Single Spin Asymmetries and QCD

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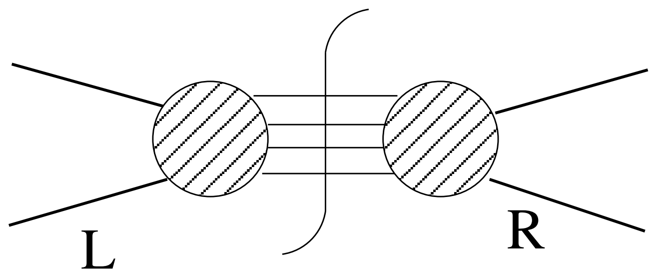
- Motivation
- "Leading twist" SSA: Which reactions? (For HERA & RHIC)
- Universality modified: Time-reversal, DIS & DY

Chiral symmetry and SSA

- Helicity basis:

$$|\text{trans.}\rangle \propto |L\rangle + \textsf{phase}|R\rangle$$

- Dependence on spin direction comes from LR interference:

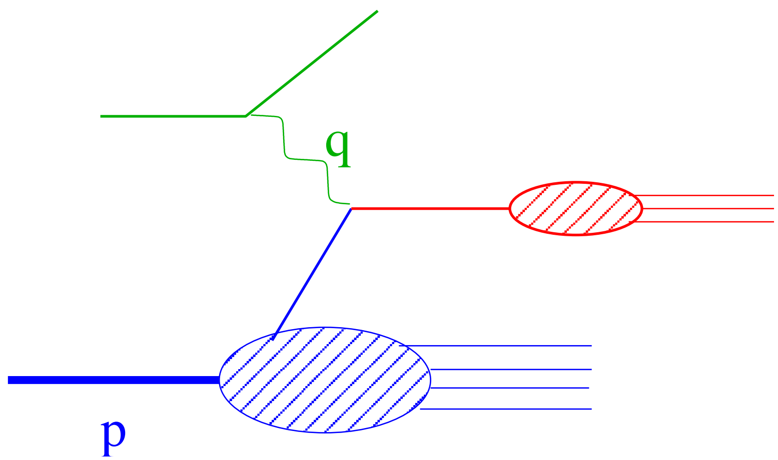


- Exact chiral sym.
  $\Longrightarrow$ LH & RH quarks different particles
  $\Longrightarrow$ No SSA

- But SSB, anomaly (non-perturbative). [And $m_q \neq 0$]

