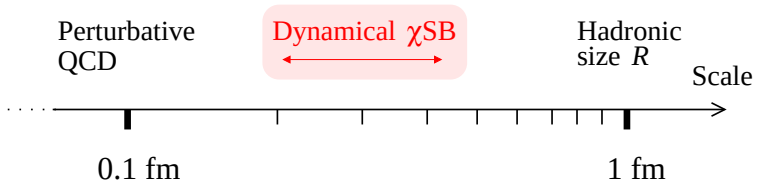
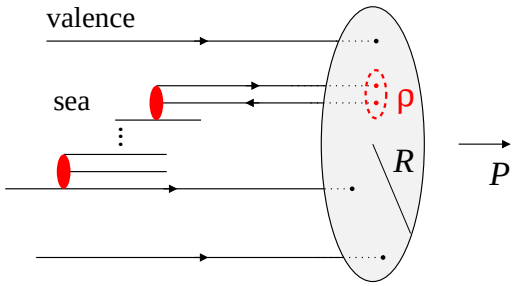
Non–perturbative short–range dynamics in TMDs

C. Weiss (JLab), QCD Evolution Workshop, 10–May–13

P. Schweitzer, M. Strikman, C. W., JHEP 1301 (2013) 163





→ Intrinsic transverse momenta
→ Parton correlations

- Transverse momentum in DIS

  QCD radiation, factorization

  TMD distribution at low scale

- 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

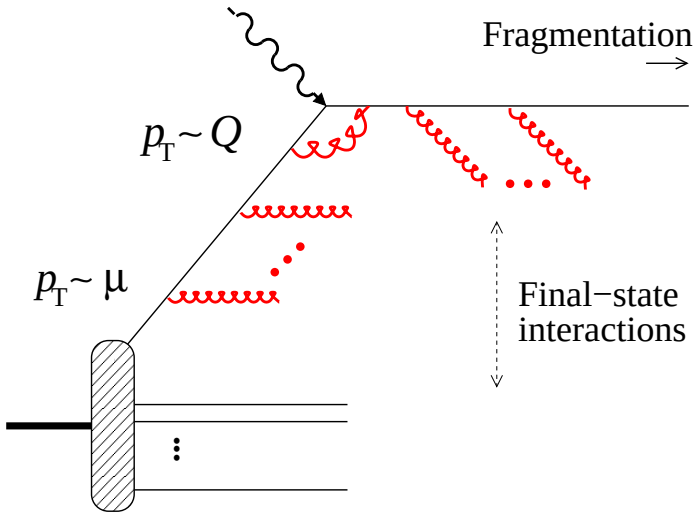
- Experimental tests

  Single–particle inclusive $P_{T,h}$ distributions
  HERMES, COMPASS, JLab12, EIC

  Correlations current $\leftrightarrow$ target regions EIC

  Multiparton interactions Tevatron, LHC

Deep–inelastic processes: Transverse momentum



$$\sigma(P_T) \sim [\text{parton density}] \sim \mu$$
$$\times [\text{radiation}]$$
$$\times [\text{scattering process}] \sim Q$$
$$\times [\text{fragmentation fn}]$$

- QCD radiation → Talks Collins, Idilbi, . . .

  Real emissions with p_T from $\sim \mu$ to Q

  Virtual radiation renormalizes couplings

- Factorization

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

  Inclusive scttering $\gamma^* N \to X$:
  Net radiation effect simple

  Semi-inclusive $\gamma^* N \to h(\text{low } P_T) + X'$:
  Radiation effect more complex: Sudakov FF
  Final–state interactions of struck parton
  Collins 11; Aybat Rogers 11 → Talks Collins, Rogers

  Parton density as $\langle N | \, \text{QCD–operator} \, | N \rangle$,
  universal, process–independent

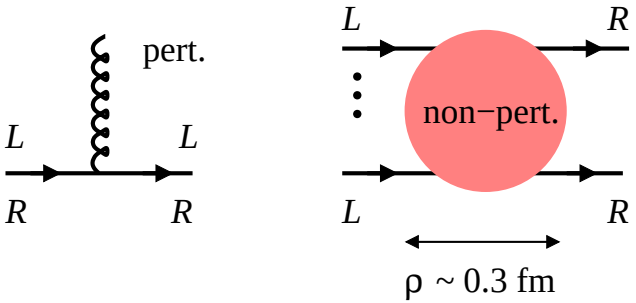
- Intrinsic p_T distribution at low scale
  This talk!

