Transversity and Friends: Where We'll Be a Decade from Now

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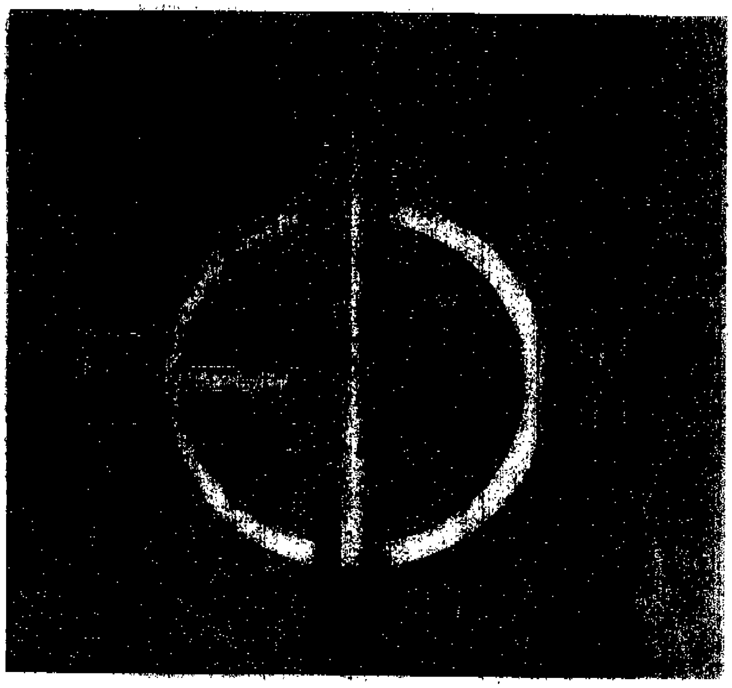
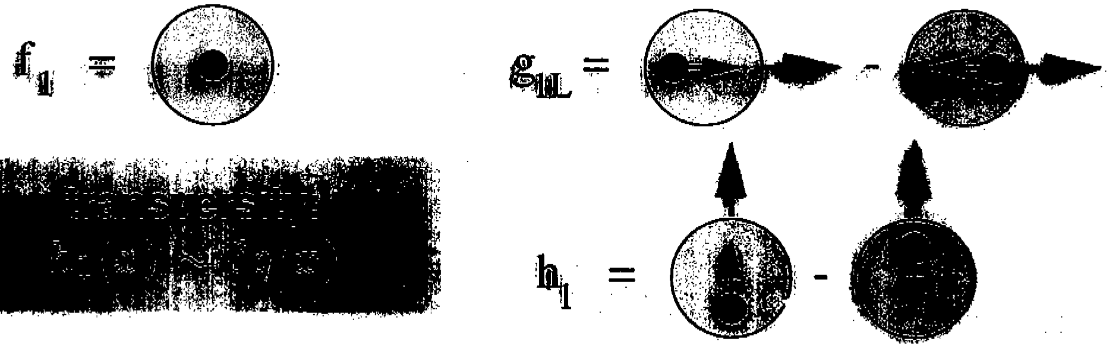


- *Transversity and Friends: the Other Leading-Twist Parton Distribution Functions*
- *Latest results from DIS*
- *Universality and e^+e^- / Drell-Yan Prospects*
- *Conclusions and Outlook: We Need the EIC!*

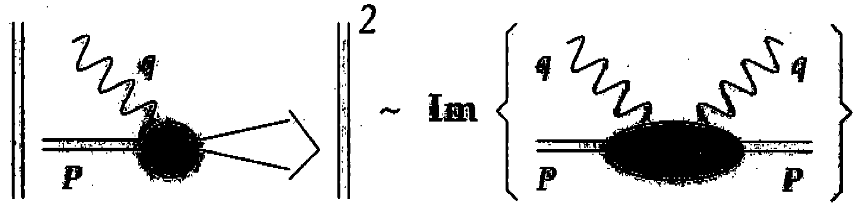
Transversity

A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution $\delta q(x)$.

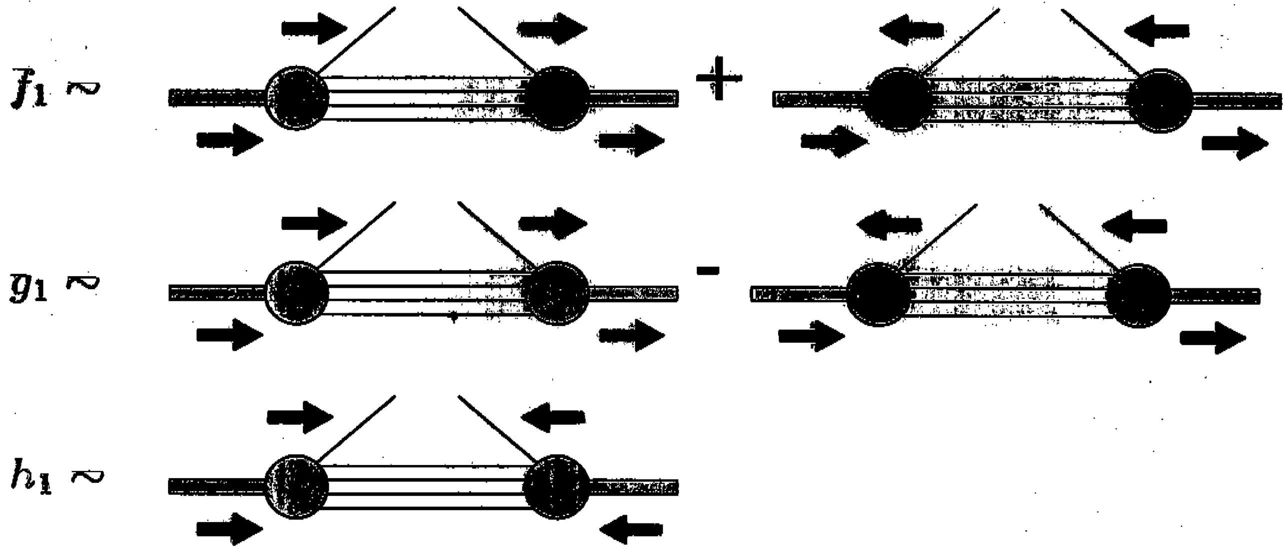


transversity
$h_1(x) \equiv \delta q(x)$

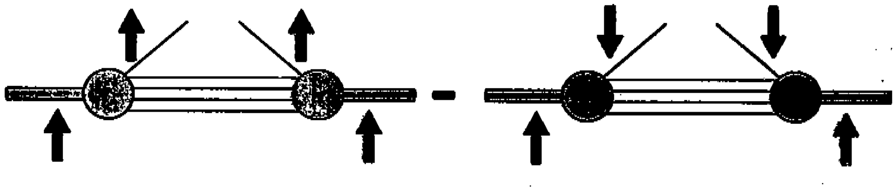
Forward Helicity Amplitudes



(optical theorem applied to DIS)



Target not in
helicity eigenstate
⇒ **transversity basis**



In Non-Relativistic Case ...

In the absence of **relativistic effects** , boosts and rotations commute:

$$\delta q(x) = \Delta q(x)$$

Tensor Charge of the Nucleon

Fundamental matrix elements:

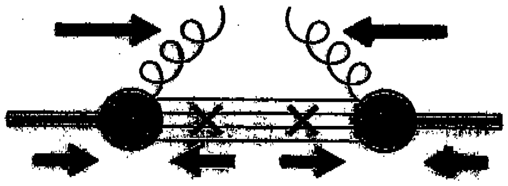
vector charge $\langle PS|\bar{q}\gamma^\mu q|PS\rangle = \int_0^1 dx\, q(x) - \bar{q}(x)$ (# q_{valence})

axial charge $\langle PS|\bar{q}\gamma^\mu\gamma_5 q|PS\rangle = \int_0^1 dx\, \Delta q(x) \mp \Delta\bar{q}(x)$ (net q spin)

tensor charge $\langle PS|\bar{q}\sigma^{\mu\nu} q|PS\rangle = \int_0^1 dx\, \delta q(x) - \delta\bar{q}(x)$

⇒ tensor charge is **pure valence object** ...
promising for comparison with lattice QCD

No Gluons

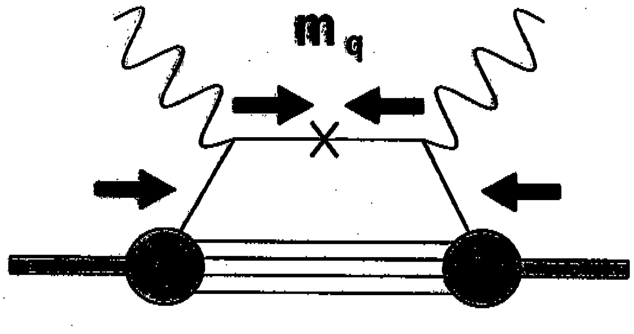


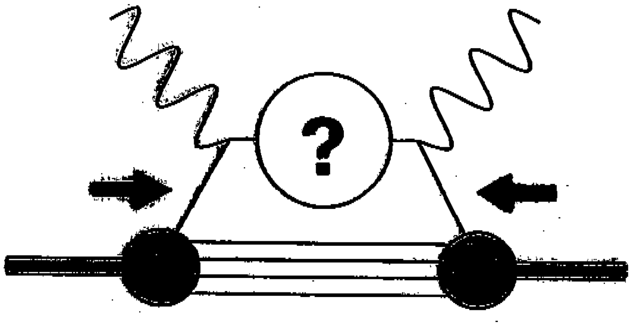
Angular momentum conservation
$\Rightarrow \Lambda - \lambda = \Lambda' - \lambda'$
Different **Q^2 evolution** than g_1.

