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AZIMUTHAL ASYMMETRIES IN HARD SCATTERING PROCESSES

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- 'Deep' structure of hadrons
- Semi-inclusive leptoproduction and intrinsic transverse momenta
- Examples in leptoproduction
- Gluon distribution and fragmentation functions
- Examples in hadron-hadron scattering
- Summary and conclusions

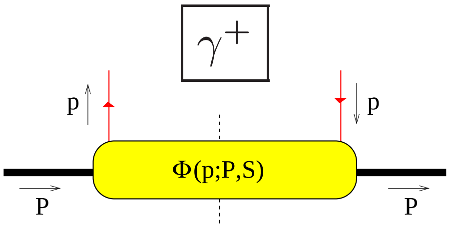
'DEEP' STRUCTURE OF HADRONS

(LEADING) QUARK DISTRIBUTION FUNCTIONS

Hadron structure enters hard processes via quark distribution functions corresponding to lightcone quark-quark correlators.

$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=\xi_T=0}$$

Leading part can be considered as a quark production matrix
For an unpolarized/spin 0 hadron:



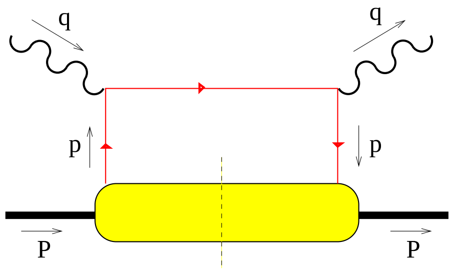
$$\sim M^{(\mathrm{prod})} \;=\; \begin{array}{cc} \begin{pmatrix} f_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & f_1 \end{pmatrix} & \begin{array}{c} \mathrm{R} \\ \\ \\ \mathrm{L} \end{array} \\ \begin{array}{cccc} \mathrm{R} & & & \mathrm{L} \end{array} & \end{array}$$

- Examples of hard processes: DIS or DY
- Yellow entries only relevant at subleading ($\propto 1/Q^{t-2}$) order, leaving only two "good" fields with chiralities right and left
- The distribution function f_1 depends on the (lightcone) fractional momentum $x = p^+/P^+$ of a quark in a hadron
- In DIS one can access distributions at $x_B = Q^2/2P\cdot q$
  In DY one can access distributions at $x_A = P_A\cdot q/P_A\cdot P_B$

SOFT PARTS IN HARD PROCESSES

Large scale Q leads in a natural way to the use of lightlike vectors: $n_+^2 = n_-^2 = 0$ and $n_+ \cdot n_- = 1$

$$\left.\begin{array}{l} q^2 = -Q^2 \\ P^2 = M^2 \\ 2\,P\cdot q = \frac{Q^2}{x_B} \end{array}\right\} \longleftrightarrow \left\{\begin{array}{l} P = \frac{x_B\,M^2}{Q\sqrt{2}}\,n_- + \frac{Q}{x_B\sqrt{2}}\,n_+ \\ \\ q = \frac{Q}{\sqrt{2}}\,n_- - \frac{Q}{\sqrt{2}}\,n_+ \end{array}\right.$$



part	'components' $-$	$+$	
HARD	$\sim Q$	$\sim Q$	
$H \to q$	$\sim 1/Q$	$\sim Q$	$\to \int dp^- \ldots$

Note: the lightlike vectors may be rescaled into dimensionful vectors $\hat{p} = (Q/x_B\sqrt{2})n_+$ and $\hat{n} = (x_B\sqrt{2}/Q)n_-$

$$P = \hat{p} + \frac{M^2}{2}\,\hat{n}$$

$$q = -x_B\,\hat{p} + \frac{Q^2}{2x_B}\,\hat{n}$$

(LEADING) QUARK STRUCTURE IN A NUCLEON

For a spin 1/2 hadron (e.g. nucleon) the quark distributions functions enter again in a quark production matrix. Omitting the higher twist entries one obtains in quark$\otimes$nucleon spin space

