Unexpected Effects of Final-State Interactions in QCD

Stan Brodsky

SLAC + JLab

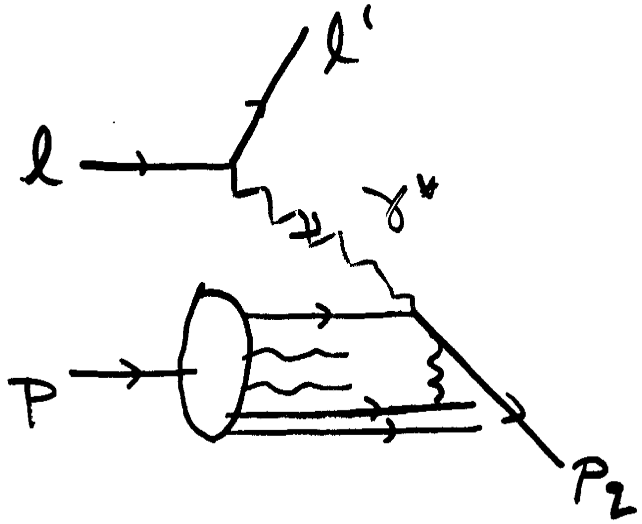
Mini-Workshop on Single Spin Asymmetries

Urbana March 27-28, 2003

* Diffraction in DIS
* Nuclear Shadowing
* Single-Spin Asymmetries - Sivers Effect

⇒ Structure Functions are not Parton Densities

Unexpected Role of Final State Interactions in Deep Inelastic Scattering



gluon exchange after photon absb

not in LF WF

* Single-spin asymmetry $\quad \vec{S}_p \cdot \vec{q} \times \vec{p}_q$ Bjorken-scaling
* Diffraction at Leading Twist
* Nuclear Shadowing (interference of diff channels)
* Energy Loss, P_T Broadening

Diffraction, Nuclear Shadowing, Pomeron not in nuclear wavefunction!

Unexpected Effects of Final-State Interactions in QCD

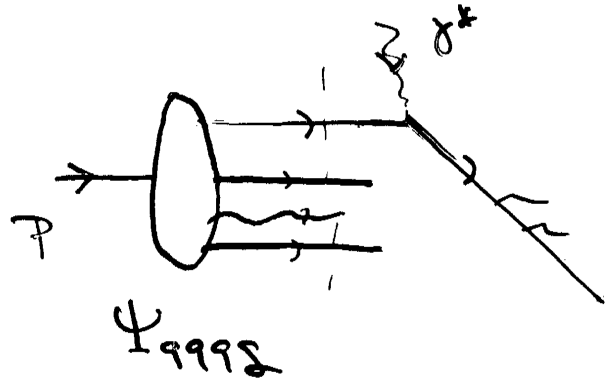
Collaborations with

- Dae Sung Hwang and Ivan Schmidt
- Paul Hoyer, Nils Marchal, Stephane Peigne, F. Sannino

Density matrix formulation with

- Carl Carlson, Dae Sung Hwang

Parton model interpretation of DIS



$$F_2(x, Q^2) = \sum_{q \in p} e_q^2 \, x \, q(x, Q^2)$$

$$q(x, Q^2) = \sum_{n \geq 3} \int^{k_\perp^2 < Q^2} d^2k_\perp \, dx \, |\Psi_n(x, k_\perp)|^2 \, \delta(x - x_q)$$

$$H_{LF} |\Psi\rangle = M^2 |\Psi\rangle$$

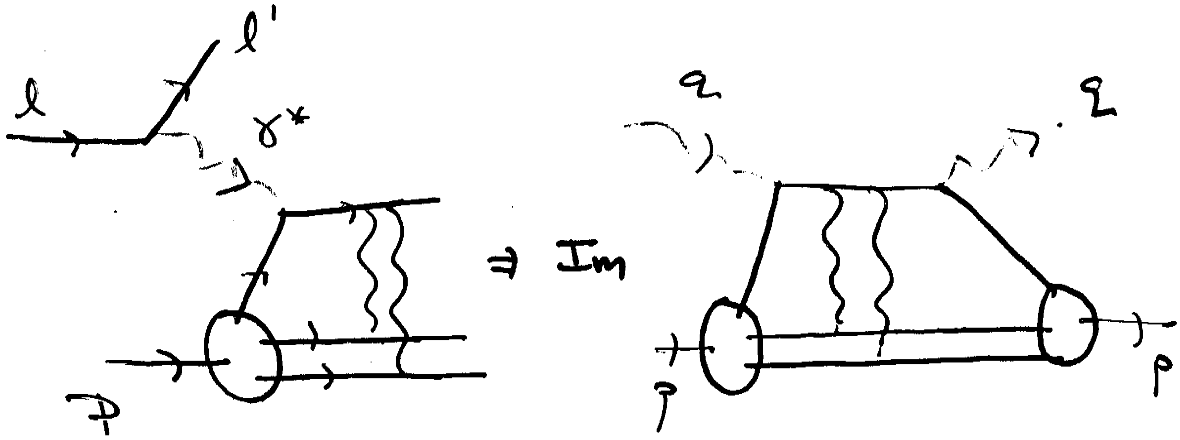
$$\langle n | \Psi \rangle = \psi_n(x, k_\perp)$$

$q(x, Q^2)$, Ψ_n determined by target LF WF alone

All final-state interactions inconsequential
– power-law, phase

Ok in Yukawa Theory

New perspectives on Final-State-Interactions



$$f_{q/N}(x_{Bj}, Q^2) = \frac{1}{8\pi}\int dy^- \, e^{-ix_B p^+ y^-}$$

$$\langle N(p) | \bar{q}(y^-) \gamma^+ P\, e^{ig\int_0^{y^-} dw^- A^+(w^-)} q(0) | N(p) \rangle$$

Usual argument $A^+ = 0$ gauge

no effect from FSI !

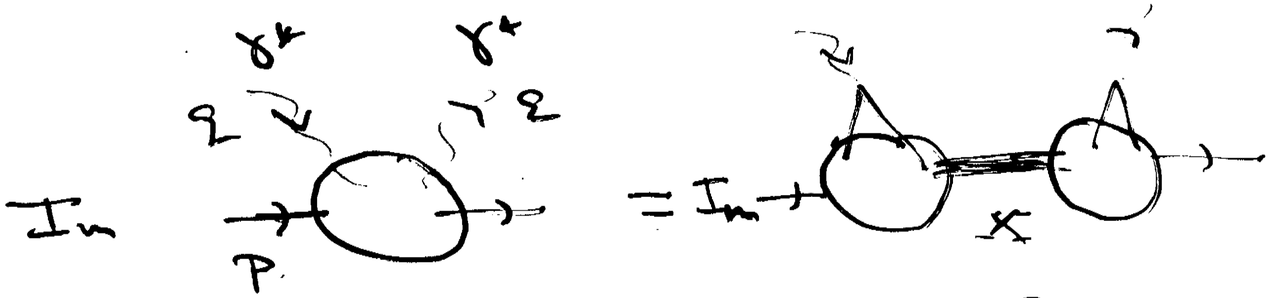
phase irrelevant

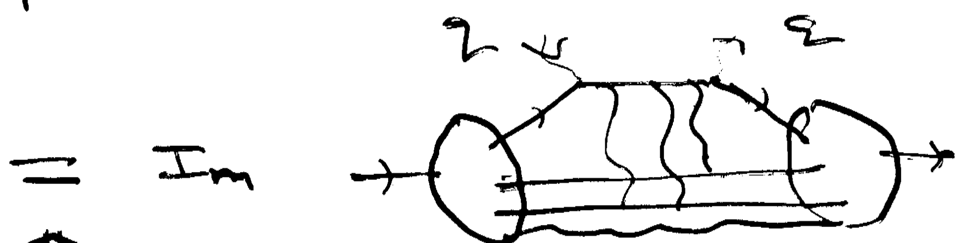
$\therefore$ Identify $f_{q/N}$ with LC Prob. Dist

$$P_{q/N}(x_B, Q^2) = \sum_n \int^{k_{\perp i}^2 < Q^2} \left[\prod dx\, d^2k_\perp\right] |\psi_n(x, \vec{k}_{\perp i})|^2 \sum_q \delta(x_B - x_q)$$

Usual proof:

QCD Factorization for virtual compton amplitude:





$\Uparrow$

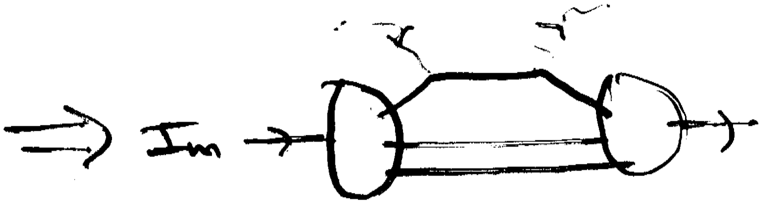
leading twist

$$P_{q/N}(x_B, Q^2) = \frac{1}{8\pi}\int dy^- \, e^{-ix_B p^+ y^-}$$

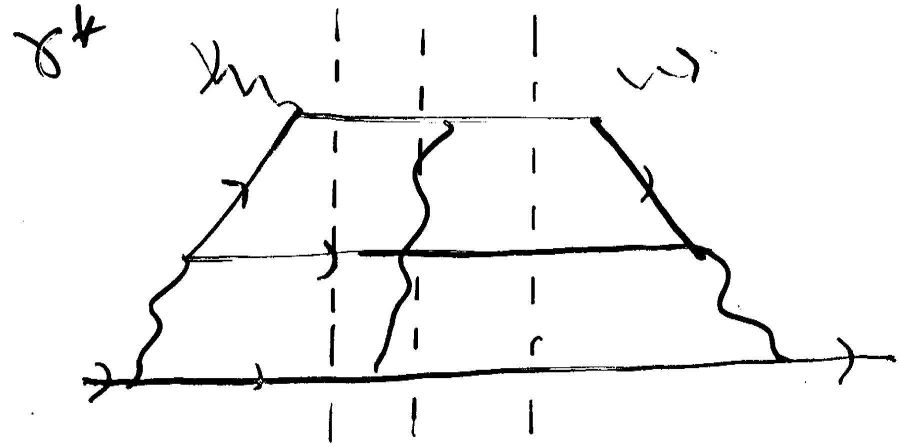
$$\langle N(p)|\, \bar{q}(y^-)\, \gamma^+ \, P\, e^{ig\int_0^{y^-} dw^- A^+(w^-)}\, q(0)|N($$

Choose light-cone gauge: $A^+ = 0$,

Path-ordered exponential $= 1$



$= \sum_n |\psi_n|^2$



Usual argument: no time for f.s.i.

- three denominators of order ν
- numerator coupling finite in l.c.g.

$\therefore$ f.s.i. suppressed by power of $\frac{1}{\nu}$

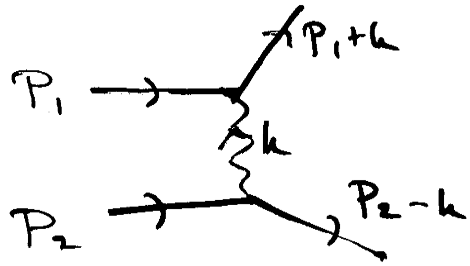
Equivalent to setting P.O.E. = 1.

$$\int_0^{y^-} dw^- \, A^+(w^-) = 0.$$

in $A^+ = 0$ gauge.

But argument is wrong!

Consider elastic scattering in QED at $s \gg -t$



$$\mathcal{M} = g^2 (2p_1+k)^\mu d_{\mu\nu} (2p_2-k)^\nu$$

$$d^{\mu\nu} = \frac{1}{k^2+i\epsilon}\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + k^\mu n^\nu}{n\cdot k}\right] \; *$$

$$\therefore \quad \mathcal{M} = -g^2 \frac{(2p_1+k)\cdot(2p_2-k)}{k^2} \cong -2g^2\frac{s}{t}$$

gauge indep (from $g^{\mu\nu}$)

However, if we assume leading term comes from

$$s = 2p_1\cdot p_2 = p_1^- p_2^+$$

Take: $\mathcal{M} \cong g^2 (2p_1^-) d_{\mu\nu} (2p_2^+)$

<u>correct</u> in Feynman gauge, <u>not</u> in l.c.g!

In l.c.g. <u>dominant</u> <u>term</u> is from <u>$d^{\perp +}$</u> $*$

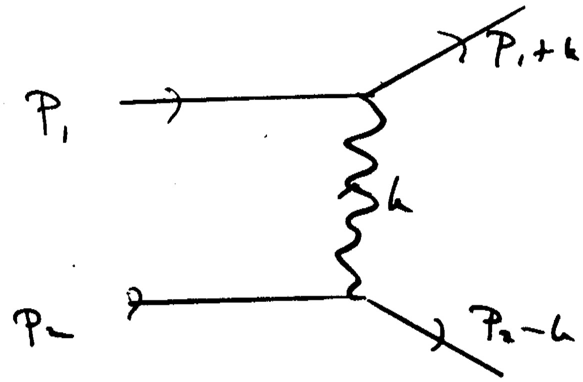
$$\mathcal{M}_{LC} = \frac{g^2}{k^2}\,\frac{-k_\perp^2\, 2p_2^+}{k^+} = -\frac{2g^2 s}{t}$$

where $k^+ = \dfrac{-k_\perp^2}{p_1^-} \to 0$ largest term from $A_\perp^\mu$ in l.c.g

Light-cone gauge evaluation

$n^\mu = (0, 2, 0_\perp)$

$n^2 = 0$



$2p_1 \cdot k + k^2 = 0$

$$\mathcal{M} = e^2 \overset{\perp}{(2p_1+k)_\mu} \frac{\left[-g^{\mu\nu} + \dfrac{\overset{\perp\,-}{n^\mu k^\nu} + k^\mu n^\nu}{n \cdot k} \right]}{k^2 + i\epsilon} \overset{+}{(2p_2 - k)_\nu}$$

where: $n \cdot k = k^+ = \dfrac{-k_\perp^2}{p_1^-} \to 0$ for $s \gg -t$

Dominant term in l.c.g. from non-eikonal current

$$\mathcal{M} = e^2 \frac{-k_\perp^2 \dfrac{2p_2^+}{k^+}}{k^2 + i\epsilon} \Rightarrow -2e^2 \frac{s}{t}$$

$\vec{A}_\perp$ plays crucial role in lcg: $k^+ = O\left(\frac{1}{p_1^-}\right)$

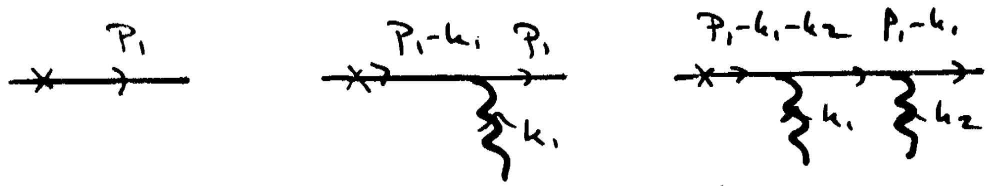
Similarly: $\int dw^\mu A_\mu \neq \int dw^- A^+$ in l.c.g.

Interpretation of $\quad P\exp\left[ig\int_0^\infty dy^- A^+(y^-)\right]$

$$1 + ig\int_0^\infty dy_1^- A^+(y_1^-)\left[1 + ig\int_{y_1^-}^\infty dy_2^- A^+(y_2^-) + \cdots\right]$$

$$= 1 + g\int_{-\infty}^{\infty}\frac{dk_1^+}{2\pi}\frac{\tilde{A}^+(k_1^+)}{k_1^+ - i\epsilon} + g^2\int_{-\infty}^{\infty}\frac{dk_1^+}{2\pi}\frac{dk_2^+}{2\pi}\frac{\tilde{A}^+(k_1^+)\,\tilde{A}^+(k_2^+)}{(k_1^+ + k_2^+ - i\epsilon)(k_2^+ - i\epsilon)} + \cdots$$

where $A^+(y^-) = \int_{-\infty}^{\infty}\frac{dk^+}{2\pi}\,\tilde{A}^+(k^+)\,e^{-ik^+y^-}$



$$\frac{g^2\; P_1^-\,\tilde{A}^+(k_1)\; P_1^-\,\tilde{A}^+(k_2)}{\left[-P_1^-(k_1^+ + k_2^+) + i\epsilon\right]\left[-P_1^- k_2^+ + i\epsilon\right]}$$

$\therefore$ POE equiv. to eikonal amplitude

* Correct in Feynman gauge
* Incorrect in l.c.g where $\tilde{A}^+(k) = 0$.

