Azimuthal asymmetry in Semi-Inclusive Deep-Inelastic Scattering

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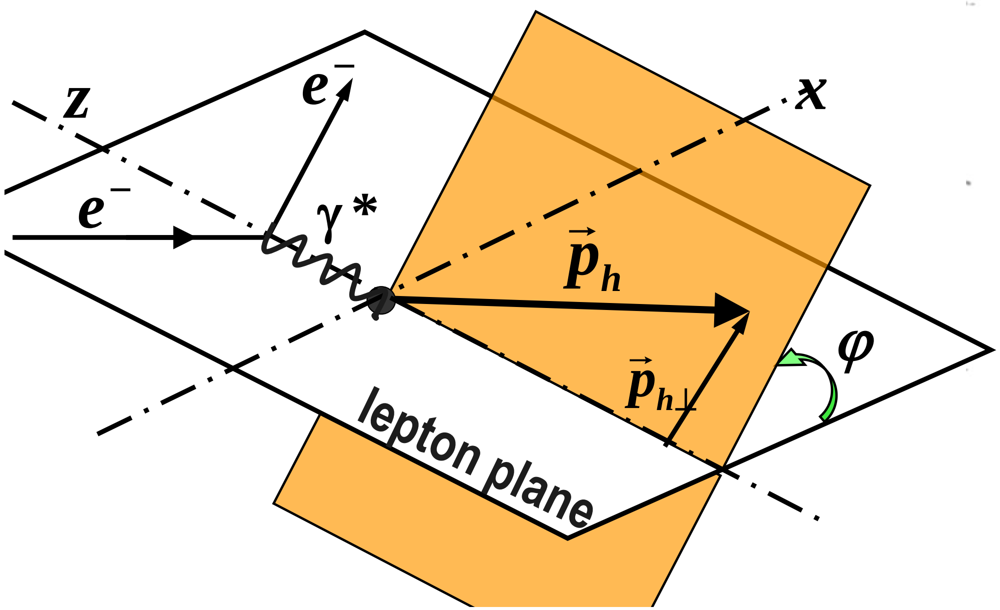
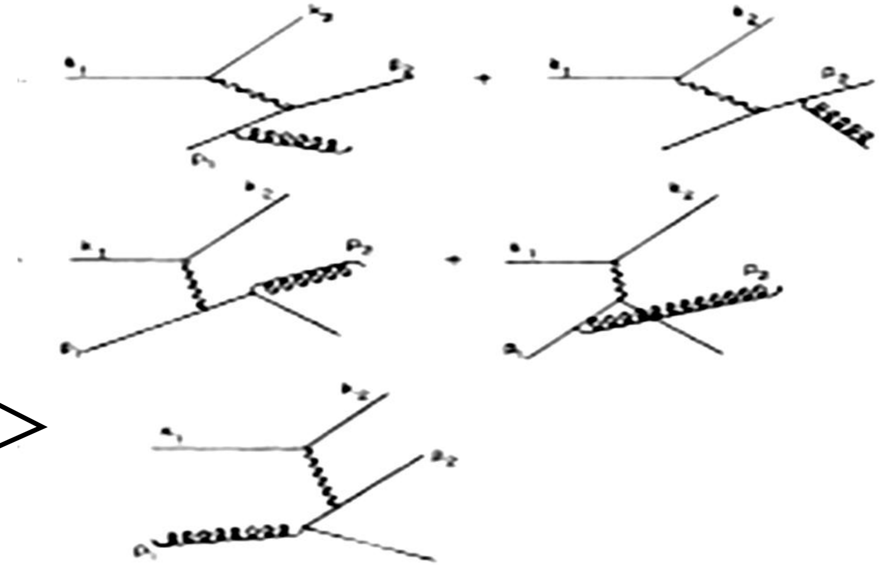
Azimuthal asymmetry in unpolarized SIDIS

1977: Georgi & Politzer, “Clean test to pQCD”, Phys. Rev. Lett. 40,3 (77).

$$e^- + p \to e^- + h + X$$





$$\langle \cos\varphi \rangle \sim -\frac{\pi}{2}\frac{B(y)}{A(y)}\kappa(1-z)^{1/2} \quad \text{for large } z,$$

$$A(y) = 1 + (1-y)^2, \qquad B(y) = 2(2-y)(1-y)^{1/2},$$

Azimuthal asymmetry in unpolarized SIDIS

1978: Cahn, Intrinsic momentum effects. Phys. Lett. B78B, 269 (1978).

