturation of Soffer bound $|h_1^a(x)| \le \frac{1}{2}(f_1^a+g_1^a)(x)$

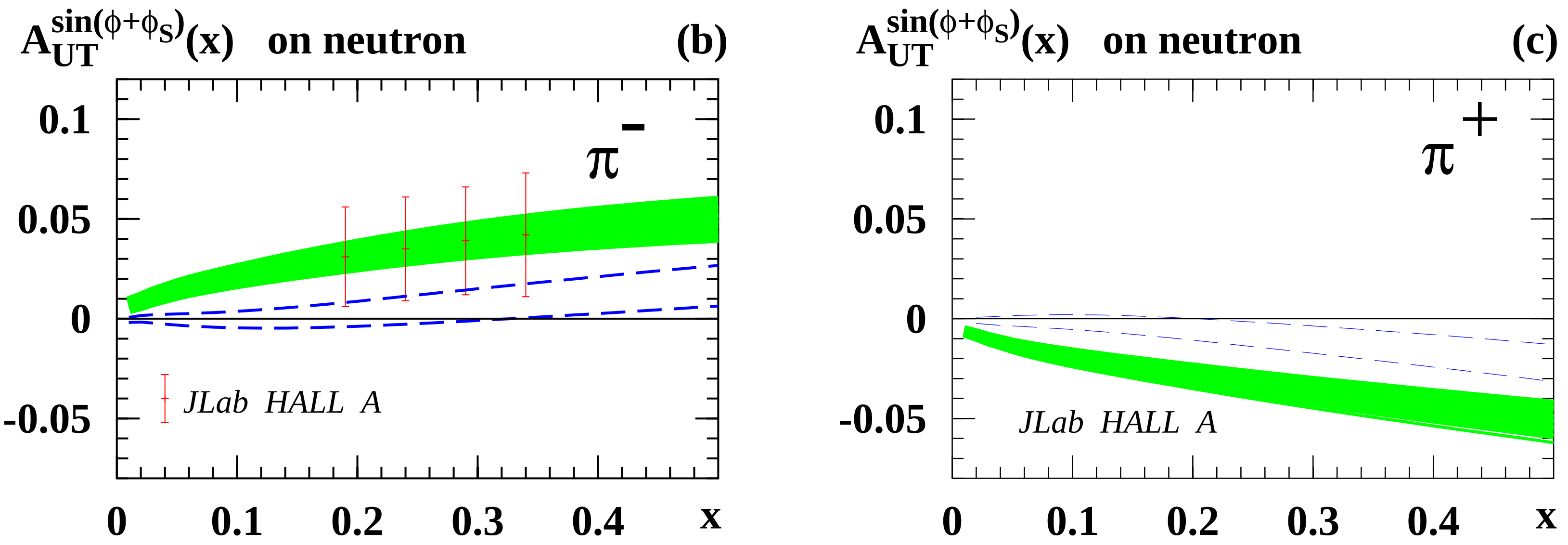
Look closer: demand extracted $\langle B_{\rm Gauss} H_1^{\perp a}\rangle$ to vary within 1-σ
Question: How much is $h_1^a(x)$ allowed to vary?
$\Rightarrow$ **Picture:** $h_1^u(x)$ within 30% of Soffer bound, other $h_1^a(x)$ unconstrained
supported by lattice QCDSF



$h_1^a(x)$ from chiral quark soliton model

- **Emerging picture of transversity from SIDIS will improve**
  - data on π^0 & kaons
  - more data from HERMES proton & deuteron target
  - more data from COMPASS deuteron & proton target
  - data from CLAS with transv. pol. target
  - data from HALL-A with transv. pol. ^{3}He $\approx$ neutron target at $\langle Q^2 \rangle \sim 2$ GeV^2 $\longrightarrow$ $h_1^d(x)$

  green: $h_1^d(x) < 0$ from chiral quark-soliton model
  dashed: $h_1^d(x)$ of opposite sign
  error bars: projections for 24 days of beam time   Chen, Jiang, Peng and Zhu et al. nucl-ex/0511031



