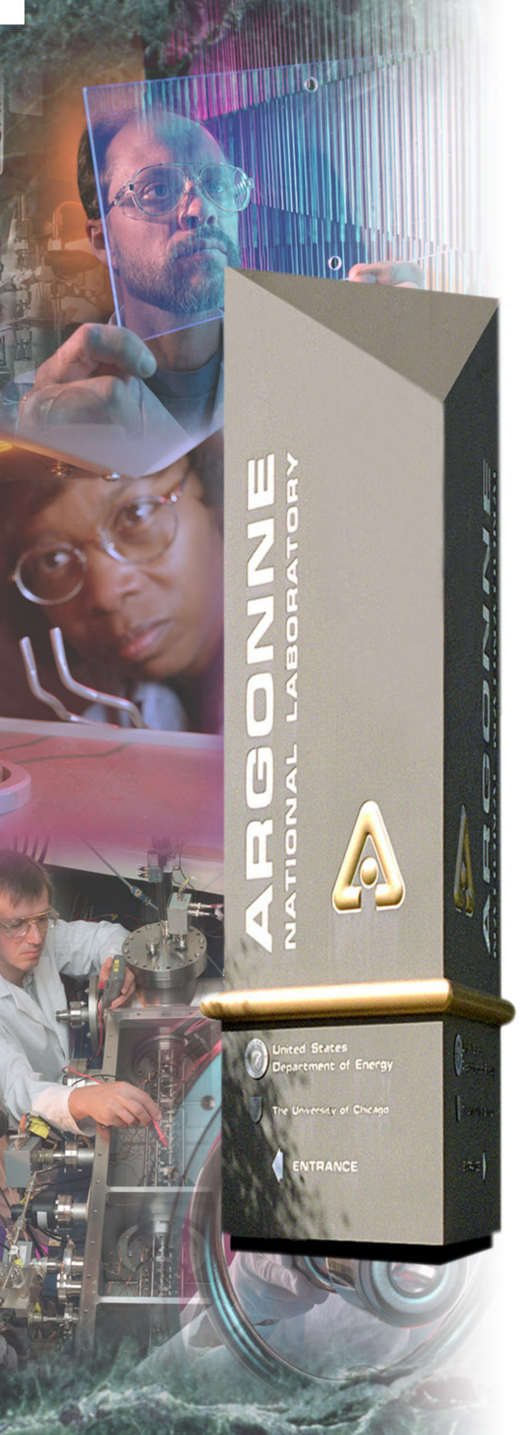

Transversity and spin structure functions

Quark transverse spin and momentum in polarized deep-inelastic scattering

H. E. Jackson

Argonne National Laboratory

Office of Science
U.S. Department of Energy

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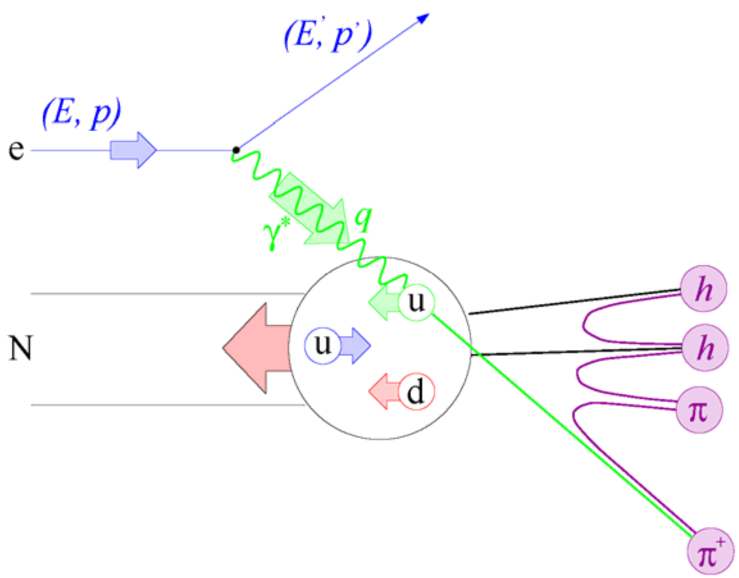
Office of Science Laboratory
Operated by The University of Chicago

Spin-dependent deep-inelastic scattering(DIS)



- **Semi-inclusive DIS where one observes a coincident hadron allows probing of the flavor structure in more detail.**
- **Inclusive polarized DIS has provided much of our knowledge of partonic structure of the nucleon.**
- **Polarized DIS with polarized targets and beams probes the spin structure of the partonic constituents**

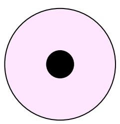
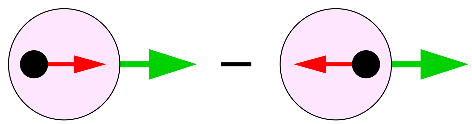
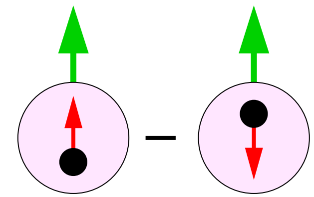
Flavor structure of leading hadron and struck quark strongly correlated

$x=Q^2/2m\nu \quad \nu = E-E' \quad Q^2=-q^2=4EE'\sin^2(\Theta/2) \quad z_h=E_{hadron}/\nu$

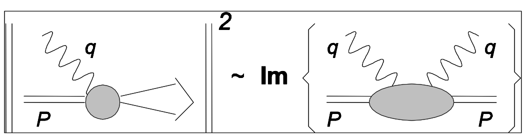
Leading order parton distribution functions

3 PDF's = complete description of the nucleon

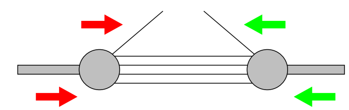
at leading twist – (integrated over transverse momentum)

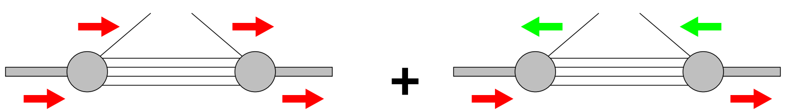
$f_1 =$  $g_1 =$  $h_1 =$ 

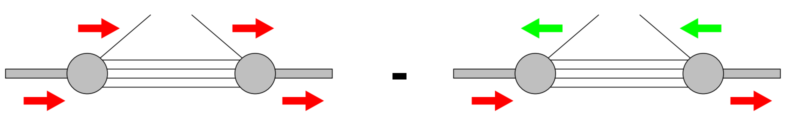
Optical theorem



$\Downarrow$

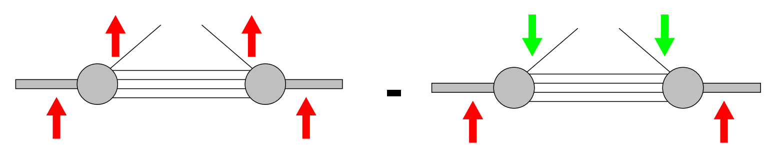
$h_1 \sim$ 

$f_1 \sim$ 

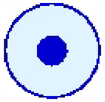
$g_1 \sim$ 

Target not helicity eigenstate

→ go to transversity basis



Unpolarized distribution function

$f_1^q =$ 

Unpolarized

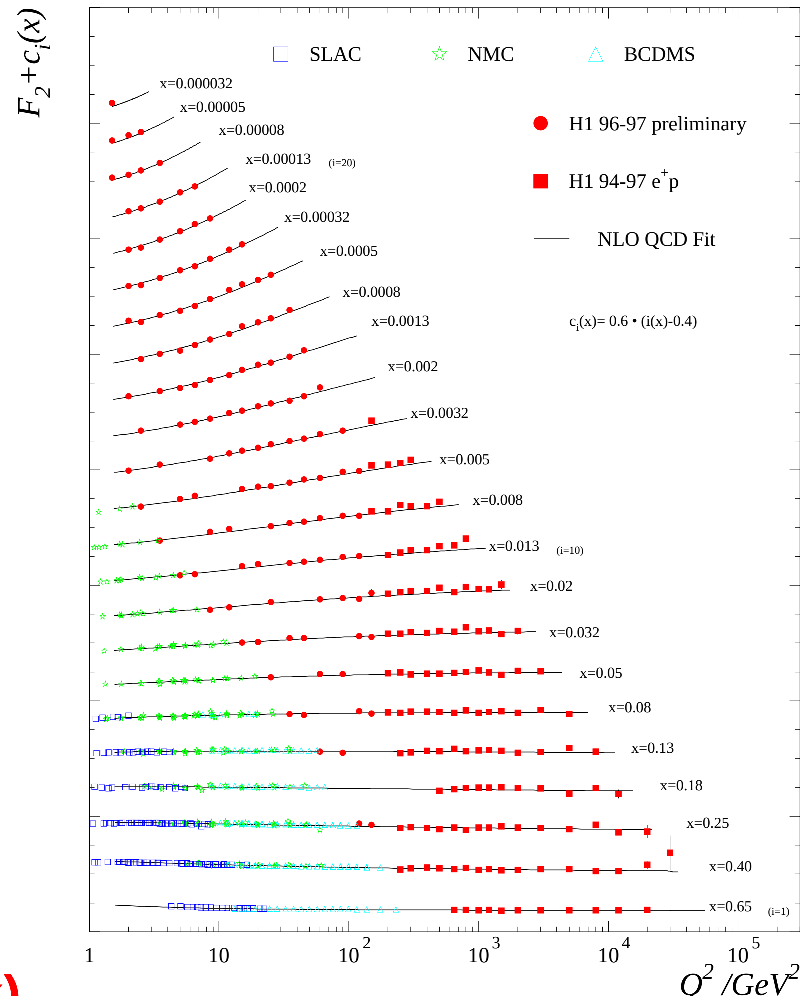
Quarks and Nucleons

Vector-charge:

$$\langle PS|\bar{\psi}\gamma^{\mu}\psi|PS\rangle =$$

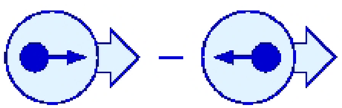
$$\int_0^1 dx\,(q(x) - \bar{q}(x))$$

$q(x)$: Spin averaged well known



$F_2(x)=x\sum_q e^2_q q(x)$

Long. Spin-dependent distribution function

$g_1^q =$ 

Longitudinally polarized

Quarks and Nucleons

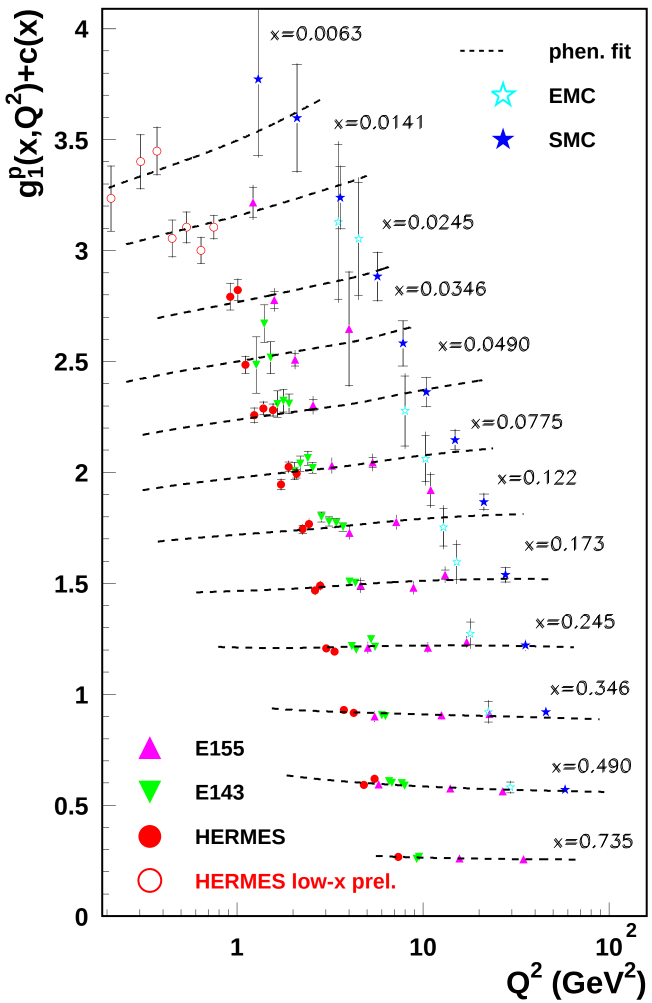
Axial charge:

$$\langle PS|\bar{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle =$$

$$\int_0^1 dx\,(\Delta q(x) + \Delta\bar{q}(x))$$

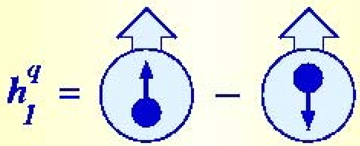
$\Delta q(x)$: Helicity difference

known



$g_1(x)=0.5\sum_q e^2_q \Delta q(x)$

Transversity, the 3rd LO distrib. function



Transversely polarized

Quarks and Nucleons

Tensor-charge:

$$\langle PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle =$$

$$\int_0^1 dx\, (\delta q(x) - \delta \bar{q}(x))$$

$\delta q(x)$: Helicity flip

chiral odd!

unknown

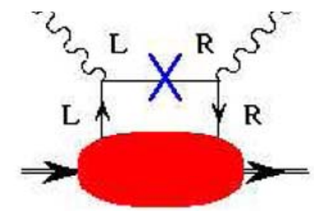
- **Measures quark spin distribution ⊥ to $\vec{p}$ at infinite p**
- **$h_1(x)$ is chiral odd, i.e. not observable in inclusive DIS**
- **Tensor charge is a quantity with QCD predictions(lattice gauge cal's)**
- **No coupling to gluons - Q^2 evolution simpler, an all valence object**
- **At low scales, $Q^2 \approx 1$ GeV^2 most theories give $h_1(x) \approx g_1(x)$**
- **Difference between g^q_1 and h^q_1 reflects relativistic motion of quarks.**