$$M^{(\mathrm{prod})} = \begin{array}{cc} \begin{pmatrix} f_1 + g_1 & 0 & 0 & 2\,h_1 \\ 0 & f_1 - g_1 & 0 & 0 \\ 0 & 0 & f_1 - g_1 & 0 \\ 2\,h_1 & 0 & 0 & f_1 + g_1 \end{pmatrix} & \begin{array}{c} R \rightarrow \\ \leftarrow R \\ L \rightarrow \\ \leftarrow L \end{array} \\ \begin{array}{cccc} R \rightarrow & \leftarrow R & L \rightarrow & \leftarrow L \end{array} & \end{array}$$

- The functions exist for every quark flavor: $f_1^q(x) = q(x)$, $g_1^q(x) = \Delta q(x)$, $h_1^q(x) = \delta q(x)$
- The three distribution functions are in principle independent!
- Positivity gives $f_1 \geq 0$ and $|g_1(x)| \leq f_1(x)$ but also the more stringent (Soffer) bound

$$|h_1(x)| \leq \frac{1}{2}\,(f_1(x) + g_1(x))$$

- The function h_1 is chirally odd and is not accessible in DIS

g_1 AND h_1 UNDER ROTATIONS

Effects of changing basis:

$$
M^{(\mathrm{prod})} \quad = \quad \begin{array}{cc}
\begin{pmatrix}
f_1 + g_1 & 0 & 0 & 2\,h_1 \\
0 & f_1 - g_1 & 0 & 0 \\
0 & 0 & f_1 - g_1 & 0 \\
2\,h_1 & 0 & 0 & f_1 + g_1
\end{pmatrix} &
\begin{array}{c} \mathrm{R}\rightarrow \\ \leftarrow\mathrm{R} \\ \mathrm{L}\rightarrow \\ \leftarrow\mathrm{L} \end{array} \\
\begin{array}{cccc} \quad\mathrm{R}\rightarrow & \quad\leftarrow\mathrm{R} & \quad\mathrm{L}\rightarrow & \quad\leftarrow\mathrm{L} \end{array} &
\end{array}
$$

$$
M^{(\mathrm{prod})} \quad = \quad \begin{pmatrix}
f_1 + h_1 & 0 & 0 & g_1 + h_1 \\
0 & f_1 - h_1 & g_1 - h_1 & 0 \\
0 & g_1 - h_1 & f_1 - h_1 & 0 \\
g_1 + h_1 & 0 & 0 & f_1 + h_1
\end{pmatrix}
$$

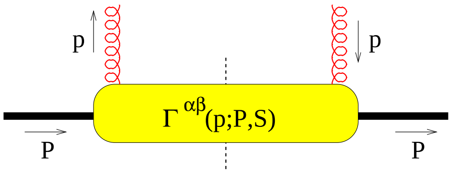
(LEADING) GLUON DISTRIBUTION FUNCTIONS

Leading gluon distribution functions correspond to lightcone correlators with transverse fields

$$\Gamma^{+\alpha;+\beta}(x) = \int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\, \langle P,S|F^{+\alpha}(0)F^{+\beta}(\xi)|P,S\rangle\Big|_{\xi^+=\xi_T=0}$$

This can be considered as a gluon production matrix

For an spin 0 or unpolarized hadron:



$$\sim M^{(\mathrm{prod})} = \begin{pmatrix} G(x) & 0 \\ 0 & G(x) \end{pmatrix}$$

