SINGLE TRANSVERSE-SPIN ASYMMETRIES

A_N AT RHIC

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*Some related references: J.Q. and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991); Nucl. Phys. B378, 52 (1992); Phys. Rev. D59, 014004 (1999); D. Boer and J.Q., Phys. Rev. D65, 034008 (2002); C. Kouvaris, J.Q., and W. Vogelsang, in preparation.

1. Introduction

- Single Spin Process at RHIC:

$$A(p, \vec{s}) + B(p') \Longrightarrow C(\ell) + X$$

  - only one initial-state hadron is polarized
  - observed particle $C(\ell)$ is unpolarized, and can be any high transverse momentum particle π, p, γ, or lepton
  - cross section: $\sigma(\ell, \vec{s})$

- Single Spin Asymmetry – definition:
  - Spin-avg X-section: $\sigma(\ell) = \frac{1}{2}[\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})]$
  - Spin-dep X-section:
  $$\Delta\sigma(\ell, \vec{s}) = \frac{1}{2}[\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})]$$
  - Single-spin asymmetry:
  $$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$
  - Single longitudinal-spin asymmetry: A_L
  particle spin $\vec{s}$ is parallel to its momentum $\vec{p}$
  - Single transverse-spin asymmetry: A_N
  particle spin $\vec{s}$ is perpendicular to its momentum $\vec{p}$

Even though X-section $\sigma(\ell, \vec{s})$ is finite, single spin asymmetry can vanish due to fundamental symmetries of interactions

- Parity and time-reversal invariance

  $\Rightarrow A_N = 0$ for inclusive DIS

  - Inclusive DIS X-section:

$$\sigma(\vec{s}_T) \propto L^{\mu\nu} W_{\mu\nu}(\vec{s}_T)$$

  - Hadronic tensor:

$$W_{\mu\nu}(\vec{s}_T) \propto \langle P, \vec{s}_T | j^\dagger_\mu(0) \, j_\nu(y) \, | P, \vec{s}_T \rangle$$

  - Parity and time-reversal invariance:

$$\begin{aligned} &\langle P, \vec{s}_T | j^\dagger_\mu(0) \, j_\nu(y) \, | P, \vec{s}_T \rangle \\ &\qquad = \langle P, -\vec{s}_T | j^\dagger_\nu(0) \, j_\mu(y) \, | P, -\vec{s}_T \rangle \end{aligned}$$

$$\Rightarrow \; W_{\mu\nu}(\vec{s}_T) = W_{\nu\mu}(-\vec{s}_T)$$

  - Spin-dependent X-section:

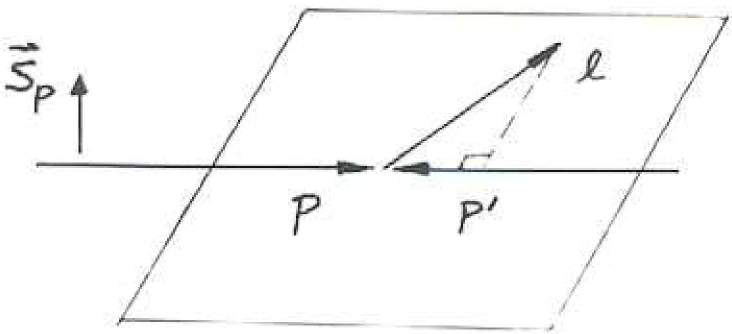
$$\begin{aligned} \Delta\sigma(\vec{s}_T) &\propto L^{\mu\nu} \left[W_{\mu\nu}(\vec{s}_T) - W_{\mu\nu}(-\vec{s}_T) \right] \\ &= L^{\mu\nu} \left[W_{\mu\nu}(\vec{s}_T) - W_{\nu\mu}(\vec{s}_T) \right] = 0 \end{aligned}$$

    because $L^{\mu\nu}$ is symmetric for a unpolarized lepton

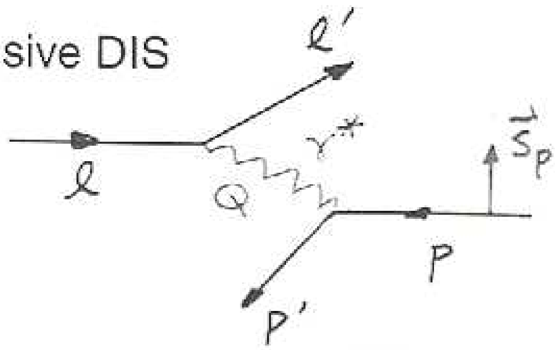
  - Above result is valid for any two-current correlators

- Parity conserved interactions $\Rightarrow A_L = 0$

- Single spin asymmetries correspond to T-odd triple product: $A_N \propto i\,\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$
  - $\vec{p}$ is beam particle's three momentum
  - $\vec{\ell}$ is momentum of observed particle
  - the phase "i" is required by time-reversal invariance
  - covariant form: $A_N \propto i\epsilon^{\mu\nu\alpha\beta}\, p_\mu s_\nu \ell_\alpha p'_\beta$

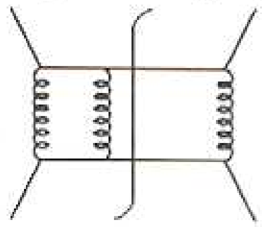


- Nonvanishing A_N requires a phase, a spin flip, and enough vectors to fix a scattering plan
  - Inclusive DIS does not have enough vectors
    Note: q and p can only fix a line
- Following examples can generate nonvanishing A_N:
  - Single hadron (or photon) at high ℓ_T
  - Drell-Yan lepton angular distribution
  - Semi-inclusive DIS
  - . . .

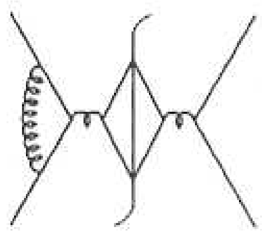


2. A_N FOR SINGLE HADRON PRODUCTION

- pQCD was first used to study single transverse-spin asymmetry by Kane, Pumplin, and Repko in 1978



+ c.c.



+ c.c.