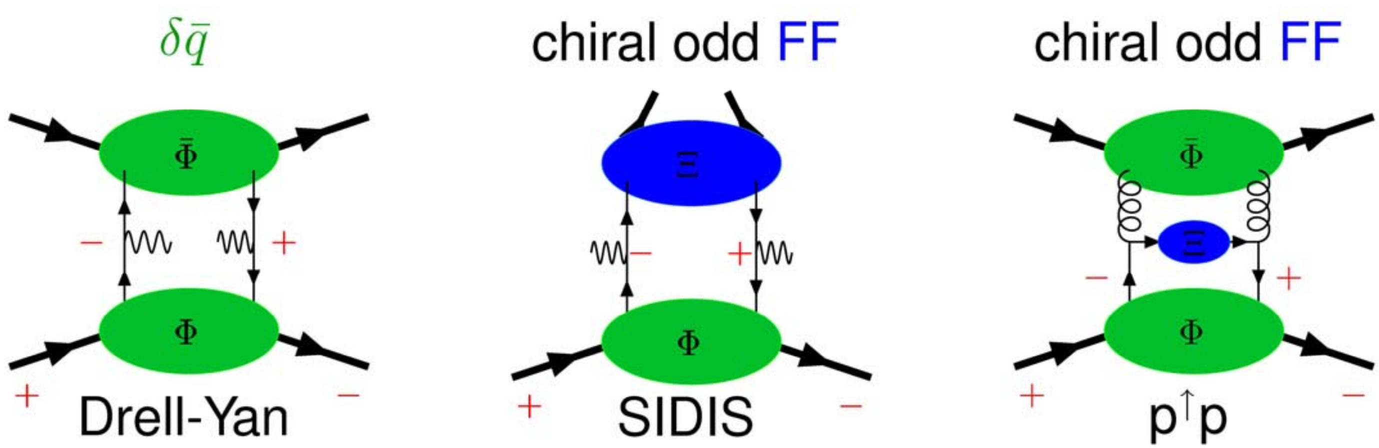
Can conserve chirality in DIS processes by coupling $h_1(x)$ to a

second chiral odd distribution

Need reactions involving

At least 2 hadrons

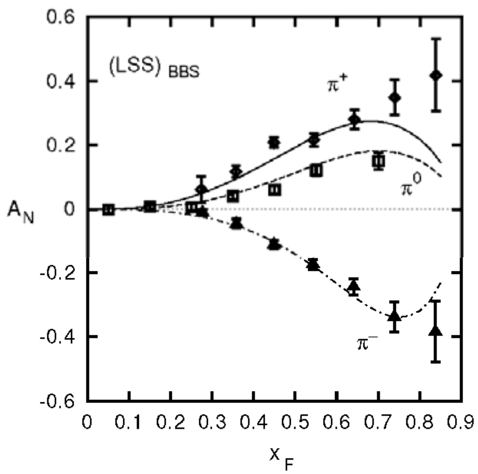




Single-spin Asymmetries

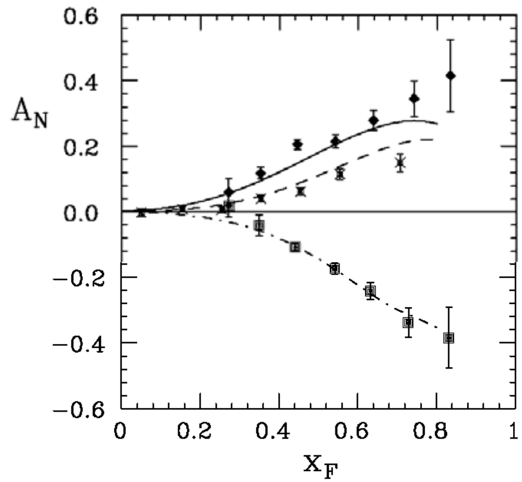
$p^{\uparrow}p$ or $\bar{p}^{\uparrow}p \rightarrow \pi^{\pm} + X$ from FNAL E704

Collins Effect

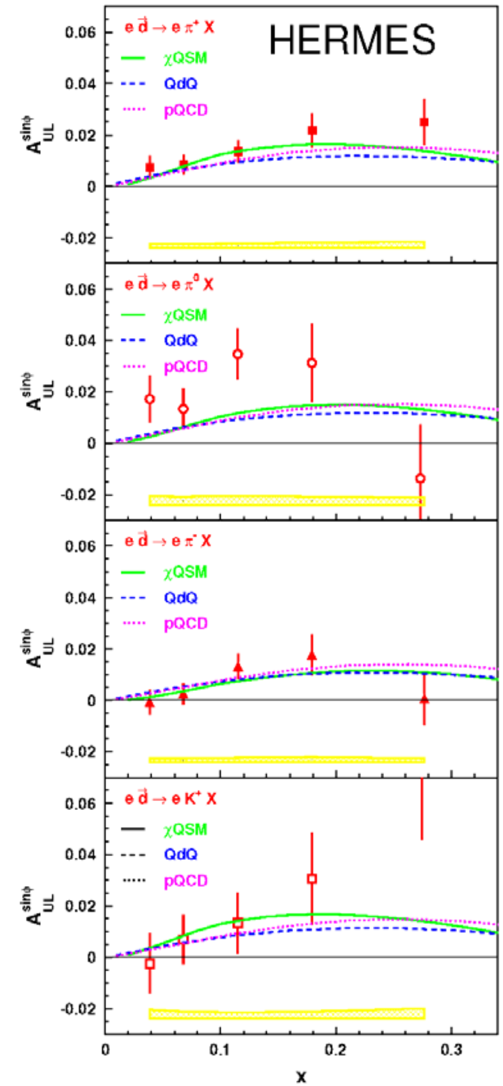


Boglione and Leader, 1999

Sivers Effect



Anselmino and Murgia, 1998



Either mechanism "explains" these data

➡ **Collins Effect**

$A_N \sim h_1(x)\, H_1^{\perp}(z)$

⇒ access to ***transversity!***

➡ **Sivers Effect**

$A_N \sim f_{1T}^{\perp}(x)\, D_1^{\perp}(z)$

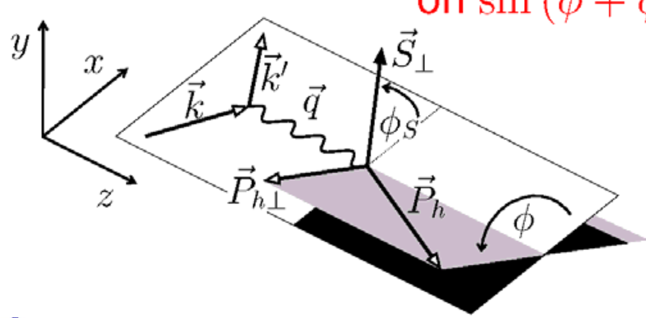
⇒ access to ***T-odd dist^{n} func***

Two T-odd Contrasting Phenomena

Single-spin asymmetries require some (naive) T-odd mechanism

Transversity + T-odd Collins FF

- Transversity: polarizations of quark and nucleon are correlated
- Photoabsorption flips quark polarization component in lepton scattering plane
- Quark polarization correlates with $k_T \rightarrow \mathbf{P}_{h\perp}$ in fragmentation
- Target spin asymmetry depends on $\sin(\phi + \phi_S)$



Sivers T-odd distribution function

- Struck quark p_T correlated with target nucleon polarization
- p_T survives fragmentation, inherited by hadron $\mathbf{P}_{h\perp}$
- $\Rightarrow$ Polarization state of virtual photon is irrelevant
- $\Rightarrow$ Orientation of lepton scattering plane is irrelevant
- Target spin asymmetry depends on $\sin(\phi - \phi_S)$

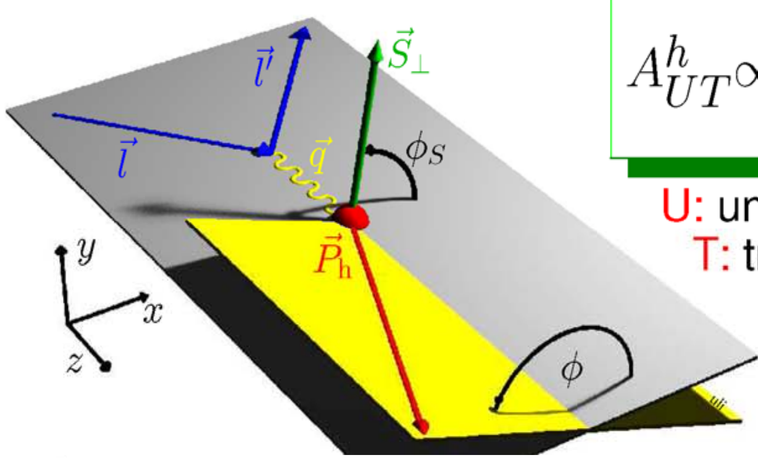
Exp's with transverse target polarization

- Collins and Sivers effect not distinguishable with longitudinally polarized target
- higher twist effects kinematically favored with long. target
- with transversely polarized target, 2 azimuthal angles exist
- Collins and Sivers effect distinguishable:

$$A_{UT}^{h} \propto S_{\perp} \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x)\ H_1^{\perp}(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\ D_1(z)}$$

$$A_{UT}^{h} \propto S_{\perp} \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\ D_1(z)}$$

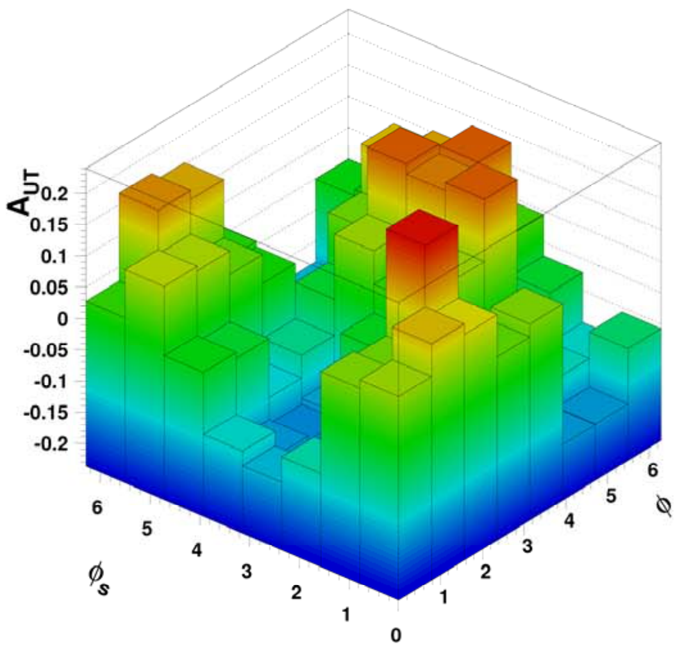
$$z \stackrel{lab}{=} \frac{E_h}{\nu}$$

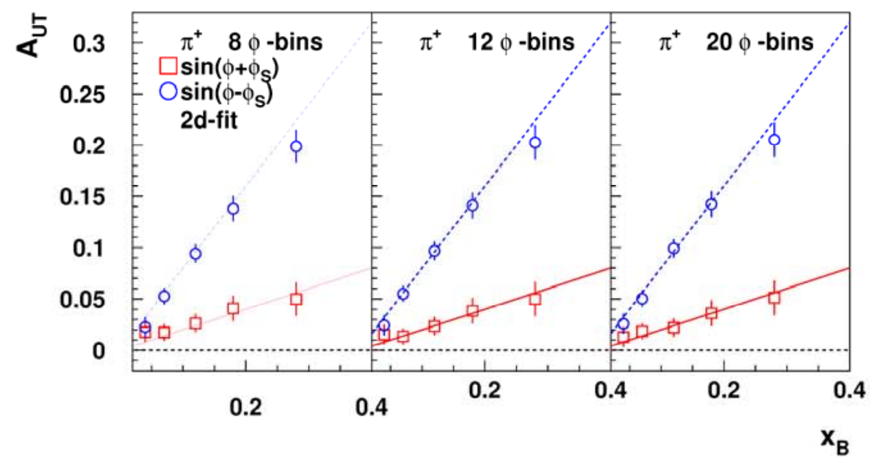


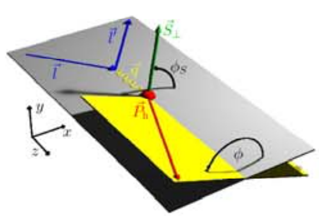
U: unpolarized e^+-beam
T: transversely polarized target

What is measured in DIS?

$$A_{UT}^{h}(\phi,\phi_S) = \frac{1}{S_T}\frac{N_h^{\uparrow}(\phi,\phi_S)-N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S)+N_h^{\downarrow}(\phi,\phi_S)}$$
$$= \bar{A}_C^h \sin(\phi+\phi_S) + \bar{A}_S^h \sin(\phi-\phi_S)\cdots$$

