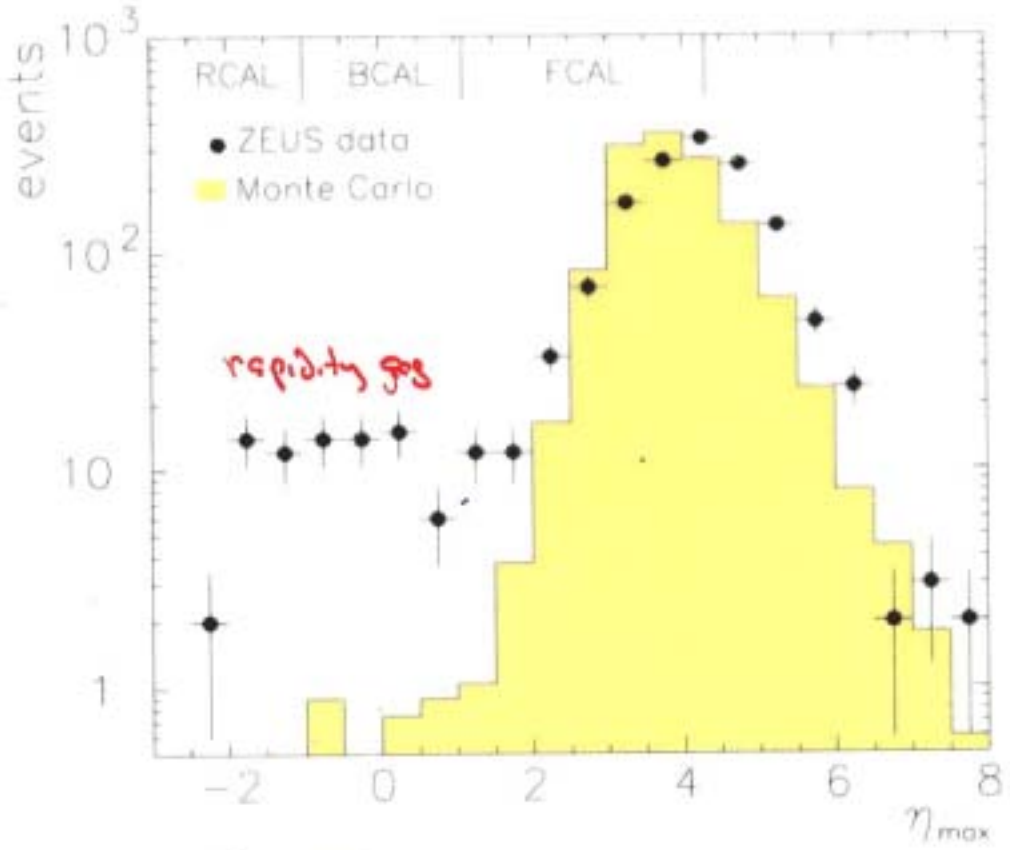
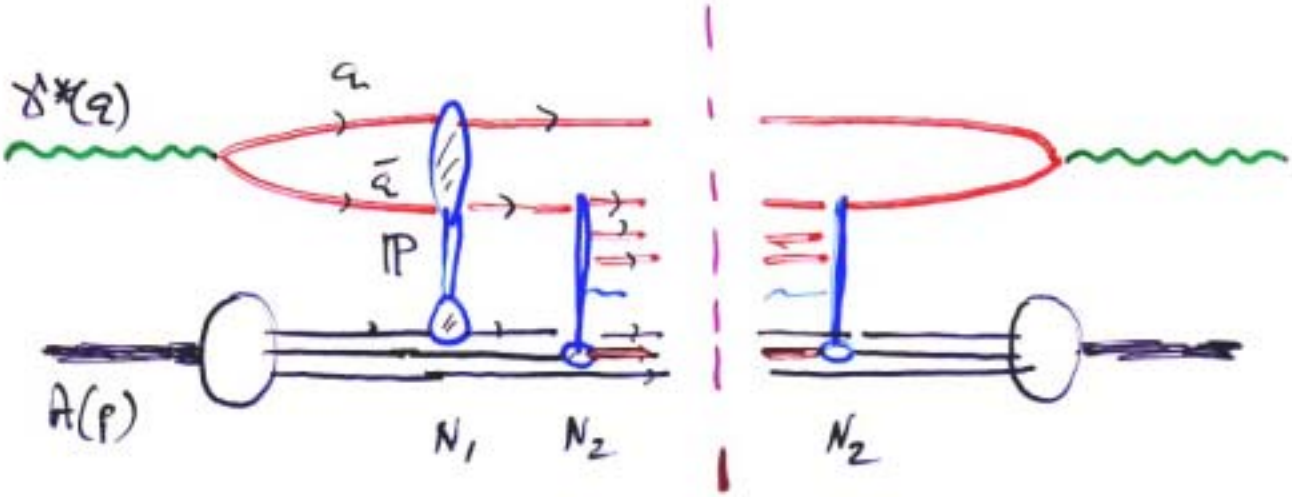


minimal excitation
of proton

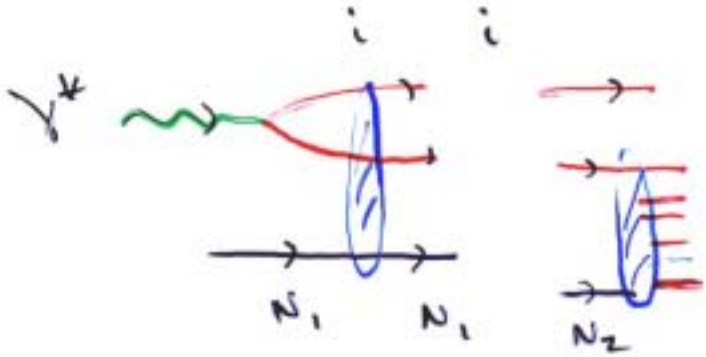
Ref: Hebecker
hep-ph/9909504



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

Glauber, Gribov
Frankfurt, Strikman
Kopeliovich

* Phase structure critical



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

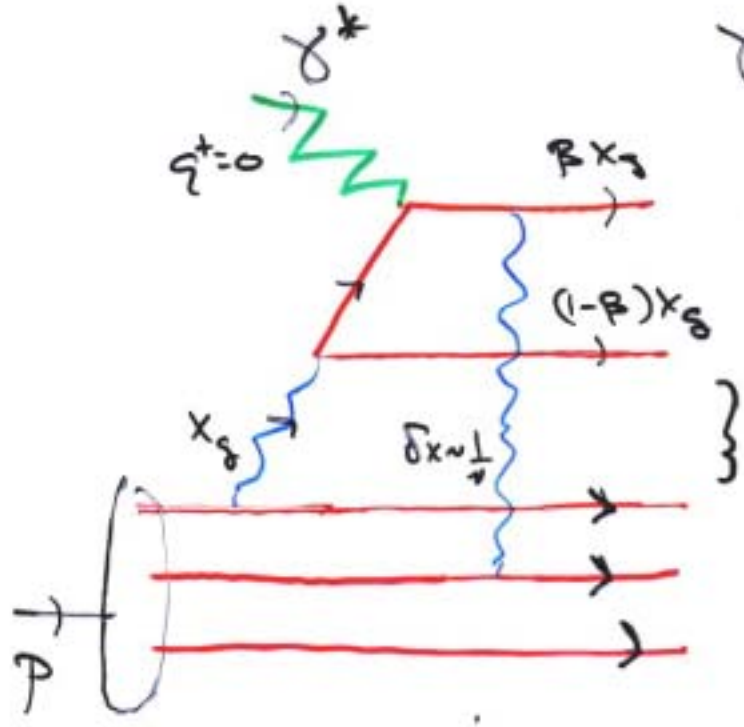
* None of this in l.c. w/f's! FSI!
  - $\Psi_n(x, k_\perp)$ real!

