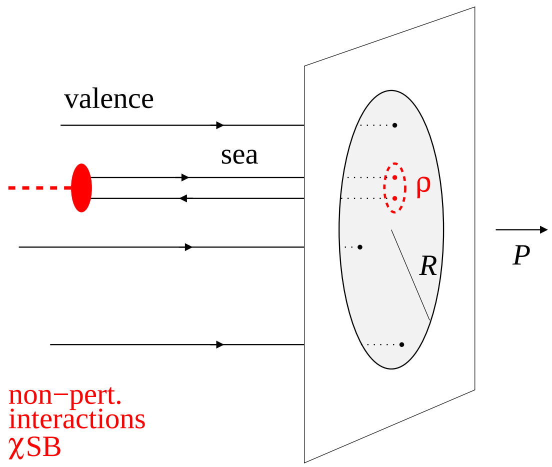
Intrinsic transverse momentum and dynamical chiral symmetry breaking

C. Weiss (JLab), Light Cone 2012, Krakow, 10–Jul–12,
based on P. Schweitzer, M. Strikman, CW 12, to appear



I) Intrinsic p_T of sea quarks?

Sea vs. valence quarks
Role of chiral symmetry breaking

II) Parton correlations in LCWF?

Mean field $\rightarrow$ correlations

- Chiral symmetry breaking in QCD

  Short–distance scale $\rho \ll R$

  Imprint on partonic structure

- Effective description of χSB

  Constituent quarks and Goldstone bosons

  Nucleon as chiral soliton $N_c \rightarrow \infty$

- Transverse momentum distributions

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

  Sea quarks "tail" $p_T \lesssim \rho^{-1}$ Qualitative difference!

  Coordinate space correlator New interpretation!

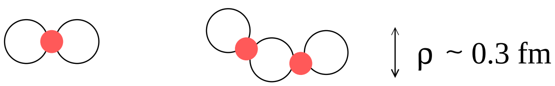
  Short–range correlations in LCWF

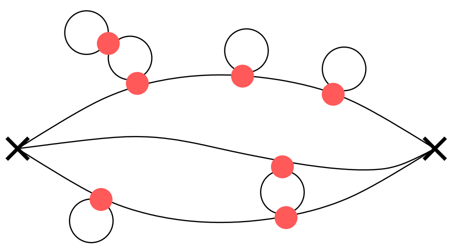
- Implications for SIDIS

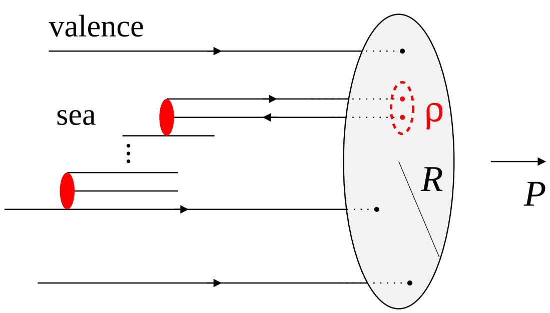
  Initial condition for QCD evolution

  Charge/flavor separaration techniques

Chiral symmetry breaking in QCD







- χSB in QCD vacuum

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

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

  Gauge–invariant measure of $q\bar{q}$ pair size
  $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi}\psi \rangle \sim 1\,\mathrm{GeV}^2$ "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

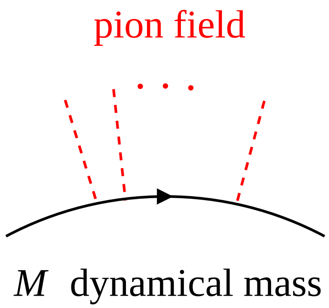
  Valence quark configurations of size $\sim R$

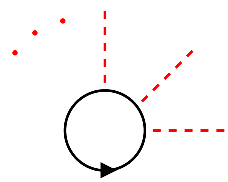
  Sea quarks in correlated pairs of size $\lesssim \rho$

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

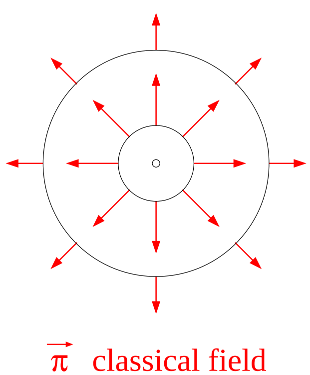
Can we quantify it? . . . Dynamical model!

