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Collins Effect in SIDIS and in e^+e^- Annihilation and Transversity

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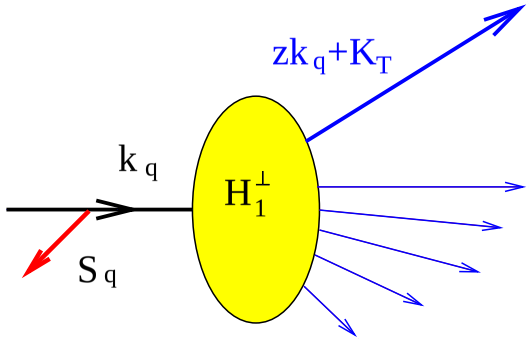
Based on PRD 73 (2006) 094025 and work in progress

Overview:

- What is Collins effect?
- Collins effect in SIDIS.
- Emerging picture of Collins function & transversity.
- Transversity and Drell-Yan.
- Collins effect in e^+e^--annihilation
- Summary & conclusions.

Collins effect in SIDIS

Asymmetry in transversally polarized parton fragmentation.



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

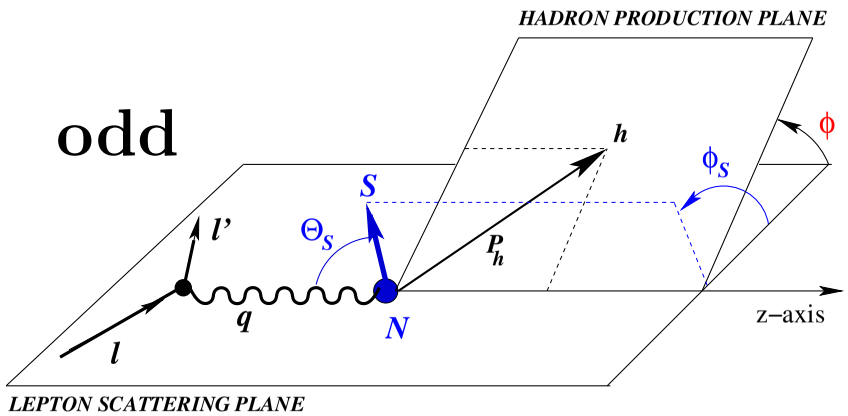
$$\frac{d^3\sigma_{UT}}{dx\,dz\,d\phi} = \frac{d^3\sigma_{\rm unp}}{dx\,dz\,d\phi}\{1 + S_T\,[\,\underbrace{\sin(\phi-\phi_S)\,A_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers effect}} + \underbrace{\sin(\phi+\phi_S)\,A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}}\,]\}$$

- $H_1^\perp(z, K_T^2)$ **"twist-2", chirally odd & "naively T-odd"**

(Collins 1992, Efremov, Mankiewicz, Tornquist 1992, ...)

- $h_1^a(x)$ **twist-2, chirally odd**

(Ralston&Soper 1979, ...)



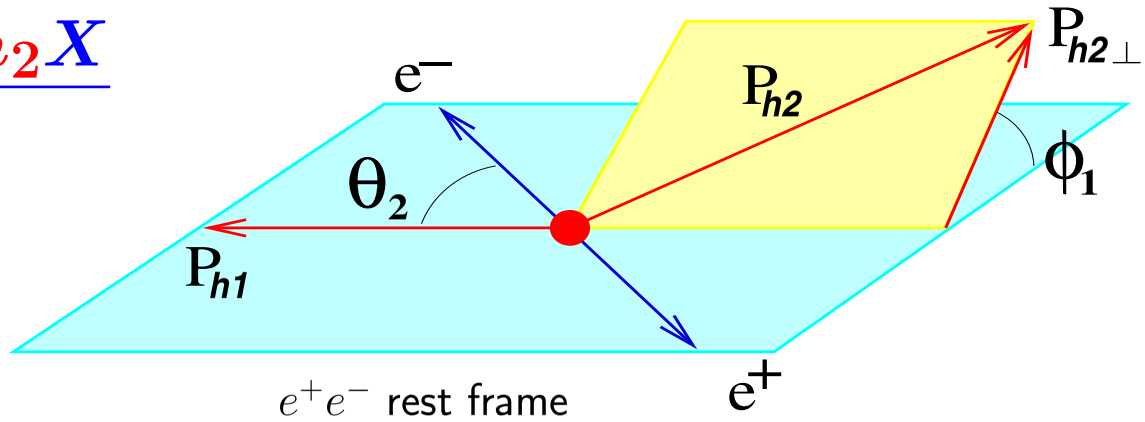
$$\Rightarrow \text{Collins SSA}: \quad A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{h_1^a(x, p_T^2)\,H_1^{\perp a}(z, K_T^2)}{f_1^a(x)\,D_1^a(z)}$$

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

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

(Boer, Jakob, Mulders, 1997)

$q\bar{q}$ transversal spins correlation.