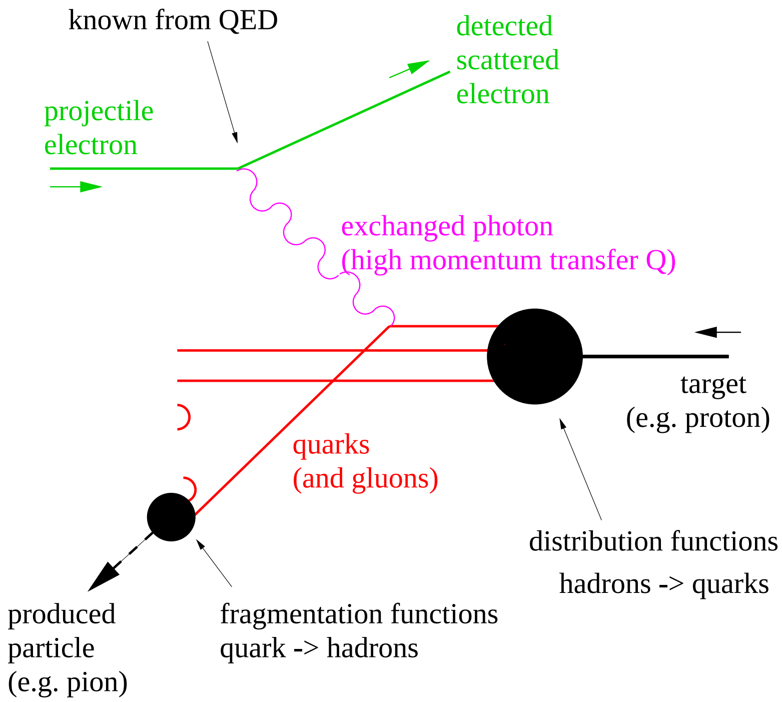
For a spin 1/2 hadron (e.g. nucleon) in gluon⊗nucleon spin space

$$M^{(\mathrm{prod})} = \begin{pmatrix} G+\Delta G & 0 & 0 & 0 \\ 0 & G-\Delta G & 0 & 0 \\ 0 & 0 & G-\Delta G & 0 \\ 0 & 0 & 0 & G+\Delta G \end{pmatrix}$$

SEMI-INCLUSIVE LEPTOPRODUCTION and INTRINSIC TRANSVERSE MOMENTA

SEMI-INCLUSIVE LEPTOPRODUCTION

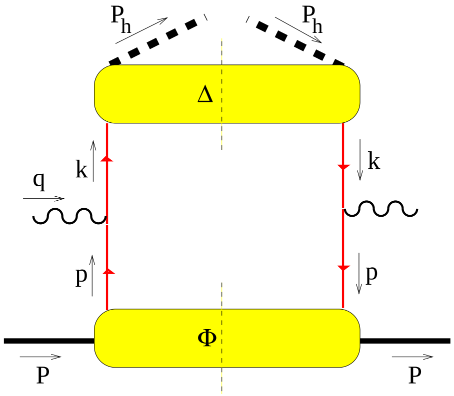
- Inclusive DIS $\longleftrightarrow$ $q(x) = f_1^q(x)$, $G(x)$ via evolution
- Polarization $\longleftrightarrow$ $\Delta q(x) = g_1^q(x) = q_R(x) - q_L(x)$, $\Delta G(x)$



- SIDIS $\longleftrightarrow$ tagging to get f_1^q and g_1^q for $q = u,\ d,\ s,\ c$
- Polarimetry $\longleftrightarrow$ measure $\delta q(x) = h_1^q(x) = q_\uparrow(x) - q_\downarrow(x)$
- Azimuthal dependence $\longleftrightarrow$ study intrinsic quark $\boldsymbol{k}_T$
- Single spin asymmetries $\longleftrightarrow$ T-odd fragmentation functions

Large scale Q leads in a natural way to the use of lightlike vectors: $n_+^2 = n_-^2 = 0$ and $n_+ \cdot n_- = 1$

$$\left.\begin{array}{l} q^2 = -Q^2 \\ P^2 = M^2 \\ P_h^2 = M_h^2 \\ 2\,P\cdot q = \frac{Q^2}{x_B} \\ 2\,P_h\cdot q = -z_h\,Q^2 \end{array}\right\} \longleftrightarrow \left\{\begin{array}{l} P_h = \frac{z_h\,Q}{\sqrt{2}}\,n_- + \frac{M_h^2}{z_h\,Q\sqrt{2}}\,n_+ \\[2ex] q = \frac{Q}{\sqrt{2}}\,n_- - \frac{Q}{\sqrt{2}}\,n_+ + q_T \\[2ex] P = \frac{x_B\,M^2}{Q\sqrt{2}}\,n_- + \frac{Q}{x_B\sqrt{2}}\,n_+ \end{array}\right.$$

