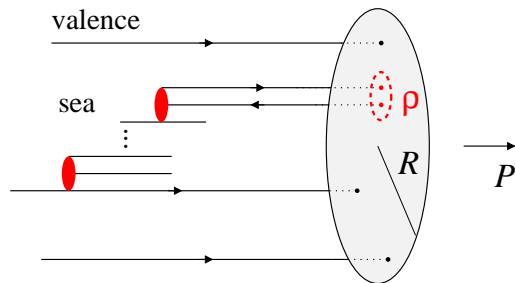
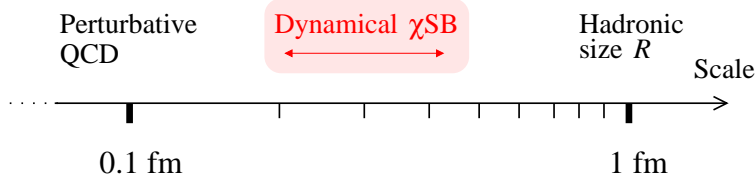


Transverse nucleon structure and chiral symmetry breaking

C. Weiss (JLab), Penn State HEP/Astrophysics Seminar, 17-Apr-13 JHEP 1301 (2013) 163

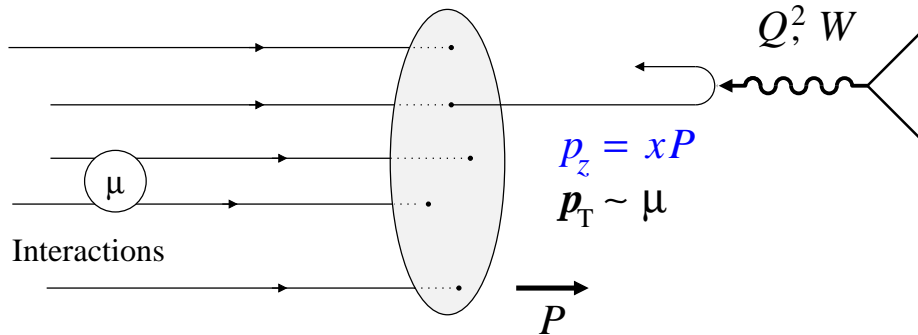


Q: How does χ SB scale $\rho \sim 0.3$ fm express itself in nucleon's partonic structure?

- Intrinsic transverse momenta
- Parton correlations

- Nucleon structure in QCD
 - Parton model
 - QCD radiation, factorization
- Chiral symmetry breaking in QCD
 - Non-perturbative scale $\rho \ll R$
 - Effective description: Constituent quarks, Goldstone bosons
- Effect on partonic structure
 - $p_T(\text{sea}) \gg p_T(\text{valence})$
 - Short-range correlations of partons
- Experimental tests
 - Single-particle inclusive $P_{T,h}$ distributions
HERMES, COMPASS, JLab12, EIC
 - Correlations current \leftrightarrow target regions EIC
 - Multiparton interactions Tevatron, LHC

Nucleon structure: Parton model



- Hadron as composite system

Pointlike constituents with interactions of finite range μ
Relativistic, can create/annihilate particles