Chiral Odd

Helicity flip amplitudes occur only at $O(m_q/Q)$ in inclusive DIS ...

but they are observable in e.g. **semi-inclusive** reactions





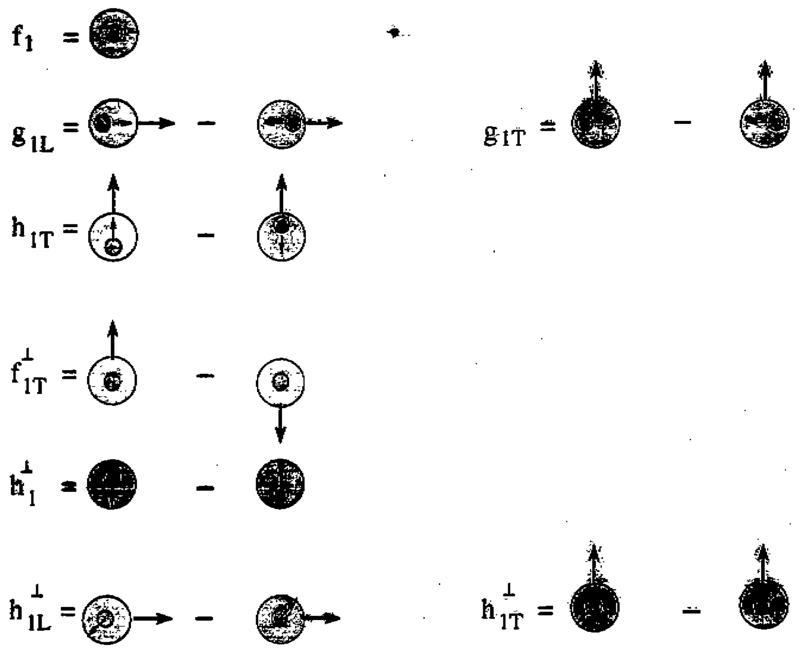
Functions Surviving on integration over Transverse Momenta

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

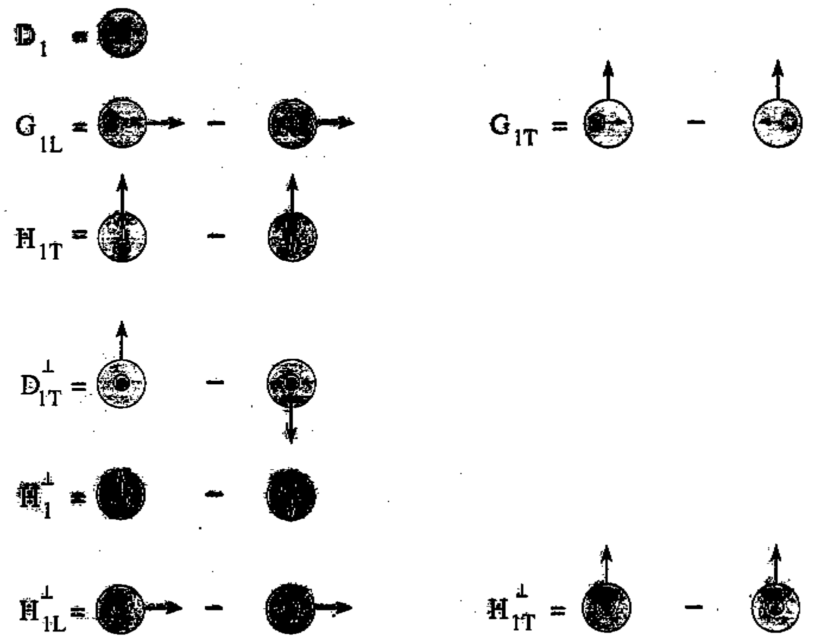
Higher Twist Functions
(no pictures)

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

Distribution Functions

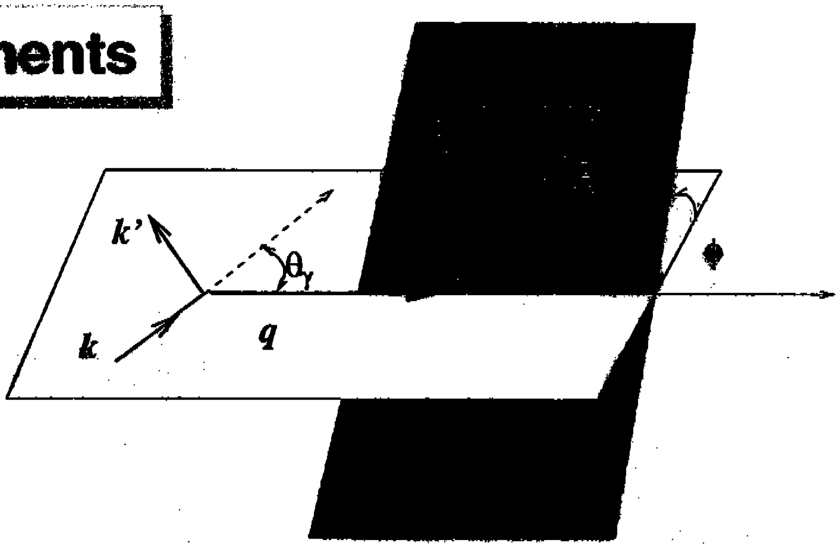


Fragmentation Functions



Azimuthal Moments

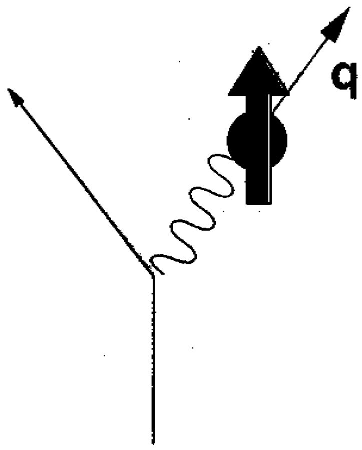
"The Bible":
Mulders & Tangerman,
PLB 461 (1996) 197



Polarized SIDIS xsec at leading order in $1/Q$:

UU	1	$\otimes f_1 =$ ●	$\otimes D_1 =$ ●
	$\cos(2\phi_h^l)$	$\otimes h_1^\perp =$ ● - ●	$\otimes H_1^\perp =$ ● - ●
UL	$\sin(2\phi_h^l)$	$\otimes h_{1L}^\perp =$ ●→ - ●→	$\otimes H_1^\perp =$ ● - ●
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes h_1 =$ ↑● - ↑●	$\otimes H_1^\perp =$ ● - ●
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes f_{1T}^\perp =$ ↑● - ●↓	$\otimes D_1 =$ ●
	$\sin(3\phi_h^l - \phi_S^l)$	$\otimes h_{1T}^\perp =$ ↑● - ↑●	$\otimes H_1^\perp =$ ● - ●
LL	1	$\otimes g_1 =$ ●→ - ●→	$\otimes D_1 =$ ●
LT	$\cos(\phi_h^l - \phi_S^l)$	$\otimes g_{1T} =$ ↑● - ↑●	$\otimes D_1 =$ ●