High p_T processes

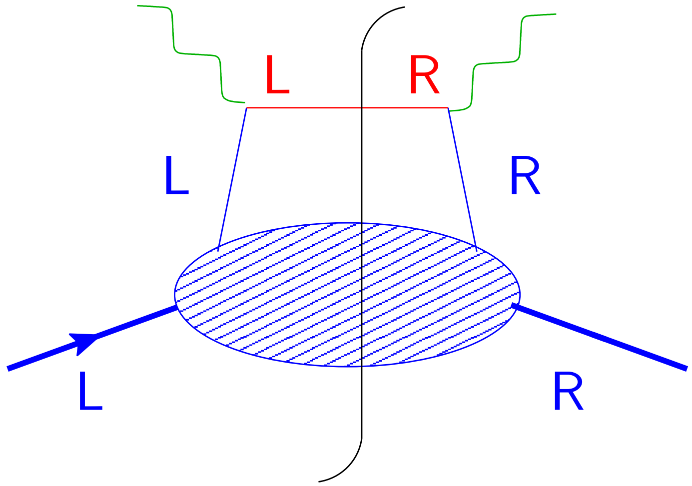
- E.g., DIS

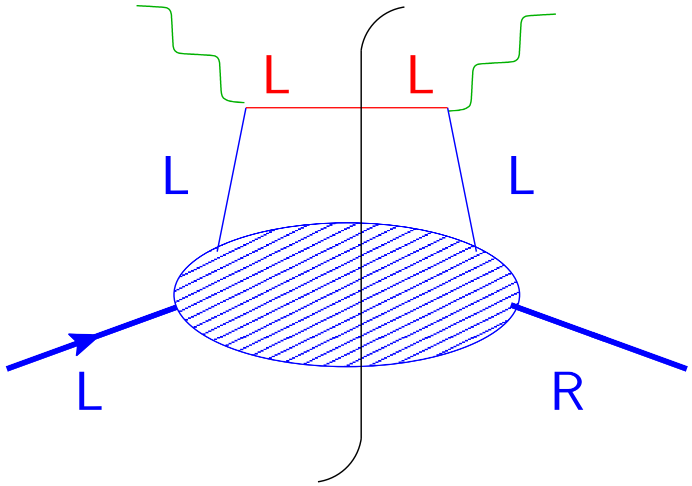


- Hard scattering part obeys chiral sym.

- Hence: SSA and high p_T probes wave function (etc.)
  [Cf. Burkardt talk]

But:



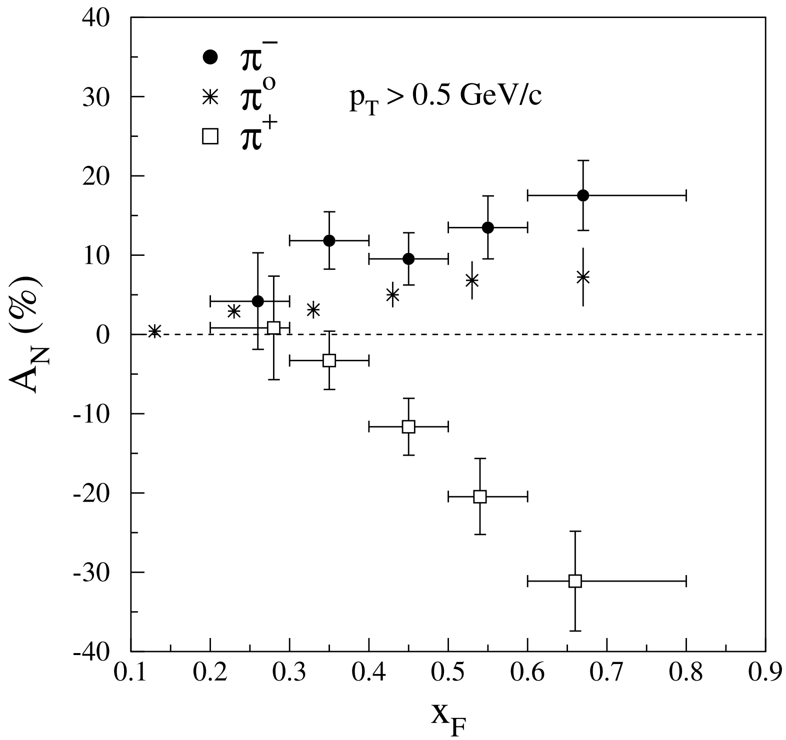


Blocked by hard scattering chiral sym. $\Longrightarrow$ quark $l_z = 1$, nonleading SSA [after average over $k_T \ll Q$]

Hence:

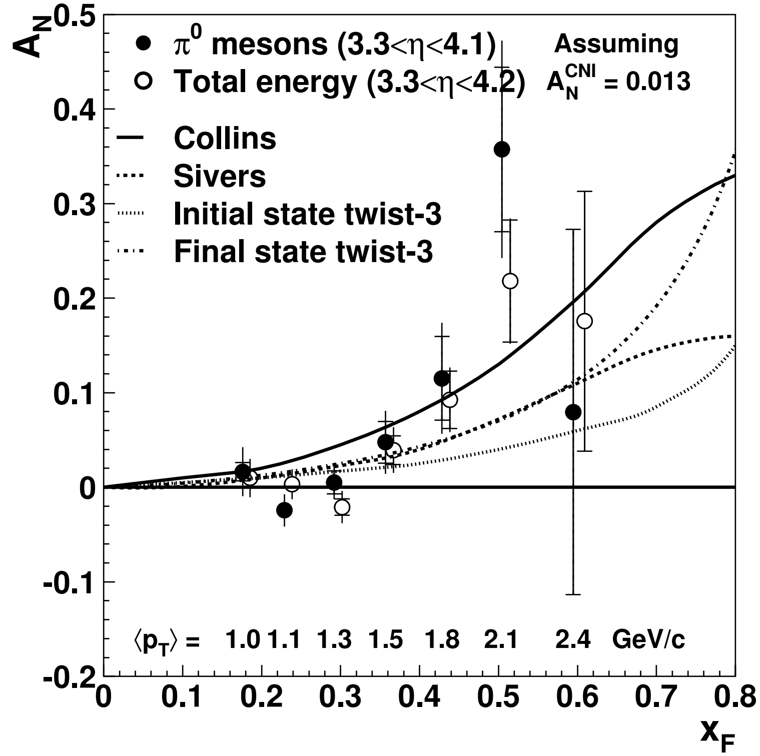
- g_2 is "twist 3"
- Twist-3 analysis (Qiu-Sterman, etc)

