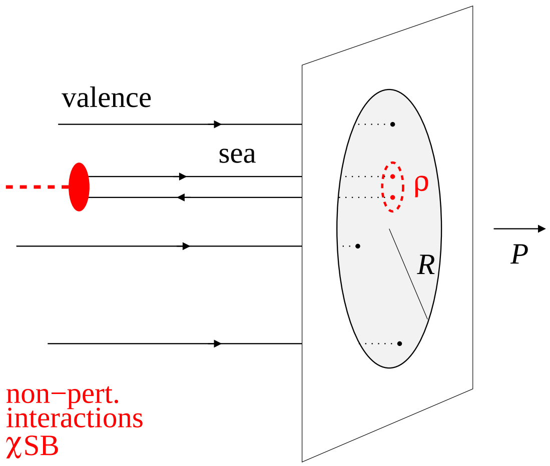
Intrinsic p_T and parton correlations from non-perturbative QCD

C. Weiss (JLab), Hall A Collaboration Meeting 10–Dec–12, arXiv:1210.1267



Q: How does nonperturbative QCD express itself in nucleon's partonic structure?

Short-distance scale $\rho \sim 0.3$ fm from chiral symmetry breaking

$\rightarrow$ Intrinsic p_T
$\rightarrow$ Parton correlations

- Chiral symmetry breaking in QCD

  Short–distance scale $\rho \ll R$

  Dynamical model: Chiral constituent quarks

- Effect on partonic structure

  $p_T(\text{sea}) \gg p_T(\text{valence})$

  Short–range correlations in nucleon LC wave function

- Experimental tests

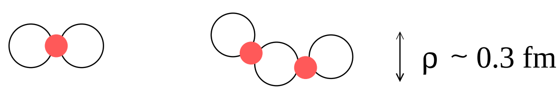
  Single–particle inclusive: $P_{T,h}$ distributions, valence vs. sea HERMES, COMPASS, JLab12, EIC

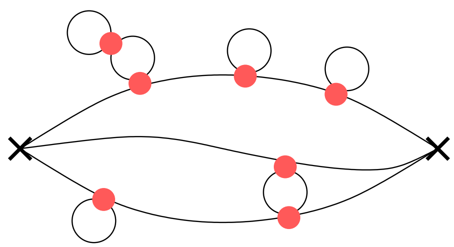
  Hadron correlations between current and target fragmentation regions JLab12, medium-energy EIC with forward detection

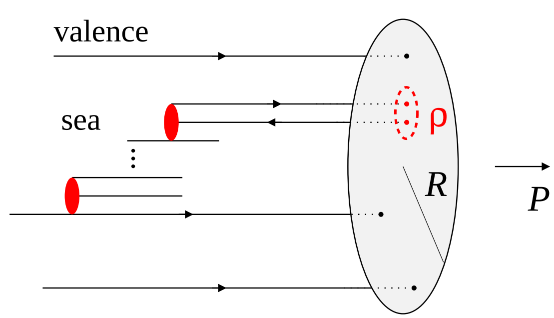
  Exclusive meson production JLab12
  Multiparton interactions Tevatron, LHC

  Conceptual aspects: TMD definition, QCD evolution, mean-field and correlations in LCWF $\rightarrow$ Theory seminar

Chiral symmetry breaking: Short–distance scale







- χSB in QCD vacuum

  Strong gluon fields of size $\rho \ll R \sim 1\,\text{fm}$
  Shuryak; Diakonov, Petrov 80's

  Condensate of $q\bar{q}$ pairs, π as collective excitation

  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

  Nucleon: Dynamical mass, short–range interactions
  Euclidean correlation functions $\rightarrow$ Lattice, analytic methods

- How does it affect partonic structure?

  Nucleon fast–moving $P \rightarrow \infty$:
  Wave function description Feynman, Gribov 70's

  Valence quark configurations of size $\sim R$

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

  Soft wave function at scale ρ^{-2}
  QCD radiation builds up $p_T^2 \sim Q^2$ in hard processes

Can we quantify it? . . . Dynamical model!