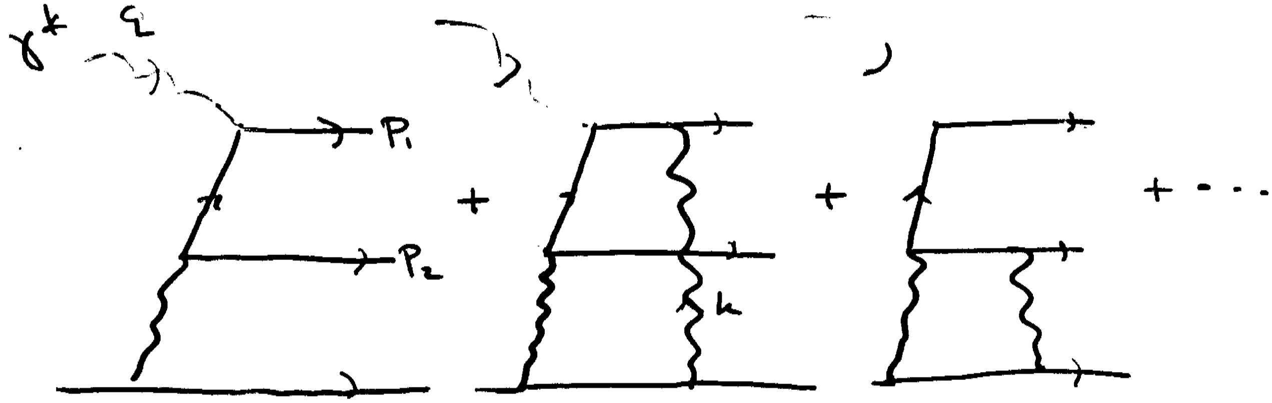
$\Rightarrow$ Need to keep $\int dy_\mu A^\mu$ in l.c.g.

since $(2\vec{P}_1 - \vec{k}_2)\cdot\vec{A}_\perp$ contributes at l.o.

$$\boxed{\text{Explicit calculation of FSI}}$$

BHMPS

$q^+ \le 0$ frame



LFTOPT: gluon exchanged after photon acts

Find non-zero leading-twist FSI effect

Leading twist diffraction, Eikonal form

Shadowing correction, not Coulomb phase

Gauge-independent:

Checked: Feynman, LCG $[A^+=0]$ $\left\{\begin{matrix} ML \\ PV \\ k \end{matrix}\right.$ prescriptions

Lesson for LCG:

$$g^{\mu\nu} - \frac{n^\mu k^\nu + k^\nu n^\mu}{n\cdot k}$$

At pole: $n\cdot k = k^+ = O(\frac{1}{\nu})$.

$n^\mu = (0, 2, \vec{0}_\perp)$

$n \cdot n = 0$

Light-Cone Gauge Prescriptions

$$d^{\mu\nu}_{LC}(k) = \frac{i}{k^2 + i\epsilon}\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + k^\mu n^\nu}{n \cdot k}\right]$$

The pole at $n \cdot k = k^+ = 0$ requires an analytic presc:

$$\frac{1}{k^+} = \begin{cases} \dfrac{k^+}{(k^+ - i\eta)(k^+ + i\eta)} & \text{Principal value} \\ \dfrac{1}{k^+ - i\eta} & \text{Kovchegov} \\ \dfrac{1}{k^+ - i\eta\,\epsilon(k^-)} & \text{Mandelstam-Liebbrandt} \end{cases}$$

$$\epsilon(x) = \theta(x) - \theta(-x)$$

M-L : $\dfrac{k^-}{k^- k^+ - i\eta} = \dfrac{k^-}{k^2 - k_\perp^2 - i\eta}$. causal

similar to Feynman-prop.

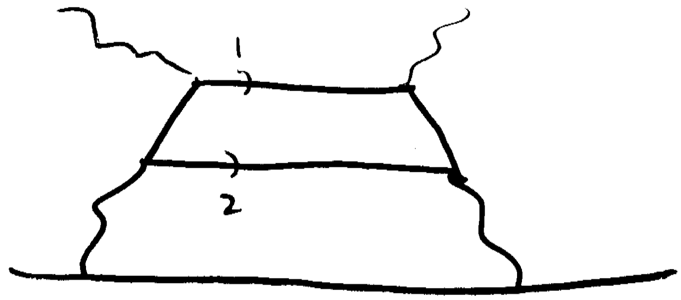
Kovchegov : non-causal !

* Find FSI of current jet vanishes in K pres!

* But corresponds to solving LC w.f. in external field!

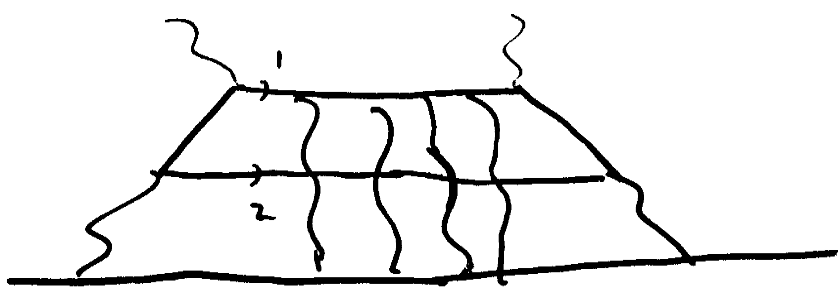
McLerran et al

Consider



$q^+ \leq 0$

In Feynman gauge, must keep



Shadowing effect from on-shell states

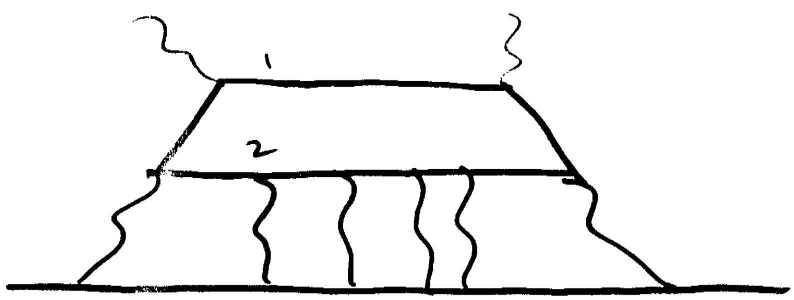
$$|M|^2 \Rightarrow \left| \frac{\sin[g^2 W(r_\perp, R_\perp)/2]}{g^2 W(r_\perp, R_\perp)/2} \; M_0 \right|^2$$

$$W(r_\perp, R_\perp) = \int d^2k_\perp \, \frac{1 - e^{+i r_\perp \cdot \vec{k}_\perp}}{k_\perp^2} \, e^{i \vec{R}_\perp \cdot \vec{k}_\perp}$$

$$= \frac{1}{2\pi} \log\left(\frac{|\vec{R}_\perp + \vec{r}_\perp|}{|R_\perp|}\right)$$

In Light-Cone gauge (kovchegov prescription)

must keep



Final state rescattering of P_2 line

These graphs are suppressed in Feynman gauge

but in l.c.g

$$d_{LC}^{\mu\nu} = \frac{i}{k^2+i\epsilon}\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + n^\nu k^\mu}{n\cdot k}\right]$$

and $n\cdot k = k^+ = O\left(\frac{1}{\nu}\right)$ for on-shell states!

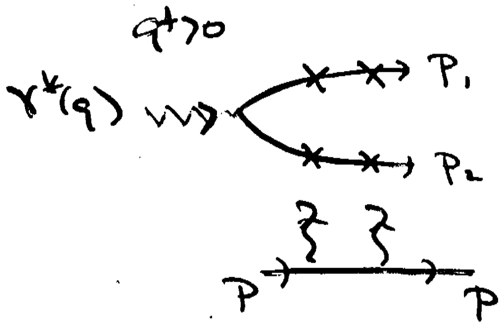
* Result: identical answer as Feynman gauge

* Not included in l.c.g wavefunctions!

M-L, PV prescriptions differ by resid. g. trans.

Effect of Rescatterings on the DIS Cross Section

$q^+ > 0$



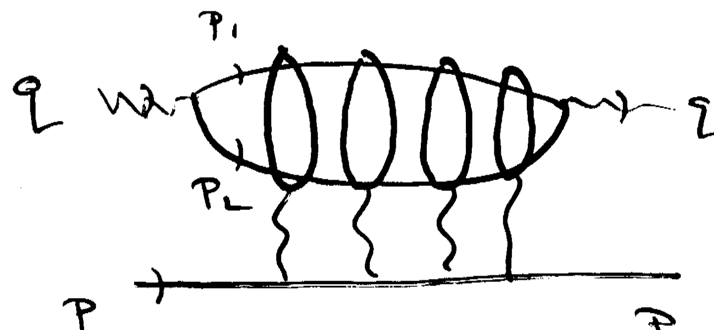
p_1: aligned jet
p_2: spectator jet

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-} d^2r_\perp\, d^2R_\perp\, |M|^2$$

$$|M| = \left| \frac{\sin[g^2 W(\vec{r}_\perp, \vec{R}_\perp)/2]}{g^2 W(\vec{r}_\perp, \vec{R}_\perp)/2} M_{Born}(p_2^-, \vec{r}_\perp, \vec{R}_\perp) \right|$$

< 1 for all $\vec{r}_\perp, \vec{R}_\perp$

Equiv. to sum of cuts of forward virt. Compt. ampl.



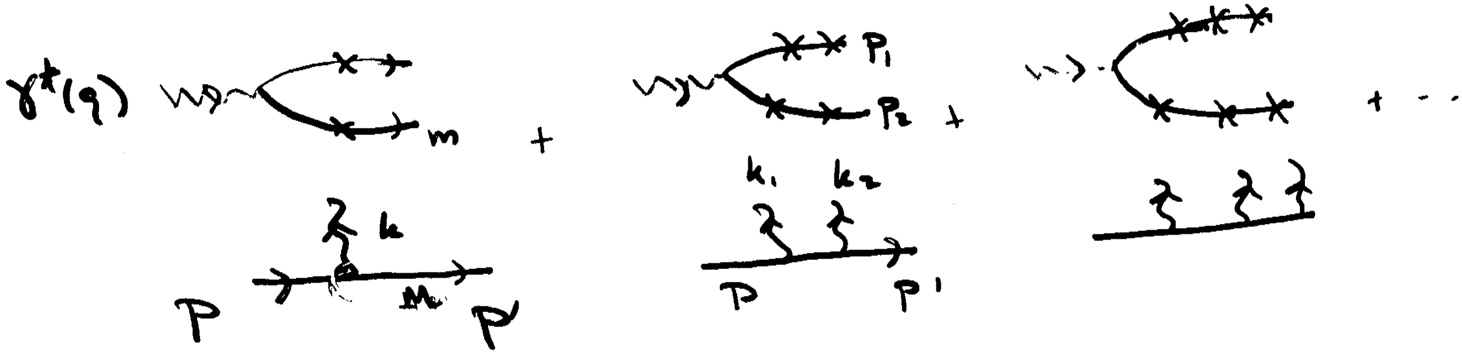
Find shadowing only arises from diagrams involving attachments to p_1 in F.G. !

cuts give Glauber-Gribov shadowing

Same result in Feynman, l.c.g. (ML)

from $2\frac{\vec{p}_{1\perp} \cdot \vec{r}_\perp}{k^+}$ term

<u>Model calculation</u>



Scalar quarks, crossed + uncrossed graphs, large + seagulls

Eikonal factorization in $\vec{r}_\perp$, $\vec{R}_\perp$

verified to 3-loops in Feynman, l.c.g.

$$* \quad \mathcal{M} = \mathcal{M}_{Born}\left[1 - e^{-ig^2 W}\right]$$

$$\mathcal{M}_{Born} = -2ieMQ\,P_2^- V(m_{\parallel}, r_\perp)$$

$$V(m_{\parallel}, r_\perp) = \int \frac{d^2p_\perp}{(2\pi)^2} \frac{e^{i\vec{r}_\perp\cdot\vec{p}_\perp}}{p_\perp^2 + m_{\parallel}^2} = \frac{1}{2\pi} K_0(m_{\parallel} r_\perp$$

$$m_{\parallel}^2 = P_2^- M x_B + m^2$$

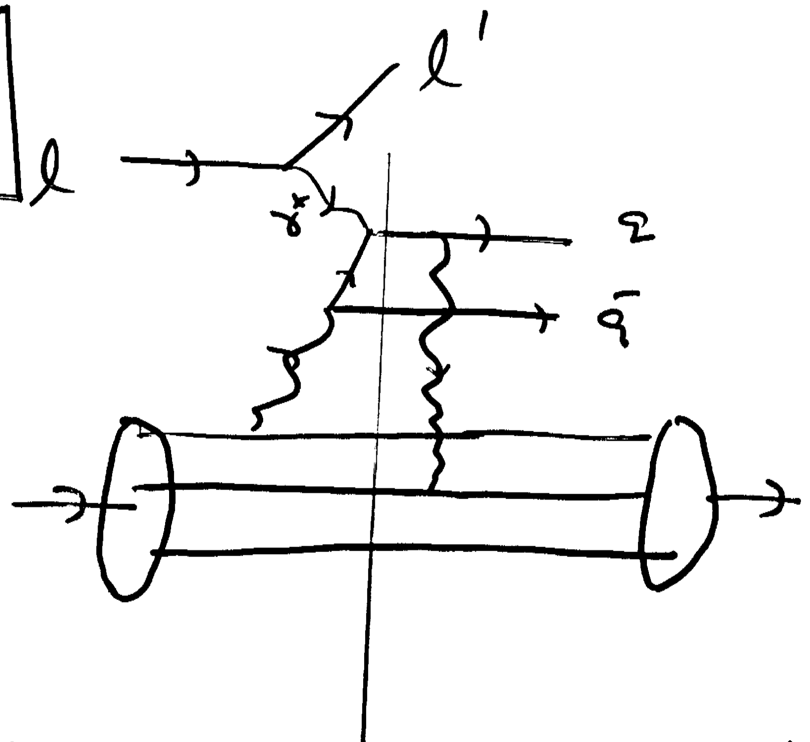
$$W(\vec{r}_\perp, \vec{R}_\perp) = \int \frac{d^2k_\perp}{(2\pi)^2} \frac{1 - e^{i\vec{r}_\perp\cdot\vec{k}_\perp}}{k_\perp^2} e^{i\vec{R}_\perp\cdot\vec{k}_\perp} = \frac{1}{2\pi}\ln$$

$$Q^4 \frac{d\sigma}{dQ^2\,dx_B} = \frac{\alpha}{16\pi^2}\frac{1-y}{y^2}\frac{1}{2M\nu}\int \frac{dP_2^-}{P_2^-} d^2r_\perp\, d^2R_\perp\, |\mathcal{M}|^2$$

Non-universal Pomeron Coupling

Hoyer, Peigne, Marchal, Sannino, SJB

DIS Diffraction



$\ell p \to \ell' p' X$

(rap gap)

- 2nd gluon exchange occurs after γ^* interaction
- Cut gives imaginary phase !
- Coupling depends on color dipole moment of $q\bar{q}$

Hebecker, Quack, SJB

∴ Pomeron not part of proton w.f.

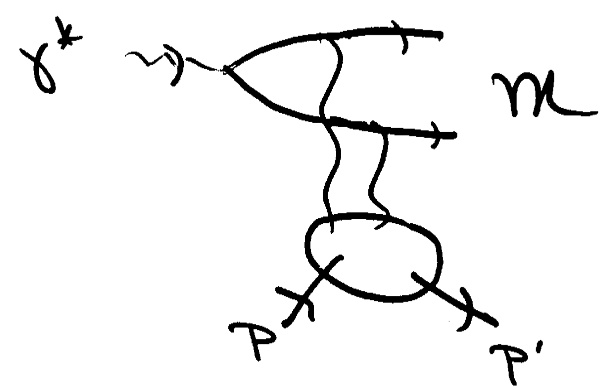
Not universal !

No!

