Understanding Single Spin Asymmetry in QCD

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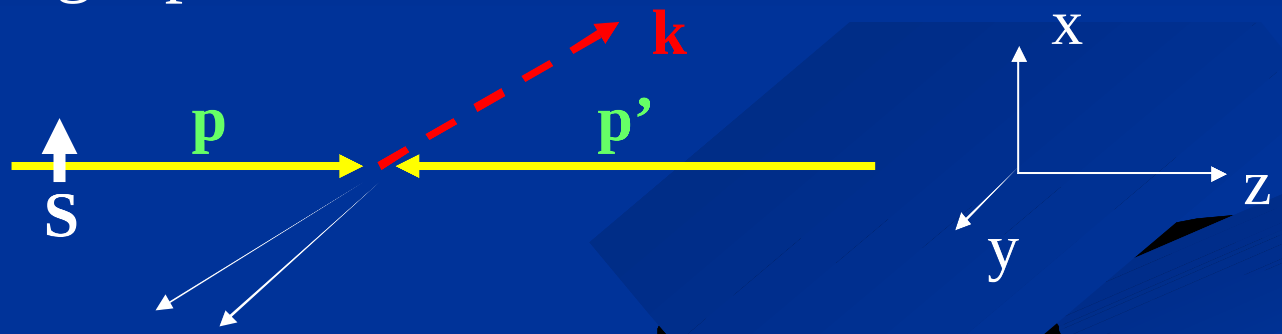
Outline

- Introduction: what is SSA?
- Why naïve parton model fails
- Quark-gluon correlation and Qiu-Sterman mechanism
- Sivers function and SSA in SIDIS
- Sivers function at RHIC
- What we learn from SSA?
- Summary

What is Single Spin Asymmetry?

- Consider scattering of a transversely-polarized spin-1/2 hadron (S, p) with another hadron, observing a particle of momentum k



The cross section can have a term depending on the azimuthal angle of **k**

$$ds \sim \vec{S}\cdot(\vec{p}\times\vec{k})$$

which produce an asymmetry A_N when **S** flips: **SSA**

Sample Exp. Data

- A. Bravar et al., E704, PRL77, 2626 (1996)

$$\bar{p}_{\uparrow} p \longrightarrow \pi + X$$

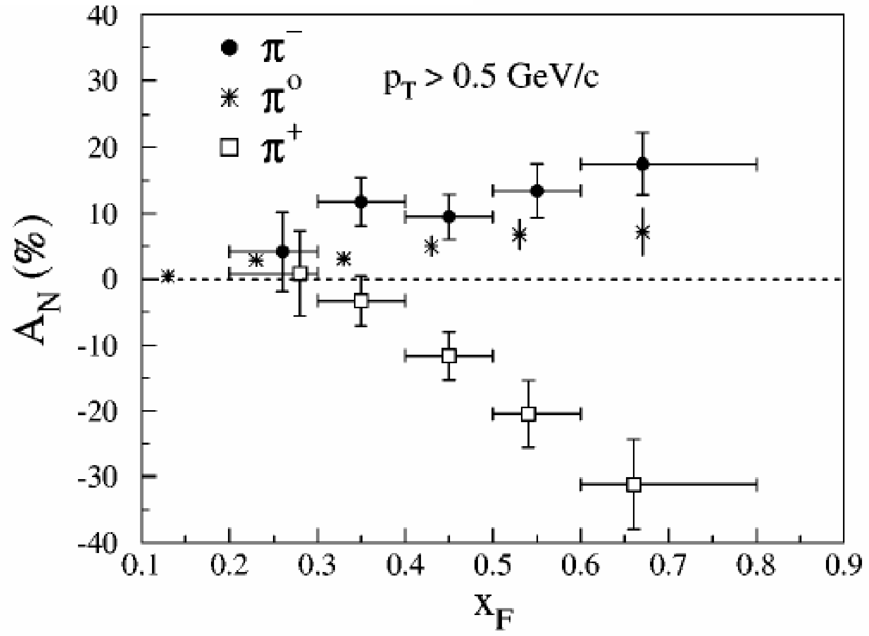
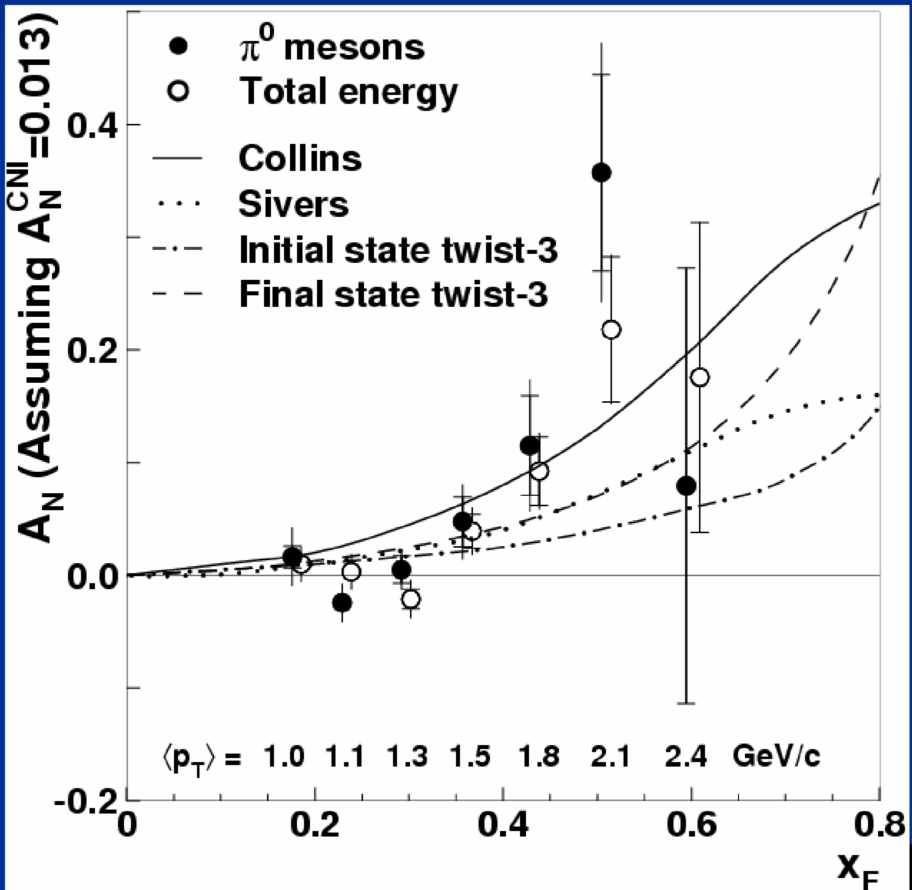
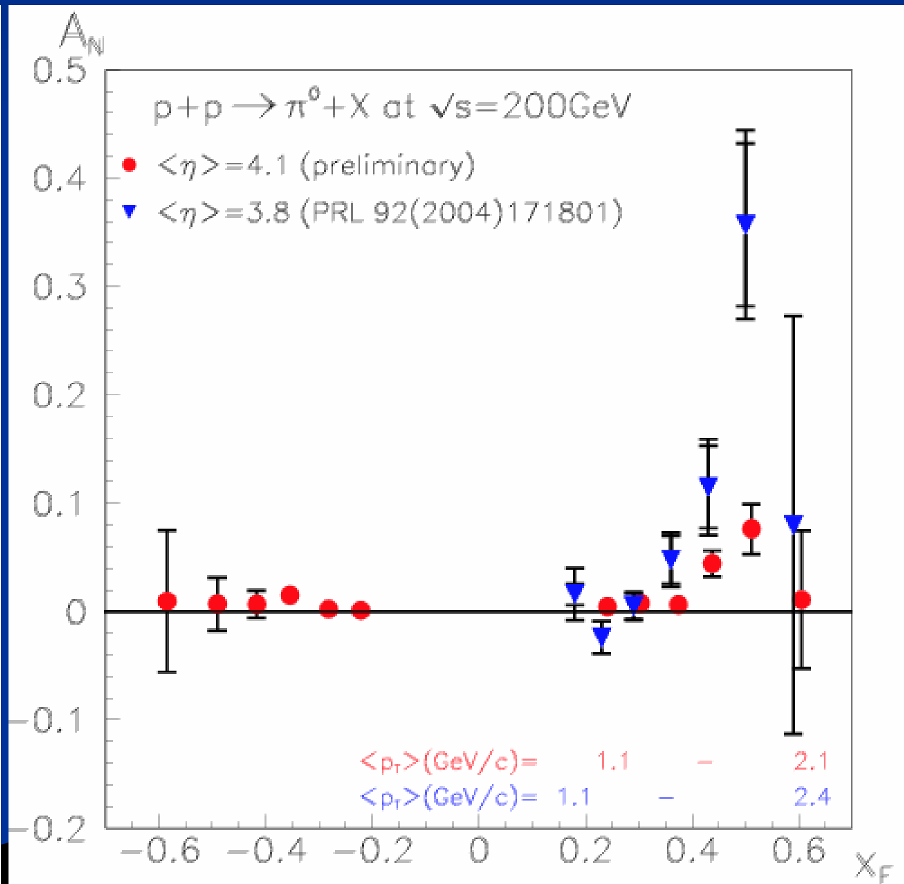