Chiral symmetry breaking: Objectives

- Construct dynamical model of partonic wave function at low scale

  Effective degrees of freedom: Constituent quarks, chiral fields

- Follow guiding principles

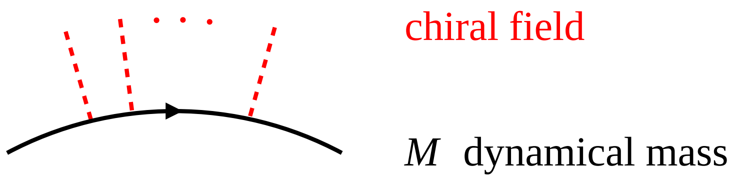
Scales	Short–distance scale $\rho \ll R$
Symmetries	Chiral invariance
Parametric expansion	$1/N_c$ expansion

- Explore qualitative features of partonic structure

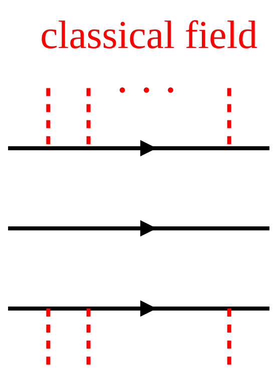
  Proof of principle

  Detailed modeling possible with further phenomenological input

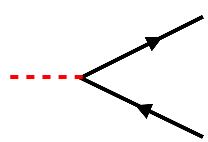
Chiral symmetry breaking: Dynamical model



$$L_{\text{eff}} = \bar{\psi} \left(i\not{\partial} - M e^{i\gamma_5 \boldsymbol{\tau}\boldsymbol{\pi}/f_\pi} \right) \psi$$



binds valence quarks



creates quark–antiquark pairs

- Effective description of χSB
  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 χSB scale ρ^{-2}: Matching with QCD quarks/gluons

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

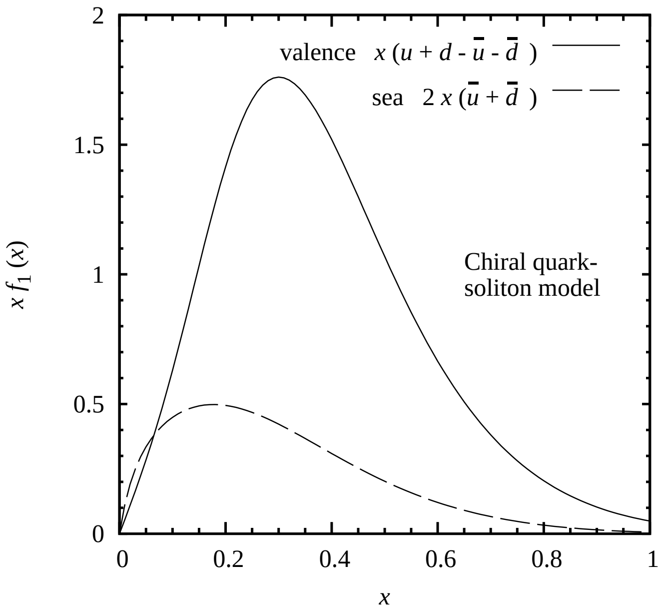
- Nucleon as chiral soliton
  Diakonov, Petrov, Pobylitsa 88; Kahana, Ripka 84

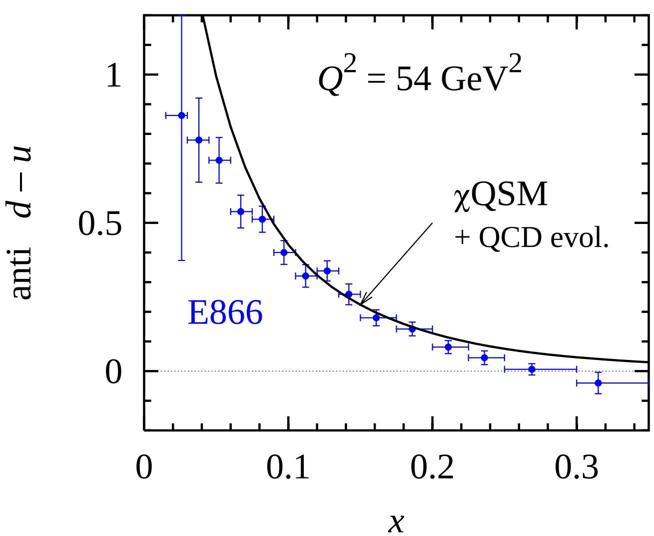
  Classical chiral field
  "Hedgehog" $\boldsymbol{\pi} \parallel \boldsymbol{r}$ in rest frame

  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+

$$f^q(x, \boldsymbol{p}_T) = \langle N|\, a^\dagger a(xP, \boldsymbol{p}_T)\, |N\rangle_{P\to\infty}$$
$$f^{\bar{q}}(x, \boldsymbol{p}_T) = \qquad b^\dagger b$$

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

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

  Intrinsic p_T distributions, not "TMDs" no FSI!