$P_{\gamma/p}(x)$, $P_{q/p}(x)$, $P_{g/p}(x)$, ~~$P_{pom/p}(x)$~~

Diffractive Dissociation (large rapidity gaps)

is leading twist in QCD



$$\frac{d\sigma}{dM^2}(\gamma^* p \to M p')$$

Review by Hebecker, Kopeliovich, Nicolaescu

$$\frac{d\sigma_T}{dM^2} \sim \left(\frac{1}{M^2+Q^2}\right)^2, \quad \sigma_T \sim \frac{1}{Q^2}$$

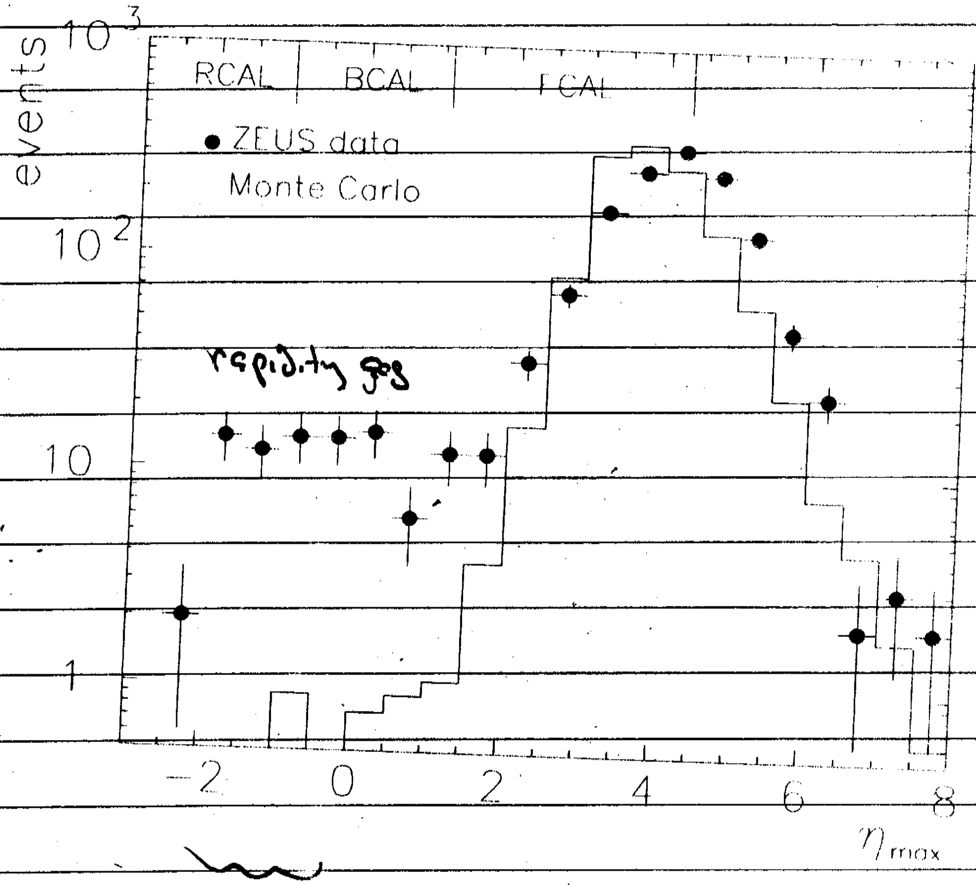
aligned jet regime Bj + Kogut

large color dipole Hoyer, Magnea, SJB

— Coherence for $L_{Ioffe} = \frac{2\nu}{Q^2} > R_N$

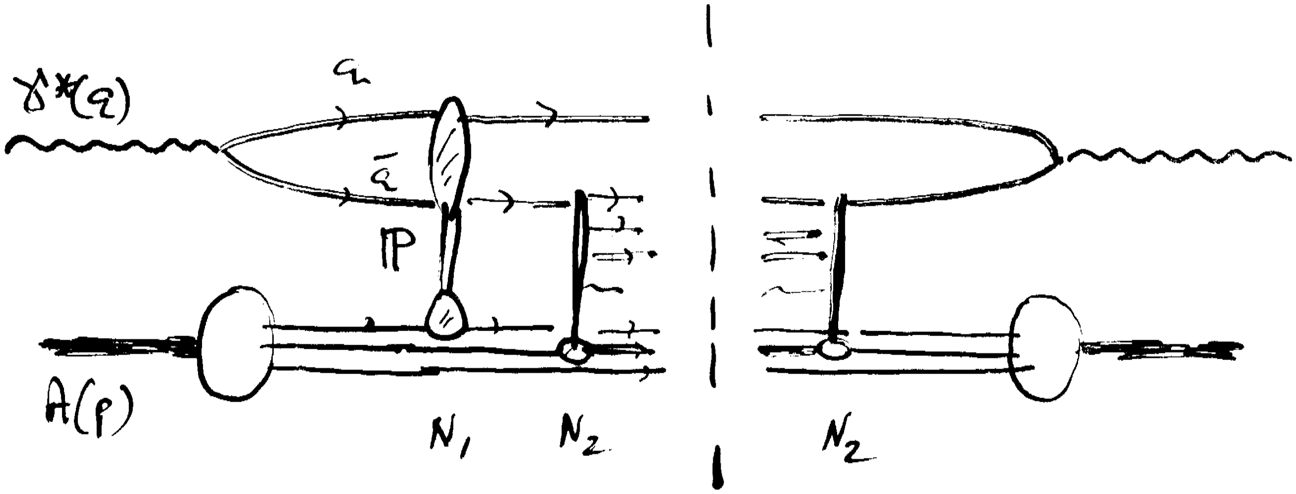
— Shadowing in nuclei for

$$L_{Ioffe} = \frac{2\nu}{Q^2} > R_A$$



minimal excitation
of proton

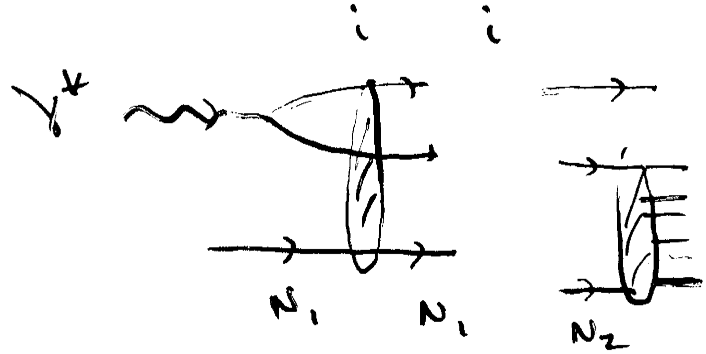
Ref: Hebecker
hep-ph/9909504



- Nuclear shadowing due to destructive interference of diffraction amplitude (2-step + 1-step)

Glauber, Gribov

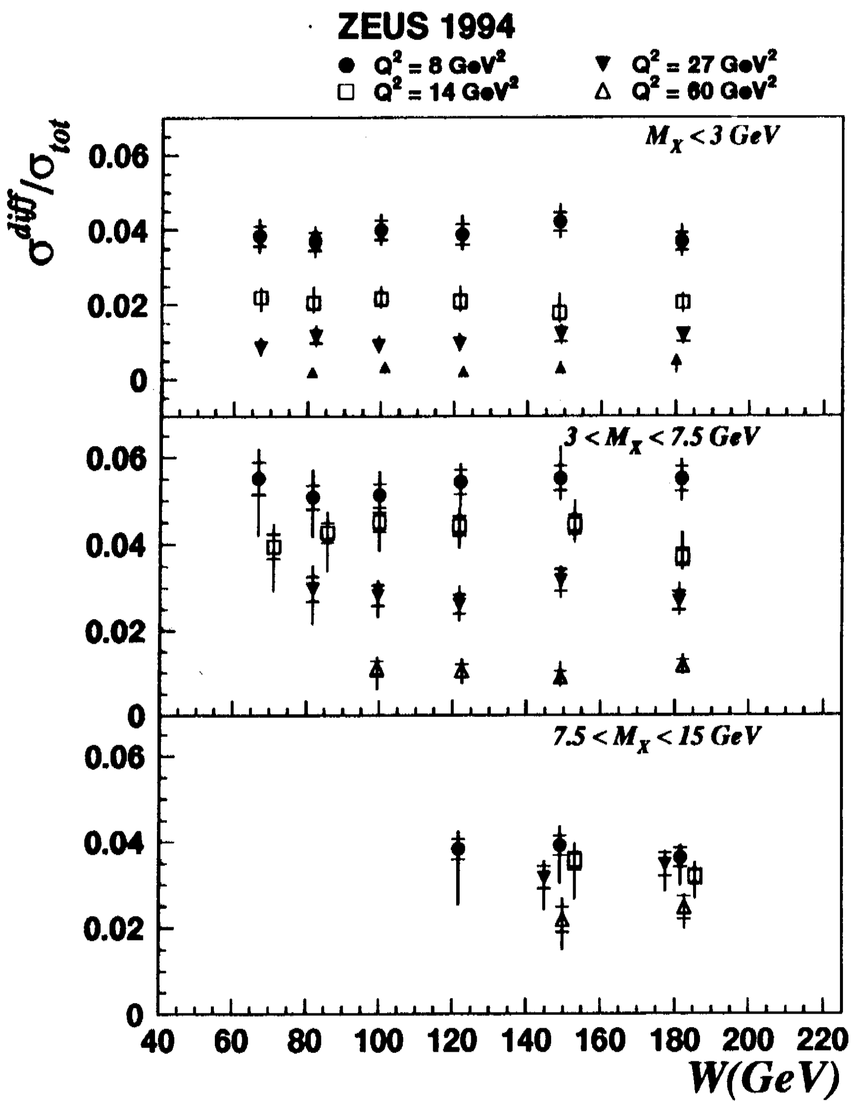
* Phase structure critical



- Diffraction $\gamma^* N_1 \to \bar{q} q N_1'$ { leading twist; finite fraction of DIS }

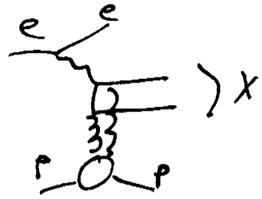
* None of this in l.c. wfs! FSI!
  - $\psi_n(x, k_\perp)$ real!

Comparison of diffractive and DIS cross sections



Diffractive cross section has same energy dependence as inclusive cross section !

pQCD



$$\frac{\sigma^{diff}}{\sigma^{tot}} \sim \frac{(xg)^2}{(xg)} \sim (W^2)^{\lambda_{eff}}$$

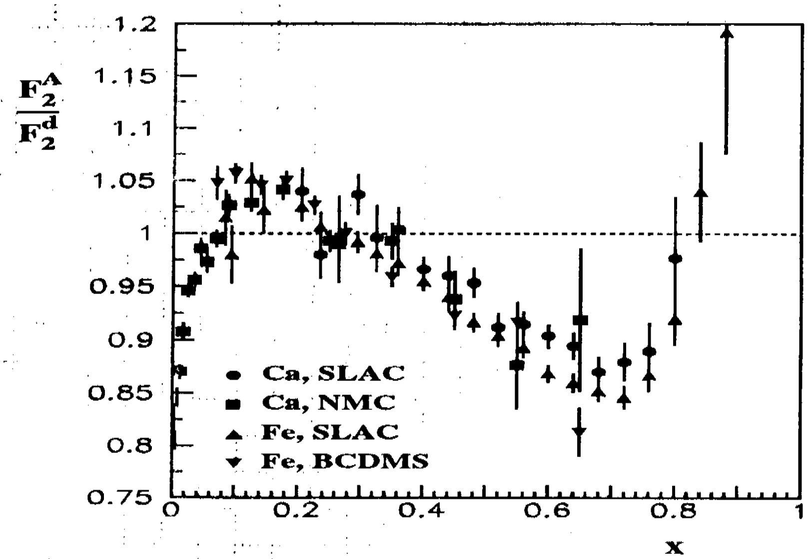
optical theorem

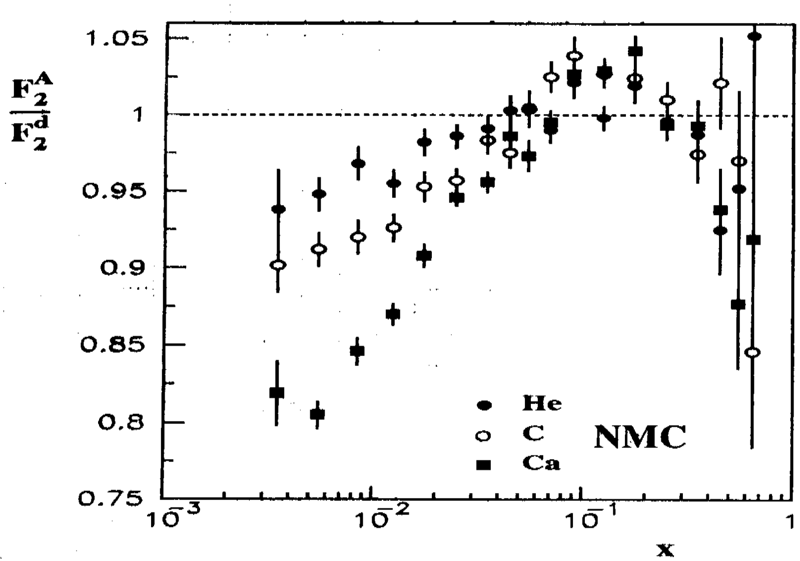
$$\left.\frac{d\sigma^{diff}}{dt}\right|_{t=0} \sim \sigma^{diff} \sim (\sigma^{tot})^2 \sim (W^2)^{\lambda_{eff}}$$

Regge

$$\sigma^{diff} \simeq (W^2)^{0.08}$$

Nuclear structure functions





coherence length of hadronic configurations

$$\lambda \simeq \frac{1}{Mx} > 2\,\mathrm{fm} \leftrightarrow x < 0.1$$

* Nuclear shadowing due to destructive interference of diffractive channels.

Pomeron exchange $\Rightarrow i$ $\qquad \left(-e^{i\pi\alpha_P(0)}\right)$

Cut contribution $\Rightarrow i$

* But $\psi_{n/N}(x_i, \vec{k}_{\perp i}, \lambda_i)$

$\psi_{n/A}(x_i, \vec{k}_{\perp i}, \lambda_i)$

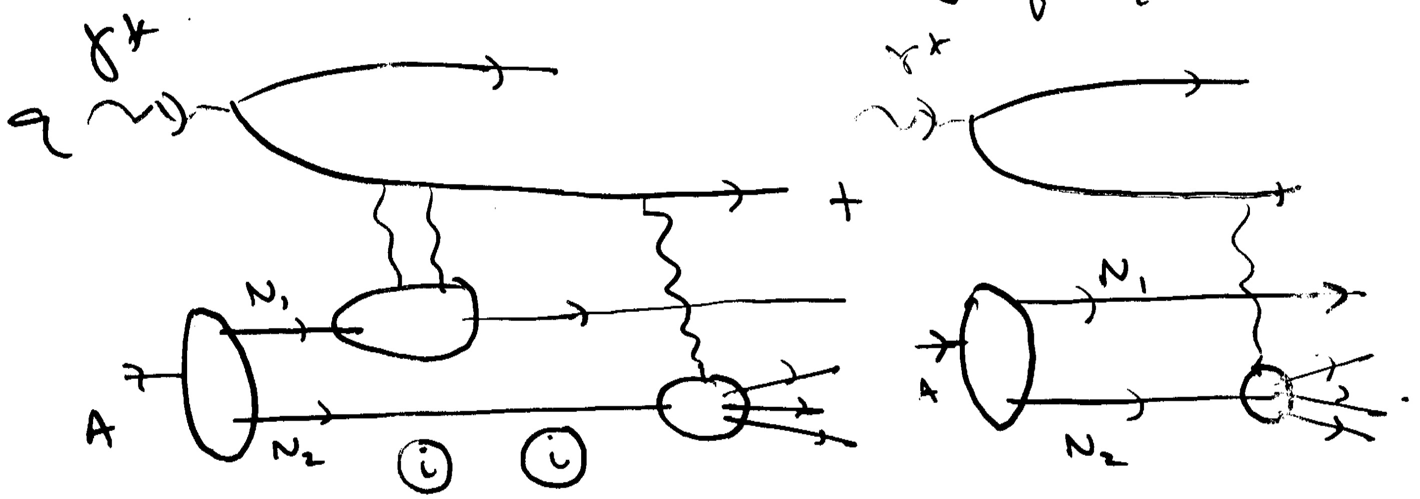
are real! No phase info from intermediate on shell states for stable targets.

— Anti-shadowing from non-singlet Reggeon exchange.

H.J. Lu
+ S.J.B.

Diffraction leads to nuclear shadowing :

Gribov, Glauber
Pumplin, SJB
Gottfried, Yennie γA



* Destructive interference leads to shadowing at low x.

  Frankfurt, Strikman

* Shadowing ↘ quark, gluon distributions

* Reggeon exchange leads to antishadowing

  Lu, SJB

Paradox :

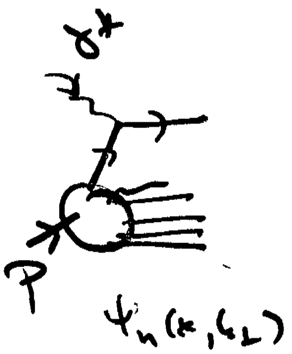
* Nuclear shadowing is result of
  - destructive interference of diffraction amplitudes

  $\therefore$ phases are critical

* Diffractive Dissociation of Photon
  - leaves proton intact
  - leading twist, finite fraction of DIS

$\Rightarrow$ Contradiction with usual assumption (parton model)

$$\boxed{F_2(x,Q^2) = \sum_q e_q^2\, x\, q(x,Q^2)}$$

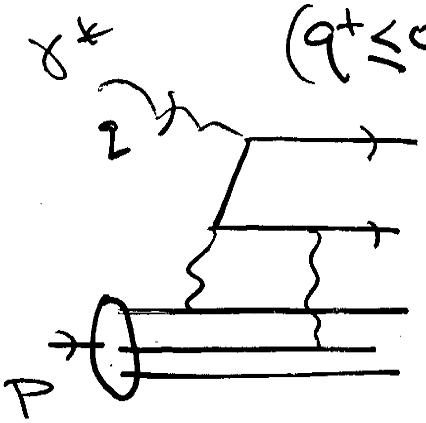


$$q(x,Q^2) = \sum_n \int [d^2k_\perp][dx]\, |\psi_n(x,k_\perp)|^2$$

light-cone prob. distributions

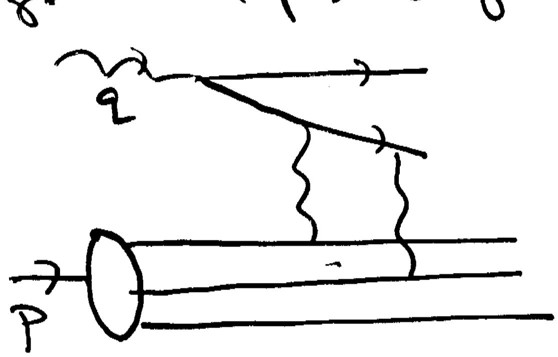
$\psi_n(x,\vec{k}_\perp)$ are real!

($q^+ \leq 0$ frame)



Non-zero
Diffractive contribution
to DIS
Leading Twist.