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

$$C_{\rm Gauss}(z_1, z_2) = \frac{16}{\pi}\frac{z_1 z_2}{z_1^2+z_2^2}$$

Actually same angular dependence from radiative and acceptance effects

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

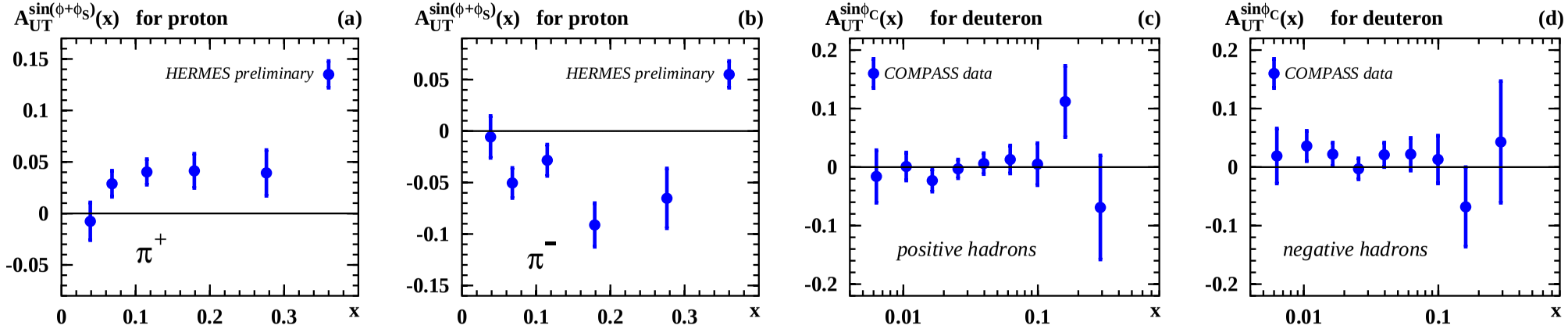
Universality: expect the same Collins function in e^+e^- and SIDIS

(Metz 2002, Collins & Metz 2005)

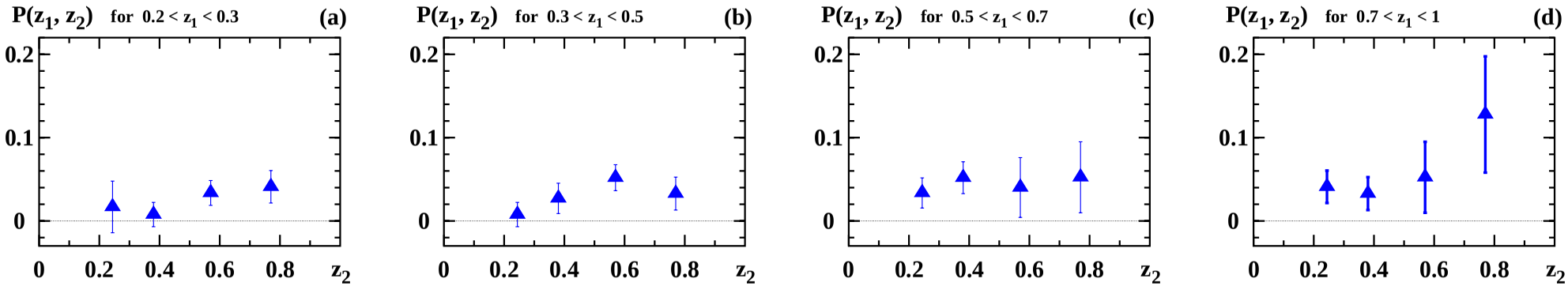
though . . . not yet everybody fully convinced (Amsterdam group).

Available data

- SIDIS: HERMES (PRL94,012002(2005), hep-ex/0408013 & AIP 792,933(2005), hep-ex/0507013)
- SIDIS: COMPASS (PRL94,202002(2005), hep-ex/0503002)



- e^+e^- BELLE (hep-ex/0507063). (Recently A_1^U/A_1^C was reported (R.Seidl,QCD-N06)).