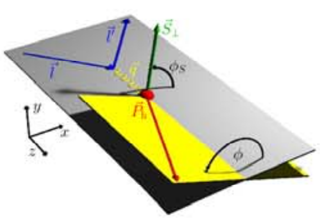






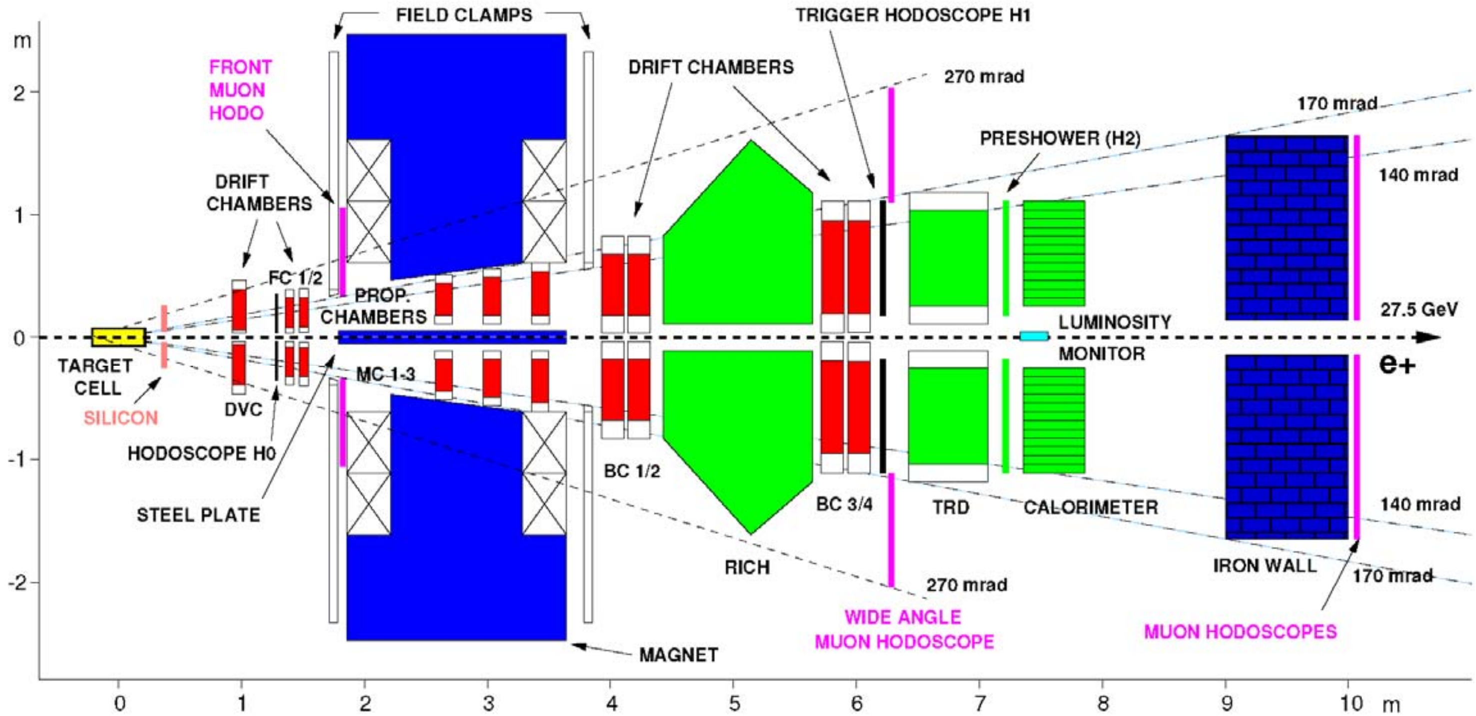
fit both asymmetries simultaneously

HERMES Experiment at HERA



E_{e^+}=27.6 GeV

The HERMES Spectrometer



- Pure nuclear-polarized atomic hydrogen target with rapid spin flipping
- Kinematic range: $0.02 \leq x \leq 0.8$ for $Q^2 > 1\,\text{GeV}^2$ and $W > 2\,\text{GeV}$
- Positron identification: TRD, Preshower and Calorimeter
- Dual-radiator Ring-imaging Čerenkov detector identifies pions and kaons in $2 < P < 20\,\text{GeV}$

Technical point – deconvoluting $p_t(k_t)$

- A p_T-dependent DF (*e.g.* Sivers) or a k_T-dependent FF (*e.g.* Collins) appears inside a convolution integral over p_T and k_T
- Model-independent deconvolution requires $|\mathbf{P}_{h\perp}|$-weighted asymmetries:

The Collins asymmetry

$$\left\langle \frac{|\mathbf{P}_{h\perp}|}{(zM_h)} \sin(\phi+\phi_S) \right\rangle_{UT}(x,y,z) \equiv \frac{\int d\phi_S\, d^2\mathbf{P}_{h\perp}\, |\mathbf{P}_{h\perp}|/(zM_h)\, \sin(\phi+\phi_S)\; d^6\sigma_{UT}}{\int d\phi_S\, d^2\mathbf{P}_{h\perp}\; d^6\sigma_{UU}}$$

$$= |\mathbf{S}_T| \frac{(1/xy^2)\, B(y) \sum_q e_q^2\, h_1^q(x)\, H_1^{\perp(1)q}(z)}{(1/xy^2)\, A(y) \sum_q e_q^2\, f_1^q(x)\, D_1^q(z)}$$

Including $1/z$ in the weight relates the asymmetry to the first z-moment of the Collins function

The Sivers asymmetry

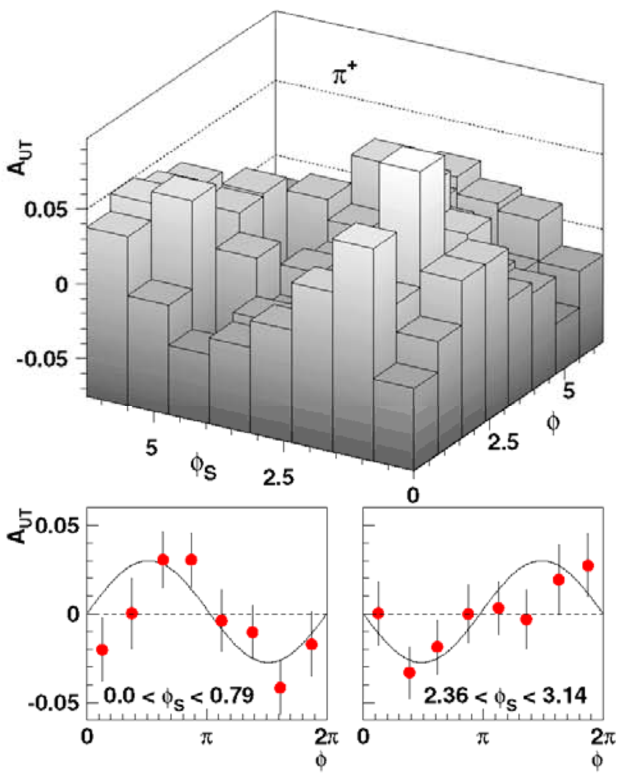
$$\left\langle \frac{|\mathbf{P}_{h\perp}|}{(zM_p)} \sin(\phi-\phi_S) \right\rangle_{UT}(x,y,z) = |\mathbf{S}_T| \frac{(1/xy^2)\, B(y) \sum_q e_q^2\, f_{1T}^{\perp q}(x)\, D_1^q(z)}{(1/xy^2)\, A(y) \sum_q e_q^2\, f_1^q(x)\, D_1^q(z)}$$

Including $1/z$ in the weight relates the asymmetry to the first x-moment of the Sivers function

Virtual-photon asymmetries

$$A_{UT}^h(\bar{x},\bar{z},\phi,\phi_S) = \frac{1}{|S_T|}\frac{\sum_{i=1}^{N_h^\uparrow(\phi,\phi_S)}|P_{h\perp}(i)|/z(i) - \sum_{i=1}^{N_h^\downarrow(\phi,\phi_S)}|P_{h\perp}(i)|/z(i)}{2\left(N_h^\uparrow(\phi,\phi_S)+N_h^\downarrow(\phi,\phi_S)\right)}$$

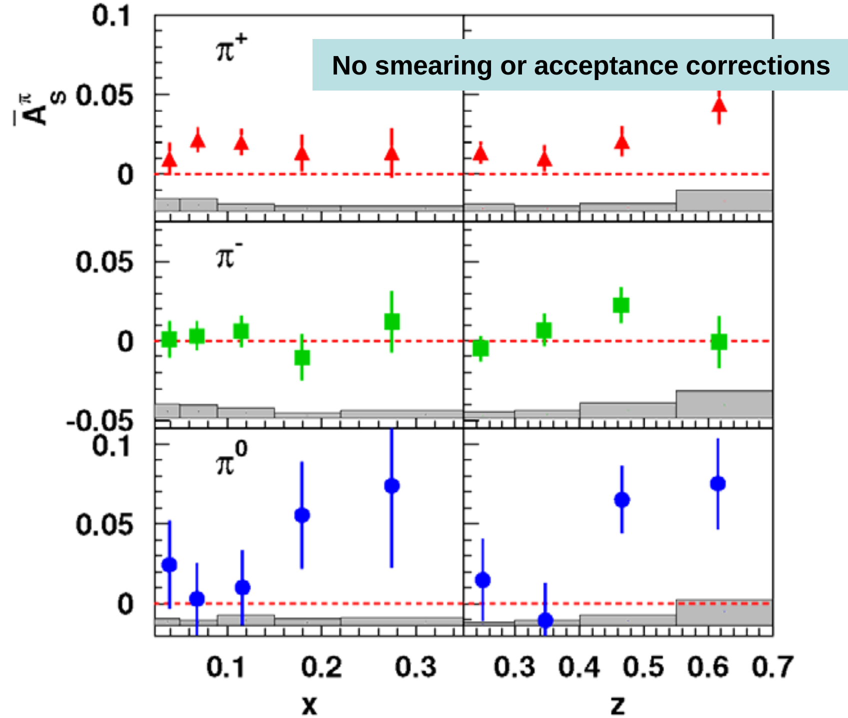
$$= M_h A_C^h \frac{B(\langle y\rangle)}{A(\langle x\rangle,\langle y\rangle)}\sin(\phi+\phi_S) + M_p A_S^h \sin(\phi-\phi_S)$$



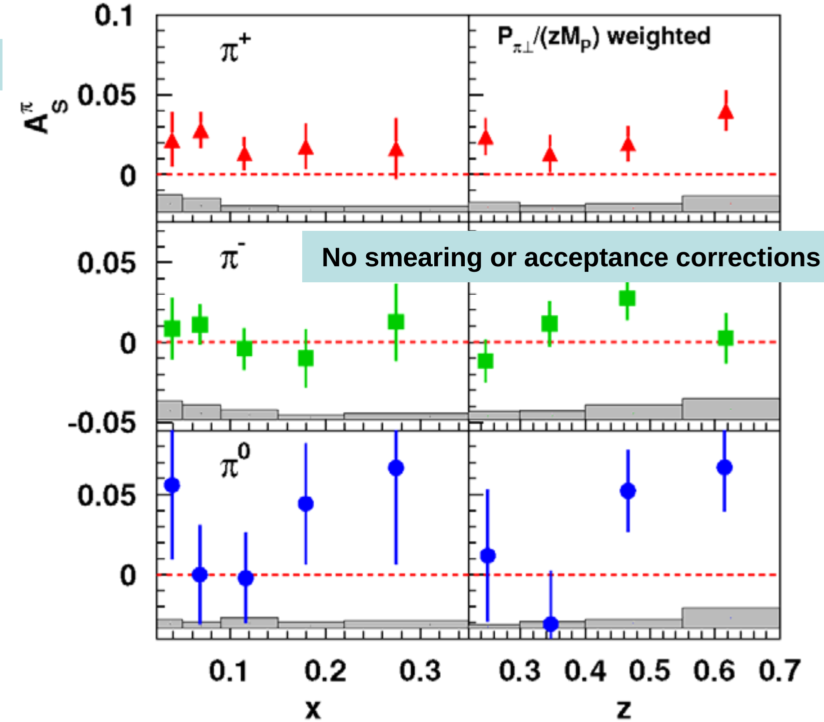
- Effects of acceptance, smearing and QED radiation all found to be negligible in Monte Carlo studies
- Inclusion of terms in $\sin(3\phi-\phi_S)$, $\sin\phi_S$ and $\sin(2\phi-\phi_S)$ in the fit resulted in negligible amplitudes, and no effect on the main amplitudes.