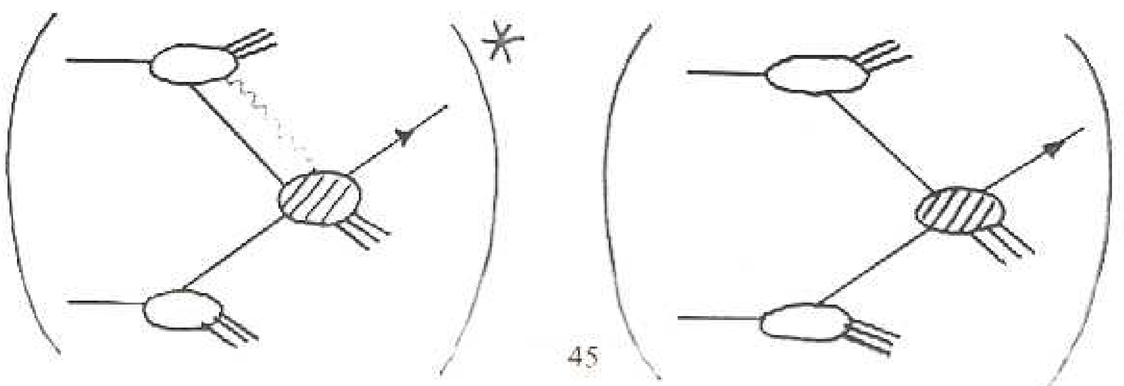
  - imaginary part of the loop provides the phase
  - quark mass provides the needed spin flip
  - $A_N \propto \frac{m_q}{\ell_T}\langle p, \vec{s}_T|\bar{\psi}\Gamma\psi|p, \vec{s}_T\rangle$ where $\Gamma = \gamma^+\gamma_5\gamma_T, ...$

- The fact that $A_N \propto m_q$ indicates that A_N is a twist-3 effect in QCD perturbation theory

- QCD dynamics is much richer than the parton model
  - twist-3 arises from "intrinsic" k_T

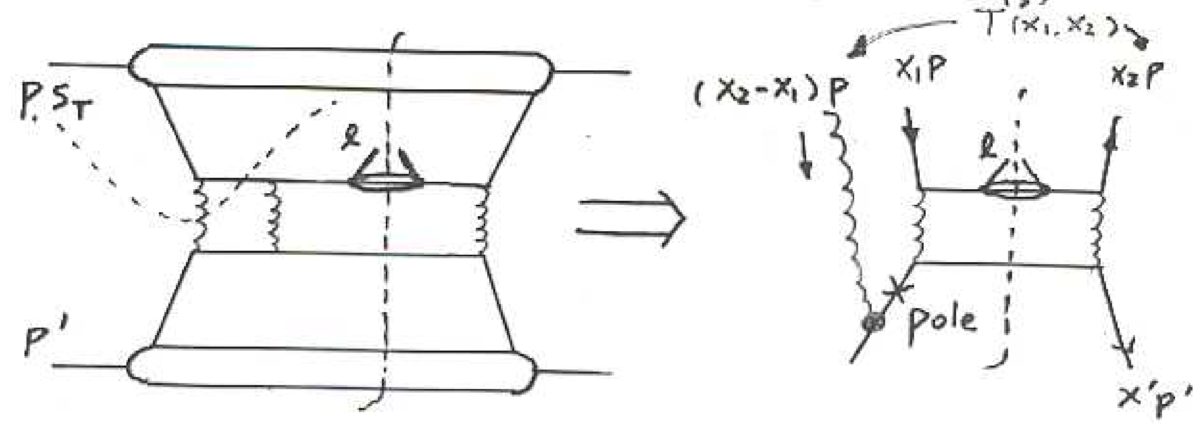
    $\Rightarrow\ A_N \propto T_{k_T} \sim \langle p, \vec{s}_T|\bar{\psi}\Gamma\partial_T\psi|p, \vec{s}_T\rangle$
  - twist-3 from interference between a quark state and a quark-gluon state

    $\Rightarrow\ A_N \propto T_{A_T} \sim \langle p, \vec{s}_T|\bar{\psi}\Gamma A_T\psi|p, \vec{s}_T\rangle$



+ C.C.

A_N FROM POLARIZED TWIST-3 CORRELATIONS



- Unpinched pole $\Rightarrow$ $i\delta(x_1 - x_2)$
- Color gauge invariance combines T_{k_T} and T_{A_T} to

$$\begin{aligned} T_{D_T}(x_1, x_2) &\propto \langle p, \vec{s}_T|\bar{\psi}\Gamma D_T\psi|p, \vec{s}_T\rangle \\ T_F(x_1, x_2) &\propto \langle p, \vec{s}_T|\bar{\psi}\Gamma F_T^+\psi|p, \vec{s}_T\rangle \end{aligned}$$

- $A_N \neq 0$ requires
  - $T(x_1, x_2, \vec{s}_T) \neq 0$ when $x_1 = x_2$
  - $T(x_1, x_2, \vec{s}_T) \neq T(x_1, x_2, -\vec{s}_T)$
  - Combination of $T(x_1, x_2, \vec{s}_T)$ and partonic part is real

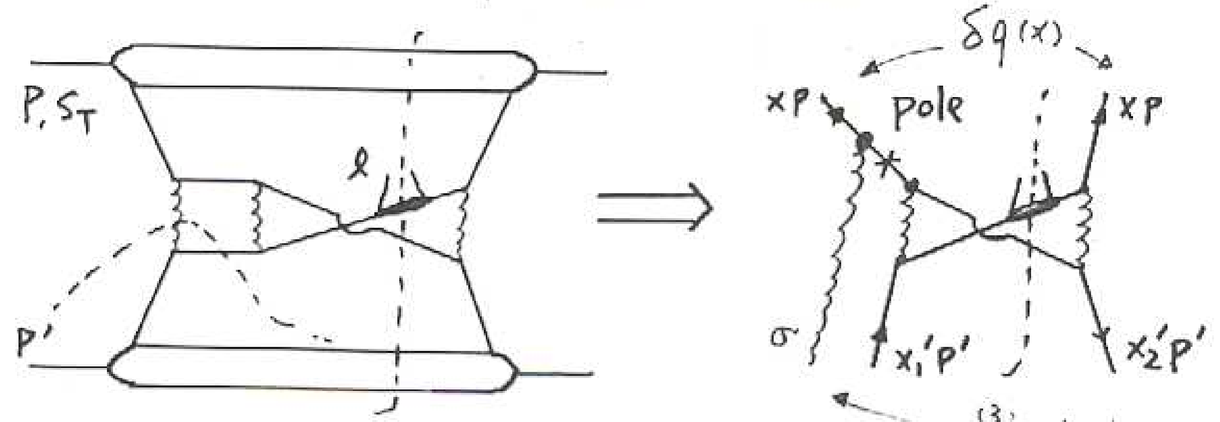
$\Rightarrow$ $A_N \propto T_F(x_1, x_2)$ with $x_1 = x_2$, and

$$T_F(x_1, x_2) = \int \frac{dy_1^- dy_2^-}{4\pi} \mathrm{e}^{ix_1P^+y_1^- + i(x_2-x_1)P^+y_2^-}$$
$$\times \langle P, \vec{s}_T|\bar{\psi}_a(0)\gamma^+ \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma^{\ +}(y_2^-)\right] \psi_a(y_1^-)|P, \vec{s}_T\rangle$$

- Three field operator does not have the probability interpretation of normal parton distributions