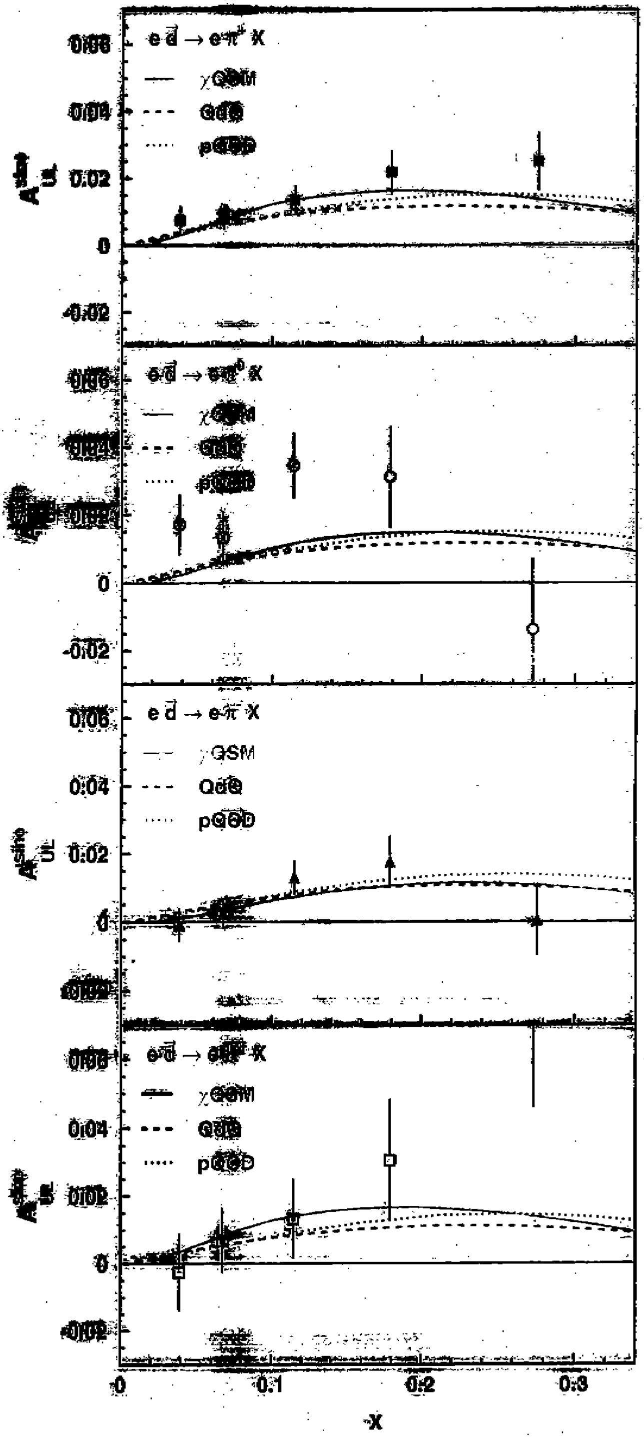
Spin-Azimuthal Asymmetry A_{UL}



$$A(\phi) = \frac{1}{P_{\text{target}}} \frac{N^{p\rightarrow}(\phi) - N^{p\leftarrow}(\phi)}{N^{p\rightarrow}(\phi) + N^{p\leftarrow}(\phi)}$$

$$A_{\mathrm{UL}}^{\sin\phi} = \frac{S_L \langle \sin\phi \rangle_{\mathrm{UL}} + S_T \langle \sin\phi \rangle_{\mathrm{UT}}}{S \langle 1 \rangle_{\mathrm{UU}}}$$

with $\boxed{S_L/S \approx 1,\ S_T/S \approx 1/Q}$

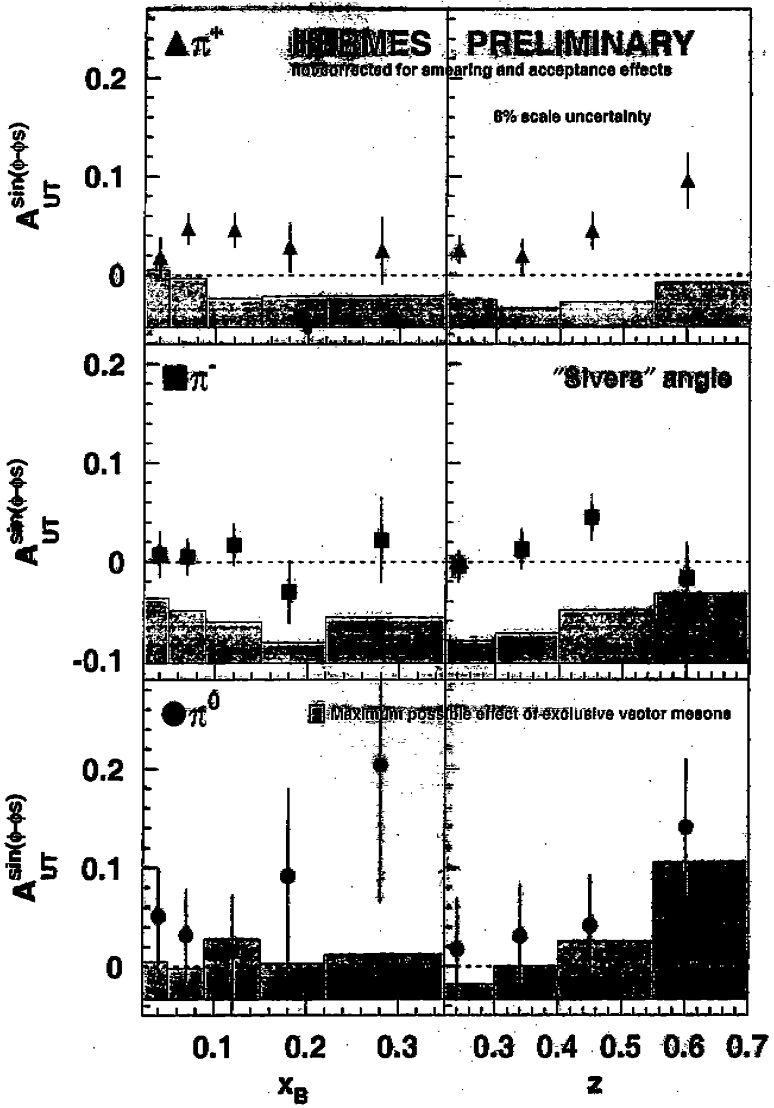


Theory predictions see to explain the data well …
but contain a lot of assumptions

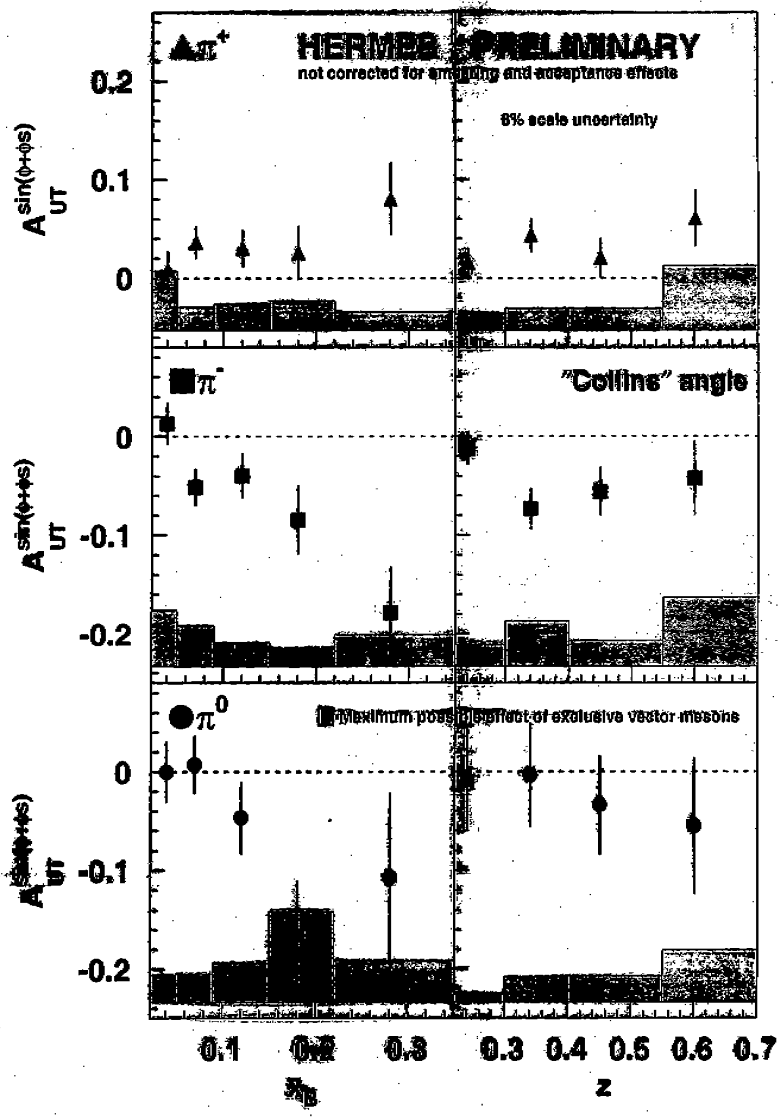
- $\langle \sin\phi \rangle_{\mathrm{UT}} \sim h_1\, H_1^{\perp}$ accounts for only 30% of the asymmetry (best estimate)
- $\langle \sin\phi \rangle_{\mathrm{UL}}$ contains twist-3 functions
- magnitude of $H_1^{\perp}/D_1 \approx 4$ — 12%
- unknown Sivers contribution not considered