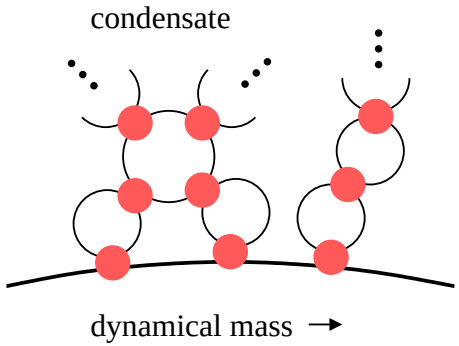
  Non–pert. dynamics, nucleon structure?

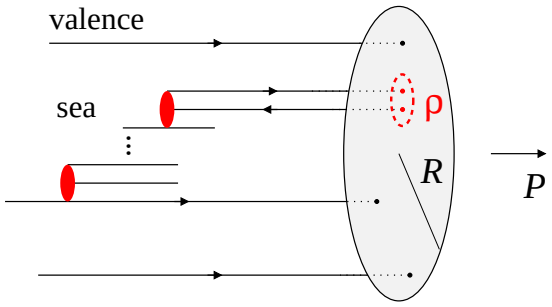
  Natural scale μ?

  Effect on observables?

Chiral symmetry breaking: Physical picture







- Chiral symmetry breaking in QCD

  pQCD interactions conserve quark chirality

  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 → Lattice, analytic methods

- Short–range interactions $\rho \sim 0.3\,\mathrm{fm}$

  New dynamical scale $\rho \ll R$
  Shuryak; Diakonov, Petrov 80's

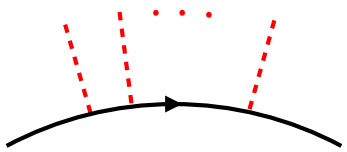
  Gauge–invariant measure of $q\bar{q}$ pair size
  $\langle \bar{\psi} \nabla^2 \psi \rangle / \langle \bar{\psi} \psi \rangle \sim 1\,\mathrm{GeV}^2$ "average virtuality"
  Lattice: Teper 87, Doi 02, Chiu 03. Instantons: Polyakov, CW 96

- How does it affect partonic structure?

  Sea quarks with $p_T \sim \rho^{-1} \gg R^{-1}$

  Parton short–range correlations

Chiral symmetry breaking: Dynamical model



chiral field

M dynamical mass

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

- Effective description of χSB
  Diakonov, Eides 83; Diakonov, Petrov 86

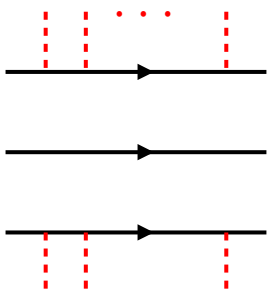
  Constituent quarks/antiquarks
  with dynamical mass $M \sim$ 0.3-0.4 GeV

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

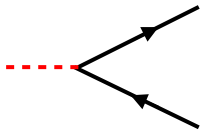
  Solved non–perturbatively
  using $1/N_c$ expansion

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

classical field



binds valence quarks



creates quark–antiquark pairs

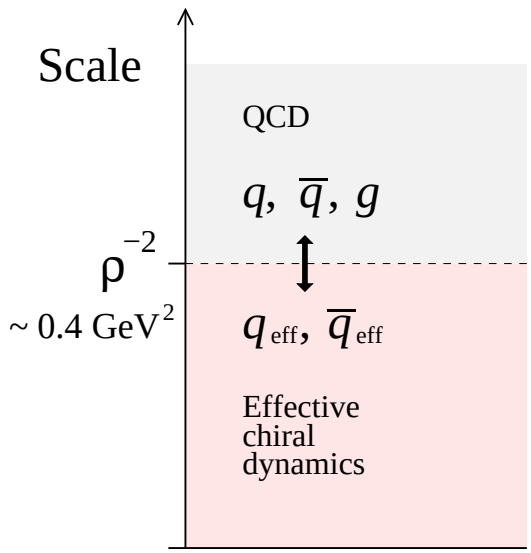
- Nucleon as chiral soliton
  Diakonov, Petrov, Pobylitsa 88; Kahana, Ripka 84