In progress

Hager
Ingelman Enberg
SJB

Structure Function of Pomeron

$\gamma^* p \to M_{q\bar{q}} + p'$



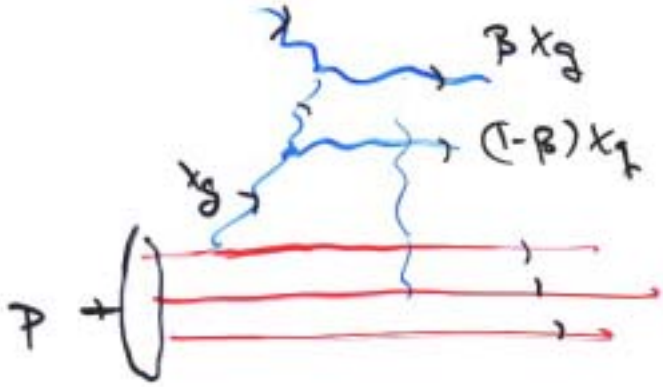
Diffractive DIS

$$F_{2\,\text{pomeron}}^{(\beta)} = F_{2\,g/p}^{(\beta)}$$

β - distribution
Same as
$g \to q\bar{q}$

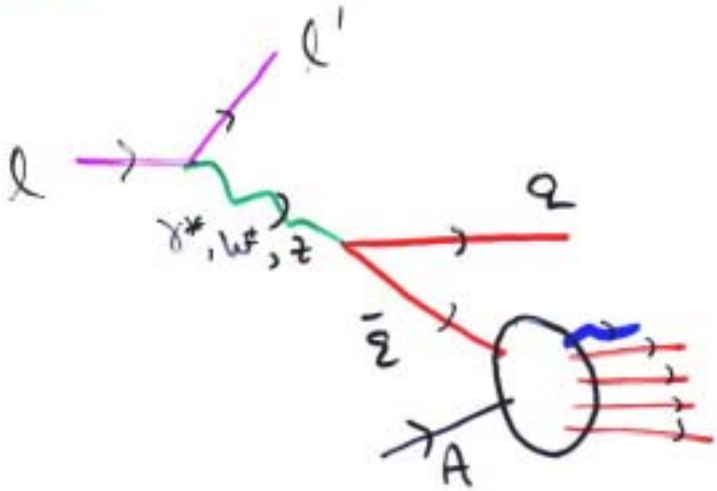
$\Delta t = O\left(\frac{1}{v}\right)$

Different for hadron collisions!



β - Dist.
Same as
$g \to gg$

Theory of Nuclear Shadowing in DIS



L.P.S :

$$k^2_{\bar{q}} = \frac{x(s+\vec{k}_\perp^2)}{1-x} - x M^2 + k_\perp^2$$

fixed

$$s_{qN} \sim \frac{1}{x}$$

$T_{\bar{q}A}$, T_{qA} computed from Glauber theory

Pomeron, Odderon, Reggeon exchange

↑ multiscattering suppressed

$T_{\bar{q}N}$, T_{qN} fixed from $F_{2N}(x)$

- S.J.B + H.J.Lu : PRL 64 (1990) 1372
- I. Schmidt, J.-J. Yang, SJB (prelim)

↑ application to neutrino DIS

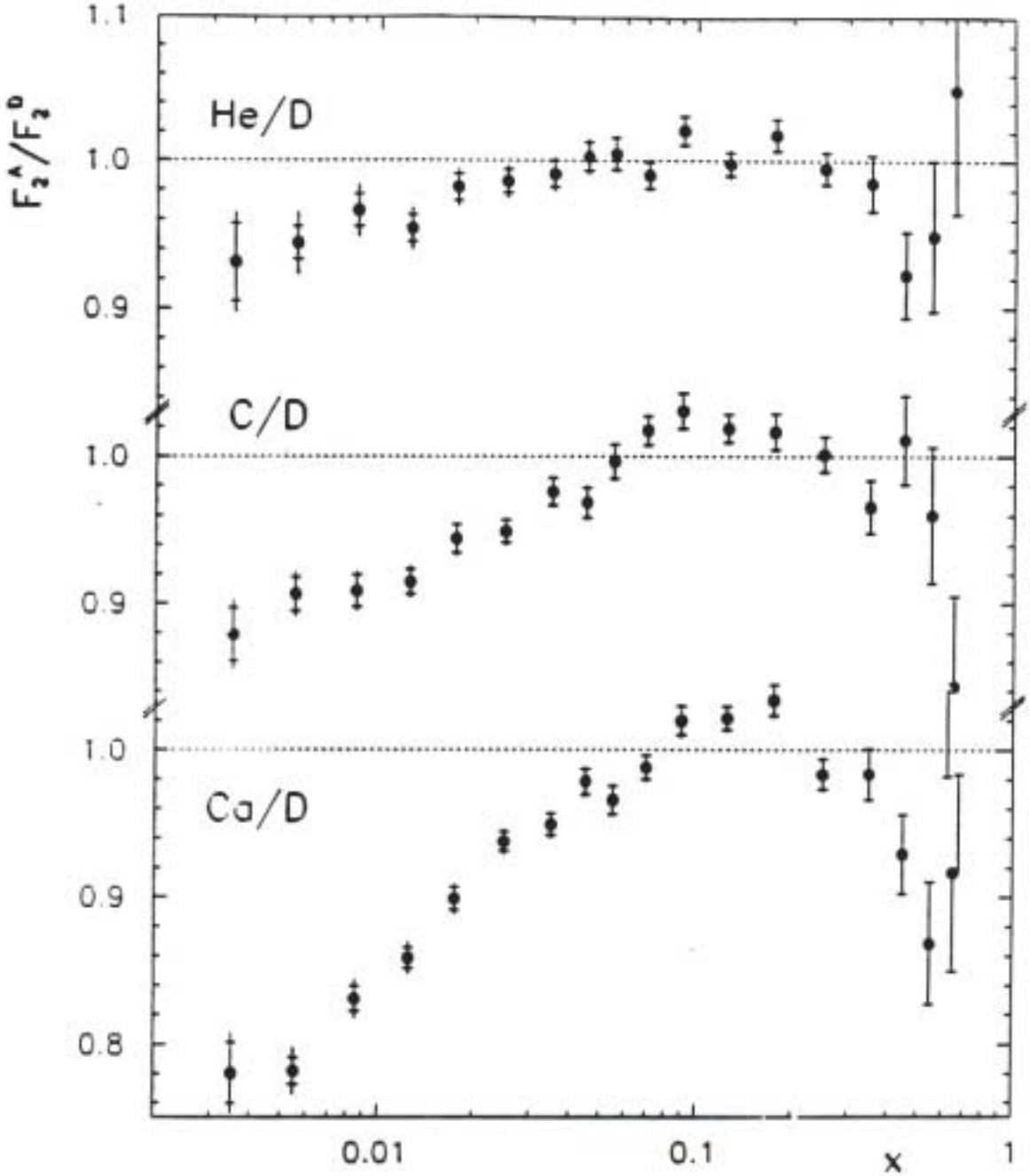


Fig.2

EMC 91

→ Final State Interaction Produces

Single-Spin Asymmetry

with respect to the jet production plane

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

Find jet 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 $F_2(0)$

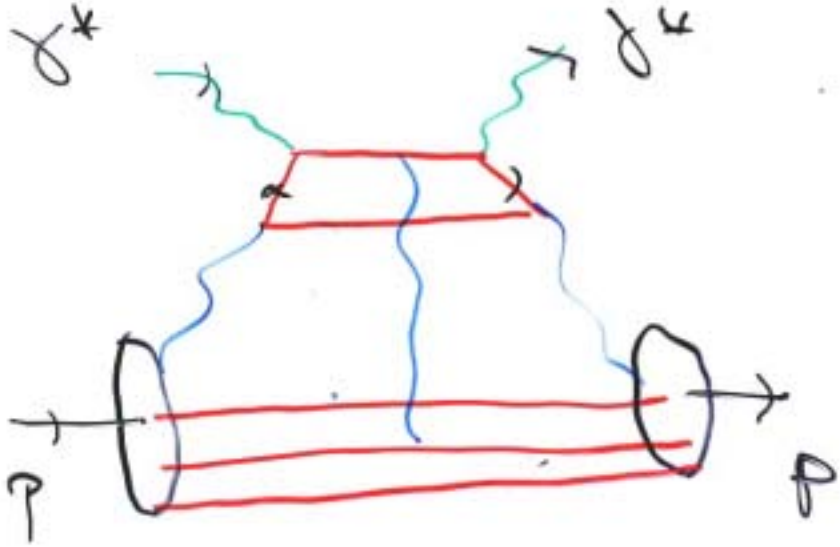
Single Spin Asymmetry $\underline{A_N} = A_{UN}$

$$i\,\vec{S}_p \cdot \vec{p}_\pi \times \vec{q}$$

"Sivers Effect"

