Unraveling the partonic structure of hadrons

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HELMHOLTZ GEMEINSCHAFT

DESY

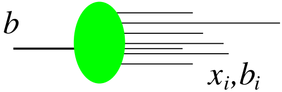
1. The main players: k_T and b_T dependent distributions
2. Polarization
3. Analyzing hard processes (selected remarks)
4. Conclusions

Transverse momentum dependent distributions

- describe emission of a parton with long. mom. fraction x and transverse mom. $\boldsymbol{k}_T$
  in fast hadron with $p_T = 0$
- appear in processes with measured transverse mom. $\boldsymbol{q}_T$ in final state
  more precisely: need process with large scale $Q \gg q_T$
- required to describe essential characteristic of final state
- extract from data using parameterizations
  calculate in models
  not accessible to lattice

Impact parameter dependent distributions

- describe emission of a parton with long. mom. fraction x and transverse position $\boldsymbol{b}_T$
  w.r.t. center of hadron localized in transv. plane



$b = \Sigma\, x_i b_i$

- $q(x, \boldsymbol{b}, Q)$ and hence $\boldsymbol{b}$ distribution
  depends on resolution (renormalization) scale Q
  calculable using standard DGLAP evolution

Impact parameter dependent distributions

- describe emission of a parton with long. mom. fraction x and transverse position $\boldsymbol{b}_T$
  w.r.t. center of hadron localized in transv. plane
- connected with generalized parton distributions

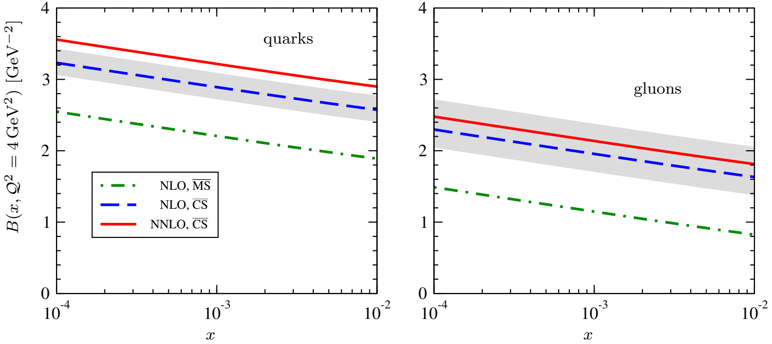
$$q(x, \boldsymbol{b}) = (2\pi)^{-2} \int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{\Delta b}}\, H^q(x, \xi = 0, t = -\boldsymbol{\Delta}^2)$$

  $\boldsymbol{\Delta} \leftrightarrow$ mom. transfer in exclusive processes

- extract from exclusive data using parameterizations
  calculate in models
  accessible to lattice $\rightarrow$ talk Ph. Hägler

Recent analysis of small-x DVCS and DIS data

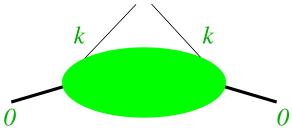
K. Kumerički, D. Müller and K. Passek-Kumerički, hep-ph/0703179



- $\langle b^2 \rangle = 4B(x, Q^2)$ different for sea quarks and gluons
- for gluons consistent with measurements of $\gamma p \to J/\Psi p$

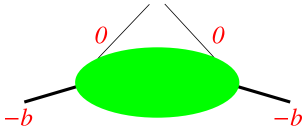
Mind the difference

k_T dependent distributions



$\int d^2\boldsymbol{z}\, e^{-i\boldsymbol{z}\boldsymbol{k}}\, \langle \mathbf{0}|\bar{q}(-\frac{1}{2}\boldsymbol{z}) \ldots q(\frac{1}{2}\boldsymbol{z})|\mathbf{0}\rangle$

impact parameter distributions



$\int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{b}\boldsymbol{\Delta}}\, \langle -\frac{1}{2}\boldsymbol{\Delta}|\bar{q}(\mathbf{0}) \ldots q(\mathbf{0})|\frac{1}{2}\boldsymbol{\Delta}\rangle$

(longitudinal variables not shown for simplicity)

Fourier conjugates:

average transv. momentum $\leftrightarrow$ difference of transv. positions

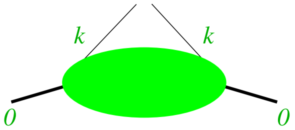
$q(x, \boldsymbol{k})$ — Wilson lines, Sudakov resummation, ...

difference of transv. momenta $\leftrightarrow$ average transv. position

$H(x, \boldsymbol{\Delta})_{\xi=0}$ — $q(x, \boldsymbol{b})$

Mind the difference

k_T dependent distributions



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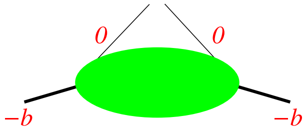