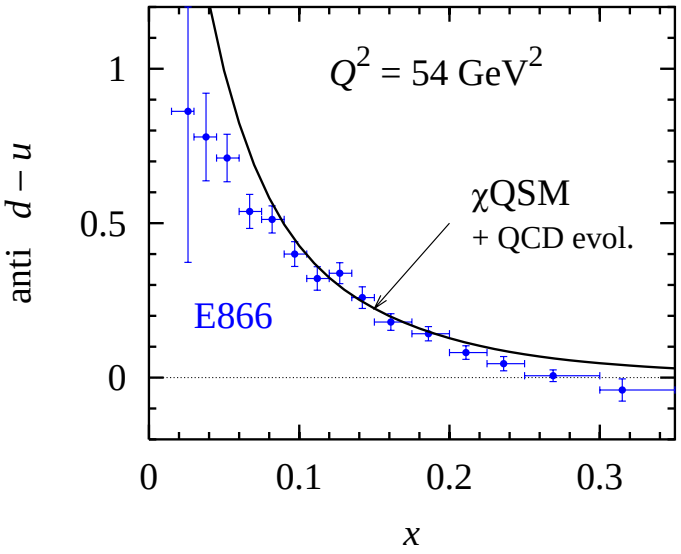
  Classical chiral field
  "Hedgehog" $\boldsymbol{\pi} \parallel \boldsymbol{r}$ in rest frame, cf. skyrmion

  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 chiral soliton model
  Diakonov, Petrov, Pobylitsa, Polyakov, CW 96+; Wakamatsu et al. 97+
  Alt. approach through structure functions: Gamberg, Weigel, Reinhardt 96+

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

  Equivalent to quark field correlation function $\langle N|\, \bar\psi(0)\ldots\psi(z)\, |N\rangle$ in rest frame → Talk X. Ji

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

  Intrinsic p_T distributions, no FSI Extension possible

- Interpretation

  x and p_T distribution of effective DOF: Constituent quarks and antiquarks

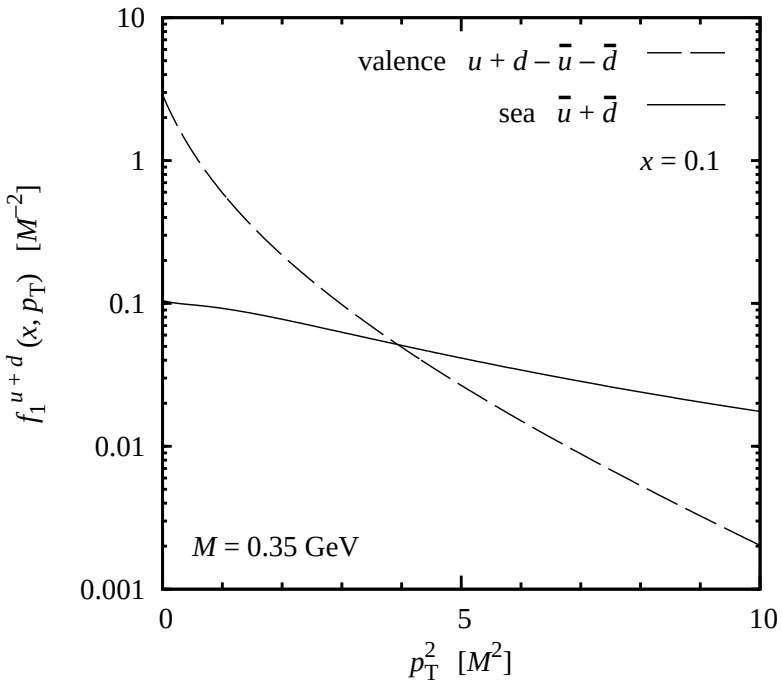
  Matching with QCD $q, \bar q, g$ at scale ρ^{-2}

  PDF fits at $\mu^2 \sim 0.5\,\mathrm{GeV}^2$ show 30% of nucleon momentum carried by gluons: "Accuracy" of matching

- Flavor asymmetries

  Describes well measured $\bar d - \bar u$ E866 Drell-Yan
  Predicts sizable $\Delta\bar u - \Delta\bar d$ DSSV, RHIC W → Talk Surrow

Partonic structure: p_T distributions



Sea quark p_T distribution qualitatively different from valence quarks!