Need interfering amplitudes with non-zero phase.

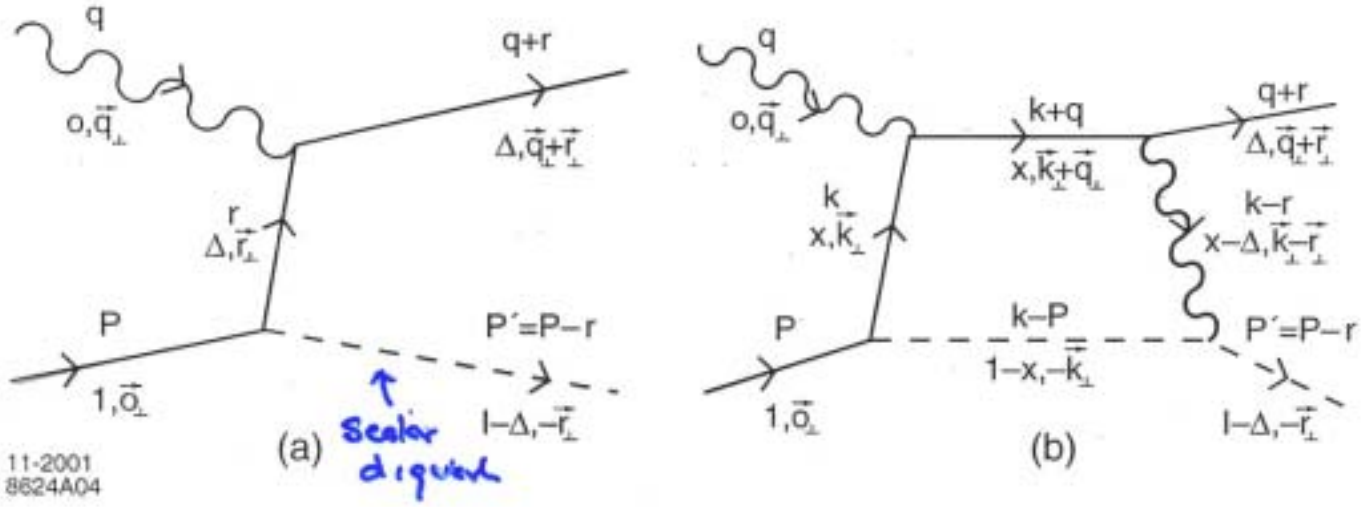
(otherwise $\not{T}$)



Gauge invariant

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

Hoyer, Marchal, Sannino, Peigne, BJS

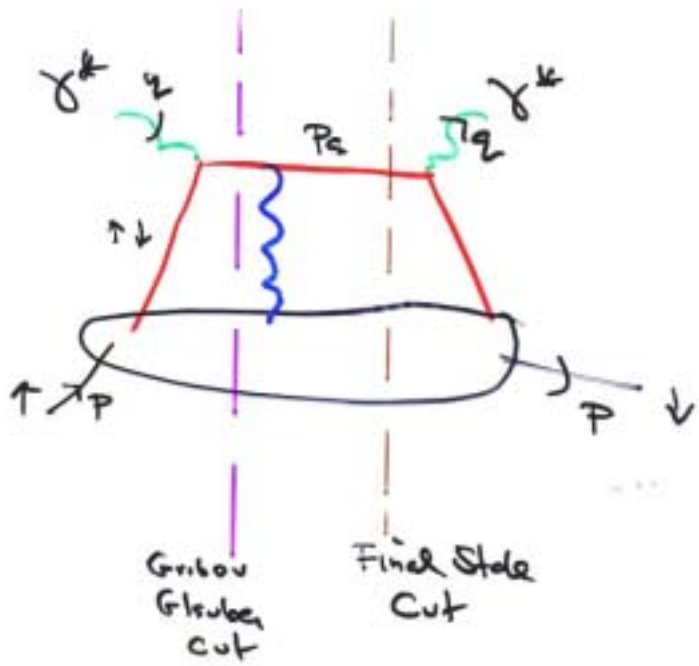


Dae Sung Hwang
Ivan Schmidt
SJB

Explicit calculation of FSI SSA

D. S. Hwang
I. A. Schmidt
SJB
hep-ph/0201296

Collins, X. Ji, Belitsky



Overlap of wavefunctions with $\Delta L_z = 1$

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

$\chi_1 - \chi_2$: IR Finite

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

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

Approximate at large $\vec{r}_\perp$:

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

Bjorken scaling for finite $r_\perp$

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

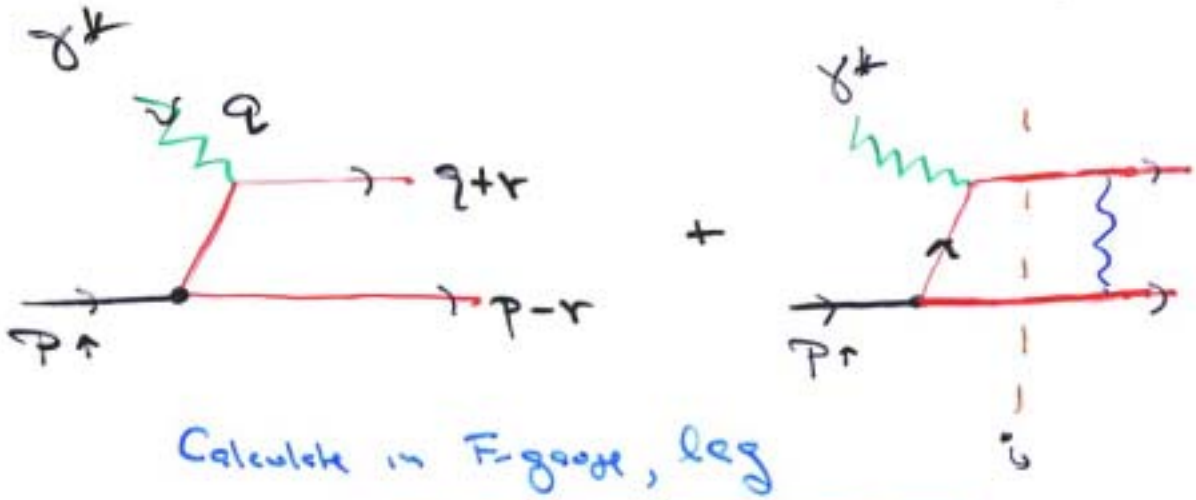
Covariant Form of Single-Spin Asymmetry

$$\frac{1}{M^2}\,\epsilon^{\mu\nu\sigma\tau}\,P_\mu\,S_\nu\,q_\sigma\,k_\tau$$

$$= \frac{1}{M}\,\vec{S}\cdot\vec{q}\times\vec{r}$$

rest system

$k = P_y = q + r$



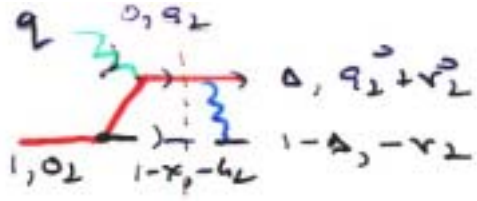
Calculate in F-gauge, leg

BHS

$$\boxed{P_y = A_{UN} \sim \frac{\alpha_s\,|\vec{r}_\perp|\,M}{r_\perp^2 + M^2}}$$