The Sivers asymmetries

Unweighted

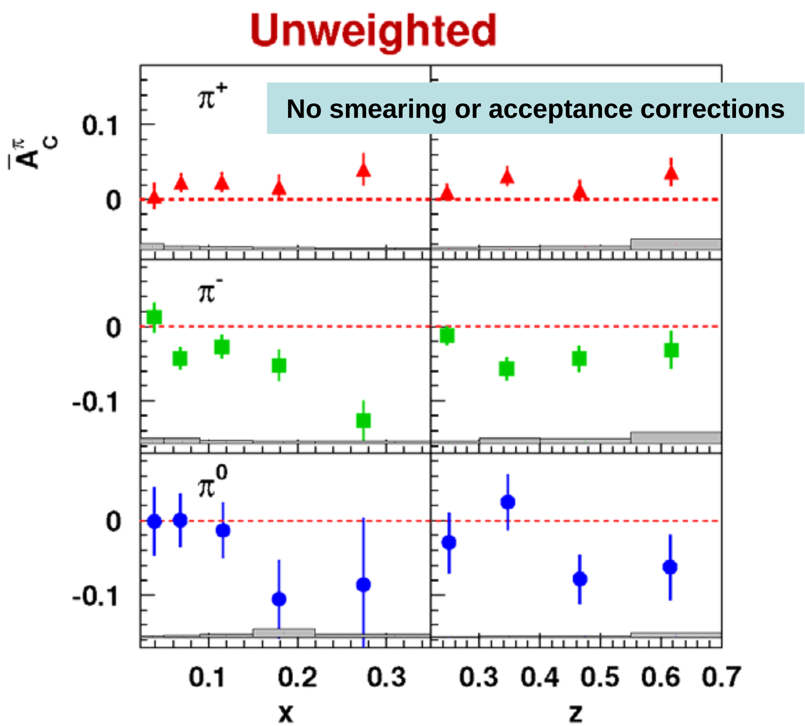


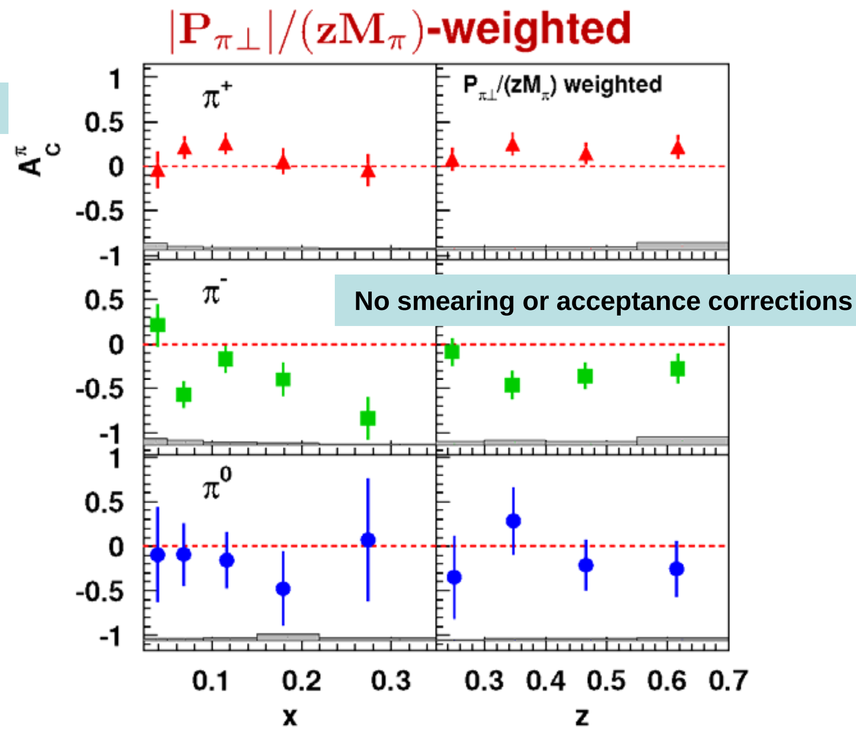
$|P_{\pi\perp}|/(zM_p)$-weighted



- **The π^+ Asymmetries appear to be positive and nonzero**
- Little kinematic dependence is visible
- Little difference is seen between weighted and unweighted asymmetries

Collins virtual-photon asymmetries

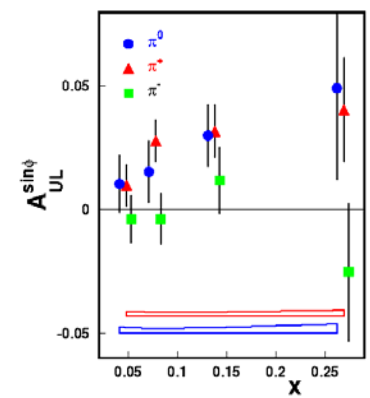




In view of up quark dominance of both π^+ and π^-,
and existing longitudinal single-spin asymmetries $\Rightarrow\Rightarrow$

How can the negative π^- asymmetry be at least similar in magnitude to π^+?

Unweighted asymmetries depend little on z, contrary to expectations.



Related experiments – in progress

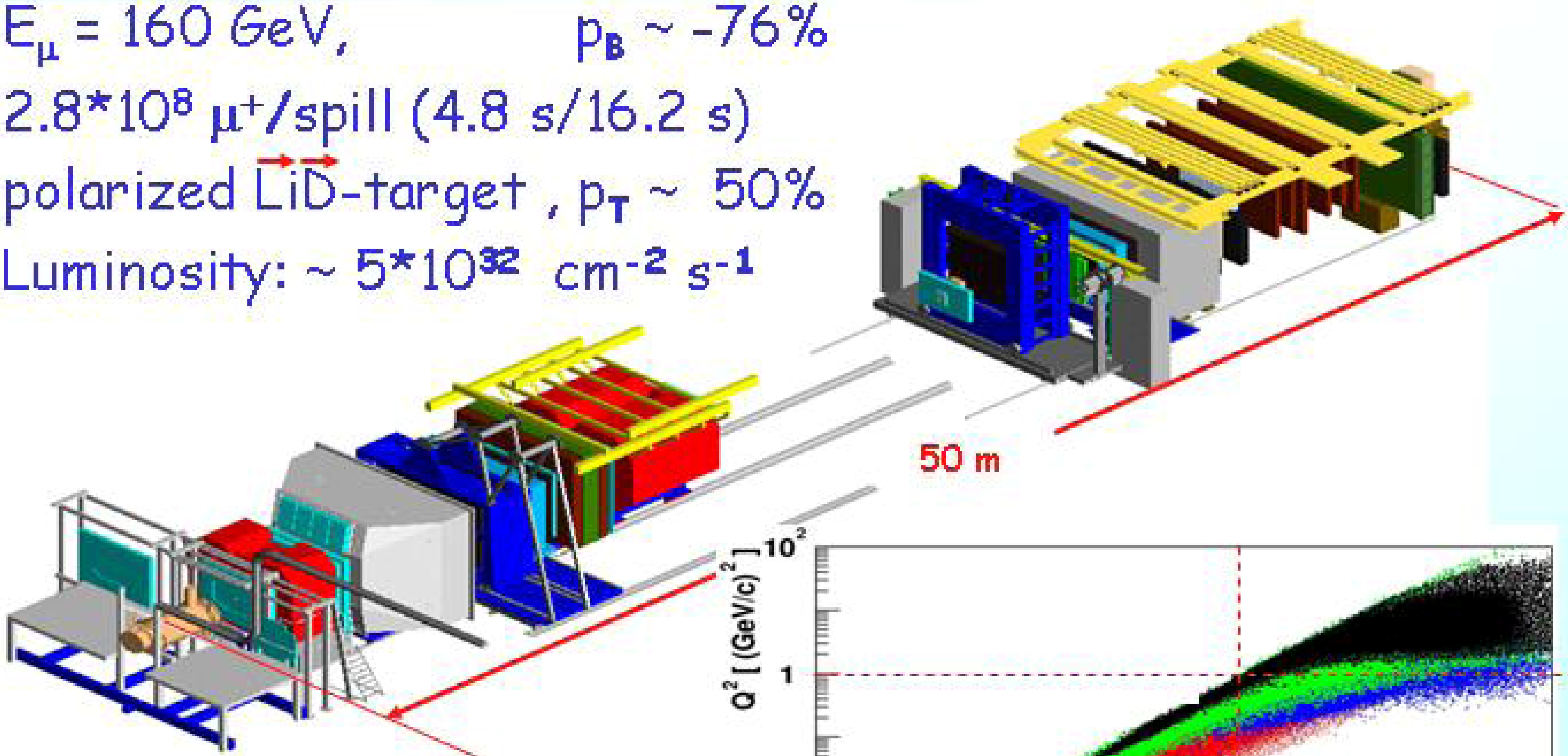
- Measurements at **BELLE-KEKB** will determine $H_1^{\perp}(z)$ in $e^+e^- \rightarrow \pi^+\pi^- X$ by studying azimuthal angle correlations.

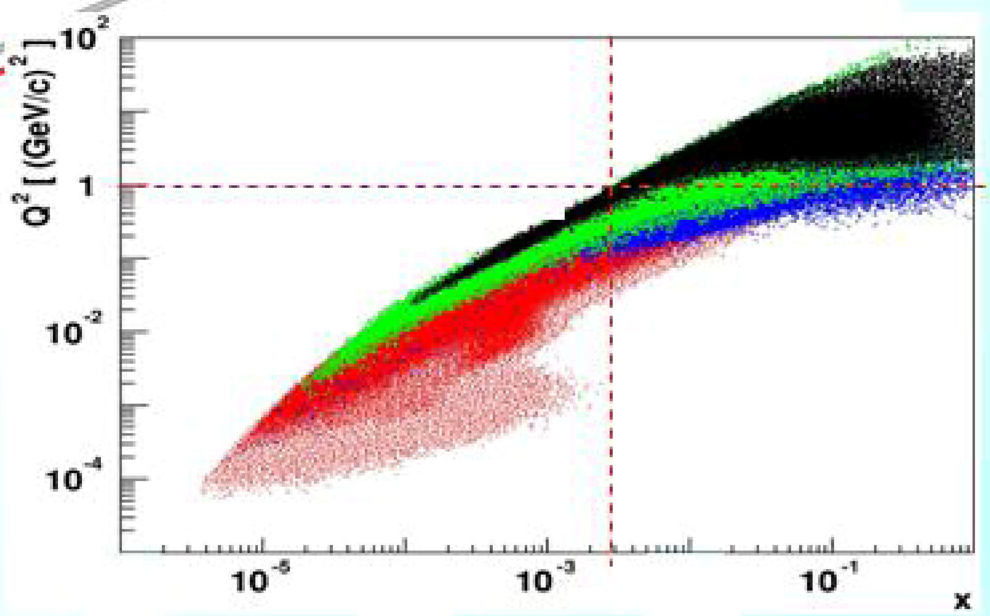
- At RHIC measurements are planned of Sivers/Collins effects in $p\uparrow p$ reactions. **PHENIX** already has reported observable SSA's for π^0's .

- The **COMPASS** experiment at CERN is studying the Collins asymmetry using a ^{6}LiD "deuteron" target.

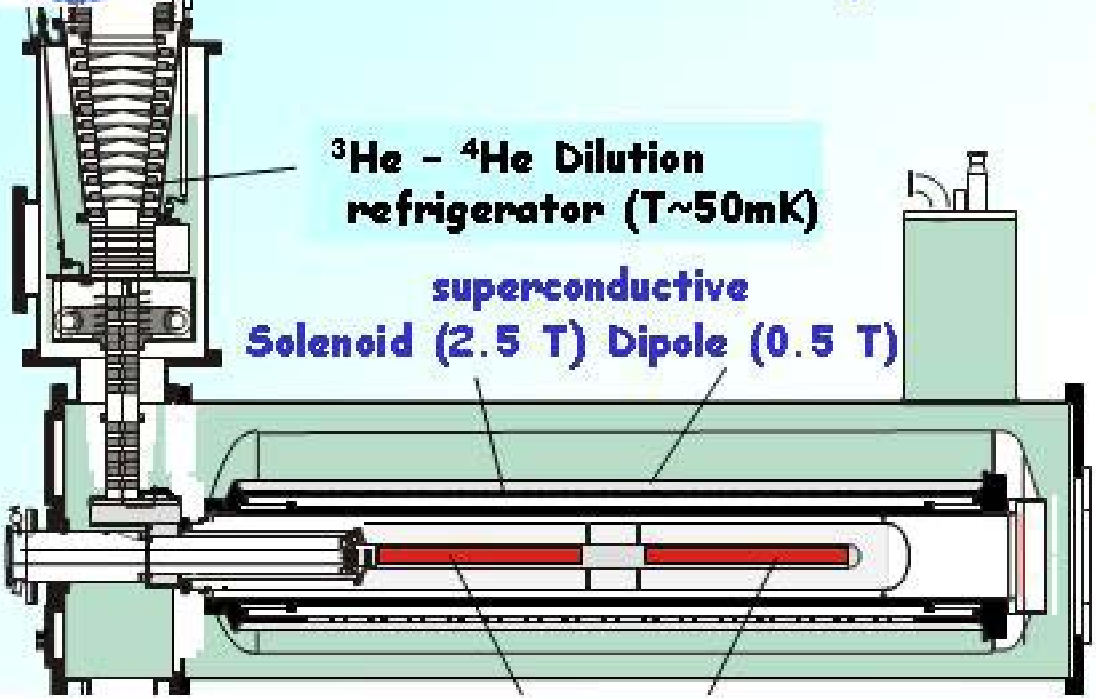
COMPASS at CERN

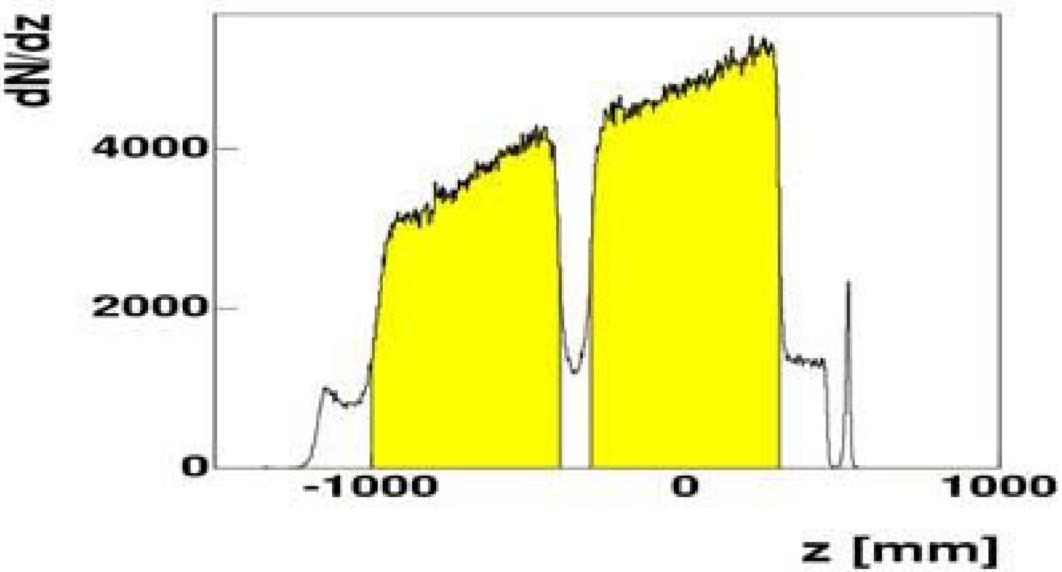
- E_μ = 160 GeV, $p_B \sim -76\%$
- $2.8 \cdot 10^8\ \mu^+$/spill (4.8 s/16.2 s)
- polarized $\vec{L}\vec{i}\vec{D}$-target, $p_T \sim 50\%$
- Luminosity: ~ $5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$