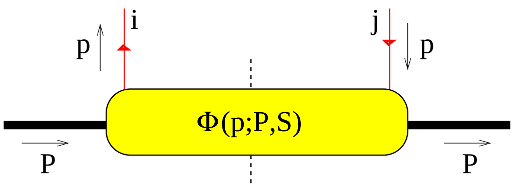


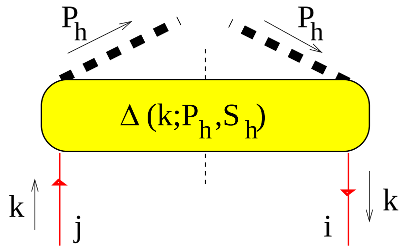
	$-$	$+$	
$q \to h$	$\sim Q$	$\sim 1/Q$	$\to \int dk^+ \ldots$
HARD	$\sim Q$	$\sim Q$	
$H \to q$	$\sim 1/Q$	$\sim Q$	$\to \int dp^- \ldots$

Three external momenta (P, P_h, q) $\to$ transverse direction relevant

$$q_T = q + x_B\,P - \frac{P_h}{z_h} = -\frac{P_{h\perp}}{z_h}$$

SOFT PART IN SIDIS





Hard inclusive (polarized) deep inelastic leptoproduction involves the soft part Φ integrated over all momenta except $p^+ \equiv x\, P^+$

$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi}\; e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=\xi_T=0}$$

Hard semi-inclusive (polarized) deep inelastic lepton-hadron scattering involves soft part Φ integrated over p^- with $p^+ \equiv x\, P^+$ and p_T

$$\Phi_{ij}(x,p_T) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3}\; e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=0}$$

Fragmentation into a hadron involves soft part integrated over k^- leaving $P_h^- = z k^-$ and $P_{h\perp} = -z k_T$

$$\Delta_{ij}(z,k_T) = \int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3}\; e^{ik\cdot\xi}\, \langle 0|\psi_i(\xi)|P_h,X\rangle\langle P_h,X|\overline{\psi}_j(0)|0\rangle\Big|_{\xi^-=0}$$

(LEADING) QUARK FRAGMENTATION FUNCTIONS

Quark fragmentation functions into unpolarized or spin 0 hadrons relevant in hard scattering processes are specific entries in the quark decay matrix in Dirac space

$$M^{(\mathrm{dec})} = \begin{array}{cc} \left(\begin{array}{cccc} D_1 & 0 & 0 & i\,\frac{|k_T|\,e^{-i\phi}}{M_h}\,H_1^\perp \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -i\,\frac{|k_T|\,e^{+i\phi}}{M_h}\,H_1^\perp & 0 & 0 & D_1 \end{array}\right) & \begin{array}{c} \mathrm{R} \\ \\ \\ \mathrm{L} \end{array} \\ \begin{array}{cccc} \mathrm{R} & \qquad & \qquad & \mathrm{L} \end{array} & \end{array}$$

- Examples of hard processes: e^+e^- annihilation and SIDIS
- Yellow entries only relevant at subleading ($\propto 1/Q^{t-2}$) order
- In quark decay time reversal invariance cannot be used $\longrightarrow$ T-odd fragmentation functions, in this case $H_1^\perp$
- The functions D_1 and $H_1^\perp$ depend on the ratio of (lightcone) momenta $z = P_h^-/k^-$ and on the transverse momentum of the quark wrt hadron (k_T)
- In SIDIS one can access the fragmentation functions at $z_h = P \cdot P_h / P \cdot q$ and $P_{h\perp} = -z_h\, k_T$
- The function $H_1^\perp$ is chiral-odd!

