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

$$P_y \Rightarrow \vec{S}_p \cdot (\vec{q} \times \vec{p}_\pi) \quad \text{correlation}$$

T-odd : requires spin amplitudes with different phase

Conventional argument :

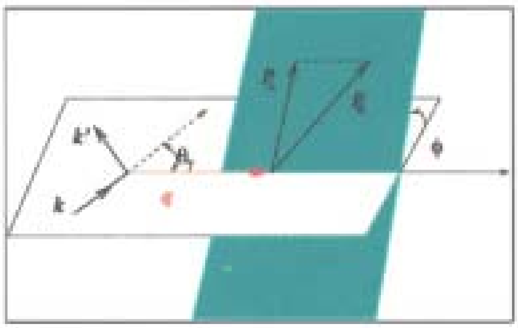
FSI from gluon exchange are twist-3 : $\therefore$ suppressed in Bj limit

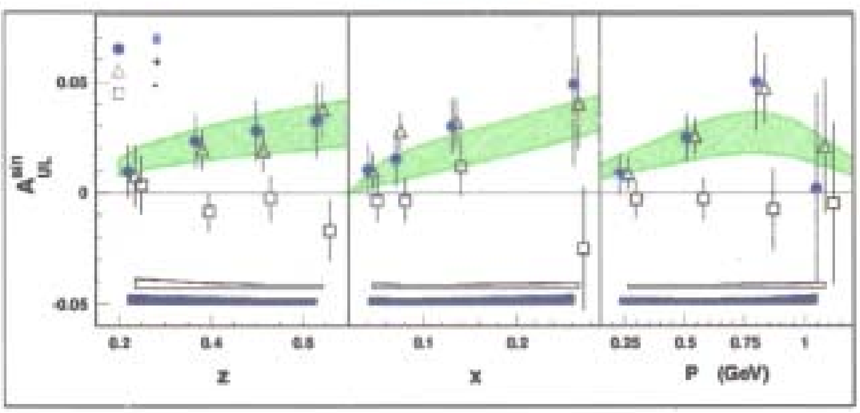
Collins, Jaffe : opportunity to measure transversity : $\delta q \times H_{1\perp}$

HERMES Azimuthal Asymmetry and Transversity!

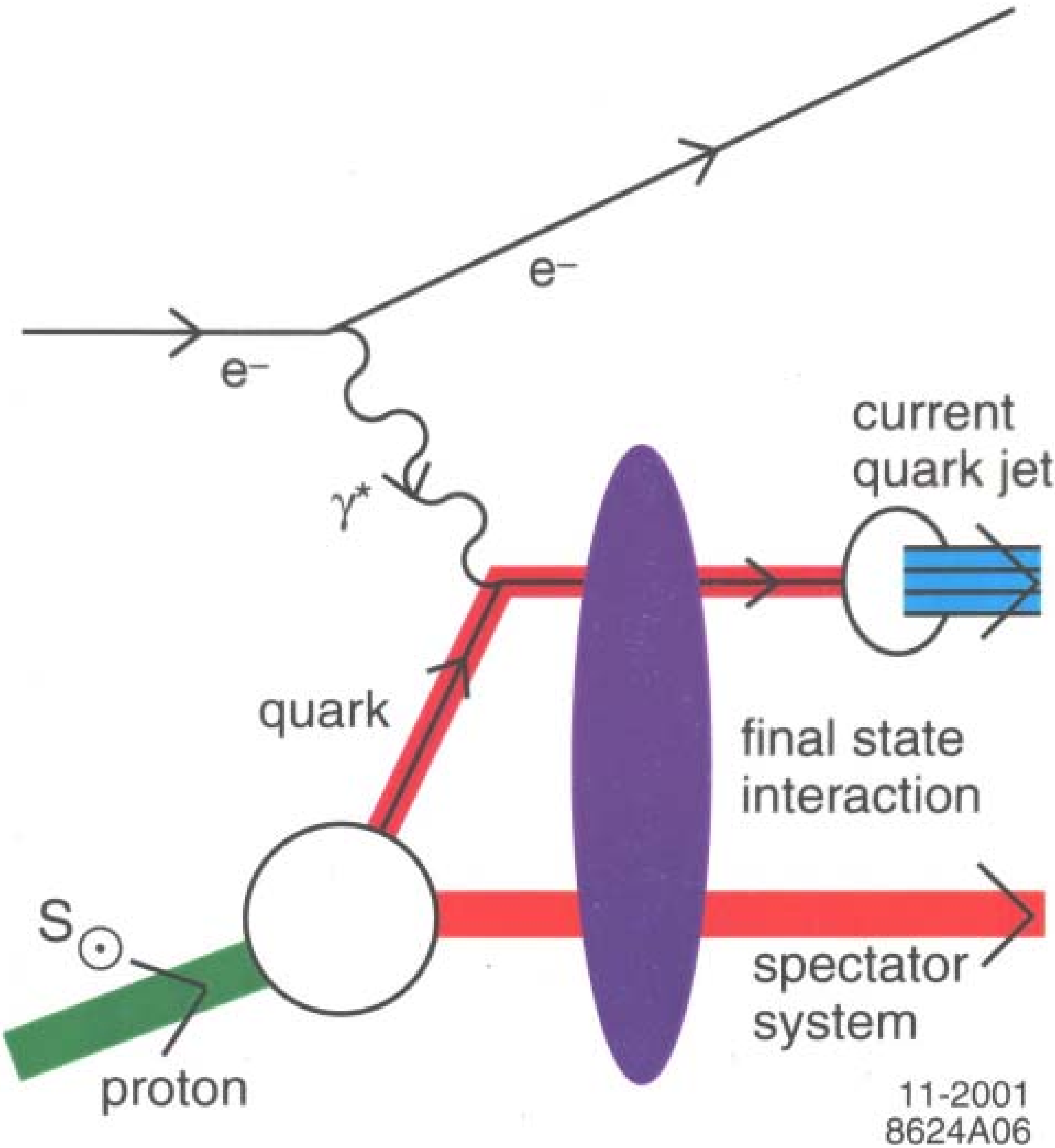
Observations

- Azimuthal asymmetry observed at HERMES in $e\vec{p} \to e'\pi X$ with target polarization parallel to lepton beam.