Hadronic SSA at high x_F



E704

[PRL 77,2626 (1996)]



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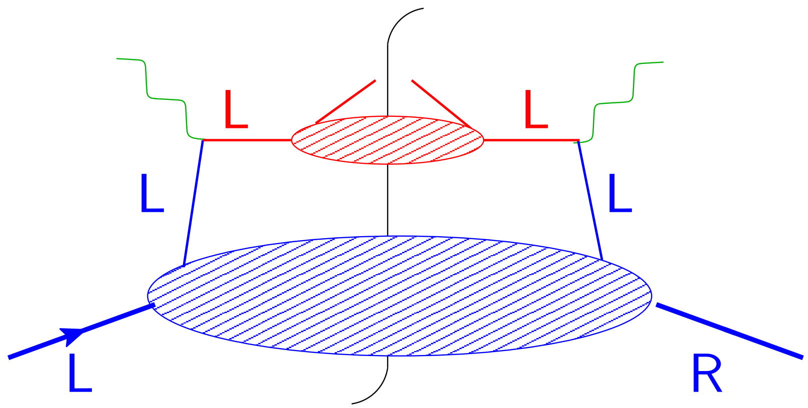
[hep-ex/0310058]

How to make high-p_T, SSA, leading power?

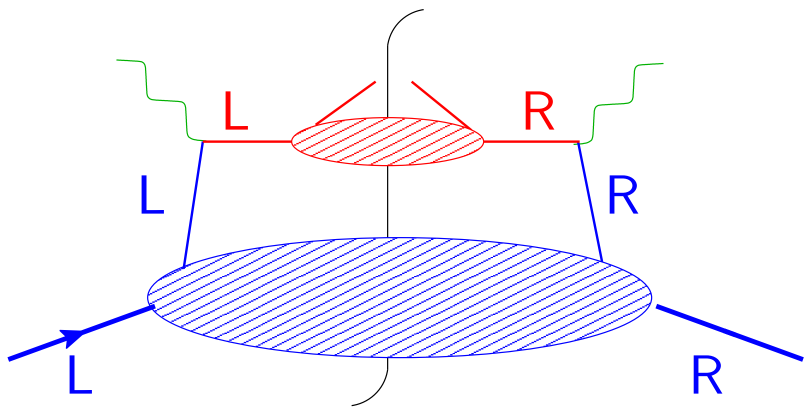
Incoming quark k_T (Sivers)
Orbital $L_z \implies$ azimuthal dep.:

$$\frac{dN}{\mathrm{d}^2 k_T} \propto \text{const} + \text{const} |k_T| \sin(\phi - \phi_S)$$