Asymmetry normal to production plane

Leading twist, indep of Q^2, Bj-scaling



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

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

$$\Psi_{+\frac{1}{2}}(x, \vec{k}_\perp) = \left(M + \frac{m}{x}\right)\varphi \qquad L_z = 0$$

$$\Psi_{-1/2}(x, k_\perp) = -\frac{k^1 + ik^2}{x}\,\varphi \qquad L_z = 1$$

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

$$A(\uparrow\uparrow \to \uparrow) = \left(M + \frac{m}{\Delta}\right) G \left(h + i\,\frac{e_1 e_2}{8\pi}\, g_1\right)$$

$$A(\downarrow\uparrow \to \uparrow) = \left(\frac{r^1 - ir^2}{\Delta}\right) G \left(h + i\,\frac{e_1 e_2}{8\pi}\, g_2\right)$$

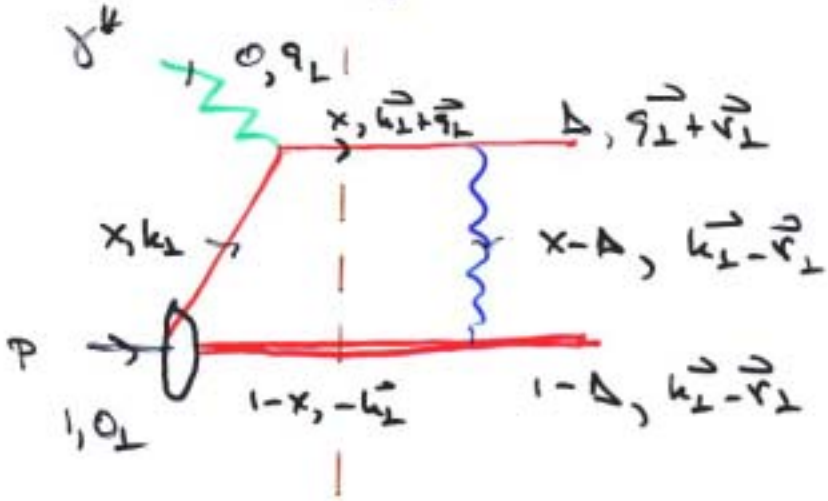
$$G = -g e_1 P^+ \sqrt{\Delta}\; 2\Delta(1-\Delta)$$

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

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

$\Rightarrow e^{i(\chi_1 - \chi_2)}$, $\frac{e_1 e_2}{4\pi} \Rightarrow C_F \alpha_s(M^2)$

Calculation of Final State Phases



$\Delta \Rightarrow x_{Bj}$

Denominator has imaginary part

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

$$= \frac{i\pi}{p^+} \frac{\Delta^2}{q_\perp^2} \delta(x - \Delta - \bar{\delta}) \quad , \quad \bar{\delta} = 2\Delta \frac{\vec{q}_\perp \cdot (\vec{k}_\perp - \vec{r}_\perp)}{q_\perp^2}$$

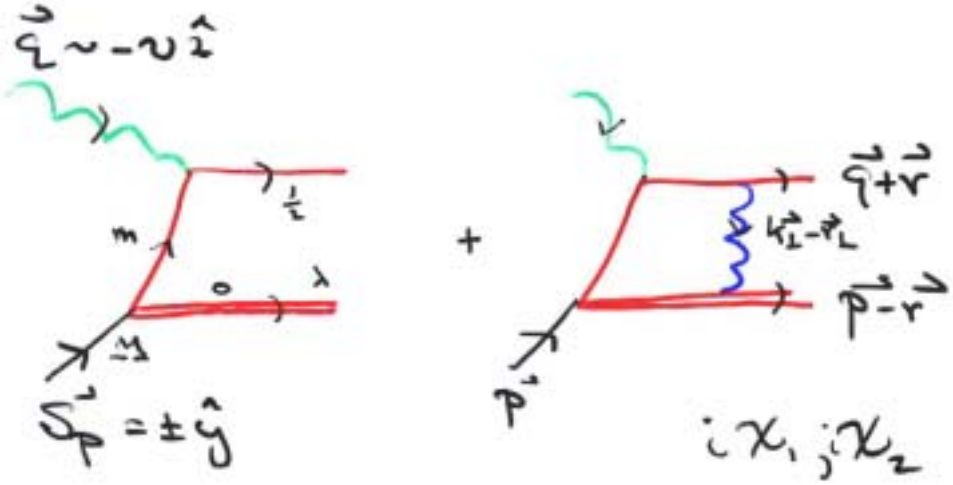
Do x, $\vec{k}_\perp$ integral

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

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

$$g_1(L_z = 0) - g_2(L_z = 1) = \int_0^1 \frac{1-\alpha}{[\ ]}$$

* IR finite for $\lambda_g^2 \Rightarrow 0$.



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

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

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

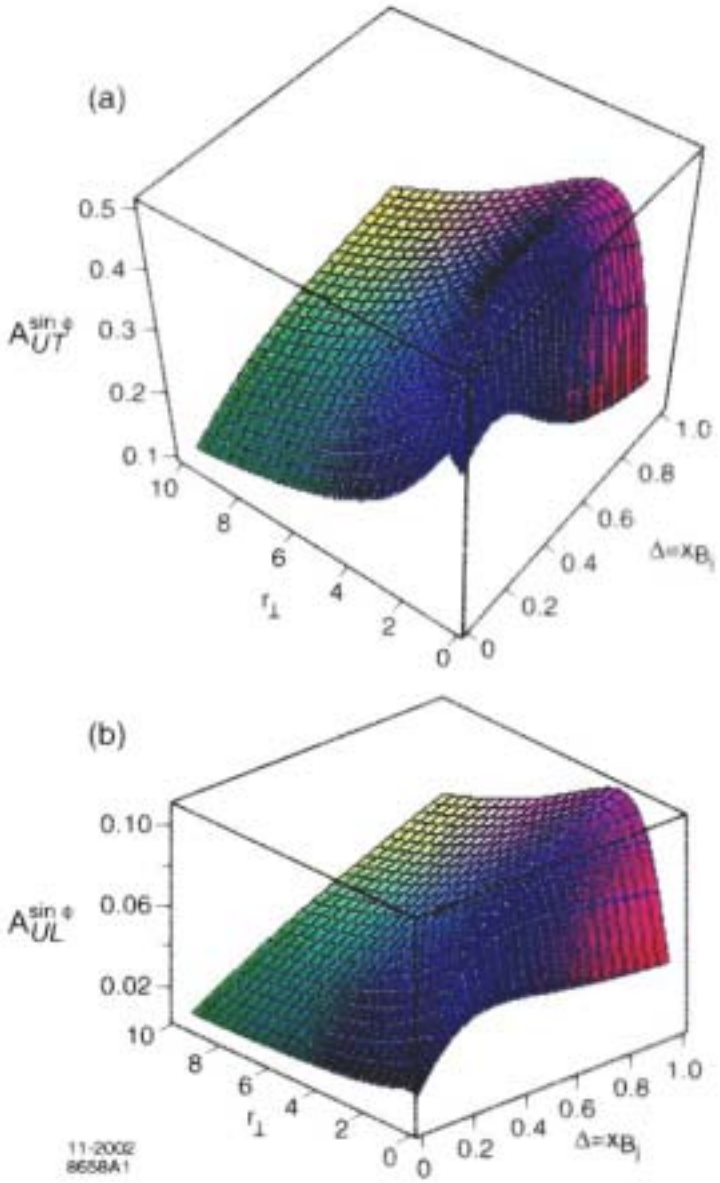
$$= \frac{C_F \alpha_s(\mu^2)(\Delta M + m) r_x}{(\Delta M + m)^2 + r_\perp^2}$$