Generalized parton model to include an intrinsic transverse momentum $\vec{k}_\perp$ but no gluon radiation in the final state:

$$\langle \cos\varphi \rangle = -\frac{|\vec{k}_\perp|}{Q}\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

twist 3

$$\langle \cos 2\varphi \rangle = -\frac{|\vec{k}_\perp|^2}{Q^2}\frac{2(1-y)}{1+(1-y)^2}$$

twist 4

"Realistic studies": Monte-Carlo, experiments etc.

small $p_{h\perp}$, moderate Q, intrinsic $k_\perp$ contribution dominates;
large $p_{h\perp}$, large Q, Georgi-Politzer mechanism dominates.

$\Longrightarrow$ **In DIS at intermediate energies: intrinsic transverse momentum $k_\perp$ effects have to be taken into account.**

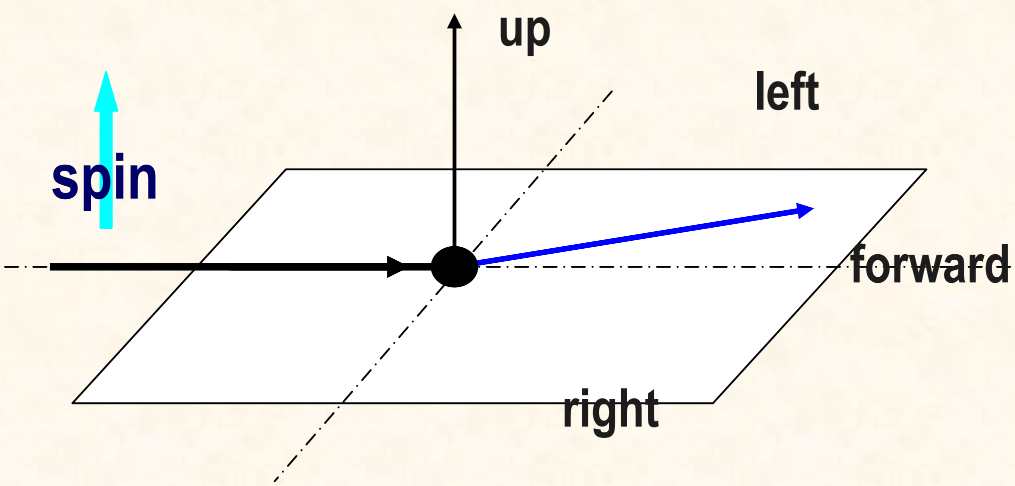
Azimuthal asymmetry in polarized SIDIS

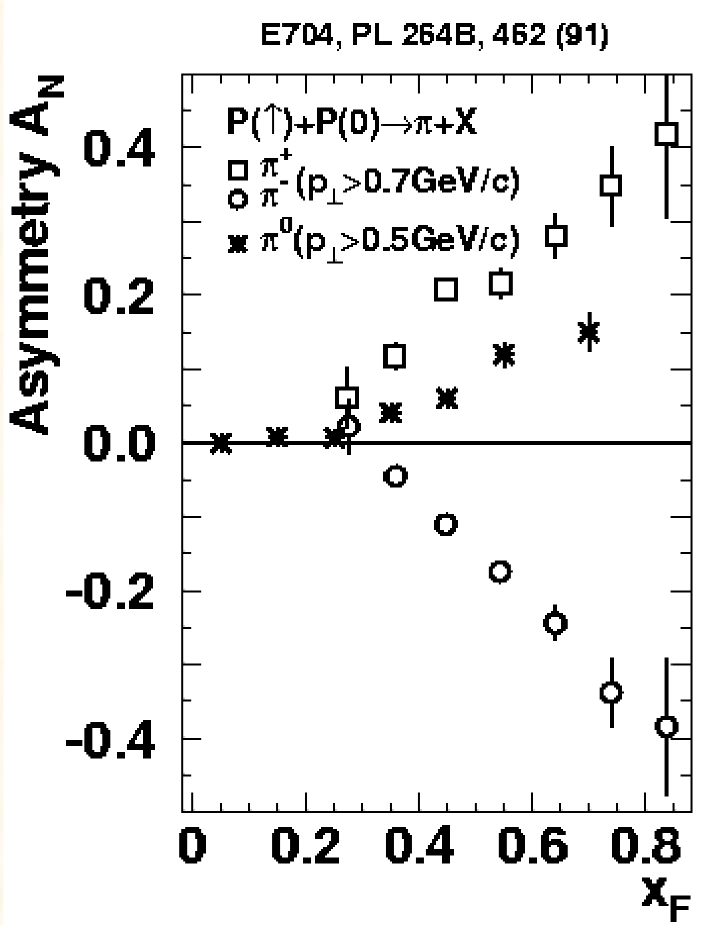
Motivation: Single-spin asymmetry in pp collisions

