Transverse momentum, spin, and position
distributions of partons in hadrons
Trento, 11 - 15 June, 2007

Collins Asymmetry in SIDIS and e^+e^- Annihilation

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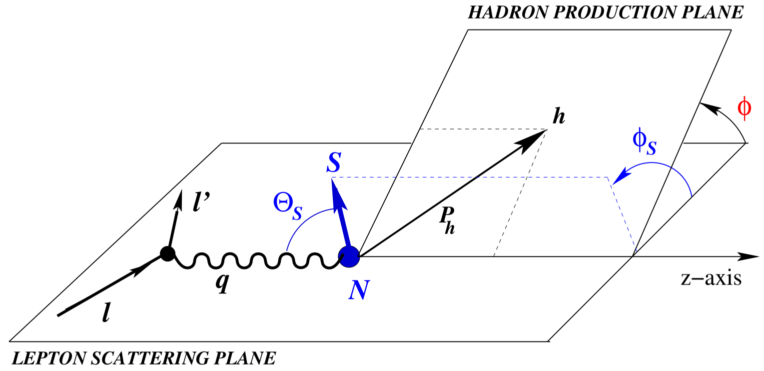
Based on PRD 73 (2006) 094025 and work in progress.

Overview:

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

Collins effect in SIDIS



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

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

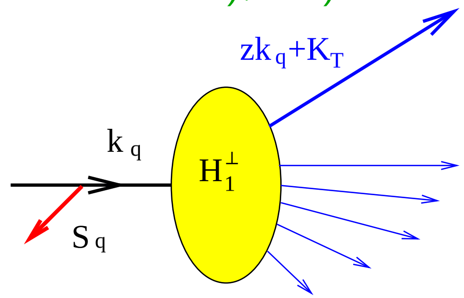
$$\Rightarrow \text{Collins SSA}: \quad A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{h_1^a(x,p_T^2)\otimes H_1^{\perp a}(z,K_T^2)}{f_1^a(x)D_1^a(z)}$$

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

(Collins 1992, Efremov, Mankiewicz, Tornquist 1992 (transversal handedness ≡ interference PFF), ...)

- Left-right asymmetry in fragmentation process
- **Transversity** $h_1^a(x)$, twist-2, chirally odd

(Ralston&Soper 1979, ...)

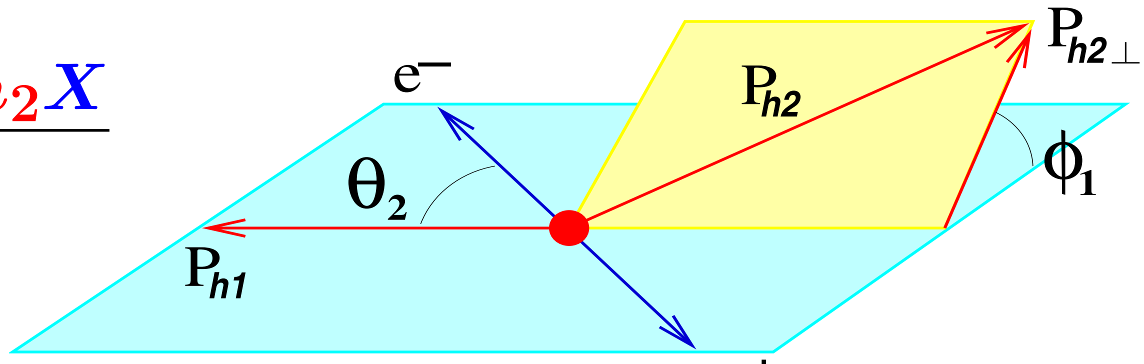


- **Long. polarized target**: $A_{UL}^{\sin 2\phi} \propto H_1^{\perp}$ at HERMES ~ 0; promising preliminary CLAS data.