Quark poln. measurement

– Single-hadron azimuth
– Two-hadron azimuth
– Hadron (Λ) polarization

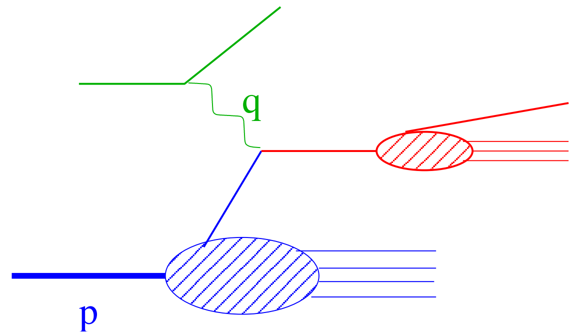


All cases: **Must have azimuthal angle to measure**

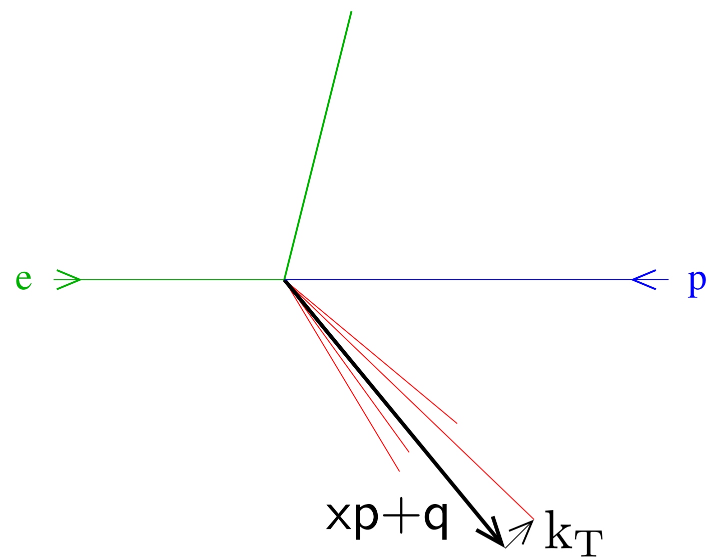
SIDIS k_T

- Process: $e + p \to e' + \pi + X$

  [SIDIS = Single-particle Inclusive DIS]



- Measure hadron k_T (and azimuth) relative to "parton model axis"



Single-spin asymmetry in SIDIS

- Process: $e + p \to e' + \pi + X$

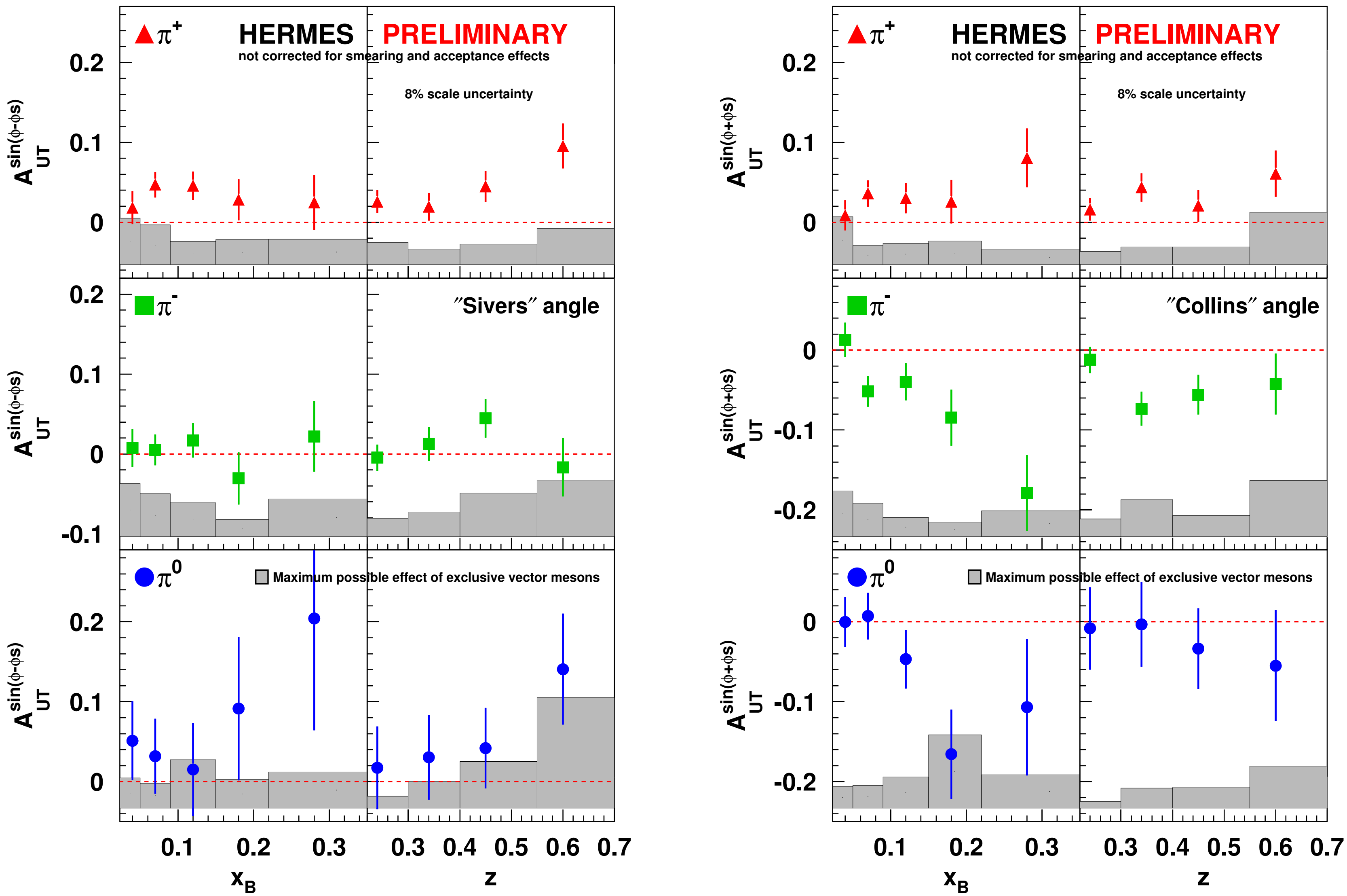
- Sivers: $\sin(\phi - \phi_1)$ [ϕ_1 = proton spin axis]
  Collins: $\sin(\phi - \phi_2)$ [ϕ_2 = outgoing quark spin axis]