—— azimuthal asymmetry in singly polarized pp collisions

$$p(\uparrow) + p \rightarrow \pi + X$$

$$A_N \equiv \frac{N_L - N_R}{N_L + N_R}$$





Azimuthal asymmetry in polarized SIDIS

History: theoretical studies on single-spin asymmetry in p(↑)+p→π+X

Factorization $d\sigma_{p(\uparrow)+p\to\pi+X} \propto (p.d.f.) \otimes d\hat{\sigma}_{q(\uparrow)+q\to q+X} \otimes (frag.\ fun.)$

1978, Kane, Pumplin, Repko: pQCD $a_N[q(\uparrow)+q\to q+q]=0$.

1991, Sivers: asymmetric quark distribution (Sivers effect)

1993, Boros, Liang, Meng: quark orbital angular momentum & "surface effect"

Collins: Proof of non-existence of Sivers effect, asymmetric fragmentation function (Collins effect).

2002, Brodsky, Hwang, Schmidt: quark orbital angular momentum & "final state interaction".

Ji, Yuan: "final state interaction" = "gauge link"

Collins: 1993's proof is wrong because forgot gauge link.

Azimuthal asymmetry in polarized SIDIS

Conclusion:

both Sivers and Collins effects can exist when gauge link is taken into account.

⇨ intrinsic transverse momentum and gauge link are important in studying azimuthal asymmetries in SIDIS.

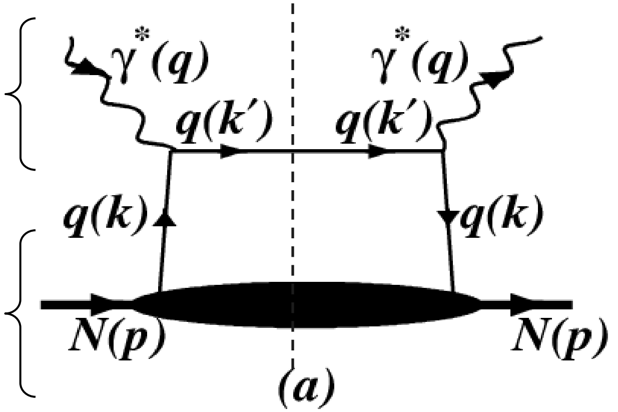
Question:

Where does the gauge come from?

DIS without QCD interaction

$$W_{\mu\nu}(q,p,S)=\sum_X \langle p,S|J_\mu(0)|X\rangle\langle X|J_\nu(0)|p,S\rangle(2\pi)^4\delta^4(p+q-p_X)$$

$$W_{\mu\nu}(q,p,S)=\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}[\hat{\varphi}(k,p,S)\hat{H}_{\mu\nu}(k,q)]$$



The hard part: $\hat{H}_{\mu\nu}(k,q)=\gamma_\mu(\not k+\not q)\gamma_\nu(2\pi)\delta_+\left((k+q)^2\right)$

contracted with the leptonic tensor

⇨ $d\sigma(e^-q\to e^-q)$

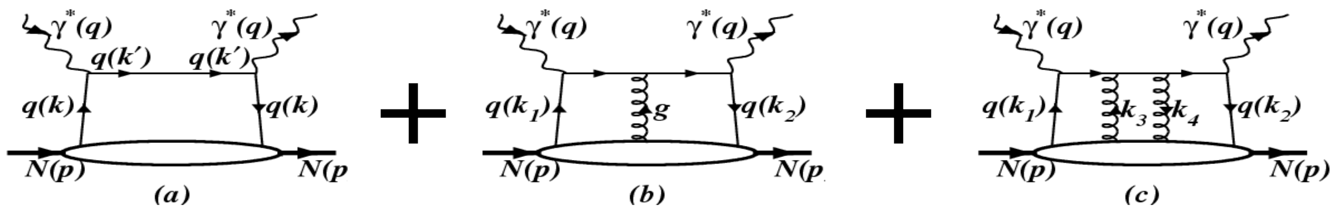
The matrix element: $\hat{\varphi}(k,p,S)=\int d^4z e^{ikz}\langle p,S|\bar{\psi}(0)\psi(z)|p,S\rangle$

⇨ parton distributions

No QCD interactions.
Not (color) gauge invariant.