FULL QUARK & HADRON SPIN STRUCTURE

Quark distributions accessible including azimuthal asymmetries

$$
\begin{pmatrix}
f_1 + g_{1L} & \frac{|p_T|}{M}\, e^{i\phi}\, g_{1T} & \frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp} & 2\, h_1 \\
\frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T} & f_1 - g_{1L} & \frac{|p_T|^2}{M^2}\, e^{-2i\phi}\, h_{1T}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp} \\
\frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp} & \frac{|p_T|^2}{M^2}\, e^{2i\phi}\, h_{1T}^{\perp} & f_1 - g_{1L} & -\frac{|p_T|}{M}\, e^{i\phi}\, g_{1T} \\
2\, h_1 & -\frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T} & f_1 + g_{1L}
\end{pmatrix}
$$

- Transverse momentum dependence requires 2 hadrons: SIDIS/DY
- Transverse momentum dependent functions relate to twist three, but appear at leading order in $1/Q$
- T-odd functions appear as imaginary parts of off-diagonal entries for fragmentation functions: $G_{1T} + i\, D_{1T}^{\perp}$ and $H_{1L}^{\perp} + i\, H_1^{\perp}$
  New bounds (see BBHM, PRL 58 (2000) 712)
- Straightforward extensions for gluons, spin 1 hadrons, ...

RELATIONS IMPOSED BY LORENTZ INVARIANCE

$$\Phi(x) = \frac{1}{2}\left\{ f_1\, \not{n}_+ + \lambda\, g_1 \gamma_5\, \not{n}_+ + h_1\, \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} \right\}$$
$$+ \frac{M}{2P^+}\left\{ e + g_T\, \gamma_5\, \not{S}_T + \lambda\, h_L\, \frac{[\not{n}_+, \not{n}_-]\gamma_5}{2} \right\}$$

T-odd

$$+ \frac{M}{2P^+}\left\{ f_T\, \epsilon_T^{\rho\sigma} S_{T\rho}\gamma_\sigma - i\,\lambda\, e_L\, \gamma_5 + h\, \frac{i\,[\not{n}_+, \not{n}_-]}{2} \right\}$$

$$\frac{1}{M}\,\Phi_\partial^\alpha(x) = \frac{1}{2}\left\{ g_{1T}^{(1)}\, S_T^\alpha\, \gamma_5\, \not{n}_+ + \lambda\, h_{1L}^{\perp(1)}\, \frac{[\not{n}_+, \gamma^\alpha]\gamma_5}{2} \right.$$

T-odd

$$\left. + f_{1T}^{\perp(1)}\, \epsilon_T^{\alpha\beta} S_{T\beta}\, \not{n}_+ + h_1^{\perp(1)}\, \frac{i\,[\not{n}_+, \gamma^\alpha]}{2} \right\}$$

$$g_{1T}^{(1)} = g_{1T}^{(1)}(x) \equiv \int d^2\boldsymbol{p}_T\, \frac{\boldsymbol{p}_T^2}{2M^2}\, g_{1T}(x, \boldsymbol{p}_T)$$

From the most general (covariant) form for $\langle \overline{\psi}(0)\, \psi(\xi) \rangle$:

$$\underbrace{g_T - g_1}_{g_2} = \frac{d}{dx}\, g_{1T}^{(1)} \qquad \underbrace{h_L - h_1}_{\frac{1}{2}h_2} = -\frac{d}{dx}\, h_{1L}^{\perp(1)}$$

T-odd

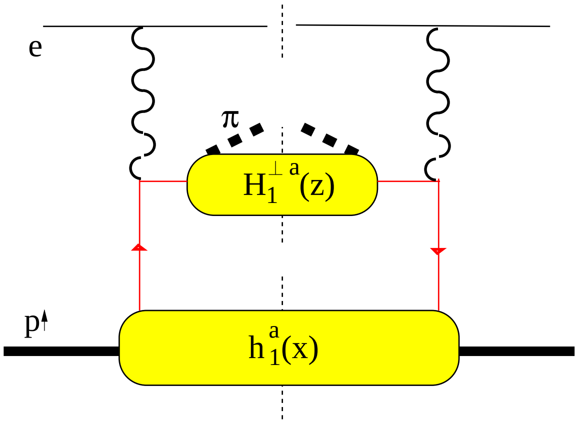
$$f_T = -\frac{d}{dx}\, f_{1T}^{\perp(1)} \qquad h = -\frac{d}{dx}\, h_1^{\perp(1)}$$