Wakamatsu 09: Numerical observation.
Schweitzer, Strikman, CW 13: Analytic structure, microscopopic origin

- 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}

  Coefficient $C(x)$ determined by low–energy chiral dynamics, model–independent

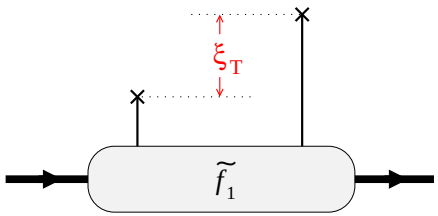
  $p_T^2 \sim \rho^{-2}$: Residual model dependence from UV cutoff scheme

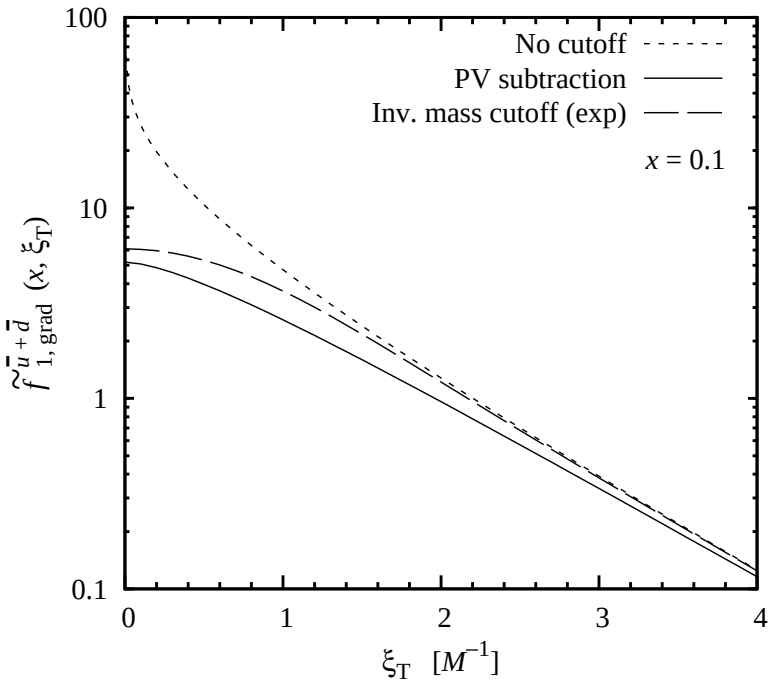
  Similar large–p_T tail in $\Delta\bar{u} - \Delta\bar{d}$

- Qualitative difference valence $\leftrightarrow$ sea

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

Partonic structure: Coordinate–space correlator





Sea quark coordinate space correlator.
Schweitzer, Strikman, CW 13

- Quark field correlator w. transverse separation

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

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

  Defined within effective model:
  Intrinsic p_T, no final–state interactions

- Interesting properties

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

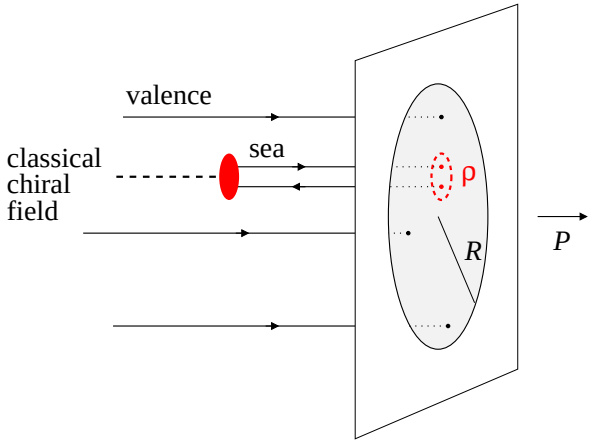
$$\xi_T \to \infty \quad \tilde{f}^{\bar{u}+\bar{d}}(x,\xi_T) \sim e^{-M\xi_T} \quad \text{“mass gap”}$$