Inclusive DIS with QCD interaction

$$W_{\mu\nu}(q,p,S)=W^{(0)}_{\mu\nu}(q,p,S)+W^{(1)}_{\mu\nu}(q,p,S)+W^{(2)}_{\mu\nu}(q,p,S)+\ldots$$



multiple gluon scattering

$$W^{(0)}_{\mu\nu}(q,p,S)=\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left[\hat{\phi}^{(0)}(k,p,S)\hat{H}^{(0)}_{\mu\nu}(k,q)\right]$$

$$W^{(1)}_{\mu\nu}(q,p,S)=\int\frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\mathrm{Tr}\left[\hat{\phi}^{(1)}_{\rho}(k_1,k_2,p,S)\hat{H}^{(1)\rho}_{\mu\nu}(k_1,k_2,q)\right]$$

$$\hat{H}^{(0)}_{\mu\nu}(k,q)=\gamma_\mu(\not{k}+\not{q})\gamma_\nu(2\pi)\delta_+\left((k+q)^2\right);\quad \hat{H}^{(1,L;si)}_{\mu\nu}(k,q)=\gamma_\mu\frac{(\not{k}_1+\not{q})\gamma^\rho(\not{k}_2+\not{q})}{(k_2+q)^2-i\varepsilon}\gamma_\nu(2\pi)\delta_+\left((k_1+q)^2\right)$$

Parton distribution/correlation:

$$\hat{\phi}^{(0)}(k,p,S)=\int d^4z\,e^{ikz}\langle p,S|\bar{\psi}(0)\psi(z)|p,S\rangle$$

$$\hat{\phi}^{(1)}_{\rho}(k_1,k_2,p,S)=\int d^4z\,d^4y\,e^{ik_1y+ik_2(z-y)}\langle p,S|\bar{\psi}(0)gA_\rho(y)\psi(z)|p,S\rangle$$

Not gauge invariant!

Inclusive DIS with QCD interaction

Ellis, Furmanski, Petronzio, (82)
Qiu, Sterman (90,91)

Collinear expansion:

- Expanding the hard parts around *k* =*xp:*

$$\hat{H}^{(0)}_{\mu\nu}(k,q) = \hat{H}^{(0)}_{\mu\nu}(x) + \frac{\partial \hat{H}^{(0)}_{\mu\nu}(x)}{\partial k^{\rho}} \omega_{\rho}{}^{\rho'} k_{\rho'} + \ldots\ldots$$

$$\hat{H}^{(1)\rho}_{\mu\nu}(k,q) = \hat{H}^{(1)\rho}_{\mu\nu}(x_1,x_2) + \frac{\partial \hat{H}^{(1)\rho}_{\mu\nu}(x_1,x_2)}{\partial k_1^{\sigma}} \omega_{\sigma}{}^{\sigma'} k_{1\sigma'} + \ldots\ldots$$

- Decomposition of the gluon field:

$$A_{\rho}(y) = n\cdot A(y)\frac{p_{\rho}}{n\cdot p} + \omega_{\rho}{}^{\rho'} A_{\rho'}(y)$$

$$x = k^+ / p^+$$

$$\omega_{\rho}{}^{\rho'} \equiv g_{\rho}{}^{\rho'} - \bar{n}_{\rho} n^{\rho'}$$

$$\omega_{\rho}{}^{\rho'} k_{\rho'} = (k - xp)_{\rho}$$

$$k^{\pm} = \frac{1}{\sqrt{2}}(k_0 \pm k_3)$$

$$n = (0,1,\vec{0}_{\perp})$$

$$\bar{n} = (1,0,\vec{0}_{\perp})$$

- Using the identities such as,

$$\frac{\partial \hat{H}^{(0)}_{\mu\nu}(x)}{\partial k^{\rho}} = -\hat{H}^{(1)\rho}_{\mu\nu}(x,x), \qquad p_{\rho}\hat{H}^{(1,L)\rho}_{\mu\nu}(x_1,x_2) = \frac{\hat{H}^{(0)}_{\mu\nu}(x_1)}{x_2 - x_1 - i\varepsilon}$$

to replace the derivatives etc.