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

$h_1 \in$ jet$_1$, $h_2 \in$ jet$_2$

(Boer, Jakob, Mulders, 1997)



e^+e^- rest frame

$$\frac{d^2\sigma^{e^+e^-\to h_1h_2X}}{d\phi_1 d\cos\theta_2} = \frac{d^2\sigma_{\text{unp}}}{d\phi_1 d\cos\theta_2}\Big[\underbrace{1+\cos(2\phi_1)\frac{\sin^2\theta_2}{1+\cos^2\theta_2}C_{\text{Gauss}}\frac{\sum_a e_a^2 H_1^{\perp a(1/2)}\otimes H_1^{\perp\bar{a}(1/2)}}{\sum_a e_a^2 D_1^a D_1^{\bar{a}}}}_{\equiv A_1}\Big]$$

$$C_{\text{Gauss}}(z_1,z_2) = \frac{16}{\pi}\frac{z_1z_2}{z_1^2+z_2^2}, \quad H_1^{\perp(1/2)a}(z) = \int d^2\mathbf{K}_T \frac{|\mathbf{K}_T|}{2zm_\pi} H_1^{\perp a}(z,\mathbf{K}_T) \le \tfrac{1}{2}D_1^a(z)$$

Same azimuthal dependence comes from radiative and acceptance effects

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

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

(Metz 2002, Collins & Metz 2005)

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

Available data & Main assumptions

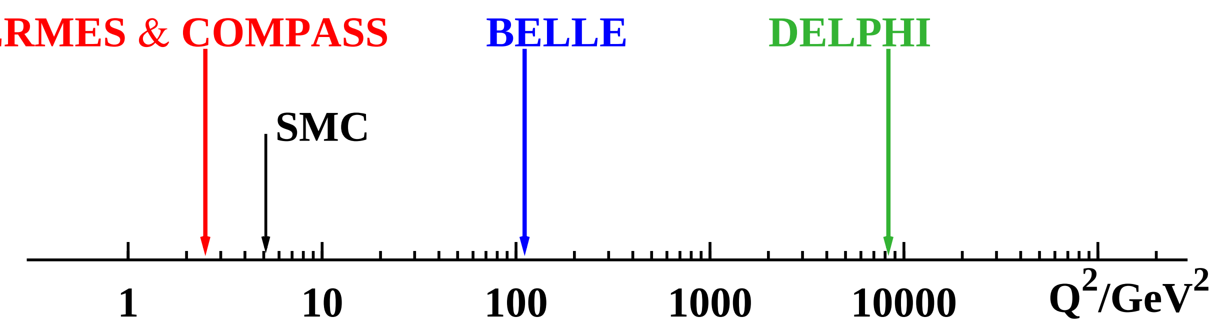
- SIDIS: HERMES (PRL94(2005)012002, hep-ex/0408013 & AIP 792(2005)933, hep-ex/0507013)
- SIDIS: COMPASS (PRL94,202002(2005), NPB765(2007)31)
- e^+e^- BELLE (PRL**96**(2006)232002). Very recently A_1^U/A_1^C was reported (hep-ex/0607014).

also:

- SIDIS: SMC preliminary (Bravar, Nucl.Phys.Proc.Suppl.**79**(1999)520)
- e^+e^- DELPHI preliminary (Efremov,Smirnova,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** $\boldsymbol{H_1^\perp/D_1}$ (presumably less scale-dependent).
- $f_1^a(x)$ from GRV98, $D_1^a(z)$ from Kretzer2000; Kretzer,Leader,Christova2001.
- $h_1^a(x)$ from chiral quark-soliton model (PRD64(2001)034013) — about 20% accuracy.
- $\boldsymbol{F(x,k_T) = F(x)\cdot G(k_T)}$&Gaussian, if $\langle P_{h\perp}\rangle \ll \langle Q\rangle$ ✓& at HERMES ✓ (D'Alesio&Murgia2004)

$\Rightarrow$ **Basically two unknown** $\boldsymbol{\langle H_1^{\perp \mathrm{fav}}\rangle}$, $\boldsymbol{\langle H_1^{\perp \mathrm{unf}}\rangle}$ can be extracted from π^+, π^- HERMES – modulo uncertainties due to our assumptions.

