# For RHIC Retreat

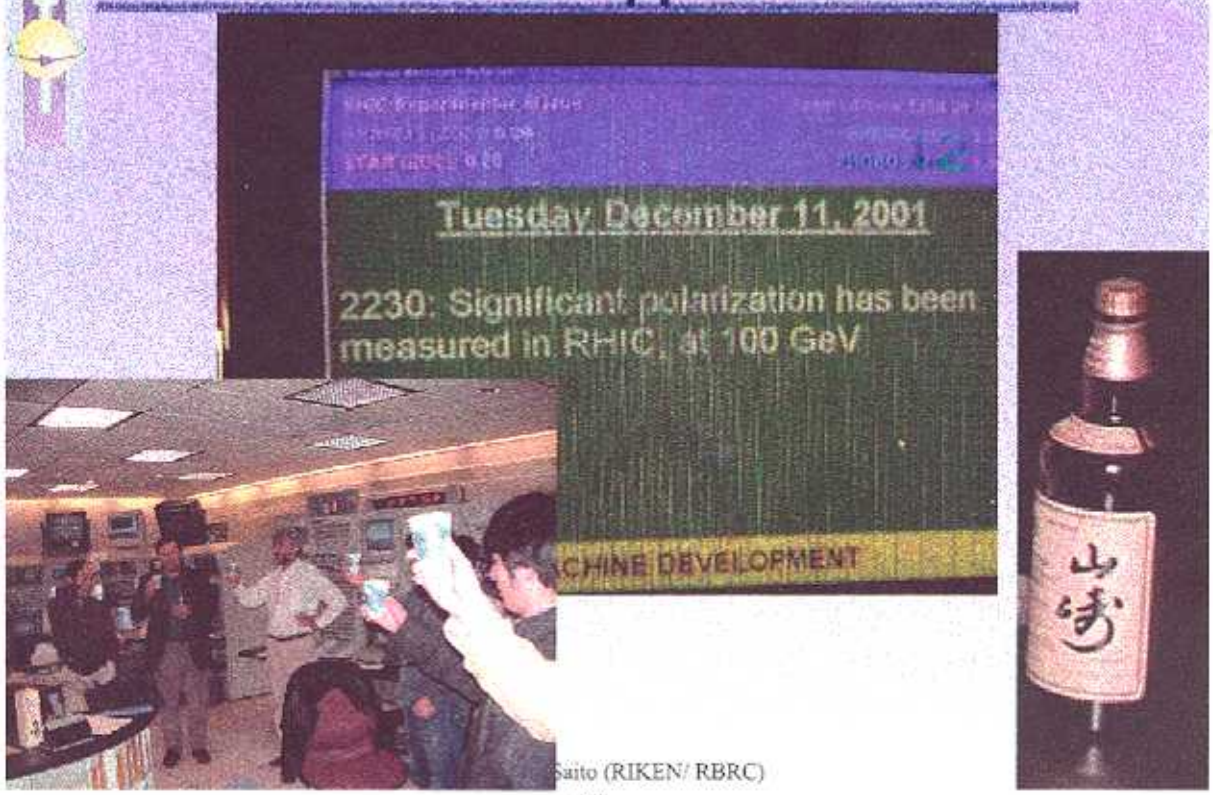
RHIC Spin Collaboration Meeting

February 22, 2002

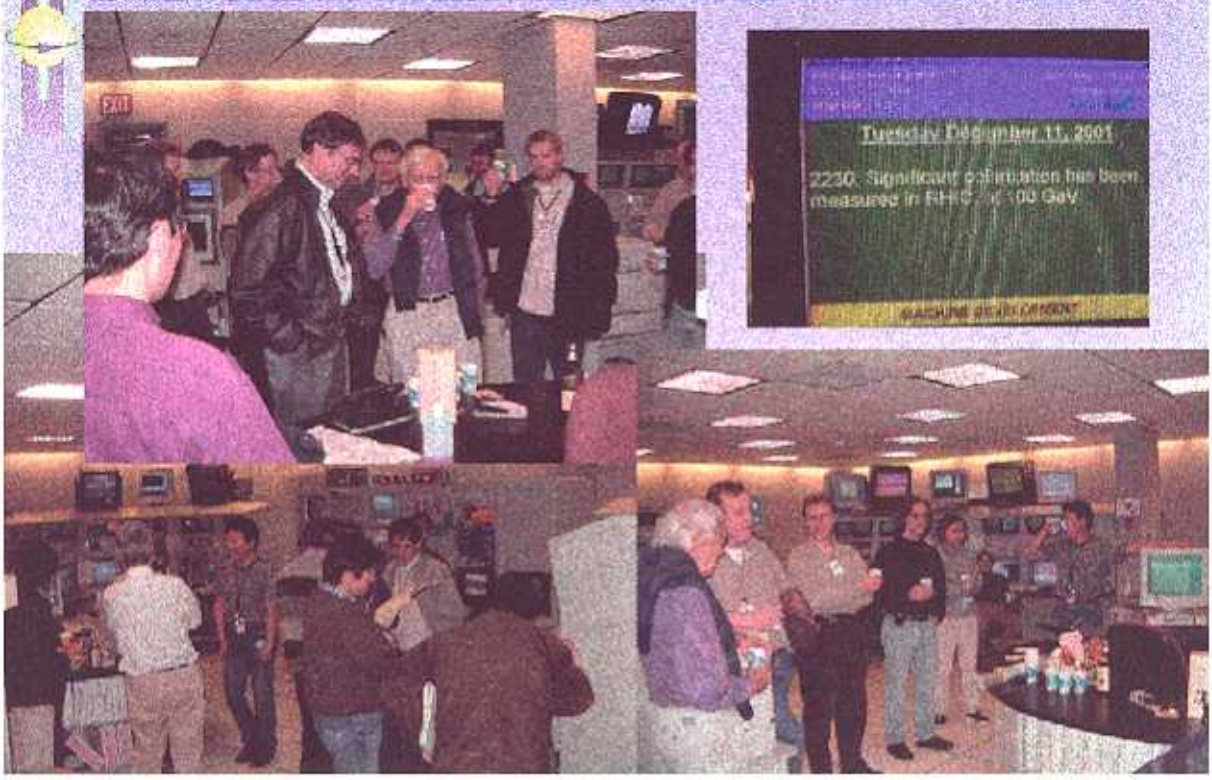
Naohito Saito

RIKEN / RIKEN BNL Research Center

## The First Polarized pp Collider



# RHIC Spin Excitement 12/11/01



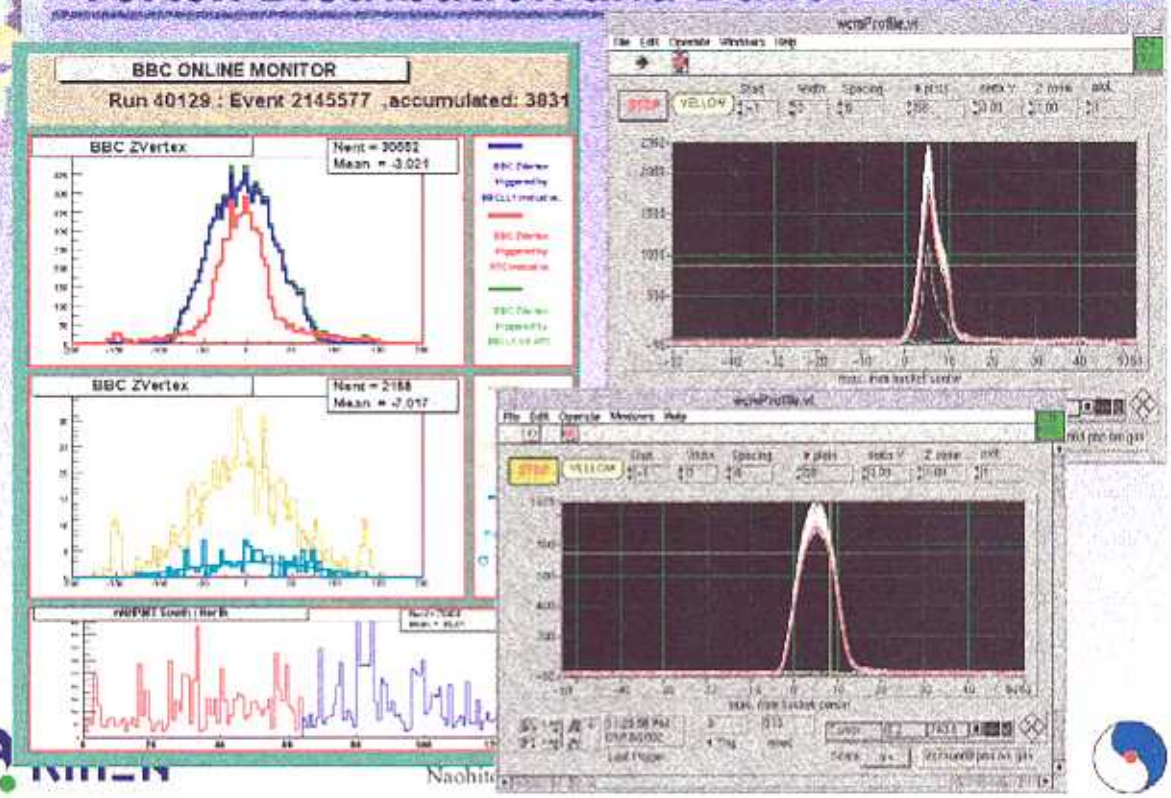

# RHIC Spin Retreat

- Questions on Run-2 Performance and Run-3 Plan → Gerry

*In Addition, I would add:*

- Usefulness of "Gerry's Meeting"
  - Timely discussion for re-focusing efforts towards most optimal working plan
  - Coherent view among all experiments and all machinists
- Better communication with MCR
  - Polarization Measurement
  - Steering
  - Cog / Re-cog / Spin Flip
  - Scraping
  - Dump
  - Spin Pattern Change
  - Experimental Magnet Control
  - Shift-to-Shift Information transfer among MCR shift crews

# Vertex Distribution and Bunch Profile




# RHIC Spin Retreat (continued)

- Better Performance and Reproducibility
  - Diagnosis at each step:
    - Source -> 200 MeV -> Booster -> AGS Injection -> AGS extraction -> RHIC Injection -> RHIC flat top
  - Understand systematics of monitoring system
    - Redundant measurements
      - Multiple measurements at RHIC ( cf. Emittance growth ?)
      - E880 vs new AGS Polarimeter
      - RHIC CNI Polarimeter and possible Local Polarimeters
- Commissioning of New Devices and re-commissioning of "OLD" Devices
  - Spin Rotators
    - highly coupled with Local Polarimeters
  - Snakes / Spin Flipper / Polarimeter
  - Source → Linac → Booster → AGS → AtR

# RHIC Spin Retreat (continued)

- Roadmap towards Full-Fledged RHIC Spin Operation
  - Absolute Polarization Calibration
    - Pol-J target
    - Better calibration at injection energy
    - Down ramp
  - Develop Robust Operation Phase space
    - Source → Linac → Booster → AGS → RHIC
    - Any additional device to achieve this goal?
      - "Strong" AGS Partial Snake
- How can we arrange these developments with minimal interference with Spin and HI PHYSICS program ?

RIKEN

Naohito Saito (RIKEN/ RBRC)

# Agenda (hope still visible...)

| Opening Session - March 5 (morning) | | |
|---|---|---|
| 8:30-10:10 | | |
| Welcome: | F.Pilat | 5 |
| Opening address: | D.Lowenstein | 15 |
| Physics goals for the the next run: | S.Aronson | 40 |
| Machine goals for the next run: | T.Roser | 40 |
| 10:10-10:40 | coffee break | |
| 10:40-12:00 | | |
| The injectors: | L.Ahrens | 20 |
| The gold run: | D.Trbojevic | 20 |
| The proton run: | W.MacKay | 20 |
| Retreat organization: | F.Pilat | 20 |

| Machine Reliability - March 6 (morning) | | |
|---|---|---|
| 8:30-10:10 | | |
| Overview and some definitions: | M. Brennan | 20 |
| Reliability of Tune/Chromaticity/Orbit: | I. Lobachevsky | 20 |
| Reliability of Schedule: | A. Drees | 20 |
| Correlations in FY01 statistics: | P. Ingrassia | 40 |
| 10:10-10:40 | coffee break | |
| 10:40-12:00 | | |
| Summaries of systems hardware plans: | | |