Note approximate with u-quark dominance. Should be $\pi^+ : \pi^0 : \pi^- :: 2 : 1 : 0$. Data show $\pi^+ \sim \pi^0 \gg \pi^-$



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

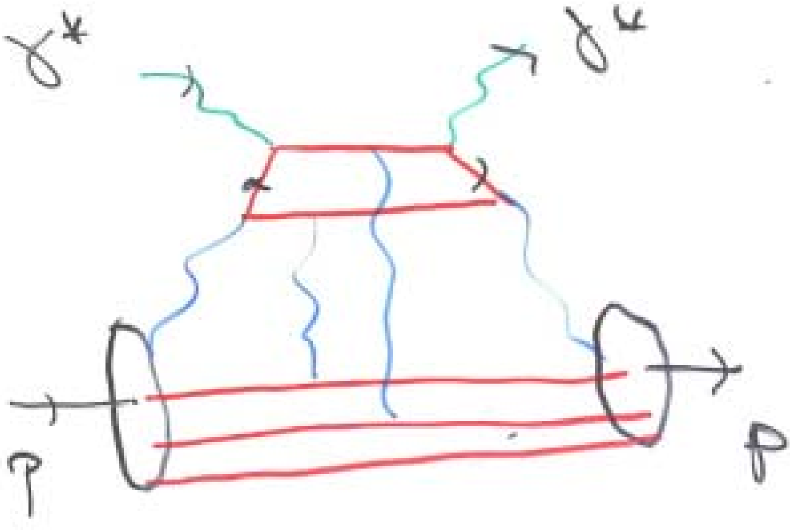
Single Spin Asymmetry $\underline{A_N}$

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

Need interfering amplitudes with non-zero phase.

(otherwise $\not{T}$)

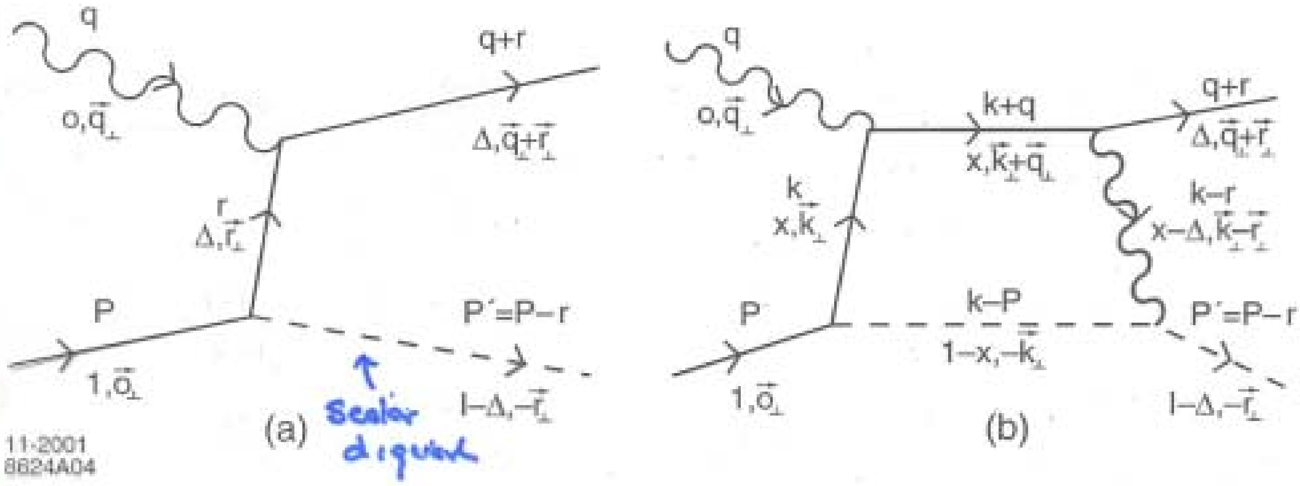
Jaffe



Gauge invariant

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

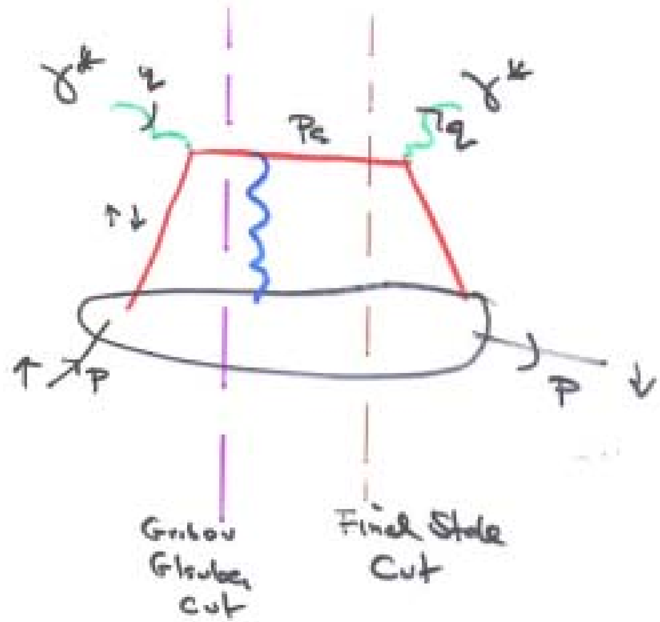
Hoyer, Marchal, Sannino, Peigne, SJB


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

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

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

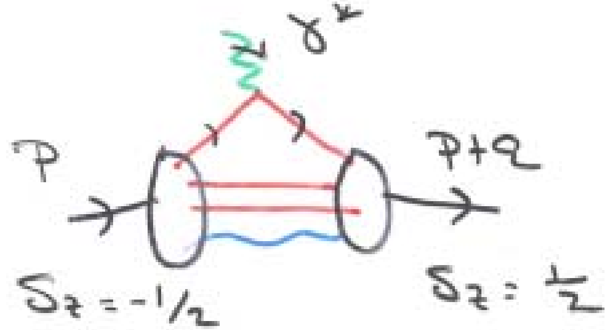
$$\vec{p}_q = \vec{q} + \vec{r}$$

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

Bjorken scaling for finite $r_\perp$

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

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



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

e.g. (3q)