Results I: Unweighted Moments

“Sivers” Moments



“Collins” Moments

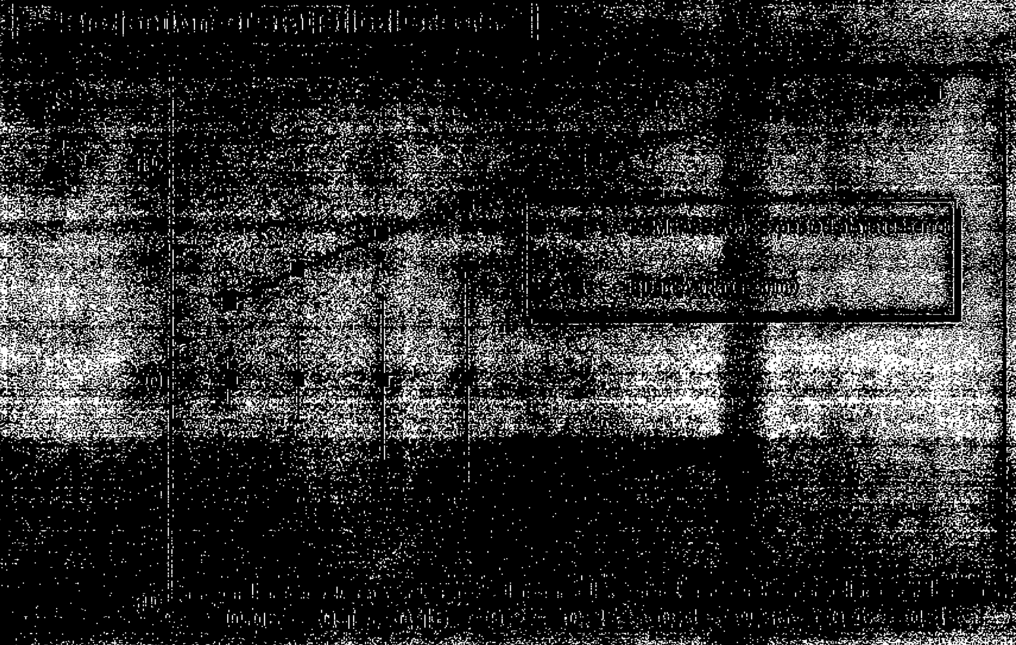


Sivers $\langle A^{\pi^+} \rangle$ *3σ away from zero* ... Collins *asym large for π^0 and π^-*

Azimuth Asymmetries

20% of 2002 running with transverse polarized ^{6}LiD-target

Error on asymmetry projected from preliminary analysis

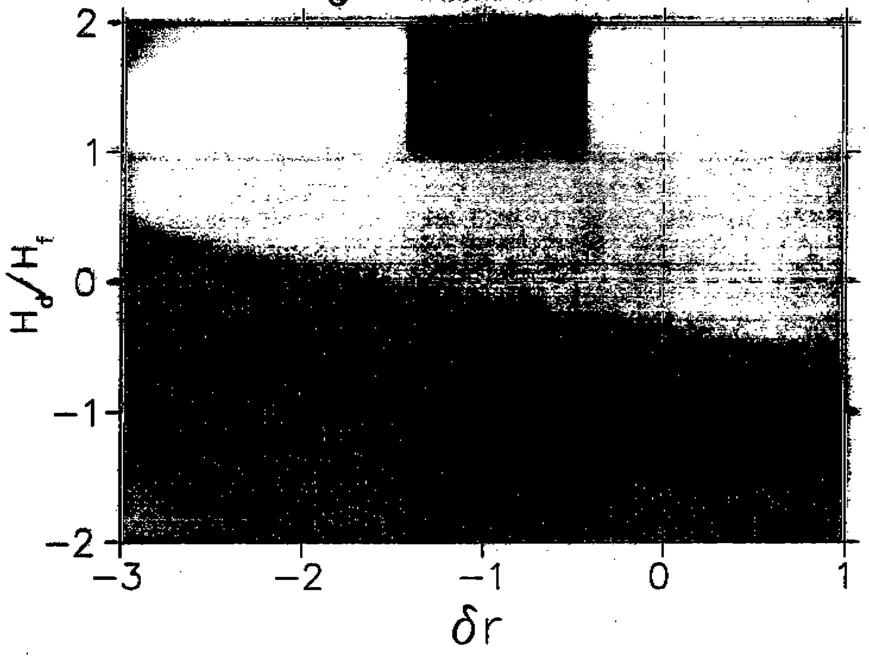


Interpretation of Collins Results

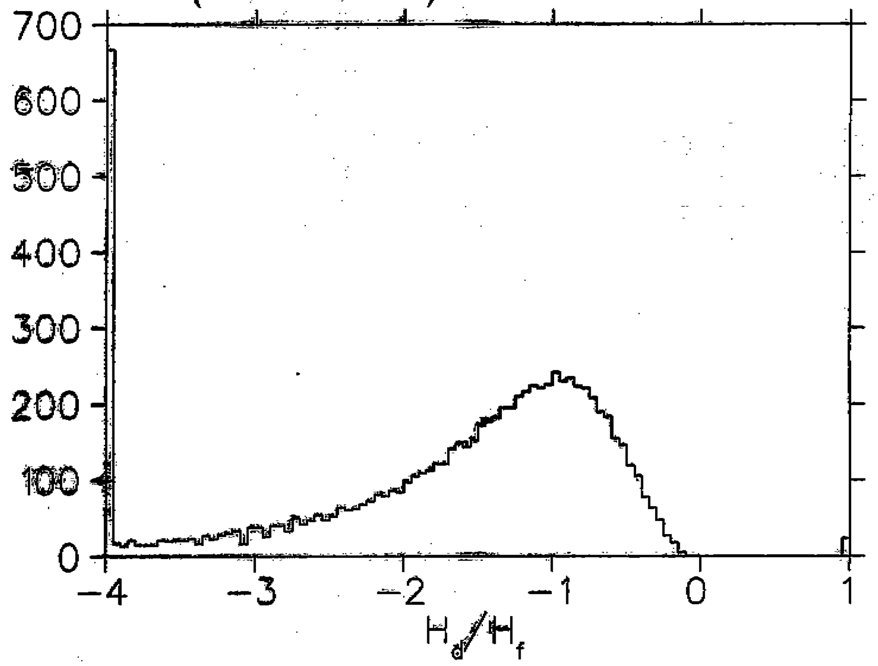
① **Constraint equation:** well satisified by both weighted and unweighted asymmetries (within 1σ statistical) ➡ no problem with internal consistency

② **Solution space** for $\boxed{\delta r \approx \delta d/\delta u}$ vs $\boxed{\eta_H = H_{\rm dis}/H_{\rm fav}}$

solution space populated
according to statistical errors



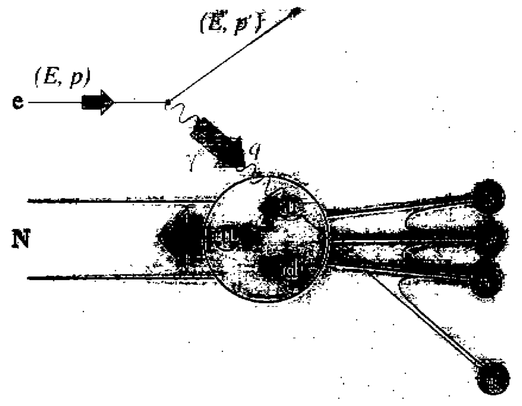
η_H solutions at χQSM value
(Wakamatsu) $\delta r = -0.93$



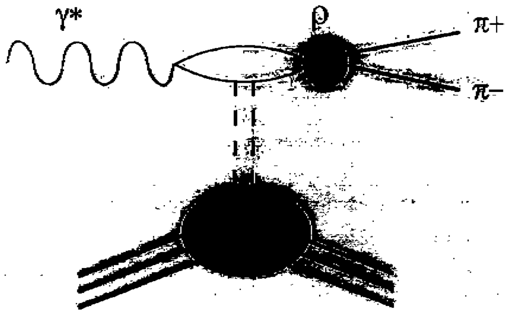
***Neglecting** possible diffractive contamination* , there seems to be a pronounced indication that $H_{\rm fav} \approx -H_{\rm dis}$

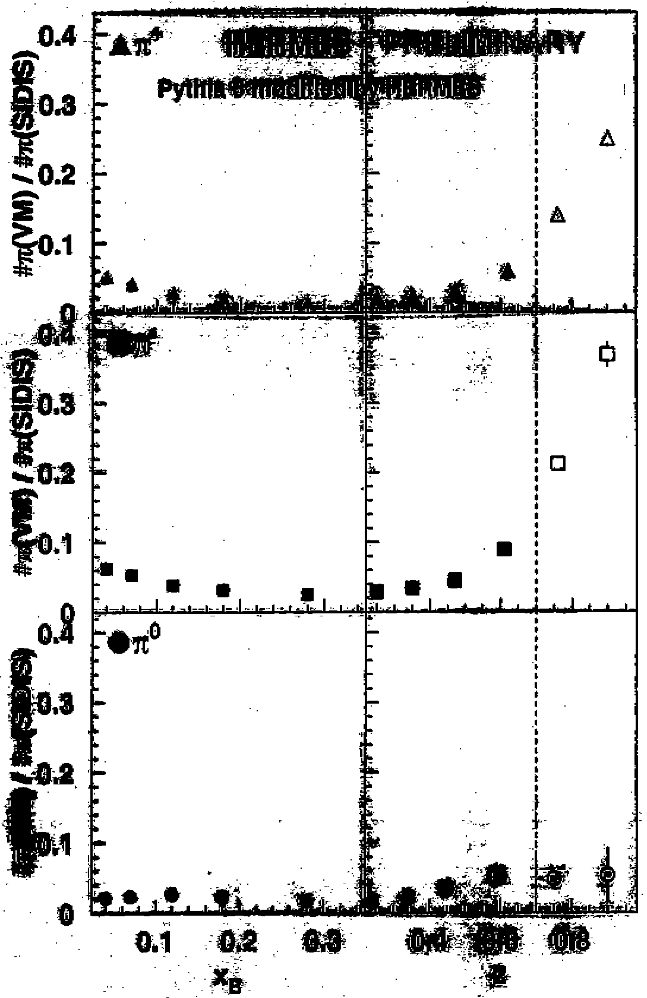
Interpretive Uncertainty from Diffractive VM Contribution

Desired process: SIDIS $ep \rightarrow \pi^+ X$



Diffractive ρ^0 production: different physics ... ?