| -RF | M. Brennan | 10 |
| -Power supplies | D. Bruno | 10 |
| -Cryo | A. Nicoletti | 10 |
| -Quench detection | G. Ganetis | 10 |
| -Controls | S. Carter | 10 |
| -Vacuum | H.C. Hasch | 10 |
| Reliability of Machine Physics: | S. Peggs | 20 |

| Machine Experiments and Diagnostics - March 7 AM | | |
|---|---|---|
| 8:30-10:00 | | |
| Tune and Chromaticity: | F. Damerin | 20 |
| LHC Chromaticity Control: | H. Schmickler | 15 |
| E-detectors, IPMs, and Trans. Emittance: | R. Connolly | 15 |
| Longitudinal Dampers: | M. Brennan | 10 |
| Transverse Coherence Monitor: | M. Brennan | 5 |
| Beta-tectors, IPMs, and Trans. emittance: | R. Connolly | 20 |
| Transverse Dampers: | A. Drees | 10 |
| 10:00-10:30 | coffee break | |
| 10:30-12:00 | | |
| Benefits of Beam Experiments: | F. Pilat | 5 |
| Transition Crossing Studies: | C. Montag | 10 |
| Local Non-linear IR Correction: | V. Pitlyn | 15 |
| Transv. and Longit. Instabilities: | M. Blaskiewicz | 10 |
| Beam-beam Effects: | W. Fischer | 15 |
| Polarized Beam Manipulations: | M. Bai | 15 |
| Pressure rise: | G-Y Zhang | 20 |

| Machine Performance - March 5 (afternoon) | | |
|---|---|---|
| 14:00 - 15:30 | | |
| Linear lattice, optics matching: | T.Satogata | 15 |
| Coupling, working point: | F.Pilat | 15 |
| Chromaticity, snapback, transverse emittance: | S.Tepikian | 15 |
| beta squeeze, triplet correction/performance: | V.Pitlyn | 15 |
| 110 bunches, beam-beam/ramping, e-cloud: | W.Fischer | 15 |
| Au transition crossing, triplet vibration: | C.Montag | 15 |
| 15:30-16:00 | coffee break | |
| 16:00-17:30 | | |
| Impedances and instabilities, single-bunch imax: | M.Blaskiewicz | 20 |
| Backgrounds, collimation, gap cleaning: | A.Drees | 15 |
| Abort performance and issues: | L.Ahrens | 15 |
| AGS polarization efficiency/plans: | H.Huang | 15 |
| RHIC polarization transmission, issues: | V.Pitlyn | 15 |
| d/Au performance issues: | J.Van Zeijts | 15 |

| Machine Integration - March 6 (afternoon) | | |
|---|---|---|
| 14:00-15:30 | | |
| RHIC experiments integration: | A. Drees | 10 |
| Brahms: | F. Videbaek | 10 |
| Phenix: | A. Trautov | 10 |
| Phobos: | R. Pak | 10 |
| PP2PP: | W. Guryn | 10 |
| Star: | W. Christie | 10 |
| Spin Physics: | N.Saito | 10 |
| Polarimeter: | TBD | 10 |
| Discussion: | | 10 |
| 15:30-16:00 | coffe break | |
| 16:00-17:30 | | |
| RHIC and Injectors Integration: | J.Morris | 15 |
| Logger System: | R. Lee | 15 |
| Ramps at Battery: | J. van Zeijts | 10 |
| Cryogenics Integration: | A. Nicoletti | 10 |
| Quench tuning: | G.Ganetis | 10 |
| RF ramp integration: | M. Brennan | 15 |
| MCR operation: | G. Marr | 15 |

| Closing Session - March 7 (afternoon) | | |
|---|---|---|
| 14:00-16:00 | | |
| The RHIC e-cooling projects: | I.Ben-Zvi | 20 |
| The EIC project: | G.Peggs | 20 |
| RHIC: the CERN perspective: | H.Schmickler | 20 |
| RHIC: the FNAL perspective: | M.Syphers | 20 |
| Preliminary summary: | F.Pilat | 20 |