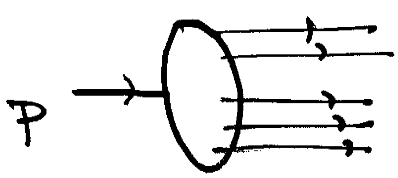
($q^+ > 0$ frame)



Color Dipole
Model
for Diffractive DIS

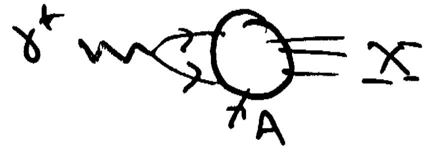
Not part of LC Prob. Distribution!

Complex Phase vs. Real LC Wave Function

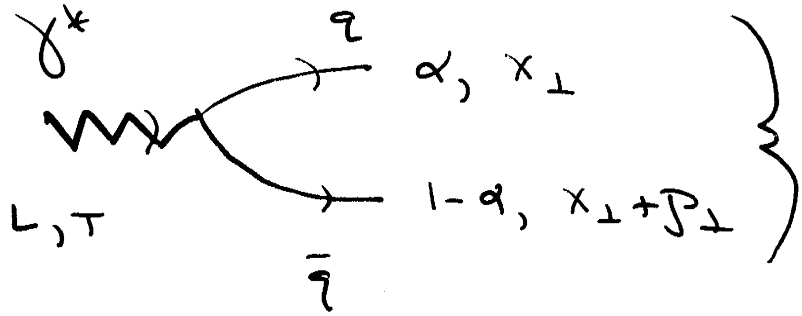


Real w.f. for stable proton

Color dipoles $\Rightarrow$ analyzing quark interactions in nuclei



Kopeliovich
SJB, Hebecker, Quack, Piller et al



$\Psi_{\gamma^*}(\alpha, \rho_\perp)$

DIS:

$\bar{q}q$ cross section on target

$$\sigma^{\gamma^*}_{T,L}(\nu, Q^2) = \int_0^1 d\alpha \int d^2\rho_\perp \, \sigma(\rho_\perp) \, W_{T,L}(\alpha, \rho_\perp)$$

$$W_T(\alpha, \rho_\perp) = \frac{6\alpha_{em}}{(2\pi)^2} N^2 \left[\alpha^2 + (1-\alpha)^2 \right] K_1^2(N\rho)$$

$$W_L(\alpha, \rho_\perp) = \frac{24\alpha_{em}}{(2\pi)^2} N^2 \left[\alpha(1-\alpha) \right] K_0^2(N\rho)$$

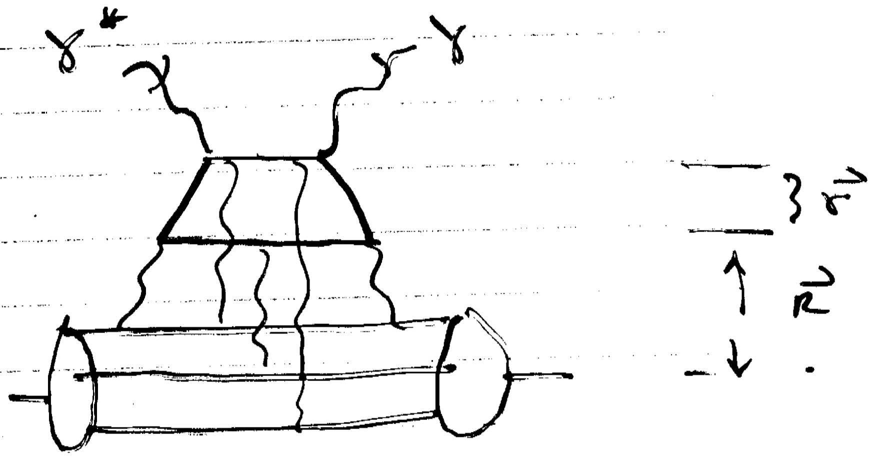
$N^2 = \alpha(1-\alpha)Q^2$

* W_T : large ρ : $A^{2/3}$

* W_L : small ρ : A^1 color transp.

Drell-Yan: σ_T, σ_L, σ_{LT}, σ_{TT}

$\boxed{\text{Is the handbag approximation for DVCS accurate?}}$



Dipole-dipole interactions

Kharzeev? Hebecker, Quack, SJB

In DIS, FSI cause shadowing, diffraction

$$W = \frac{1}{2\pi}\log\frac{|\vec{R}+\vec{r}|}{|\vec{R}|}$$

Correction factor $\dfrac{\sin^2 W g^2/2}{W^2 g^2/2} < 1$

Hoyer, Peigne, Marchal, Sannino, SJB

Expect phases, $\vec{S}_p \cdot \vec{k} \times \vec{k}'$ SSA.
in DVCS

Hwang, Schmidt, SJB

Hwang, Vanderhaeghen (in progress)
SJB

Alternate: Regge form gives phase for $\gamma^* p \to \gamma p'$.
Close, Gunion, SJB   LPS model

References

"Structure functions are not parton probabilities"

S.J.B., P. Hoyer, N. Marchal, S. Peigné + F. Sannino

PRD 65 114025 (2002) hep-ph/0104291

"Final-state interactions and Single-spin Asymmetries in Semi-inclusive Deep Inelastic Scatt."

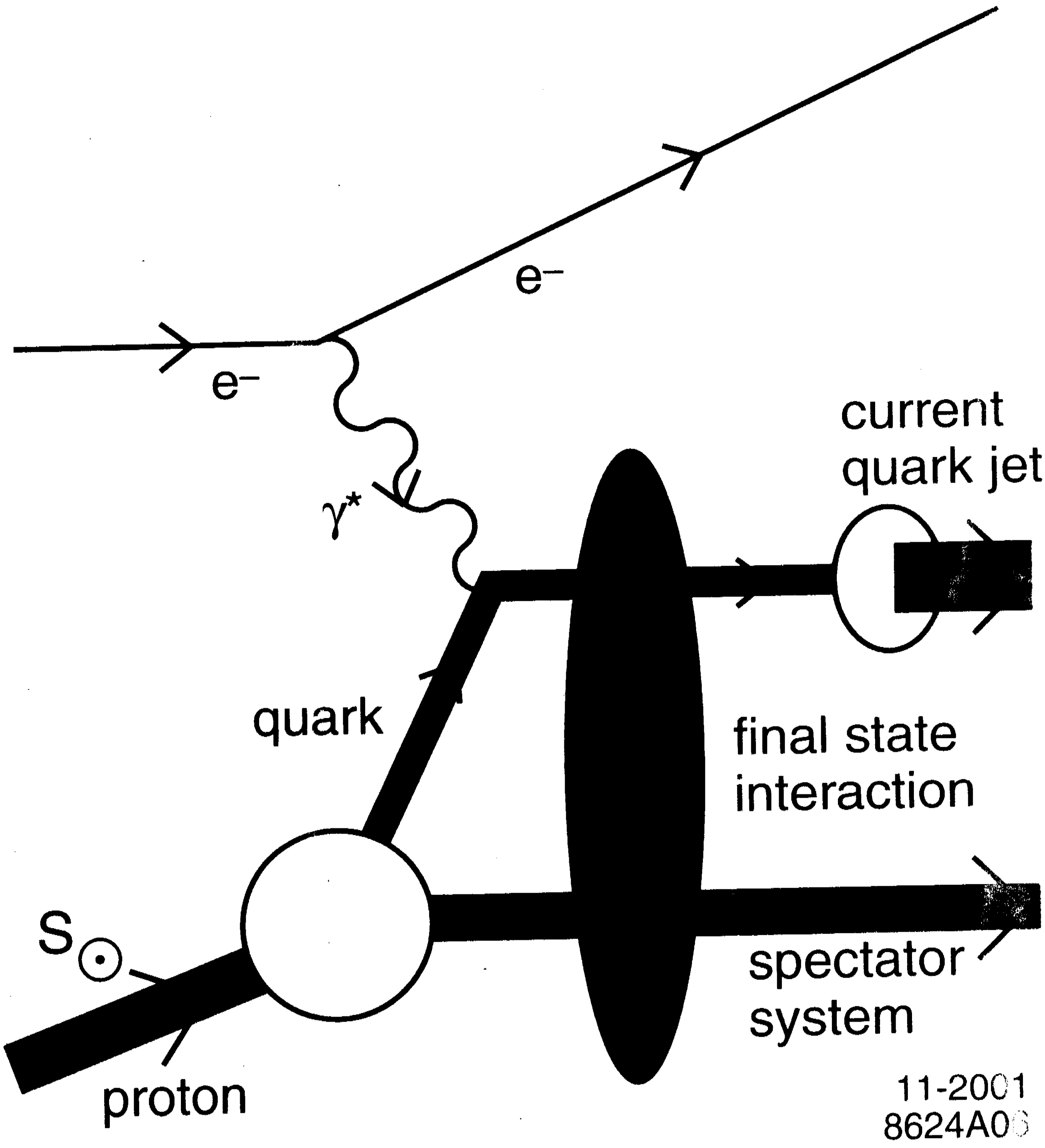
S.J.B., Dae Sung Hwang, I. Schmidt

PLB 530 99 (2002) hep-ph/0201296

* J.C. Collins hep-ph/0204004

* X. Ji + F. Yuan hep-ph/0206057

* S.J.B, A. Hebecker + E. Quack PRD 5[illegible], 2584 (1997)



e⁻
e⁻
γ*
current quark jet
quark
final state interaction
S
spectator system
proton
11-2001
8624A06

$$\boxed{\begin{array}{c}\text{Hermes, SMC observe} \\ \text{large proton spin asymmetry} \\ \text{in} \quad e\vec{p} \to e' \pi X\end{array}}$$

$A_{UN} = P_y \Rightarrow \vec{S}_p \cdot (\vec{q} \times \vec{p}_\pi)$ correlation

T-odd : requires spin amplitudes with different phase

Conventional argument :

FSI from gluon exchange are twist-3 ; ∴ suppressed in Bj limit

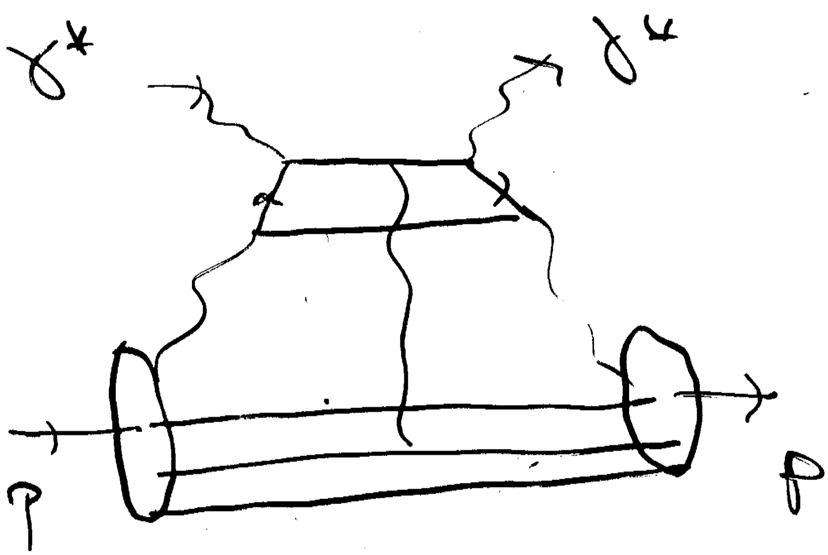
Collins, Jaffe : opportunity to measure tranversity : $\delta q \times H_{1\perp}$

Single Spin Asymmetry $\underline{A_N} = A_{UN}$

$$\underset{\substack{\uparrow \\ T}}{i}\ \vec{S} \cdot \vec{p} \times \vec{q}$$

Need interfering amplitudes
with non-zero phase.

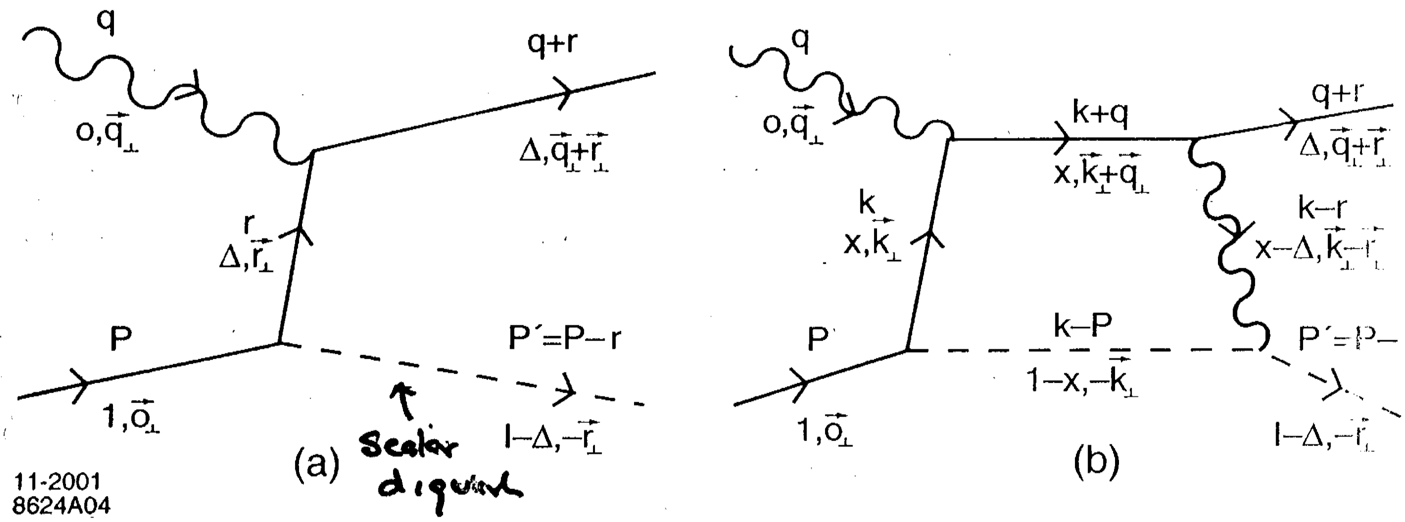
(otherwise $\not{T}$)



gauge
invariant

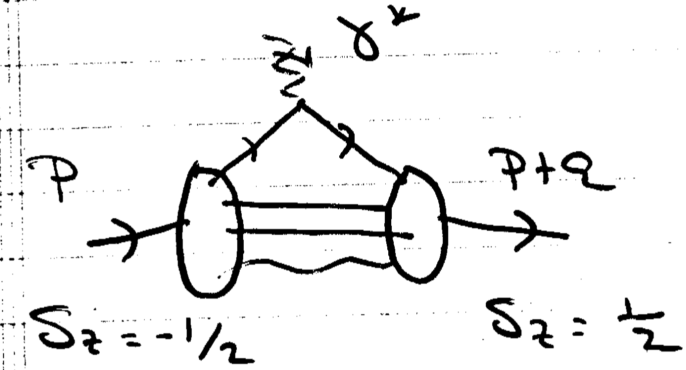
Rescattering $\Rightarrow$ non-unitary phase
at leading twist!