System moves with $P \gg \mu$

Constituents' momenta
longitudinal $p_z = xP$
transverse $p_T \sim \mu$

$$\sigma_T \sim \frac{x f(x)}{Q^2} \quad \text{Bjorken scaling}$$

$$f(x) = \int d^2 p_T f(x, p_T)$$

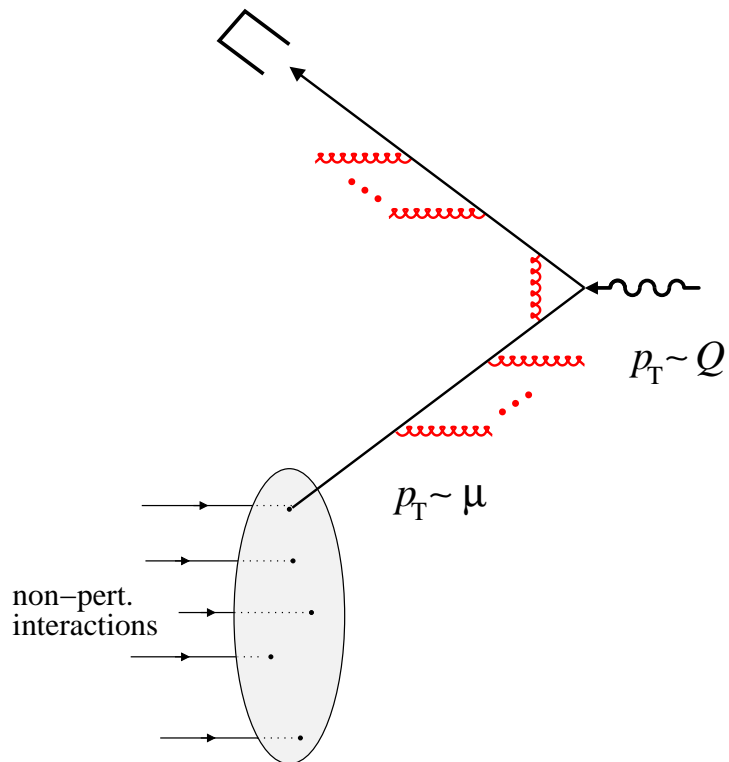
Parton density in
longit. momentum

- Scattering process $Q^2, W^2 \gg \mu^2$

Electron scatters from quasi-free constituent with momentum fraction $x = Q^2 / (W^2 - M_N^2 + Q^2)$

Transverse momenta integrated over, integral converges $p_T \sim \mu$

Nucleon structure: QCD



$$\begin{aligned} \sigma_T &\sim [\text{parton density}] && \sim \mu \\ &\times [\text{radiation}] \\ &\times [\text{scattering process}] && \sim Q \end{aligned}$$

- QCD radiation

Real emissions with p_T from $\sim \mu$ to Q
 Virtual radiation renormalizes couplings

- Factorization

Separation of scales in regime $Q^2 \gg \mu^2$

Inclusive scattering $\gamma^* N \rightarrow X$:
 Net radiation effect simple
 Factorization well understood

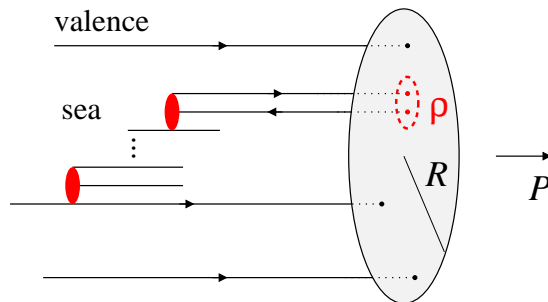
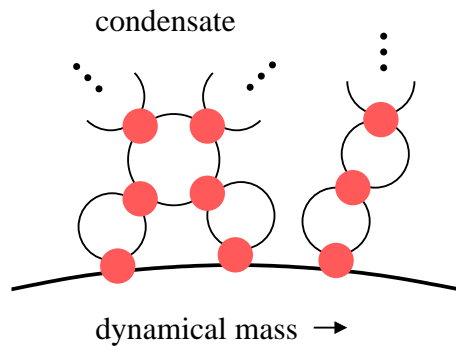
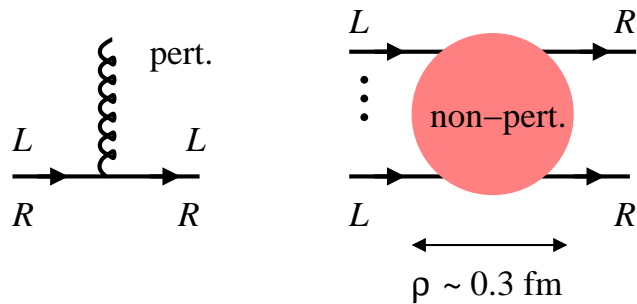
Semi-inclusive $\gamma^* N \rightarrow h(\text{low } P_T) + X'$:
 Radiation effect more complex
 Final-state interactions of struck parton
 Factorization more challenging
 Much progress: Collins 11 \rightarrow Seminar T. Rogers

Parton density as $\langle N | \text{QCD-operator} | N \rangle$,
 universal, process-independent
 Collins, Soper 82, . . .

- Parton transverse momentum

$p_T \sim Q$ pert. QCD, calculable
 $p_T \sim \mu$ nonpert. interactions \leftarrow this talk!