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

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

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

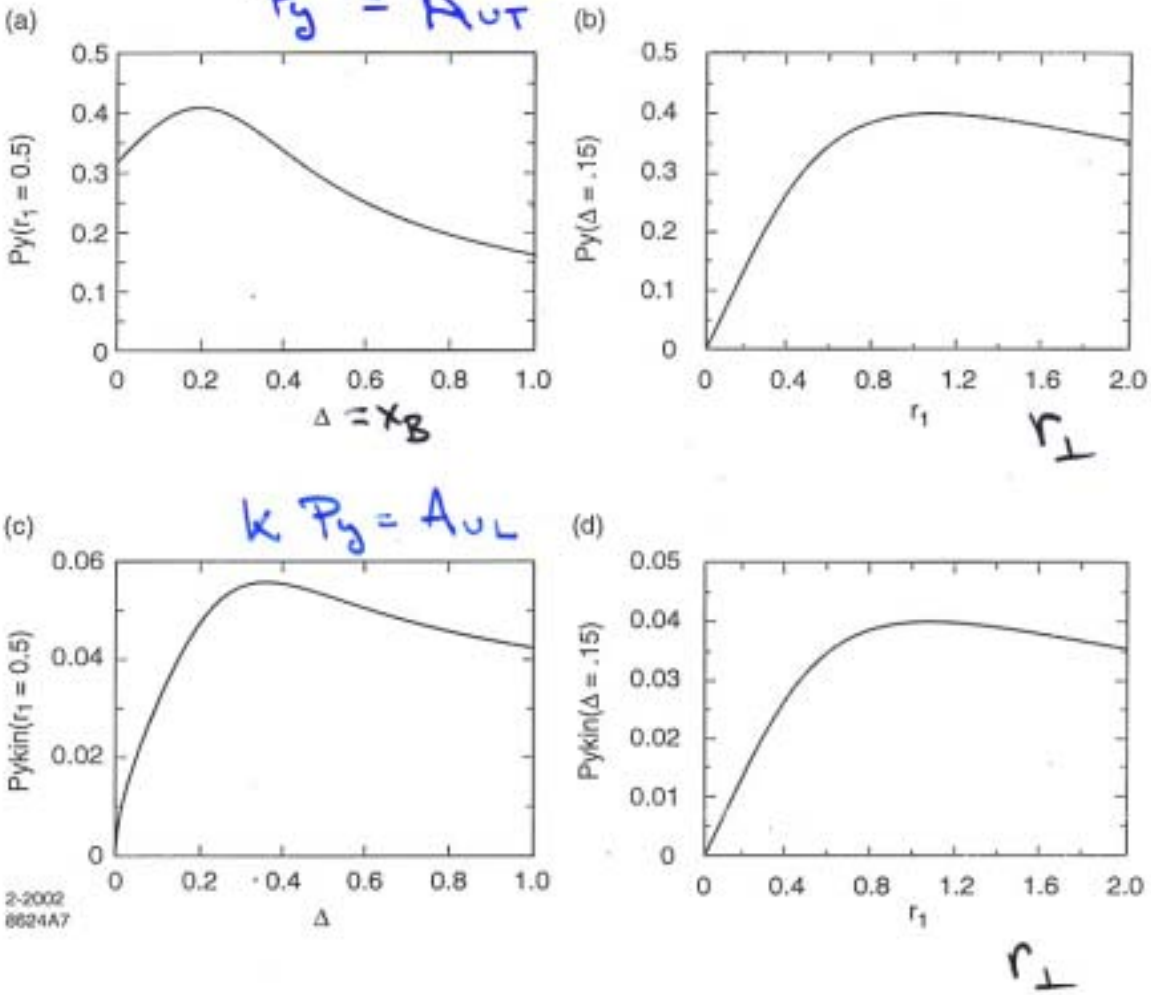
BMS


(a)
0.5
0.4
$A_{UT}^{\sin\phi}$
0.3
0.2
0.1
10
8
6
4
2
0
$r_\perp$
0
0.2
0.4
0.6
0.8
1.0
$\Delta = x_{B_j}$
(b)
0.10
0.06
$A_{UL}^{\sin\phi}$
0.02
10
8
6
4
2
0
$r_\perp$
0
0.2
0.4
0.6
0.8
1.0
$\Delta = x_{B_j}$
11-2002
8658A1

$P_y = A_{UT}$

$k\, P_y = A_{UL}$

for $\vec{S}$ along $\vec{P}_e$



Jaffe $\quad k = \frac{Q}{\nu}\sqrt{1-y} = \sqrt{\frac{2Mx_B}{E}}\sqrt{\frac{1-y}{y}}$ $\quad \sim 0.26\sqrt{x_B}$ for Hermes

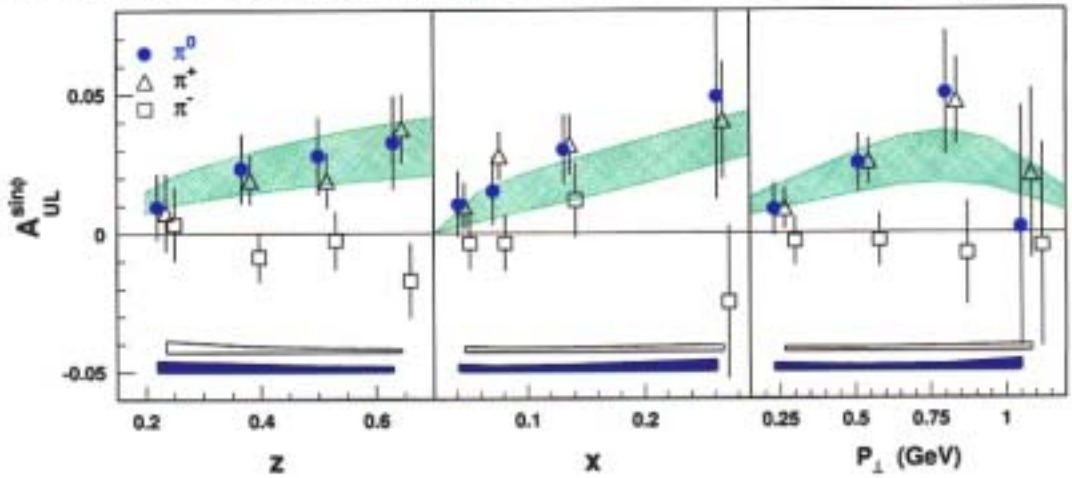
kinematic factor for $\hat{S}_p = \hat{\ell}$

proton polarization along incident lepton

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).

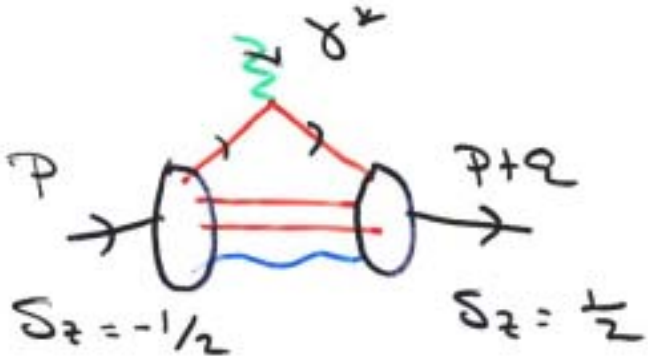
Light cone gauge approach: X. Ji and F. Yuan, PLB 543, 66(2002).