Hoyer, Marchal, Sannino, Peigne, SJB



q
o,$\vec{q}_\perp$
q+r
$\Delta,\vec{q}_\perp+\vec{r}_\perp$
r
$\Delta,\vec{r}_\perp$
P
1,$\vec{o}_\perp$
P′=P−r
l−Δ,−$\vec{r}_\perp$
(a)
Scalar diquark
k+q
x,$\vec{k}_\perp+\vec{q}_\perp$
k
x,$\vec{k}_\perp$
k−r
x−Δ,$\vec{k}_\perp-\vec{r}_\perp$
k−P
1−x,−$\vec{k}_\perp$
(b)
11-2001
8624A04

Pauli Form Factor $F_2(q^2)$ $\qquad \kappa = F_2(0)$



Required overlap of LCWFs with $\underline{\Delta L_z = 1}$

Drell + SJB

e.g. (3q)

$\psi^{1/2}_{-1/2\,-1/2\,-1/2} \otimes \psi^{-1/2}_{-1/2\,-1/2\,-1/2}$

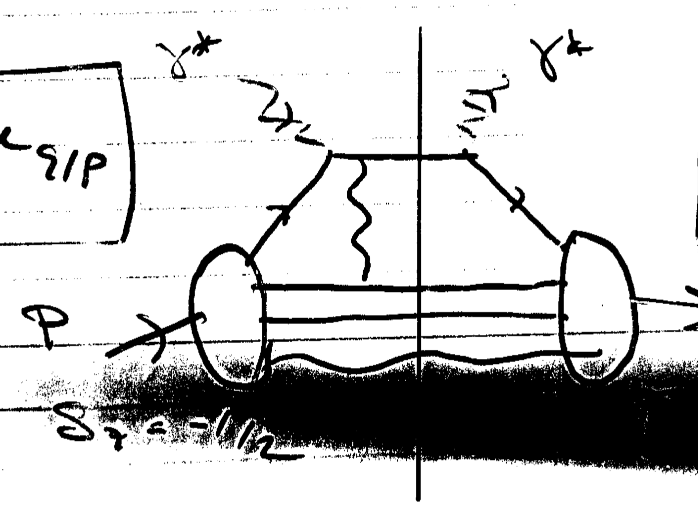
$L_z = +2 \qquad L_z = +1$

$\psi^{1/2}_{1/2\,1/2\,-1/2} \otimes \psi^{-1/2}_{\frac{1}{2}\,1/2\,-1/2}$

$L_z = 0 \qquad L_z = -1$

<u>Same matrix elements appear in SSA</u>

$$\boxed{\kappa_p = \sum_{q \in p} e_q \kappa_{q/p}}$$



$A_{UN} = SSA$

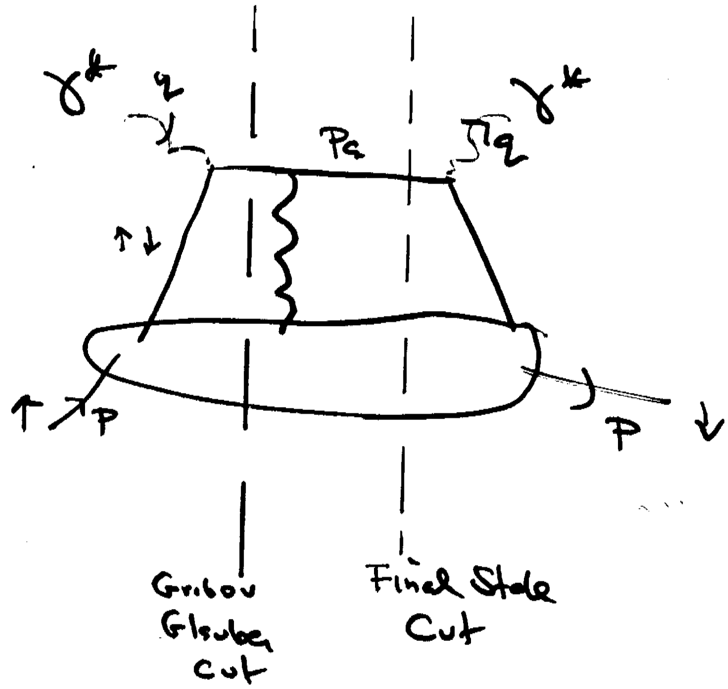
$\propto \sum e_q^2 \kappa_{q/p} \alpha_s$

Explicit calculation of FSI SSA

D. S. Hwang
I. A. Schmidt
SJB

hep/ph/0201296

Collins, X. Ji



Overlap of wavefunctions with $\Delta L_z = 1$

$\left[e^{i(\chi_1 - \chi_2)}\right]$

$\chi_1 - \chi_2$: IR Finite

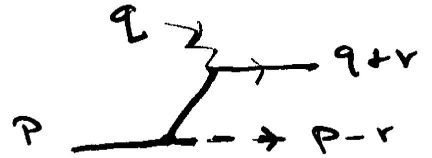
$$i \vec{S}_p \cdot \vec{q} \times \vec{p}_q = i \vec{S}_p \cdot \vec{q} \times \vec{r}$$

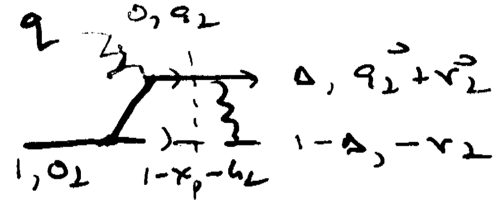
$$\vec{p}_q = \vec{q} + \vec{r}$$

$$P_y = A_n \cong \frac{\alpha_s(r_\perp^2)\, x_{Bj}\, M |\vec{r}_\perp| \ln r_\perp^2}{r_\perp^2}$$

Bjorken scaling for finite $r_\perp$

Same matrix elements as $a_p = F_2(0)$





$$|\psi^{\uparrow}(P^+, \vec{P}_\perp = 0)\rangle$$

$$= \int \frac{d^2k_\perp\, dx}{\sqrt{x(1-x)}\, 16\pi^3} \Big[\psi^{\uparrow}_{+1/2}(x, k_\perp)\, |\tfrac{1}{2}; xP^+, \vec{k}_\perp\rangle$$

$$+ \psi^{\uparrow}_{-1/2}(x, \vec{k}_\perp)\, |-\tfrac{1}{2}; xP^+, \vec{k}_\perp\rangle$$

$$\left[\begin{array}{lll} \psi_{+\frac{1}{2}}(x, \vec{k}_\perp) = \left(M + \frac{m}{x}\right)\varphi & & L_z = 0 \\ \psi_{-1/2}(x, k_\perp) = -\frac{k^1 + ik^2}{x}\varphi & & L_z = 1 \end{array}\right.$$

$$\varphi = \varphi(x, k_\perp) = \frac{\dfrac{g}{\sqrt{1-x}}}{M^2 - \dfrac{k_\perp^2 + m^2}{x} - \dfrac{k_\perp^2 + \lambda^2}{1-x}}$$

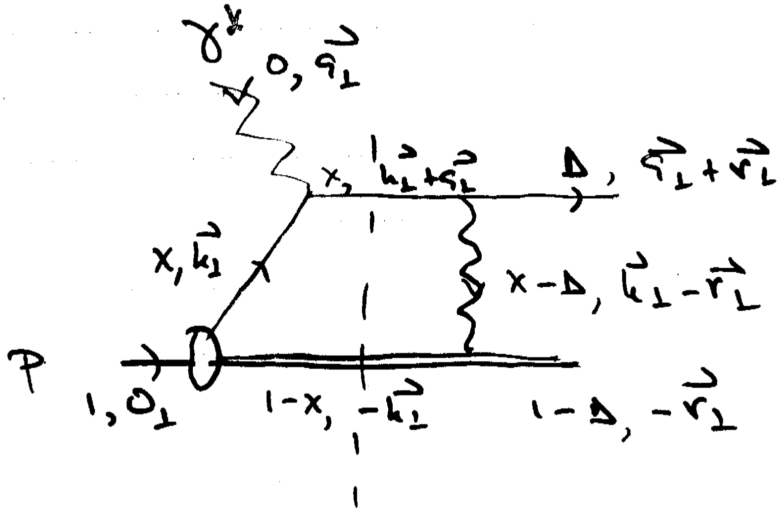
$$\left[\begin{array}{l} A(\Uparrow \to \uparrow) = \left(M + \frac{m}{\Delta}\right) G \left(h + i\frac{e_1 e_2}{8\pi} g_1\right) \\ A(\Downarrow \to \uparrow) = \left(\frac{r^1 - ir^2}{\Delta}\right) G \left(h + i\frac{e_1 e_2}{8\pi} g_2\right) \end{array}\right.$$

$$G = -g e_1 P^+ \sqrt{\Delta}\, 2\Delta(1-\Delta)$$

$$h = \frac{1}{\vec{r}_\perp^{\,2} + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)}$$

g_1, g_2 Coulomb phase for $L_z = 0, 1$

Calculation of Final-State Phase



$\Delta \Rightarrow x_{Bj}$

Cut: $$i\pi\,\delta\left(p^- + q^- - \frac{\lambda^2+k_\perp^2}{(1-x)p^+} - \frac{m^2+(\vec k_\perp+\vec q_\perp)^2}{x\,p^+}\right)$$

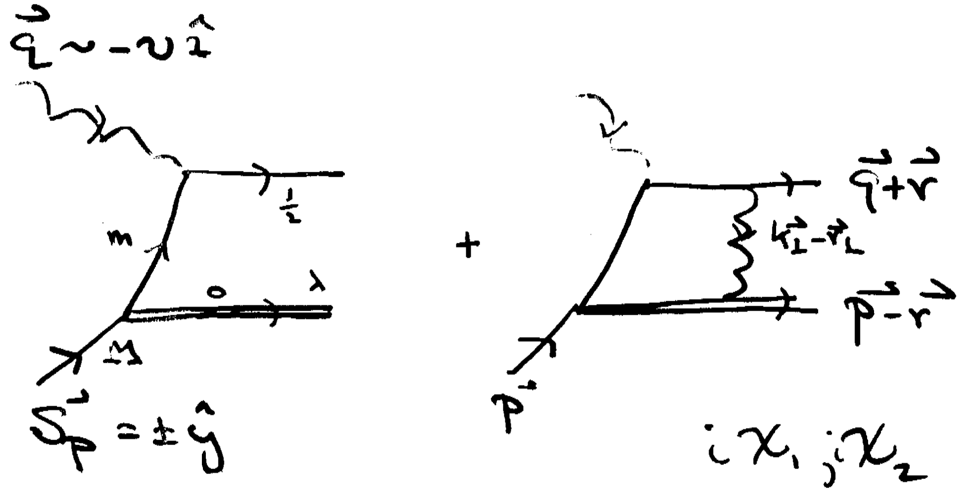
$$= \frac{i\pi}{p^+}\,\frac{\Delta^2}{q_\perp^2}\,\delta(x-\Delta-\bar\delta), \qquad \bar\delta = 2\Delta\,\frac{\vec q_\perp\cdot(\vec k_\perp-\vec r_\perp)}{q_\perp^2}$$

$$g_1(L_z=0) = \int_0^1 d\alpha\,\frac{1}{\alpha(1-\alpha)r_\perp^2 + \alpha\lambda_g^2 + (1-\alpha)\Delta(1-\Delta)\left(-M^2+\frac{m^2}{\Delta}+\frac{\lambda^2}{1-\Delta}\right)}$$

$$g_2(L_z=1) = \int_0^1 d\alpha\,\frac{\alpha}{[\quad]}$$

$*$ $$g_1 - g_2 = \int_0^1 d\alpha\,\frac{1-\alpha}{[\quad]}$$: IR finite for $\lambda_g^2 \to 0$,

$\frac{e_1 e_2}{4\pi} \Rightarrow C_F\,\alpha_s(\mu^2 = e^{-5/3}(\vec k_\perp-\vec r_\perp)^2)$ in $\overline{MS}$.



$\hat{r} = \hat{x}$

$$\sigma \propto \epsilon^{\mu abc} P_\mu S_a q_b r_c = M \vec{S} \cdot \vec{q} \times \vec{r}$$

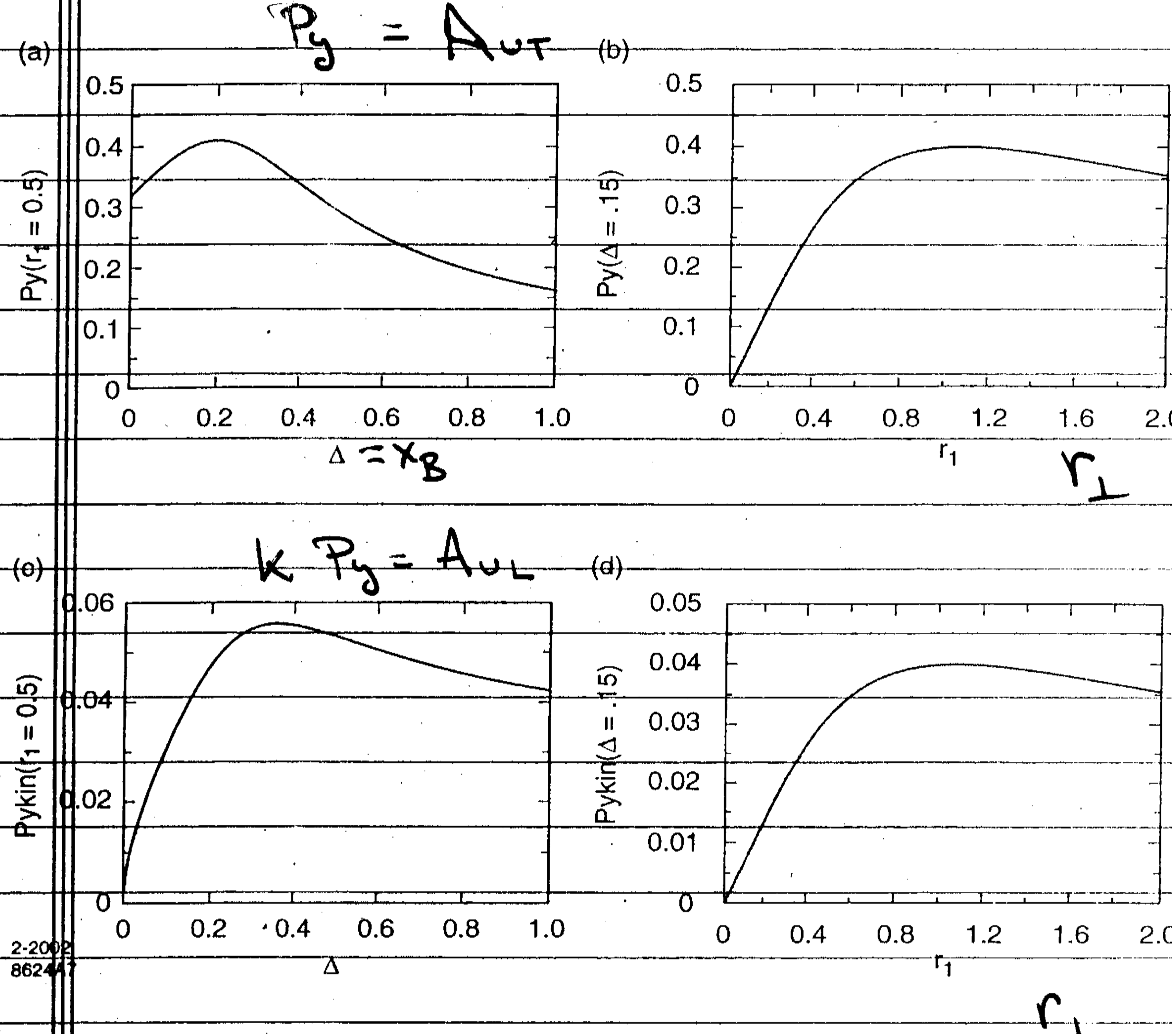
$$A_n = P_y = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$= \frac{C_F \alpha_s(\mu^2)(\Delta M + m)\, r_x}{(\Delta M + m)^2 + r_\perp^2}$$

$$\otimes \left[r_\perp^2 + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)\right]$$

$$\otimes \left[\frac{1}{r_\perp^2} \ln \frac{r_\perp^2 + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)}{\Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)}\right]$$

$\Delta = x_{Bj}$, $\qquad \mu^2_{\overline{MS}} = \langle e^{-5/3} (\vec{k}_\perp - \vec{r}_\perp)^2 \rangle$



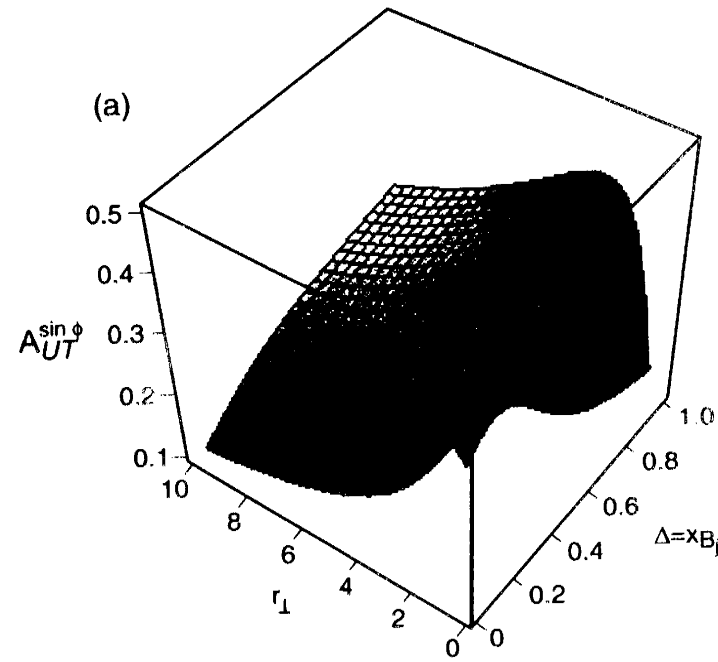
$$k = \frac{Q}{\nu}\sqrt{1-y} = \sqrt{\frac{2Mx_{Bj}}{E}}\sqrt{\frac{1-y}{y}} \sim 0.26\sqrt{x_{Bj}}$$

for Hermes

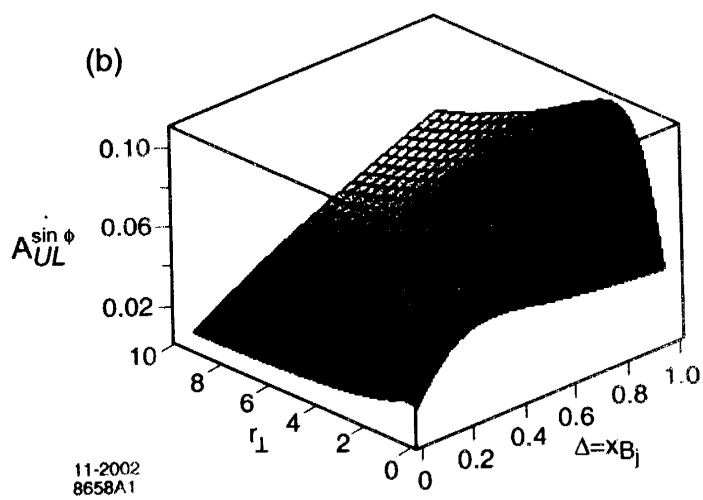
kinematic factor for $\hat{S}_p = \hat{l}$

~~Proton~~ polarization along incident lepton

(a)