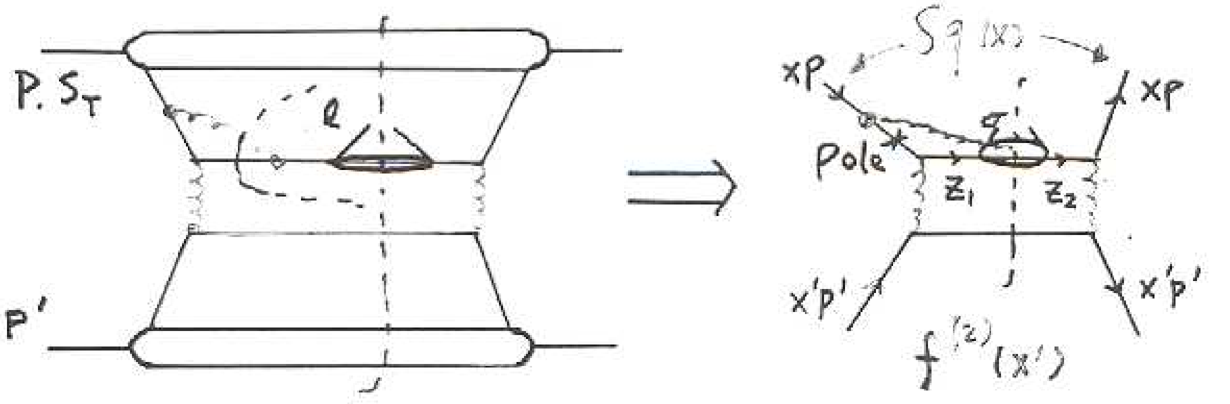
A_N FROM TWIST-2 TRANSVERSITY DISTRIBUTION

- Twist-3 initial-state unpolarized correlation[a]



  - even γ's in operator definition of $\delta q(x)$
    $\Rightarrow$ much smaller number of diagrams
  - double suppression from $\delta q(x)$ and chiral-odd twist-3 correlation function
  - contribution to A_N is a factor of 5-10 smaller than that from polarized initial-state T_F

- Twist-3 unpolarized fragmentation function



  - Expect to be of similar size, and much smaller than that from polarized initial-state T_F

[a] Y. Kanazawa and Y. Koike, Phys. Lett. B490 (2000) 99

- Generalized factorization formula for hadronic single transverse-spin asymmetries

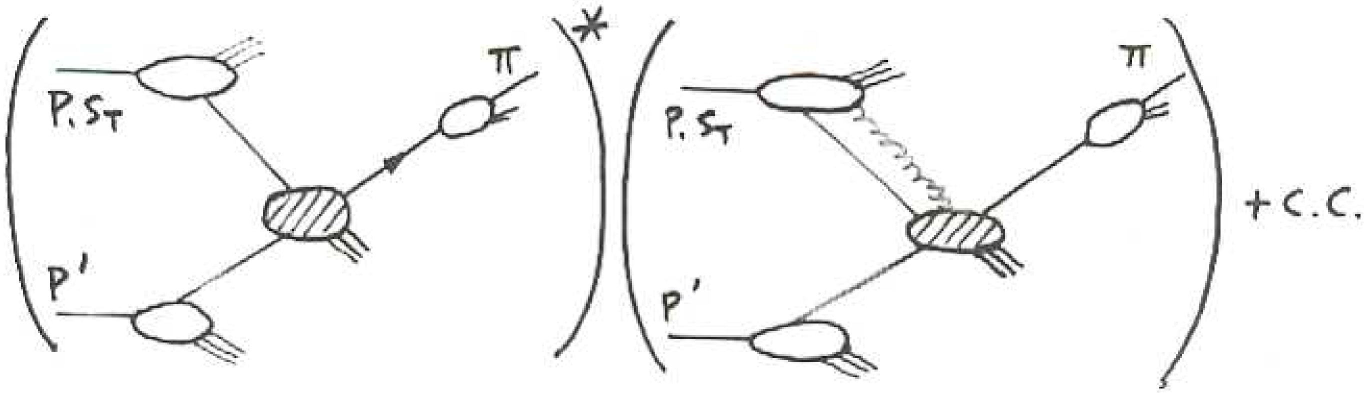
$$
\begin{aligned}
\Delta\sigma_{AB\to h}(\vec{s}_T) = & \sum_{abc} T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x') \\
& \qquad \otimes \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z) \\
& + \sum_{abc} \delta q^{(2)}_{a/A}(x, \vec{s}_T) \\
& \otimes \Big\{ f_{b/B}(x') \otimes \hat{\sigma}'_{ab\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to h}(z_1, z_2) \\
& \quad + f^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}''_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z) \Big\}
\end{aligned}
$$

- $\hat{\sigma}$, $\hat{\sigma}'$, and $\hat{\sigma}''$ are perturbatively calculable
- T,P–invariance $\longrightarrow$ at least one function has TWO x's
- Chiral-odd $\delta q(x)$ requires chiral-odd $f^{(3)}_{b/B}$ and $D^{(3)}_{c\to h}$
  $\Rightarrow$ first term is larger than the other two
- Can generalize $\otimes$ to convolution in k_T for both initial-state and final-state interactions
  - Initial-state $k_T \Rightarrow$ Sivers effect
    D. Sivers, Phys. Rev. D43 (91) 261;
    M. Anselmino et al., Phys. Lett. B362 (95) 164; ...
  - Final-state $k_T \Rightarrow$ Collins effect
    J. Collins, Nucl. Phys. B396 (93) 161;
    R.L. Jaffe, et al., Phys. Rev. Lett. 80 (1998) 1166; ...

LEADING CONTRIBUTION TO THE ASYMMETRY OF PION PRODUCTION

- Minimal approach (collinear factorization):

$$\Delta\sigma_{AB\to h}(\vec{s}_T) \approx \sum_{abc} T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x')$$
$$\otimes\, \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z)$$



- Keep only quark fragmentation
  - observed momentum: $\ell_T^2 \propto x x' z^2 S$
  - parton distributions are steeply falling as $x \to 1$
    e.g., $f_q(x) \propto (1-x)^\alpha$ with $\alpha > 3-4$
  - quark fragmentation function falls slower as $z \to 1$
    e.g., $D_{q\to\pi}(z) \propto (1-z)^{n_q}$ with $n_q \sim 2$
    $\Rightarrow$

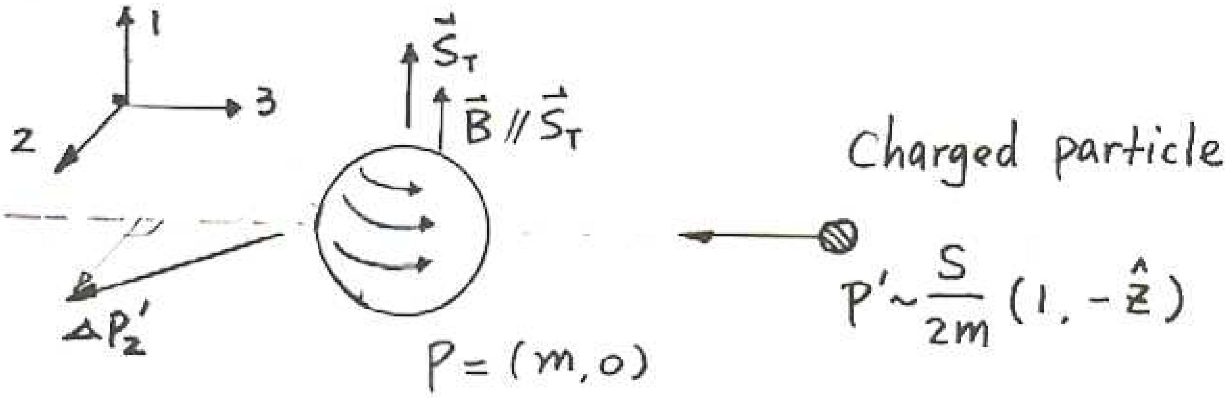
    X-section is dominated by small $x \sim x'$ and large z
- Need gluon fragmentation contribution at low ℓ_T and large S