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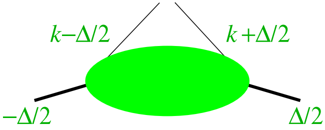
more general:

k_T dependent GPDs



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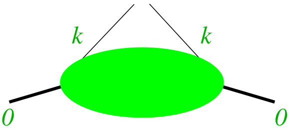

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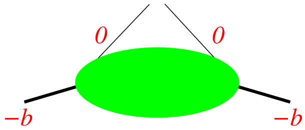

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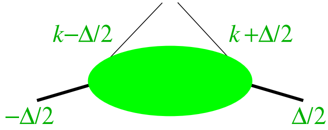

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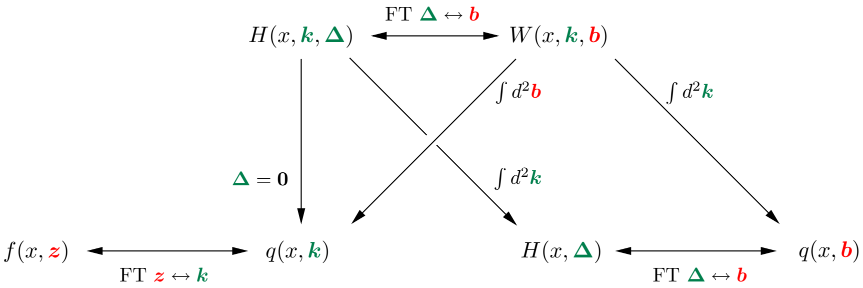
Fourier transf. from $\boldsymbol{\Delta}$ to $\boldsymbol{b}$
$\rightsquigarrow$ Wigner functions

Belitsky, Ji, Yuan '03

parton momentum and position
within limits of uncertainty rel'n

Relation between functions



- densities $q(x, \boldsymbol{k})$ and $q(x, \boldsymbol{b})$ not connected by Fourier transf.
- but descend from same function
  e.g. represent $H(x, \boldsymbol{k}, \boldsymbol{\Delta})$ through wave functions $\psi(x_i, \boldsymbol{k}_i)$
- dynamical relationship? $\rightarrow$ later

Now add spin

Basics: polarization vs. x $\Delta q(x), \quad \Delta g(x), \quad \delta q(x)$

Spin-orbit correlations: polarization vs.

- transverse momentum

$$f(x,\boldsymbol{k}^2) + \frac{(\boldsymbol{S}\times\boldsymbol{k})_z}{m}\, f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{(\boldsymbol{s}\times\boldsymbol{k})_z}{m}\, h_1^{\perp}(x,\boldsymbol{k}^2) + \ldots$$

$f_{1T}^{\perp}$ $\leftrightarrow$ Sivers effect $h_1^{\perp}$ $\leftrightarrow$ Boer-Mulders effect

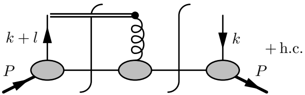
- transverse position

$$H(x,\boldsymbol{b}^2) - \frac{(\boldsymbol{S}\times\boldsymbol{b})_z}{m}\,\frac{\partial}{\partial\boldsymbol{b}^2} E(x,\boldsymbol{b}^2) - \frac{(\boldsymbol{s}\times\boldsymbol{b})_z}{m}\,\frac{\partial}{\partial\boldsymbol{b}^2} \bar{E}_T(x,\boldsymbol{b}^2) + \ldots$$

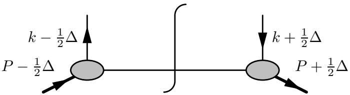
E $\leftrightarrow$ Pauli form fact. $F_2(t)$ for $\bar{E}_T$ no hard process known

Dynamical relations

- Sivers and Boer-Mulders functions are T-odd
  phases from initial/final state interactions
  between spectators and hard-scattering subproc.
  $\rightsquigarrow$ Wilson lines
- parton density: probab. to find parton
  given specified spectator interactions
- transv. polarization $\rightarrow$ spatial deformation of density
  $\rightarrow$ spectator interactions deform transv. mom. distribution
  chromodynamic lensing M. Burkardt '04
- spectator models generate both effects:



$f_{1T}^{\perp}$, $h_1^{\perp}$

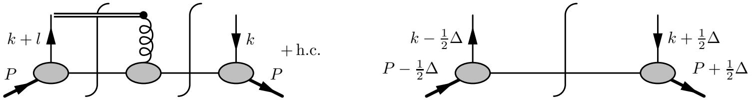


E, $\bar{E}_T$

Different relations

Burkardt; Burkardt, Hwang; Lu, Schmidt

- recent overview and extension: Meissner, Metz, Goeke '07
  - scalar quark-diquark model, quark/ gluon target in QCD
  - all twist-two functions