RHIC Spin Collaboration Meeting at Brookhaven

# SINGLE TRANSVERSE-SPIN ASYMMETRIES

# $A_N$ AT RHIC

Jianwei Qiu *

Iowa State University

February 22, 2002

## Table of Contents:

1. Introduction

2. $A_N$ for single hadron production

3. $A_N$ for direct photon

4. $A_N$ for Drell-Yan massive dilepton

5. Summary and outlook

* 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 $\pi$, $p$, $\gamma$, 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:

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

  - Parity and time-reversal invariance:

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

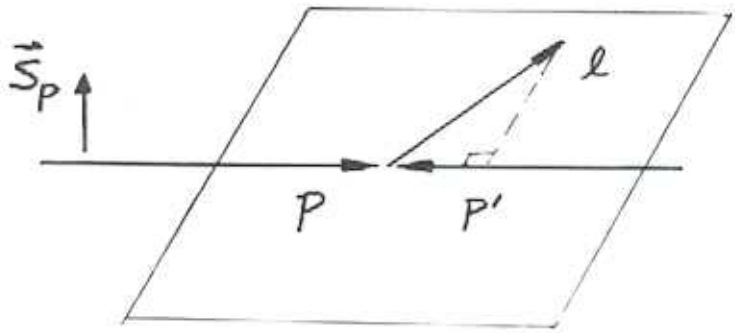
  $\Rightarrow\ W_{\mu\nu}(\vec{s}_T) = W_{\nu\mu}(-\vec{s}_T)$

  - Spin-dependent X-section:

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

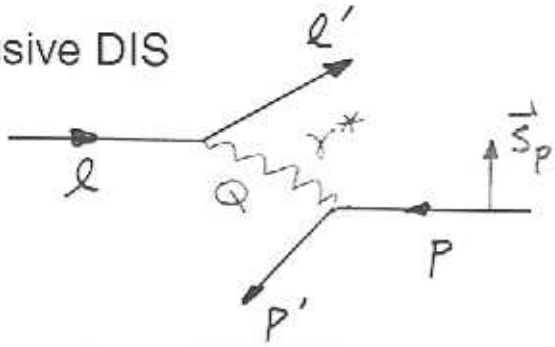
    because $L^{\mu\nu}$ is symmetric for a unpolarized lepton
  - Above result is valid for any two-current correlators
- Parity conserved interactions $\Rightarrow A_L = 0$

- 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: $A_N \propto i\epsilon^{\mu\nu\alpha\beta}\, p_\mu s_\nu \ell_\alpha p'_\beta$



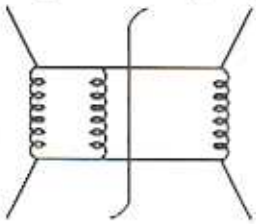

- Nonvanishing $A_N$ requires a phase, a spin flip, and enough vectors to fix a scattering plan
  - Inclusive DIS does not have enough vectors
    Note: $q$ and $p$ can only fix a line

- Following examples can generate nonvanishing $A_N$:
  - Single hadron (or photon) at high $\ell_T$
  - Drell-Yan lepton angular distribution
  - Semi-inclusive DIS
  - ...



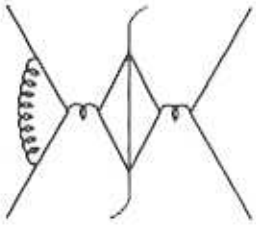
## 2. $A_N$ FOR SINGLE HADRON PRODUCTION

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



+ c.c.

  - imaginary part of the loop provides the phase
  - quark mass provides the needed spin flip



+ c.c.

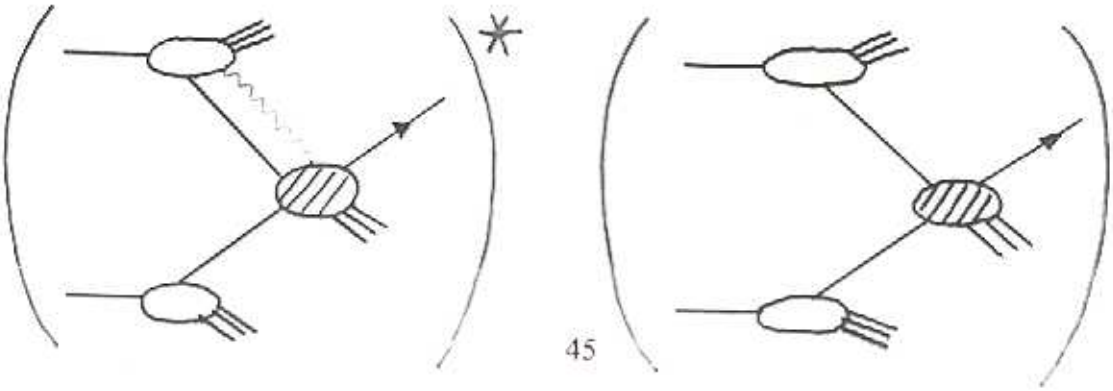
  - $A_N \propto \frac{m_q}{\ell_T} \langle p, \vec{s}_T | \bar{\psi} \Gamma \psi | p, \vec{s}_T \rangle$ where $\Gamma = \gamma^+ \gamma_5 \gamma_T, \ldots$

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

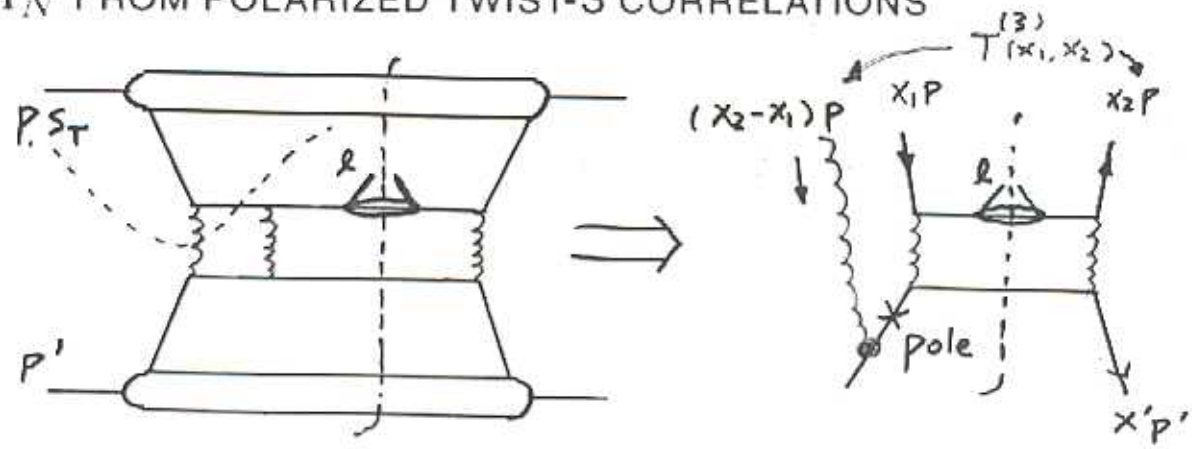
- QCD dynamics is much richer than the parton model
  - twist-3 arises from "intrinsic" $k_T$