Inclusive DIS with QCD interaction

$$W_{\mu\nu}(q,p,S) = \tilde{W}^{(0)}_{\mu\nu}(q,p,S) + \tilde{W}^{(1)}_{\mu\nu}(q,p,S) + \tilde{W}^{(2)}_{\mu\nu}(q,p,S) + \ldots$$

$$\tilde{W}^{(0)}_{\mu\nu}(q,p,S) = \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left[\hat{\Phi}^{(0)}(k,p,S)\ \hat{H}^{(0)}_{\mu\nu}(x)\ \right]$$

$$\hat{\Phi}^{(0)}(k,p,S) = \int d^4z e^{ikz} \langle p,S|\bar{\psi}(0)\mathcal{L}(0,z)\psi(z)|p,S\rangle$$

$$\mathcal{L}(0,z) = Pe^{ig\int_0^z dy^- A^+(0,y^-,\vec{0}_\perp)} = 1 + ig\int_0^{z^-} dy^- A^+(0,y^-,\vec{0}_\perp) + (ig)^2 \int_0^{z^-} dy^- A^+(0,y^-,\vec{0}_\perp) \int_0^{y^-} dy'^- A^+(0,y'^-,\vec{0}_\perp) + \ldots$$

$$\tilde{W}^{(1)}_{\mu\nu}(q,p,S) = \int \frac{d^4k_1}{(2\pi)^4} \frac{d^4k_2}{(2\pi)^4} \mathrm{Tr}\left[\hat{\Phi}^{(1)}_{\rho'}(k_1,k_2,p,S)\quad \hat{H}^{(1)\rho}_{\mu\nu}(x_1,x_2)\ \omega_\rho^{\ \rho'}\ \right]$$

$$\hat{\Phi}^{(1)}_{\rho}(k_1,k_2,p,S) = \int d^4z d^4y e^{ik_1y + ik_2(z-y)} \langle p,S|\bar{\psi}(0)\mathcal{L}(0,y)D_\rho(y)\mathcal{L}(y,z)\psi(z)|p,S\rangle$$

$$D_\rho(y) = -i\partial_\rho + gA_\rho(y)$$

Contain QCD interactions.

(Color) gauge invariant !

Inclusive DIS with QCD interaction

Conclusion:

Gauge link comes from the multiple gluon scattering and collinear expansion is the necessary procedure to obtain the correct form of gauge invariant parton distributions.

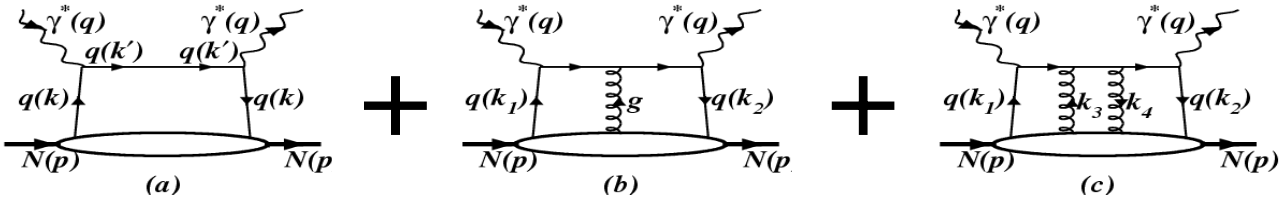
Question: How about semi-inclusive DIS?

Semi-Inclusive DIS with QCD interaction

Consider first $e + p \to e + q + X$, i.e., NO fragmentation

$$W_{\mu\nu}^{(si)}(q,p,k',S) = \sum_X \langle p,S|J_\mu(0)|k',X\rangle\langle k',X|J_\nu(0)|p,S\rangle(2\pi)^4\delta^4(p+q-p_X)$$

$$= W_{\mu\nu}^{(0,si)}(q,p,S,k') + W_{\mu\nu}^{(1,si)}(q,p,S,k') + W_{\mu\nu}^{(2,si)}(q,p,S,k') + \ldots$$



$$W_{\mu\nu}^{(0,si)}(q,p,S,k') = \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}[\hat{\phi}^{(0)}(k,p,S)\hat{H}_{\mu\nu}^{(0,si)}(k,q)]$$

$$\hat{H}_{\mu\nu}^{(0,si)}(k,q) = \gamma_\mu(\not{k}+\not{q})\gamma_\nu(2\pi)^4\delta^4(k'-k-q)$$

C.f.: $$\hat{H}_{\mu\nu}^{(0)}(k,q) = \gamma_\mu(\not{k}+\not{q})\gamma_\nu(2\pi)\delta_+\left((k+q)^2\right)$$

Using the mathematical identity:

$$(2\pi)^4\delta^4(k'-k-q)=(2\pi)\delta_+\left((k-q)^2\right)(2\pi)^3(2E_{k'})\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