Emerging picture of Collins function from SIDIS

$$A_{UT}^{\sin(\phi+\phi_S)} = 2\,\frac{\sum_a e_a^2\, x h_1^a(x)\, B_{\text{Gauss}} H_1^{\perp(1/2)a}(z)}{\sum_a e_a^2\, x f_1^a(x)\, D_1^a(z)} \qquad B_{\text{Gauss}}(z) = \frac{1}{\sqrt{1+z^2\,\langle \mathbf{p}_{h_1}^2\rangle/\langle \mathbf{K}_{H_1}^2\rangle}} \le 1$$

For pions, two functions :

$$H_1^{\perp\text{fav}} = H_1^{\perp u/\pi^+} = H_1^{\perp d/\pi^-} = \dots$$
$$H_1^{\perp\text{unf}} = H_1^{\perp u/\pi^-} = H_1^{\perp d/\pi^+} = \dots$$

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

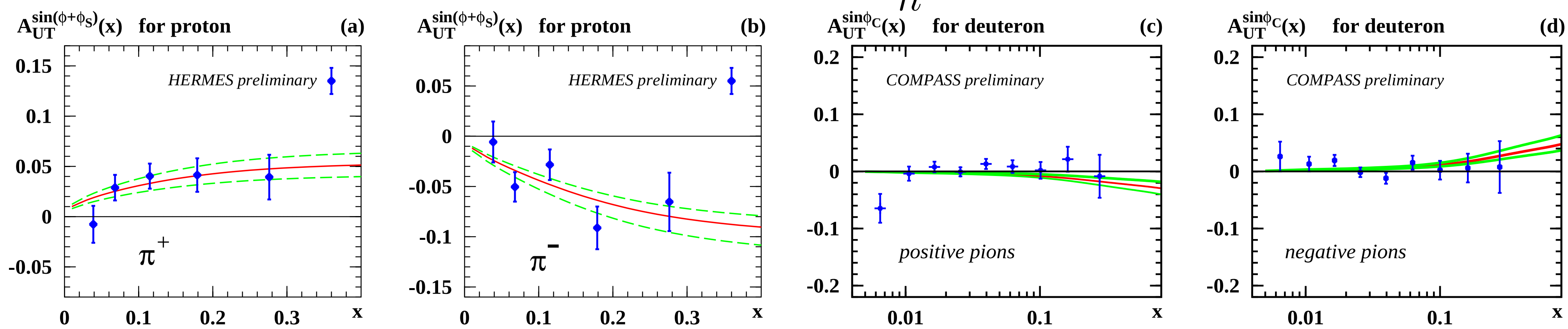
Fit HERMES $\Rightarrow$

$$\langle B_{\text{Gauss}} H_1^{\perp(1/2)\text{fav}}\rangle = (3.5 \pm 0.8)\cdot 10^{-2}$$
$$\langle B_{\text{Gauss}} H_1^{\perp(1/2)\text{unf}}\rangle = -(3.8 \pm 0.7)\cdot 10^{-2}$$

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

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

$\longrightarrow$ Schäfer-Teryaev sum rule $\sum_h \langle z^2 H_1^{\perp(1)}\rangle = 0$ (PRD61(2000)077903)



- Good description of HERMES
- compatible with COMPASS

Emerging picture of transversity from SIDIS

How model dependent is our result?

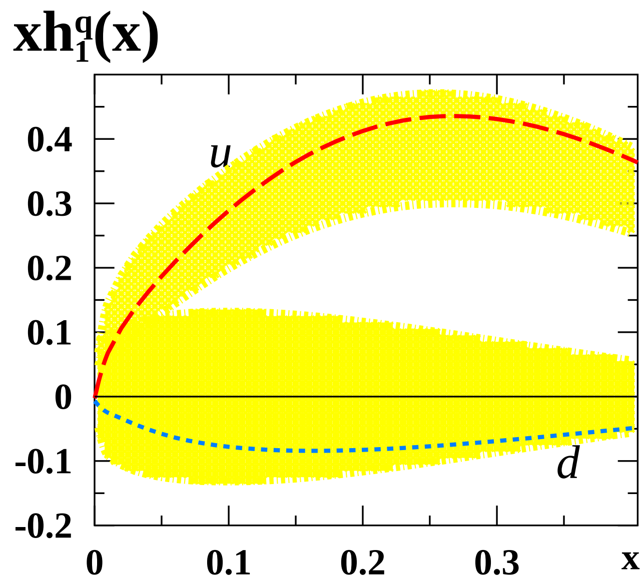
Look closer: demand extracted $\langle B_{\rm Gauss} H_1^{\perp} \rangle$ to vary within 1-σ.