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

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



## $A_N$ 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

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

- $A_N \neq 0$ 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

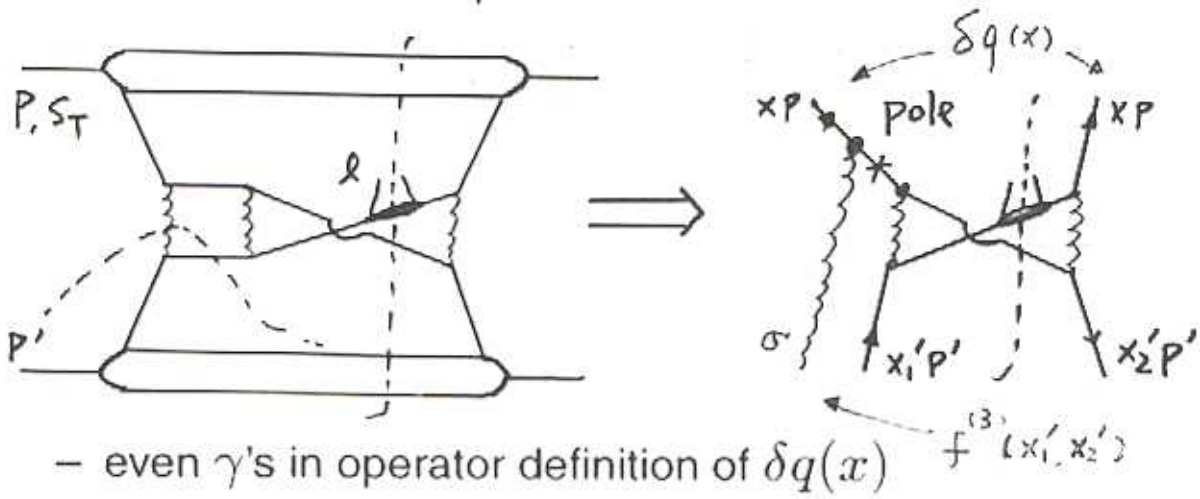
  $\Rightarrow A_N \propto T_F(x_1, x_2)$ with $x_1 = x_2$, and

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

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

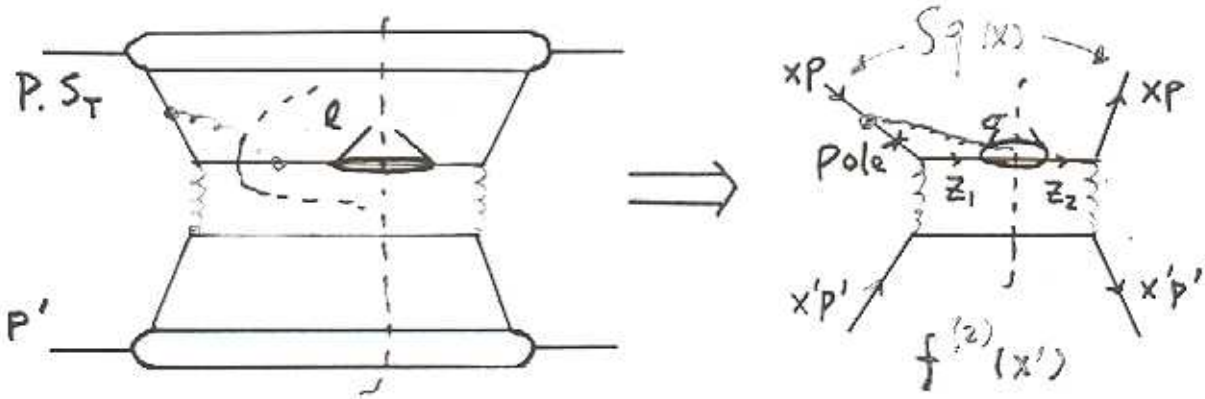
## $A_N$ FROM TWIST-2 TRANSVERSITY DISTRIBUTION

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




  - even $\gamma$'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

## FACTORIZABLE SINGLE TRANSVERSE-SPIN ASYMMETRIES

- Generalized factorization formula for hadronic single transverse-spin asymmetries

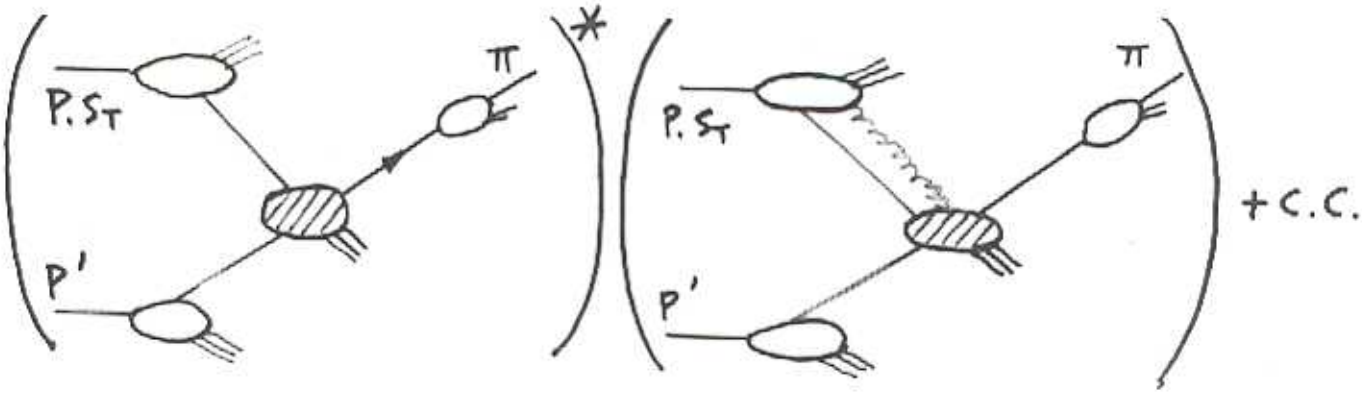
$$\Delta\sigma_{AB\to h}(\vec{s}_T) = \sum_{abc} T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x') \otimes \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z)$$
$$+ \sum_{abc} \delta q^{(2)}_{a/A}(x, \vec{s}_T) \otimes \Big\{ f_{b/B}(x') \otimes \hat{\sigma}'_{ab\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to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

- $\hat{\sigma}$, $\hat{\sigma}'$, 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):

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



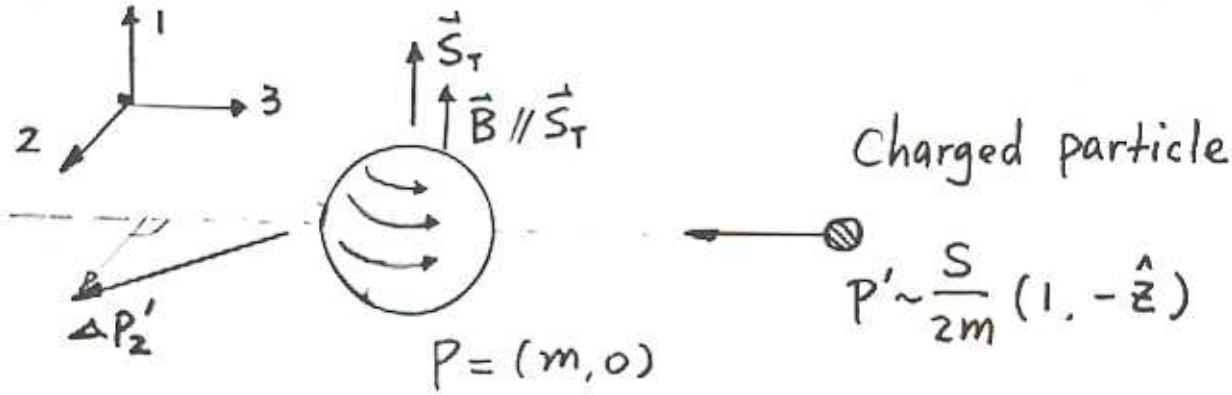

- Keep only quark fragmentation
  - observed momentum: $\ell_T^2 \propto xx'z^2S$
  - parton distributions are steeply falling as $x \to 1$
    e.g., $f_q(x) \propto (1-x)^\alpha$ with $\alpha > 3-4$
  - quark fragmentation function falls slower as $z \to 1$
    e.g., $D_{q\to\pi}(z) \propto (1-z)^{n_q}$ with $n_q \sim 2$
    $\Rightarrow$
    X-section is dominated by small $x \sim x'$ and large $z$
- Need gluon fragmentation contribution at low $\ell_T$ 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