Chiral symmetry breaking: Physical picture



- Chiral symmetry breaking in QCD

Pert. interactions conserve quark chirality L, R

Non-pert. gluon fields can flip chirality

Topological gauge fields, instantons

Condensate of $q\bar{q}$ pairs $\langle \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \rangle$, pion as collective excitation

Order parameter, Goldstone boson

Dynamical mass generation:

Constituent quarks, hadron structure

Euclidean correlation functions \rightarrow Lattice, analytic methods

- Short-range interactions $\rho \sim 0.3 \text{ fm}$

New dynamical scale $\rho \ll R$

Shuryak; Diakonov, Petrov 80's

Gauge-invariant measure of $q\bar{q}$ pair size

$\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle \sim 1 \text{ GeV}^2$ "average virtuality"

Lattice: Teper 87, Doi 02, Chiu 03. Instantons: Polyakov, CW 96

- How does it affect partonic structure?

Valence quark mostly in configurations of size $\sim R$

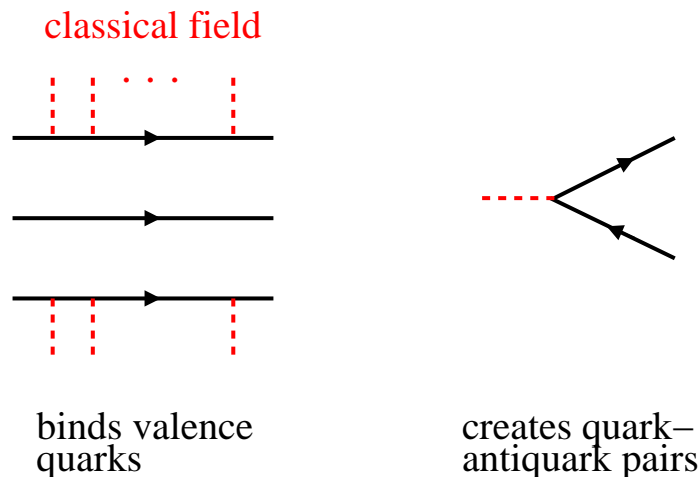
Sea quarks in correlated pairs of size $\lesssim \rho$

Can we quantify it? . . . Dynamical model!

Chiral symmetry breaking: Dynamical model



$$L_{\text{eff}} = \bar{\psi} (i\partial - M e^{i\gamma_5 \tau \pi / f_\pi}) \psi$$



- Effective description of χ SB

Diakonov, Eides 83; Diakonov, Petrov 86

Constituent quarks/antiquarks with dynamical mass $M \sim 0.3-0.4$ GeV

Coupled to chiral field (Goldstone boson) with eff. coupling $M/f_\pi = 3-4$ strong!