We obtain:

$$\hat{H}^{(0,si)}_{\mu\nu}(k,q)=\hat{H}^{(0)}_{\mu\nu}(k,q)(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

$$\hat{H}^{(1,\rho,c,si)}_{\mu\nu}(k_1,k_2,q)=\hat{H}^{(1,\rho,c)}_{\mu\nu}(k_1,k_2,q)(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_c-\vec{q})$$

$$\Rightarrow W^{(0,si)}_{\mu\nu}(q,p,S,k')=\underbrace{\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}[\hat{\phi}^{(0)}(k,p,S)\hat{H}^{(0)}_{\mu\nu}(k,q)]}_{W^{(0)}_{\mu\nu}(q,p,S)}(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

$$W^{(1,si)}_{\mu\nu}(q,p,S,k')=\underbrace{\int\frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\sum_{c=L,R}\mathrm{Tr}[\hat{\phi}^{(1)}_{\rho}(k_1,k_2,p,S)\hat{H}^{(1,c)\rho}_{\mu\nu}(k_1,k_2,q)]}_{W^{(1)}_{\mu\nu}(q,p,S)}\times(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_c-\vec{q})$$

Semi-Inclusive DIS with QCD interaction

The same collinear expansion leads to

$$W_{\mu\nu}^{(si)}(q,p,S,k')=\tilde{W}_{\mu\nu}^{(0,si)}(q,p,S,k')+\tilde{W}_{\mu\nu}^{(1,si)}(q,p,S,k')+\tilde{W}_{\mu\nu}^{(2,si)}(q,p,S,k')+\ldots$$

$$\tilde{W}_{\mu\nu}^{(0,si)}(q,p,S,k')=\int\frac{d^4k}{(2\pi)^4}\mathrm{Tr}[\hat{\Phi}^{(0)}(k,p,S)\hat{H}_{\mu\nu}^{(0)}(x)]\,(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

$$\tilde{W}_{\mu\nu}^{(1,si)}(q,p,S,k')=\int\frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\sum_{c=L,R}\mathrm{Tr}[\hat{\Phi}_{\rho'}^{(1)}(k_1,k_2,p,S)\hat{H}_{\mu\nu}^{(1,c)\rho}(x_1,x_2)\omega_\rho^{\ \rho'}]\times(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_c-\vec{q})$$

$$\tilde{W}_{\mu\nu}^{(2,si)}(q,p,S,k')=\int\frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k}{(2\pi)^4}\sum_{c=L,C,R}\mathrm{Tr}[\hat{\Phi}_{\rho'\sigma'}^{(2)}(k_1,k_2,k,p,S)\hat{H}_{\mu\nu}^{(2,c)\rho\sigma}(x_1,x_2,x)\omega_\rho^{\ \rho'}\omega_\sigma^{\ \sigma'}]\times(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_c-\vec{q})$$

Gauge invariant parton distributions/correlations (with gauge link)

SIDIS with $k_\perp$: Direct consequence I

Consider the contribution from $\tilde{W}^{(0,si)}_{\mu\nu}(q,p,S,k')$

Cross section for $ep \to eqX$	$d\sigma(e+p \to e+q+X)$

$=$ Parton distributions $q(x)$ $\otimes$ Cross section for $eq \to eq$ without $\vec{k}_\perp$ $d\sigma(eq \to eq)|_{k=xp}$

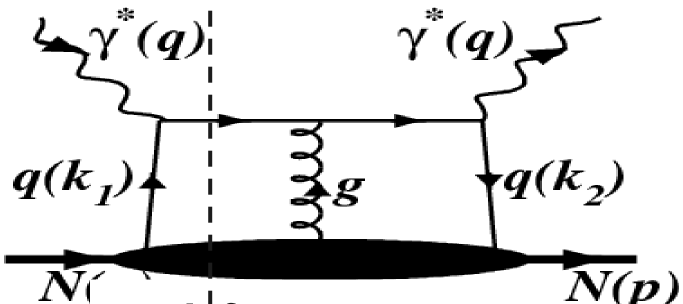
(without transverse momentum)

$\Longrightarrow$ $q(x,\vec{k}_\perp)$ $\otimes$ $d\sigma(eq \to eq)|_{k=xp}$

(with transverse momentum)

SIDIS with $k_\perp$: Direct consequence II

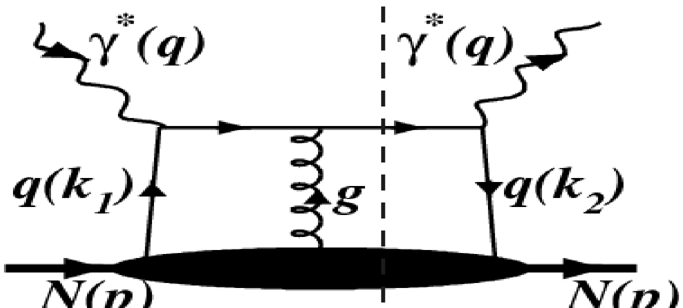
A simplification of $\tilde{W}^{(1,si)}_{\mu\nu}(q,p,S,k')$



left cut

$$\hat{H}^{(1,L)\rho}_{\mu\nu}(x_1,x_2)\omega_\rho^{\ \rho'}$$
$$=\frac{\pi}{2q\cdot p}\delta(x_1-x_B)\omega_\rho^{\ \rho'}\gamma_\mu\not{n}\gamma^\rho\bar{\not{n}}\gamma_\nu$$
$$\equiv\hat{H}^{(1)\rho'}_{\mu\nu}(x_1)$$

independent of x_2!