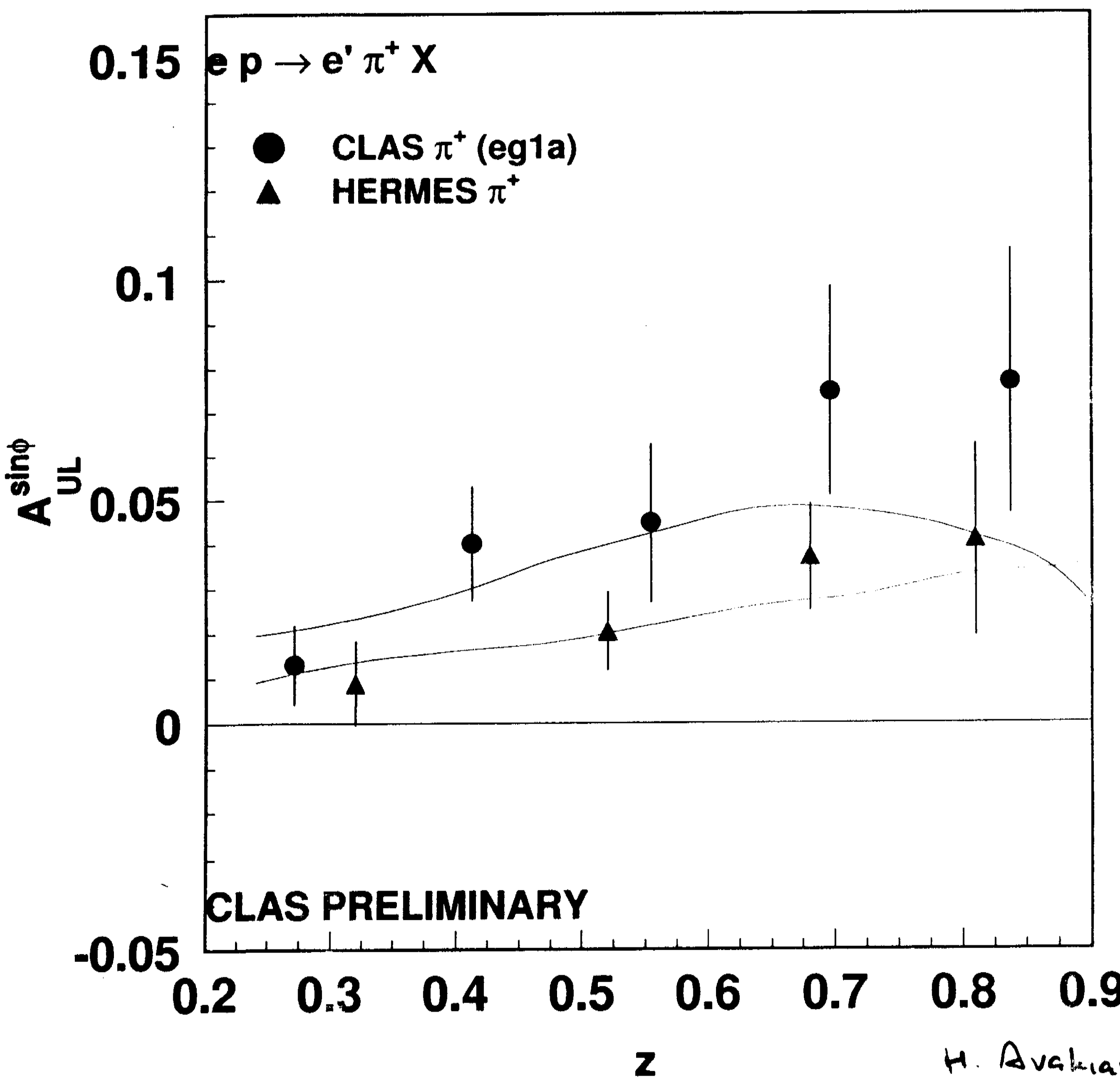


(b)



11-2002
8658A1

Prediction from BHS : Sivers Effect

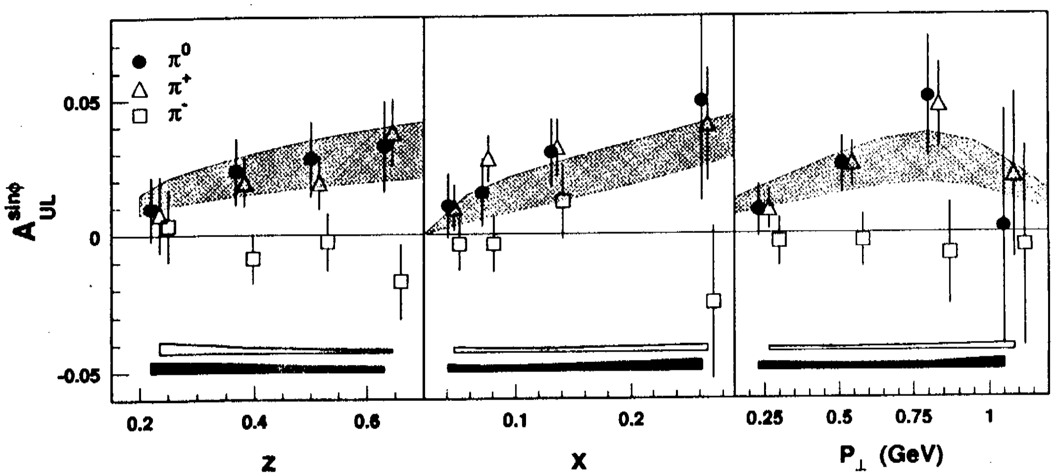


H. Avakian

Does Hermes see the Collins effect in A_{UL} ?

Yes ?

- Data agrees with u-quark dominance, follow predictions.
- Not much constraint on h_1, band shows $g_1 \leq h_1 \leq (f_1 + g_1)/2$.



No ?

- Effect is suppressed with a longitudinal target.
- Compete with other higher-twist effects.
- Could be the Sivers Effect ?

Sivers Effect is T-odd, allowed in SIDIS?

S. Brodsky, D.S.Hwang and I. Schimdt, PLB 530, 99(2002).

- Quark final state interactions $\Rightarrow$ a phase difference.
- T-odd Sivers distribution f_{1T} allowed at the leading order.

Confirmed by J. C. Collins, PLB 536, 43(2002).

Light cone gauge approach: X. Ji and F. Yuan, PLB 543, 66(2002).

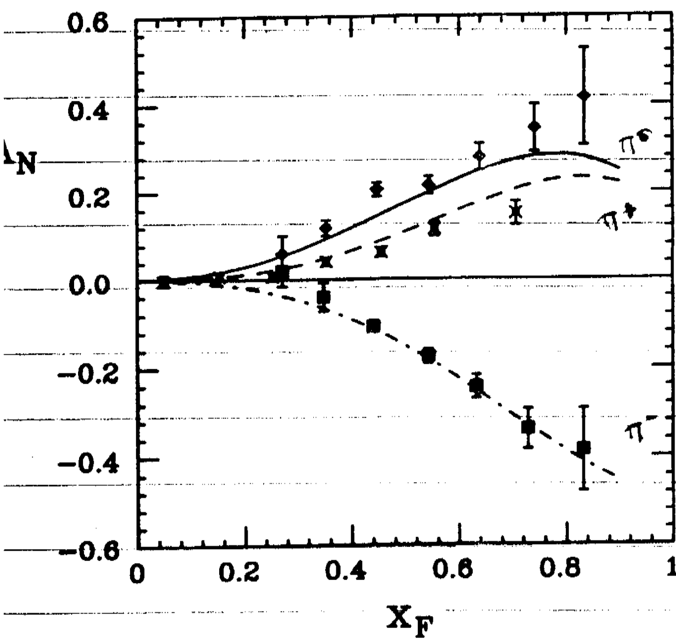
➡ SSA $A_{UT} \propto \kappa_N$ nucleon anomalous magnetic moment.
$A_{UT}^{\pi^+}(p)$ and $A_{UT}^{\pi^-}(n)$ similar in size, opposite in sign.

Collins Effect and Transversity

ıere is another possible explanation ...
ɘ E704 single-spin asymmetry could be due to:

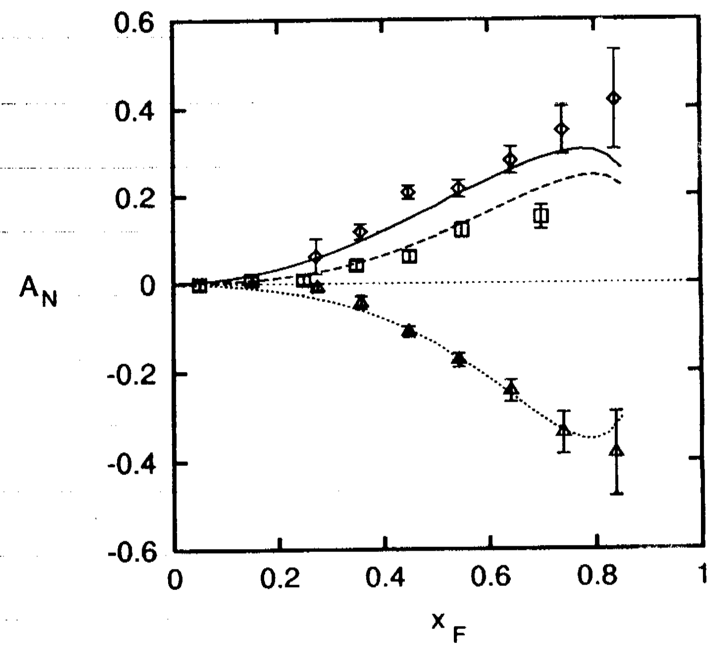
Sivers Effect:

Γ-odd **distributⁿ function**



Collins Effect:

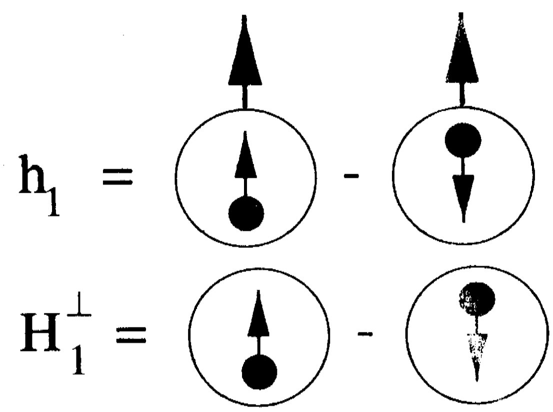
T-odd **fragmentatⁿ function** $H_1^\perp$



ollins Effect

In this case, $A_N \sim h_1(x)\, H_1^\perp(z)$

$\Rightarrow$ access to **transversity!**

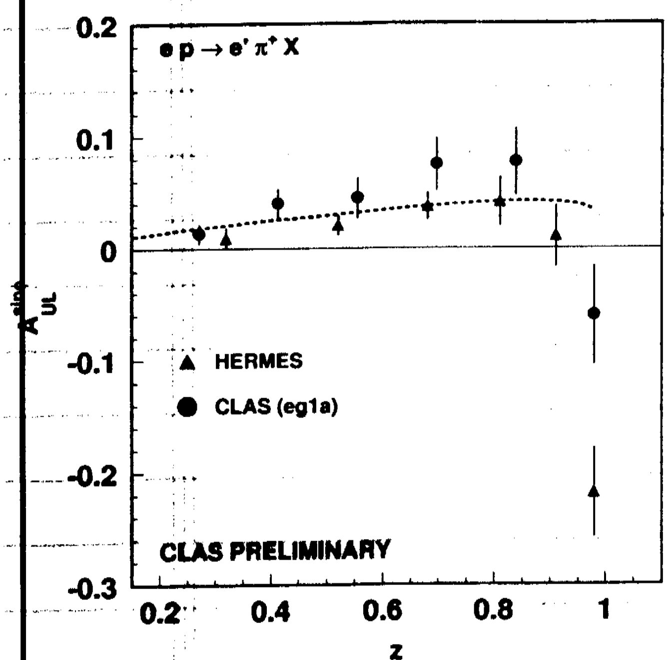


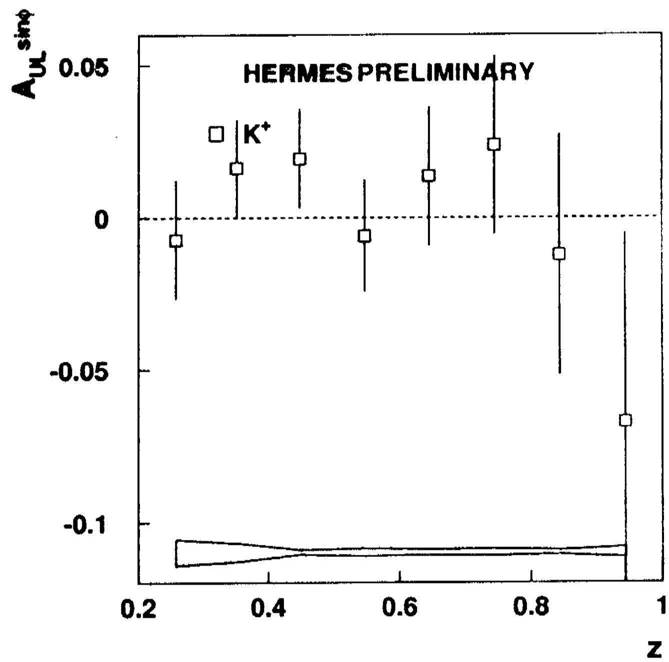
ow to separate?

Single Spin Asymmetries in DIS

LPol Target SSA for π^+ and K^+

$$A_{UL} \propto D_L(y) \times \frac{h_L^u(x)}{u(x)} \frac{H_1^u(z)}{D_1^u(z)} \quad ?$$





The z-dependence of target SSA from CLAS is consistent with HERMES measurement.

The behavior of target SSA for π^+ and K^+ is consistent in agreement with factorization and u-quark dominance.

$z \to 1$ Exclusive limit ; coherence

Anomalous moment $\kappa = F_2(0)$

$$\kappa_p = \sum_q e_q \kappa_{q/p}$$

3 quark model:

$$\kappa_p = 2(2/3)\kappa_{u/p} + (-1/3)\kappa_{d/p}$$

$$\kappa_n = 2(-1/3)\kappa_{d/n} + (2/3)\kappa_{u/n}$$

Isospin: $\kappa_p + \kappa_n = 2/3\, \kappa_{u/p} + 1/3\, \kappa_{d/p}$

~ 0

$$\boxed{\kappa_{u/n} = \kappa_{d/p} \cong -2\kappa_{u/p}}$$

* Predict large SSA for neutron target

* $SSA(\gamma^* n \to u X)$

$= -2\, SSA(\gamma^* p \to u X)$

* $SSA(\gamma^* p \to d X) = -2\, SSA(\gamma^* p \to u X)$

⇒ Final State Interaction Produces

<u>Single - Spin</u> <u>Asymmetry</u>

with respect to the jet production plane

$$\boxed{\vec{S}_p \cdot \vec{q} \times \vec{P}_{Jet}}$$

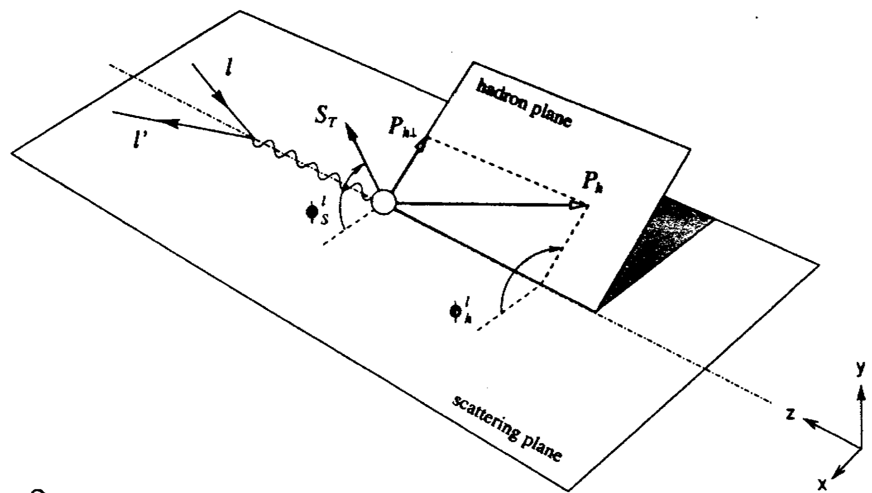
Find <u>jet</u> direction using thrust, etc.

Quark Fragmentation leads to

$$\boxed{\vec{S}_p \cdot \vec{q} \times \vec{P}_{\pi}}$$

* New QCD mechanism
* Bjorken scaling
* Reflects $\Delta L_z \neq 0$ Matrix elements.
* Similar to $F_2(0)$

Collins effect vs Sivers effect



$$\sigma_{UT}(x,z,\boldsymbol{P}_{h\perp}^2) = (\sigma_{UT})_{Collins} + (\sigma_{UT})_{Sivers}$$

$$= \quad |\boldsymbol{S}_T|(1-y)\cdot\frac{P_{h\perp}}{zM_h}\,\sin(\phi_h^\ell+\phi_S^\ell)\cdot\sum e_q^2\,h_1^q(x)H_1^{\perp q}(z,\boldsymbol{P}_{h\perp}^2)$$

$$+|\boldsymbol{S}_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\,\sin(\phi_h^\ell-\phi_S^\ell)\cdot\sum e_q^2\,f_{1T}^{\perp(1)q}(x)D_1^q(z,\boldsymbol{P}_{h\perp}^2)$$

- Longitudinal target has $\phi_S^\ell = 0$. Need a transversely polarized target (Hermes run-II).
- Collins angle: $\phi_C = \phi_h^l + \phi_S^l$, ➡ target spin rotation $\approx$ out-of-plane detection.