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

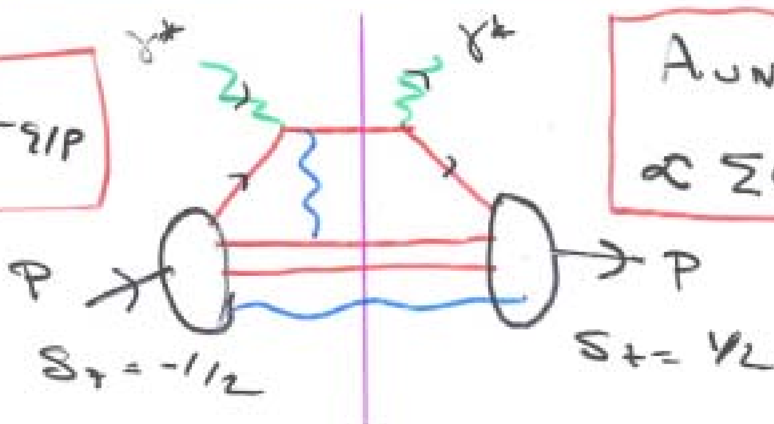
$L_z = +2 \qquad L_z = +1$

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

$L_z = 0 \qquad L_z = -1$

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

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



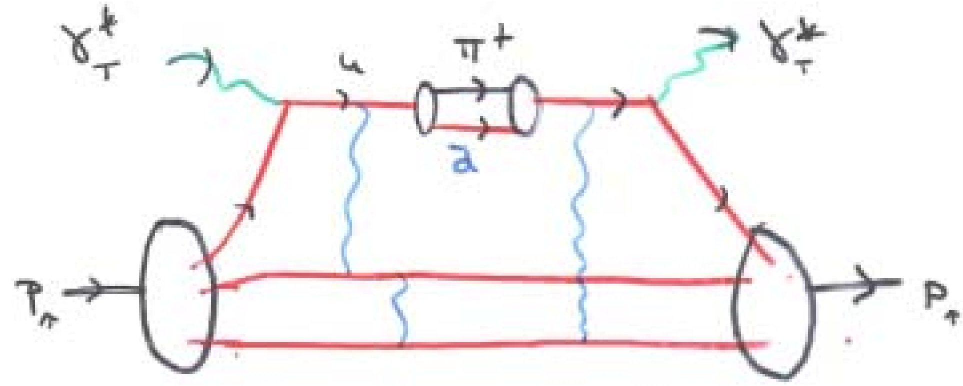
A_{UN} = SSA

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

$\gamma^* p_T \to \pi^+ X$

A_{UL} : $\quad i\, \vec{\Sigma}_p \cdot \vec{p}_\pi \times \vec{q}$

need phase!



Forward $u \to \pi^+ \bar d$

FSI in $q^+ = 0$ Frame

BHMPS

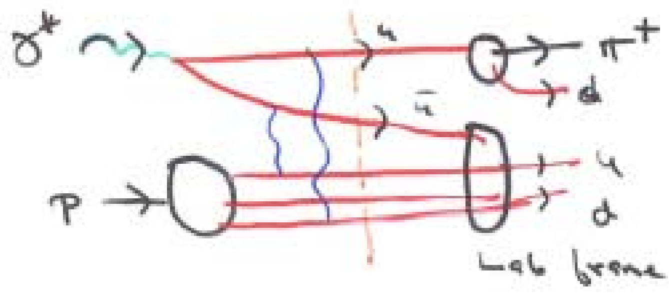
$$\mathcal{M} \Rightarrow \mathcal{M}[1 - e^{-ig^2 W}]$$

eikonal form

Gauge invariant result (Feynman; 3 l.c.g prescriptions)

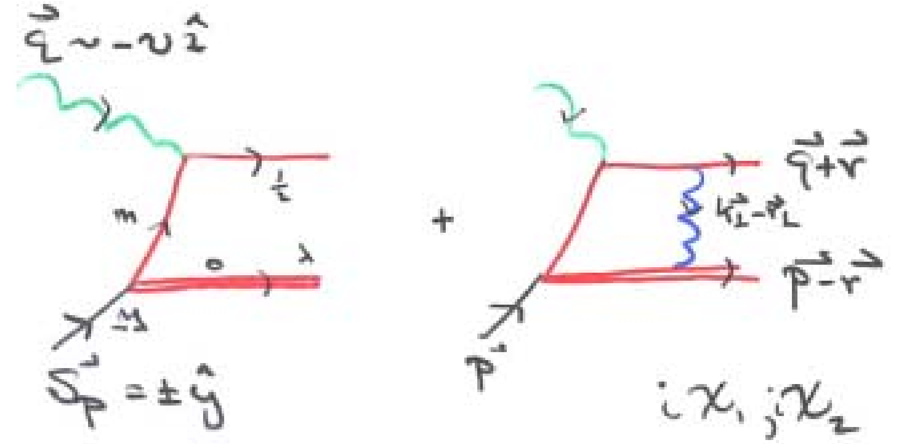
Non-unitary

Same effect produces diffraction, shadowing



On-shell intermediate State

Gives phase



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

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

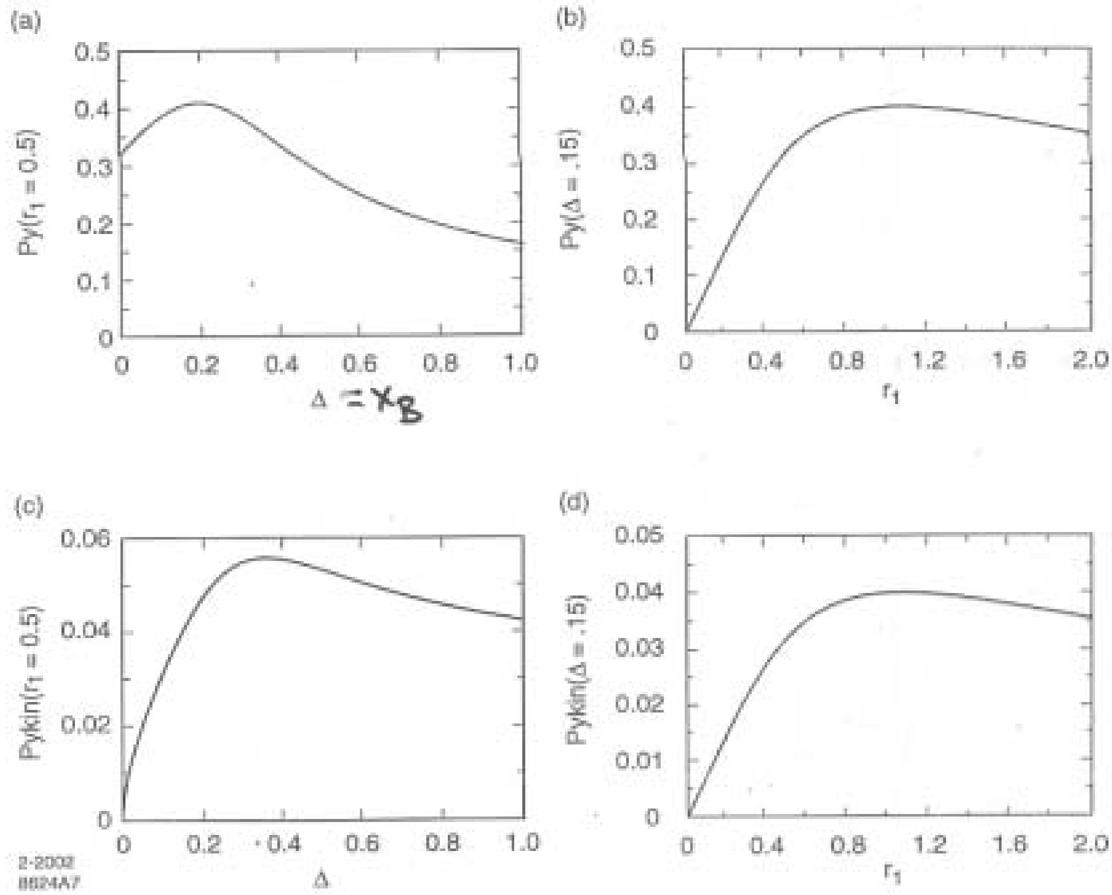
$$A_N = P_y = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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