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

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

other $h_1^a(x)$ unconstrained.

However, COMPASS data for deuteron limited positivity for $h_1^d(x)$ (See Elena talk).



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

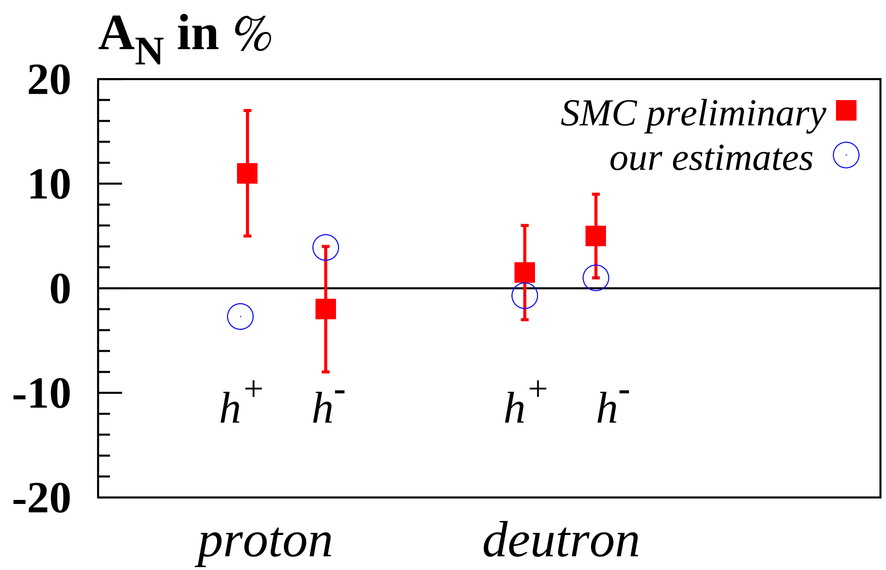
- **Grain of salt: preliminary SMC**

  charged hadrons

  $\langle Q^2 \rangle \sim 5\,\text{GeV}^2, \quad \langle x \rangle \sim 0.08$

  $\langle z \rangle \sim 0.45$ and $\langle P_{h\perp} \rangle \sim (0.5 - 0.8)\,\text{GeV}$

Reason to worry? Data are preliminary . . .