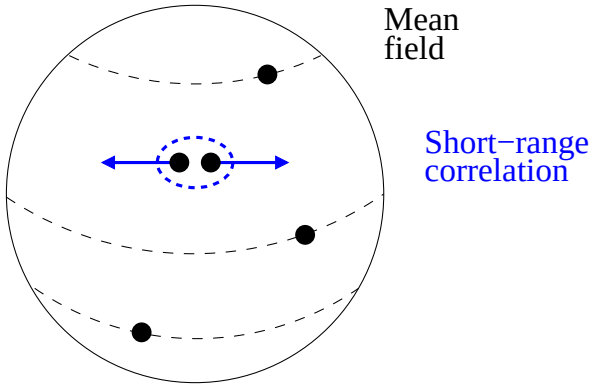
  Intermediate ξ_T tightly constrained

- New framework for parametrizing TMDs

  Initial condition for CSS evolution

Partonic structure: Short–range correlations





Parton SRCs as imprint of χSB on partonic structure

- Parton short–range correlations
  Schweitzer, Strikman CW 13

  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 with distinctive spin-isospin structure: Scalar–isoscalar Σ, pseudoscalar–isovector Π, $L = 1$ components of pair LCWF

  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 $O(1)$
  General LC wave function of large–N_c nucleon: Average configs, valence quarks. Petrov, Polyakov 02; Diakonov, Petrov 04; Lorce 07+

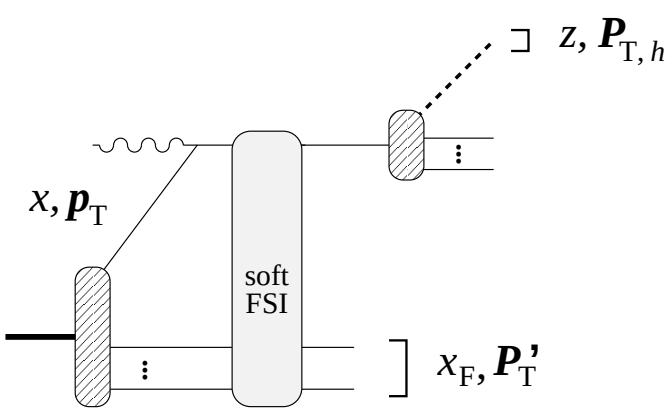
- Cf. NN short–range correlations in nuclei

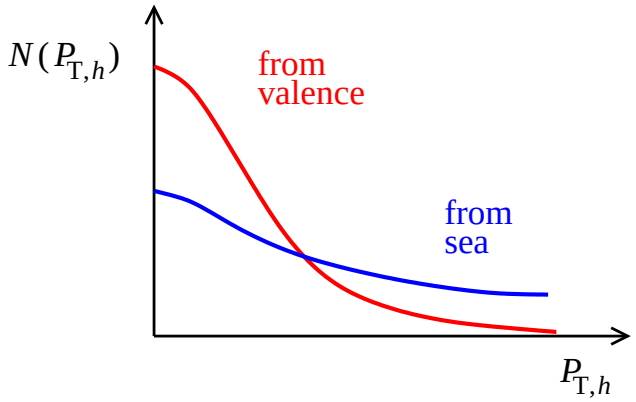
  Mean field $\Psi(\boldsymbol{r}_1, ...\boldsymbol{r}_N) \approx \prod_i^N \Phi(\boldsymbol{r}_i)$

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

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

Measurements: Semi–inclusive DIS





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 compounded

  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 JLab 12, EIC: Kinematic coverage