EXAMPLES IN LEPTOPRODUCTION

WHERE DO THE FUNCTIONS SHOW UP

- twist t of correlation functions
  $\Rightarrow$ behavior $(1/Q)^{t-2}$
- k_T-dependent functions
  $\Rightarrow$ azimuthal dependence $(\phi_\ell,\ \phi_h,\ \phi_S)$
- cross sections are chirally even
  Examples: $\propto f_1 \otimes D_1$
  $\propto h_1 \otimes H_1$
  $\propto e \otimes H_1^\perp$
  $\propto m\, f_1 \otimes H_1^\perp$
- $\#$ of spin vectors is even in case of a T-even combination
  Examples: $\propto \lambda_e\, S_L\, g_1 \otimes D_1$
  $\propto \lambda_e\, |\boldsymbol{S}_T|\, g_{1T}^{(1)} \otimes D_1$
  $\propto |\boldsymbol{S}_T|\, |\boldsymbol{S}_{hT}|\, h_1 \otimes H_1$
- $\#$ of spin vectors is odd in case of a T-odd combination (single spin asymmetries)
  Examples: $\propto \lambda_e\, e \otimes H_1^\perp$
  $\propto S_L\, h_L \otimes H_1^\perp$
  $\propto S_L\, h_{1L}^\perp \otimes H$
  $\propto |\boldsymbol{S}_T|\, h_1 \otimes H_1^\perp$
  $\propto |\boldsymbol{S}_T|\, f_{1T}^\perp \otimes D_1$

MEASURING h_1 VIA A SINGLE SPIN ASYMMETRY



J. Collins, NPB 396 (1993) 161

$$\left\langle \frac{Q_T}{M_\pi} \sin(\phi_h^\ell + \phi_S^\ell) \right\rangle_{OTO} = \frac{2\pi\alpha^2\, s}{Q^4}\, |\boldsymbol{S}_T|\, 2(1-y) \sum_{a,\bar{a}} e_a^2\, x_B\, h_1^a(x_B) H_1^{\perp(1)a}(z_h)$$

How large can $H_1^{\perp(1)}(z)$ become?

$$|H_1^{\perp(1)}(z, -z\boldsymbol{k}_T)| \quad = \quad |\frac{\boldsymbol{k}_T^2}{2M_\pi^2}\, H_1^{\perp}(z, -z\boldsymbol{k}_T)| \leq \frac{|\boldsymbol{k}_T|}{2M_\pi}\, D_1(z, -z\boldsymbol{k}_T)$$

With assumption

$$D_1(z, -z\boldsymbol{k}_T) \quad = \quad D_1(z)\, \frac{R_\pi^2(z)}{\pi\, z^2}\, e^{-\boldsymbol{k}_T^2\, R_\pi^2}$$

one finds

$$|H_1^{\perp(1)}(z)| \leq \underbrace{\frac{\sqrt{\pi}}{4M_\pi R_\pi(z)}}_{\mathcal{O}(1)}\, D_1(z)$$