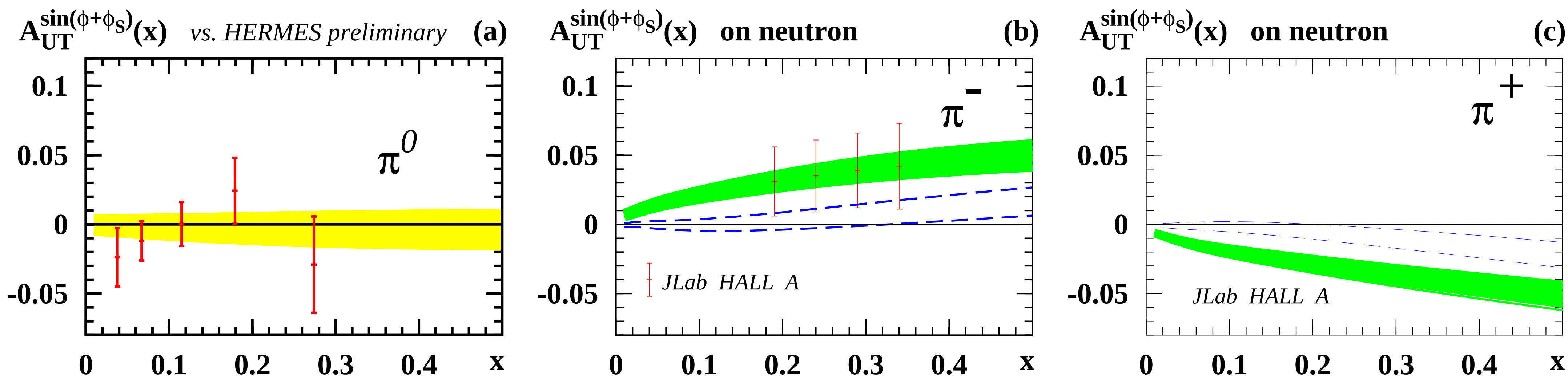


- **Emerging picture of transversity from SIDIS will improve**
  - Data on π^0 & kaons.
  - More data from HERMES proton & deuteron target.
  - More data from COMPASS deuteron & proton target (See Elena talk).
  - Data from CLAS with transv. pol. target.
  - Data from HALL-A, transv. ^{3}He $\approx$ 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.



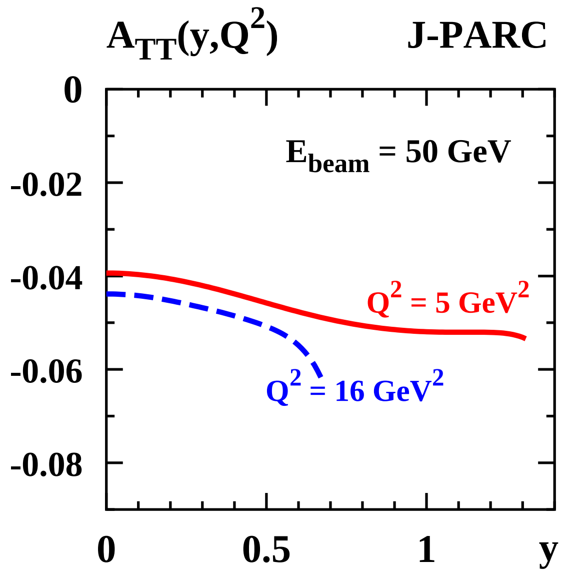
Transversity and Drell-Yan

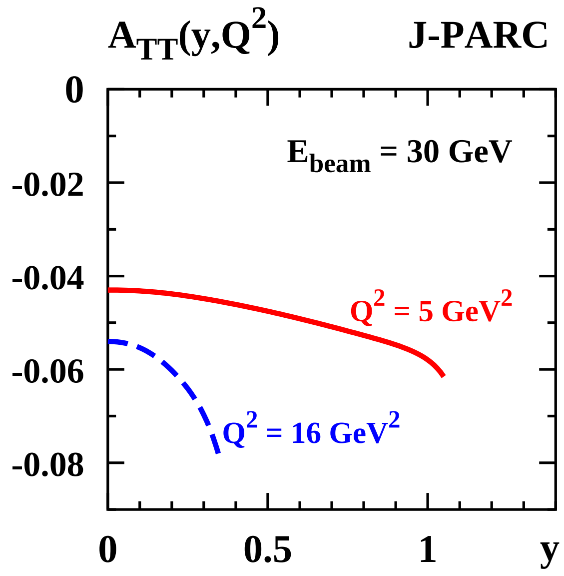
The best and the cleanest way to access transversity h_1

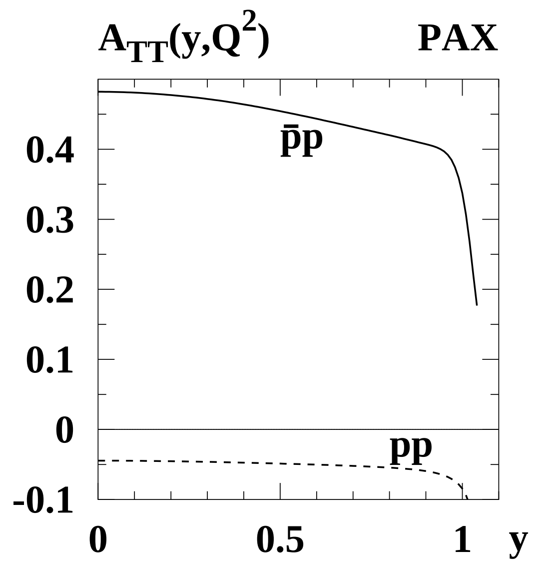
$$A_{TT}(y,Q^2) = \frac{\sum_a e_a^2 h_1^a(x_1,Q^2) h_1^{\bar{a}}(x_2,Q^2)}{\sum_a e_a^2 f_1^a(x_1,Q^2) f_1^{\bar{a}}(x_2,Q^2)}, \qquad x_{1/2} = \sqrt{\frac{Q^2}{s}} e^{\pm y}$$