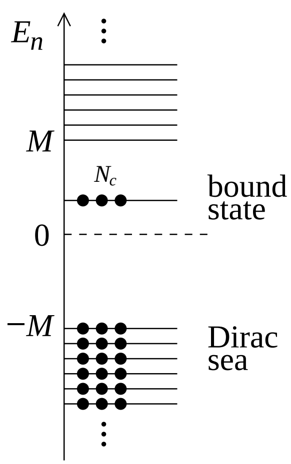
Chiral quark–soliton model: Dynamics





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





- 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 Goldstone boson field
  with eff. coupling $M/f_\pi =$ 3–4 strongly coupled!

  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" rest frame

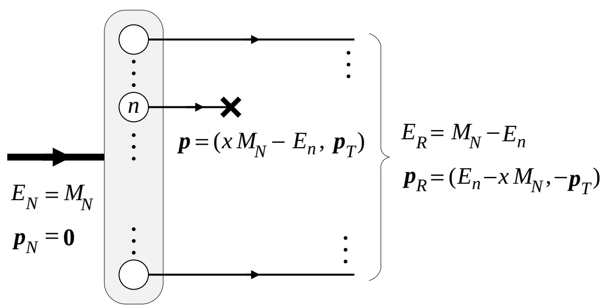
  Quarks in single–particle orbits:
  Bound state, Dirac continuum
  Relativistic mean–field approximation

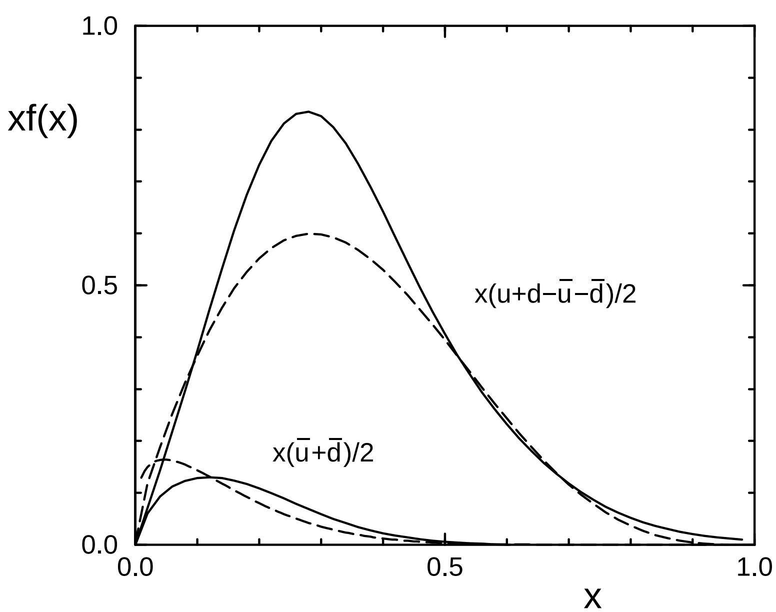
  Fully field–theoretical: Completeness,
  conservation laws, positivity $\rho^{-2} \gg M^2$
  No Fock space truncation!

  $\rightarrow$ PDFs, sea quarks

Chiral quark–soliton model: Parton distributions

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





- Parton densities in χQSM
  Diakonov, Petrov, Pobylitsa, Polyakov, CW 96+.
  Also: Gamberg, Weigel, Reinhardt 96+; Wakamatsu et al. 97+

  Quark number densities at $P \to \infty$
  Light–cone "plus" momentum density
  Equivalent! Relativistic field-theoretical formulation

  Sum over single–particle levels rest frame

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

- Interpretation of distributions

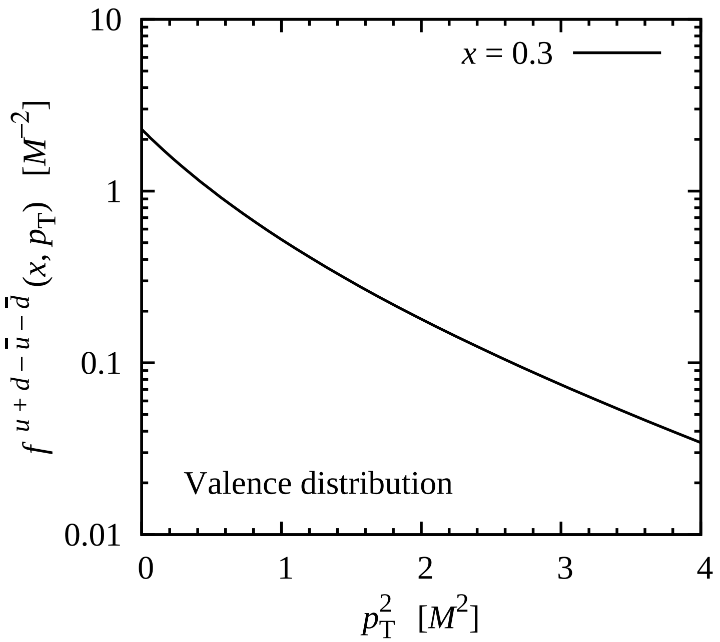
  x and p_T distribution of constituent quarks and antiquarks