➡ 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.

N. Makins

Pauli Form Factor $F_2(q^2)$

$\kappa = F_2(0)$



Required overlap of LCWFs with $\Delta L_z = 1$

Drell + SJB

e.g. (3q)

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

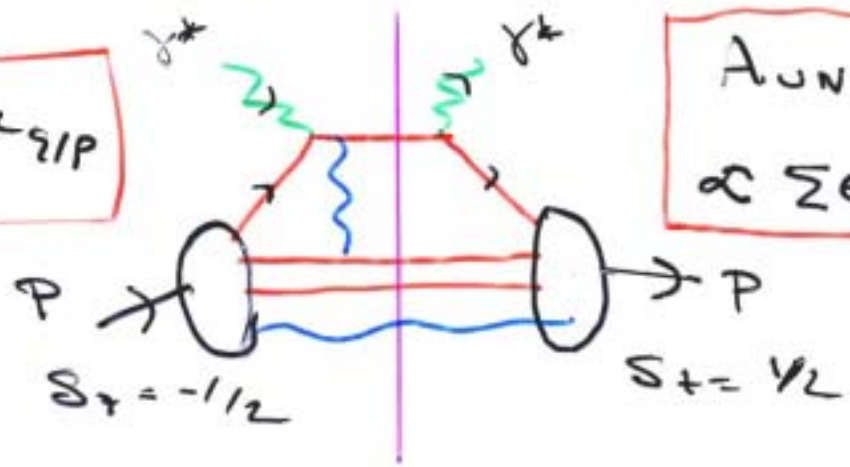
$L_z = +2$ $\qquad$ $L_z = +1$

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

$L_z = 0$ $\qquad$ $L_z = -1$

Same matrix elements appear in SSA

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



$$A_{UN} = SSA \propto \sum e_q^2 \kappa_{q/p} \alpha_s$$

BKS
Burkardt

Anomalous moment $\kappa = F_2(0)$

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

3 quark model:

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

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

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

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

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: $\sin(\phi_H^\ell - \phi_{S_p}^\ell)$ indep. of ϕ_ℓ !
- Collins: $\sin(\phi_H^\ell + \phi_{S_p}^\ell)$

- Sivers: A_{UL}, A_{UT} same in $\nu p_n \to H X$ charged current *

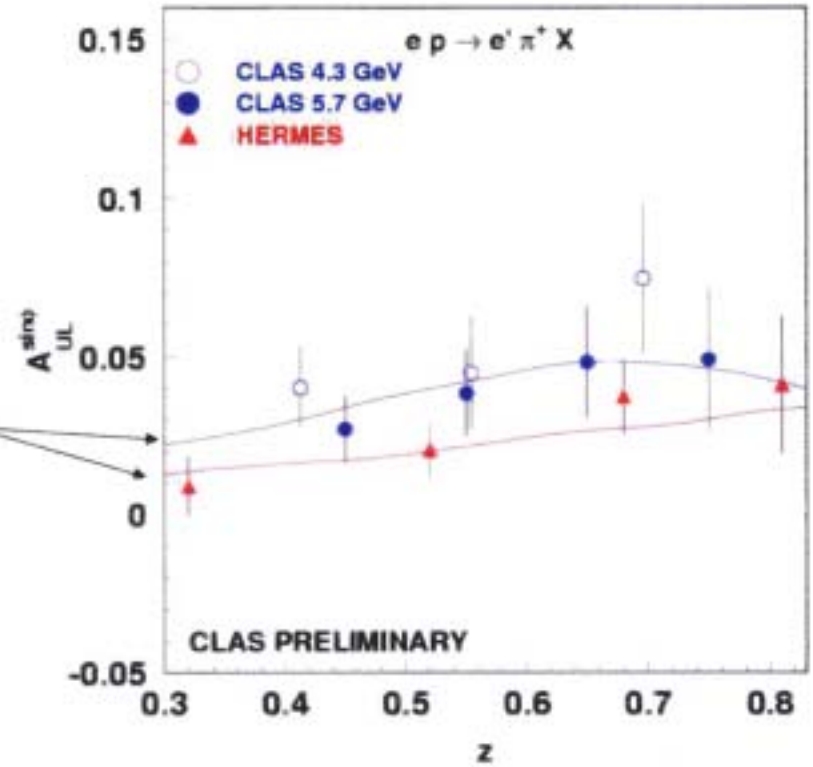
  Collins: A_{UL}, $A_{UT} = 0$ *

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

Longitudinally Pol. Target: SSA for π^+

Target SSA: CLAS (4.3 GeV, and 5.7 GeV) consistent with HERMES (27.5 GeV)

predictions for **Sivers effect** from BHS Phys.Lett.B53099,2002
Sivers only interpretation require large A_{UT}



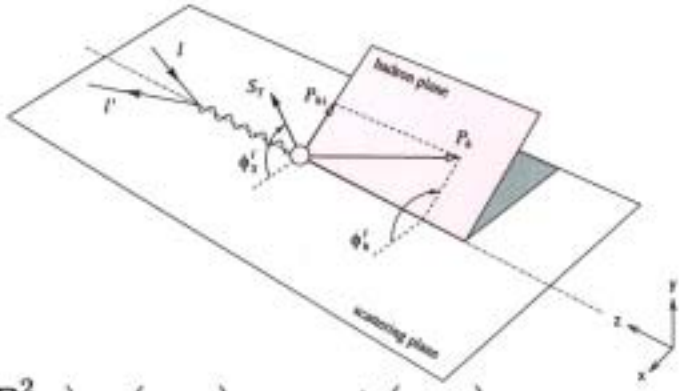
A_{UL} **z**-dependence also consistent both in magnitude and sign with predictions based on **Collins mechanism**

$$A_{UL} \propto \sin\theta_\gamma \times A_{UT} \propto \sin\theta_\gamma \frac{f_{1T}^{\perp u}(x)}{u(x)}$$

Conclusions

* T-odd SSA :
  - New insight into role of ISI, FSI in QCD
* Sivers + Collins Effects - both present
  - Mechanisms only understood at perturbative level $\alpha_s(\mu_0^2)$?
* FSI in DIS $\Rightarrow$ Diffraction, Shadowing
  Antishadowing - role of Odderon
* $k_\perp$ effects, energy loss from ISI, FSI
  Hoyer, SJB
* DIS Structure functions $\Rightarrow$
  require augmented LFWFs (external field)
  Belitsky, Ji, Yuan
  Collins
* New questions :
  - Momentum Sum Rule, OPE Hoyer, SJB
  - Factorization (process independence)
  - DHG for nuclei

Collins effect vs Sivers effect



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

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

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

Sivers

- 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 ϕ_ℓ

: hadronisation not necessary

In general,

initial, final state interactions

will produce single-spin asymmetries

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

wrt virtually any production n

scattering plane!