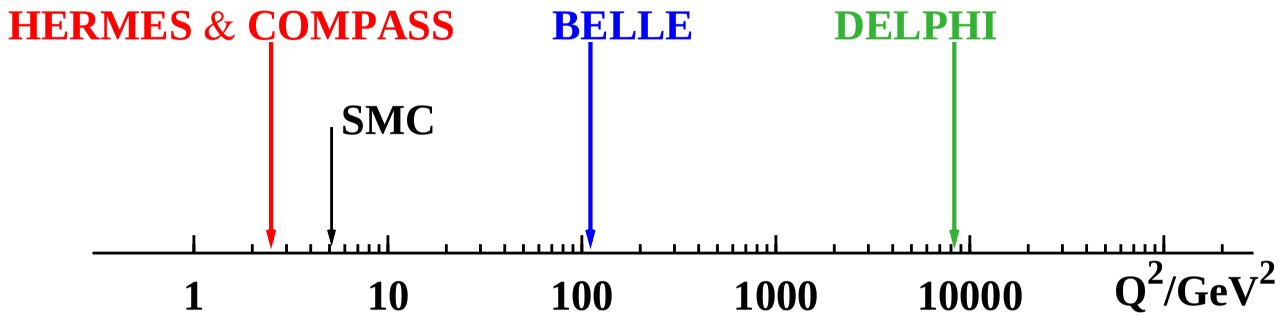


and:

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

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

Problems :



- Different scales.
  Unknown $H_1^\perp$ evolution.
- Soft factors.
- Sudakov suppression.
- Unknown k_T-dependence.
- Unknown functions $H_1^\perp(z, K_T)$, $h_1^a(x, p_T)$.

Way out:

- Different scales $\Rightarrow$ **compare $H_1^\perp/D_1$**, presumably less scale-dependent.
- Neglect soft factors, disregard Sudakov suppression.
- $\boldsymbol{F(x, k_T) = F(x) \cdot G(k_T)}$&Gaussian, if $\langle P_{h\perp}\rangle \ll \langle Q\rangle$ ✓& at HERMES ✓
  (D'Alesio&Murgia2004)
- $h_1^a(x)$ from chiral quark-soliton model (PRD64(2001)034013) — about 20% accuracy.
- $f_1^a(x)$ from GRV98, $D_1^a(z)$ from Kretzer2000; Kretzer,Leader,Christova2001.

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

Emerging picture of Collins function & transversity

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

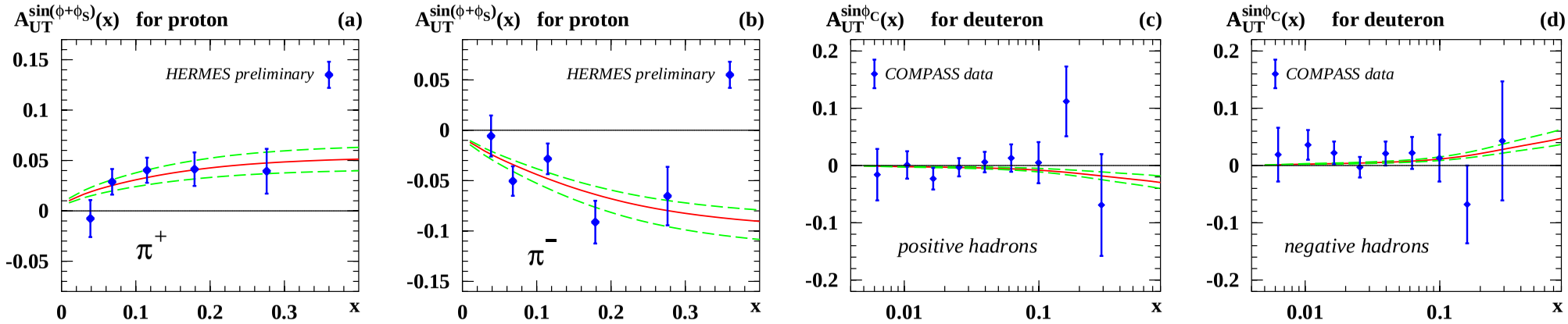
$$H_1^{\perp(1/2)a}(z) = \int d^2\mathbf{K}_T \frac{|\mathbf{K}_T|}{2zm_\pi} H_1^{\perp a}(z,\mathbf{K}_T) \le \tfrac{1}{2} D_1^a(z)$$