Conservative approach: calculate systematic error for full range of possible diffractive ρ asymmetries: $A_{\mathrm{UT}}^{\mathrm{Collins},\rho}$ *and* $A_{\mathrm{UT}}^{\mathrm{Sivers},\rho} = \pm 1$

Other Ways to Measure $h_1(x)$

① **Interference Fragmentation Function to two pions**

Good possibilities at PH✳ENIX

② **Higher Twist Fragmentation Function $\tilde{E}$**

$$d\sigma_{LT} \sim \cos(\phi_S^l)\left[\frac{Mx}{Q}\cdot g_T(x)\,D_1(z) + \frac{M_h}{zQ}\cdot \mathbf{h}_1(x)\,\tilde{E}(z)\right]$$

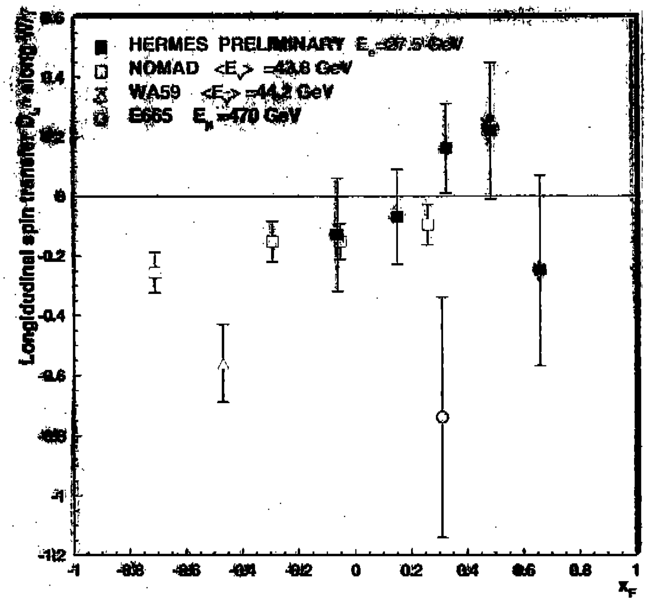
... calculation of Ji & Zhu suggests $\tilde{E}(z) = \frac{m_q}{M} z D_1(z) \approx \frac{1}{3} z D_1(z)$

③ **Final State Polariz^{n}**

(spin transfer to Λ)

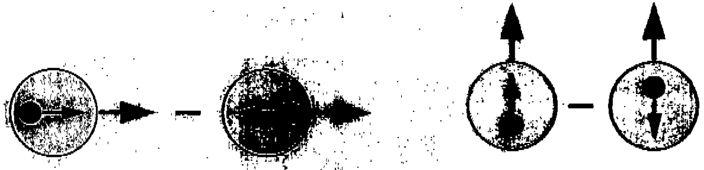
$$\boxed{d\sigma_{UTT} \sim \cos(\phi_h^l + \phi_{S_h}^l)\cdot \mathrm{h}_1(x)\,H_1(z)}$$

Method requires significant *spin transfer* from quark to Λ in fragmentation process ...



longitudinal spin transfer: $G_1(z)$

transverse spin transfer: $H_1(z)$



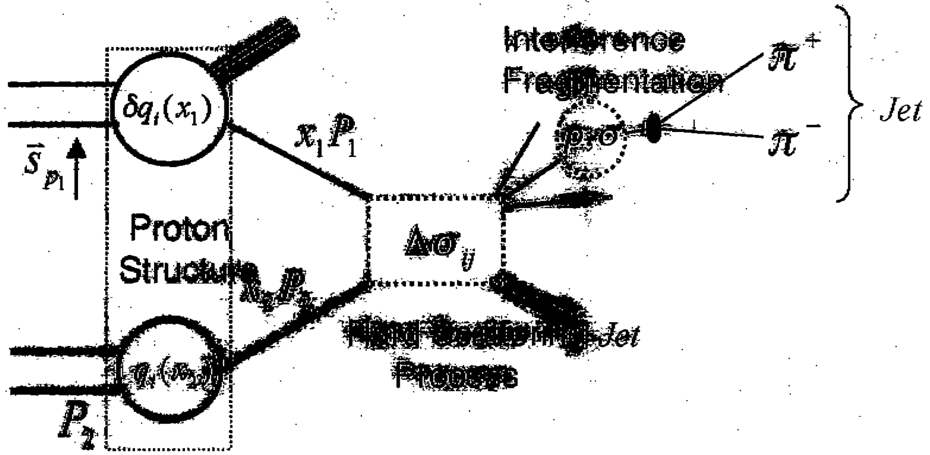
⋮

⇐ **small** $G_1(z)$ at **HERMES kinematics** ☹

⇒ **But situation could be quite different at EIC ! ☺**

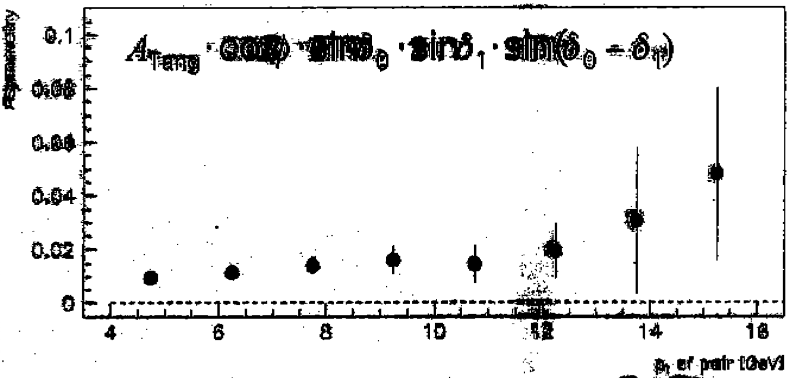
PHENIX: Interference Frag Function

- Transversity measurement at PHENIX
  - near future
    - $\pi^+\pi^-$ interference fragmentation function
      - for 32pb^{-1}, small asymmetry below 5% but good rate



$$A_\perp = \frac{1}{P_{beam}}\frac{N^\rightarrow - N^\leftarrow}{N^\rightarrow + N^\leftarrow} = -\frac{\sqrt{6}\pi}{4}\sin\delta_0\sin\delta_1\sin(\delta_0-\delta_1)\cdot\cos(\phi)\cdot\frac{[\delta q(x_1)\cdot G(x_2)\cdot\delta\hat{q}_I(z)]\delta\hat{\sigma}^{qg}_{gg}+\ldots}{[G(x_1)\cdot G(x_2)]\hat{\sigma}^{q\bar{q}}_{gg}+\ldots][\sin^2\delta_0\hat{q}_0(z)+\sin^2\delta_1\hat{q}_1(z)]}$$

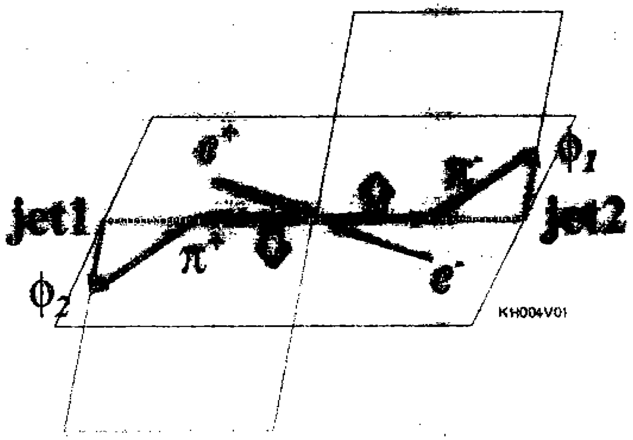
    - Collins effect in jets
    - inclusive jet production
  - luminosity upgrade: 8pb^{-1}
    - direct photon
    - Drell-Yan