Valid up to χ SB scale ρ^{-2} :
Matching with QCD quarks/gluons

Field theory, solved non-perturbatively in $1/N_c$ expansion

- Nucleon as chiral soliton

Diakonov, Petrov, Poblitsa 88; Kahana, Ripka 84

Classical chiral field

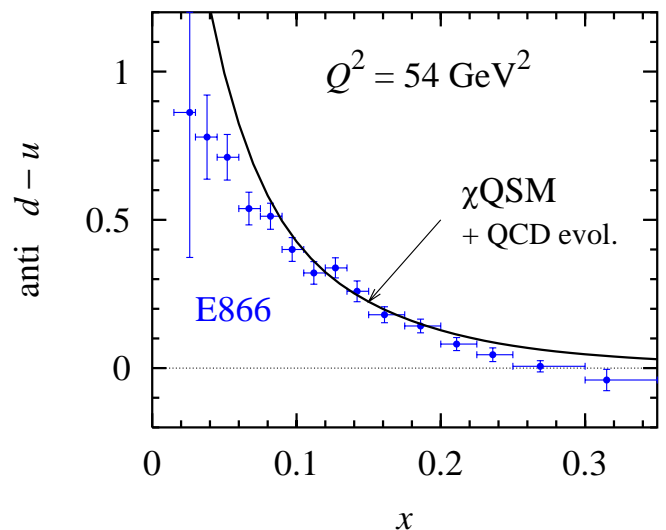
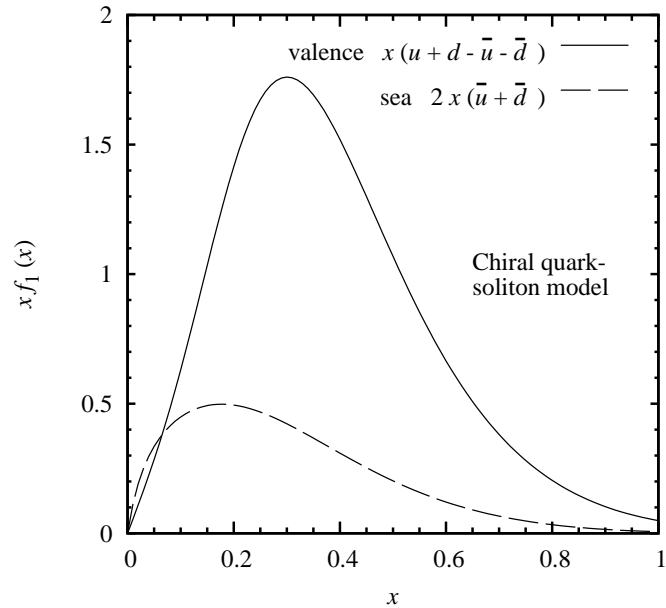
"Hedgehog" $\pi \parallel \mathbf{r}$ in rest frame, cf. skyrmion

Binds valence quarks, creates quark-antiquark pairs

Relativistic mean-field approximation

Field theory: Completeness, conservation laws, positivity $\rho^{-2} \gg M^2$
No Fock space truncation! \rightarrow PDFs, sea quarks

Chiral symmetry breaking: Parton distributions



- Parton densities in model

Diakonov, Petrov, Pobylitsa, Polyakov, CW 96+; Wakamatsu et al. 97+

$$f^q(x, \mathbf{p}_T) = \langle N | a^\dagger a(xP, \mathbf{p}_T) | N \rangle_{P \rightarrow \infty}$$

$$f^{\bar{q}}(x, \mathbf{p}_T) = b^\dagger b$$

Quark/antiquark number densities at $P \rightarrow \infty$
equivalent to light-cone correlation function $\bar{\psi} \dots \psi$

p_T integral convergent due to cutoff ρ^{-2}

Intrinsic p_T distributions, not “TMDs” no FSI!

- Interpretation

x and p_T distribution of constituent quarks and antiquarks effective DOF

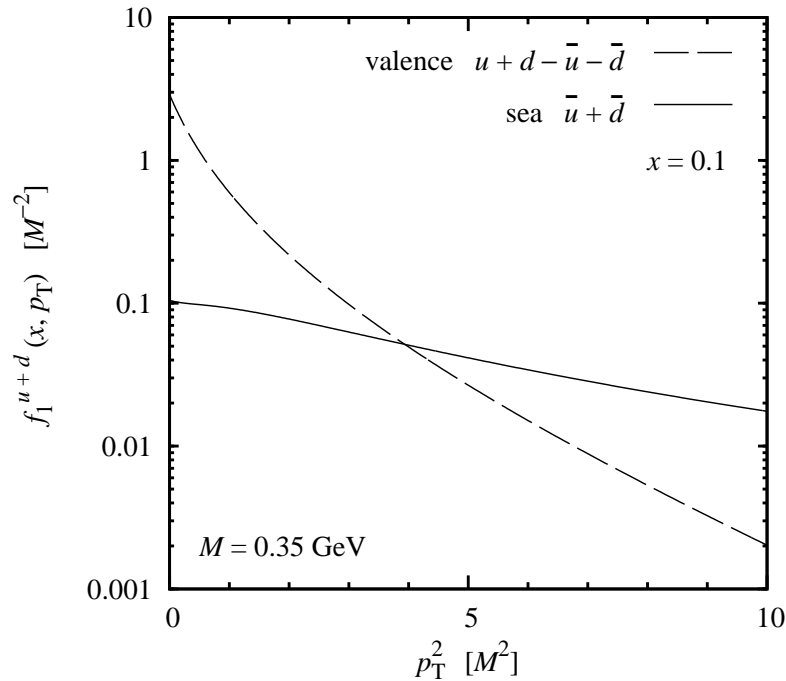
Matching with QCD quarks, antiquarks and gluons at scale ρ^{-2}