FIG. 3. A_N data as a function of x_F for π^- and π^+ for $p_T \geq 0.5$ GeV/c. A_N data for π^0 in a similar p_T range are also shown [5]. The first π^- and π^+ data points are offset by -0.01 and $+0.01$ x_F units, respectively.

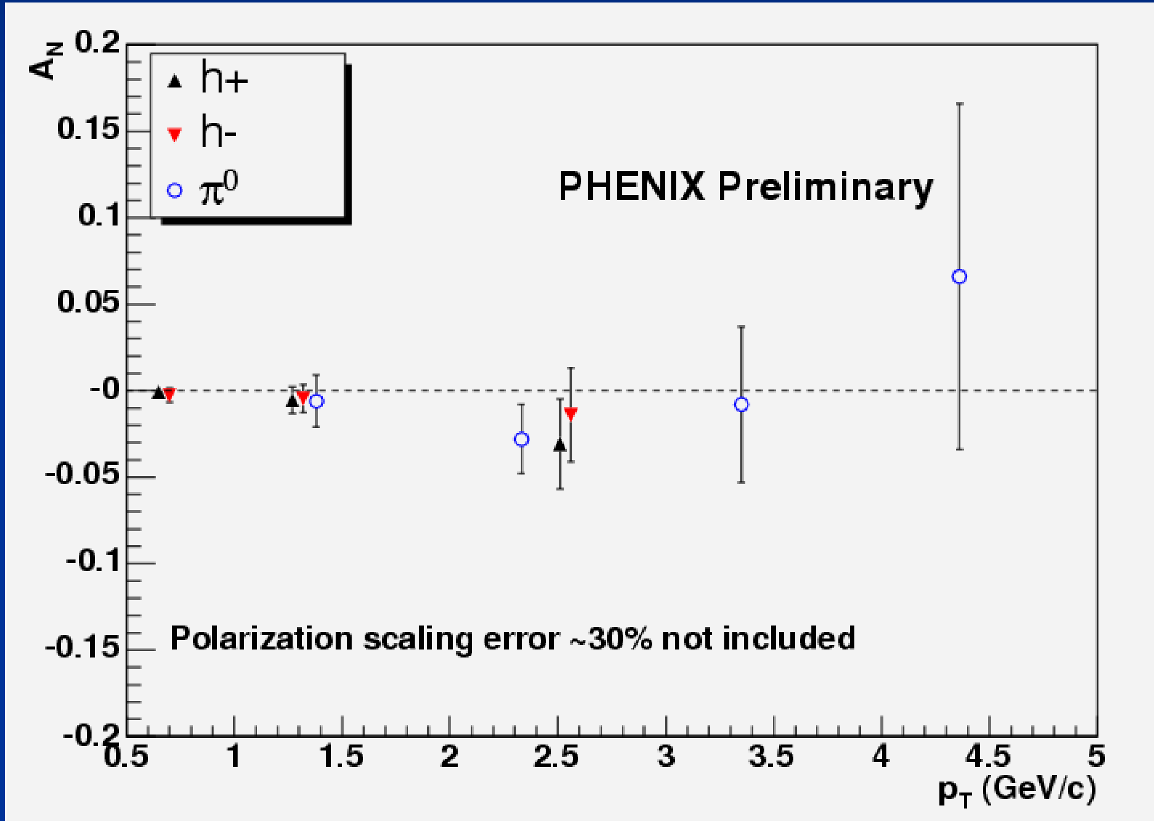
SSA at RHIC

STAR Collaboration, Phys.Rev.Lett.92:171801,2004; hep-ex/0412035



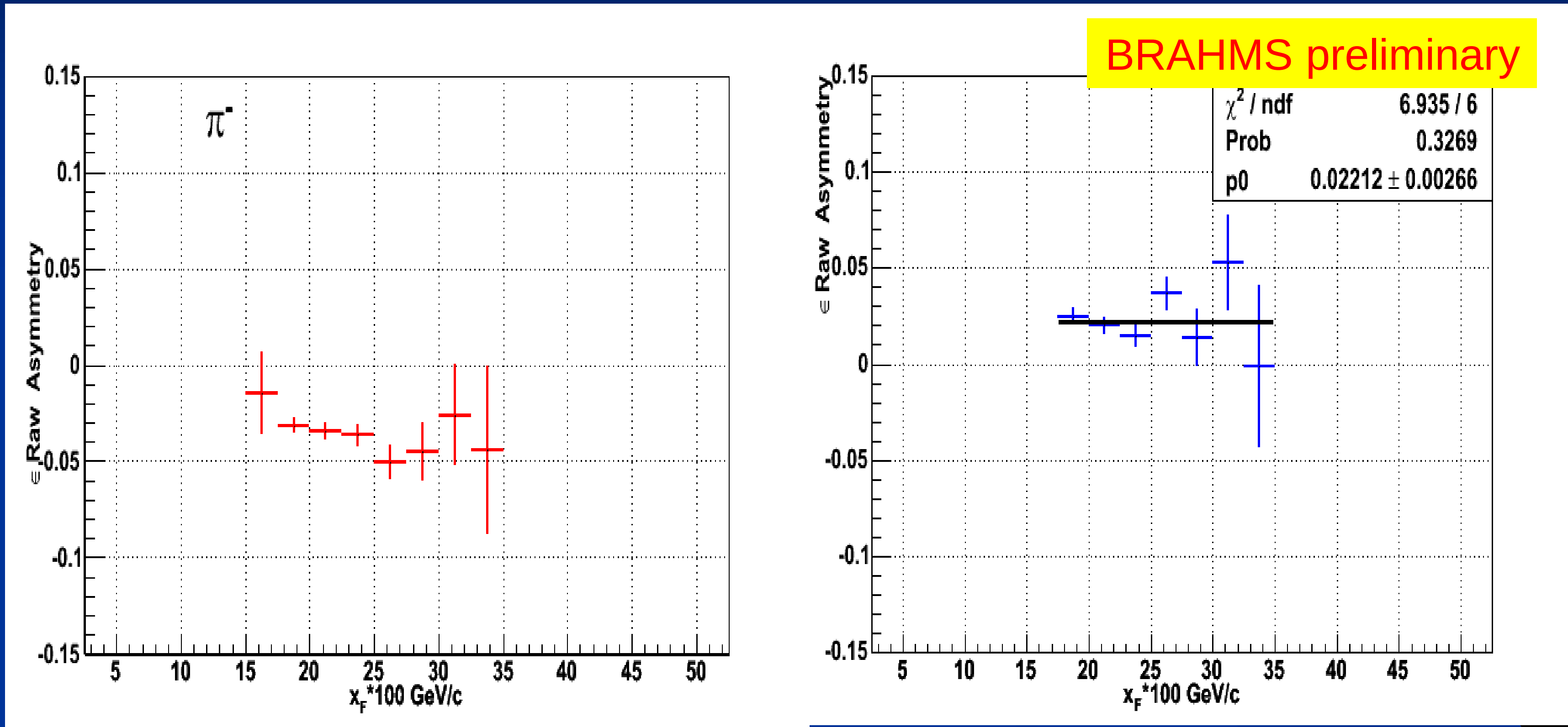


PHENIX Collaboration, hep-ex/0410003



Central rapidity!!