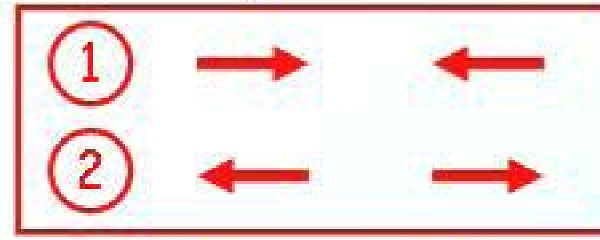


COMPASS polarized LiD target



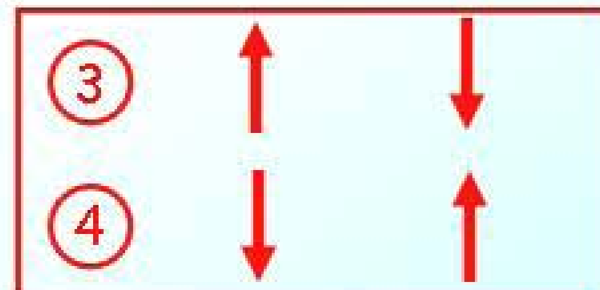


4 possible spin combinations:



reversed every 8 hours

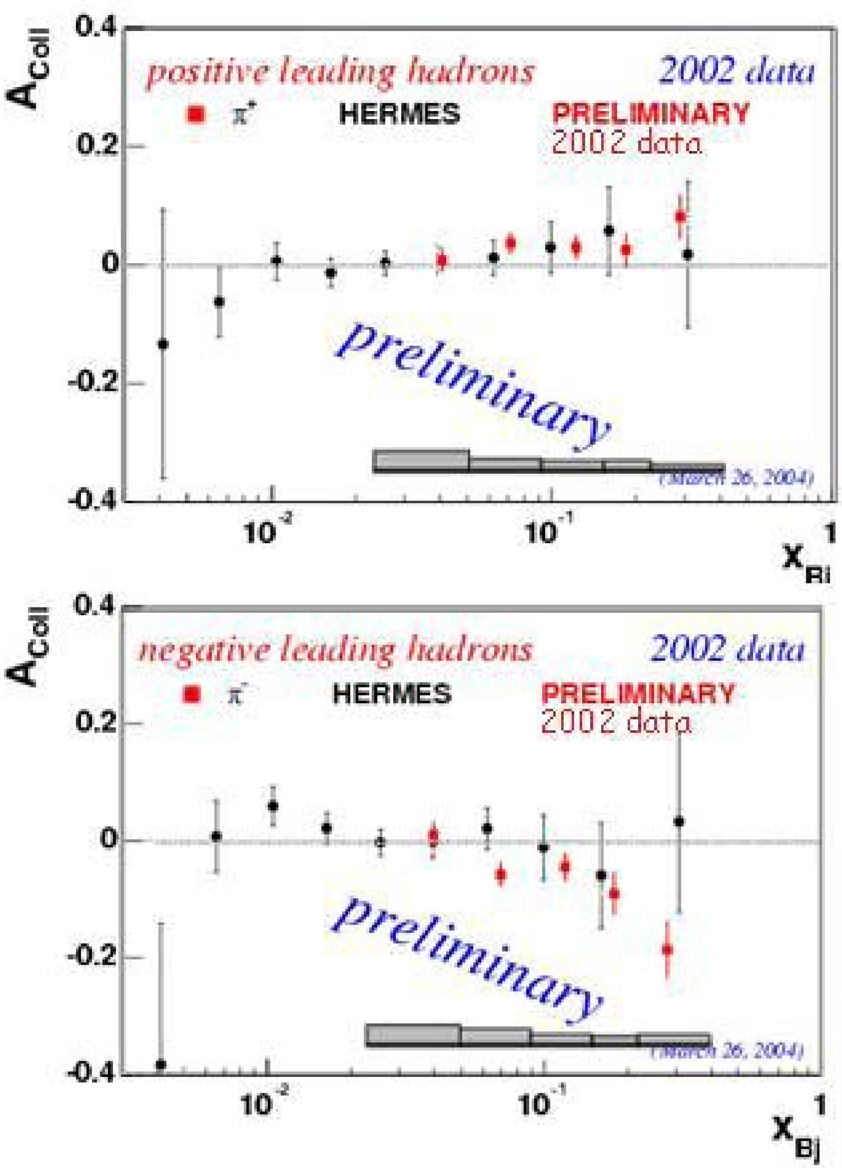
or:

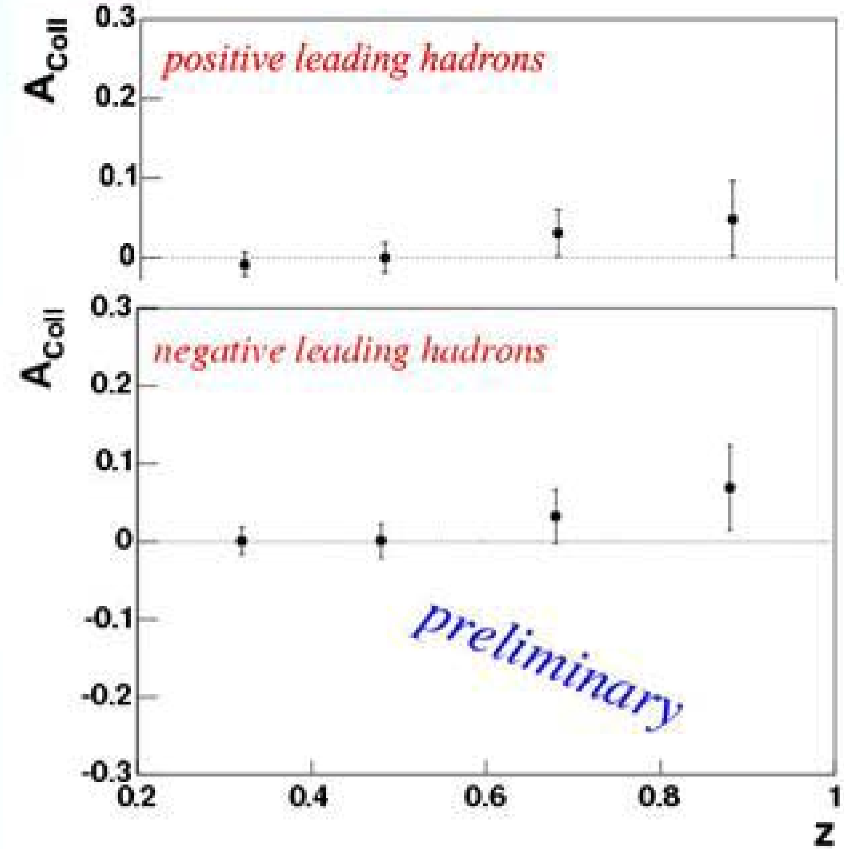


reversed once a week

Polarization: ~50%

Collins asymmetry from COMPASS

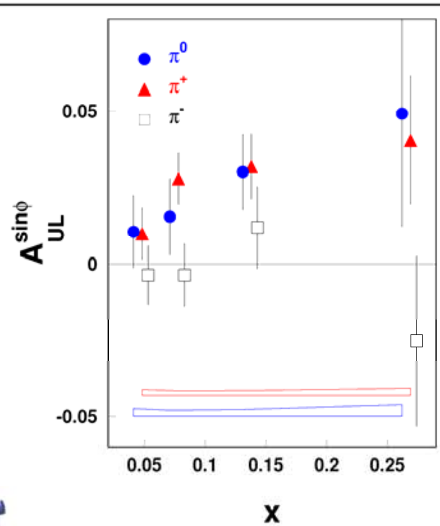




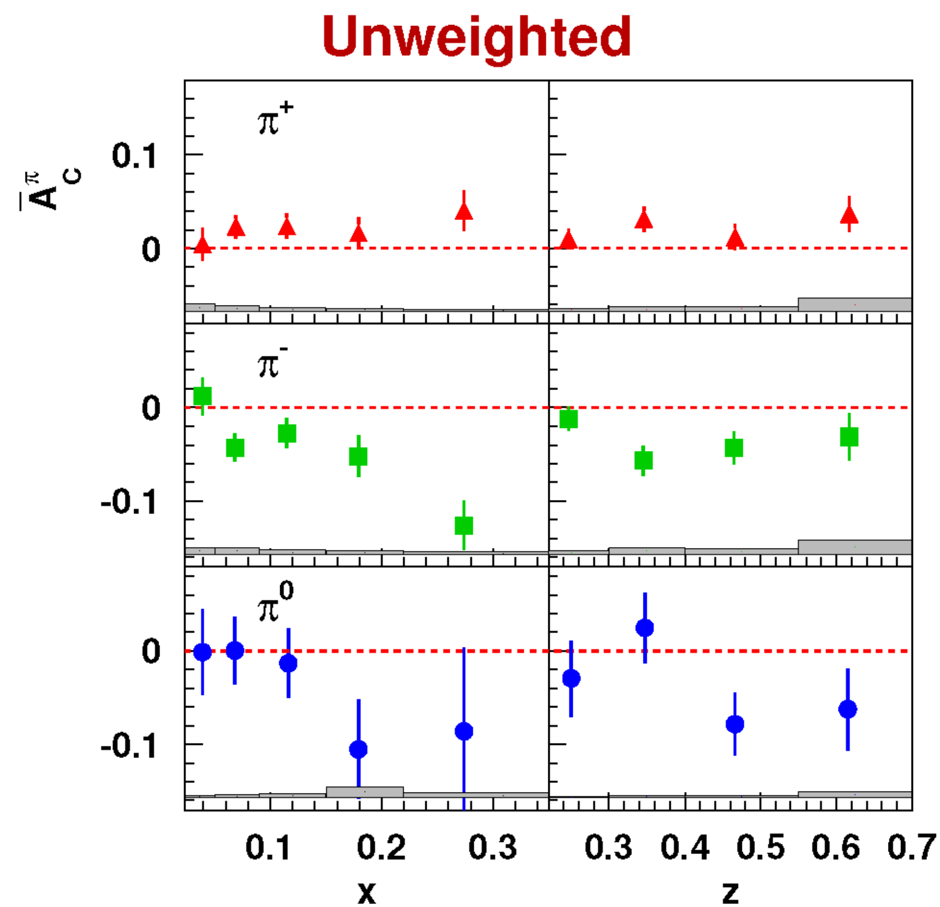
Interpretation of Collins results

The Collins results for π^+,π^- and π^0 show an unexpected behavior...
Expectation: u-quark dominance in Quark distributions
$\delta u > 0$,$\delta d < 0 \Rightarrow A^{\pi^+} > A^{\pi^0} > 0$
and $A^{\pi^-} \leq 0$ and $|A^{\pi^-}| < |A^{\pi^+}|$

A_{UL} from Proton (HERMES)



[PRL 84(2000) 4047]



New data for $A_{UT}^{Collins}$ shows $A^{\pi^+} > 0$
but $A^{\pi^0} \simeq A^{\pi^-} < 0$ and $|A^{\pi^-}| > |A^{\pi^+}|$

Interpretation in the leading order QPM

Can these data usefully constrain transversity or the Collins function?

Analyze $|P_{\pi\perp}|/(zM_\pi)$-weighted asymmetries averaged over entire acceptance.

Assumptions

- Neglect strange sea
- The usual isospin symmetry among fragmentation functions

$$
\begin{aligned}
D_{fav} &\equiv D_1(u \to \pi^+) \simeq D_1(d \to \pi^-) \simeq D_1(\bar{d} \to \pi^+) \simeq D_1(\bar{u} \to \pi^-) \\
D_{dis} &\equiv D_1(u \to \pi^-) \simeq D_1(d \to \pi^+) \simeq D_1(\bar{d} \to \pi^-) \simeq D_1(\bar{u} \to \pi^+) \\
\frac{1}{2}(D_{fav} + D_{dis}) &\simeq D_1(u \to \pi^0) \simeq D_1(d \to \pi^0) \simeq D_1(\bar{u} \to \pi^0) \simeq D_1(\bar{d} \to \pi^0)\,,
\end{aligned}
$$

- Similar symmetry among Collins functions:

$H_{fav} \equiv H_1^{\perp(1)}(u \to \pi^+)$, etc. $\qquad H_{dis} \equiv H_1^{\perp(1)}(d \to \pi^+)$, etc.

Leading order quark parton model

The $|P_{\pi\perp}|/(zM_\pi)$-weighted Collins asymmetries can then be written as:

$$A_C^{\pi^+}(x,z) = \frac{(4\delta u + \delta\bar{d})H_{fav} + (\delta d + 4\delta\bar{u})H_{dis}}{(4u + \bar{d})D_{fav} + (d + 4\bar{u})D_{dis}}$$

$$A_C^{\pi^-}(x,z) = \frac{(4\delta u + \delta\bar{d})H_{dis} + (\delta d + 4\delta\bar{u})H_{fav}}{(4u + \bar{d})D_{dis} + (d + 4\bar{u})D_{fav}}$$

$$A_C^{\pi^0}(x,z) = \frac{(4\delta u + \delta\bar{d} + \delta d + 4\delta\bar{u})(H_{fav} + H_{dis})}{(4u + \bar{d} + d + 4\bar{u})(D_{fav} + D_{dis})}$$

Isolate fewer degrees of freedom that the data might constrain

Collect all observables of the same type in each of four flavour ratios:

Spin-independent

$$r(x) \equiv \frac{d(x) + 4\bar{u}(x)}{u(x) + \frac{1}{4}\bar{d}(x)}$$

$$\mathcal{D}(z) \equiv \frac{D_{dis}(z)}{D_{fav}(z)}$$

Transverse-spin dependent

$$\delta r(x) \equiv \frac{\delta d(x) + 4\delta\bar{u}(x)}{\delta u(x) + \frac{1}{4}\delta\bar{d}(x)}$$

$$\mathcal{H}(z) \equiv \frac{H_{dis}(z)}{H_{fav}(z)}$$

Express the QPM equations in terms of these ratios . . .