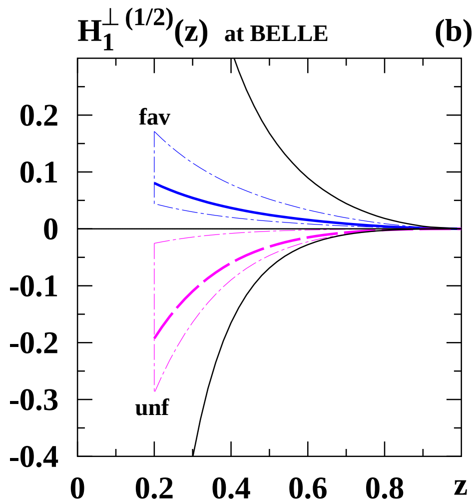
Collins effect in e^+e^-

- **BELLE** $\quad e^+e^- \to \gamma^* \to h_1 h_2 X \quad$ with $h_{1,2} = \pi^\pm$

$$\frac{A_1^U(\phi)}{A_1^L(\phi)} \equiv 1 + \cos(2\phi_1)\,\mathbf{P_1} \quad \text{with} \quad \mathbf{P_1}(z_1,z_2) = F(H_1^{\rm fav}, H_1^{\rm unf}, \text{Gauss})$$

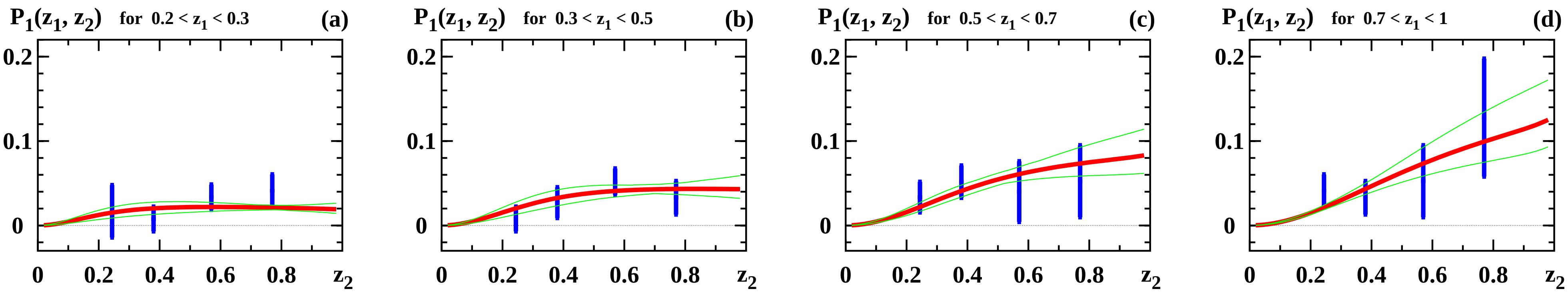
include $s, \bar{s} \to H_1^{\rm unf}$ (fine for D_1)

symmetric $z_1 \leftrightarrow z_2$ or fav $\leftrightarrow$ unf



best Ansatz $H_1^{\perp(1/2)a} = C_a\, z\, D_1^a(z)$ other Ansätze not excluded

best fit results: $\underbrace{C_{\rm fav} = \mathbf{0.15}, \quad C_{\rm unf} = \mathbf{-0.45}}_{\text{sign preferred by HERMES}}$ or vice versa: fav $\leftrightarrow$ unf



good description !

• DELPHI preliminary $e^+e^- \to Z_0 \to h_1 h_2 X$ with $h_{1,2}$ = charged hadrons

$$\frac{\mathrm{d}\sigma(e^+e^- \to h_1 h_2 X)}{\mathrm{d}\phi_1} = P_0 \left(1 + \cos(2\phi_1)\, P_2\right) \text{ with } P_{2,\mathrm{DELPHI}} = -(0.26 \pm 0.18)\% \pm \text{unestimated systematics}$$

$$P_2 = \tilde{F}(H_1^{\mathrm{fav}}, H_1^{\mathrm{unf}})$$

- different scales! Assume $\left.\frac{H_1^\perp}{D_1}\right|_{\textbf{one scale}} \approx \left.\frac{H_1^\perp}{D_1}\right|_{\textbf{another scale}}$
- what about $H_1^{\perp c},\ H_1^{\perp b}$? Since $m_c,\ m_b \ll M_Z$: **Maybe unfavoured like D_1. Maybe zero . . .**
- charged hadrons $= \pi^\pm,\ K^\pm,\ \ldots$ with $\lim_{m_\pi \to 0} \frac{H_1^{\perp(1/2)a/\pi}}{D_1^{a/\pi}} = \lim_{m_K \to 0} \frac{H_1^{\perp(1/2)a/K}}{D_1^{a/K}}$