PDF fits show 30% of nucleon momentum carried by gluons at $\mu^2 \sim 0.5 \text{ GeV}^2$: “Accuracy” of model

- Flavor asymmetries

Describes well measured $\bar{d} - \bar{u}$ E866 Drell-Yan
Predicts sizable $\Delta \bar{u} - \Delta \bar{d} \rightarrow$ DSSV, RHIC W

Partonic structure: p_T distributions



Sea quark p_T distribution qualitatively different from valence quarks!

- Valence quarks $q - \bar{q}$

$p_T \sim R^{-1}$, approximate Gaussian shape

$\langle p_T^2 \rangle \approx 0.15 \text{ GeV}^2$, weakly x -dependent

- Sea quarks \bar{q}

Power-like tail $f^{\bar{q}}(x, p_T) \sim C(x)/p_T^2$
up to cutoff scale ρ^{-2}

Structure determined by low-energy
chiral dynamics, model-independent

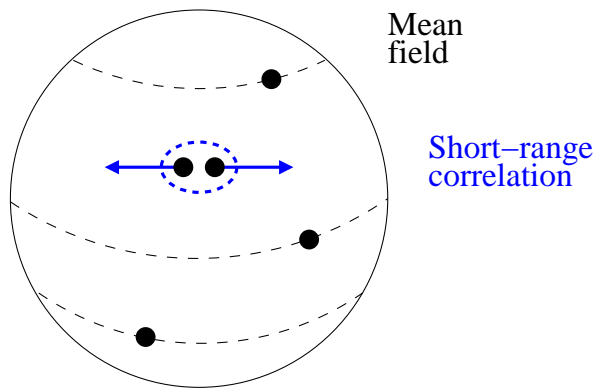
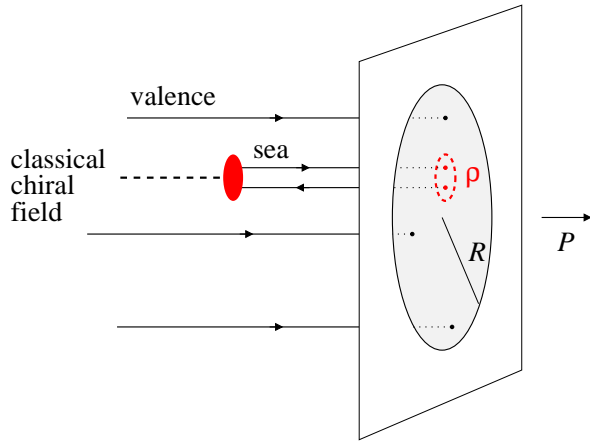
$p_T^2 \sim \rho^{-2}$: Some model dependence
from UV cutoff

Similar tail in $\Delta\bar{u} - \Delta\bar{d}$

- Qualitative difference

Generic feature, rooted in
dynamical scale $\rho \ll R$

Partonic structure: Short-range correlations



Parton SRCs as imprint of χ SB on partonic structure

- Parton short-range correlations

Sea quarks in nucleon LC wave function partly in correlated pairs of size $\rho \ll R$
Explains high-momentum tail of p_T distribution

Pairs have distinctive spin-isospin structure:
Scalar-isoscalar Σ , pseudoscalar-isovector Π

Restoration of chiral symmetry at high p_T :
 $|\Psi_\Sigma|^2 = |\Psi_\Pi|^2$ at $p_T^2 \sim \rho^{-2} \gg M^2$

Large effect: Fraction of correlated sea is $O(1)$

- Cf. NN short-range correlations in nuclei

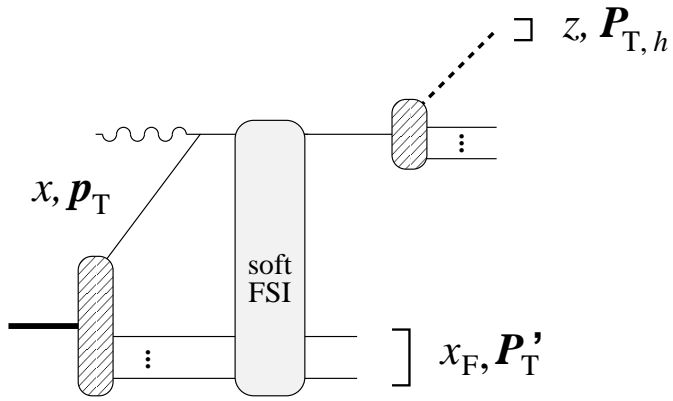
Mean field $\Psi(\mathbf{r}_1, \dots, \mathbf{r}_N) \approx \prod_i^N \Phi(\mathbf{r}_i)$