WHAT $T_F(x,x)$ TELLS US?

$$T_F(x,x) \propto \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- a classical (Abelian) analog:

  rest frame of $(p, \vec{s}_T)$



  – change of transverse momentum

$$\frac{d}{dt} p_2' = e(\vec{v}' \times \vec{B})_2 = -ev_3 B_1 = ev_3 F_{23}$$

  – in the c.m. frame

$$(m, \vec{0}) \to \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \to n = (0, 1, 0_T)$$

$$\Longrightarrow \quad \frac{d}{dt} p_2' = e\, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}$$

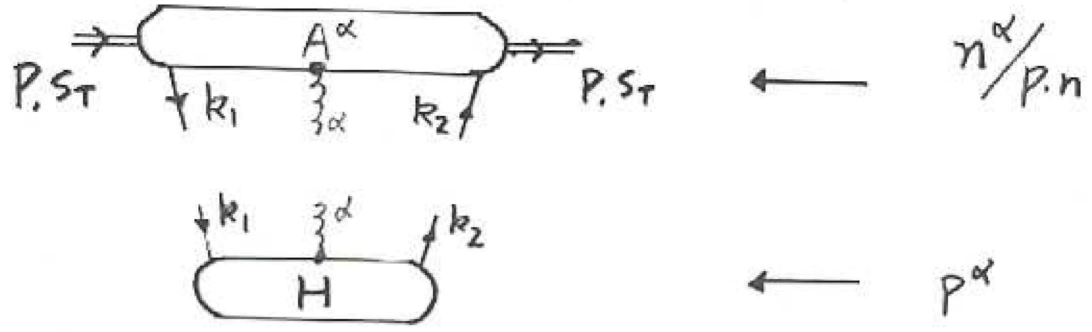
  – total change: $\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y^-)$

- Color field strength $F^{+\sigma}$ alone is not gauge invariant

- T_F represents a fundamental quantum correlation between quark and gluon inside a hadron

TECHNICAL STEPS TO CALCULATE THE ASYMMETRIES

— in a color covariant gauge



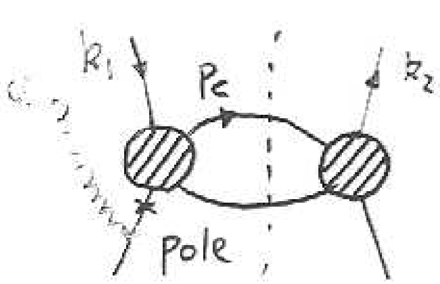
- gluon field: $A^\alpha \to n \cdot A = A^+$
- expand $H(k_1, k_2)$ to linear in k_T

$$H(k_1, k_2) \to H(x_1 p, x_2 p) + \frac{\partial H}{\partial k_{2\sigma}} (k_{2_T} - k_{1_T})^\sigma + \ldots$$

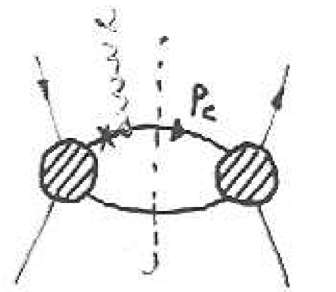
- convert $(k_{2_T} - k_{1_T})^\sigma A^+ \to \partial^\sigma A^+ \to F^{\sigma +}$
- factorized formula:

$$\Delta\sigma(\vec{s}_T) = \int dx_1 dx_2 \, T_F(x_1, x_2) \left[i\epsilon^{\sigma s_T n \bar{n}} \frac{\partial H}{\partial k_{2\sigma}} \right]_{k_{2_T}=0}$$

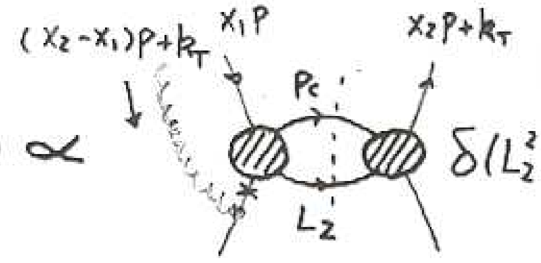
- either x_1 or x_2 is fixed by the pole in partonic part.

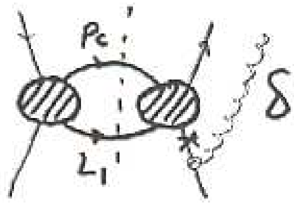


Initial-state



Final-state

$H(x_1, x_2, k_T) \propto$ 

$\delta(L_2^2) +$ 

$\delta(L_1^2)$

(L) (R)

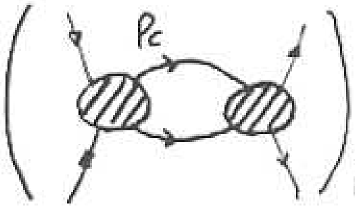
- Soft-gluon pole gives the needed phase:

$$\frac{1}{x_2 - x_1 + i\epsilon} \to -i\pi\delta(x_2 - x_1)$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:

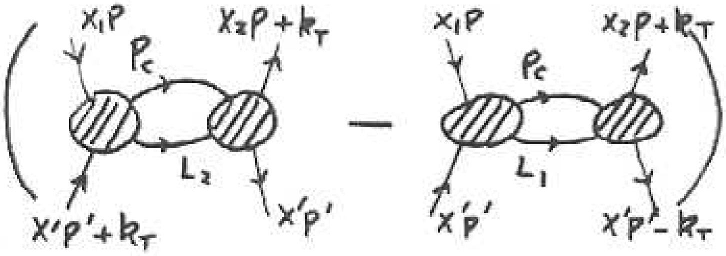
$L_2 = x_2 P + x' p' - P_c + k_T$

$L_1 = x_1 P + x' p' - P_c$



$\Big|_{k_T = 0} * \left[\delta(L_2^2) - \delta(L_1^2)\right]$

$o(k_T)$



$* \ \delta(L_1^2)$

- phase space δ-functions $\Rightarrow$ derivative term

  $\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x\frac{d}{dx}T_F(x,x)$

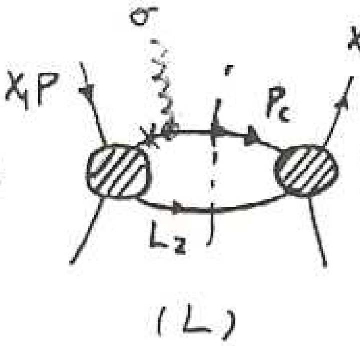
- non-derivative term

  $(L) - (R) \propto \frac{2p_c \cdot k_T}{\hat{u}} \Rightarrow T_F(x,x)$

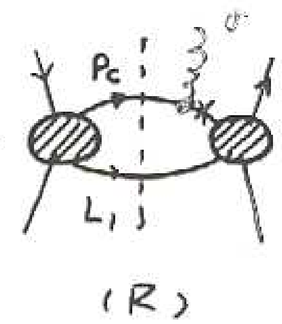
- in forward region, $x\frac{d}{dx}T_F(x,x) \gg T_F(x,x)$
  because $T_F(x,x) \propto (1-x)^\alpha$ as $x \to 1$.