$$\frac{d}{dt} p_2' = e(\vec{v}' \times \vec{B})_2 = -e v_3 B_1 = e v_3 F_{23}$$

  - in the c.m. frame

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

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

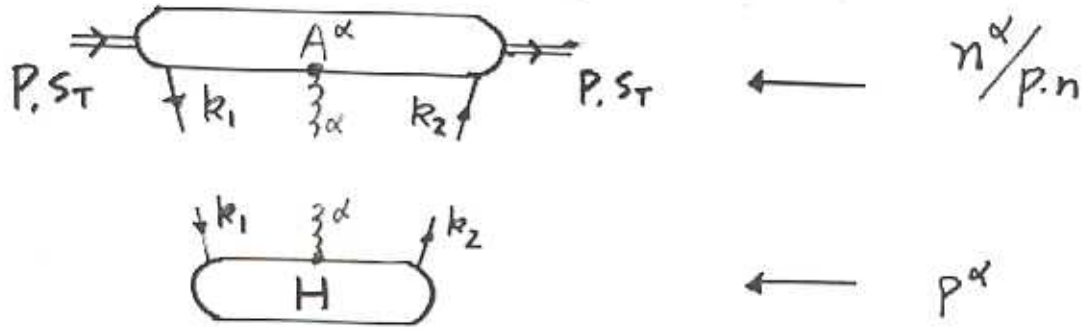
  - total change: $\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^+(y^-)$

- 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



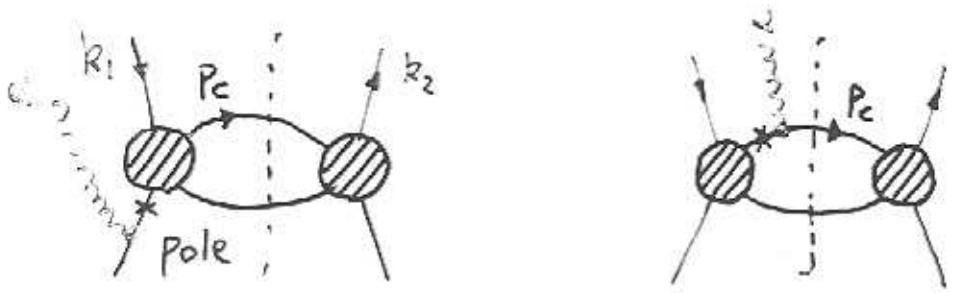

- gluon field: $A^\alpha \to n \cdot A = A^+$
- expand $H(k_1, k_2)$ to linear in $k_T$

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

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

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

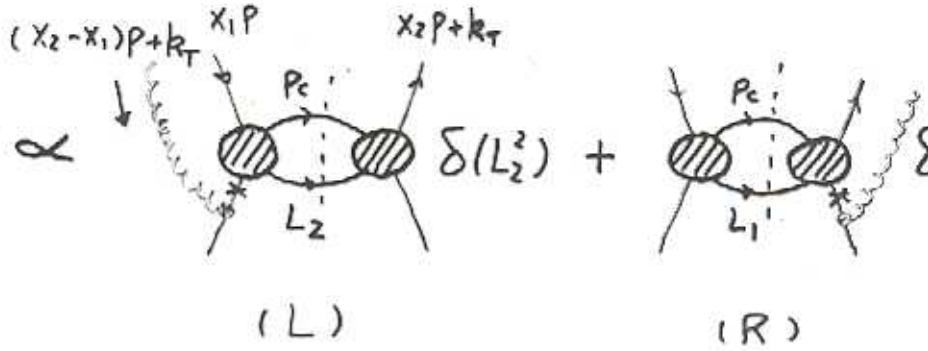
- either $x_1$ or $x_2$ is fixed by the pole in partonic part.




Initial-state Final-State

## CONTRIBUTION FROM INITIAL-STATE INTERACTION

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



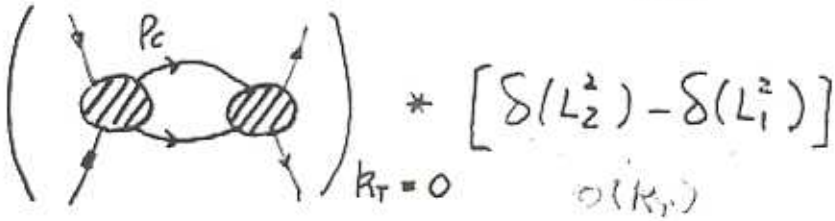

- Soft-gluon pole gives the needed phase:

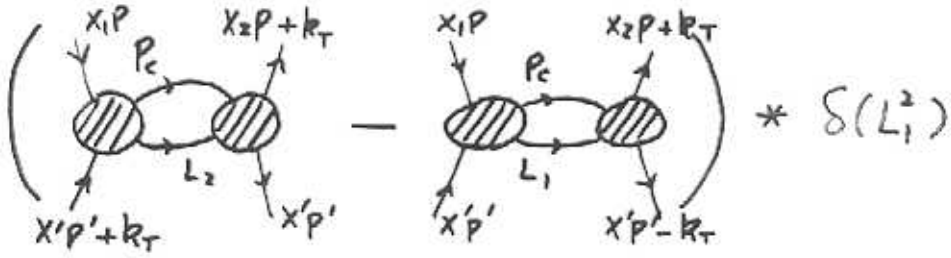
$$\frac{1}{x_2 - x_1 + i\epsilon} \to -i\pi\delta(x_2 - x_1)$$

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

$L_2 = x_2 p + x' p' - p_c + k_T$

$L_1 = x_1 p + x' p' - p_c$




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

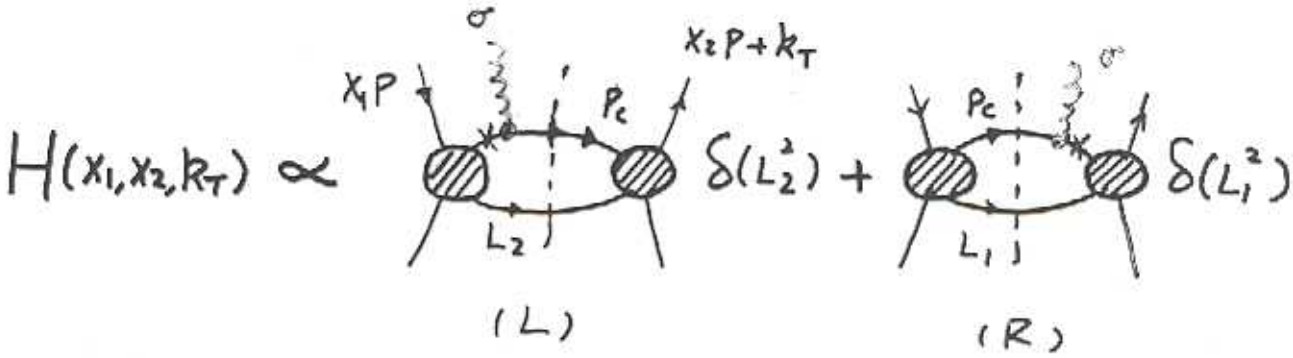
    $\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x\frac{d}{dx}T_F(x,x)$

  - 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 $x \to 1$.