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

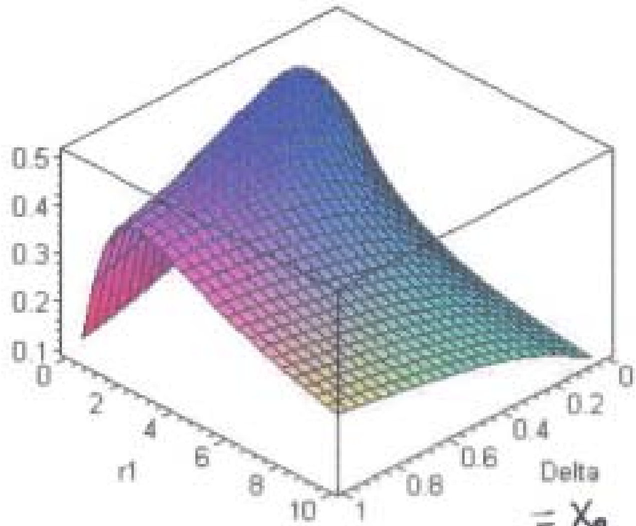
$$\otimes \left[\frac{1}{r_\perp^2} \ln \frac{r_\perp^2 + \Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)}{\Delta(1-\Delta)\left(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1-\Delta}\right)} \right]$$

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



(a)
Py(r1 = 0.5)
Δ = x_B
(b)
Py(Δ = .15)
r1
(c)
Pykin(r1 = 0.5)
Δ
(d)
Pykin(Δ = .15)
r1
2-2002
8624A7

Py



$= X_{gy}$

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: $\underbrace{\kappa_p + \kappa_n}_{\sim 0} = 2/3\,\kappa_{u/p} + 1/3\,\kappa_{d/p}$

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

* 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

Single-spin Asymmetry

with respect to the jet production plane

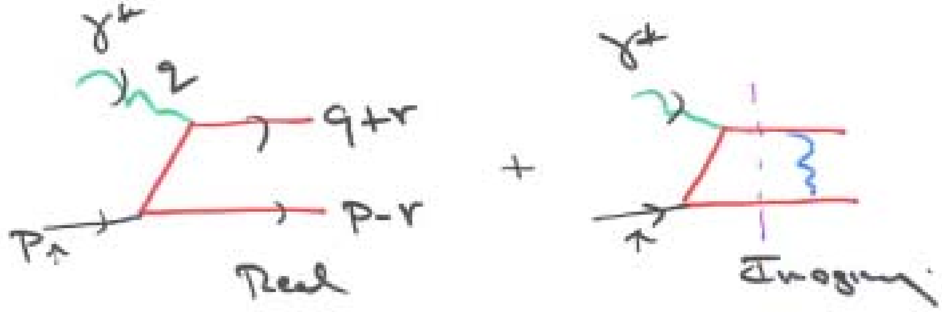
$$\boxed{\vec{S}_p \cdot \vec{q} \times \vec{p}_{Jet}}$$

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 element.
* Similar to $F_2(0)$



Explicit Calculation : Feynman Gauge
Light-Cone Gauge

D. Hwang, I. Schmidt
SJB
hep-ph/0201296

Single spin asymmetry

$$W^{\mu\nu} = \hat{p}^\mu \hat{p}^\nu \quad p \cdot C \quad W_2'$$

$$\hat{p}^\mu = \left(p^\mu - q^\mu \frac{p \cdot q}{q^2}\right)\frac{1}{M}$$

$$p \cdot C = \frac{1}{M^2} \epsilon^{\mu abc} \, p_\mu S_a q_b r_c = M^{-1} \vec{S} \cdot \vec{q} \times \vec{r}$$

(rest system)

* Leading twist, Bjorken scaling.

Asymmetry spin normal to production plane

$$P_y \sim \alpha_s \frac{|\vec{r}_\perp| M}{r_\perp^2 + M^2}$$

D.S. Hwang
8/23

Single-Spin Asymmetries in DIS

symmetric

$$L^{\mu\nu}_{(S)}\, W^{(S)}_{\mu\nu}(p,q,r,s)$$

unpolarized leptons
polarized proton target

$$W^{\mu\nu(S)} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) W_1$$

$$+ \left(\hat{p}^\mu \hat{p}^\nu\right) W_2$$

$W_4 : \vec{S}_p \cdot \vec{l} \times \vec{l}\,'$
missing structure function!

$$+ \left(\hat{p}^\mu q^\nu + \hat{p}^\nu q^\mu\right) W_4$$

$$+ \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) p\cdot c\; W_1'$$

$p\cdot c : \vec{S}_p \cdot \vec{q} \times \vec{r}$

$$+ \left(\hat{p}^\mu \hat{p}^\nu\right) p\cdot c\; W_2'$$

$$W_i = W_i(q^2, p\cdot q) \qquad \hat{p}^\mu = \left(p^\mu - \frac{p\cdot q}{q^2} q^\mu\right)\frac{1}{M}$$

$$a^\mu = \epsilon^{\mu abc} S_a p_b r_c \frac{1}{M^2}$$

$$c^\mu = \epsilon^{\mu abc} S_a q_b r_c \frac{1}{M^2}$$

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 $\vec{r}_\perp, \vec{q}_T$

New measure of $\alpha_s(\vec{r}_\perp^{\,2})$

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

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

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

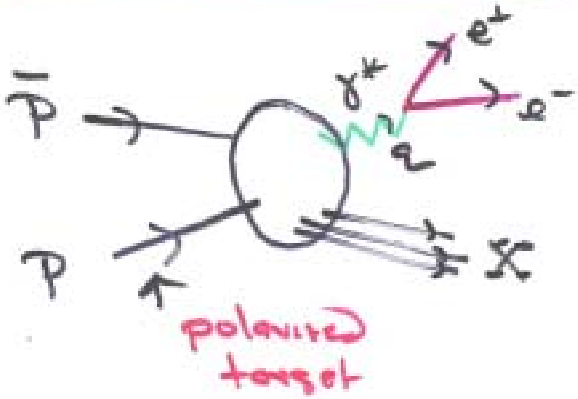
A_N: $p_\uparrow p \to \pi X$: $\vec{S}_p \cdot \vec{p}_\pi \times \vec{p}_p$