* Sivers effect : indep of $\phi_{l'}$

: hadronization not necessary

$\boxed{\text{Single - Spin Asymmetry in Semi-Inclusive DIS}}$

Distinguish Sivers vs Collins Effects

— Sivers: $\vec{S}_{\vec{p}} \cdot \vec{q} \times \vec{P}_{Jet}$

* no hadronization necessary
* observe quark direction $\vec{P}_q = \vec{P}_{Jet}$

— Collins: T-odd fragmentation necessary

$H_1^\perp$: $\vec{S}_q \cdot \vec{P}_H \times \vec{P}_q$

— Sivers: $\sin(\phi_H^l - \phi_{S_p}^l)$ indep. of $\phi_{l'}$!

— Collins: $\sin(\phi_H^l + \phi_{S_p}^l)$

— Sivers: A_{UL}, A_{UT} same in

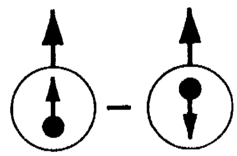
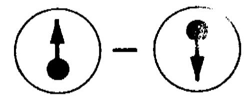
$\nu p_\uparrow \to H X$ charged current *

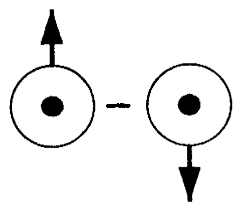
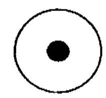
Collins: $A_{UL}, A_{UT} = 0$ *

$\propto \frac{2 C_L C_R}{C_L + C_R}$ Z^0 neutral current

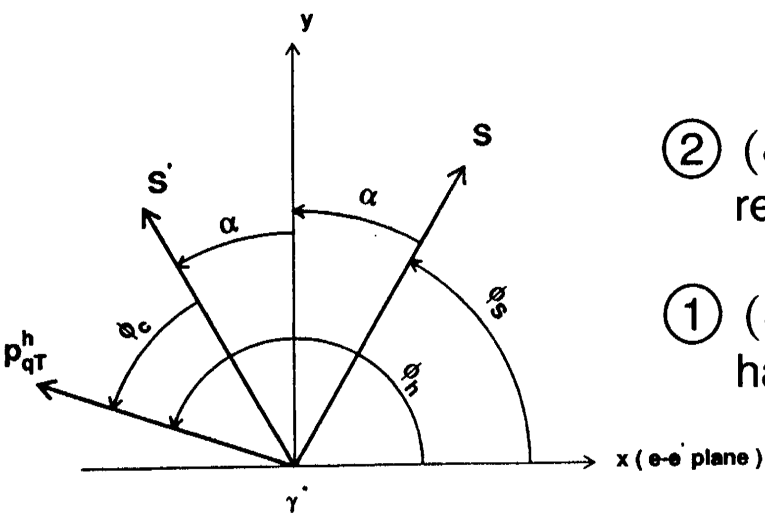
T-odd Distribution vs Fragmentation Function

There are actually **two** similar terms in $d\sigma_{\mathrm{UT}}$ ...

① $\sin(\phi^l_h + \phi^l_S)$ $\otimes\, h_1 =$  $\otimes\, H_1^\perp =$ 

② $\sin(\phi^l_h - \phi^l_S)$ $\otimes\, f_{1T}^\perp =$  $\otimes\, D_1 =$ 

$\boxed{f_{1T}^\perp = \textit{T-odd distribution function}}$



② $(\phi^l_h - \phi^l_S)$ = angle of hadron relative to **initial** quark spin

① $(\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^{l'}_S) =$ hadron relative to **final** quark spin

Cannot distinguish in:

- **longitudinal-target case** ...
  $\rightarrow$ transverse component has $\phi^l_S = 0$.
- **inclusive π production**, e.g. $p^\uparrow p \rightarrow \pi X$
  $\rightarrow$ jet axis not known

N.C.R. Makins, QCD-N02, Ferrara

In general,

initial, final state interactions

will produce single-spin asymmetries

$$\vec{S} \cdot \vec{p}_1 \times \vec{p}_2$$

wrt virtually any production or

scattering plane!

Perturbatively calculable at large $\vec{r}_\perp, \vec{q}_\perp$

New measure of $\alpha_s(r_\perp^2)$

Application to Drell-Yan: $\vec{S}_p \cdot \vec{p}_\pi \times \vec{q}$

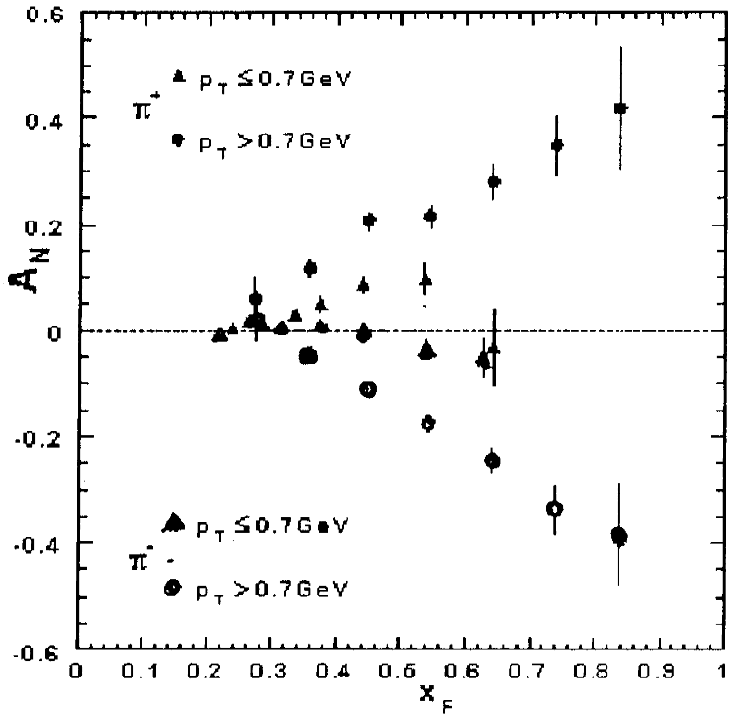
$\pi p_\uparrow \to \mu^+\mu^- X$

$e^+e^- \to \Lambda_\uparrow X$: $\vec{S}_\Lambda \cdot \vec{p}_\Lambda \times \vec{q}$

A_N: $p_\uparrow p \to \pi X$: $\vec{S}_p \cdot \vec{p}_\pi \times \vec{p}_p$

$p p \to \Lambda_\uparrow X$: $\vec{S}_\Lambda \cdot \vec{p}_\Lambda \times \vec{p}_p$

- Classic $\vec{k} \times \vec{p} \cdot \vec{s}_\perp$ asymmetry in $\vec{p}_\perp \; p \to \pi \; X$



E704 at Fermilab

- In QCD both these asymmetries are <u>twist-three effects</u>, <u>expected to vanish</u> <u>like $p_\perp/\sqrt{s}$</u>

  Nevertheless both are strikingly large. Unusual among twist three effects (for example g_2) which are usually hard to find.

- Concentrate on HERMES asymmetry here, although similar analysis applies to E704.

ISI and FSI

enhanced in nuclei

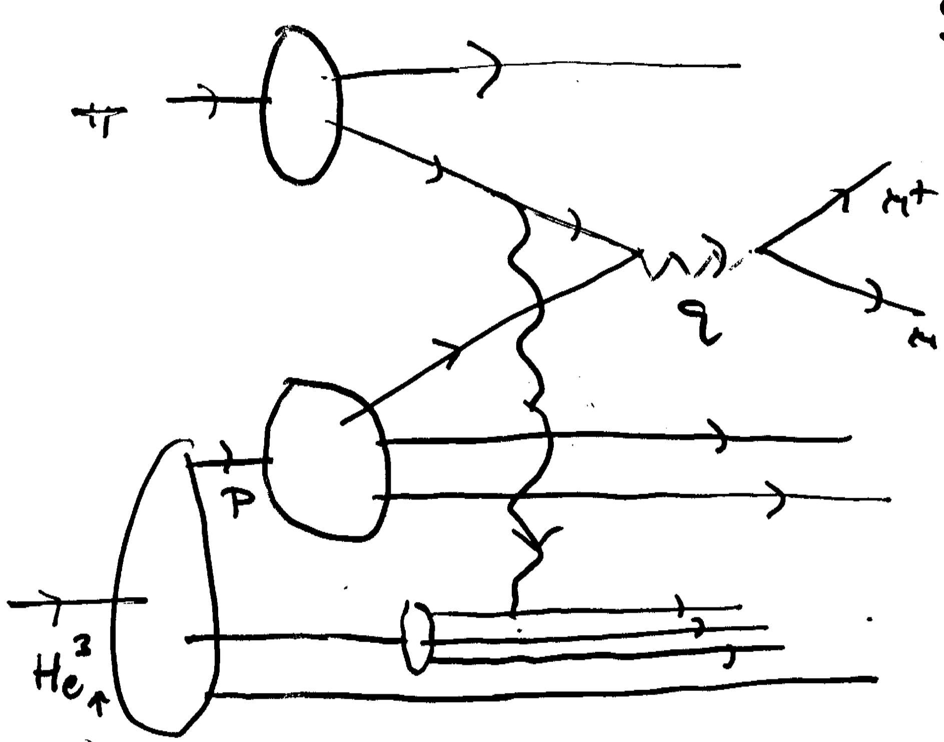
Coulomb effects

Often "leading twist" in Q^2

$$\frac{M|\vec{r}_\perp|}{r_\perp^2} \quad \text{not} \quad \frac{M|\vec{r}_\perp|}{Q^2}$$

$\vec{S}_T \cdot \vec{p}_\pi \times \vec{q}$

$\vec{q} = \vec{p}_\pi + \vec{r}_\perp$



energy loss.

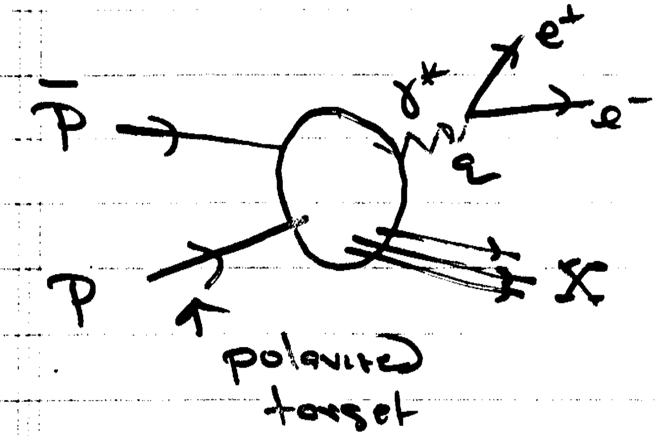
p_T spread.

Bodwin,
Lepage,
SJB

Hwang, Schmidt, [illegible]

Collins, X. Ji + Yuan

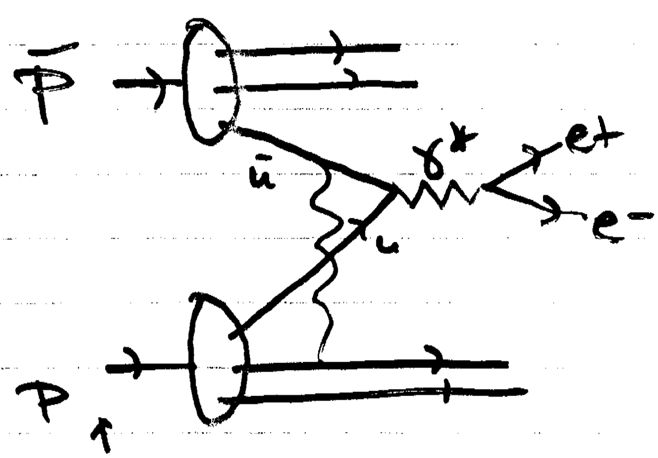
Single - Spin Asymmetries in $\bar{p}$ collision



$$\vec{S}_p \cdot \vec{P}_{\bar{p}} \times \vec{q}_\perp$$

"T-odd" observable

* New theory due to initial state gauge ints. for SIDIS



Interference of amplitudes produces phase

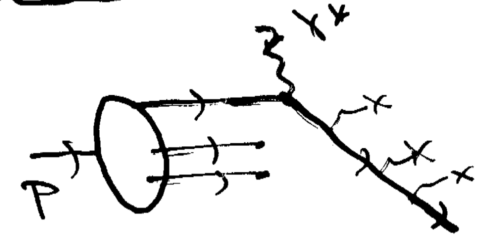
gauge - indep

Same interference of $\Delta L_z = 1$ states prod. μ_A^p

* $A_{UN} \sim \alpha_s \dfrac{M r_\perp}{r_\perp^2 + M^2} \mu_A^q$ $\qquad \vec{q} = \vec{P}_{\bar{p}} + \vec{r}_\perp$

* Scales in DY limit at fixed $r_\perp$!
* opposite in sign to SIDIS SSA

Proposed by Ji and Yuan (also Collins)



$$\Psi \to \Psi L_1$$

complex phase

Augment LFWF (lcg) with phase

$$L_1 = P \exp\left[ig \int_0^\infty d\vec{z}_\perp \cdot \vec{A}_\perp(z^- = \infty, \vec{z}_\perp$$

where $$\vec{A}_\perp = -\frac{g}{2\pi}\,\theta(z^-)\,\vec{\nabla}_\perp \ln \mu r_\perp$$

$$A^+ = A^- = 0$$

- corresponds to coulomb field of charged partic moving at v=c

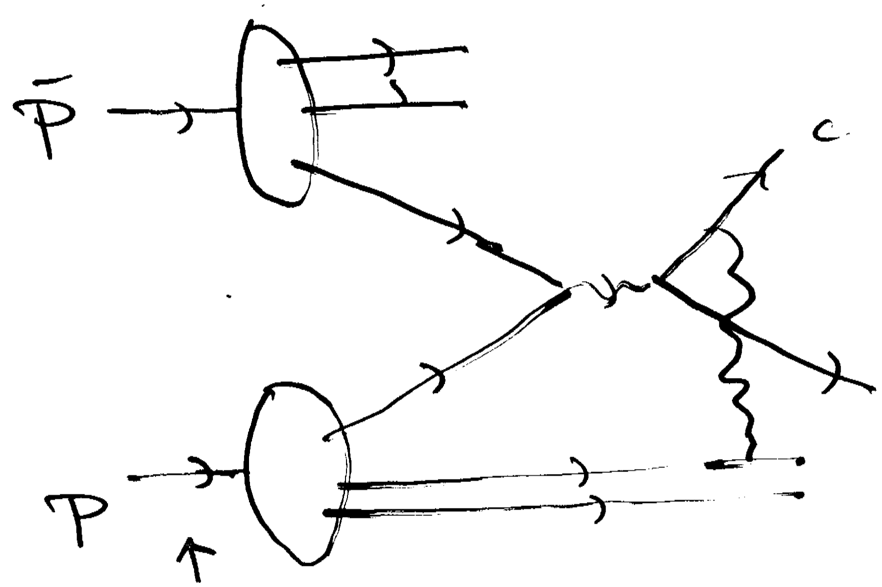
Equivalently

$$D^{\mu\nu}(q) = -\frac{i}{q^2}\left(g^{\mu\nu} - \frac{q^\mu n^\nu + q^\nu n}{q \cdot n + i\epsilon}\right.$$

* Non causal b.c. (BHMPS)

* Process specific — not universal

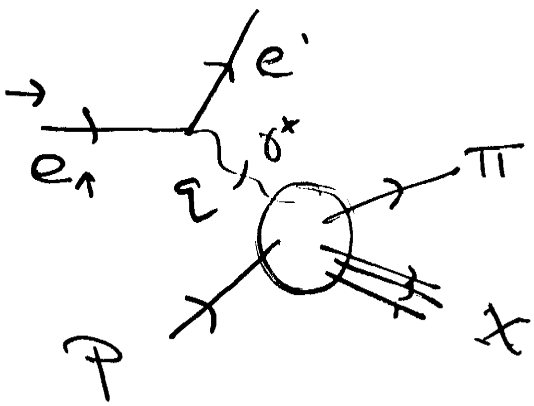
SSA in $\bar{p} p_\uparrow \to c X$



$$i \vec{S}_p \cdot \vec{\bar{p}} \times \vec{p}_c$$

Coulomb phase accumulated along

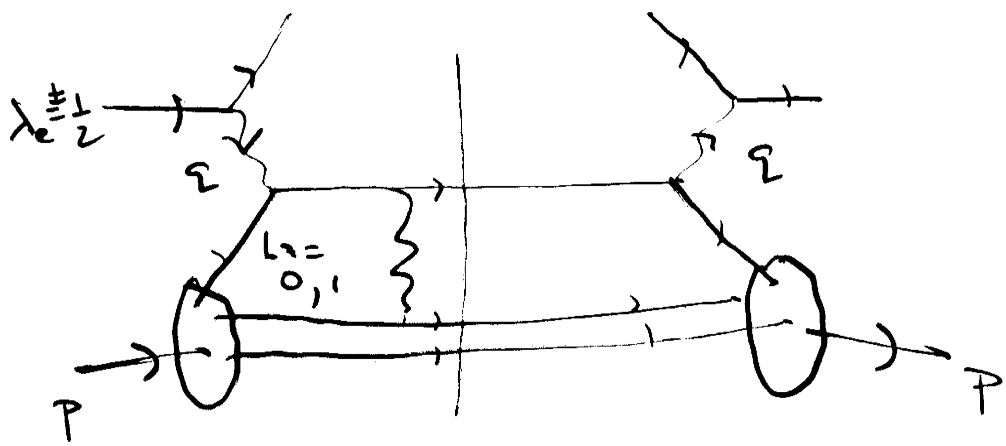
Not part of ψ_p^{LF}.