BRAHMS Collaboration, talk by Videbaek



<e>~ -0.035 => AN = -0.08 +- 0.005 +- [0.015] in 0.17 < xF < 0.32

<e>~ +0.022 => AN = +0.05 +- 0.005 +- [0.015] in 0.17 < xF < 0.32

Big SSA!

- Systematics
  - A_N is significant in the fragmentation region of the polarized beam
  - A_N and its sign show a strong dependence on the type of polarized beam and produced particles
- A related phenomenon: the transverse polarization of spin-1/2 particle in unpolarized hadron scattering.
  - G. Bunce et. al, PRL36, 1113 (1976).

Why Does SSA Exist?

- **Single Spin Asymmetry is proportional to**

  Im (M_N * M_F)

  where M_N is the normal helicity amplitude

  and M_F is a spin flip amplitude

  - **Helicity flip**: one must have a reaction mechanism for the hadron to change its helicity (in a cut diagram)
  - **Final State Interactions (FSI):** to generate a phase difference between two amplitudes

  The phase difference is needed because the structure

  $S \cdot (p \times k)$ formally violate time-reversal invariance

Naïve Parton Model Fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, PRL41, 1978)
  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass m_q
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to a_S

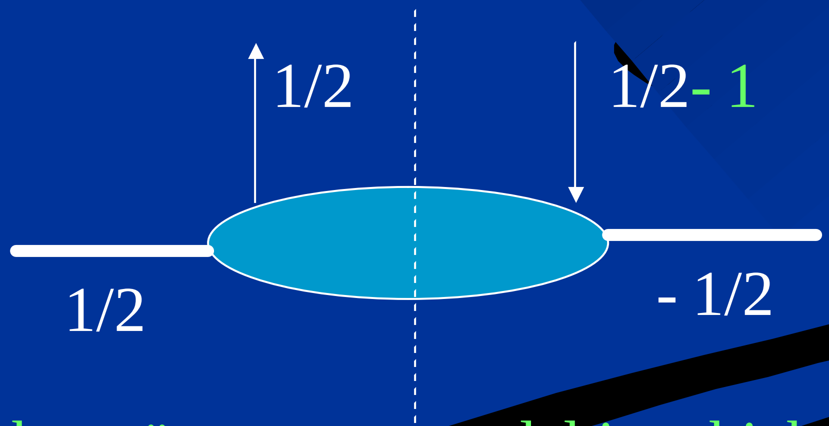
Therefore a generic pQCD prediction goes like

$A_N \sim a_S\, m_q / Q$ less than 0.1 per cent

Every factor suppresses the SSA!

Parton Orbital Angular Momentum and Gluon Spin

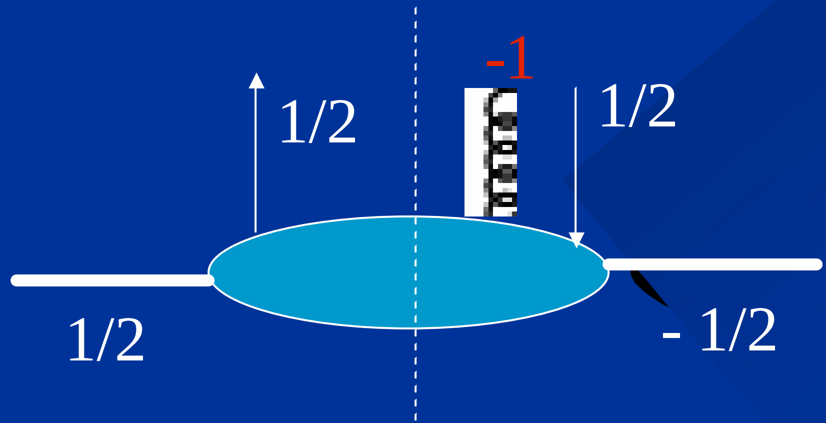
- The hadron helicity flip can be generated by other mechanism in QCD
  - Quark orbital angular momentum (OAM): Therefore, the hadron helicity flip can occur without requiring the quark helicity flip.



Beyond the naïve parton model in which quarks are collinear

Parton OAM and Gluons (cont.)

- A collinear gluon carries one unit of angular momentum because of its spin. Therefore, one can have a coherent gluon interaction



Quark-gluon quark correlation function!

What are the consequences?

- The correlations effect replaces the current quark mass by a typical QCD scale $?_{QCD}$

$$A_N \sim a_s \, ?_{QCD}/Q$$

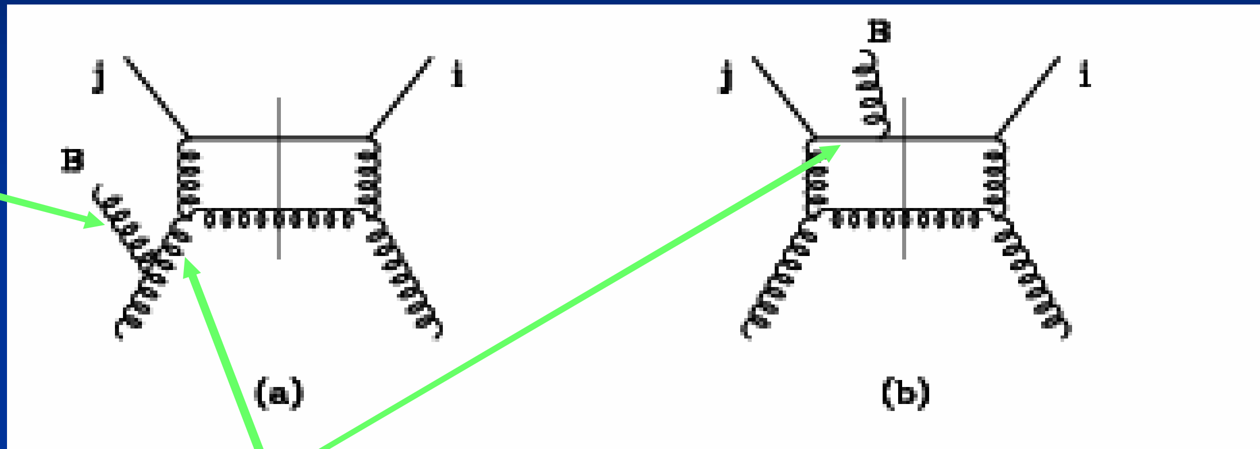
which now has a size at percent level.

- How to generate phase?
  - Perturbative QCD loops
  - A new possibility: *through the tree diagrams*. Scattering of initial and final state partons in the Coulomb field of the polarized nucleon.

$A_N \sim \; ?_{QCD}/Q$: tens of percent level!