$\Rightarrow$ $P_{2,\,\mathrm{estimate}} \approx -(0.06\ \ldots\ 0.29)\%$

⇒ Preliminary DELPHI seems not incompatible with BELLE!

intermediate STATUS :

SIDIS: HERMES & COMPASS compatible
e^+e^-: BELLE & DELPHI not incompatible

$\Rightarrow$ **What about HERMES vs. BELLE ?**

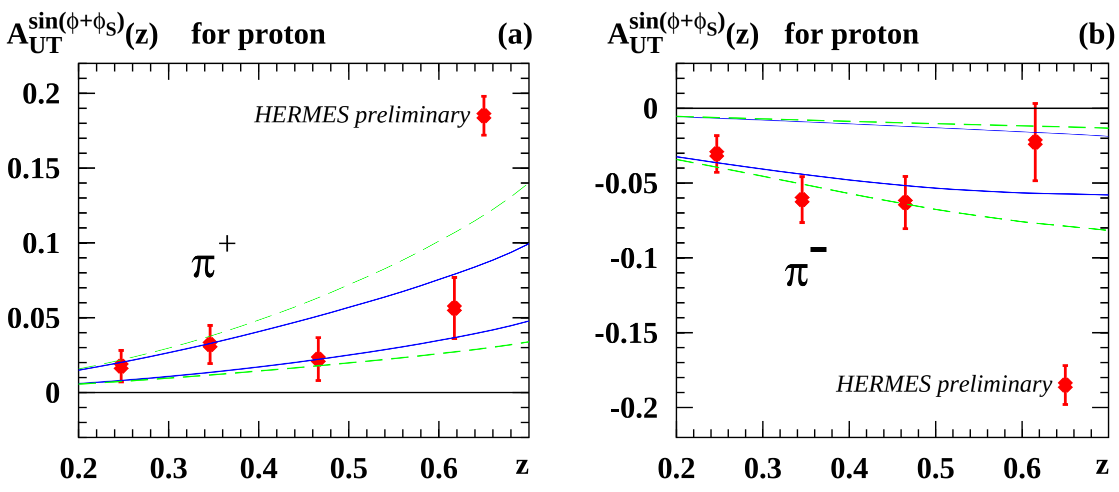
HERMES vs. BELLE

I. $$\frac{\langle 2B_{\rm Gauss}H_1^{\perp(1/2)\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\Bigg|_{\rm HERMES} = (7.2\pm1.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2)\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\Bigg|_{\rm BELLE} = (5.3\ \dots\ 20.4)\%$$

$$\frac{\langle 2B_{\rm Gauss}H_1^{\perp(1/2)\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\Bigg|_{\rm HERMES} = -(14.2\pm2.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2)\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\Bigg|_{\rm BELLE} = -(3.7\ \dots\ 41.4)\%\ .$$

1. $\Uparrow$ $B_{\rm Gauss} < 1$ **2.** $\Uparrow$ errors correlated

II. ***z*-dependence at HERMES from BELLE fit for $H_1^\perp(z)$**



$\Rightarrow$

BELLE & HERMES compatible!

Conclusions

- try of first “global” analysis of data on Collins effect
  as good as possible at present stage, but assumptions & approximations necessary

- e^+e^- **BELLE** data consistent with SIDIS **HERMES** & **COMPASS** data
  preliminary DELPHI consistent with those, preliminary SMC not

- emerging picture: $H_1^{\perp u} \approx -H_1^{\perp d}$ possible explanations: Artru et. al, Vogelsang & Yuan
  $h_1^u > 0$ and within 30 % of Soffer bound in agreement with lattice, other $h_1^a(x)$ unknown
  soon to be improved: HERMES, COMPASS, JLAB & BELLE

- use emerging picture to understand interesting data, e.g. CLAS & HERMES
  $A_{UL}^{\sin 2\phi}$ or twist-3 $A_{UL}^{\sin\phi}$ and $A_{LU}^{\sin\phi}$ $\longrightarrow$ applications

- new & more precise data coming in, improved analyses necessary
  However, **optimism!** Encouraging **progress!** We are **learning**!