- integral relations

$$\langle \boldsymbol{k}^i \rangle = \int d^2\boldsymbol{k}\; \boldsymbol{k}^i\, \frac{(\boldsymbol{S}\times\boldsymbol{k})_z}{m}\, f_{1T}^{\perp}(x,\boldsymbol{k}^2) = \int d^2\boldsymbol{b}\; \boldsymbol{I}^i(x,\boldsymbol{b})\, \frac{(\boldsymbol{S}\times\boldsymbol{b})_z}{m}\, \frac{\partial}{\partial\boldsymbol{b}^2} E(x,\boldsymbol{b}^2)$$

impulse function $\boldsymbol{I}^i(x,\boldsymbol{b}) \sim (1-x)\,\frac{\boldsymbol{b}^i}{\boldsymbol{b}^2}$

  - same for Sivers and Boer-Mulders effects
  - same for all parton species
  - differs only by gluon/spectator coupling of the model

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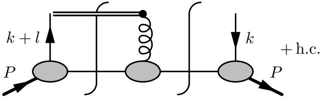

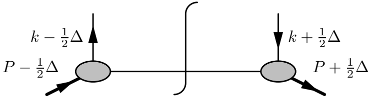

- with GPDs in momentum space

$$\int d^2\boldsymbol{k}\,\left(\frac{\boldsymbol{k}^2}{m^2}\right)^n f_{1T}^{\perp}(x,\boldsymbol{k}^2) \propto \frac{1}{1-x}\int d^2\boldsymbol{\Delta}\,\left(\frac{\boldsymbol{\Delta}^2}{m^2}\right)^{n-1} E\left(x, \frac{\boldsymbol{\Delta}^2}{(1-x)^2}\right)_{0<n<1}$$

$$\int d^2\boldsymbol{k}\, f_{1T}^{\perp}(x,\boldsymbol{k}^2) \propto \frac{1}{1-x}\,E(x,\boldsymbol{\Delta}^2=0)$$

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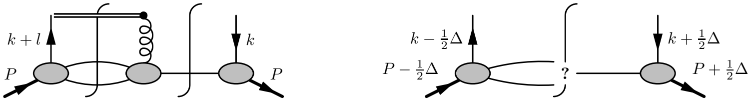

- limitations of these relations?
  - one-gluon exchange — M. Burkardt, hep-ph/0311013
  - coupling gluon/spectator(s)

how to generalize them to full QCD?

Dynamical origins (some questions)

what can we learn from

- distribution of transverse/longitudinal polarization
- spin-orbit correlations, orbital angular momentum
- flavor dependence (u vs. d), sea quarks, gluons

about QCD dynamics in hadrons?

- large-N_c limit — P. Pobylitsa '03
  spin-flavor symmetry at large N_c
- quark models — Pasquini, Boffi '07; Burkardt, Hannafious '07
  SU(6) symmetry, S wave $\oplus$ Melosh transformation
  study of Pasquini, Boffi: $m_q = 263\,\mathrm{MeV}$ vs. $m_p/3 = 313\,\mathrm{MeV}$
  study effects as fct. of $3m_q/m_p$ on lattice?

Dynamical origins (some questions)

what can we learn from

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extra insight from pion ?

- less experimental information (future opportunities?)
- model building, lattice studies possible
- different role of large-N_c limit than for baryons
- relevant for nucleon in meson-baryon fluctuation models

Single spin asymmetries

Ji, Qiu, Vogelsang, Yuan '06; Eguchi, Koike, Tanaka '06-07

twist three collinear factorization $\leftrightarrow$ twist two with transv. mom.

Qiu-Sterman $\leftrightarrow$ Sivers

- functions are related — Boer, Mulders, Pijlman '03

$$T_F(x,x) \;\propto\; \int d^2\boldsymbol{k}\; \boldsymbol{k}^2 f_{1T}^{\perp}(x,\boldsymbol{k}^2) \propto \langle \boldsymbol{k}^i \rangle$$

via operator identities $G^{+i} \to D^i \to \partial^i \to k^i$

Single spin asymmetries

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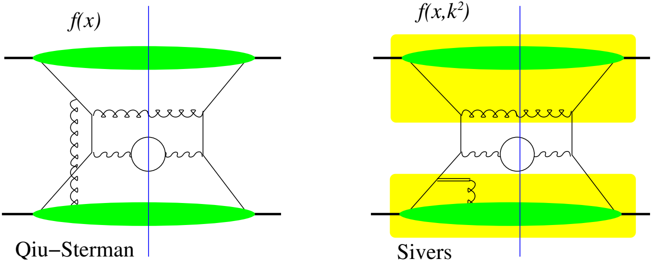
twist three collinear factorization	$\leftrightarrow$	twist two with transv. mom.
Qiu-Sterman	$\leftrightarrow$	Sivers