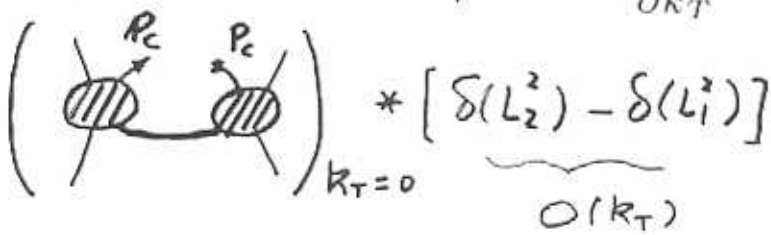
## CONTRIBUTION FROM FINAL-STATE INTERACTION

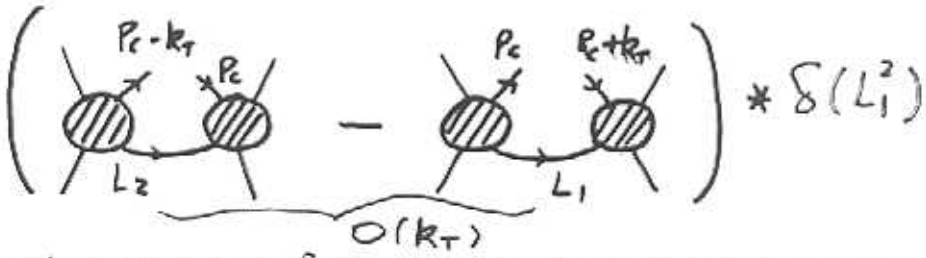



- Soft-gluon pole gives the needed phase:

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

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




  - phase space $\delta$-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 $\propto \ell_T/t \sim 1/\ell_T$

  $\Rightarrow A_N$ does not fall as fast as $1/\ell_T$ as $\ell_T$ 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

I-S 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 $T_F(x,x)$:

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

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

- Twist-2 quark distribution:

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

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

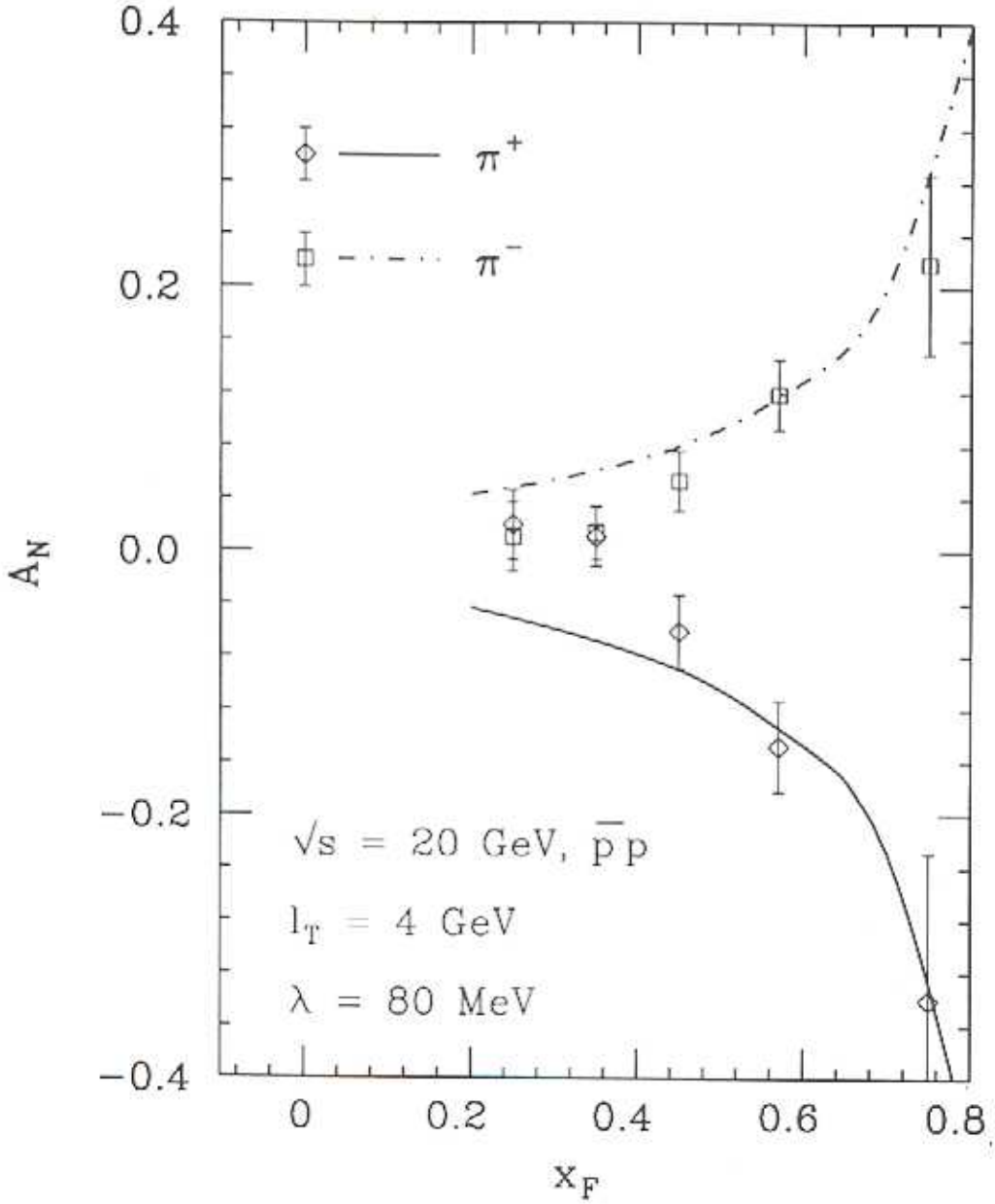
$$T_{F_a}(x,x) \equiv \kappa_a \, \lambda \, q_a(x)$$