GLUON DISTRIBUTION AND FRAGMENTATION FUNCTIONS

Gluon distributions accessible including azimuthal asymmetries

$$\begin{pmatrix} G+\Delta G_L & \frac{|p_T|e^{-i\phi}}{M}\,\Delta G_T & -\frac{|p_T|^2e^{-2i\phi}}{2M^2}\,H^\perp & 0 \\ \frac{|p_T|e^{+i\phi}}{M}\,\Delta G_T & G-\Delta G_L & 0 & -\frac{|p_T|^2e^{-2i\phi}}{2M^2}\,H^\perp \\ -\frac{|p_T|^2e^{+2i\phi}}{2M^2}\,H^\perp & 0 & G-\Delta G_L & -\frac{|p_T|e^{-i\phi}}{M}\,\Delta G_T \\ 0 & -\frac{|p_T|^2e^{+2i\phi}}{2M^2}\,H^\perp & -\frac{|p_T|e^{+i\phi}}{M}\,\Delta G_T & G+\Delta G_L \end{pmatrix}$$

- Transverse momentum dependence requires 2 hadrons: SIDIS/DY
- Bounds from positivity, e.g.

$$|H^{\perp(1)}| \le \sqrt{(G+\Delta G_L)(G-\Delta G_L)} \le G$$

$$|\Delta G_T^{(1)}| \le \frac{|p_T|}{2M}\sqrt{(G+\Delta G_L)(G-\Delta G_L)} \le \frac{|p_T|}{2M}G$$

- Interpretation of H as helicity flip amplitudes or differences of linearly polarized gluon densities

FULL GLUON & HADRON SPIN STRUCTURE

Gluon FF accessible including azimuthal asymmetries
for a spin 0 or unpolarized hadron

$$\begin{pmatrix} \hat{G}(z,-zk_T) & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat{H}^{\perp} \\ -\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat{H}^{\perp *} & \hat{G}(z,-zk_T) \end{pmatrix}$$

for a spin 1/2 hadron

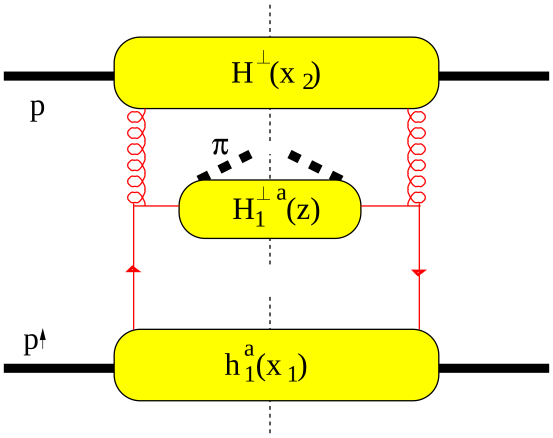
$$\begin{pmatrix} \hat{G}+\Delta\hat{G}_L & \frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat{G}_T^{*} & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat{H}^{\perp} & -i\,\frac{|k_T|^3 e^{-2i\phi}}{2M^3}\,\Delta\hat{H}_T^{\perp} \\ \frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat{G}_T & \hat{G}-\Delta\hat{G}_L & -i\,\frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat{H}_T & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat{H}^{\perp *} \\ -\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat{H}^{\perp *} & i\,\frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat{H}_T & \hat{G}-\Delta\hat{G}_L & -\frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat{G}_T \\ i\,\frac{|k_T|^3 e^{+2i\phi}}{2M^3}\,\Delta\hat{H}_T^{\perp} & -\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat{H}^{\perp} & -\frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat{G}_T^{*} & \hat{G}+\Delta\hat{G}_L \end{pmatrix}$$

T-odd functions (appearing as imaginary functions) are included except $\hat{G}_T$ and $\Delta\hat{H}_L^{\perp}$, which appear as imaginary parts: $\mathcal{I}m\,\Delta\hat{G}_T = \hat{G}_T$ and $\mathcal{I}m\,\hat{H}_{\perp} = \Delta\hat{H}_L^{\perp}$