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

For pions, two functions :

$$\underbrace{\begin{aligned} H_1^{\perp\rm fav} &= H_1^{\perp u/\pi^+} = H_1^{\perp d/\pi^-} = \dots \\ H_1^{\perp\rm unf} &= H_1^{\perp u/\pi^-} = H_1^{\perp d/\pi^+} = \dots \end{aligned}}_{\text{natural (?) to expect } |H_1^{\perp\rm fav}| \gg |H_1^{\perp\rm unf}|} \quad \Rightarrow \quad \text{HERMES} \quad \underbrace{\begin{aligned} \langle B_{\rm Gauss} H_1^{\perp(1/2)\rm fav}\rangle &= (3.5\pm0.8)\cdot10^{-2} \\ \langle B_{\rm Gauss} H_1^{\perp(1/2)\rm unf}\rangle &= -(3.8\pm0.7)\cdot10^{-2} \end{aligned}}_{H_1^{\perp\rm unf} \approx -H_1^{\perp\rm fav}}$$

$\longrightarrow$ string fragmentation (Artru,Czyżewski,Yabuki,ZPhysC73(1997)527)



- Good description of HERMES
- compatible with COMPASS

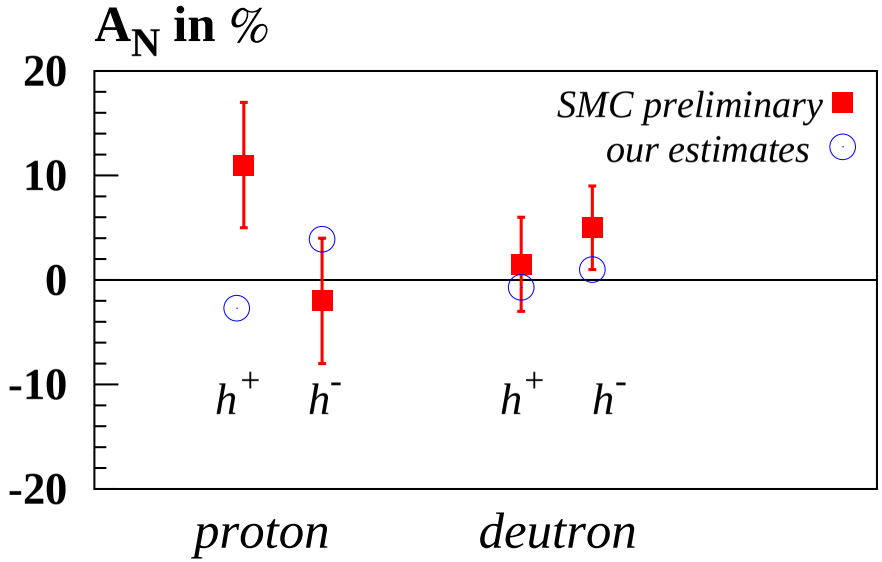
- **Grain of salt: preliminary SMC**

  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, (PRD72,054028(2005))

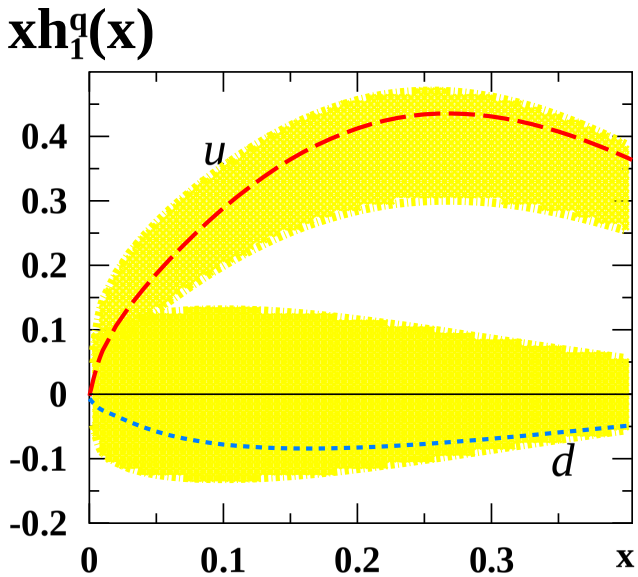
same $\langle B_{\mathrm{Gauss}} H_1^{\perp a} \rangle$ (different p_T-dependence)

but assume saturation of Soffer bound.

$|h_1^a(x)| \leq \frac{1}{2}(f_1^a + g_1^a)(x)$

Look closer: demand extracted $\langle B_{\mathrm{Gauss}} H_1^{\perp} \rangle$ to vary within 1-σ.