Thank you!

$$A_{LU}^{\sin\phi} = \frac{M_N}{Q}\left\{\, e(x)H_1^{\perp}(z) + h_1^{\perp}(x)E(z) + f_1(x)G^{\perp}(z) + g^{\perp}(x)D_1(z) \,\right\}$$

Levelt, Mulders, Tangerman, Afanasev, Carlsson, Yuan, Metz, Schlegel, Bacchetta, Pijman, Goeke 1994–present

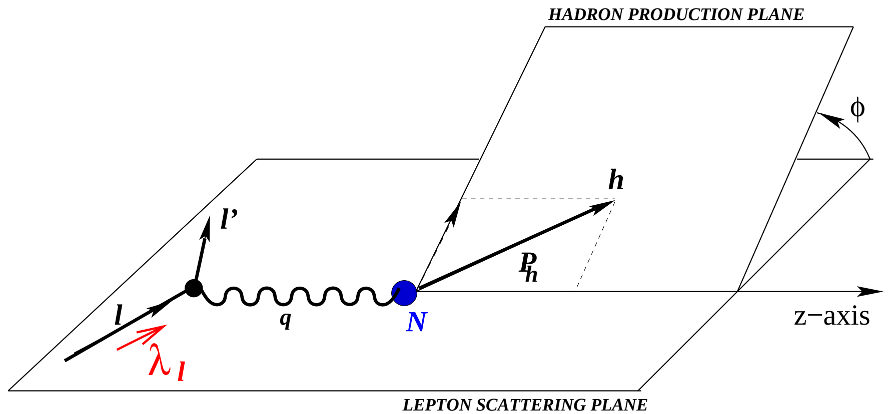
twist-3

4 unknown terms

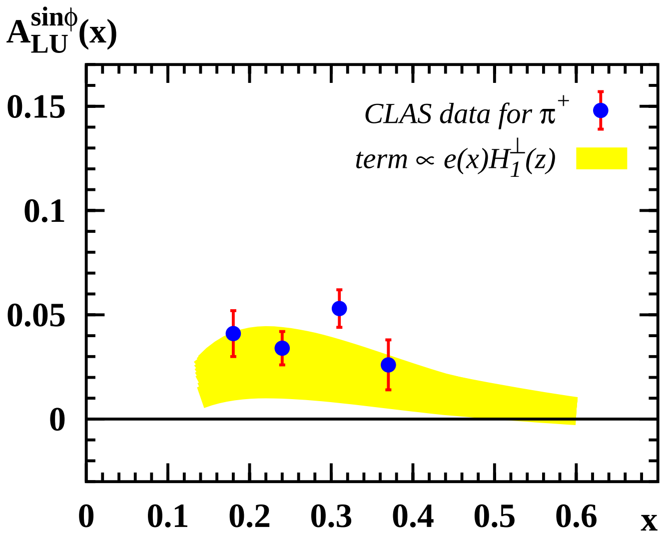
estimate contribution due to $\boxed{A_{LU\,e}^{\sin\phi} \propto e(x)H_1^{\perp}(z)}$

$e(x)$ from chiral quark-soliton model forthcoming

& $H_1^{\perp}$ from our study hep-ph/0603054



$$e(x) = C\,\delta(x) + \tilde{e}(x) \quad \text{with} \quad C \propto \sigma_{\pi N} \quad \Rightarrow \quad \underbrace{\int_0^1 dx\; e(x) \sim 10}_{\text{in theory}} \quad \text{vs.} \quad \underbrace{\int_{x_{\min}}^1 dx\; e(x) \sim 0}_{\text{experiment}} \quad !!!$$



CLAS PRD 69 (2004) 112004

- large portion of $A_{LU}^{\sin\phi}$ could be due to $e(x)H_1^{\perp}(z)$

HERMES Avetisyan, Rostomyan, Ivanilov, hep-ex/0408002

- preliminary data for π^+ consistent with CLAS
- π^-, π^0 → flavour-dependence ? Work to be done

To access $e^a(x)$ possibly better interference functions → Radici et al.