right cut

$$\hat{H}^{(1,R)\rho}_{\mu\nu}(x_1,x_2)\omega_\rho^{\ \rho'}$$
$$=\frac{\pi}{2q\cdot p}\delta(x_2-x_B)\omega_\rho^{\ \rho'}\gamma_\mu\bar{\not{n}}\gamma^\rho\not{n}\gamma_\nu$$
$$=\gamma_0\hat{H}^{(1)\rho'+}_{\mu\nu}(x_2)\gamma_0$$

independent of x_1!

SIDIS with $k_\perp$: Direct consequence II

This leads to

$$\tilde{W}_{\mu\nu}^{(1,si)}(q,p,S,k') = \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\sum_{c=L,R}\mathrm{Tr}[\hat{\Phi}_{\rho'}^{(1)}(k_1,k_2,p,S)\,\hat{H}_{\mu\nu}^{(1,c)\rho}(x_1,x_2)\,\omega_\rho^{\ \rho'}]$$
$$\times(2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_c-\vec{q})$$

$$= 2\mathrm{Re}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}[\hat{\varphi}_\rho^{(1)}(k,p,S)\hat{H}_{\mu\nu}^{(1)\rho}(xp)](2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

Only $\hat{\varphi}_\rho^{(1)}(k,p,S) \equiv \int \frac{d^4k_2}{(2\pi)^4}\hat{\Phi}_\rho^{(1)}(k,k_2,p,S)$

$$= \int d^4z e^{ikz}\langle p,S|\bar{\psi}(0)\mathcal{L}(0,z)D_\rho(z)\psi(z)|p,S\rangle$$

contributes in semi-inclusive deep-inelastic lepton-nucleon scattering.

Similar for $\tilde{W}_{\mu\nu}^{(2,si)}(q,p,S,k')$

SIDIS with $k_\perp$: differential cross-section to 1/Q^2

A complete twist-4 result for $e+N \to e+q+X$

$$\frac{d\sigma}{dxdyd^2k_\perp} = \frac{2\pi\alpha_{em}^2 e_q^2 1}{Q^2 y}\Big\{\left[1+(1-y)^2\right] f_q(x,k_\perp) - 4(2-y)\sqrt{1-y}\,\frac{|\vec{k}_\perp|}{Q}\, x f_{q\perp}(x,k_\perp)\cos\phi$$
$$-4(1-y)\frac{|\vec{k}_\perp|^2}{Q^2}\, x\left[\varphi_{\perp 2}^{(1)}(x,k_\perp) - \tilde{\varphi}_{\perp 2}^{(1)}(x,k_\perp)\right]\cos 2\phi$$
$$+8(1-y)\left(\frac{|\vec{k}_\perp|^2}{Q^2}\, x\left[\varphi_{\perp 2}^{(1)}(x,k_\perp) - \tilde{\varphi}_{\perp 2}^{(1)}(x,k_\perp)\right] + \frac{2x^2M^2}{Q^2} f_{q(-)}(x,k_\perp)\right)$$
$$-2\left[1+(1-y)^2\right]\frac{|\vec{k}_\perp|^2}{Q^2}\, x\varphi_{\perp 2}^{(2,L)}(x,k_\perp)\Big\}$$

TMD quark distribution: $$f_q(x,k_\perp) = \int \frac{dz^- d^2z_\perp}{(2\pi)^3} e^{ixp^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp}\langle p|\bar{\psi}(0)\mathcal{L}(0,z)\frac{\gamma^+}{2}\psi(z)|p\rangle$$

Quark correlation functions such as : $$f_{q\perp}(x,k_\perp) = \int \frac{dz^- d^2z_\perp}{(2\pi)^3} e^{ixp^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp}\langle p|\bar{\psi}(0)\mathcal{L}(0,z)\frac{\gamma\cdot k_\perp}{2k_\perp^2}\psi(z)|p\rangle$$

$$k_\perp^2\varphi_{\perp 2}^{(1)}(x,k_\perp) = -(2\hat{k}_\perp^\rho\hat{k}_\perp^\alpha + d^{\rho\alpha})\int \frac{dz^- d^2z_\perp}{(2\pi)^3} e^{ixp^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp}\langle p|\bar{\psi}(0)\mathcal{L}(0,z)\frac{\gamma_\alpha}{2}D_\rho(z)\psi(z)|p\rangle$$