Leading order QPM, rearranged

In terms of these flavour ratios, the asymmetries become

$$
\begin{aligned}
A_C^{\pi^+}(x,z) &= \mathcal{K}(x,z)\frac{4+\delta r(x)\mathcal{H}(z)}{4+r(x)\mathcal{D}(z)} \\
A_C^{\pi^-}(x,z) &= \mathcal{K}(x,z)\frac{4\mathcal{H}(z)+\delta r(x)}{4\mathcal{D}(z)+r(x)} \\
A_C^{\pi^0}(x,z) &= \mathcal{K}(x,z)\frac{(4+\delta r(x))(1+\mathcal{H}(z))}{(4+r(x))(1+\mathcal{D}(z))}\,, \\
\text{where}\quad \mathcal{K}(x,z) &\equiv \frac{\delta u(x)+\frac{1}{4}\delta\bar{d}(x)}{u(x)+\frac{1}{4}\bar{d}(x)}\,\frac{H_{fav}(z)}{D_{fav}(z)}
\end{aligned}
$$

These three equations are not independent:

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

where $C(x,y)$ is constructed of known spin-independent quantities:

$$C(x,z)\equiv\frac{r(x)+4\mathcal{D}(z)}{r(x)\mathcal{D}(z)+4}$$

$r(x)$ from CTEQ6 and R1990

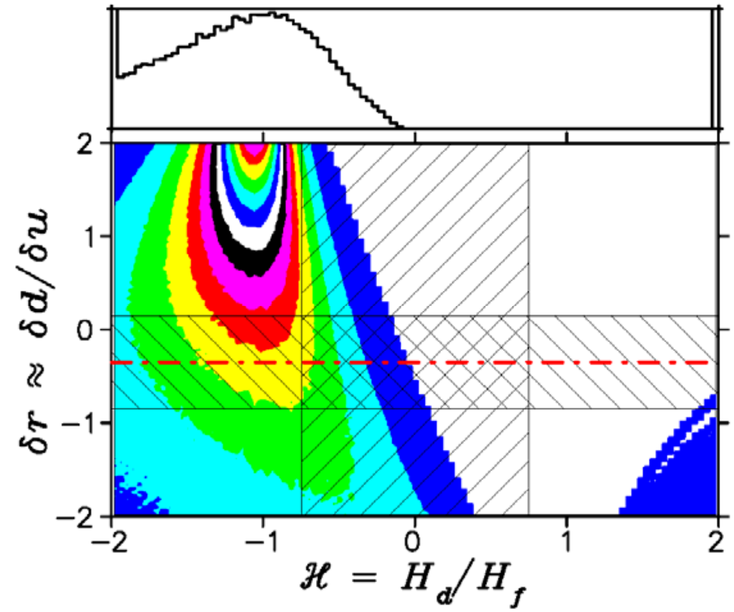
$\mathcal{D}(z)$ from *Kretzer* et al., *Eur. Phys. J. C 22 (2001) 269*

Using acceptance-averaged data

- Have two constraints in three unknowns: δr, $\mathcal{H}$ and $\mathcal{K}$.
- Take ratios of equations:
  $\Rightarrow$ eliminate the "messy" unknown $\mathcal{K}$
- Relate these two unknowns:

$$\delta r \equiv \frac{\delta d + 4\delta\bar{u}}{\delta u + \frac{1}{4}\delta\bar{d}}$$

$$\mathcal{H} \equiv \frac{H_{dis}}{H_{fav}}$$



- Sample Gaussian distributions in three asymmetries, taking all combinations
  $\Rightarrow$ set of trajectories in δr versus $\mathcal{H}$.
- Plot density of trajectories: $\Rightarrow \Rightarrow$
- Hatched bands are arbitrary guesses of previously plausible ranges

- Horizontal red line is prediction of chiral quark soliton model:
  Wakamatsu, Phys. Lett. B509 (2001) 59; Schweitzer et al., *Phys. Rev. D 64 (2001) 034013*

Disfavored Collins function is opposite in sign and large!!

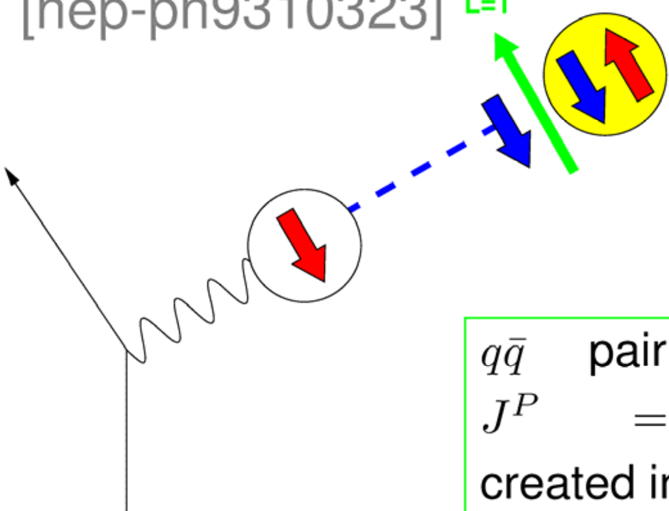
Disfavored Collins fragmentation

Possible explanation: $H_{1,\mathrm{dis}}^{\perp} \approx -H_{1,\mathrm{fav}}^{\perp}$?

unpol. Lund MC

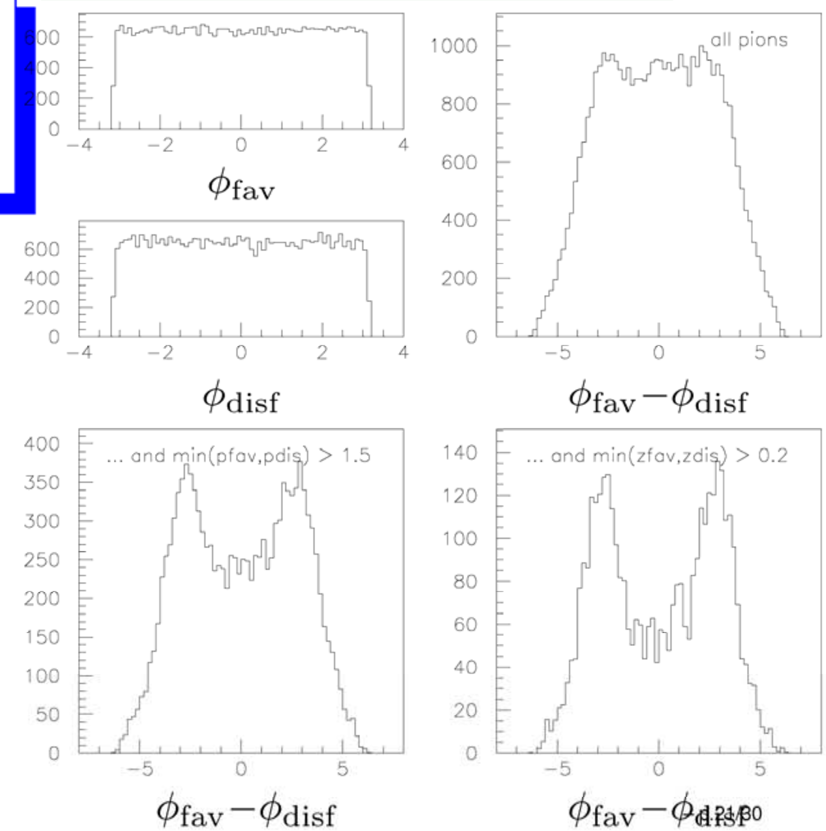
Artru model

[hep-ph9310323]



leading π into plane

$q\bar{q}$ pair with $J^P = 0^+$ created in string breaking



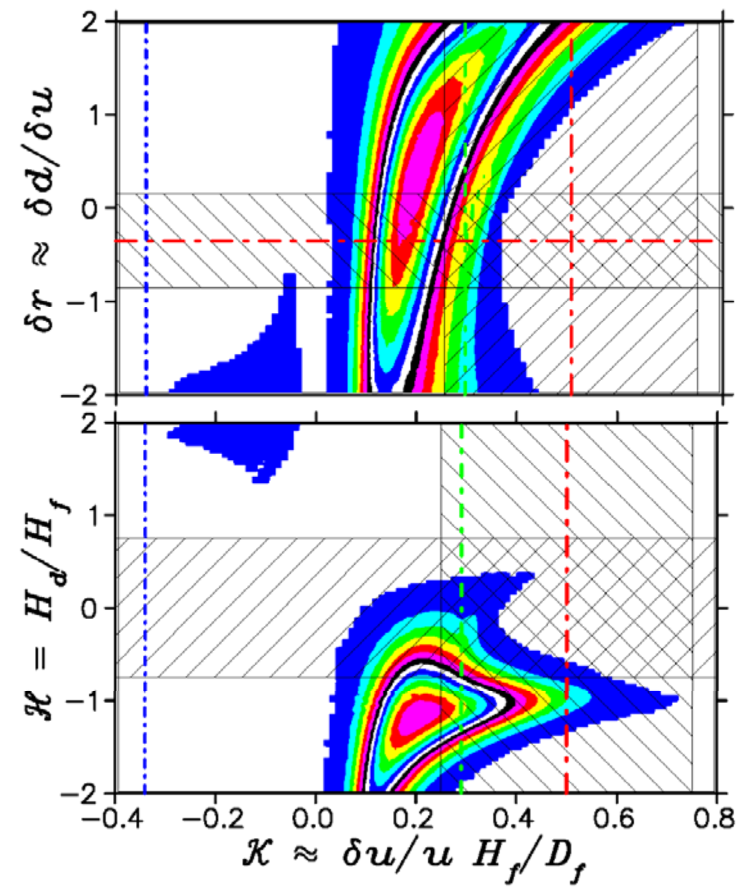
Constraints on transversity/Collins function

- The Gaussian sampling defines a set of trajectories through the 3-dimensional space in $\delta r, \mathcal{H}$ and $\mathcal{K}$
- Can view a projection on other two planes: $\Rightarrow \Rightarrow$
- Trajectories are excluded from unphysical range in other unknown
- Theoretical predictions for $\mathcal{K}$ are χQSM plus Collins functions from:

Bacchetta et al., *Phys. Rev. D 65 (2002) 094021:*
pions & constit. quarks, one-loop corrns

Gamberg et al., *Phys. Rev. D 68 (2003) 051501:*
same tree level plus gluon exchange

Bacchetta et al., *Phys. Lett. B574 (2003) 225:*
similar plus other gluon loops



Much of previously plausible space is excluded by these data

Extracting the Sivers functions

A similar analysis proceeds with one fewer unknown

(no spin-dependent fragmentation)

$\Rightarrow$ the system can be solved for first x-moments of the Sivers functions:

$$f_{1T}^{\perp(1)u} + \frac{1}{4} f_{1T}^{\perp(1)\bar{d}} = -0.044 \pm 0.016\,(\mathrm{stat})$$
$$f_{1T}^{\perp(1)d} + 4 f_{1T}^{\perp(1)\bar{u}} = 0.074 \pm 0.066(\mathrm{stat})$$

Theoretical predictions have been made by:

Yuan, Phys. Lett. B575 (2003) 45: $f_{1T}^{\perp(1)u} = -0.01$ (correct sign!) $f_{1T}^{\perp(1)d} = +0.003$

MIT bag model with one gluon exchange from gauge link

Bacchetta et al., *Phys. Lett. B578 (2004) 109:* $f_{1T}^{\perp(1)u} = 0.037$ (wrong sign) $f_{1T}^{\perp(1)d} = -0.011$

Spectator model: quark plus scalar and axial-vector diquarks, dipole form factors

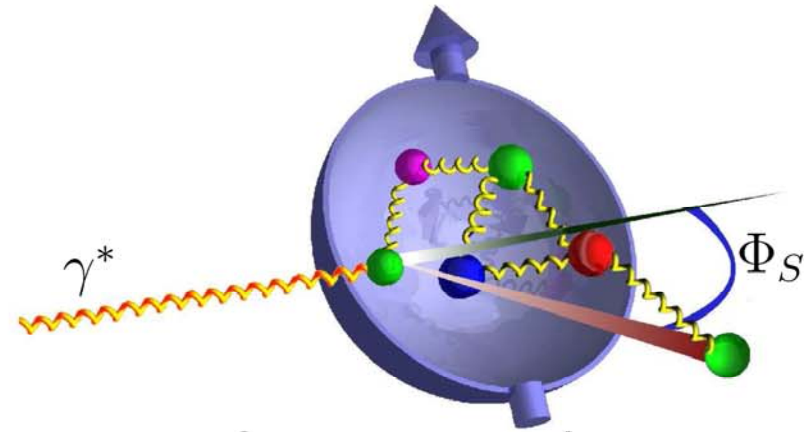
A model for the Sivers effect

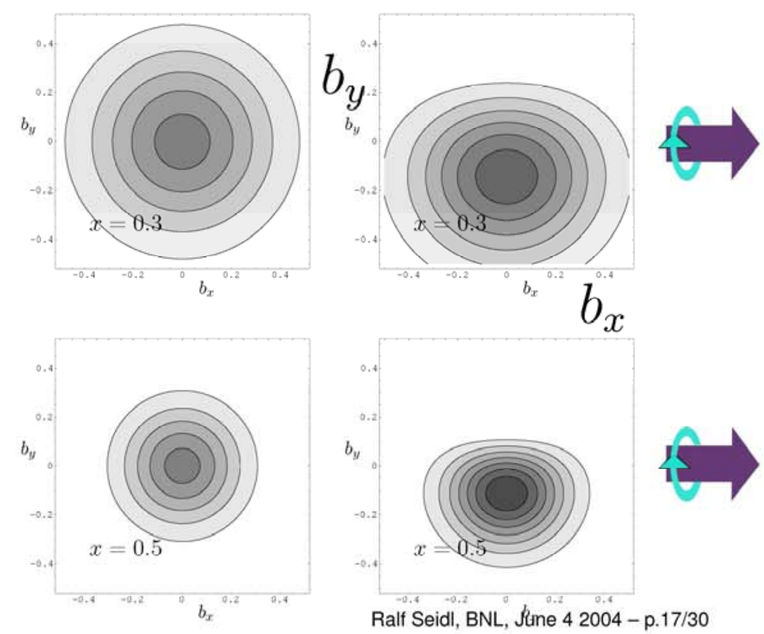
Sivers effect

- rescattering of hit quark by gluon
- M.Burkardt (hep-ph0309269) - impact parameter (b_x, b_y) formalism
- Orbital angular momentum at finite impact parameter $\rightarrow$ observed and true x_B differ

$$x_{B,obs} = x_{B,true} \pm \Delta x_B$$

- higher possibility to find quarks on one side ($q(x)$ is not flat!)