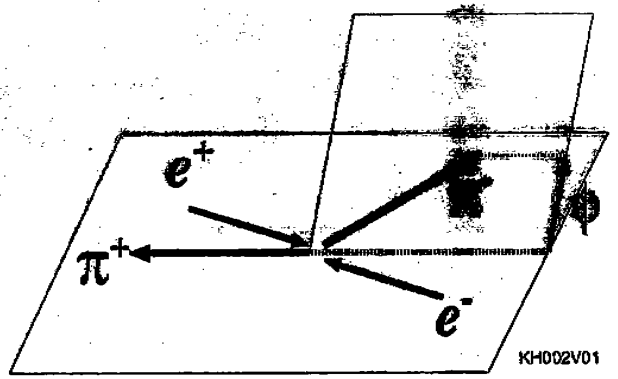


Collins Fragmentation Function at BELLE

- $e^+e^- \rightarrow \pi^+_{jet1}\pi^-_{jet2}X$
- Reaction plane defined with beam (z-axis) and jet axis
- Product (π) plane defined with π and jet axis
- ϕ: angle between the planes
- $A \propto H_1^\perp(z_1)H_1^\perp(z_2)\cos(\phi_1+\phi_2)$

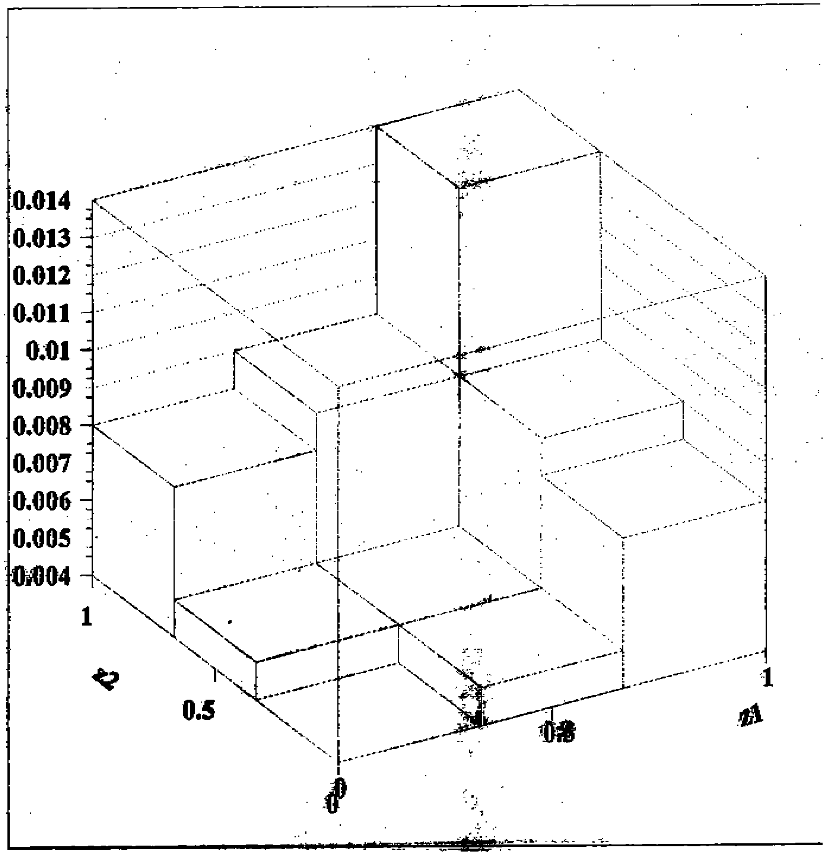
- Can analyze with/without using jet axis
  $A \propto H_1^\perp(z_1)H_1^\perp(z_2)\cos(2\phi)$





Available Statistics at BELLE (off-resonance)

- #events ~ 27M (off-resonance data)
- Event selection
  - Thrust ≫ 0.85
  - $\pi^+\pi^-$ in different hemispheres (for Collins function)
  - 8 bins in 2ϕ ($\phi_1+\phi_2$)
- $\delta A = \delta(H_1^\perp H_1^\perp)\cos(\phi_1+\phi_2)$ = 1.4% of statistical error for high z-bin (> 0.5)
- More data available on-resonance

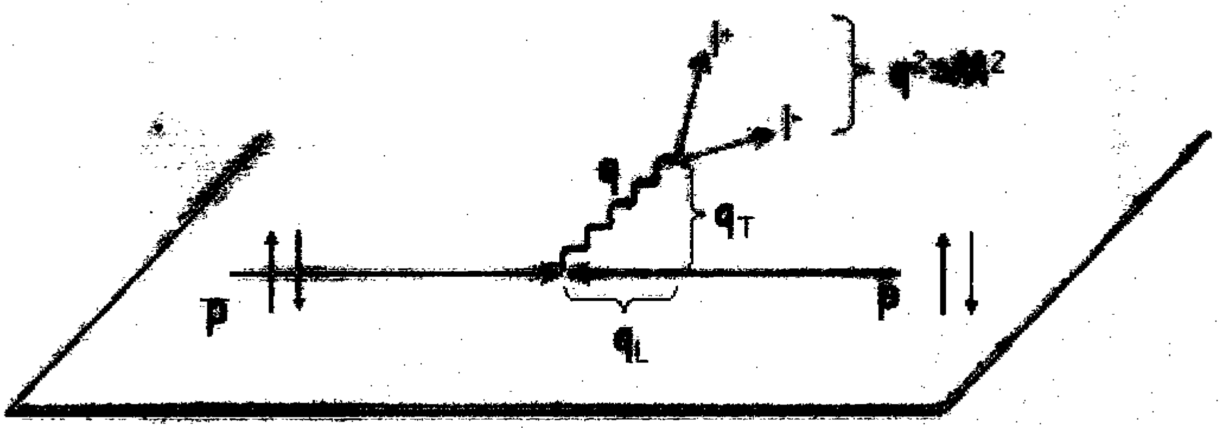


Background Sources

- The following sources can cause azimuthal asymmetries
  - Limitation of detector acceptance (and to some extent momentum resolution)
  - Gluon emission
  - Weak decays
  - Beam background

Transversity in Drell-Yan processes

PAX: Polarized antiproton beam → polarized proton target (both transverse)



$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2)\, h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2)\, \bar{q}(x_2, M^2)}$$