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

Hwang, Schmidt, Brodsky

Collins, X. Ji + Yuan

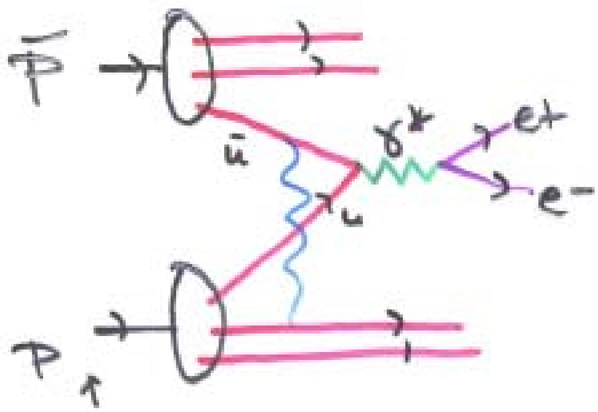
Single-Spin Asymmetries in $\bar{p}p$ collisions



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

"T-odd" observable

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



Interference of amplitudes produces phase gauge-indep

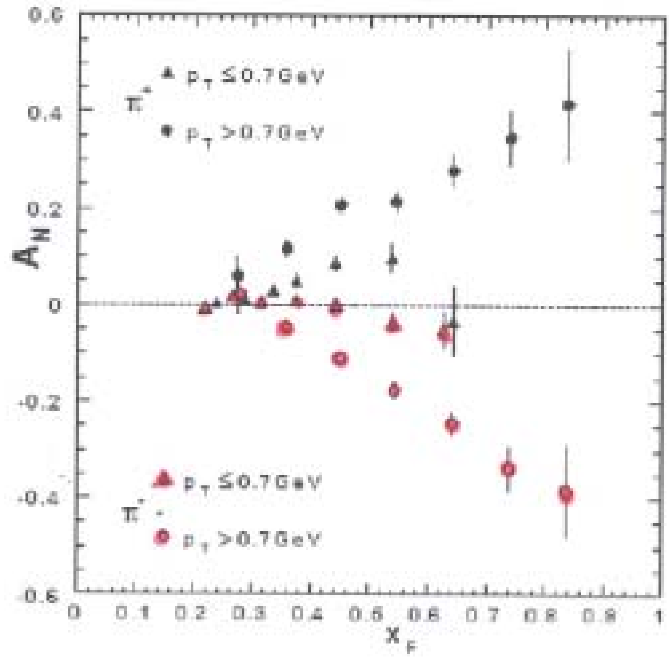
Same interference of $\Delta L_z = 1$ states prod. μ_A^p

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

* Scales in DY limit at fixed $r_\perp$!

* opposite in sign to SIDIS SSA

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



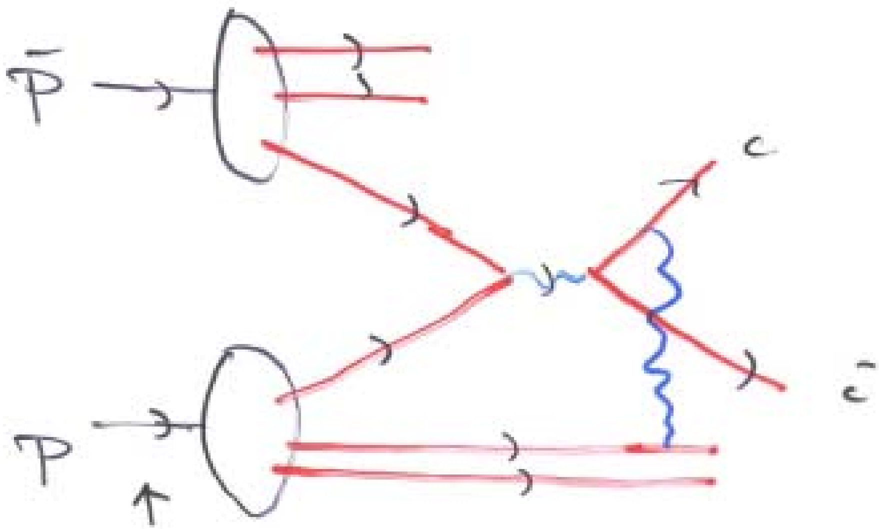
E704 at Fermilab

- 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.

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

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

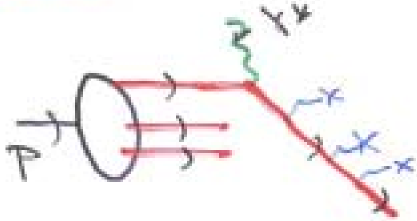


$$i\, \vec{S}_p \cdot \vec{\bar{p}} \times \vec{p}_c$$

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

Not part of ψ_p^{LF}.

Proposal by Ji and Yuan (also Collins)