- Use known chirally invariant hard scattering to probe

	$\mathrm{pdf}(x, k_T)$	$\mathrm{frag}(x, k'_T)$
Initial-state interference	Sivers	unpol.
Final-state interference	transversity	Collins

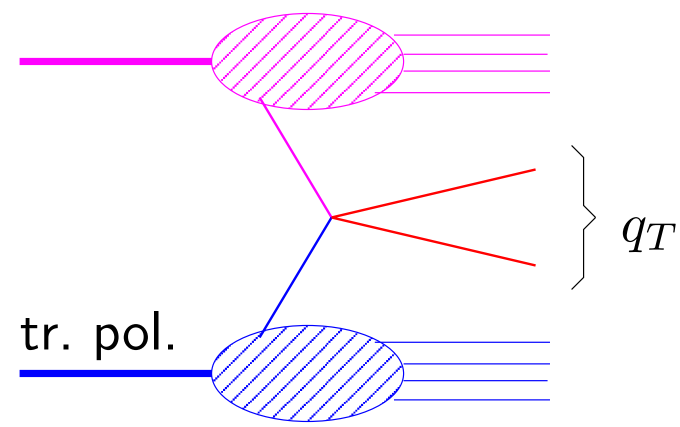
- See Mulders, HERMES

HERMES SSA



[Makins talk at Athens workshop, Oct. 2003]

RHIC processes for SSA



- Drell-Yan $\vec{q}_T$

- $\gamma + \text{jet}$ total $\vec{q}_T$

- $\text{jet} + \text{jet}$ total $\vec{q}_T$
  [Especially out-of-plane]