$q = u, \bar{u}, d, \bar{d}, \ldots$

M invariant Mass of lepton pair

Elementary QED process

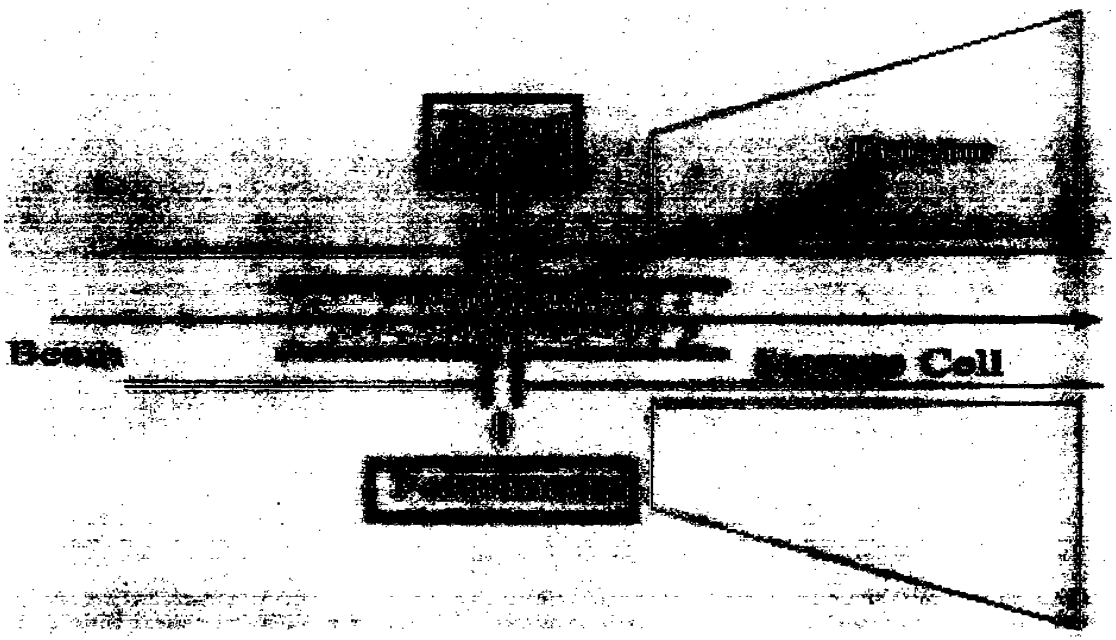
$$q\bar{q} \rightarrow l^+ l^-$$

$$\hat{a}_{TT} = \frac{\sin^2\theta}{1+\cos^2\theta}\cos 2\phi$$

θ: polar angle of lepton in l+l- rest frame

φ: azimuthal angle w.r.t. proton polarization

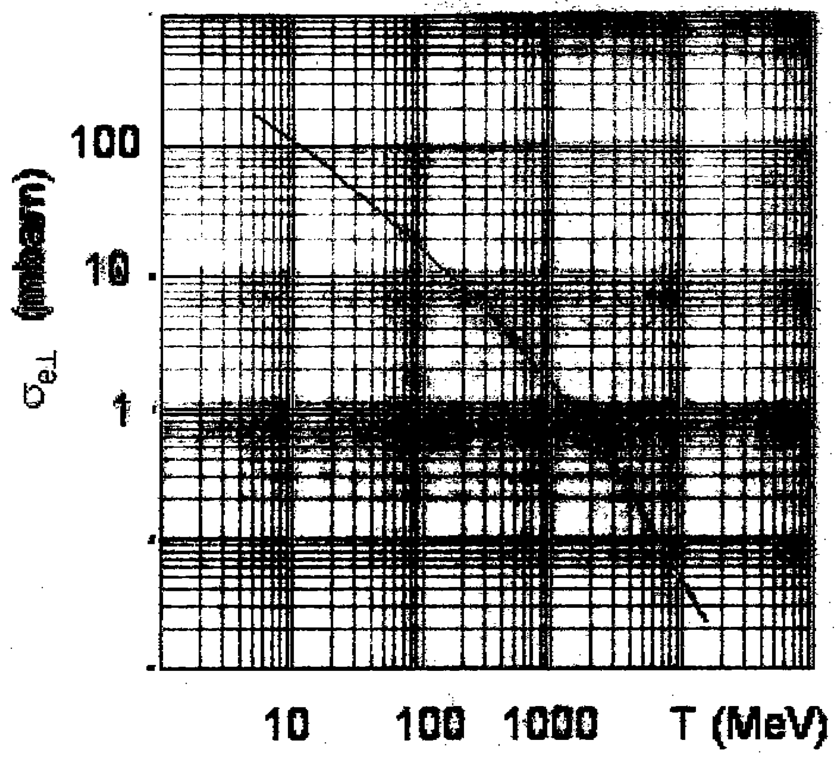
Principle of a polarized internal target



Interaction Region				
point-like	5-10 mm	free jet	low density	10^{12} cm^{-2}
extended	200-500 mm	storage cell	high density	10^{14} cm^{-2}

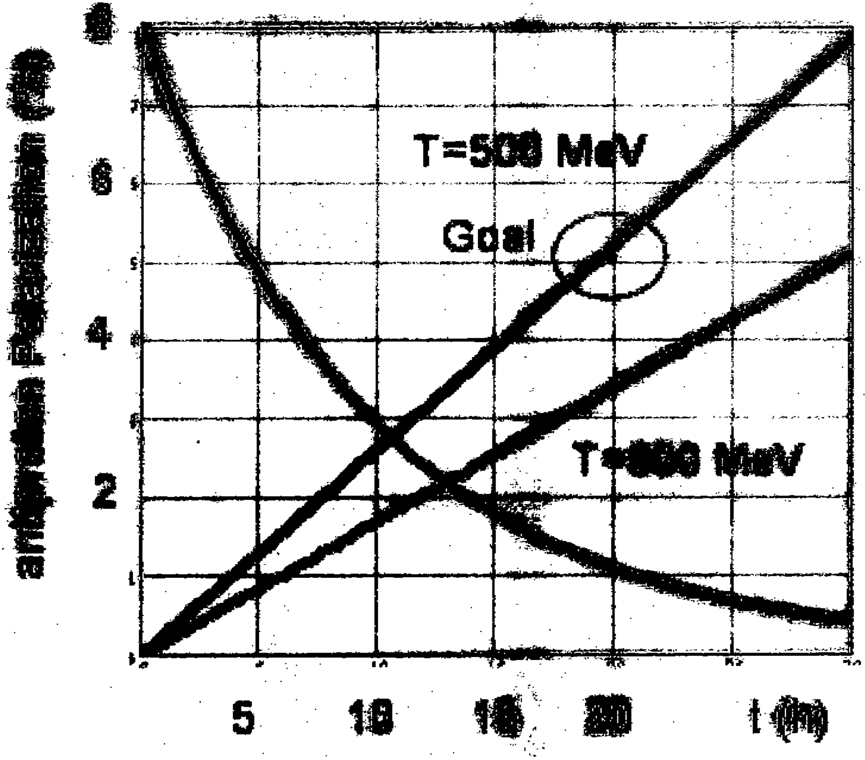
Antiproton Polarizer

Spin-transfer cross section [illegible]
(electrons in [illegible])



[illegible]

[illegible]
[illegible] 0.[illegible]



Count rate estimate

Uncertainty of Double-spin asymmetry A_{TT} depends on polarization of beam and target ($|P|>0.05$, $|Q|\sim0.9$)

[illegible]

[illegible]

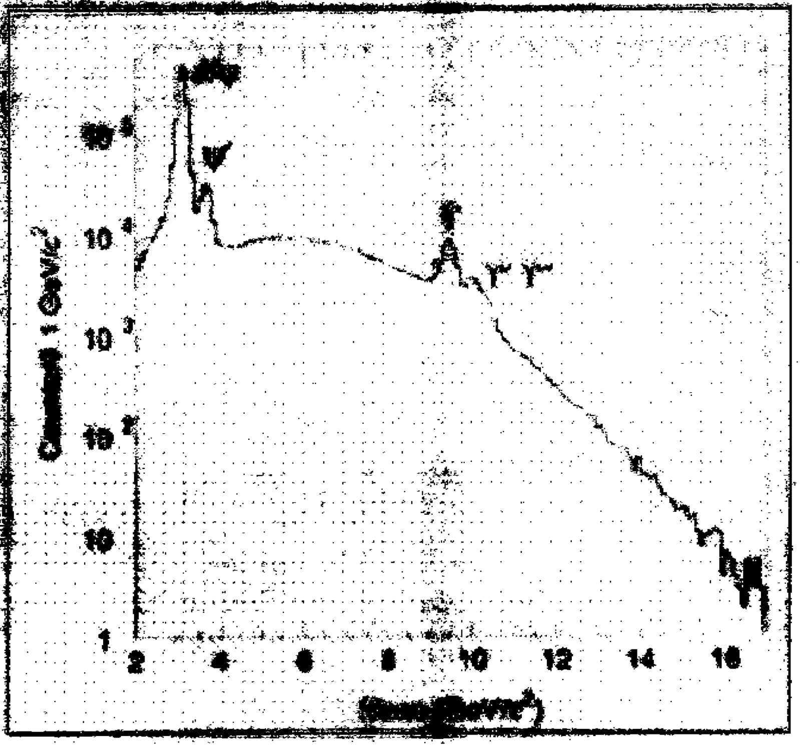
240 days		$\int_4^6 (d\sigma/dM^2)dM^2$	$\int_6^{10} (d\sigma/dM^2)dM^2$
	σ	1.1×10^{-6} GeV^{-2}	3.8×10^{-7} GeV^{-2}
$s = 30$ GeV^2	$\dot{N}$	186 events/day	65 events/day
T = 15 GeV	$\delta_{A_{TT}}$	$\boxed{10.4\ \%}$	$\boxed{17.6\ \%}$
	$\bar{x}$	$\simeq 0.40$	$\simeq 0.49$
	σ	1.9×10^{-6} GeV^{-2}	9.6×10^{-7} GeV^{-2}
$s = 45$ GeV^2	$\dot{N}$	323 events/day	161 events/day
T = 22 GeV	$\delta_{A_{TT}}$	$\boxed{7.9\ \%}$	$\boxed{11.2\ \%}$
	$\bar{x}$	$\simeq 0.33$	$\simeq 0.41$

[illegible]

Extension of the "safe" region

The determination of $h_1^q(x,Q^2)$ is not confined to the „safe" region $M > 4$ GeV!

[illegible]



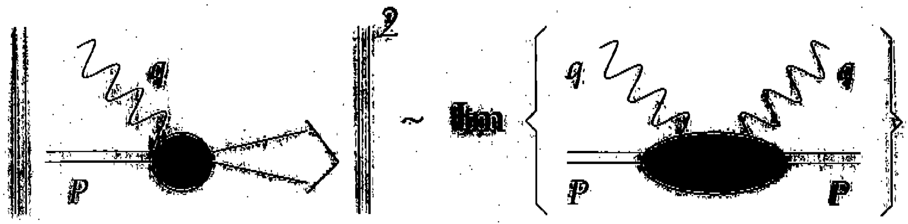
Cross section increases [illegible]

→ Drell-Yan continuum [illegible] A_{TT}

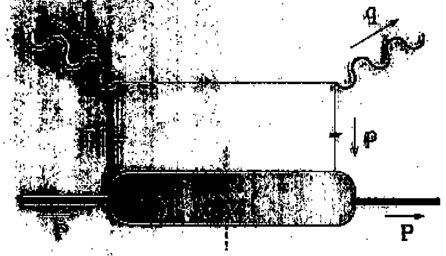
The Leading-Twist Sivers Function

Can it exist in DIS?