SIDIS with $k_\perp$: Azimuthal asymmetries

Up to twist-4

$$\langle \cos\phi \rangle = -\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{|\vec{k}_\perp|}{Q}\frac{xf_{q\perp}(x,k_\perp)}{f_q(x,k_\perp)}$$

$$\langle \cos 2\phi \rangle = -\frac{2(1-y)}{1+(1-y)^2}\frac{|\vec{k}_\perp|^2}{Q^2}\frac{x[\varphi^{(1)}_{\perp 2}(x,k_\perp)-\tilde{\varphi}^{(1)}_{\perp 2}(x,k_\perp)]}{f_q(x,k_\perp)}$$

If g=0, i.e., no multiple gluon scattering (results by Cahn):

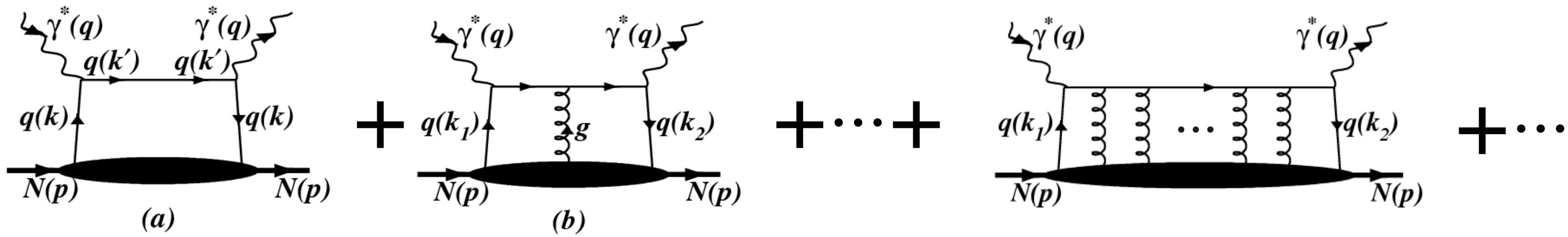
$$\langle \cos\phi \rangle |_{g=0} = -\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{|\vec{k}_\perp|}{Q},$$ **proportional to** $\frac{|\vec{k}_\perp|}{Q}$,

$$\langle \cos 2\phi \rangle |_{g=0} = -\frac{2(1-y)}{1+(1-y)^2}\frac{|\vec{k}_\perp|^2}{Q^2}$$ **proportional to** $\frac{|\vec{k}_\perp|^2}{Q^2}$,

⇨ **A good place to study such correlation functions and effects of multiple gluon scattering.**

Transverse momentum broadening in nucleus

Gauge link comes from:



Replace *N* by *A*, the gluons can connect to different nucleons in *A*.

Nuclear enhancement

Transverse momentum broadening

Transverse momentum broadening should be contained in the gauge link

With "maximal two gluon approximation":

$$f_q^A(x,\vec{k}_\perp) = \frac{A}{\pi \Delta_{2F}} \int d^2 l_\perp e^{-(\vec{k}_\perp - \vec{l}_\perp)^2/\Delta_{2F}} f_q^N(x,\vec{l}_\perp)$$

talk by Jian-hua Gao on 30th

Summary

- **Gauge link is result of multiple gluon scattering and collinear expansion is a necessary procedure to obtain the correct form.**
- **Collinear expansion can be extended to SIDIS $e+p \to e+q+X$.**
- **Naïve extension of TMD parton distributions convoluting with $eq \to eq$ cross section to include intrinsic transverse momentum is incorrect.**
- **Many other consequences.**

Summary

We see, in particular,

g=0, i.e., no multiple gluon scattering ⇨ gauge link $\mathcal{L}=1$ ⇨

① Sivers function $f_{1T}^{\perp}(x,k_\perp)=0$

② $\langle\cos\phi\rangle \propto \frac{|\vec{k}_\perp|}{Q}$,

③ $\langle\cos 2\phi\rangle \propto \frac{|\vec{k}_\perp|^2}{Q^2}$

④ may be no transverse momentum broadening in A

⑤ other effects ....

Measurements of $\langle\cos\phi\rangle$, $\langle\cos 2\phi\rangle$, A-dependence ⇨ multiple gluon scattering and structure of nucleon

Thank you for your attention!