CONTRIBUTION FROM FINAL-STATE INTERACTION

$H(x_1, x_2, k_T) \propto$



$\delta(L_2^2) +$



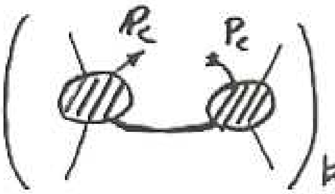
$\delta(L_1^2)$

(L) (R)

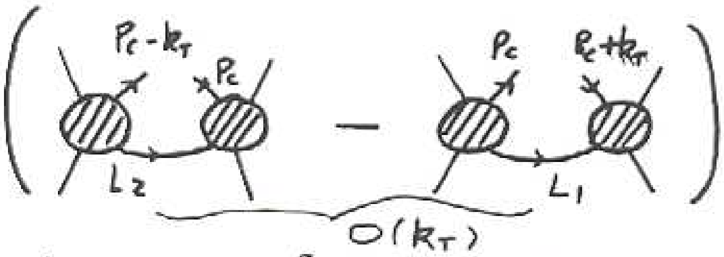
- Soft-gluon pole gives the needed phase:

$$\frac{-1}{x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p} - i\epsilon} \to -i\pi\delta(x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p})$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:



$$\left(\cdots \right)_{k_T=0} * \big[\underbrace{\delta(L_2^2) - \delta(L_1^2)}_{O(k_T)} \big]$$



$* \, \delta(L_1^2)$

 - phase space δ-functions $\Rightarrow$ derivative term

   $\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x\frac{d}{dx}T_F(x,x)$

 - non-derivative term

   $(L) - (R) \propto \left[\frac{2p_c \cdot k_T}{\hat{u}} + \frac{2p_c \cdot k_T}{\hat{t}}\right] \Rightarrow T_F(x,x)$

- most contribution to $A_N \propto \ell_T/u$

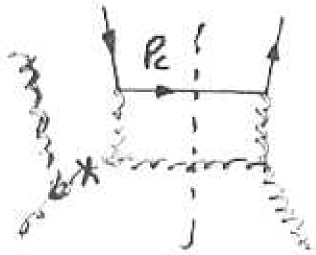
- part of final-state effect $\propto \ell_T/t \sim 1/\ell_T$

  $\to A_N$ does not fall as fast as $1/\ell_T$ as ℓ_T increases.

Leading $(\partial/\partial x)T_F(x,x)$ contribution to the asymmetries

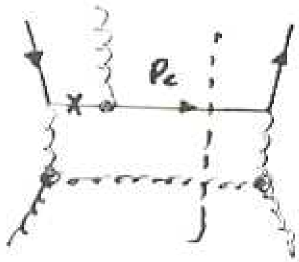
$$E\frac{d\Delta\sigma}{d^3\ell} \propto \epsilon^{\ell T s T n \bar{n}}\, D_{c\to\pi}(z) \otimes \left[-x\frac{\partial}{\partial x}T_F(x,x)\right]$$
$$\otimes \frac{1}{-\hat{u}}\left[G(x')\otimes\Delta\hat{\sigma}_{qg\to c} + \sum_{q'} q'(x')\otimes\Delta\hat{\sigma}_{qq'\to c}\right]$$

- $\Delta\hat{\sigma}_{qg\to c}$ and $\Delta\hat{\sigma}_{qq'\to c}$ are perturbatively calculable
- Example, $qg \to qg$ scattering



$+\cdots$

I-S



$+\cdots$

F-S

  - initial-state:

$$\frac{1}{2(N_C^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-N_C^2\frac{\hat{u}^2}{\hat{t}^2}\right]$$

  - final state:

$$\frac{1}{2N_C^2(N_C^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1+2N_C^2\frac{\hat{s}\hat{u}}{\hat{t}^2}\right]$$

  - unpolarized:

$$\frac{N_C^2-1}{2N_C^2}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-\frac{2N_C^2}{N_C^2-1}\frac{\hat{s}\hat{u}}{\hat{t}^2}\right]$$

- extra gluon interaction leads to a different color factor

MODEL FOR QUARK-GLUON CORRELATION $T_F(x, x)$

- Twist-3 correlation $T_F(x, x)$:

$$T_F(x,x) = \int \frac{dy_1^-}{4\pi} \mathrm{e}^{ixP^+ y_1^-}$$

$$\times \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Twist-2 quark distribution:

$$q(x) = \int \frac{dy_1^-}{4\pi} \mathrm{e}^{ixP^+ y_1^-} \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Model for $T_F(x, x)$ of quark flavor a:

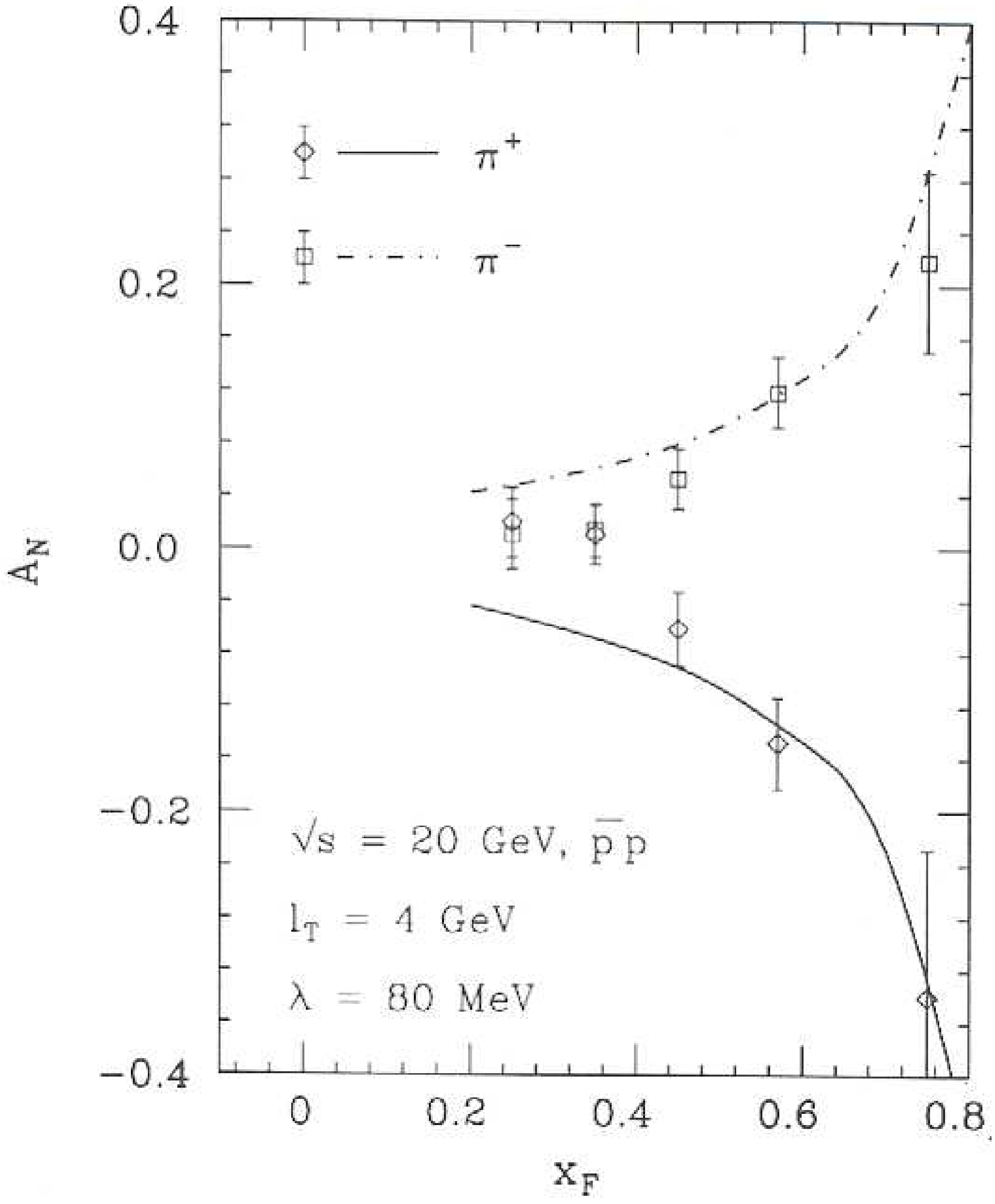
$$T_{F_a}(x, x) \equiv \kappa_a \, \lambda \, q_a(x)$$

  with $\kappa_u = +1$ and $k_d = -1$ for proton

- Fitting parameter $\lambda \sim O(\Lambda_{\mathrm{QCD}})$

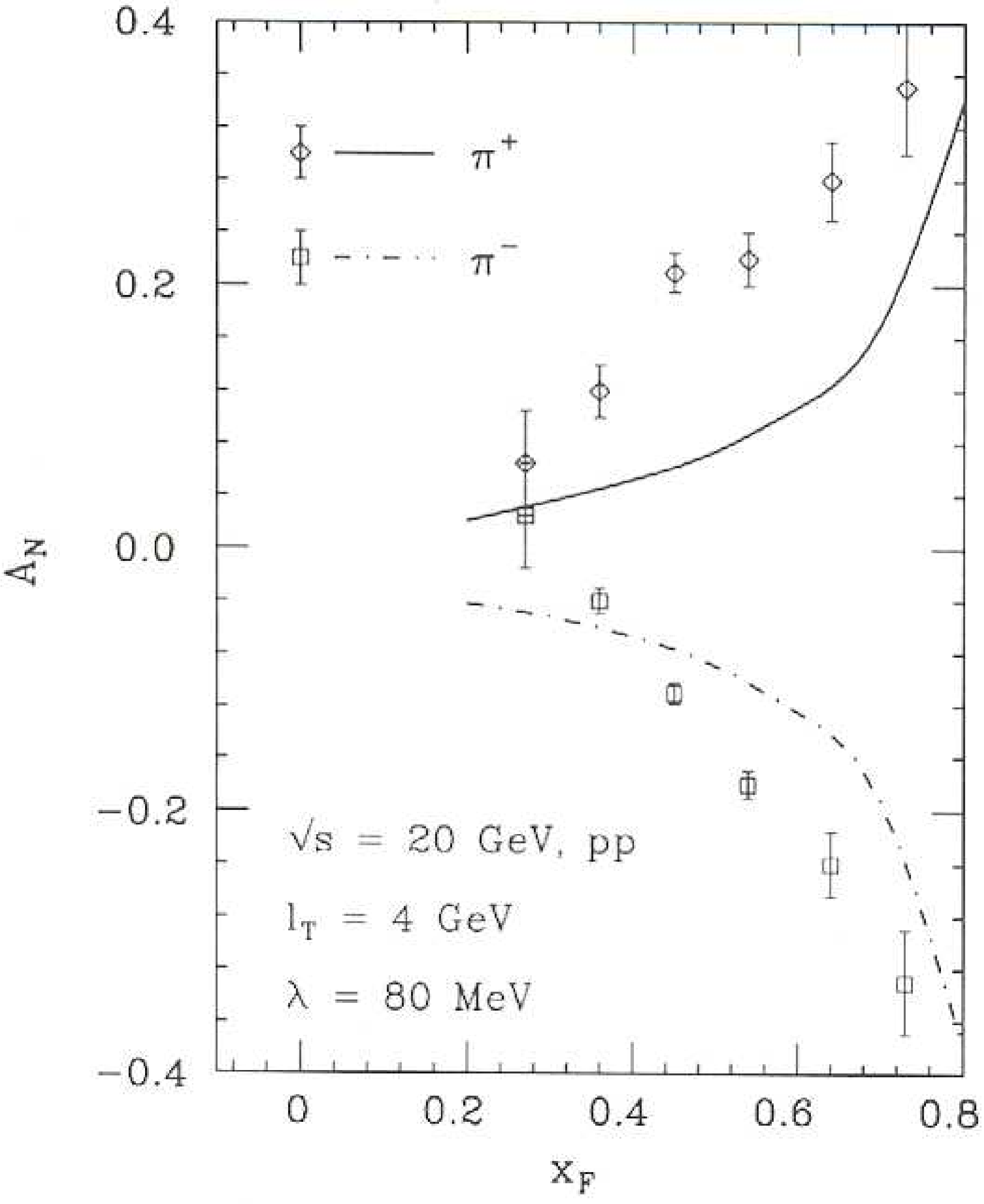
- Predictive power of the factorization approach:
  - extract $T_F(x, x)$ from one observable, say π^+ or π^-
  - use it to predict other observable, say π^0
  - $(\partial/\partial x) T_F(x, x)$ leads to enhancement of the asymmetries in forward region
  - same partonic parts can be used for calculating the asymmetries in production of other types of single hadron, say in k, or p production

COMPARE AN APPLE WITH AN ORANGE (I)