$\Psi \to \Psi L$

complex phase

Augment LFWF (lcg) with phase

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

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

$A^+ = A^- = 0$

- 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

ISI $\sim$ FSI

enhanced in nuclei

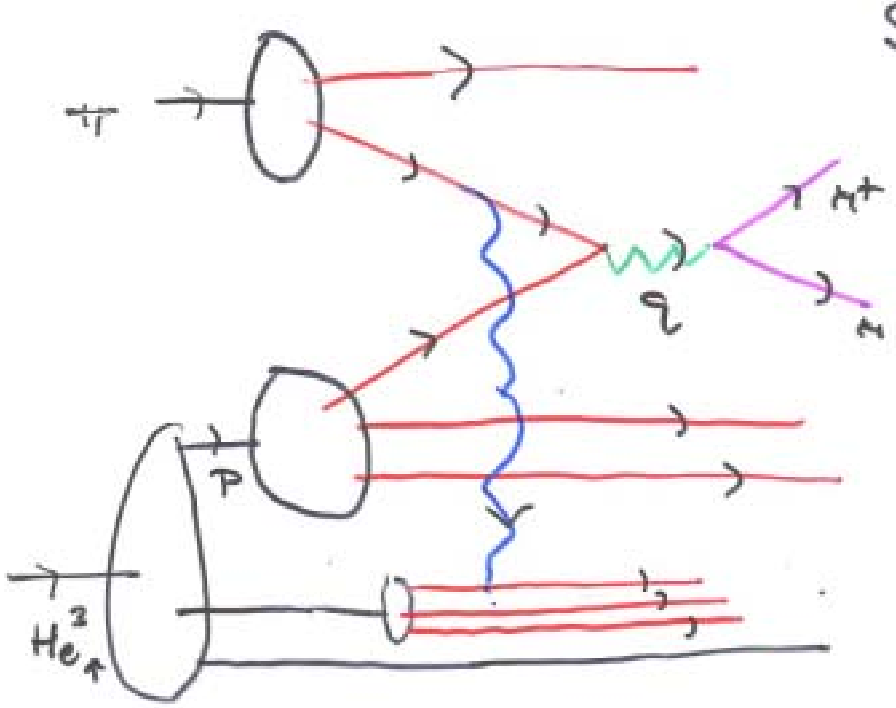
Coulomb effects

Often "leading twist" in Q^2

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

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

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

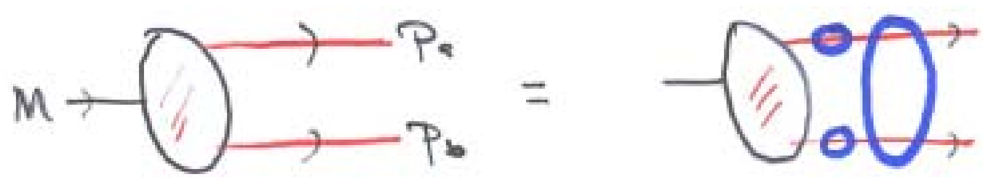


energy loss..

p_T spread..

Bodwin, Lepage, SJB

Connections to $\left\{\begin{array}{l}\text{Bethe-Salpeter}\\ \text{Schwinger-Dyson}\end{array}\right\}$ Approach



$$(\not p_a - m_a)(\not p_b - m_b)\,\psi_{BS} = K\,\psi_{BS}$$

$$\int d(p_a^- - p_b^-)\,\psi_{BS}(p_a, p_b) = \psi_{LF}^{q\bar q}(x, \vec k_\perp)$$

Much progress recently $\left\{\begin{array}{l}\text{C. Roberts, et al}\\ \text{L. Kisslinger}\end{array}\right.$

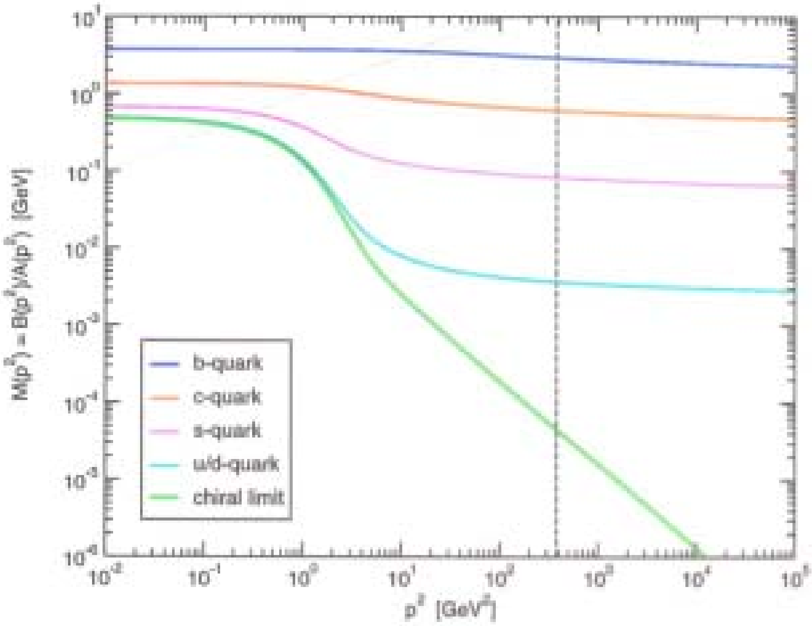
Incorporates: $m(p^2)$, $\alpha_s(p^2)$ $\quad \chi\cancel{SB}$

$\langle 0|\bar\psi\psi|0\rangle$ in hadron

$$k_F^2 + k_\perp^2 = x\left[M^2 - \sum_{\text{spect}} \frac{k_\perp^2 + m^2}{x}\right]$$

Quark propagator

momentum dependent mass function



- Explicit chiral symmetry breaking

$$M(p^2) \sim \frac{\hat{m}}{\left(\frac{1}{2}\ln\left[\frac{p^2}{\Lambda^2_{\rm QCD}}\right]\right)^{\gamma_m}}, \qquad \gamma_m = \frac{12}{33 - 2N_f}$$

- Chiral limit

$$M(p^2) \stackrel{\text{large}-p^2}{=} \frac{2\pi^2\gamma_m}{3} \frac{-\langle \bar{q}q \rangle^0}{p^2\left(\frac{1}{2}\ln\left[\frac{p^2}{\Lambda^2_{\rm QCD}}\right]\right)^{1-\gamma_m}}$$

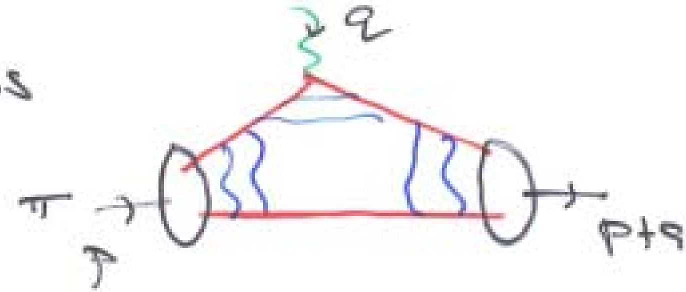
- $\hat{m}$ and $\langle \bar{q}q \rangle^0$ are renormalisation-point-invariant

(PM & Roberts, PRC56, 3369 (1997))