- Interpretation

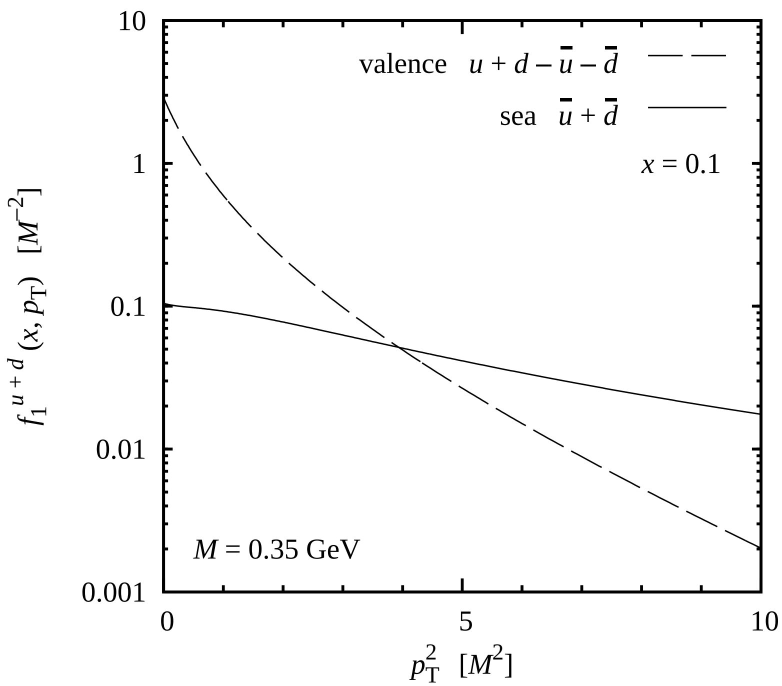
  x and p_T distribution of constituent quarks and antiquarks effective DOF

  Matching with QCD quarks, antiquarks and gluons at scale ρ^{-2}
  PDF fits show 30% of nucleon momentum carried by gluons at $\mu^2 \sim 0.5\,\mathrm{GeV}^2$: "Accuracy" of model

- Flavor asymmetries

  Describes well measured $\bar{d} - \bar{u}$ E866 Drell-Yan
  Predicts sizable $\Delta\bar{u} - \Delta\bar{d} \to$ 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

  $\langle p_T^2 \rangle \approx 0.15\,\mathrm{GeV}^2$, 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

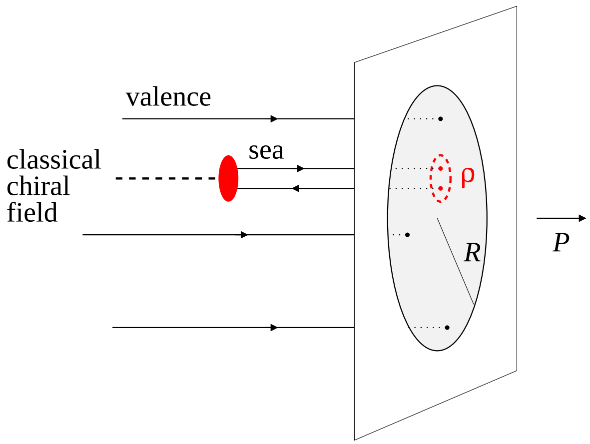
  $p_T^2 \sim \rho^{-2}$: Some model dependence from UV cutoff

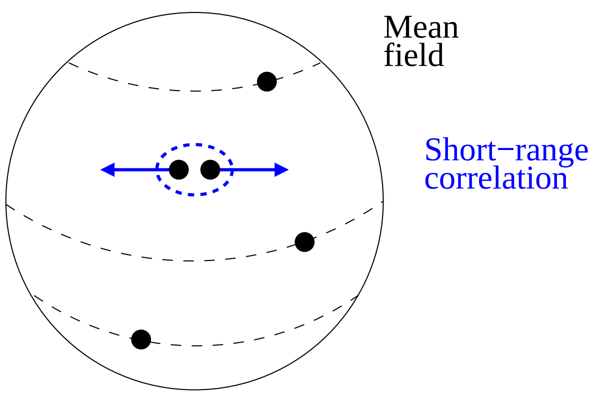
  Similar tail in $\Delta\bar{u} - \Delta\bar{d}$

- Qualitative difference

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

Partonic structure: Short–range correlations





Parton SRCs as imprint of χSB 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

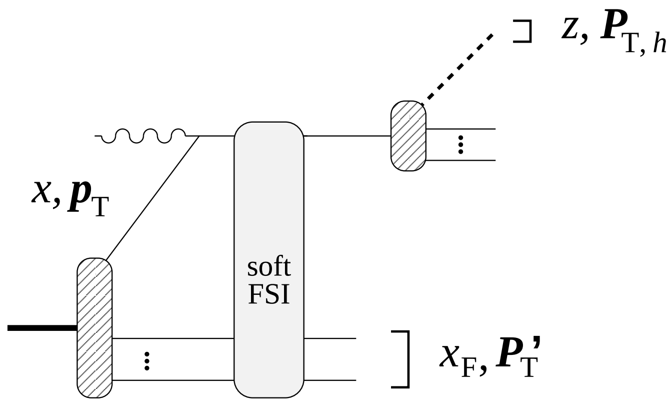
  Mean field $\Psi(\boldsymbol{r}_1, \ldots \boldsymbol{r}_N) \approx \prod_i^N \Phi(\boldsymbol{r}_i)$