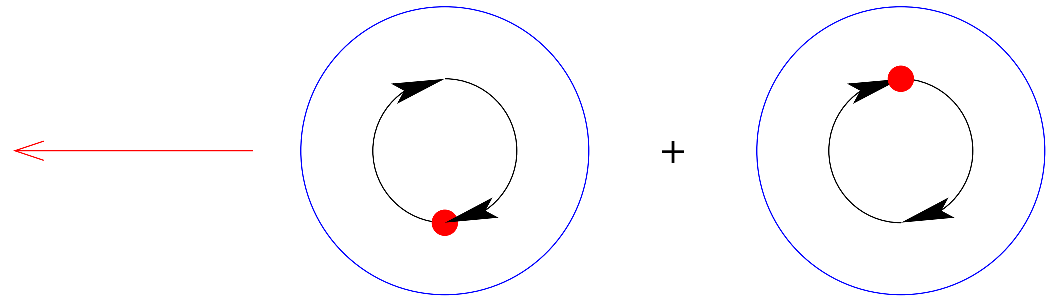
- But parton k_T much less than single-jet p_T
  $\Longrightarrow$ SSA in single-jet p_T is "higher twist", i.e., power suppressed.

- Etc.

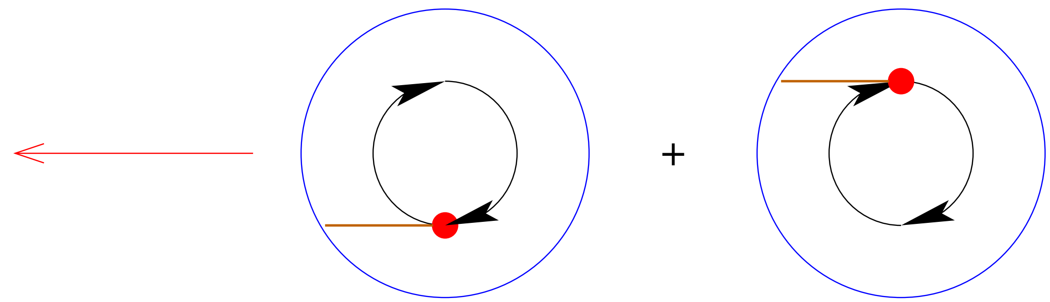
- Also target fragmentation, but that's harder for theorists!

T reversal on Sivers asymmetry

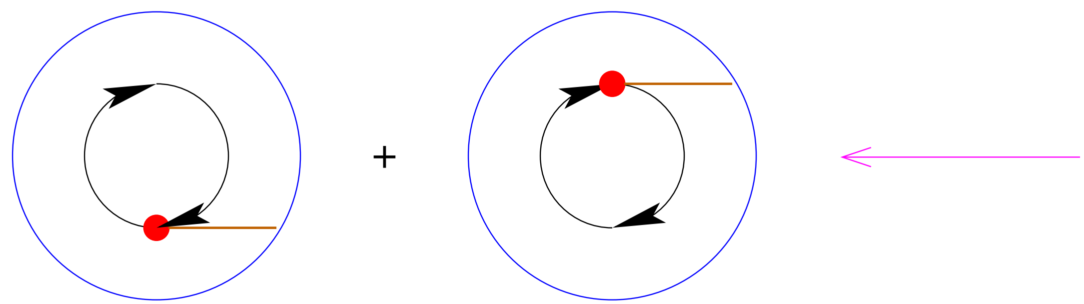
- No vector gluons
  Transverse deflections cancel
  $\Longrightarrow$ no Sivers SSA (TP)



- DIS in QCD: final-state glue
  $\Longrightarrow$ non-cancellation
  $\Longrightarrow$ Sivers SSA allowed



- Drell-Yan: initial-state glue
  $\Longrightarrow$ reversed sign of SSA
  "T-odd operator"



- Implement by Wilson lines in pdf definitions

Universality, with k_T-dependence pdfs, etc

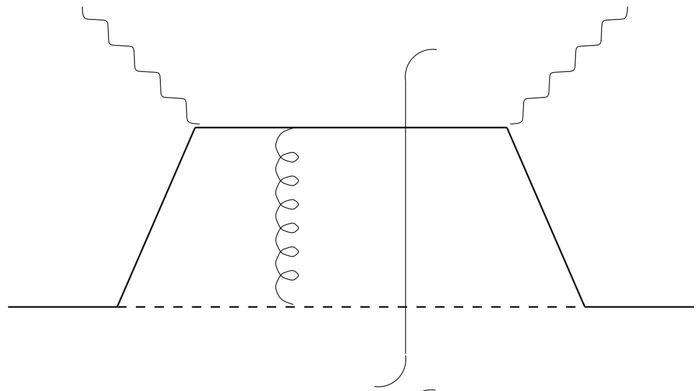
- Precise gauge invariant defn. of pdf and frag fn. needs:
  - Wilson lines in operators

$$\text{FT of } \langle p,s|\, \overline{\psi}(y)\, W(y \text{ to } \infty)^\dagger \;\; W(0 \text{ to } \infty)\, \psi(0)\; |p,s\rangle$$