Approximations

Ladder approx, Landau-gauge

Form factors



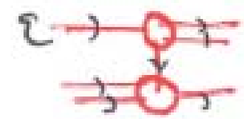
Matches to PQCD at high Q^2

Results

Spectra of mesons, baryons

Wavefunctions, static properties

Baryons: $q\,(qq)$



Form factors, transition matrix elements

⇒ Use ψ_{BS} results for init. conditi

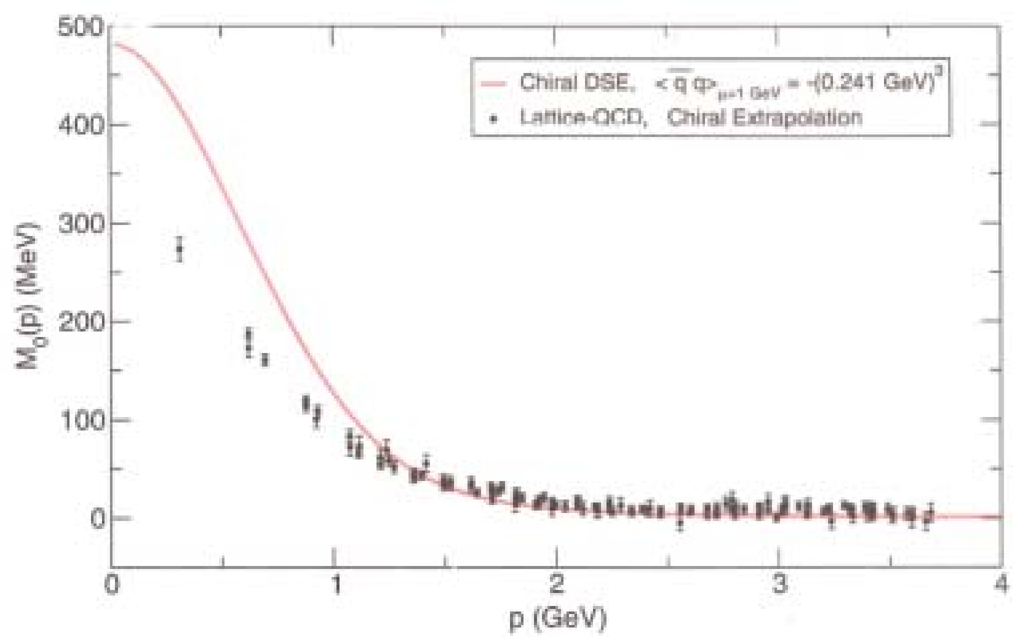
$$\delta \langle \psi^{LC}_{Trial} \,|\, H_{LC} \,|\, \psi^{LC}_{Trial} \rangle$$

Dressed quark propagator

- Dynamical chiral symmetry breaking
- Confined quark propagators: no mass-pole
- Current masses: 5.5 MeV (u/d) and 125 MeV (s)
- Constituent masses: 400 MeV (u/d) and 580 MeV (s)

DSE quark propagator compared to lattice results simulations

$$S(p) = \frac{1}{i \not p A(p^2) + B(p^2)} \quad = \quad \frac{Z(p^2)}{i \not p + M(p^2)}$$



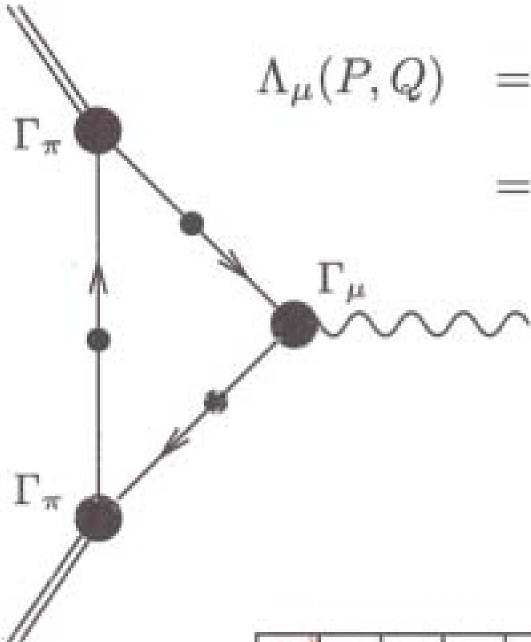
Lattice date Lattice2002, thanks to Patrick Bowman

see also Bowman, Heller, Williams, hep-lat/0203001

Pion Electromagnetic Form Factor

Peter Maris
Peter Tandy

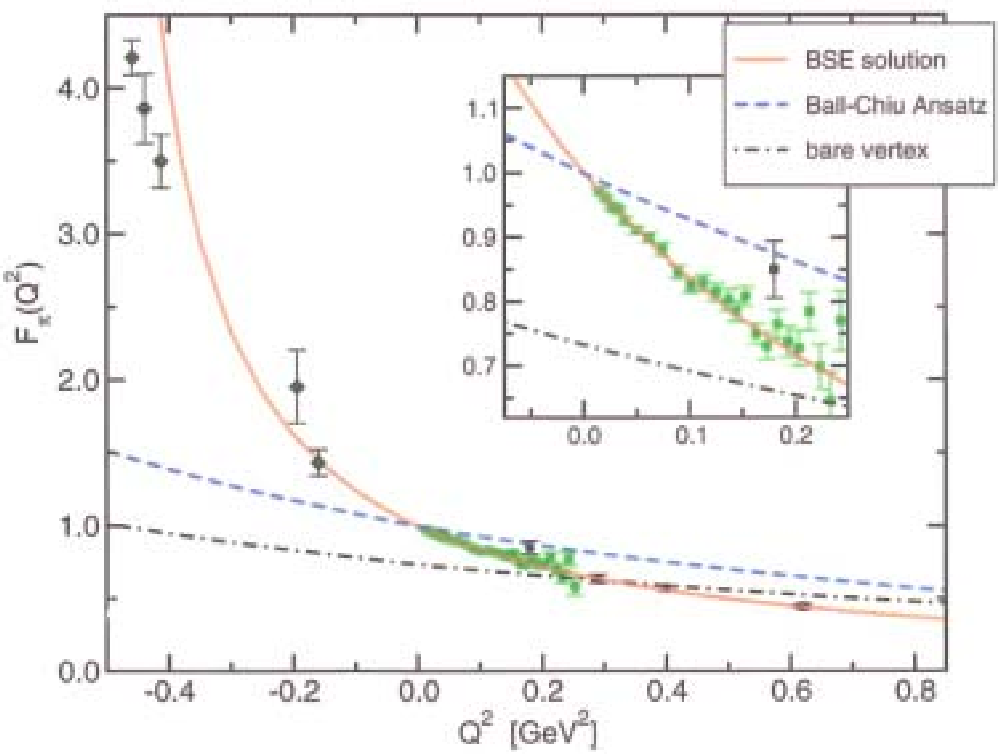
(PM & PCT, PRC61, 045202 (2000))



$$\Lambda_\mu(P,Q) = 2\,P_\mu\,F_\pi(Q^2)$$
$$= N_c \int \frac{d^4q}{(2\pi)^4}\,\mathrm{Tr}\left[\bar\Gamma^\pi\,S\,i\Gamma_\mu\,S\,\Gamma^\pi\,S\right]$$