- Separate valence and sea quarks in target

  Charge separation with pions

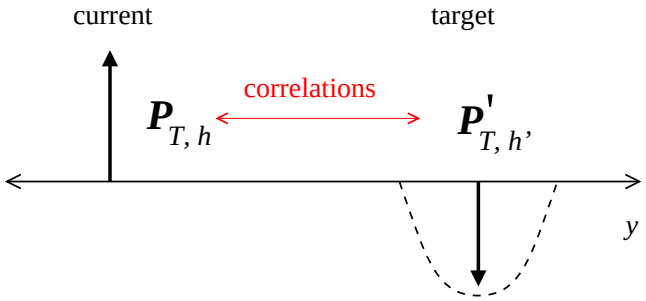
  $$N(\pi^+ - \pi^-) \propto e_u^2(u - \bar{u}) - e_d^2(d - \bar{d})$$
  $$N(\pi^+ + \pi^-) \propto e_u^2(u + \bar{u}) + e_d^2(d + \bar{d})$$

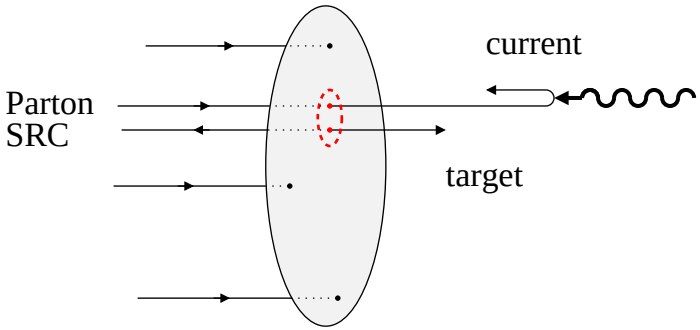
  Charge separation with kaons:
  u dominance, $s = \bar{s}$ fragmentation
  $N(K^+) \propto u$ mostly valence
  $N(K^-) \propto \bar{u}$

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

- Alt: P_T distribution of l^+l^- pairs in $pp, \bar{p}p$

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
  $Q^2 \sim$ few GeV^2

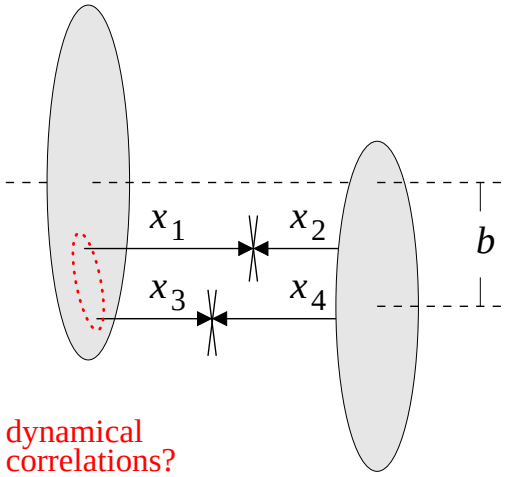
  Momentum fractions of nonperturbative sea
  $x \sim 0.05$–0.1

  $\rightarrow$ "Kinematic window" at $W^2 \approx 30\ \mathrm{GeV}^2$, $P_{T,h}^2 \approx 0.5\,\mathrm{GeV}^2$

  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



$$\frac{\sigma(12;34)}{\sigma(12)\sigma(34)} = \frac{1}{\sigma_{\rm eff}} \times \frac{f(x_1,x_3)f(x_2,x_4)}{f(x_1)f(x_2)f(x_3)f(x_4)}$$

- 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

- χSB scale $\rho \sim 0.3\,\mathrm{fm}$ natural for separating non–perturbative TMD $\leftrightarrow$ pQCD radiation

- Qualitatively different p_T distributions of valence and sea quarks: Valence $p_T \sim R^{-1}$, sea has "tail" up to $p_T \sim \rho^{-1}$

- Parton short–range correlations in nucleon: Direct imprint of χSB, $L = 1$ components of LCWF, restoration of chiral symmetry at scale ρ^{-1}

- Experimental tests

  Separate valence $\leftrightarrow$ sea quarks in SIDIS: Charged pions, kaons HERMES, COMPASS, EIC

  Correlations current $\leftrightarrow$ target fragmentation regions: Kinematic window for non–perturbative correlations COMPASS, medium–energy EIC

  Exclusive meson production: Knockout of correlated $q\bar{q}$ pair JLab 12

  Multiparton interactions in high–energy $\bar{p}p/pp$ collisions Tevatron, LHC