Question: How much is $h_1^a(x)$ allowed to vary?



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

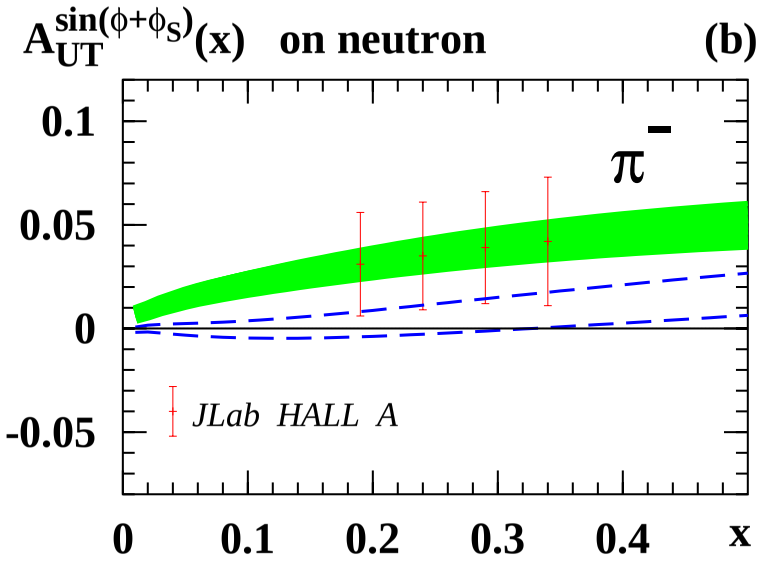
$\Rightarrow$ **Picture:** $\underbrace{h_1^u(x) \text{ within } 30\% \text{ of Soffer bound}}_{\text{supported by lattice QCDSF}}$, other $h_1^a(x)$ unconstrained.

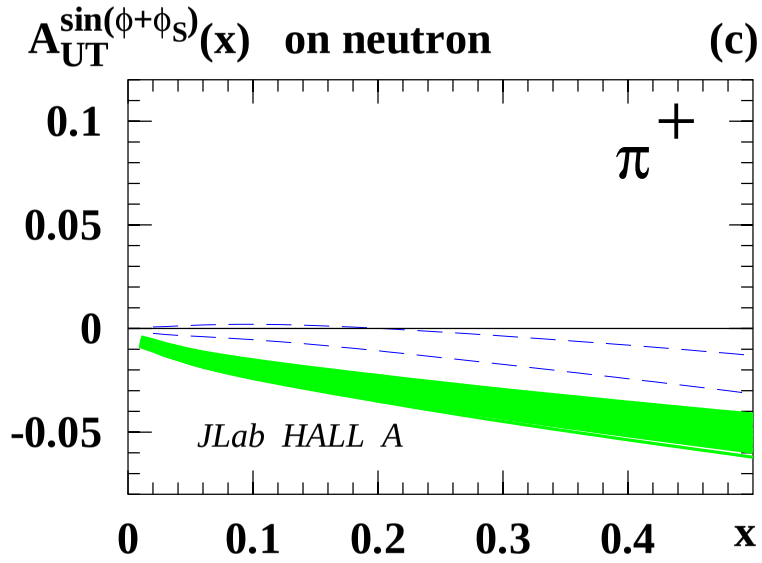
- **Emerging picture of transversity from SIDIS will improve**
  - Data on π^0 & kaons.
  - More data from HERMES proton & deuteron target.
  - More data from COMPASS deuteron & proton target.
  - Data from CLAS with transv. pol. target.
  - Data from HALL-A, transv. ^{3}He $\approx$ neutron target,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

    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, et al. nucl-ex/0511031).