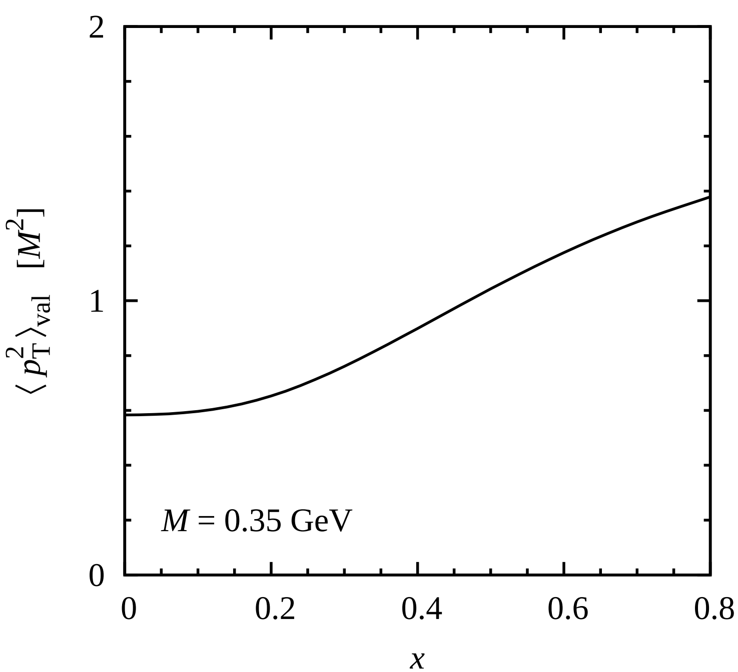
  Matching with QCD quarks, antiquarks and gluons at scale ρ^{-2}; requires info "beyond" effective dynamics

  Simplest approximation: Match constituent quarks with QCD quarks at ρ^{-2}, no gluons. Accuracy?

  PDF fits show 30% of nucleon momentum carried by gluons at $\mu^2 \sim 0.4\,\mathrm{GeV}^2$ GRV98

p_T distribution: Valence quarks





- Valence distribution $f^{q-\bar{q}}(x, p_T)$ dominated by bound–state level
  Wakamatsu 09, Schweitzer, Strikman CW 12