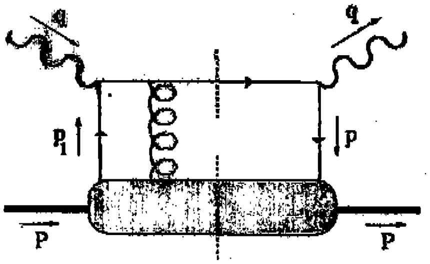
A T-odd function like $f_{1T}^{\perp}$ *must* arise from *interference* ...
but a distribution function is just a forward scattering amplitude,
how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



can interferere
with

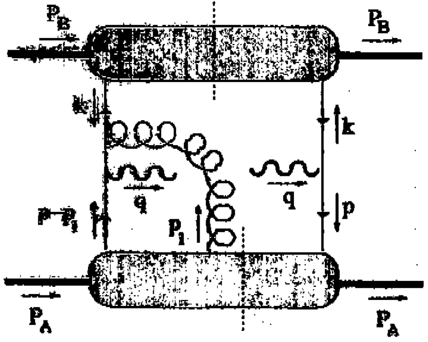


and produce a T-odd effect!
(*also requires $L_z \neq 0$* ... so does $F_2(q)$ form factor)

It looks higher-twist, but it's not ...
⟹ *these are soft gluons*

Such soft-gluon reinteractions
with the soft wavefunction are
final (or initial) state interactions ...
and may be ***process dependent*** !

⟹ *new universality issues* ...



e.g. Drell-Yan

Universality of Weighted Moments

Process-dependence of k_T-dependent distribution functions can be ***controlled*** by working with weighted moments

$$\Phi_\partial^{[\pm]\,\alpha}(x) \equiv \int d^2p_T\, p_T^\alpha\, \Phi^{[\pm]}(x, p_T)$$

$$\propto\; g_{1T}^{(1)} S_T^\alpha \oplus h_{1L}^{\perp(1)} S_L \oplus f_{1T}^{\perp(1)} \epsilon_T^{\alpha\beta} S_{T\beta} \oplus h_1^{\perp(1)}$$

Split off process-dependent term due to extra gauge link:

$$\Phi_\partial^{[\pm]\,\alpha}(x) = \Phi_\partial^\alpha(x) \pm \pi \Phi_G^\alpha(x, x)$$

process-independent
T-even

process-dependent
T-odd gluonic pole ME

T-even: $g_{1T}^{(1)[\pm]}(x) = g_{1T}^{(1)}(x) \pm \cancel{\tilde{g}_{1T}^{(1)}(x)}$

T-even: $h_{1L}^{(1)[\pm]}(x) = h_{1L}^{(1)}(x) \pm \cancel{\tilde{h}_{1L}^{(1)}(x)}$

T-odd: $f_{1T}^{\perp(1)[\pm]}(x) = \cancel{f_{1T}^{\perp(1)}(x)} \pm \tilde{f}_{1T}^{\perp(1)}(x)$

T-odd: $h_1^{\perp(1)[\pm]}(x) = \cancel{h_1^{\perp(1)}(x)} \pm \tilde{h}_1^{\perp(1)}(x)$

And some terms are forbidden by time-reversal!

Sivers function $f_{1T}^{\perp(1)}(x)$ is universal to within a sign :
see $+\tilde{f}_{1T}^{\perp}$ in SIDIS ... $-\tilde{f}_{1T}^{\perp}$ in DY

Universality II

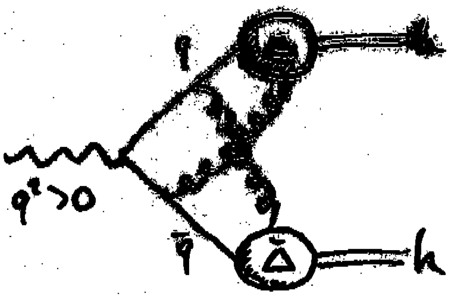
And for the *fragmentation functions?*

Time-reversal arguments don't hold, since initial / final states are not the same! → p_T-dependent fragmentation functions *may not* be universal ...

⇒ ***see plenary talk of Daniel Boer for latest news ...***

The "Big Three" Processes

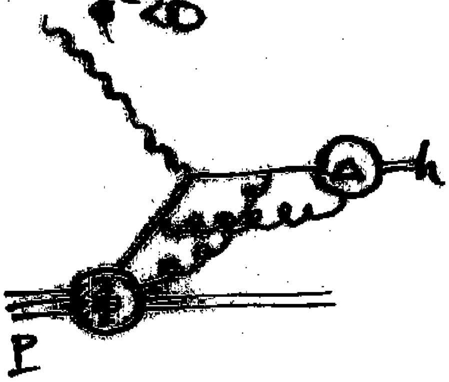
e^+e^- Annihilation



$\xi^- \to +\infty \quad \xi^+ \to +\infty$

$$\bar{\Delta}_\partial^{[+]} = \bar{\Delta}_\partial + \pi\bar{\Delta}_G$$
$$\Delta_\partial^{[+]} = \Delta_\partial + \pi\Delta_G$$

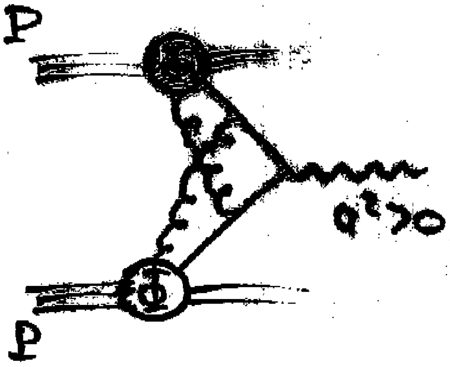
SIDIS



$\xi^- \to +\infty \quad \xi^- \to -\infty$

$$\Phi_\partial^{[+]} = \Phi_\partial + \pi\Phi_G$$
$$\Delta_\partial^{[-]} = \Delta_\partial - \pi\Delta_G$$

Drell-Yan

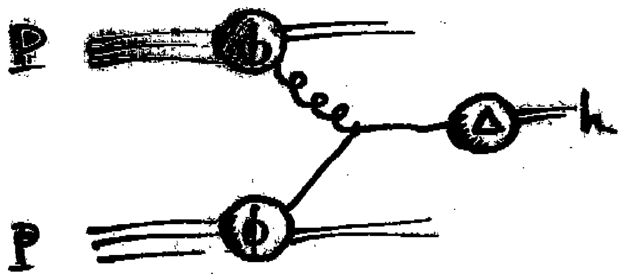


$\xi^- \to -\infty \quad \xi^+ \to -\infty$

$$\Phi_\partial^{[-]} = \Phi_\partial - \pi\Phi_G$$
$$\bar{\Phi}_\partial^{[-]} = \bar{\Phi}_\partial - \pi\bar{\Phi}_G$$

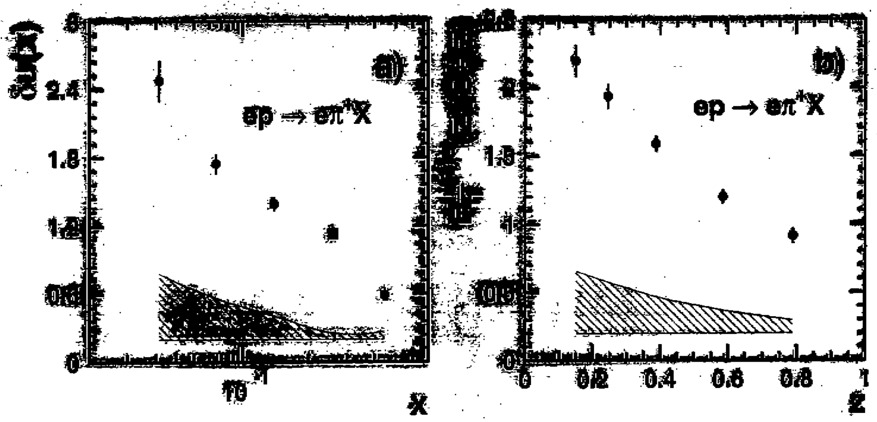
Similar topology of $\xi^\pm \to \pm\infty$ gauge links in all three ...

By comparison, E704 effect ⇒ universality for A_N from $p^\uparrow p \to \pi X$ so far *not clear at all*



Where We'll Be in 10 Years: Data on Transversity

- **HERMES** A_{UT} from p → info on $h_1^u(x)$
  (projection must be redone to reflect new results)
- **COMPASS** A_{UT} from d → info on $h_1^d(x)$
- **BELLE** → independent $H_1^\perp$ measurem't
- **PAX** → h_1 normaliz'n point (hopefully!)



The Need for EIC

- Anticipated measurements will only ***scratch the surface!***
- ***Kinematic range*** to measure tensor charge $\int_0^1 dx\, h_1(x)$
- ***4π Acceptance***: different fragmentation channels (e.g. π-from-string vs π-from-ρ decay) likely have different Collins analyzing powers
  → experiments with limited acceptance will see different mixtures of these
- ***Statistics*** to measure (x, z) dependence simultaneously, and explore ***full set*** of leading-twist distribution & fragmentation functions