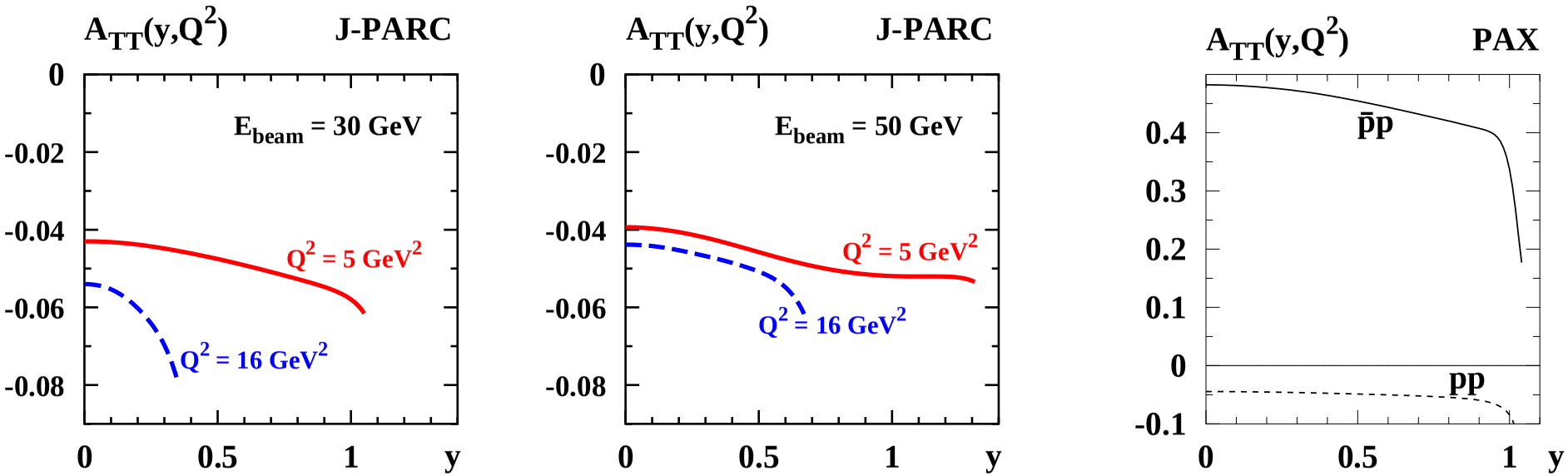
Transversity and Drell-Yan

The best and the cleanest way to access transversity h_1

$$A_{TT}(y,Q^2) = \frac{\Sigma_a e_a^2 h_1^a(x_1,Q^2) h_1^{\bar{a}}(x_2,Q^2)}{\Sigma_b e_b^2 f_1^b(x_1,Q^2) f_1^{\bar{b}}(x_2,Q^2)}\,, \quad x_{1/2} = \sqrt{\frac{Q^2}{s}}\, e^{\pm y}\,.$$

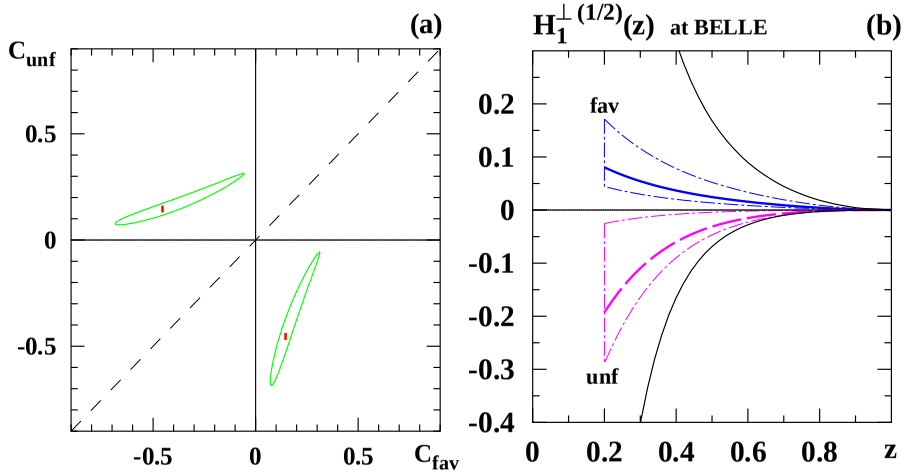
Are planned to be measured at PAX & J-PARC. Our predictions (χQSM):

(A.E.,Goeke, Schweitzer EPJC35:207(04) and work in progress)



- Rather noticeable effect even for $p\uparrow\ \bar{p}\uparrow$!
- Mostly sensitive to $h_1^u(x)$.
- Allow discriminate models (e.g. popular guess $h_1^a(x) \approx g_1^a(x)$ would give $A_{TT} \approx 30\%$)