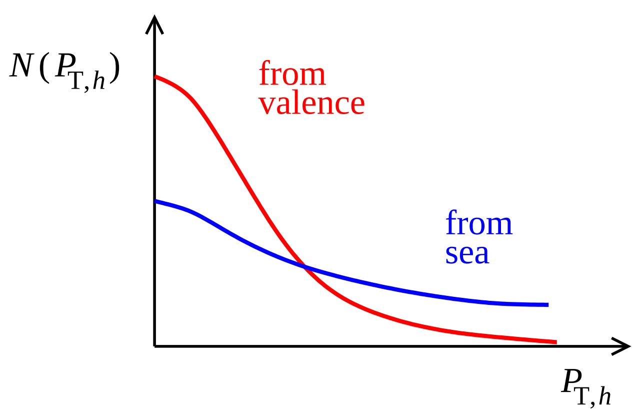
  Rare configs with $|\boldsymbol{r}_i - \boldsymbol{r}_j| \ll$ average experience short-range NN interaction, generate high momentum components

  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





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

- 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

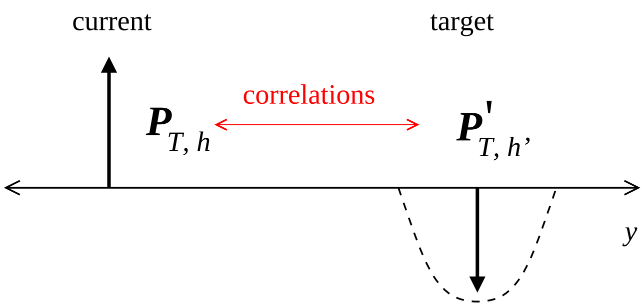
  $$N(\pi^+ - \pi^-) \quad \propto \quad e_u^2(u - \bar{u}) - e_d^2(d - \bar{d})$$
  $$N(\pi^+ + \pi^-) \quad \propto \quad e_u^2(u + \bar{u}) + e_d^2(d + \bar{d})$$

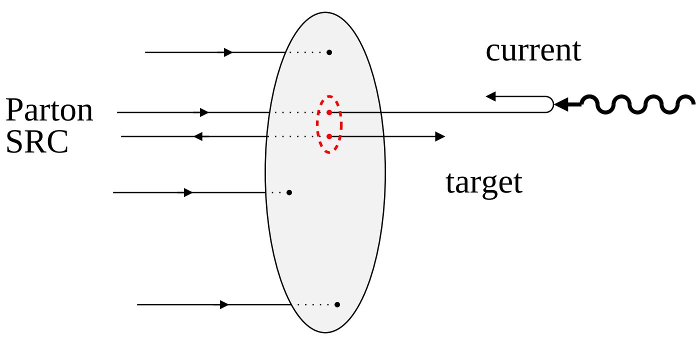
  Charge separation with kaons:
  u dominance, $s = \bar{s}$ fragmentation

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

  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 χSB

- 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
  $Q^2 \sim \text{few GeV}^2$

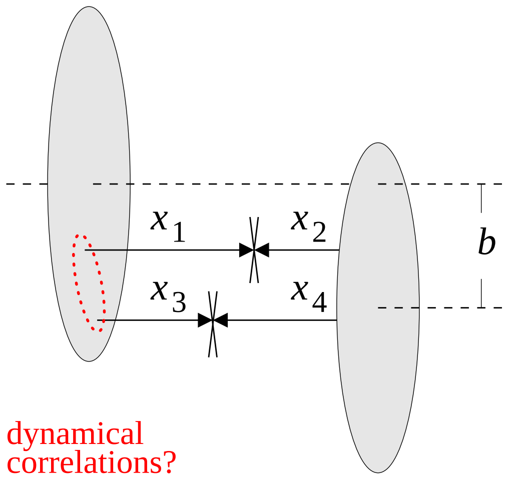
  Momentum fractions of nonperturbative sea
  $x \sim$ 0.05–0.1

  $\rightarrow$ "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 energiesideal
  JLab12: Probably marginal, but should be explored

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

Outlook: Multiparton processes in pp



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

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

- Double dijet rate parametrized by $\sigma_{\rm eff}^{-1}$

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

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

- 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. mulitparton processes?
  Many challenges. Blok, Dokshitzer, Frankfurt, Strikman 11

- 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 χSB in QCD creates short–distance scale $\rho \ll R \sim 1\,\mathrm{fm}$

  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