Novel Way to Generate Phase

Coulomb gluon



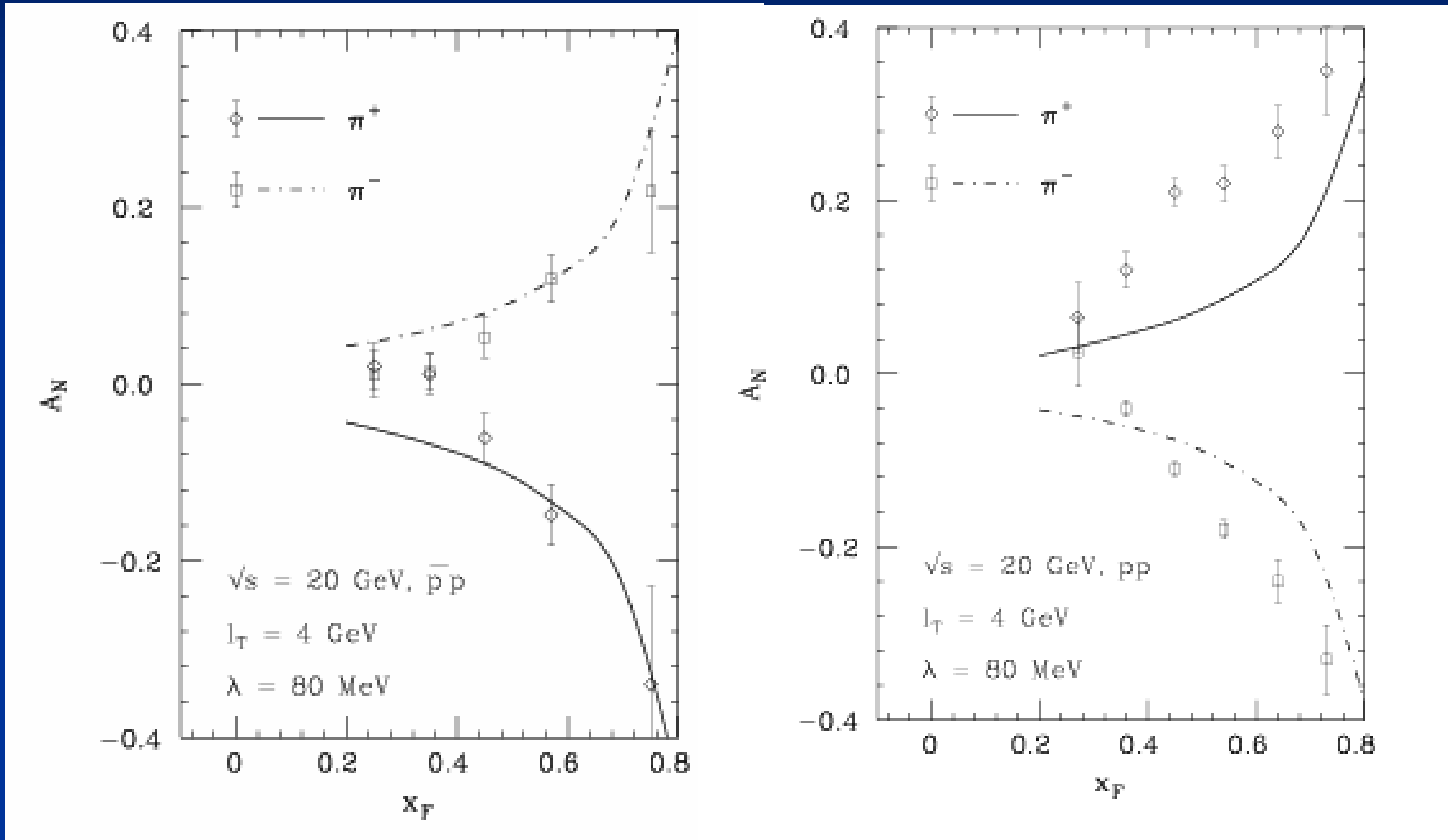
Some propagators in the tree diagrams go on-shell

$$\frac{1}{k^2 - m^2 + i\epsilon} = \mathcal{P}\frac{1}{k^2 - m^2} - i\pi\delta(k^2 - m^2)$$

No loop is needed to generate the phase!

Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

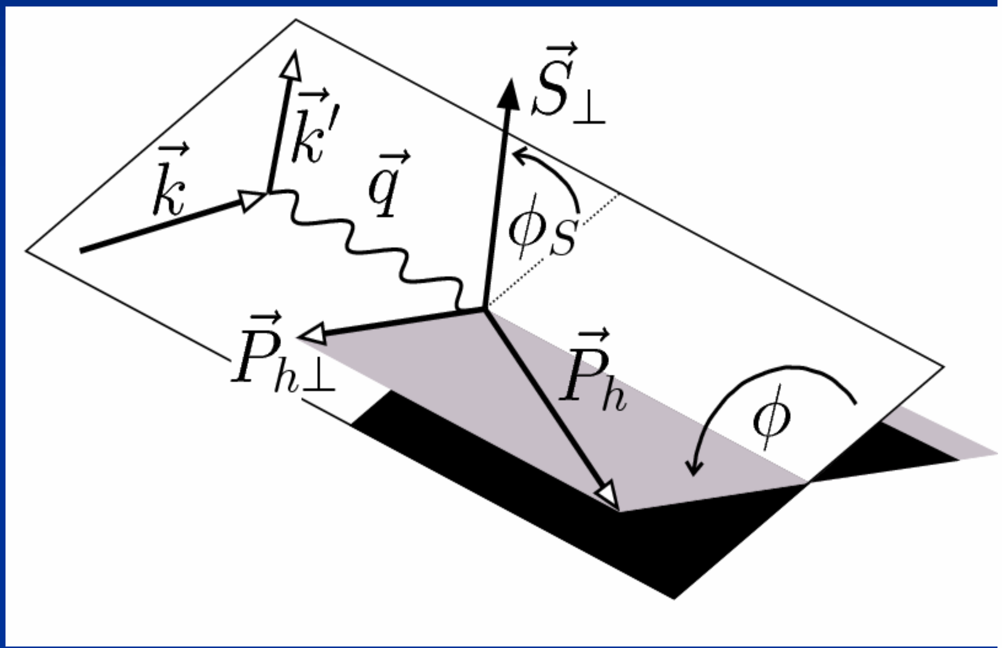
Comparison With Data

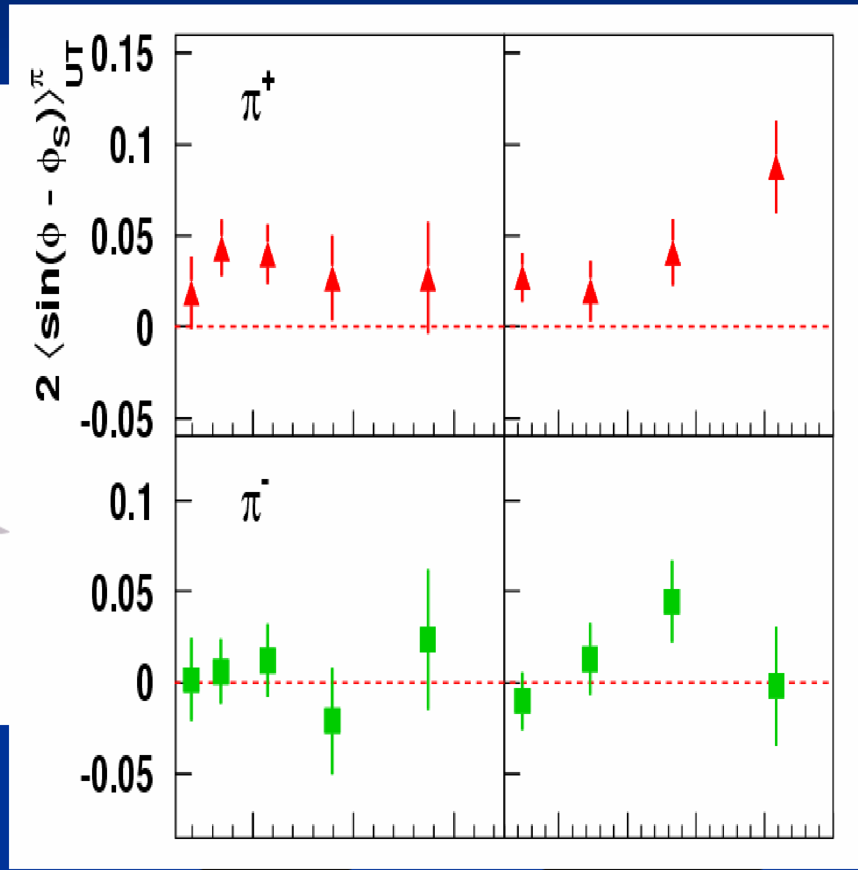


Qiu & Sterman, PRD59, 014004 (1999)