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

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

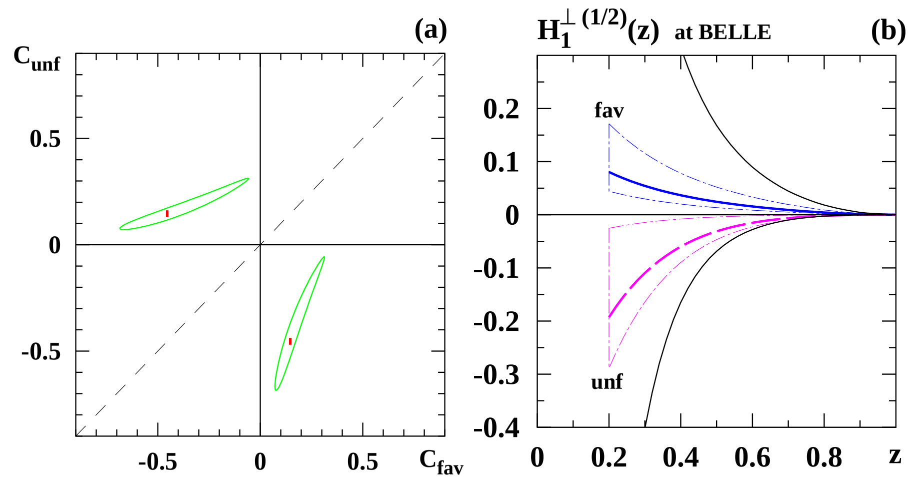






- Rather noticeable effect even for $p_\uparrow p_\uparrow$! (Similar for polarized U-70, Protvino.)
- Mostly sensitive to $h_1^u(x)$.
- Allow discriminate models (e.g. popular guess $h_1^a(x) \approx g_1^a(x)$ would give $A_{TT} \approx 30\%$).

Collins function from e^+e^-



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

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

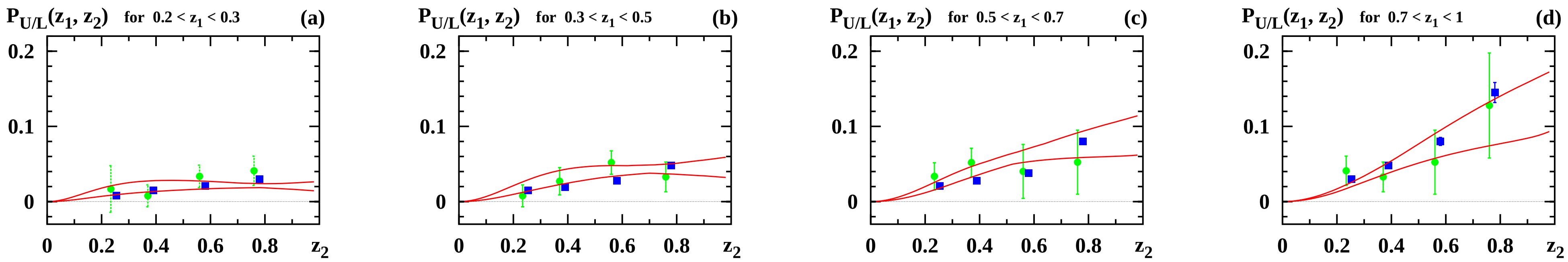
with $\mathbf{P_1}(z_1, z_2) = F(H_1^{\rm fav}, H_1^{\rm unf}, \text{Gauss})$

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

symmetric $z_1 \leftrightarrow z_2$ or 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: $\underbrace{C_{\rm fav} = 0.15, \quad C_{\rm unf} = -0.45}_{\text{sign preferred by HERMES}}$ or vice versa: fav $\leftrightarrow$ unf