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

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

* Application to Drell-Yan: $\vec{S}_p \cdot \vec{p}_\pi \times \vec{q}$
  $\pi p_\uparrow \to \mu^+\mu^- X$

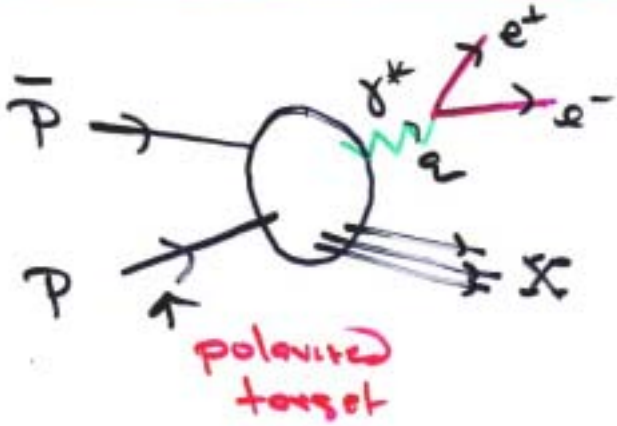
* $e^+e^- \to \Lambda_\uparrow X$: $\vec{S}_\Lambda \cdot \vec{p}_\Lambda \times \vec{q}$

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

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

Hwang, Schmidt, ...
Collins, X. Ji + Yuan

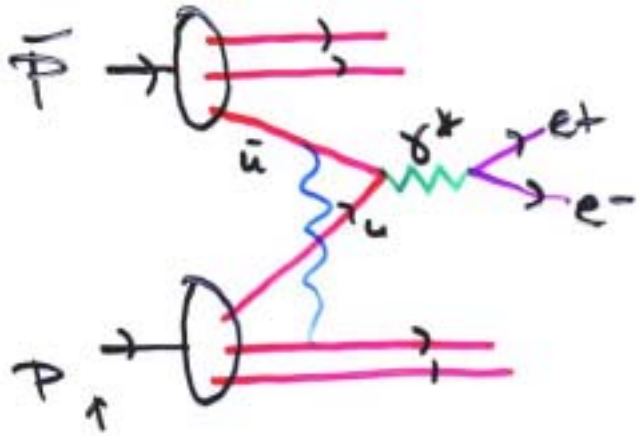
Single-Spin Asymmetries in $\bar{p}$ collisions



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

"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. M_A^p

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

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

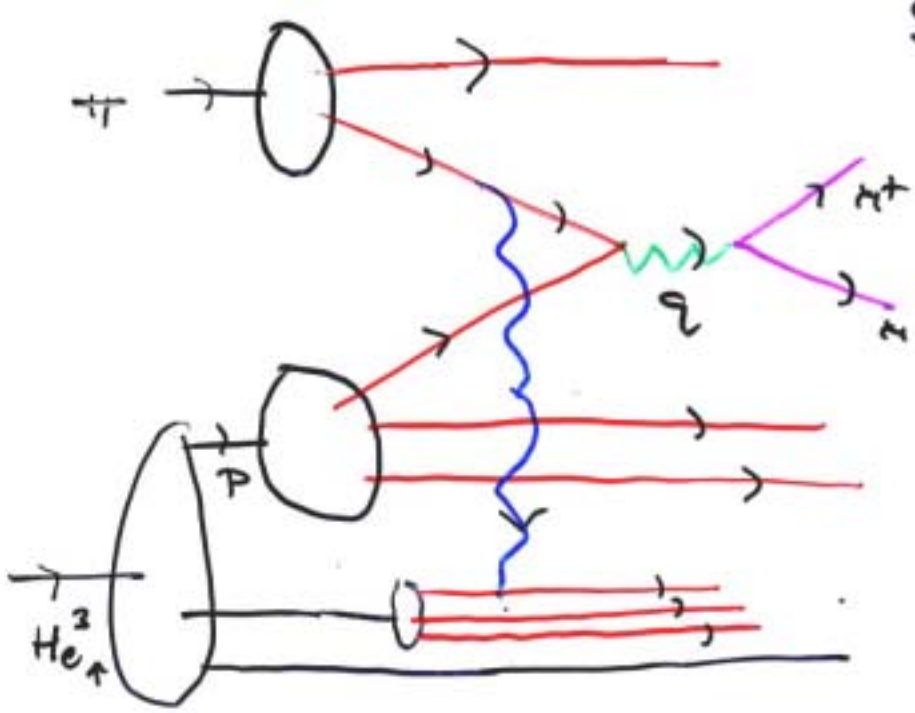
ISI and FSI

- enhanced in nuclei
- Coulomb effects
- Often "leading twist" in Q^2

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

Application to DY:

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

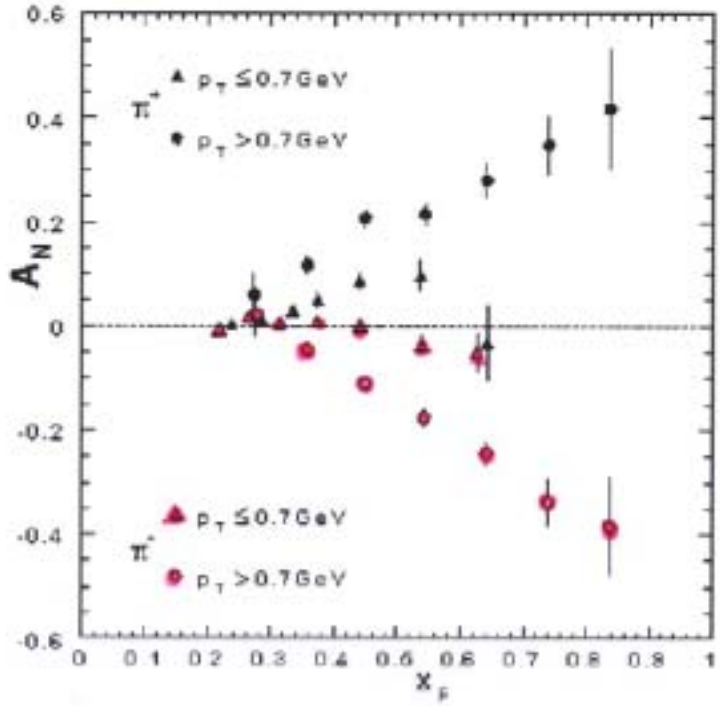


$$\vec{q} = \vec{p}_\pi + \vec{r}_\perp$$

energy loss.
p_T spread.

Bodwin, Lepage, SJB

- 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 twist-three effects, expected to vanish like $p_\perp/\sqrt{s}$

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

  Qiu Sterman

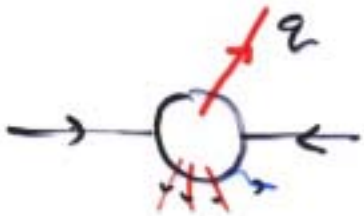
- Concentrate on HERMES asymmetry here, although similar analysis applies to E704.

Single-Spin Asymmetry in $p_\uparrow p$ collisions

$$i\,\vec{S}_p \cdot \vec{p}_\pi \times \vec{p}$$

T-odd Sivers Effect

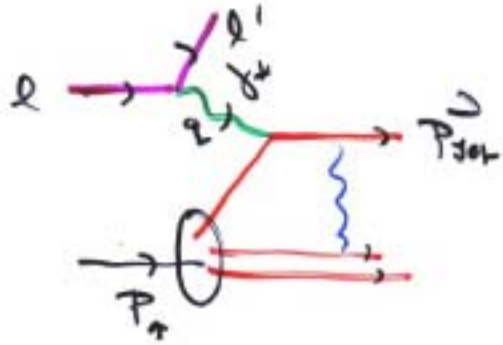
Jet Asymmetry

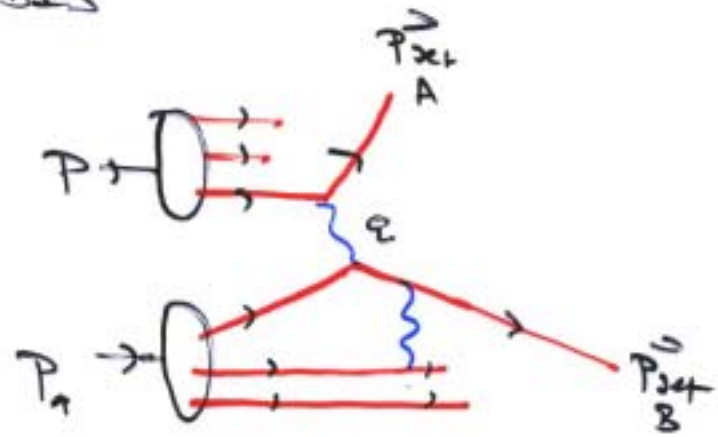


use thrust axis

$$i\,\vec{S}_p \cdot \vec{p}_{jet} \times \vec{p}$$

Analog Effect in DIS





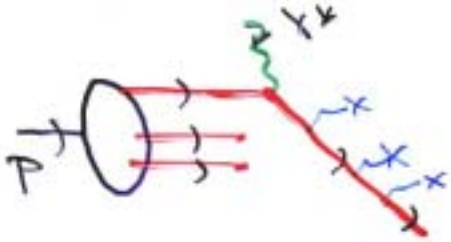
$$i\,\vec{S}_{\vec{p}} \cdot \vec{p}_{jet} \times \vec{q}$$