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

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

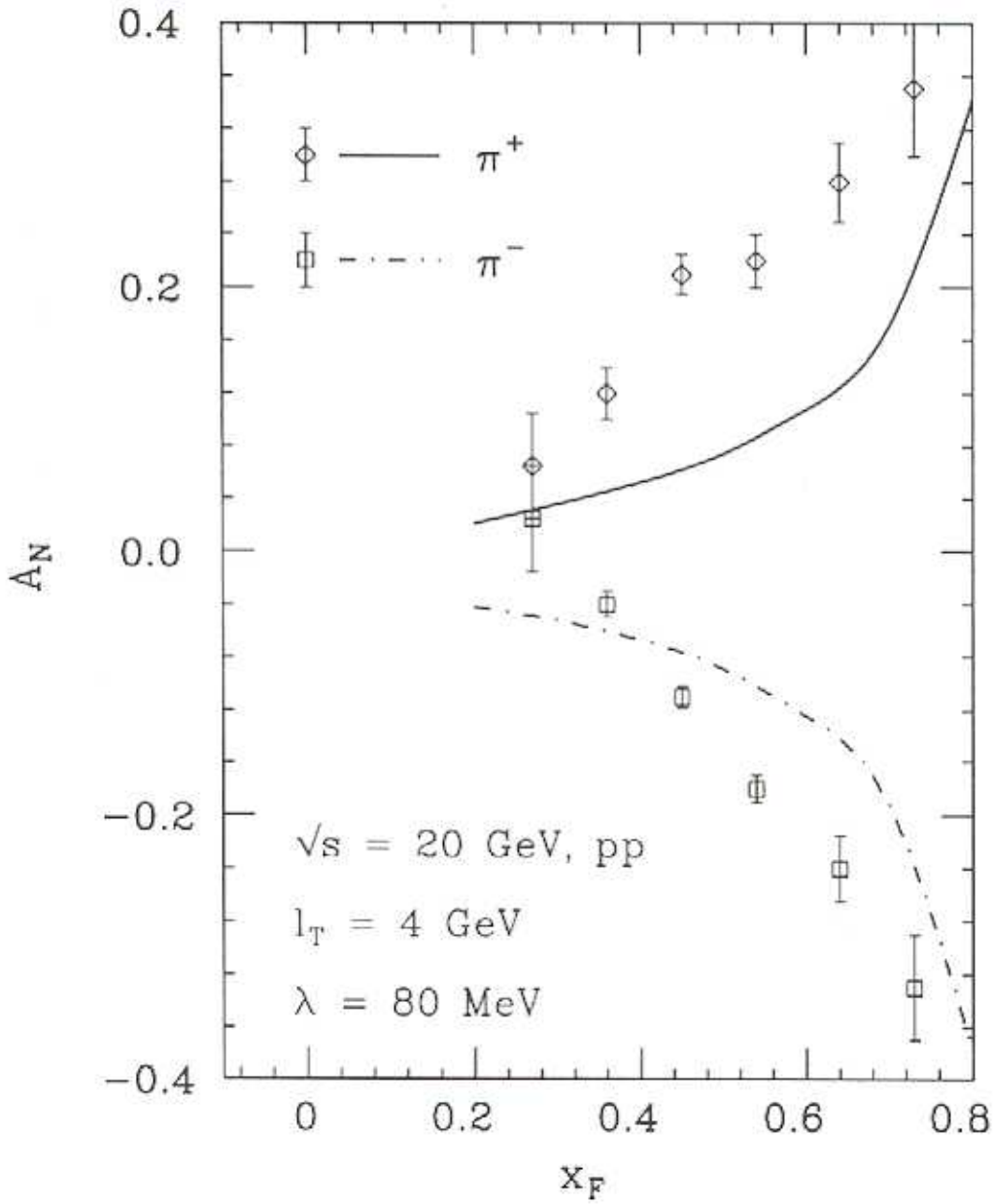
- Predictive power of the factorization approach:
  - extract $T_F(x,x)$ from one observable, say $\pi^+$ or $\pi^-$
  - use it to predict other observable, say $\pi^0$
  - $(\partial/\partial x)T_F(x,x)$ leads to enhancement of the asymmetries in forward region
  - same partonic parts can be used for 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 $\ell_T$ up to 1.5 GeV

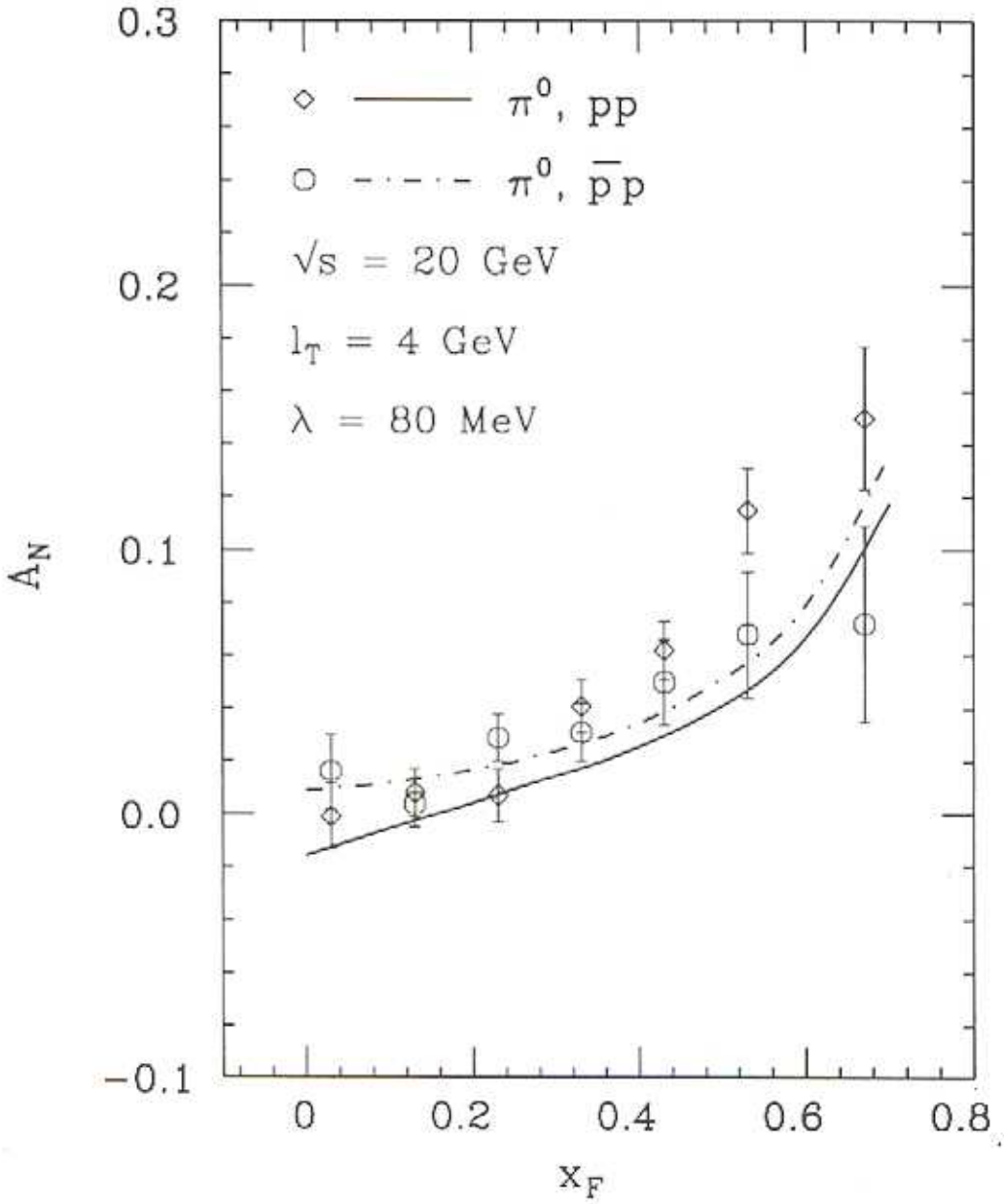
## COMPARE AN APPLE WITH AN ORANGE (II)