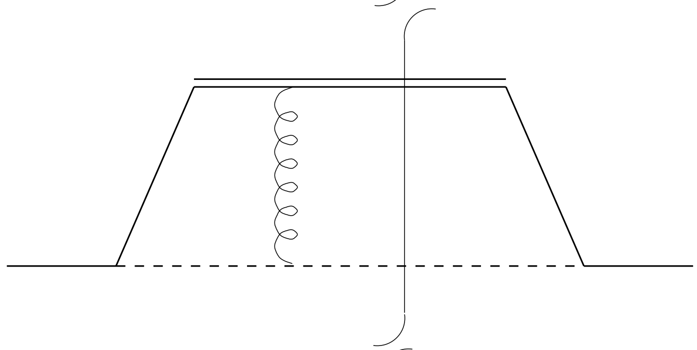
  - Direction:
    - Future or past?
    - Non-light-like: rapidity of line?
- Wilson line direction related to measurement:
  - Future $\Longleftrightarrow$ Outgoing struck parton
  - Past $\Longleftrightarrow$ Incoming anti-parton
  - Rapidity $\Longleftrightarrow$ y_{gluon} cutoff:
    - With light-like line: Divergences for $y_{\text{gluon}} \to -\infty$
    - $\Longrightarrow$ Need cutoff or "generalized renormalization"
    - Usual dogma about real-virtual cancellation does not apply
- Universality between all processes? (JCC & Metz)

Simplest SSA graphs

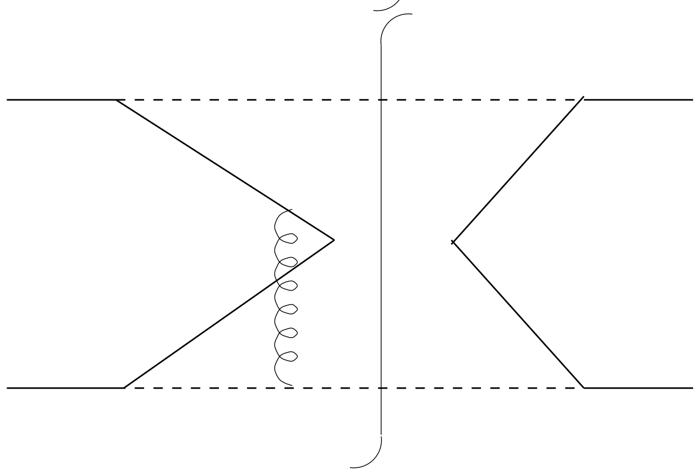
DIS:



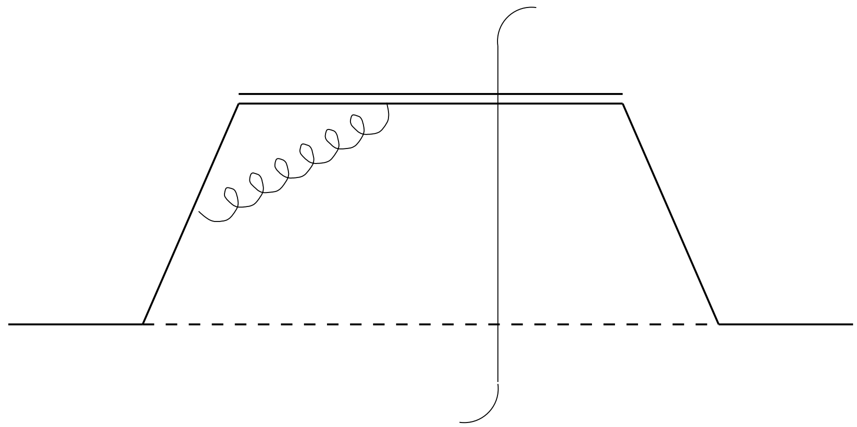
In parton density:

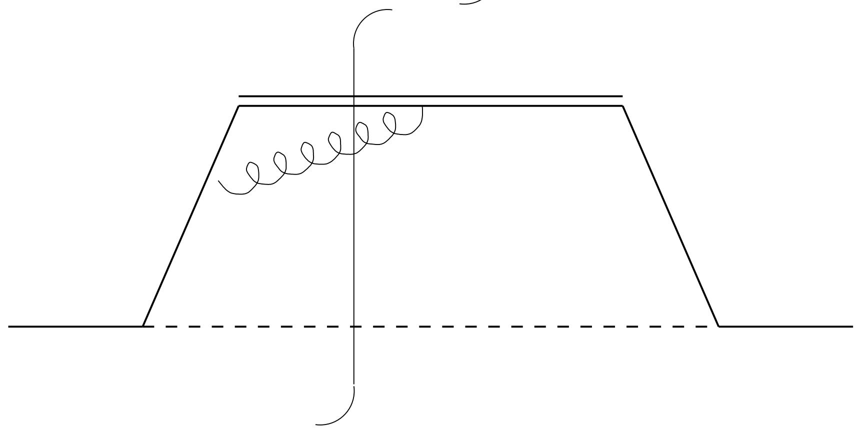


Drell-Yan:



Simplest rapidity divergence graphs





Sudakov dilution

- Unintegrated pdf: $f(x, k_T, \Delta y, \mu)$. [where $\Delta y = y_p - y_{\rm CM}$]

- Second evolution eq. (Collins-Soper-Sterman)

$$\frac{\partial f}{\partial \Delta y} = (K + G) \otimes f$$

- Kernel independent of polarization; depends only on color of parton

- Recoil against azimuthally symmetric gluon emission:
  Spreads parton k_T distribution as energy increases

- Dilutes SSA

- Similarly for k_T-dependent fragmentation

Conclusions

- SSAs in hard processes are interesting probes of
  - space-time structure of hadrons, and their chiral structure
  - chiral structure of fragmentation
  - space-time structure of hard collisions
- Need close examination of QCD theory
- Data arriving (HERMES & RHIC)

Possible definition of unintegrated pdf

Unintegrated pdf is Fourier transformation of coordinate-space pdf:

$$P_i(x, \mathbf{k}_T, \zeta, \mu) = \int \frac{dy^- \, d^2\mathbf{y}_T}{16\pi^3} \mathrm{e}^{-ixp^+y^- + i\mathbf{k}_T\cdot\mathbf{y}_T} \, \tilde{P}_i(y^-, \mathbf{y}_T, \zeta, \mu),$$

where the coordinate-space pdf is:

$$\tilde{P}_i(y^-, \mathbf{y}_T, \zeta, \mu) = \frac{\langle p| \, \bar{\psi}_i(0, y^-, \mathbf{y}_T) \, W_y(n)^\dagger \, I_{n;y,0} \, \gamma^+ \, W_0(n) \, \psi_i(0) \, |p\rangle_R}{\langle 0| \, W_y(n)^\dagger \, W_y(u') \, I_{n;y,0} \, I^\dagger_{u';y,0} \, W_0(n) \, W_0(u')^\dagger \, |0\rangle_R},$$

with $W_y(u)$ denoting the following Wilson line operator (for DIS)

$$W_y(u) = P \exp\left[-ig_{(0)} \int_0^\infty d\lambda \, u^\mu \, A^{(0)}_\mu(y + \lambda u) \right].$$

– Numerator for $\tilde{P}$ is the simplest gauge-invariant defn.
– It has $y_{\mathrm{gluon}} \longrightarrow -\infty$ divergences (n^μ is light-like)
– Denominator "renormalizes" the divergences (u^μ space-like)
– $\zeta = (2p \cdot u)^2/(-u^2) = 2m^2 \sinh^2(y_p - y_u)$