Collins effect in e^+e^-



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

$$\frac{A_1^U(\phi)}{A_1^L(\phi)} \equiv 1 + \cos(2\phi_1)\ \mathbf{P_1}$$

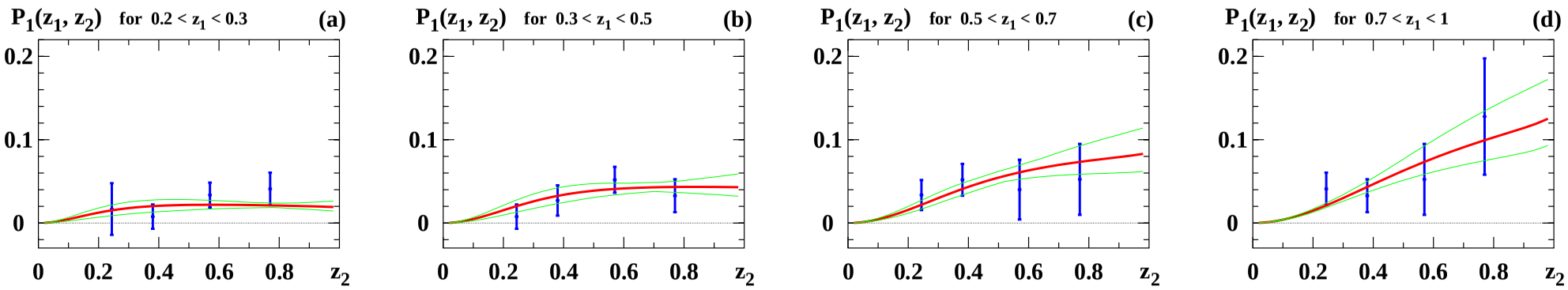
with $\mathbf{P_1}(z_1, z_2) = F(H_1^{\rm fav}/H_1^{\rm unf}, \text{Gauss})$

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

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

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

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

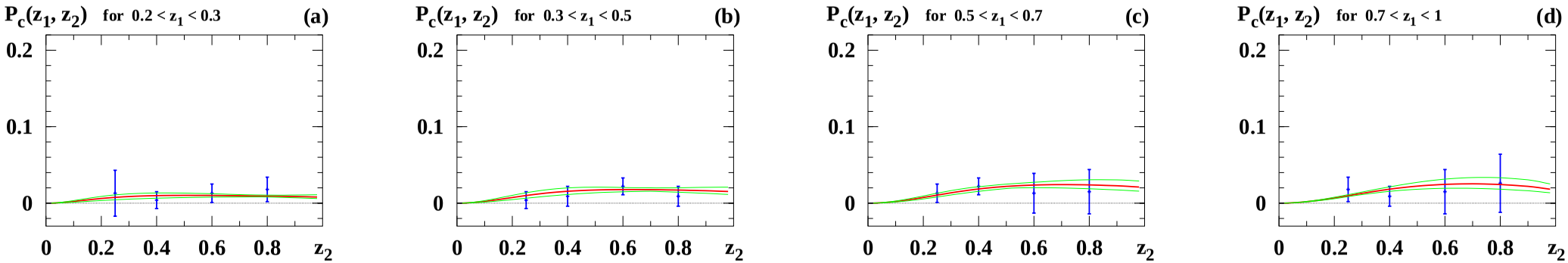


Good description !

Important most recent news from BELLE (hep-ex/0607014)

New double ratio was measured, could decrease $C_{\rm fav}$, $C_{\rm unf}$ correlation

$$\frac{A_1^U(\phi)}{A_1^C(\phi)} \equiv 1 + \cos(2\phi_1)\ \mathbf{P_c}(H_1^{\rm fav}/H_1^{\rm unf}, \text{Gauss})$$



Excellent confirmation of our picture of Collins effect!

Faith in our first understanding of Collins effect strengthened.
New (preliminary) data, will provide valuable constraints and improve the fits after officially released.

• **DELPHI preliminary** (AE, Smirnova, Tkatchev, Nucl.Phys.Proc.Suppl.**79**(1999)554)

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

$$\frac{\mathrm{d}\sigma(e^+e^- \to h_1 h_2 X)}{\mathrm{d}\phi_1} = P_0\,(1+\cos(2\phi_1)\; P_2), \quad P_2 = \tilde{F}(H_1^{\mathrm{fav}} + H_1^{\mathrm{unf}})$$

with $\boldsymbol{P_{2,\mathrm{DELPHI}} = -(0.26 \pm 0.18)\%}\pm$ unknown systematics.