$\vec{S}_e \cdot \vec{q} \times \vec{p}_\pi$

T-odd

A_{LU}



interference
L, T
current

Insensitive to target spin

$$A_{LU} \sim \alpha_s \frac{Q r_\perp}{Q^2 + r_\perp^2}$$

similar to BHS

$\boxed{\text{Afanasev Carlson}}$

$\alpha_s \sim 0.3$

same for $\pi, K, p, \ldots$

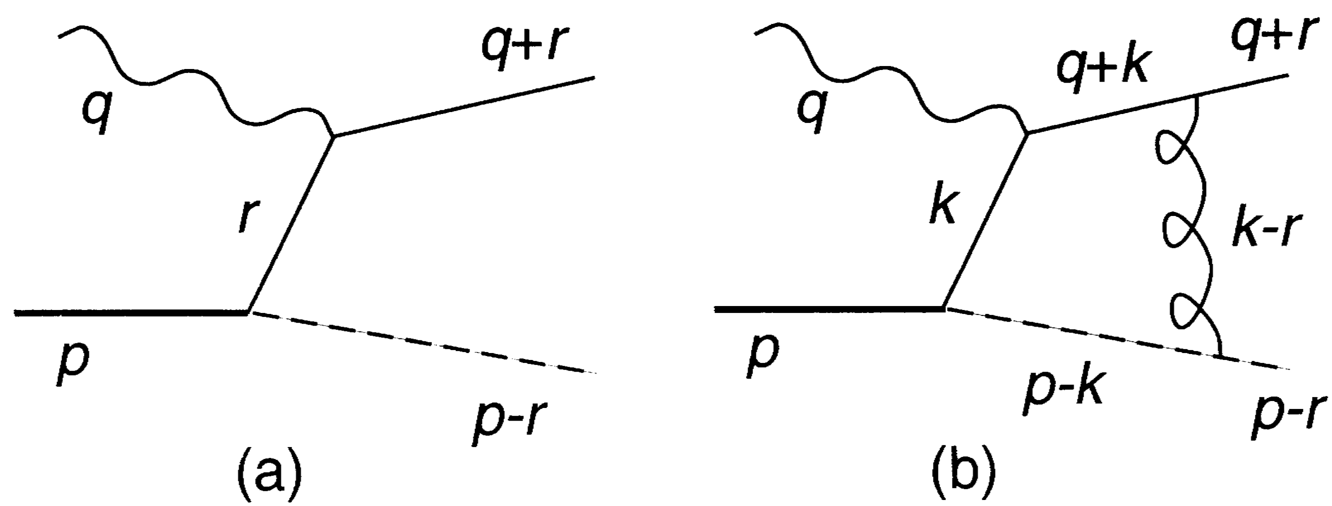
Carlson
Hwang
SJB

$$\Sigma_1 \gamma^* \cdot \vec{q} \times \vec{p}_\pi$$

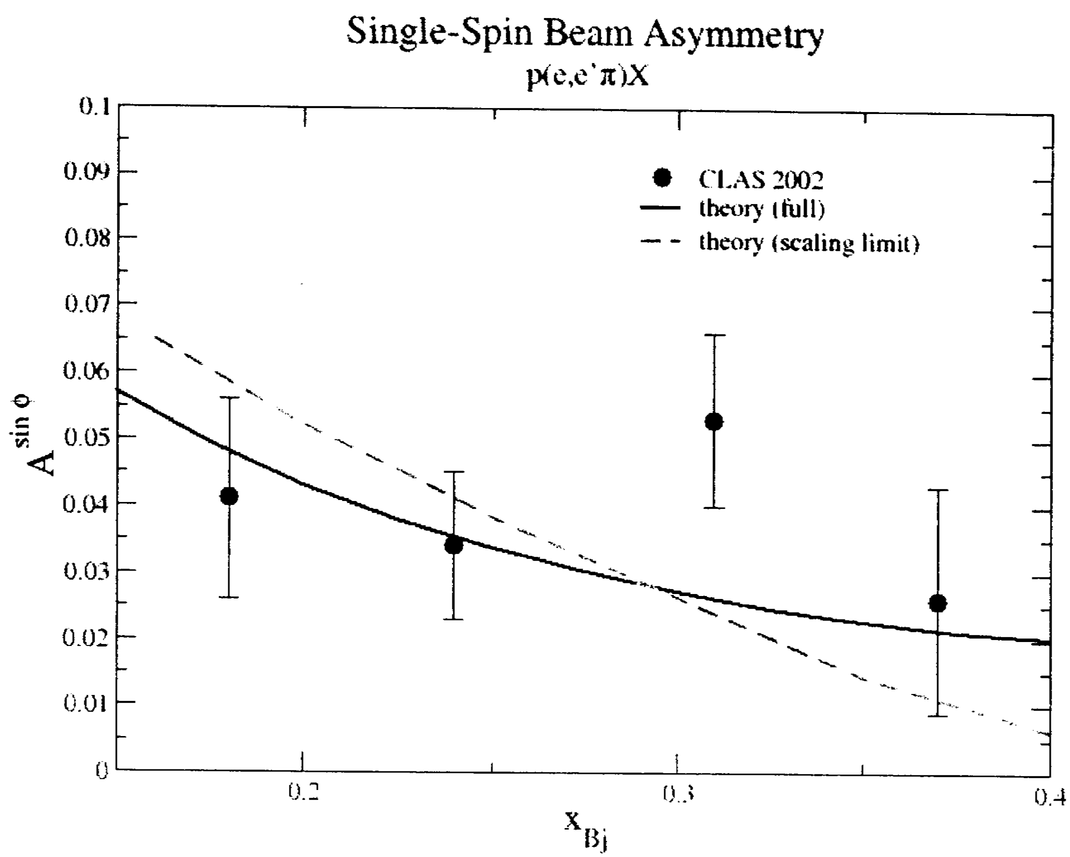
vector pol of virtual γ
density matrix $\Sigma_{\gamma^*} \propto \lambda_e$

AA+C. Carlson on Beam SSA

- Assume BHS mechanism for generating single-spin asymmetries, viz.
  - Gluon exchange takes place in the final state, generating both phase differences and transverse-momentum dependence
  - No assumptions are required on the details of nucleon spin structure



Calculations vs CLAS Data (from Afanasev&Carlson)



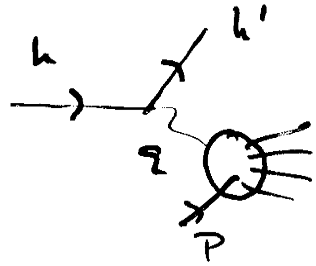
A_{LU}

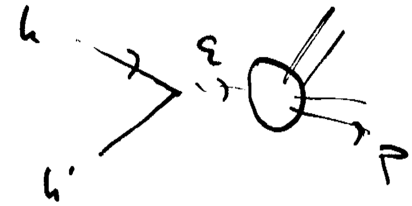
Parity-Conserving Single-Spin Asymmetries in Scattering Processes
(Early history)

- George C. Stokes, *Trans. Cambr. Phil. Soc.* **9**, 399 (1852), introduced parameters describing polarization states of light.
- N. F. Mott, *Proc. R. Soc. (London),* **A124**, 425 (1929), noticed that polarization and/or asymmetry is due to spin-orbit coupling in the Coulomb scattering of electrons (Extended to high energies by AA et al., hep-ph/0208260).
- Julian Schwinger, *Phys. Rev.* **69**, 681 (1946); *ibid.*, **73**, 407 (1948), suggested a method to polarize fast neutrons via spin-orbit interaction in the scattering off nuclei
- Lincoln Wolfeinstein, *Phys. Rev.* **75**, 1664 (1949); A. Simon, T.A.Welton, *Phys. Rev.* 90, 1036 (1953), formalism of polarization effects in nuclear reactions

Carlson
Hwang
[illegible]

Density Matrix of Virtual Photon





$$L^{\mu\nu} W_{\mu\nu} = \eta^{ac}\eta^{bd}\left[\epsilon_a^{\mu *} L_{\mu\nu}\epsilon_b^{\nu}\right]\left[\epsilon_c^{\rho} W_{\rho\sigma}\epsilon_d^{\sigma *}\right]$$

$$\equiv \eta^{ac}\eta^{bd}\ \rho^{l}_{ab}\ \rho^{h}_{cd}$$

$$\equiv \widetilde{\mathrm{Tr}}\left[\rho^{l}\rho^{h}\right]$$

$\eta^{ab} = (1,-1,-1,-1)$ $\qquad$ $\epsilon^{\mu} \propto q^{\mu}$ gives 0

timelike: $\quad a = 1, 2, 3$ $\quad$ $SO(3)$
spacelike: $\quad a = 0, 1, 2$ $\quad$ $SO(2,1)$

$$\underset{3\times 3}{\rho} = \frac{1}{3}\Big[\underset{3\times 3}{I} + \frac{3}{2} S^{i}\underset{3\times 3}{\Sigma^{i}} + 3\,T^{ij}\underset{3\times 3}{\Sigma^{ij}}\Big]$$

$i, j = 1, 2, 3$

e.g.:

$$\rho^{l} = -2\left(k^{i}k'^{j} + k'^{i}k^{j}\right)\Sigma^{ij}$$ tensor pol

$$+\frac{4}{3}\left(k^{i}k'^{i} + q^{2}\right) I$$ of virtual γ (timelike)

$$-2\left(\lambda_e\, q^{0} k^{i}\right)\Sigma^{i}$$ vector pol

tensor + vector polarization

of virtual photon

interacts with

tensor + vector polarization

of hadronic current

$$\left[S^{i}_{\gamma^*} , S^{i}_{had} \right]$$

$$\left[T^{ij}_{\gamma^*} \quad T^{lm}_{had} \right] \qquad \mathrm{Tr}\left[\Sigma^{ij} \Sigma^{lm} \right]$$

$\frac{1}{2}\delta^{il}\delta^{jm} + \frac{1}{2}\delta^{im}\delta^{jl}$

$-\frac{1}{3}\delta^{ij}\delta^{lm}$

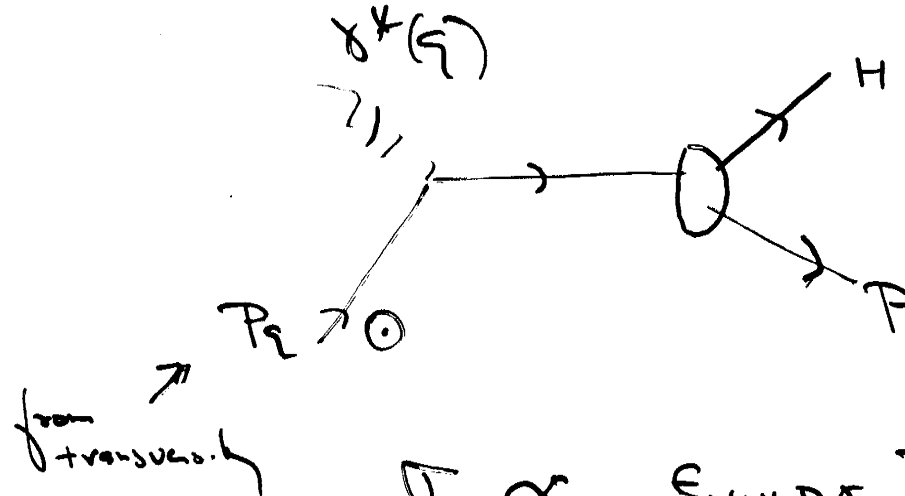
inv.

$SO(3)$, $SO(2,1)$

reduces $L^{\mu\nu} W_{\mu\nu}$ to

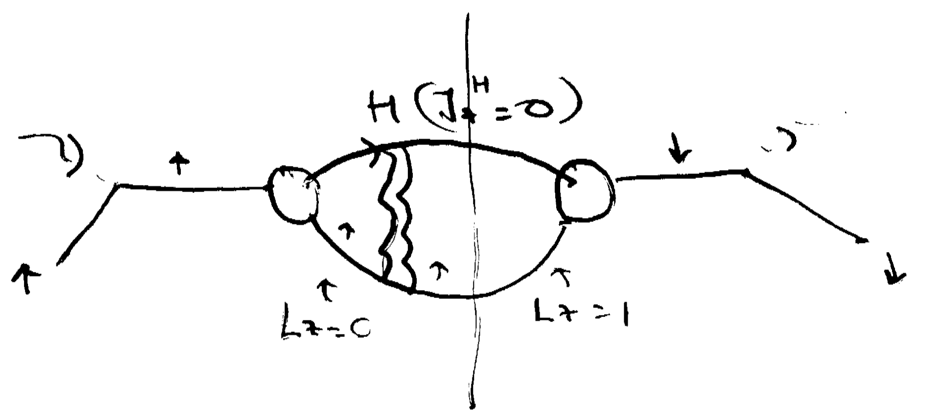
eff. degrees of freedom

BHS-type Theory of Collins Function $H_{1\perp}(z)$



$$\sigma \propto \epsilon_{\mu\nu\rho\sigma} P_H^{\mu} q^{\nu} P_q^{\rho} S_q^{\sigma}$$

$$\Rightarrow \times \mathcal{M}\, \vec{S}_q \cdot \vec{q} \times \vec{P}_H$$



FSI from pomeron

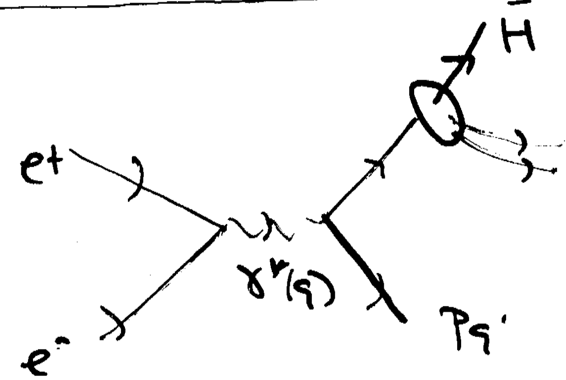
Different orbitals for $J_z^H = 0, 1$!

$\therefore$ Collins effect depends on J_z^H

e.g.: $\rho_{J_z=0}$, $\rho_{J_z=\pm 1}$

π^+, $\rho^+_{J_z=1}$ different

SSA in e^+e^- annihilation

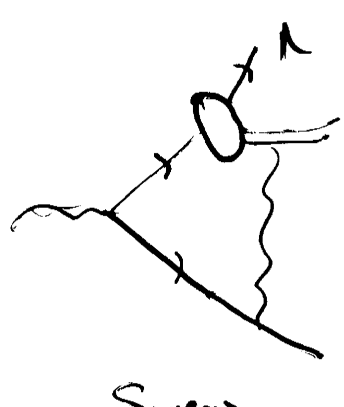


$$e^+ e^- \to \Lambda_\uparrow\, p_{q'}\, X$$

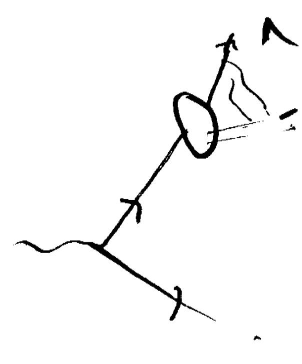
$$p_{q'} \hookrightarrow \pi,\ K$$

$$\sigma \propto \epsilon_{\mu\nu\rho\sigma}\, S_\Lambda^\mu\, P_\Lambda^\nu\, q^\rho\, P_{q'}^\sigma$$

$$\underset{cm}{\Rightarrow} \sqrt{s}\ \vec{S}_\Lambda \cdot \vec{P}_\Lambda \times \vec{P}_{q'}$$



~ Sivers



~ Collins

Conclusions

* T-odd Physics
  ∃ new insight into QCD
  role of ISI, FSI

* Sivers + Collins effects both present in QCD
  BHS, Collins
* Mechanisms understood at perturbative level
* $\alpha_s(\mu^2)$?
* SSA related to Diffractive DIS, Shadowing
* $k_\perp$ distributions, energy loss from ISI, FSI

  Bodwin, Lepage, SJB ; Boer, Hwang, SJB
  Metz, Polyakov et al ; Boer, Mulders

* DIS structure functions measure augmented LFWFs — BHMPS
  Ji, Yang
  ∃ Solve QCD in external field

* Many questions of principle
  Sum rules; factorization (process indep?); DHG in nuclei

New Questions:

* How is momentum sum rule maintained in the face of shadowing?

* What is the mechanism which produces anti-shadowing?

→ Reggeons, $\gamma N \to \rho N$: constructive phases at threshold

* How does the DHG sum rule account for shadowing?

$$\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left[\sigma_P^{\gamma A} - \sigma_A^{\gamma A}\right] = \frac{2\pi^2 \alpha\, \kappa_A^2}{M_A^2}$$

Back face is shadowed at high ν!

Antishadowing from $\gamma N \to \rho^0 N$ at threshold?