Fermilab data with ℓ_T up to 1.5 GeV

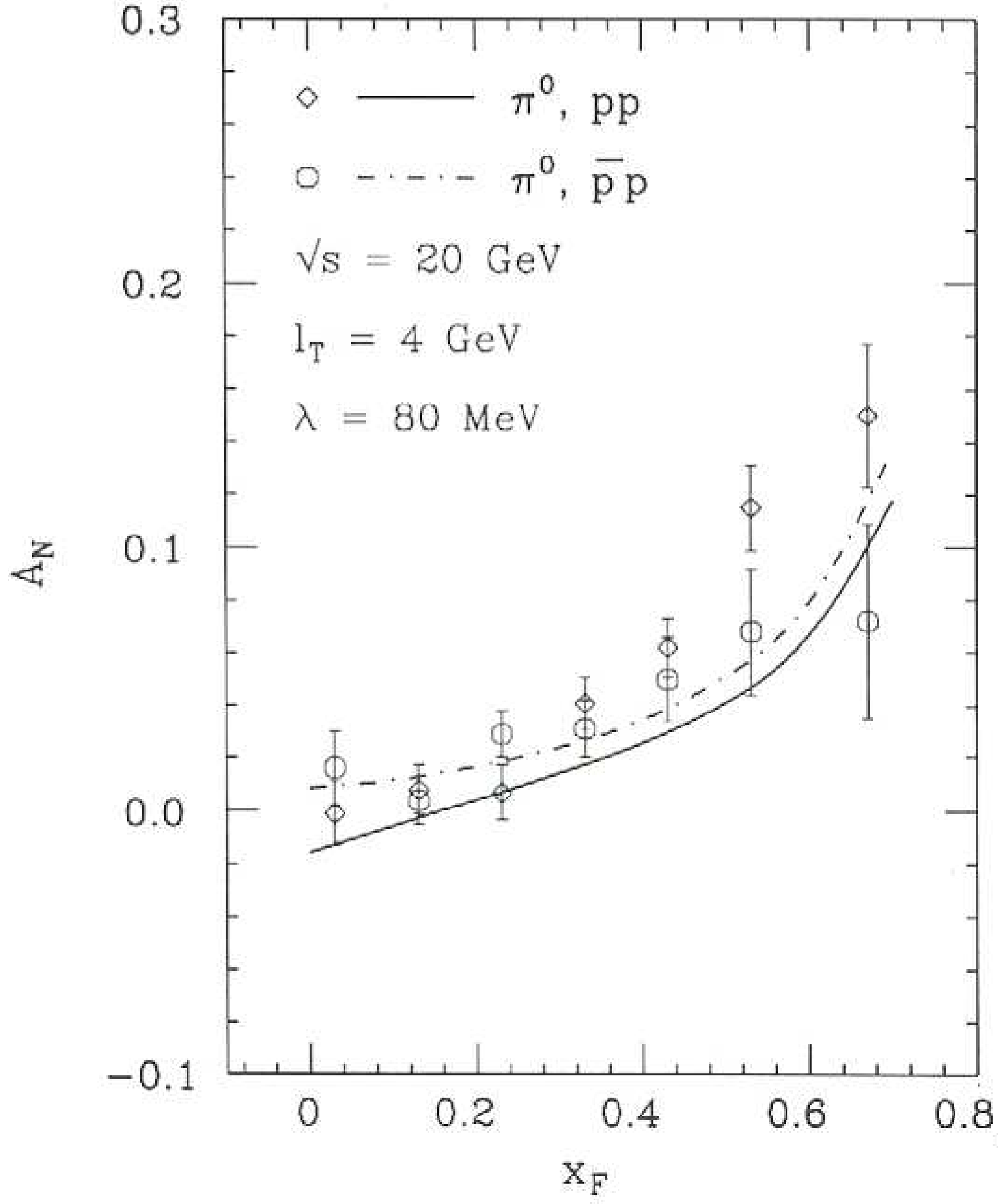
COMPARE AN APPLE WITH AN ORANGE (II)



Fermilab data with ℓ_T up to 1.5 GeV

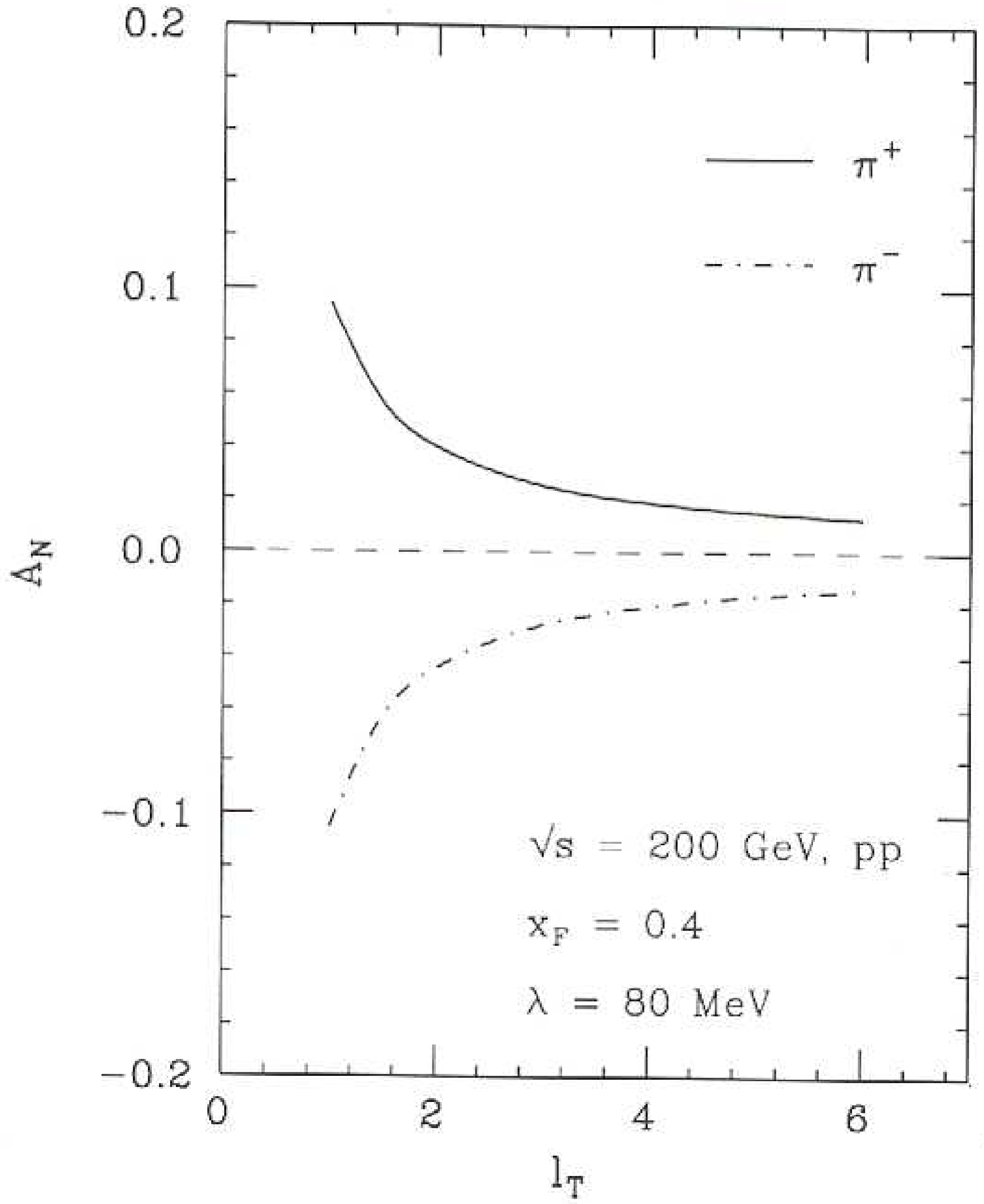
Theory curves fit data better if evaluated at a lower ℓ_T