EXAMPLES IN HADRON-HADRON SCATTERING

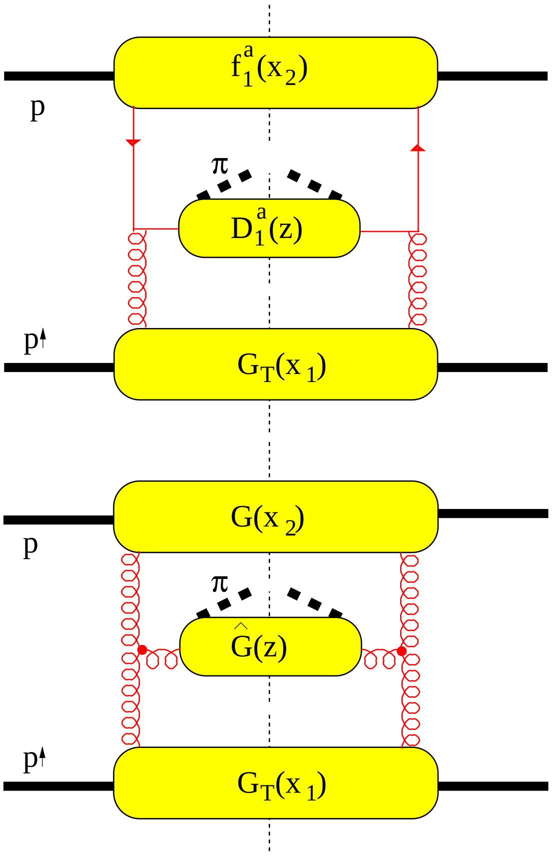
Three ways to get a single spin asymmetry:

Note: one of the soft parts must be asymptotic ($\propto \alpha_s/|p_T|^2$)



analogy of Collins asymmetry in ℓH

$$\propto \; \sin(\phi_\pi + \phi_S)\,(h_1^a \times H^{\perp}) \times (H_1^{\perp a})$$



other single-spin asymmetries
(a la Sivers effect)

$$\propto \; \sin(\phi_\pi - \phi_S)\,(G_T \times f_1^a) \times (D_1^a)$$

$$\propto \; \sin(\phi_\pi - \phi_S)\,(G_T \times G) \times (\hat{G})$$

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

Inclusive leptoproduction

- Quark DF $f_1^q(x)$ and $\bar{f}_1^q(x)$ for $q = u$, d, s, c
- Chirality distributions $g_1^q(x)$ and $\bar{g}_1^q(x)$
- Sum rules ($\longrightarrow$ moments of DF) and evolution (coupling to gluons)
- Gluon distributions, $G(x)$ and $\Delta G(x)$
- Higher twist distributions ($\longrightarrow$ quark-gluon correlations)

Semi-inclusive leptoproduction

1. **Flavor sensitivity** . . .
2. **Full forward spin structure** . . .
3. **Full spin structure (with k_T)** . . .

Hadroproduction

1. **Full spin structure (with k_T) accessible** . . .
2. **Need for specific situations** . . .

Semi-inclusive leptoproduction

1. **Flavor sensitivity**
   - Production via (favored) FF: $u \longrightarrow \pi^+$, $\bar{u} \longrightarrow \pi^-$, ...

$$\sum_q e_q^2\, f_1^q(x) \Rightarrow \sum_q e_q^2\, D_1^{q\to h}(z)\, f_1^q(x)$$

   - Gluon DF via charm production
2. **Full forward spin structure**
   - Access to chiral-odd DF h_1^q (need transverse pol.)
   - No mixing with gluons under evolution for chiral-odd DF
3. **Full spin structure**
   - p_T-dependent DF $\Rightarrow$ QCD dynamics (cf. higher twist)
   - Obtained from azimuthal dependence, in most cases requiring also polarization
   - T-odd FF (for spin 0 and 1/2 necessarily p_T-dependent) appear in single-spin asymmetries
   - The FF $H_1^\perp$ (chiral-odd and T-odd) can be used to access h_1^q via single-spin asymmetries

Hadroproduction

1. **Full spin structure (with k_T)**
   - Access to chiral-odd DF h_1^q (need transverse pol.)
   - . . . and many more functions obtained by looking at azimuthal dependences, in most cases requiring also polarization
2. **Need for specific situations**
   - lepton pair production (Drell-Yan)
   - Single-spin asymmetries pointing to production via T-odd fragmentation functions