Rare configs with $|\mathbf{r}_i - \mathbf{r}_j| \ll$ average
experience short-range NN interaction,
generate high momentum components

Indirect probes: Momentum distributions, $x > 1$
Direct probes: $(e, e' NN)$ in special kinematics
JLab Hall A, CLAS, Hall C at 12 GeV

... What about parton correlations?

Measurements: Single-particle inclusive



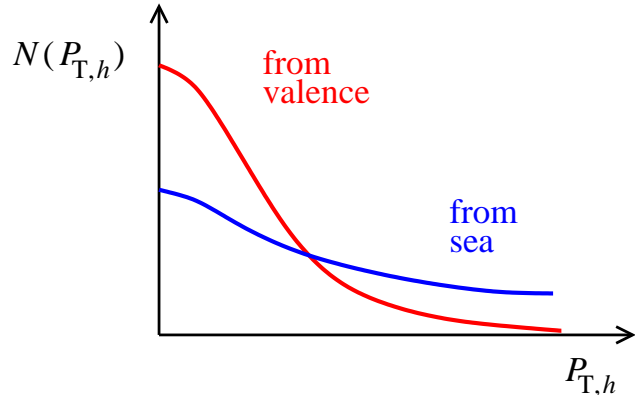
- Hadron $P_{T,h}$ distributions in SIDIS

Intrinsic p_T in WF
 Final-state interaction
 Parton fragmentation

} Observable $P_{T,h}$

External handles: $z \leftrightarrow x, z \leftrightarrow P_{T,h}$
 To be explored with CLAS12: Kinematic coverage

- Separate valence and sea quarks in target



Charge separation with pions

$$N(\pi^+ - \pi^-) \propto e_u^2(u - \bar{u}) - e_d^2(d - \bar{d})$$

$$N(\pi^+ + \pi^-) \propto e_u^2(u + \bar{u}) + e_d^2(d + \bar{d})$$

Charge separation with kaons:
 u dominance, $s = \bar{s}$ fragmentation

$$N(K^+) \propto u \quad \text{mostly valence}$$

$$N(K^-) \propto \bar{u}$$

Sea quarks contribute only at $x \sim 0.1$
 Intrinsic p_T manifest only at $z > 0.5$
 12 GeV kinematics probably marginal.
 Schweitzer, Strikman, CW 12; simulations in progress

Different widths of valence/sea affect
 flavor separation if $P_{T,h}$ coverage incomplete
 Frankfurt et al. 89; Christova, Leader 01

Measurements: Correlations

- Hadron correlations between current and target fragmentation regions

Unravel SIDIS mechanism:
What balances observed $P_{T,h}$?

Observe nonpert. correlations induced by χ SB

- Kinematics for nonperturbative correlations

Sufficient separation in rapidity
 $\Delta y \approx \ln[W^2 / (P_{T,h}^2 + m_h^2)] \gtrsim 4$