SSA In Semi-inclusive Deep Inelastic Scattering

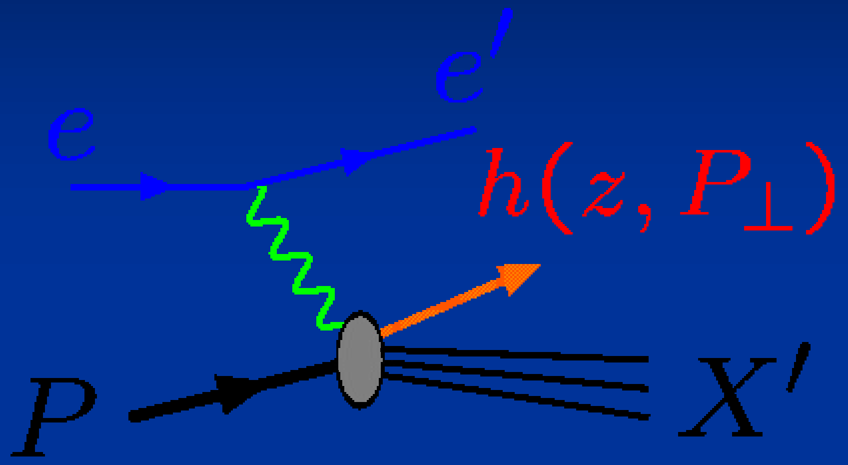
In Deep Inelastic Scattering, HERMES, A. Airapetian *et al.*, hep-ex/0408013,





$\langle Q^2 \rangle = 2.41 GeV^2$, $\langle P_? \rangle = 0.41 GeV$
$0.023<x<0.4$, $0.2<z<0.7$

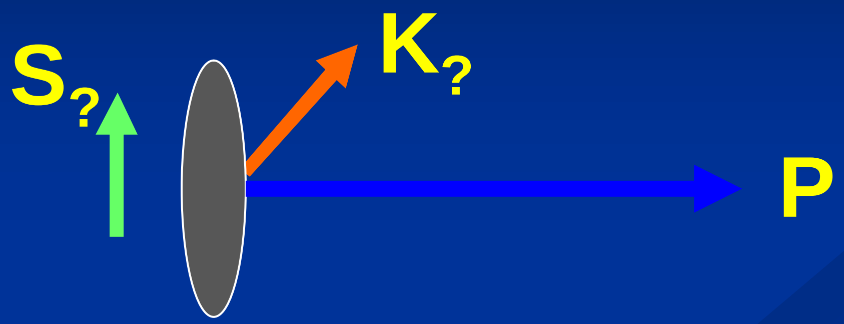
Semi-inclusive DIS



Semi-inclusive DIS:
Probe additional information including the transverse distribution

- **The Sivers function leads to SSA in order of 1 in the scaling (Bjorken) limit, i.e., twist-2 effect**
- **Transverse momentum could be small on the order of Λ_{QCD}, require new factorization theorem.**

What is Sivers function



$$q(x,k_\perp) = q_s(x,k_\perp) + \sin(\phi_k - \phi_s) q_t(x,k_\perp)$$

- Sivers function is the asymmetric part of k? distribution in a transversely polarized hadron
- It generates novel SSA in SIDIS and hadron-hadron collisions

Physics of Sivers function

Non-perturbative hadron structure involving

- **Hadron helicity flip**

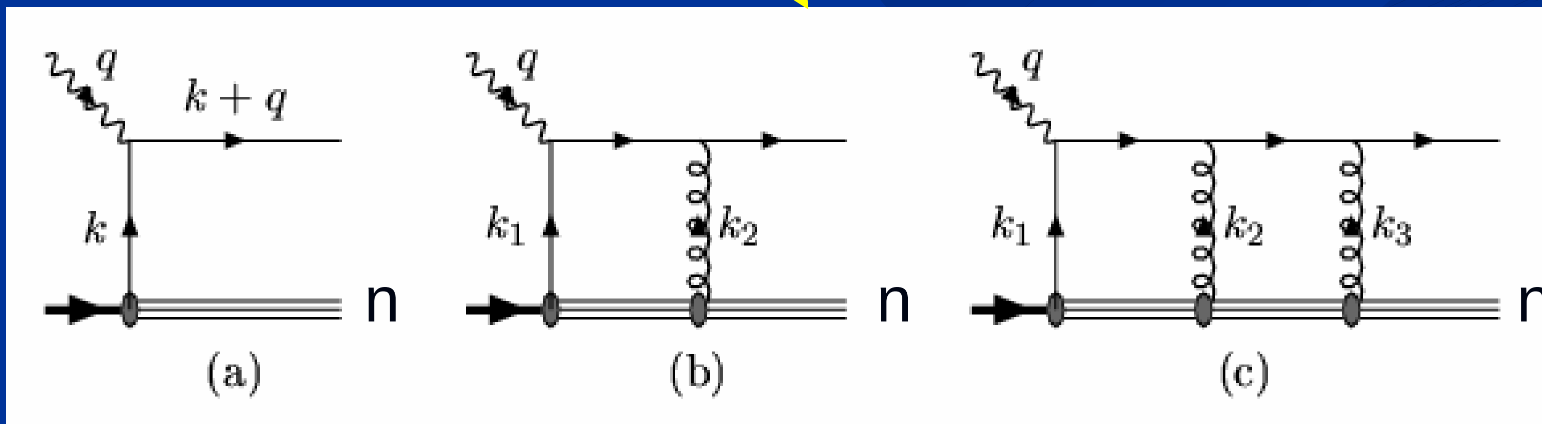
  quarks can be in S- and P-waves
- **Final state interactions (FSI)**
  - **The hadron structure has no FSI phase, therefore Sivers function vanishes by time-reversal (Collins, 1993)**
  - **There is final state interaction leading to single spin asymmetry at leading twist in SIDIS (Brodsky et al. 2002)**
  - ***FSI can arise from the scattering of jet with background gluon field in the nucleon (Collins, 2002)***
  - **The resulting gauge link is part of the parton dis.**

Physical origin of the gauge link

Parton distributions with full gauge link

$$q(x) = \frac{1}{2}\sum_n \int \frac{dx^-}{2p} \langle P|\bar{\psi}(0)\gamma^+ e^{ig\int_0^\infty dx^- A^+(x^-)}|n\rangle$$

$$\times \langle n| e^{-ig\int_{x^-}^\infty dx^- A^+(x^-)} \psi(x^-)|P\rangle$$

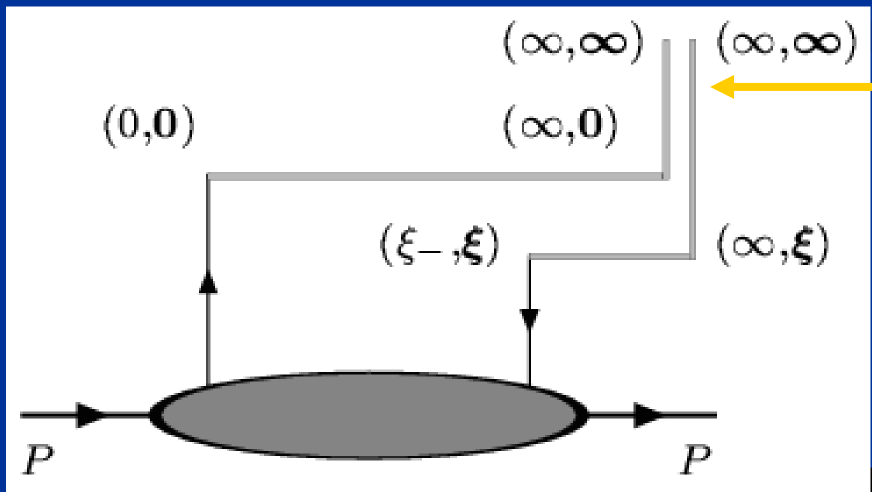


Factorizable Final State Interactions

TMD Parton Distributions

- **The gauge invariant definition**

$$
\begin{aligned}
f(x,k_\perp) \;=\; & \frac{1}{2}\int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3} e^{-i(\xi^- k^+ - \vec{\xi}_\perp\cdot\vec{k}_\perp)} \\
& \times \langle PS|\overline{\psi}(\xi^-,\xi_\perp) L^\dagger_{\xi_\perp}(\xi^-)\gamma^+ L_0(0)\psi(0)|PS\rangle
\end{aligned}
$$