COMPARE AN APPLE WITH AN ORANGE (III)



Fermilab data with ℓ_T up to 1.5 GeV

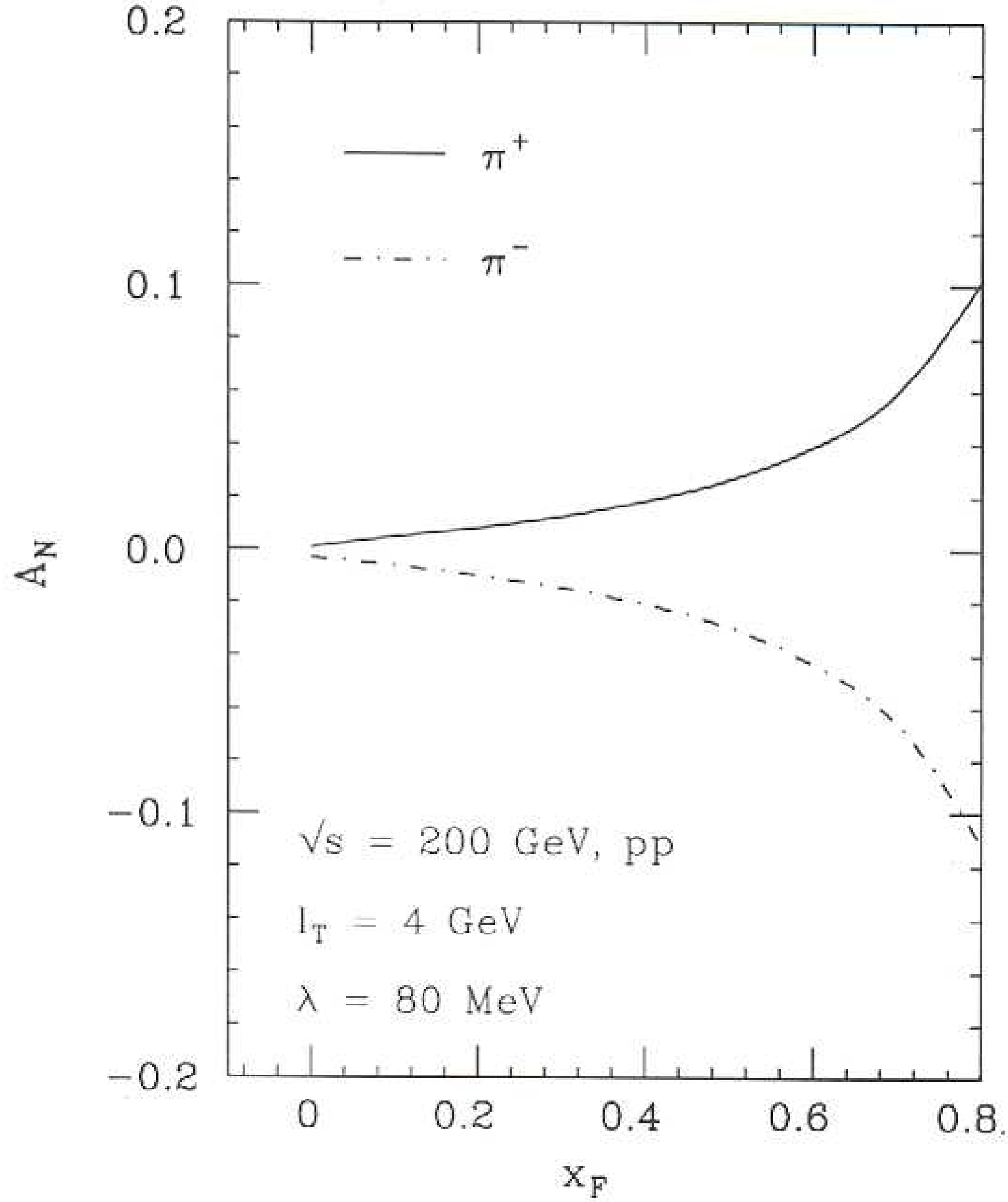
A_N AT RHIC ENERGY (I)



Derivative term only for partonic hard part

Non-drivative term are getting calculated by Kouvaris, Qiu, and Vogelsang

A_N AT RHIC ENERGY (II)



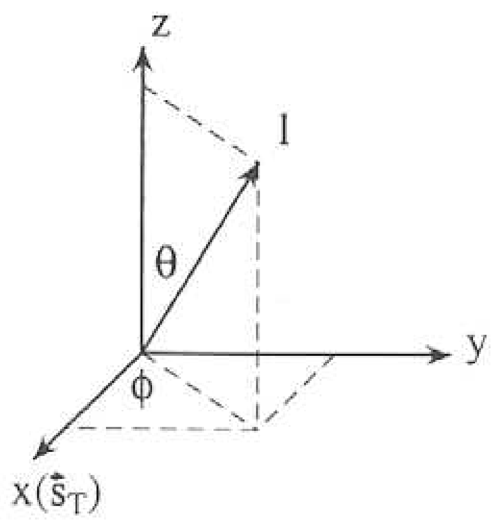
Derivative term only for partonic hard part

4. A_N FOR DRELL-YAN MASSIVE DILEPTON[a]

- Process:

$$A(p,\vec{s}) + B(p') \Rightarrow \gamma^*(Q)[\to \ell\bar{\ell}] + X$$

- Frame:



- Single transverse-spin asymmetry in $\frac{d\sigma}{dQ^2 d\Omega}$

$$A_N = \sqrt{4\pi\alpha_s}\left[\frac{\sin 2\theta \sin\phi}{1+\cos^2\theta}\right]\frac{1}{Q} \times \frac{\sum_q e_q^2 \int dx\, T_q(x,x)\, \bar{q}(Q^2/xS)}{\sum_q e_q^2 \int dx\, q(x)\, \bar{q}(Q^2/xS)}$$

- No derivative term at the tree level!
- In principle, there is no free parameter!
- A_N is very small and is estimated to be 2-4%

[a] D. Boer and J.Q., Phys. Rev. D65 (2002) 034008, and references therein.

5. Summary and Outlook

- Single transverse-spin asymmetry is a unique tool to explore nonperturbative physics beyond parton distributions
- QCD factorization approach allows to quantify the size of high order corrections, because of infrared safe partonic hard parts
- QCD factorization approach provides a systematic way to calculate the asymmetries in different processes
- Single transverse spin asymmetry in single hadron production is an excellent observable to test the QCD factorization
- Data on the asymmetries provide nonperturbative information on quark-gluon correlation
- Theoretical calculation with derivative term only are consistent with Fermilab data
- A full leading order calculation will soon be available.
- Drell-Yan single transverse-spin asymmetry is a clean probe. But, the asymmetry is small