Predicts opposite signs for Sivers effect on u and d

Flavor decomposition of Sivers effect?

- The photon-nucleon Sivers Asymmetry is

$$A_S^h(x) = -|S_T| \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 q(x) \cdot z D_q^h(z)}{\int_{z_{min}}^1 dz \sum_{q'} e_{q'}^2 q'(x) \cdot D_{q'}^h(z)} \cdot \frac{f_{1T}^{\perp q}(x)}{q(x)}$$

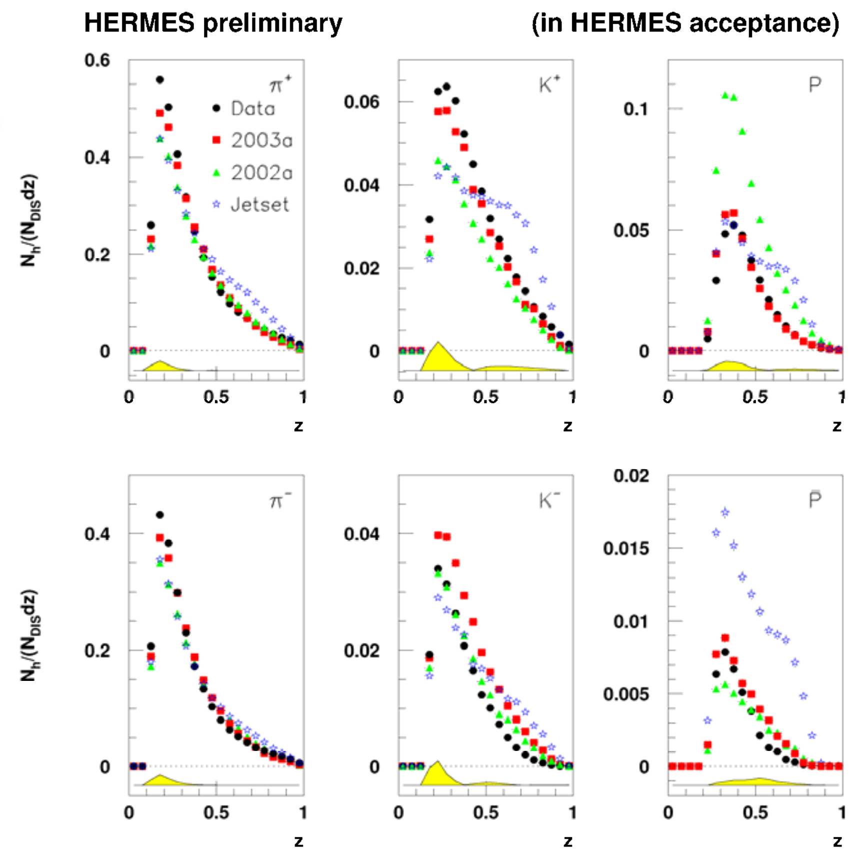
$$= \sum_q P_q^h(x) \frac{f_{1T}^{\perp q}(x)}{q(x)}$$

- The hadron quark-purity $P_q^h(x)$ is the probability that a quark q was struck in an event $l + N \longrightarrow l' + X$ - is a spin-independent quantity

- Define

$$\vec{A} = \begin{pmatrix} A^{h_1}(x) \\ \dots \\ A^{h_n}(x) \end{pmatrix}, \vec{Q} = \begin{pmatrix} f_{1T}^{\perp 1}(x)/q_1(x) \\ \dots \\ f_{1T}^{\perp n}(x)/q_n(x) \end{pmatrix}, P = [P_q^h(x)]$$

$$\vec{A} = P\vec{Q}$$



Perform a simultaneous global analysis of all $A^h{}_S(x)$'s

Summary and outlook

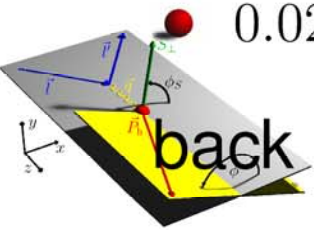
- First measurements of asymmetries directly related to transversity
- The flavor-disfavored Collins function appears to be opposite in sign to the favored one, and be of comparable magnitude
- A quantity containing δu and the favored Collins function can constrain theoretical models
- Nonzero Sivers asymmetries are observed – a manifestation of quark orbital angular momentum
- Running with a transversely polarized target will continue until mid-2005

Acknowledgements

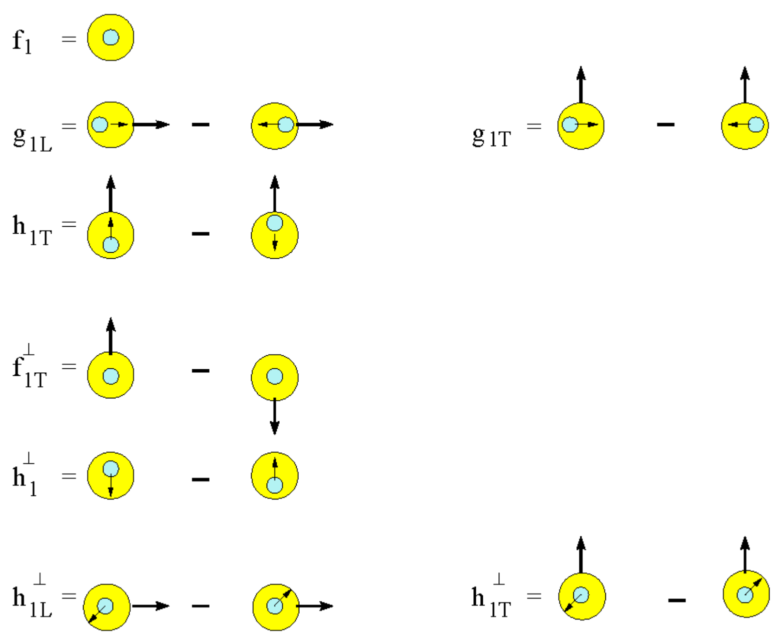
It is a pleasure to acknowledge the work of the HERMES transversity group and, in particular, that of Ulrike Elschenbriosh(Gent), Ralf Seidl (Erlangen), Gunar Schnell(Tokyo), and Naomi Makins(Illinois) who furnished much of the source material for this talk.

- vertex and acceptance cuts
- $0.1 \leq y < 0.85$
- $0.023 < x < 0.4$
- $W^2 > 10\ \mathrm{GeV}^2$
- $Q^2 > 1\ \mathrm{GeV}^2$
- $2\ \mathrm{GeV} < p_{\mathrm{track}} < 15\ \mathrm{GeV}$
- $4\ \mathrm{GeV} < p_{\mathrm{track}} < 13.8\ \mathrm{GeV}$ (A^p_{UL})
- π^0 :$0.1\ \mathrm{GeV} < M_{\gamma\gamma} < 0.17\ \mathrm{GeV}$
- $0.2 < z < 0.7$
- $0.02\ \mathrm{rad} < \theta_{\gamma,\mathrm{had}}$

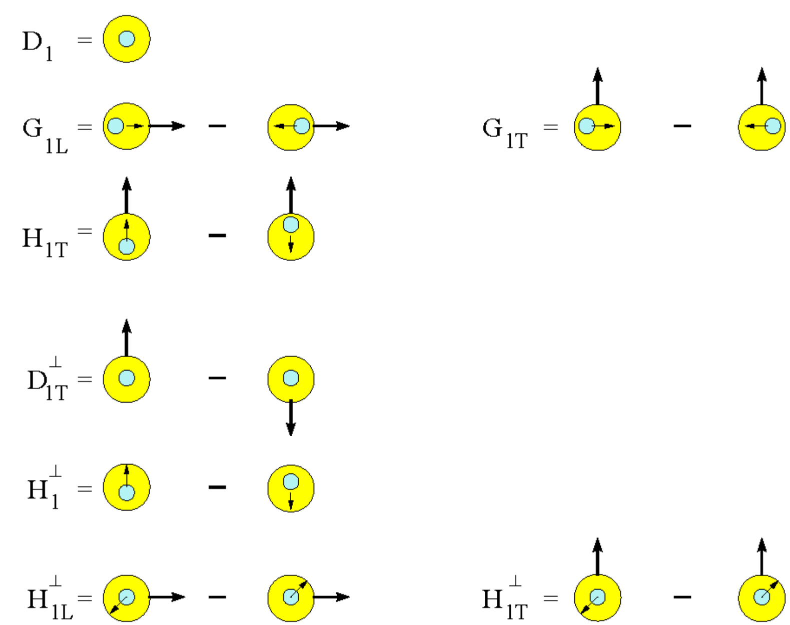
year	target gas	orientation	# pol. DIS
96-97	p	L	2.4M
98-00	d	L	8.9M
02-	p	T	1.5M



Distribution Functions



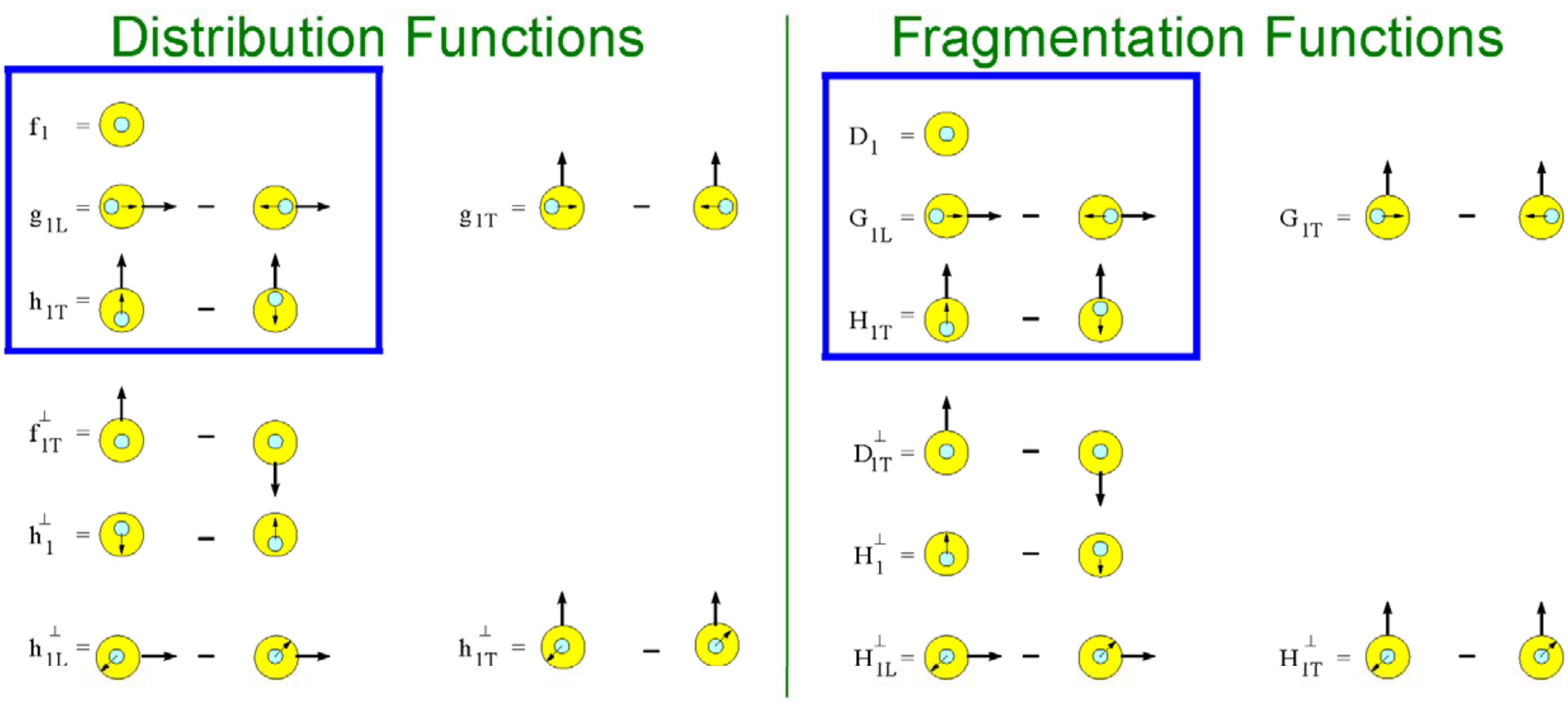
Fragmentation Functions



hermes

Functions Surviving on Integration over Transverse Momenta

- The others are sensitive to intrisic $< k_t >$ in the nucleon & in the fragmentation process