Light-cone gauge: Additional Gauge link at x^-=§1

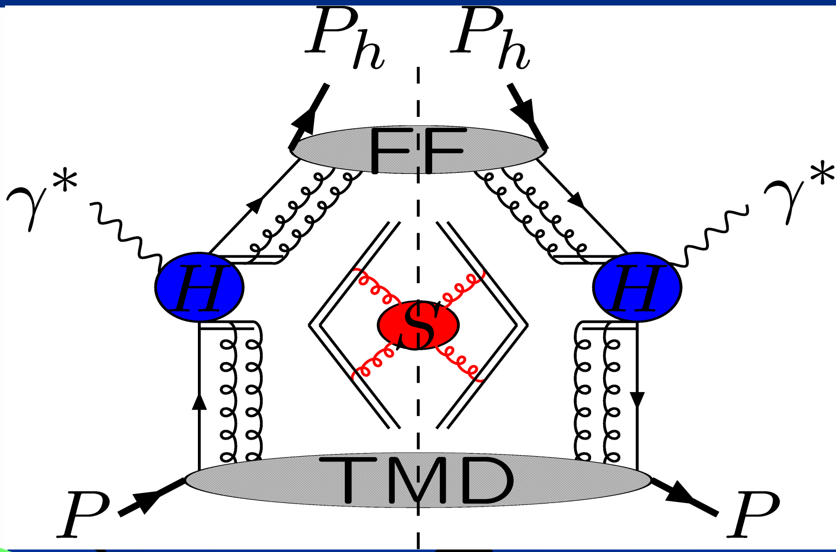
Ji, Yuan (02)
Belitsky, Ji, Yuan (03)

These definitions are also consistent with QCD factorization

SIDIS Cross Section: QCD Factorization

At leading power of 1/Q

$$
\begin{aligned}
d\sigma \propto\ & (1-y+y^2/2)x_B F_{UU}^{(1)} \\
& -(1-y)x_B\cos(2\phi_h)F_{UU}^{(2)} \\
& +\lambda_\ell \lambda y(1-y/2)x_B F_{LL} \\
& +\lambda_\ell |S_\perp| y(1-y/2)x_B\cos(\phi_h-\phi_S)F_{LT} \\
& +\lambda(1-y)x_B\sin(2\phi_h)F_{UL} \\
& +|S_\perp|(1-y+y^2/2)x_B\sin(\phi_h-\phi_S)F_{UT}^{(1)} \\
& +|\vec{S}_\perp|(1-y)x_B\sin(\phi_h+\phi_S)F_{UT}^{(2)} \\
& +|\vec{S}_\perp|(1-y)x_B\sin(3\phi_h-\phi_S)F_{UT}^{(3)}/2
\end{aligned}
$$



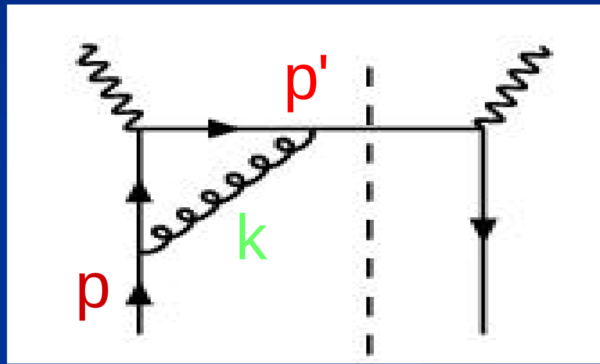
Sivers Asym.

Collins Asym.

Ji, Ma, Yuan, hep-ph/0404183,hep-ph/0405085

How does factorization work?

- **Vertex corrections at one-loop (single quark target)**

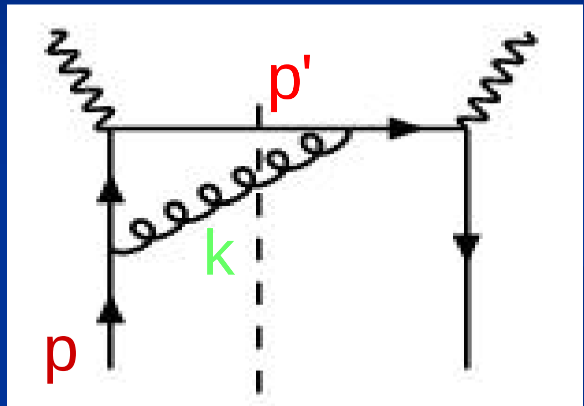


Four possible regions for the gluon momentum k:

1) k is collinear to p (parton distribution)
2) k is collinear to p' (fragmentation)
3) k is soft (Soft factor)
4) k is hard (pQCD correction)

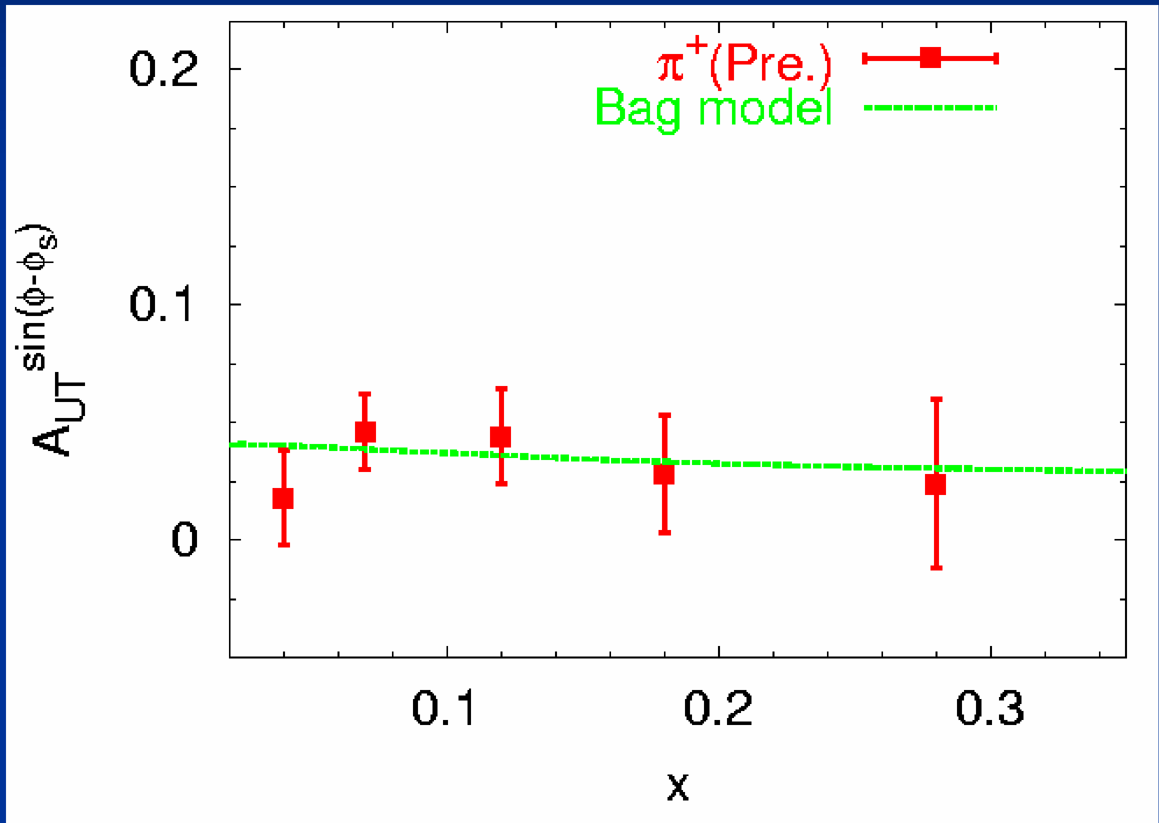
One-Loop Factorization (cont.)