  Concentrated at $p_T^2 \sim M^2 \sim R_{\text{nucl}}^{-2}$

  Not sensitive to scale ρ^{-2}

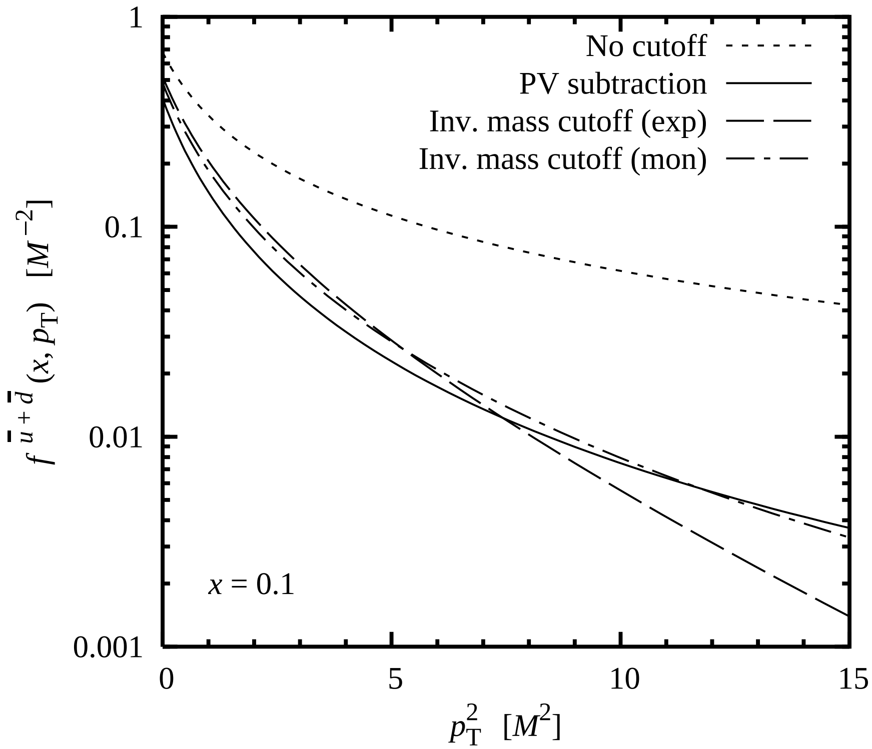
  Roughly Gaussian shape

- Average $\langle p_T^2 \rangle_{\text{val}}$ increases with x

  General property of relativistic bound state
  Cf. bag model, light–front quark model

Valence quark $p_T \sim 1/R_{\text{nucl}}$

p_T distribution: Sea quarks



Schweitzer, Strikman, CW 12

- Sea quark distribution $f^{\bar{q}}(x, p_T)$ dominated by Dirac continuum

  Analytic expression from expansion in $\nabla\pi/M$ "Gradient expansion" DPPPW96

  $$f^{\bar{q}}(x, p_T) \sim \frac{C(x)}{p_T^2 + M^2}$$

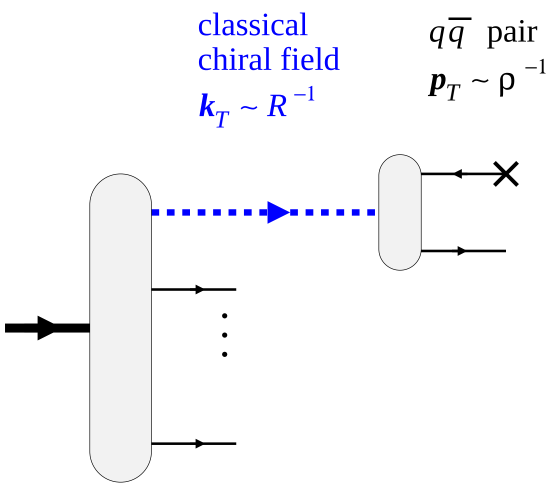
  Power–like tail at $p_T^2 \gg M^2$, regularized by cutoff ρ^{-2}

  Numerical distributions at $p_T^2 \sim$ few M^2 not sensitive to regularization scheme
  Physical conditions: Schweitzer, Strikman, CW 12

- Average $\langle p_T^2 \rangle_{\text{val}}$ not a sensible measure of "width" of sea quark distribution

> Sea quark p_T distribution qualitatively different from valence quarks

p_T distribution: Short–range correlations



$$f^{\bar{q}}(x, \boldsymbol{p}_T) \; = \; \int_x \frac{dy}{y} \; \int d^2 k_T$$

$$\times f_{\text{ch}}(y, \boldsymbol{k}_T) \; f_{\text{pair}}(x/y; \boldsymbol{p}_T)$$

Gradient expansion as partonic convolution,
cf. DGLAP evolution. SSW 12

- Origin of configurations with $p_T^2 \sim \rho^{-2}$?

- Two–scale picture $\rho \ll R$

  Classical chiral field $k_T^2 \sim R^{-2}$ creates $q\bar{q}$ pair

  $q\bar{q}$ pair has intrinsic $p_T^2 \lesssim \rho^{-2}$

  Analogy with "pion cloud model," but rigorous formulation based on $1/N_c$ expansion: Strong coupling, all orders, classical field!

- Wave function of correlated pairs

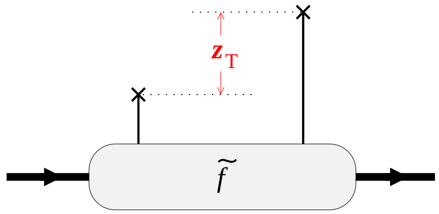
  Quantum numbers σ, π

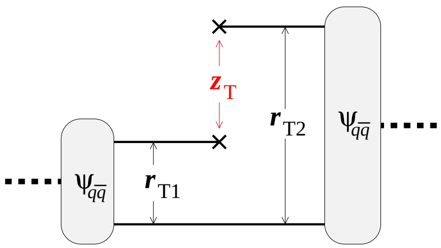
  Restoration of chiral symmetry at high p_T
  $\Psi_\sigma^2 = \Psi_\pi^2$ at $p_T^2 \sim \rho^{-2} \gg M^2$