BSE vertex: $r_\pi = 0.68$ fm

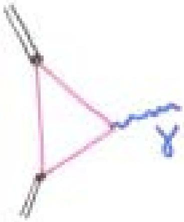
expt.: $r_\pi = 0.663 \pm .006$



Results for Electroweak processes

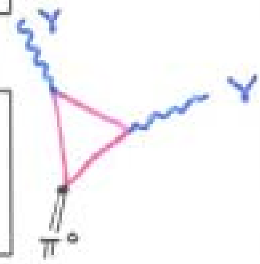
in impulse approximation

Pseudoscalar charge radii



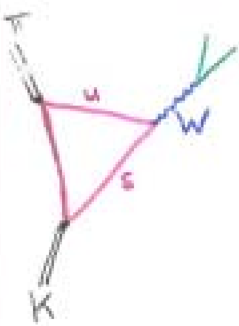
	expt.	calc.
r^2_π	0.44 fm^2	0.45
$r^2_{K^+}$	0.34 fm^2	0.38
$r^2_{K^0}$	-0.054 fm^2	-0.086

$\gamma\,\pi\,\gamma$ transition



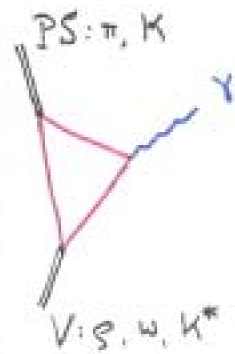
$g_{\pi\gamma\gamma}$	0.50	0.50
$r^2_{\pi\gamma\gamma}$	0.42 fm^2	0.39

Weak K_{l3} decay



$\lambda_+(e3)$	0.028	0.027
$\Gamma(K_{e3})$	$7.6 \cdot 10^6\ \mathrm{s}^{-1}$	7.38
$\Gamma(K_{\mu 3})$	$5.2 \cdot 10^6\ \mathrm{s}^{-1}$	4.90

Vector meson radiative decay



$g_{\rho\pi\gamma}/m_\rho$	0.74 GeV^{-1}	0.69
$g_{\omega\pi\gamma}/m_\omega$	2.31	2.07
$g_{K^{*+}K^+\gamma}/m_{K^*}$	0.83	0.99
$g_{K^{*0}K^0\gamma}/m_{K^*}$	1.28	1.19

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S.J.B.

Light-Front Quantization of Standard Model $SU(2) \otimes U(1)$

* $n \cdot A = A^+ = 0$ gauge

  $\Rightarrow$ physical gauge quanta, unitary, renormalizable

* SSB from zero mode of scalar field

$$\phi^{(0)} = \frac{v}{\sqrt{2}}$$

$$\phi(x) = \frac{1}{\sqrt{2}}\left(v + h(x) + i\eta(x)\right)$$

$$\partial \cdot A = M\eta \quad , \quad M = ev$$

* Goldstone field $\eta(x)$ restores ϵ_L:

$$\epsilon^{(L)}_\mu = \frac{n_\mu M}{n \cdot k} - \frac{k_\mu M}{k^2} \qquad (\epsilon \cdot k = 0)$$

* LC vacuum remains trivial

* Amplitude Event Generator

  $\Rightarrow$ Renormalized Amplitudes from LF T-O PTh

  Ghost-Free, $\prod d^2k_\perp dx$, DLCQ discret.

Other Applications of LF Quantization

Light-Front Thermodynamics

Set boundary conditions at fixed $\tau = t + z/c$
not t

$$Z_{LF} = \sum_n \exp - \frac{m_n^2}{T_{LF}}$$

Light-Front Lippmann-Schwinger

$$T = H_I + H_I \frac{1}{M^2 - \sum \frac{m_\perp^2}{x} + i\epsilon} T$$

Variational Solutions to Bound-State Probs:

minimize $\langle \Psi_{trial} | H_{LF} | \Psi_{trial} \rangle$

Construct $\langle \Psi_{trial} | n \rangle = \Psi_n^{trial}(x_i, k_{\perp i}, \lambda_i)$

using numerators from L_z
ladder relations

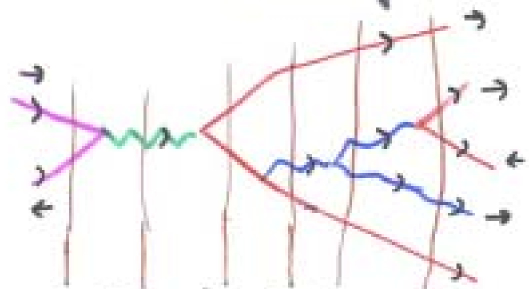
"Event Amplitude Generator"

Generate amplitude from LF TOPTh $\begin{cases}\text{Tree +}\\ \text{Virtual}\end{cases}$

$$\mathcal{M} = \sum_{\substack{\text{time-}\\ \text{orderings}}} \mathcal{M}_\alpha \quad (\text{specific spins } S_z)$$

e^+

e^-



D_1 D_2 D_3 D_4

$$\mathcal{M}_\alpha = H_I \frac{1}{D_1} H_I \frac{1}{D_2} \cdots$$

$\sum k^+$, $\sum_i k_\perp$, $\sum_i J_z$ conserved

$k^+ > 0$: few surviving LF time-orderings

Physical polarization sums: $\sum_{(i)} \epsilon^{(i)}_\mu \epsilon^{(i)}_\nu$

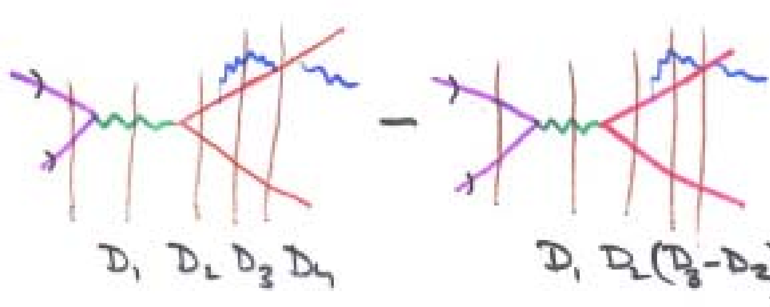
$(i) = 1, 2, 3$ ↑ Standard Model W

Compute renormalized amplitude

– "alternating denominator" method

Roskies
Suaya
SJB

Example:



$D_1\ D_2\ D_3\ D_4$ $\qquad$ $D_1\ D_2 (D_3 - D_2)\ D_4$

equivalent to subtracting mass counterterm!

$(D_3 - D_2)$

$\pi\, d^2k_\perp dx$, unitary, no ghosts.