Fermilab data with $\ell_T$ up to 1.5 GeV

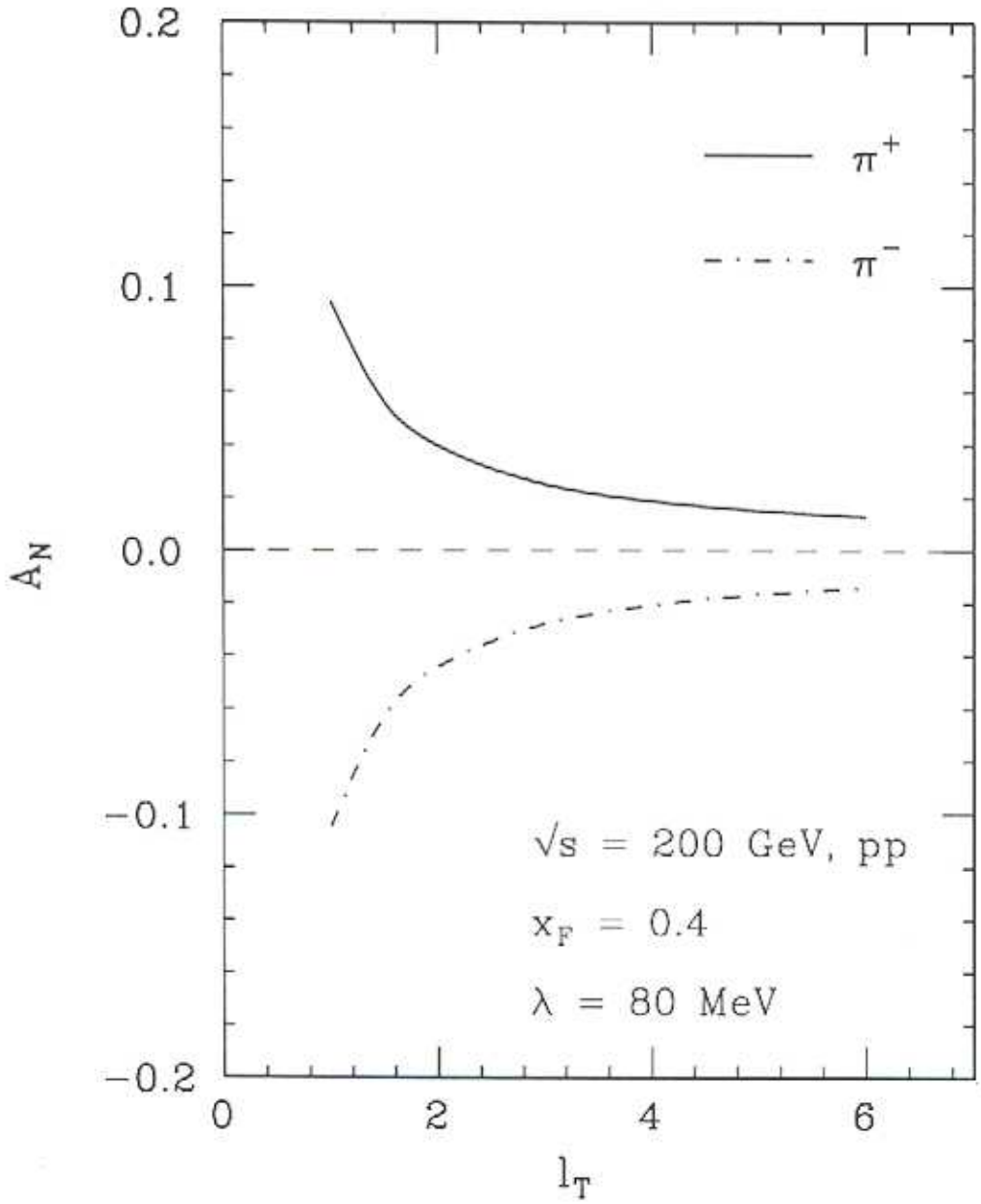
Theory curves fit data better if evaluated at a lower $\ell_T$

# COMPARE AN APPLE WITH AN ORANGE (III)




Fermilab data with $\ell_T$ up to 1.5 GeV

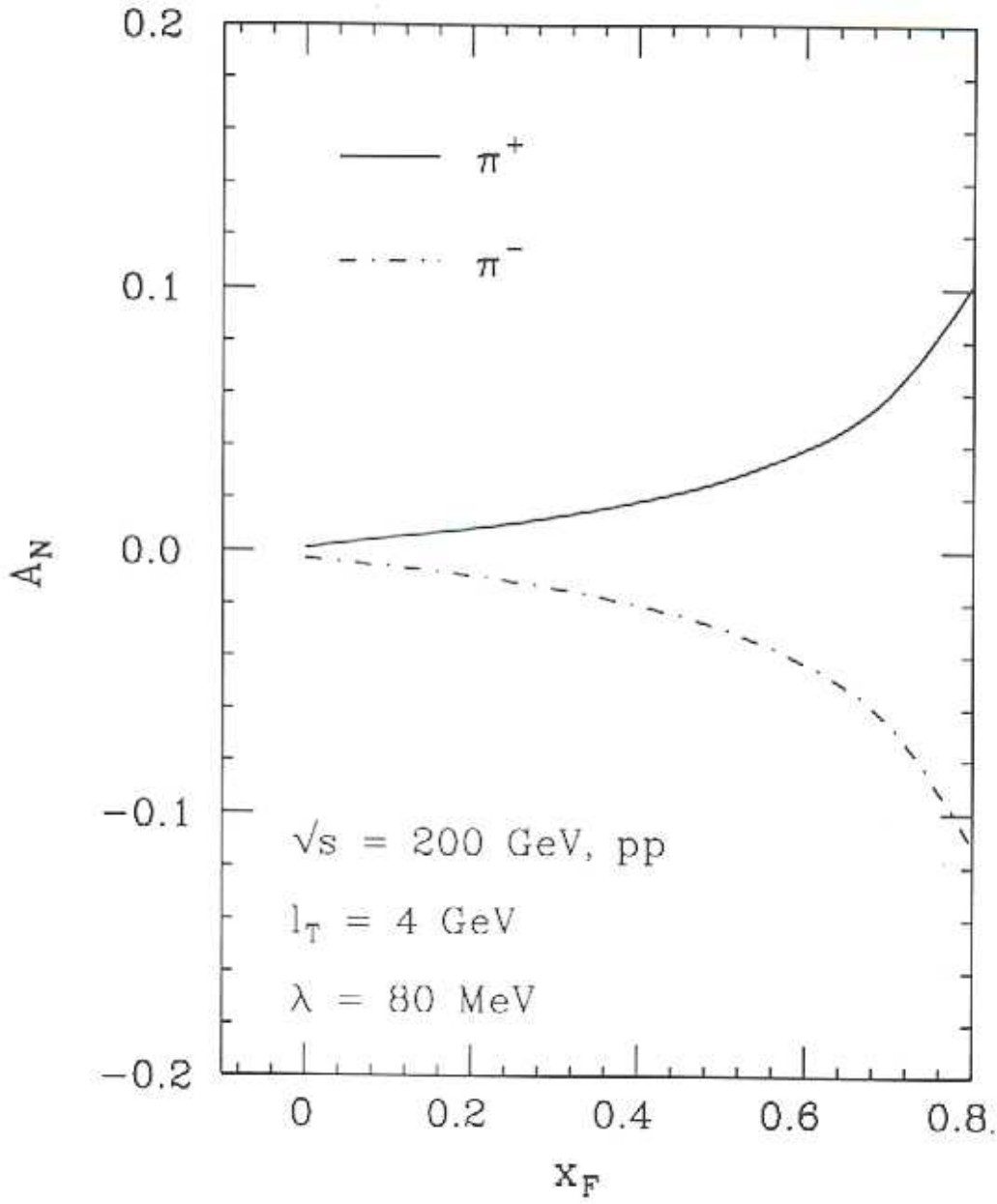
# $A_N$ AT RHIC ENERGY (I)




Derivative term only for partonic hard part

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

# $A_N$ AT RHIC ENERGY (II)



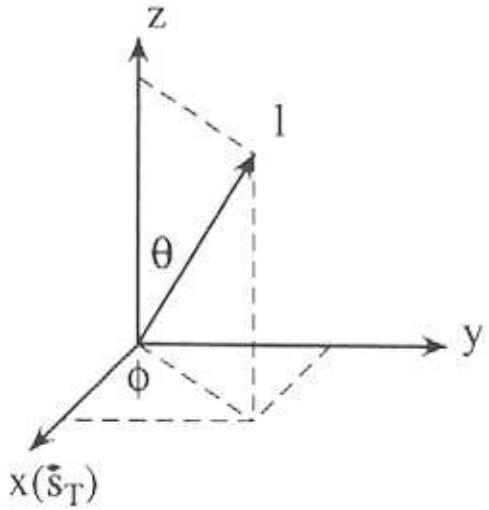

Derivative term only for partonic hard part

## 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