- **Gluon Radiation (single quark target)**



Three reagions for the gluon momentum k:
1) k is collinear to p (parton distribution)
2) k is collinear to p' (fragmentation)
3) k is soft (Soft factor)

Model calculations



Bag model calculation of
The Sivers function, F. Yuan
Phys. Lett. B575, 45 (2003):

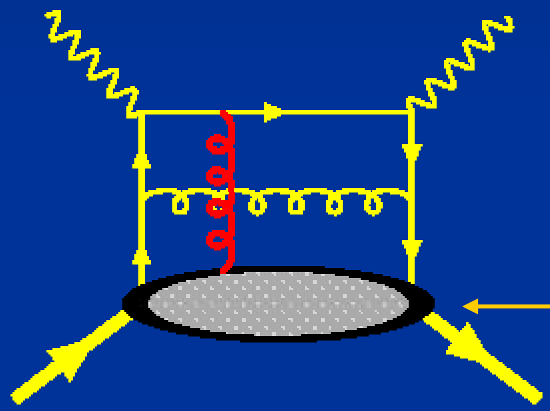
In the bag model, quarks are
In S- and P-wave states, and
The quark orbital angular
Momentum contributes to 40%
Of the proton spin

Exp. Data: HERMES,
Hep-ph/0408013

SSA at Large $P_?$ in SIDIS
(Sivers function and twist-3 correl.)

- Sivers function from Qiu-Sterman mechanism

Ji, Ma, Yuan, in progress

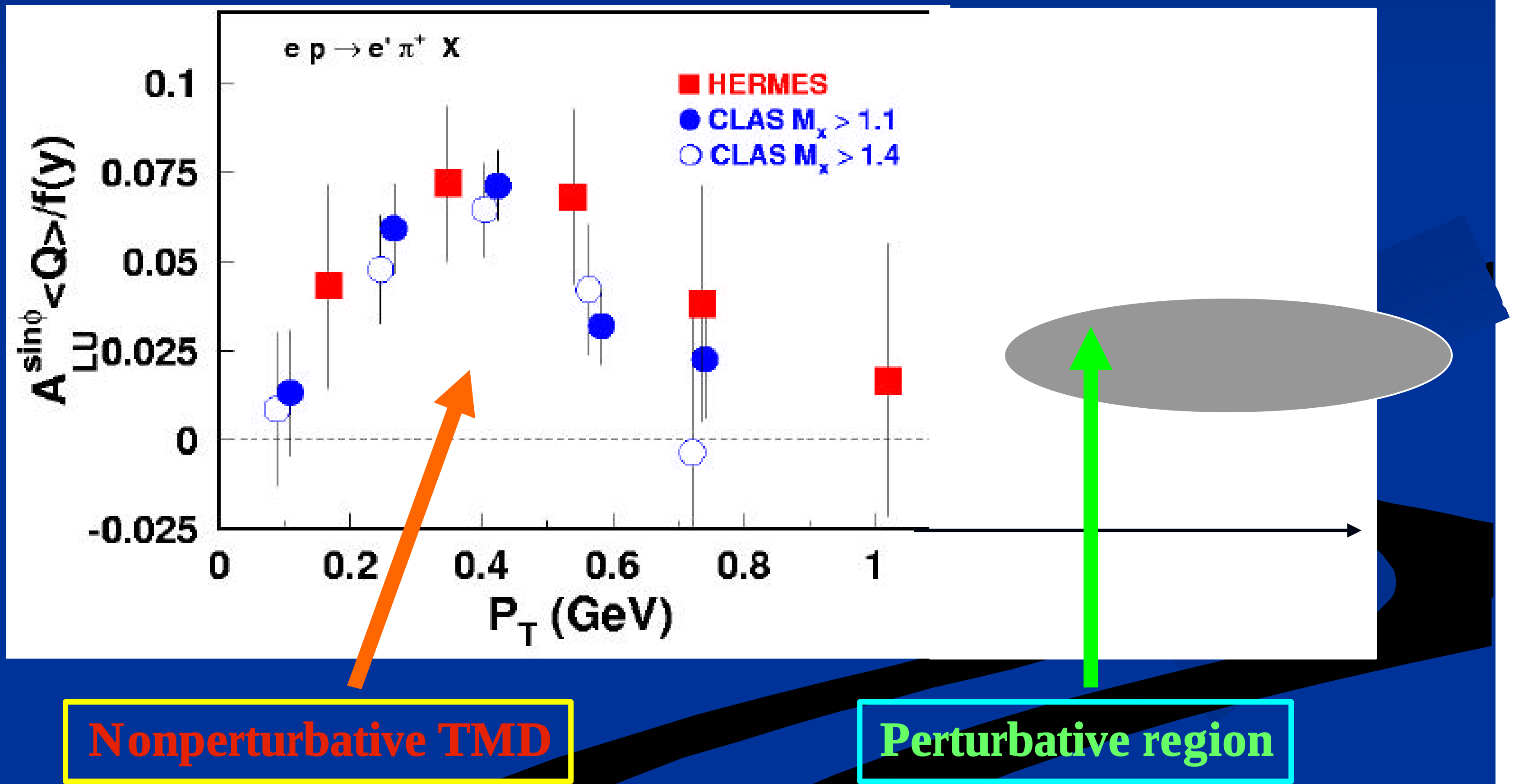


Quark-gluon correlations

- It is not suppressed by 1/Q, but by 1/$P_?$
- eRHIC and/or EIC can measure this asymmetry, plus many others, and provide information on quark-gluon correlations in nucleon

Transition from Perturbative region to Nonperturbative region?