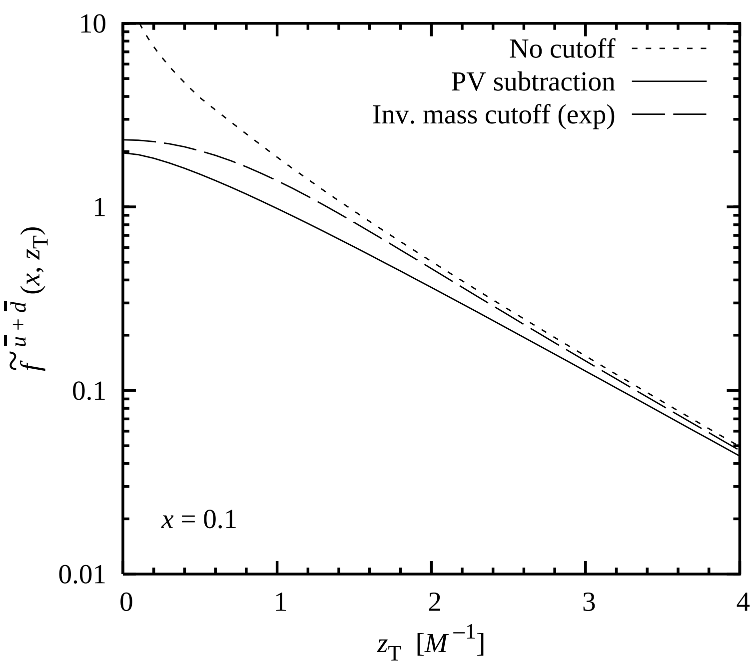
  General LC wave function of large–N_c nucleon: Average configs, valence quarks. Petrov, Polyakov 02; Diakonov, Petrov 04; Lorce 07+

Short–range correlations: Imprint of χSB on partonic structure

p_T distribution: Coordinate–space correlator







- Quark field correlator w. transverse separation

$$\tilde{f}(x, \boldsymbol{z}_T) = \int dz^- e^{ixP^+z^-} \times \langle P|\bar{\psi}(0)\gamma^+\psi(z)|P\rangle_{z^+=0}$$

Fourier transform of $f(x, \boldsymbol{p}_T)$

Defined here within effective model;
no relation to "TMD" in QCD
Intrinsic p_T, no final–state interactions

- Interesting properties

$z_T = 0$ $\quad \tilde{f}^{\bar{u}+\bar{d}}(x, 0) = f^{\bar{u}+\bar{d}}(x)$ PDF

$z_T \rightarrow \infty$ $\quad \tilde{f}^{\bar{u}+\bar{d}}(x, z_T) \sim e^{-Mz_T}$ "mass gap"

Intermediate z_T tightly constrained
New general framework for modeling p_T distributions?

- Interpretation within model

Measures size distribution of correlated
$q\bar{q}$ pairs in nucleon

Intrinsic p_T: Hard processes

- Model describes "intrinsic" p_T due to non–perturbative dynamics.
  In hard processes $p_T \lesssim Q$ are built up by QCD radiation

- QCD evolution should start at χSB scale $\rho^{-2} \approx 0.4\,\mathrm{GeV}^2$, "GRV scale," cf. PDF fits
  not $R^{-2} \approx 0.04\,\mathrm{GeV}^2$

  Non–perturbative short–distance scale!

  Data show that $\langle P_T^2 \rangle_{\mathrm{hadron}}$ in SIDIS practically independent of Q^2, varies only with W.
  Suggests limited role of QCD evolution.
  EMC 91: $\langle P_T^2 \rangle_{\mathrm{hadron}}$ unchanged between $Q^2 = 2\,\mathrm{GeV}^2$ and $60\,\mathrm{GeV}^2$

- Charge/flavor separation techniques in SIDIS may need to be modified
  if valence and sea quarks have different p_T distributions
  Frankfurt et al 89; Christova, Leader 00

$$\int_{\text{finite range}} d^2 p_T \, [f^q(x, p_T) - f^{\bar{q}}(x, p_T)] \quad \text{not simply related to} \quad f^q_{\mathrm{val}}(x)$$

Summary and outlook

- 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" $p_T \lesssim \rho^{-1}$

- Short–range correlations in partonic wave function

  Imprint of QCD vacuum on partonic structure

  Coordinate–space z_T distribution measures size of correlated $q\bar{q}$ pairs

- Outlook

  Implications for single–particle inclusive DIS

  Direct study of $q\bar{q}$ correlations through simultaneous measurements of current and target fragmentation regions
  Identify kinematic region dominated by non–perturbative correlations. Schweitzer, Strikman, CW, in progress

  Multiparton interactions in high–energy pp collisions LHC. New field of study!