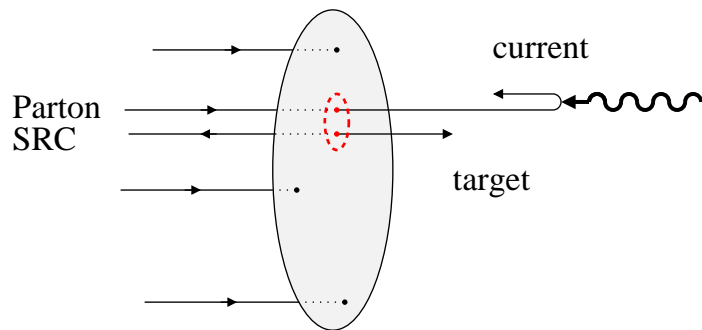
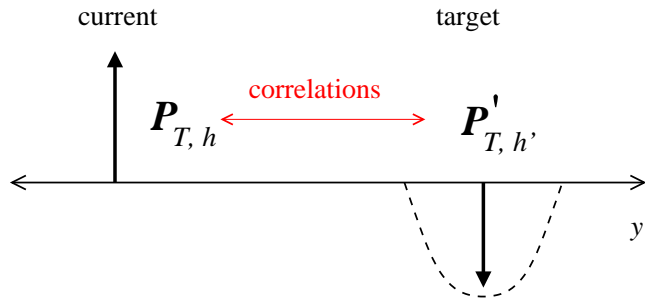
Moderate virtuality to avoid pQCD radiation
 $Q^2 \sim \text{few GeV}^2$

Momentum fractions of nonperturbative sea
 $x \sim 0.05\text{--}0.1$

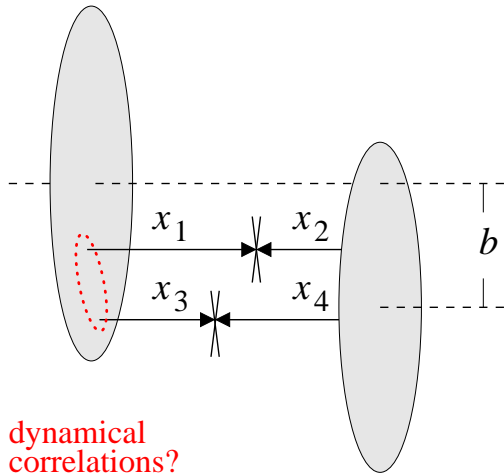
→ “Kinematic window” at $W^2 \approx 30 \text{ GeV}^2$,
 $P_{T,h}^2 \approx 0.5 \text{ GeV}^2$

COMPASS: Detection of target fragments? EIC: Medium energies ideal
JLab12: Probably marginal, but should be explored

- Other option: Exclusive meson production
“Knockout” of correlated $q\bar{q}$ pairs. Many possibilities with JLab12!



Measurements: Multiparton processes in pp



- Double dijet rate parametrized by σ_{eff}^{-1}

Mean field $\sigma_{\text{eff}} = \pi R_{13}^2$ avg distance btw collision points.
Calculable from transverse distributions

$$\sigma_{\text{eff}}^{-1} (\text{mean field}) = \int d^2b P_{12}(b) P_{34}(b)$$

- Observed enhancement

CDF/D0 3jet + γ rate two times larger than mean field with $\langle \rho^2 \rangle (x \sim 0.1)$

Possible explanation: Parton correlations
FSW, *Annalen Phys.* 13 (2004)

Perturbative vs. nonperturbative correlations?
Higher-order vs. multiparton processes?

Many challenges. Blok, Dokshitzer, Frankfurt, Strikman 11

$$\frac{\sigma(12; 34)}{\sigma(12)\sigma(34)} = \frac{1}{\sigma_{\text{eff}}}$$

$$\times \frac{f(x_1, x_3)f(x_2, x_4)}{f(x_1)f(x_2)f(x_3)f(x_4)}$$

- LHC: High rates for multijet events

Background to new physics processes

Detailed studies of parton correlations

New field of study. Great interest! MPI@TAU Tel Aviv 2012

Summary

- Dynamical χ SB in QCD creates short-distance scale $\rho \ll R \sim 1 \text{ fm}$

Natural scale for separating soft wave function \leftrightarrow pQCD radiation

- Qualitatively different p_T distributions of valence and sea quarks

Valence quarks $p_T \sim R^{-1}$

Sea quarks “tail” $p_T \lesssim \rho^{-1}$

- Parton short-range correlations in nucleon

Imprint of QCD vacuum on partonic structure

- Experimental tests

Separate valence and sea quarks in single-particle inclusive DIS:
Charged pions, kaons. Details simulations in progress.

Correlations between current and target fragmentation regions:
Kinematic window for non-perturbative correlations. Ideal for medium-energy EIC

Exclusive meson production: Knockout of correlated $q\bar{q}$ pair.
Exploratory studies in progress.

Multiparton interactions in high-energy pp collisions