- Compare different region of $P_?$



Sivers function at RHIC

Opportunities at RHIC

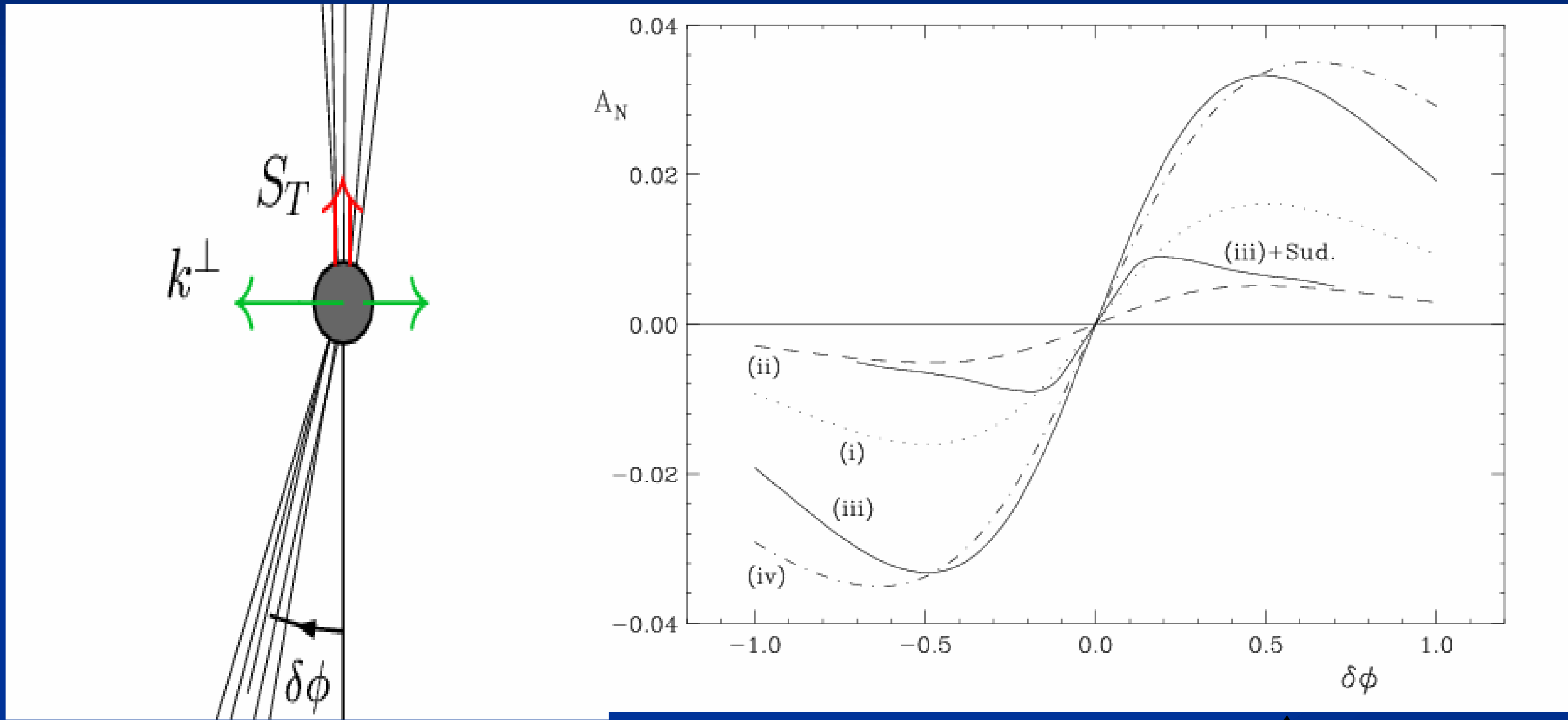
Quark Sivers function

- SSA for Drell-Yan: Sivers function has opposite sign, $q_T^{DY}=-q_T^{DIS}$, because of the gauge link changing direction.

Gluon and quark Sivers function

- Di-jet correlation (Boer & Vogelsang, 2003)
- Heavy quark/quarkonium
- Di-photon, di-hadron, hadron+photon, …

Asym. Jet correlation probe Gluon Sivers function at RHIC



Boer, Vogelsang, PRD69:094025,2004

What do we learn from SSA?

Nonzero Sivers function probes

- **Quark Orbital Angular Momentum**

  e.g, Siver's function ~ the wave function amplitude with orbital angular momentum!

  Vanishes if quarks only in s-state!

  Friends:

  - Pauli Form Factor $F_2(t)$
  - Spin-dependent structure function $g_2(x)$
  - Generalized Parton Distribution E(x, ?, t)

L_z? 0 Amplitude and Sivers Function

- All distributions can be calculated using the wave function. The amplitudes are not real because of FSI. Siver's function:

$$q_T(x,k_\perp) = \frac{M}{k_\perp^2}\int d[1]d[2]d[3]\sqrt{x_1 2x_2 2x_3}\,\mathrm{Im}[F_q] .$$

The functions F_q for the u-quark is

$$F_u = 2\Big\{\delta^{(3)}(k-k_1)\tilde{\psi}_j^{(1,2)*}(1,2,3)\tilde{\psi}_j^{(3,4)}(1,2,3) - \delta^{(3)}(k-k_2)\tilde{\psi}_j^{(1,2)}(1,2,3)\tilde{\psi}_j^{(3,4)*}(2,1,3)$$

$L_z=0$ $L_z=1$

- Similar expressions for $F_2(Q)$, $g_2(x)$ and $E(x,t)$

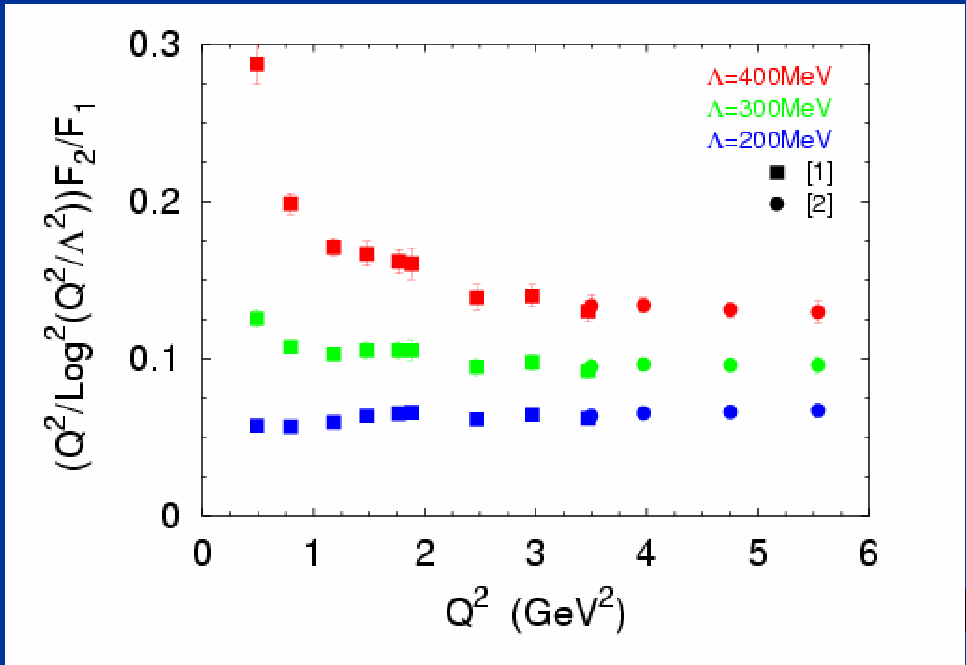
Ji, Ma, Yuan, Nucl. Phys. B (2003)

A perturbative QCD calculation of $F_2(Q)$

$$F_2(Q^2) = \int [dx_i][dy_i] \left[x_3 \Phi_4(x_1, x_2, x_3) T_\Phi(x_i, y_i) + x_1 \Psi_4(x_2, x_1, x_3) T_\Psi(x_i, y_i) \right] \Phi_3(y_i)$$

$L_z=1$

$L_z=0$



It predicts that F_2 goes like $(\ln^2 Q^2)/Q^6$ and hence $F_2/F_1 \sim (\ln^2 Q^2)/Q^2$

Belitsky, Ji & Yuan, PRL, 2003

Spin Structure of the Proton

- Pin down the L_z? 0 component of the proton wave function is very important. It can help us to determine how much of the nucleon spin is carried by orbital angular momentum.
- It also help to determine to what extent, the proton is not spherically symmetric (or deformed).
- It is wonderful to see that all seemingly unrelated physics are tied together after all.

Summary

- SSA in hadronic reactions provides much more information about nucleon structure: especially the quark orbital angular momentum, and the quark-gluon quark correlations.
- A QCD factorization has been proved for Semi-inclusive DIS
- Two mechanisms generating SSA in QCD merge at large $P_?$ SSA in SIDIS or Drell-Yan

TMD Gluon Distributions

- The definition

$$g(x, k_\perp, \mu, x\zeta) = \int \frac{d\xi^- d^2\xi_\perp}{xP^+(2\pi)^3} e^{-ixP^+\xi^- + i\vec{k}_\perp \cdot \vec{\xi}_\perp} \times \left\langle P \middle| F_a(\xi^-, \xi_\perp)^+{}_\mu \mathcal{L}^\dagger(\xi^-, \xi_\perp) \mathcal{L}(0, 0_\perp) F_a^{\mu+}(0) \middle| P \right\rangle$$

$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A^\mu_b A^\nu_c$

Gauge Link