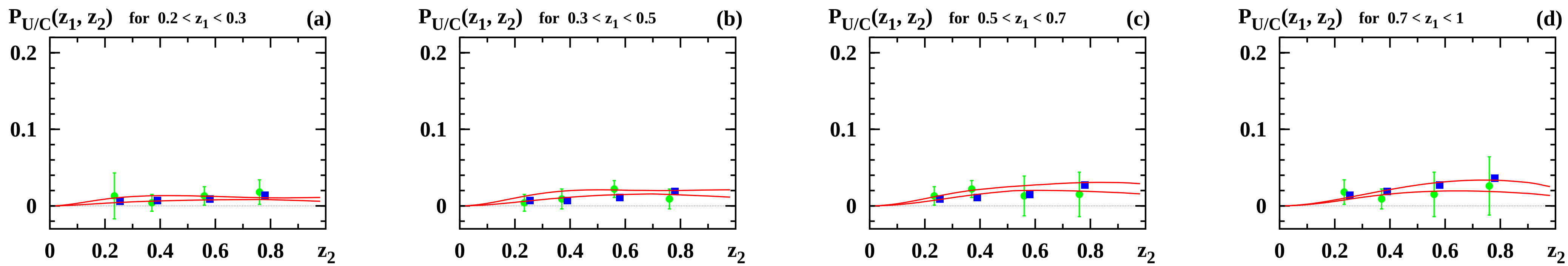


(Blue square - new preliminary data.) **Good description!**

•Important most recent news from BELLE

New double ratio is measured (hep-ex/0607014 and DIS-2007)

$$\frac{A_1^U(\phi)}{A_1^C(\phi)} \approx 1 + \cos(2\phi_1)\ \mathbf{P_c}$$



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**

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

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

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

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

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

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

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

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

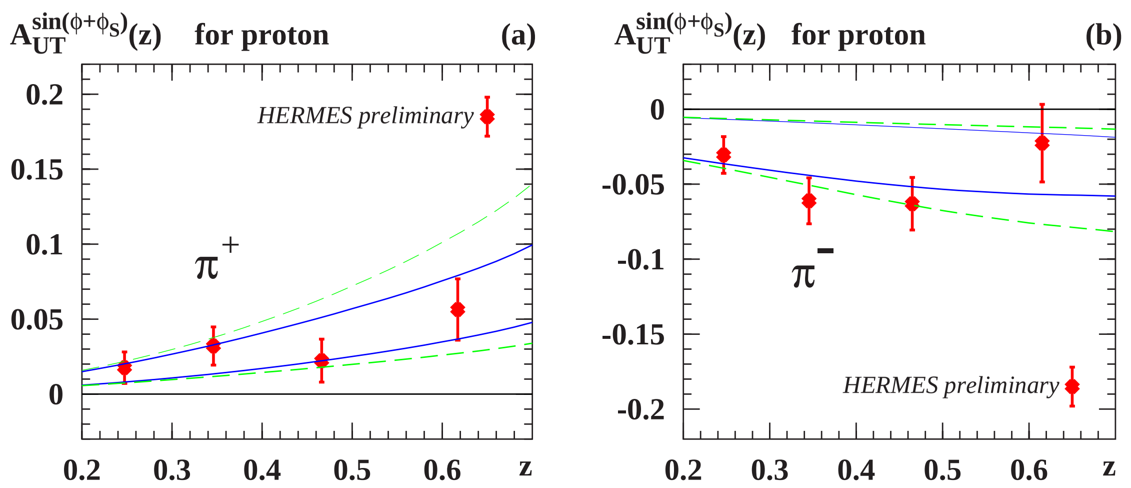
1. $\Uparrow$ $B_{\text{Gauss}} < 1$

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

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



⇒ BELLE & HERMES compatible!

Summary & Conclusions

- Collins effect: try of first "global" analysis of data. In good agreement with later global fit (Anselmino at al. PRD75(2007)054032)
- 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: string fragmentation, Schäfer–Teryaev sum rule.
- $h_1^u > 0$ and within $30\,\%$ of Soffer bound in agreement with lattice.
- Other $h_1^a(x)$ less known, soon 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, scale dependence, transverse momenta,...). However, **optimism!** New & more precise data coming in, improved analyses necessary. We are **learning**!

Thank you!