- describe same dynamics in Drell-Yan for $M \ll q_T \ll Q$



also for SIDIS

Sudakov resummation ... and all that

- Phenomenological work on unpolarized $p\bar{p}$ high-energy data
  Drell-Yan, W, Z or Higgs prod'n with measured q_T

  see e.g. C.-P. Yuan, talk at DIS 07

- based on formalism of Collins, Soper, Sterman '85
  joining low- and high-q_T descriptions

simplified:

$$\frac{d\sigma}{dQ^2\, d\boldsymbol{q}^2\, dy} \propto \int d^2\boldsymbol{b}\, e^{i\boldsymbol{bq}}\, \tilde{W}(\boldsymbol{b}, Q, x_1, x_2) + \text{term for } \boldsymbol{q}^2 \sim Q^2$$

$$\tilde{W} = e^{-S(b^*,Q)}\, f(x_1; 1/b^*)\, f(x_2; 1/b^*)\, e^{-F_1(b,x_1) - F_1(b,x_2) - F_2(b) \log Q^2}$$

$S =$ Sudakov factor $\qquad b^* = b/\sqrt{1 + b^2/b^2_{max}} \le b_{max}$

$f(x;\mu) =$ collinear PDFs $\qquad F_{1,2} =$ non-perturb. functions, e.g. $\propto g_{1,2}\, b^2$

- relation with $f(x, \boldsymbol{k}^2)$? universality ?

Proper definition of transv. mom. distributions

Collins, Soper, Hautmann, Ji, Metz, ... $\rightarrow$ talk J. Collins

- must be adequate for factorization of considered process
- construction of Wilson lines $\leftrightarrow$ spectator interactions
  universality of fragmentation fcts. (e^+e^-, SIDIS)
- for k_T dependent fcts.
  light-like Wilson lines $\rightarrow$ divergences in parton rapidity
  requires regulator/subtraction: not unique choice

  e.g. Ji, Ma, Yuan '04:

  $$q(x, \boldsymbol{k}^2; \mu, x\zeta, \rho)$$

  where $\mu =$ UV subtraction, $\alpha_s(\mu)$
  $\zeta, \rho =$ rapidity regulator and soft subtraction
- relation $\int d^2\boldsymbol{k}\; q(x, \boldsymbol{k}^2; \ldots) \overset{?}{\leftrightarrow} q(x; \mu)$

Establishing factorization (or its breaking)

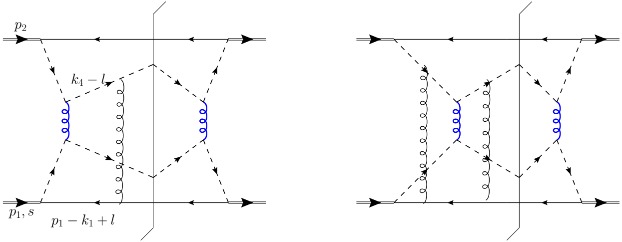
- beyond (k_T dependent) twist two in e^+e^-, SIDIS, DY ?
  e.g. Cahn effect → azimuthal distributions

Establishing factorization (or its breaking)

- hadron-hadron collisions with jets, heavy flavor, ... ?

J. Collins, J.-W. Qiu '07

"Factorization is violated in production of high-transverse-momentum particles in hadron hadron collisions"



dijet production with measured transv. momenta
fact. breaking already in unpolarized cross section

Establishing factorization (or its breaking)

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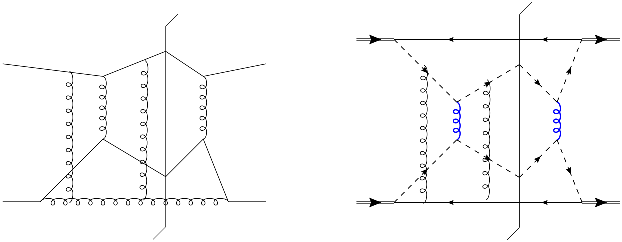

  dijet production with measured transv. momenta
  fact. breaking already in unpolarized cross section

- in hard scattering mechanism only appears at NNNLO

Conclusions

quarks and gluons don't live in one dimension

- distribution of partons in transverse momentum and position:
  fundamental properties
- even in unpolarized sector still not well known
- spin ⇝ windows for insight into dynamics/novel effects
  orbital angular momentum $\boldsymbol{L} = \boldsymbol{x} \times \boldsymbol{p}$
- proper theoretical treatment of k_T remains challenge
  correct and useful definitions
  (limits of) factorization

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Much remains to be done
$\rightarrow$ let's have a fruitful workshop