Leading Twist
BKS

$$i\,\vec{S}_{\vec{p}} \cdot \vec{p}_{jet\,A} \times (\vec{p}_{jet\,B} - \vec{p})$$

Leading Twist

Proposal by Ji and Yuan (also Collins)



$$\Psi \to \Psi L$$

complex phase

Augment LFWF (lcg) with phase

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

where $\vec{A}_\perp = -\frac{g}{2\pi}\,\theta(z^-)\,\vec{\nabla}_\perp \ln \mu \vec{r}_\perp$ $\left\{ \begin{array}{l} \text{Finite} \\ \text{at} \\ z^- = 0 \end{array} \right.$

$A^+ = A^- = 0$

- corresponds to Coulomb field of charged particle moving at $v = c$

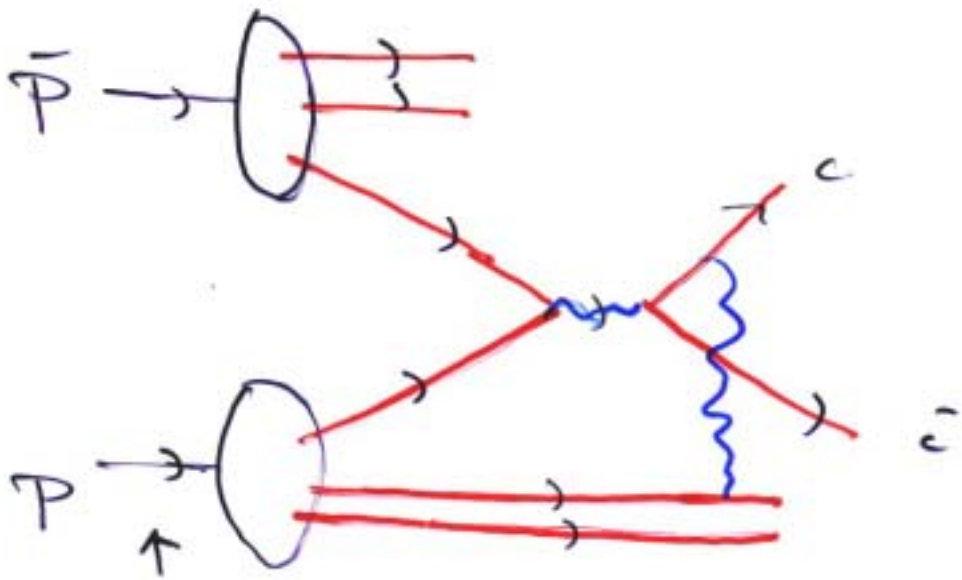
Equivalently

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

* Non-causal b.c. (BHMPS)

* Process specific – not universal

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

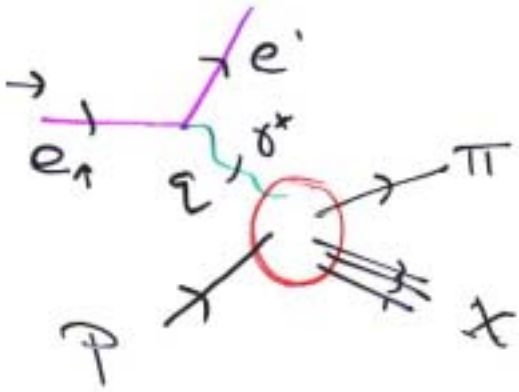


$$i \vec{S}_p \cdot \vec{\bar{p}} \times \vec{p}_c$$

Coulomb phase accumulated along $\vec{p}_c$

Not part of ψ_p^{LF}.

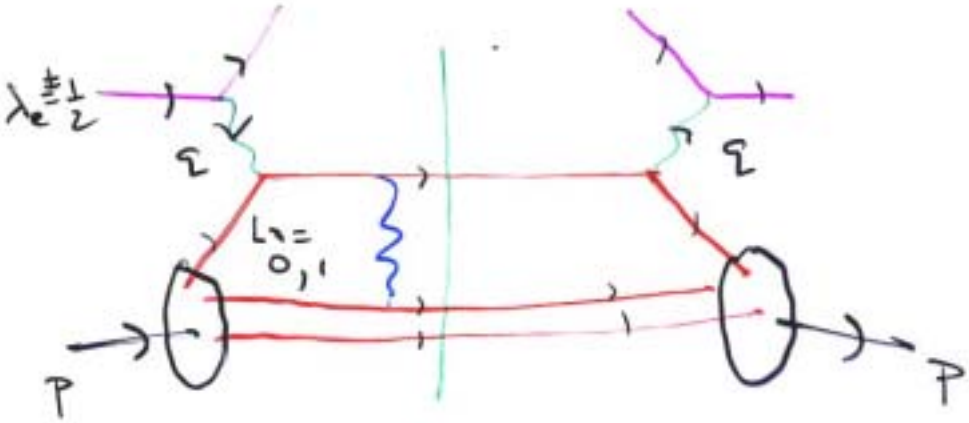
Polarized lepton



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

T-odd

A_{LU}



interference

L, T

currents

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 $\pi, k, \rho, \ldots$

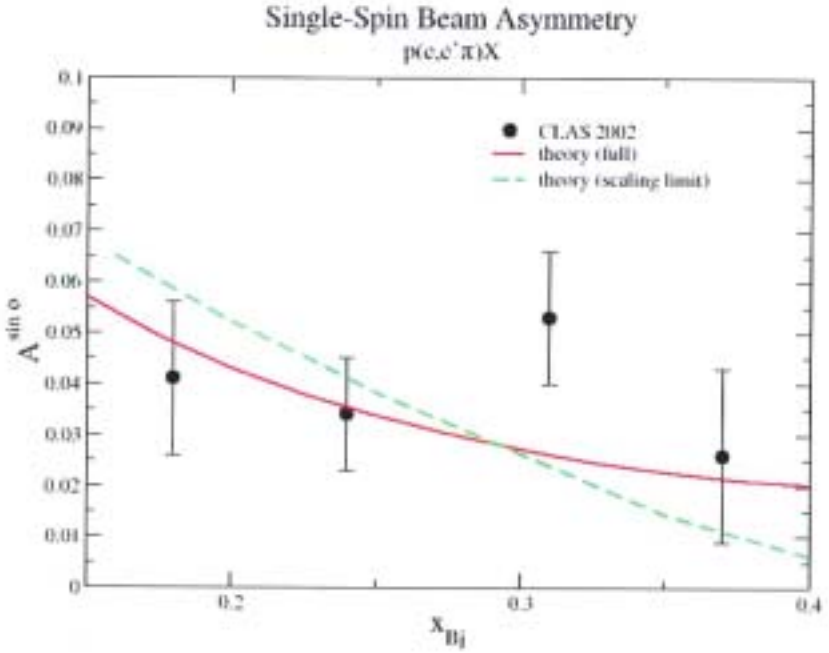
Carlson Kuwang SJB

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

vector pol of virtual γ

density matrix $\Sigma_{\gamma^*} \alpha \lambda_e$

Calculations vs CLAS Data (from Afanasev&Carlson)



A_{LU}