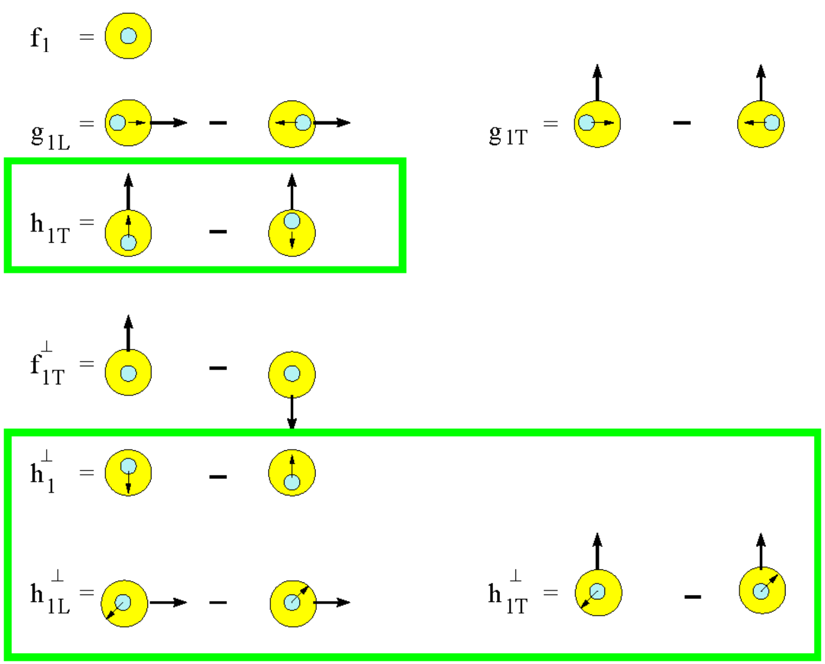
Higher Twist Functions (no pictures)

- Sensitive to parton-parton correlations
- Have a twist-2 part ... e.g. $h_L(x) = 2x \int_x^1 dy \frac{h_1(y)}{y^2}$

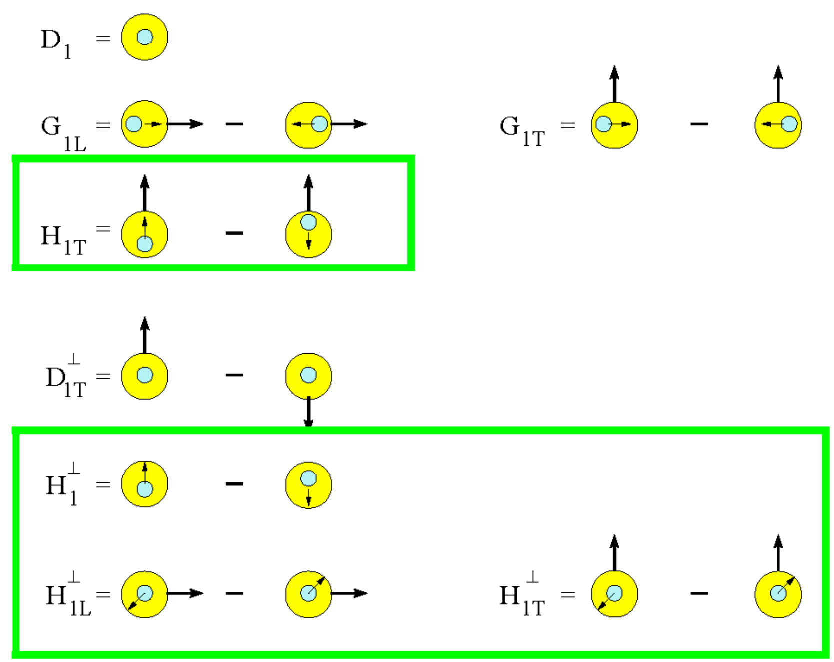
Chiral-Odd Functions

- Involve helicity flip of transverse quark
- Appear in pairs in cross-sections

Distribution Functions



Fragmentation Functions



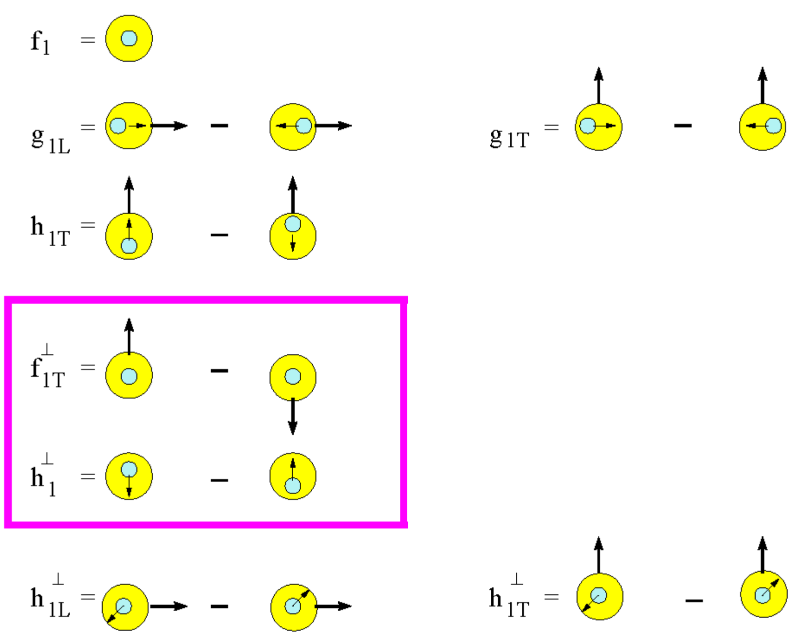
e.g. Transversity $h_1(x)$

- $h_1(x) \sim \delta q(x)$ ... cf. $f_1(x) \sim q(x), g_1(x) \sim \Delta q(x)$
- $\delta q(x) \neq \Delta q(x) \rightarrow$ relativistic / spin-orbit effects

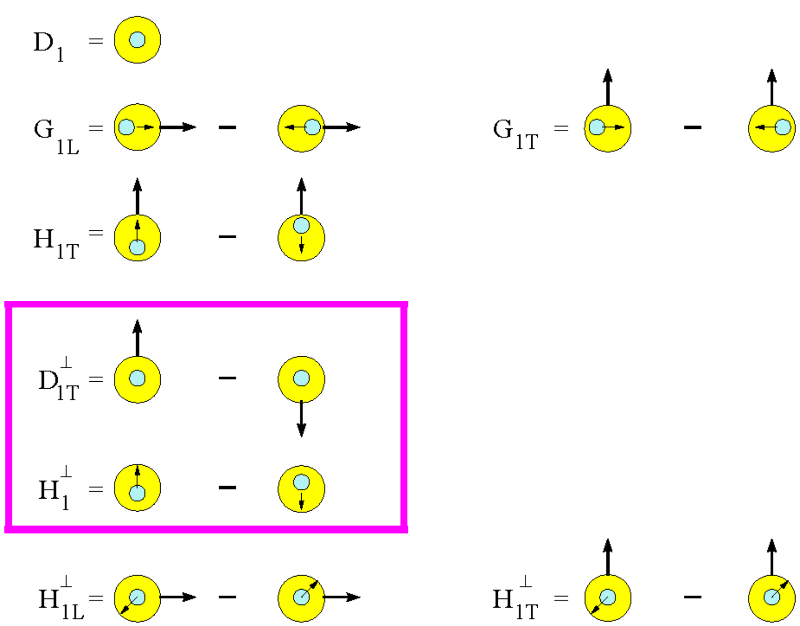
T-Odd Functions

- one T-odd functon required to produce single spin asymmetries in SIDIS
- sensitive to transversely polarized quarks/hadrons given unpolarized hadrons/quarks

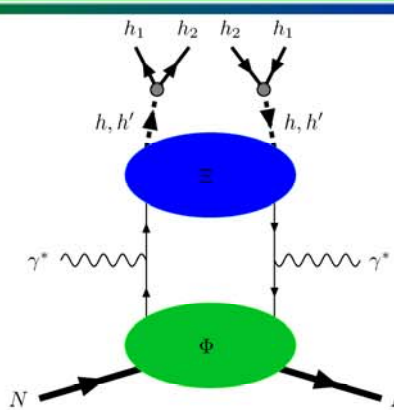
Distribution Functions

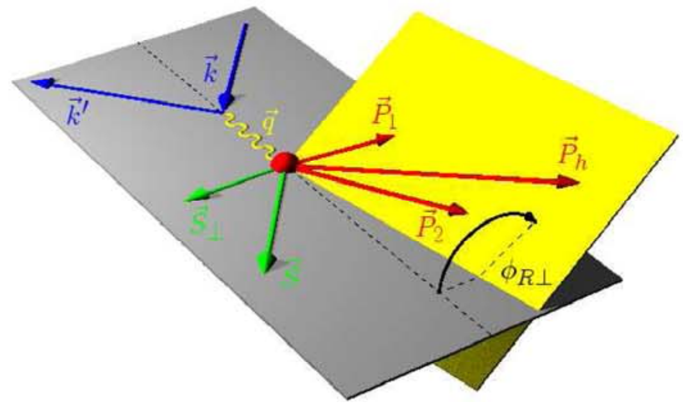


Fragmentation Functions



Interference Fragmentation function (IFF)





- Production of 2 Mesons around $\rho(\pi^+\pi^-)$, $\phi(K\bar{K})$ or $K^*(K\pi)$ mass region

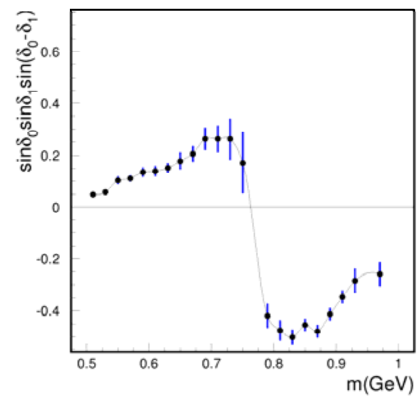
$$\cos\phi_{RT} = \frac{\vec{P}_+ \times \vec{P}_- \cdot \vec{k} \times \vec{k}'}{|\vec{P}_+ \times \vec{P}_-| \cdot |\vec{k} \times \vec{k}'|}$$

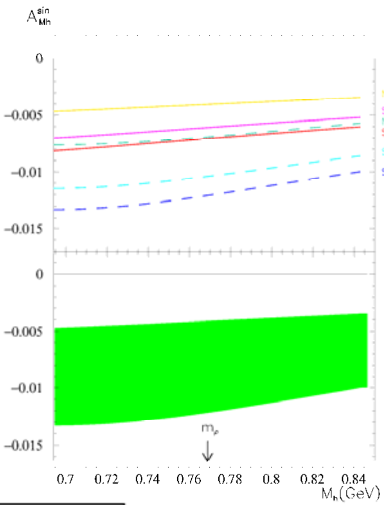
- Interference of s- und p-waves of 2-meson-system
- different mechanisms proposed with different M_h behaviour
- T-even $\Rightarrow$ Factorization is safe

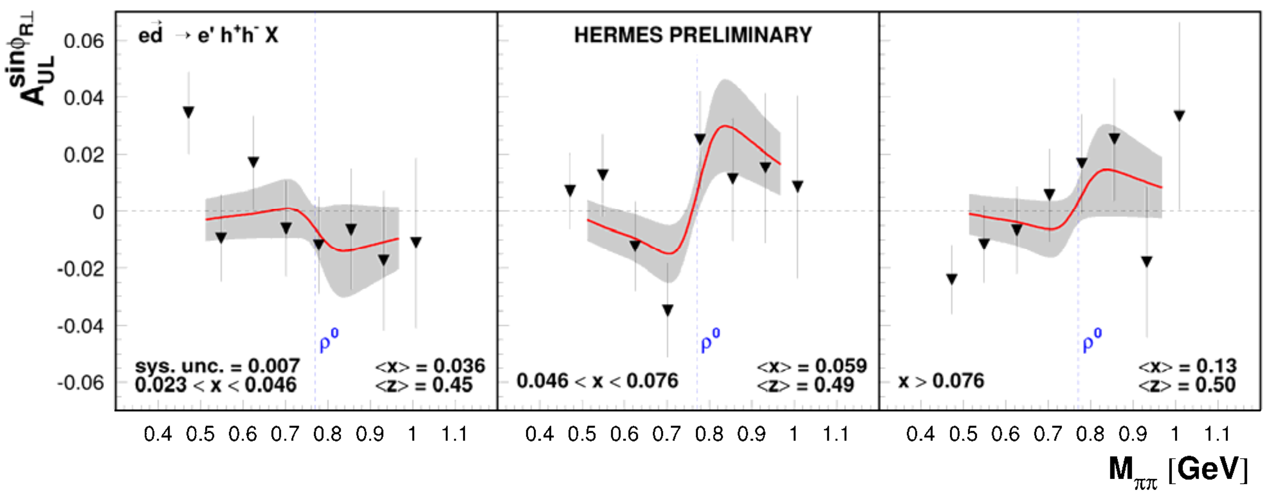
$$\frac{d^7\sigma_{UT}}{d\zeta dM^2_{\pi\pi} d\phi_R dz dx dy d\phi_S} =$$
$$\sum_q \frac{2\alpha^2 e_q^2}{s M^2_{\pi\pi}} |\mathbf{S}_T||R| B(x,y) \sin(\phi_R + \phi_S) \sin\Theta \delta q \left[H^{\sphericalangle q}_{1,UT} + H^{\sphericalangle q}_{1,LT} \cos\Theta \right]$$

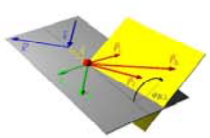
First longitudinal *IFF* asymmetries

Information on
$\pi^+\pi^-$ phase
shifts available
(since '70s)









Ralf Seidl, BNL, June 4 2004 – p.23/30