- Different scales! Assume $\dfrac{H_1^\perp}{D_1}\Big|_{\text{one scale}} \approx \dfrac{H_1^\perp}{D_1}\Big|_{\text{another scale}}$
- $H_1^{\perp c}, H_1^{\perp b}$? Since $m_c, m_b \ll M_Z$: **Maybe unfavoured? Maybe zero?**
- Charged hadrons $= \pi^\pm, K^\pm, \ldots$ with $\displaystyle\lim_{m_\pi \to 0} \frac{H_1^{\perp (1/2)a/\pi}}{D_1^{a/\pi}} = \lim_{m_K \to 0} \frac{H_1^{\perp (1/2)a/K}}{D_1^{a/K}}$

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

$\Rightarrow$ **Preliminary DELPHI seems not incompatible with BELLE!**

Intermediate STATUS :

$\left.\begin{array}{l}\text{SIDIS: HERMES \& COMPASS compatible}\\ e^+e^-\text{: BELLE \& DELPHI not incompatible}\end{array}\right\} \Rightarrow$ **What about HERMES vs. BELLE?**

• HERMES vs. BELLE

I. $$\frac{\langle 2B_{\rm Gauss}H_1^{\perp(1/2)\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\Big|_{\rm HERMES} = (7.2\pm 1.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2)\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\Big|_{\rm BELLE} = (5.3\ \ldots\ 20.4)\%$$

$$\frac{\langle 2B_{\rm Gauss}H_1^{\perp(1/2)\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\Big|_{\rm HERMES} = -(14.2\pm 2.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2)\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\Big|_{\rm BELLE} = -(3.7\ \ldots\ 41.4)\%\,.$$

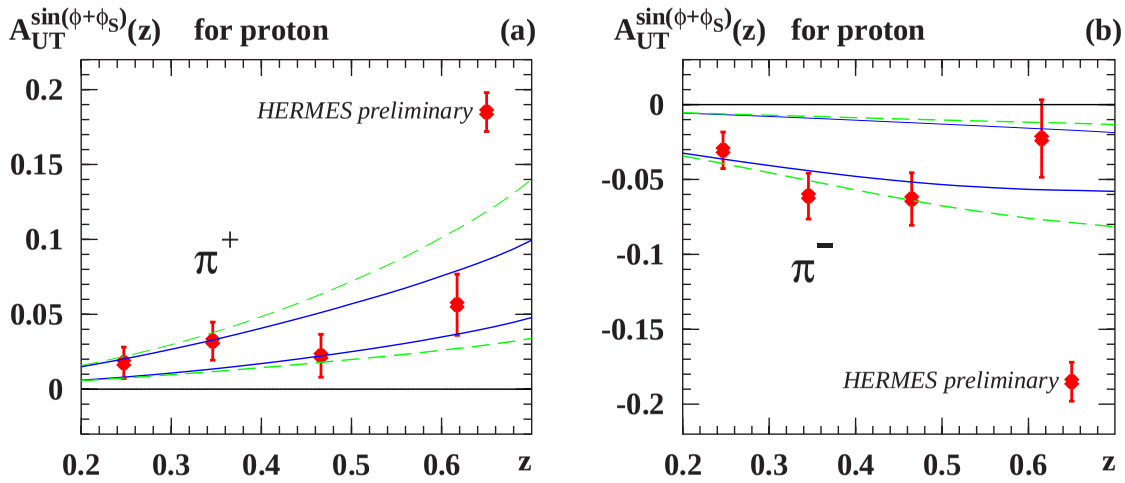
Central values of HERMES systematically lower then of BELLE.
Evolution? But:

$\boxed{\textbf{1.}}$ $\Uparrow$ $B_{\rm Gauss} < 1$ $\qquad$ $\boxed{\textbf{2.}}$ $\Uparrow$ Errors correlated!

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

Solid lines – 1σ-range.
Dashed line – unknown Gaussian widths

$$1 \lesssim \frac{\langle \mathbf{p}_{h_1}^2\rangle}{\langle \mathbf{K}_{H_1}^2\rangle} \lesssim 4\,.$$



$\Rightarrow$ **BELLE & HERMES compatible!**

Summary & Conclusions

- Collins effect: try of first "global" analysis of data. As good as possible at present stage, but assumptions & approximations necessary.
- e^+e^- **BELLE** consistent with SIDIS **HERMES** & **COMPASS**, 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, to be improved: HERMES, COMPASS, JLAB & BELLE.
- Use emerging picture to understand other 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 (to be done).
- Encouraging **progress!** (In spite of many forced theoretical uncertainties: soft factor, $1/N_c$, scale dependence, transverse momenta,...) However, **optimism!** New & more precise data coming in, improved analyses necessary. We are **learning**!

Thank you!