Parton correlations from dynamical chiral symmetry breaking

C. Weiss (JLab), Target Fragmentation Mini-Workshop, LNF Italy, 18–Mar–15

- Transverse momentum in QCD
  Parton model
  QCD radiation, factorization

- Chiral symmetry breaking in QCD
  Non–perturbative scale \( \rho \ll R \)

- Effect on partonic structure
  \( p_T(\text{sea}) \gg p_T(\text{valence}) \)
  Parton short–range correlations

- Experimental tests
  SIDIS current region \( P_{T,h} \) distributions
  HERMES, COMPASS, JLab12, EIC
  Correlations current \( \leftrightarrow \) target regions
  CLAS12?, EIC
  Dileptons in \( pp \) and \( \bar{p}p \)
  FNAL, RHIC, GSI?
  Multiparton interactions in \( pp \)
  Tevatron, LHC

→ Intrinsinc transverse momenta
→ Parton short–range correlations

Schweitzer, Strikman, Weiss, JHEP 1301 (2013) 163
**Transverse momentum: Parton model**

- Relativistic composite system
  - Pointlike constituents with interactions of finite range $\mu^{-1}$
  - Particles created/annihilated
  - System moves with $P \gg \mu$, internal motion “frozen”
  - Wave function description: Feynman, Gribov 70’s
- Constituents’ momenta
  - Longitudinal $p_z = xP$
  - Transverse $p_T \sim \mu$
- 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 $p_T \sim \mu$

\[\begin{align*}
\sigma_T & \sim \frac{x f(x)}{Q^2} \quad \text{Bjorken scaling} \\
\int d^2 p_T \ f(x, p_T) & \quad \text{Parton density in longit. momentum}
\end{align*}\]
Transverse momentum: QCD

- **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
  Semi-inclusive $\gamma^*N \rightarrow h(\text{low } P_T) + X'$:
  Radiation effect more complex,
  final–state interactions of struck parton
  Factorization: Collins 11, Aybat, Rogers 11

Parton density as $\left\langle N \mid \text{QCD–operator} \mid N \right\rangle$, universal, process–independent
Collins, Soper 82, ...

- **Parton transverse momentum**
  $p_T \sim Q$ pert. QCD, calculable
  $p_T \sim \mu$ nonpert. interactions ← This talk!

\[
\sigma_T \sim [\text{parton density}] \sim \mu
\times [\text{radiation}]
\times [\text{scattering process}] \sim Q
\]
Chiral symmetry breaking in QCD

- Chiral symmetry breaking
  
  Non-perturb. gluon fields can flip chirality

  Condensate of \( q\bar{q} \) pairs \( \langle \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \rangle \),
  pion as collective excitation – Goldstone boson

  Dynamical mass generation:
  Constituent quarks, hadron structure
  Euclidean correlation functions → 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 \( \lesssim \rho \)
Partonic structure: $p_T$ distributions

- Dynamical model of $\chi_{SB}$
  Diakonov, Eides 83; Diakonov, Petrov 86

  Effective degrees of freedom:
  Constituent quarks, Goldstone bosons

  Strongly coupled system, solved
  non-perturbatively in $1/N_c$ expansion
  Nucleon as chiral soliton

  PDFs at scale $\mu^2 \sim \rho^{-2} \approx 0.5$ GeV$^2$

- Transverse momentum distributions

  Valence quarks: Drops steeply,
  $\langle p_T^2 \rangle \approx 0.15$ GeV$^2 = O(R^{-2})$

  Sea quarks: Power-like tail extends
  up to cutoff scale $\rho^{-2}$

  Generic feature, rooted in $\chi_{SB}$
  and dynamical scales $\rho \ll R$

  Similar tail in $\Delta \bar{u} - \Delta \bar{d}$
Parton short–range correlations

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

Pairs have distinctive spin-isospin structure:
Scalar–isoscalar $\sigma$, pseudoscalar–isovector $\pi$

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

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

Cf. $NN$ short–range correlations in nuclei

Mean field $\Psi(r_1, \ldots r_N) \approx \prod_i^N \Phi(r_i)$

Rare configs with $|r_i - r_j| \ll$ 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
Measurements: Inclusive hadrons in $ep$

- Hadron $P_{T,h}$ distributions in SIDIS
  - Intrinsic $p_T$ in WF
  - Final–state interaction
  - Parton fragmentation

  Observable $P_{T,h}$

  External handles: $z \leftrightarrow x$, $z \leftrightarrow P_{T,h}$

- 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:
  \[
  N(K^+) \propto u \text{ mostly valence}
  \]
  \[
  N(K^-) \propto \bar{u}
  \]

- Need better understanding of SIDIS mechanism, especially at $z > 0.5$

Sea quarks contribute only at $x \sim 0.1$
Intrinsic $p_T$ manifest only at $z > 0.5$

Strikman, Weiss 14: Preliminary study based on HERMES/COMPASS/EMC/E665 multiplicity data
Measurements: Hadron correlations in $ep$

- Hadron correlations between current and target fragmentation regions

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

Observe nonpert correlations from $\chi_{SB}$?

- Kinematics for nonperturbative correlations

Sufficient separation in rapidity

$\Delta y \approx \ln\left[\frac{W^2}{(P_{T,h}^2 + m_h^2)}\right] \gtrsim 4$

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 energies ideal

JLab12: Probably marginal, but should be explored
Measurements: Dileptons in $pp$ and $\bar{p}p$

- $l^+l^-$ produced in parton–parton collision

$P_T$ distribution of $l^+l^-$ pairs sensitive to intrinsic $p_T$ of quarks/antiquarks

$pp$ valence $\times$ sea $\quad x_{1,2} \gtrsim 0.1$

$\bar{p}p$ valence $\times$ valence

Expect broader $P_T$ distribution in $pp$ than in $\bar{p}p$ at same $x_{1,2}$

- Experimental data

$P_T(pp) > P_T(\bar{p}p)$ seen in FNAL Drell-Yan data at $P_T^2 \sim$ few GeV$^2$

Aidala, Field, Gamberg, Rogers 14

Need more $pp$ and $\bar{p}p$ in same kinematics, low $P_T \lesssim 1$ GeV
• Two parton–parton collisions in same $pp$ event

Rate parametrized by $\sigma_{\text{eff}}^{-1}$

Calculable as geometric overlap if spatial distributions of partons are independent from each other (mean field)

• Observed enhancement

CDF/D0 3jet + $\gamma$ rate two times larger than mean field with realistic radius

Possible explanation: Parton correlations

Perturbative vs. nonperturbative correlations? Higher–order vs. multijet 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!
Summary

- Dynamical $\chi$SB in QCD creates short-distance scale $\rho \ll R \sim 1 \text{ fm}$
  
  Natural scale for separating soft wave function ↔ 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. Needs detailed simulations.

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

  Comparison of dilepton distributions in $\bar{p}p$ and $pp$

  Multiparton interactions in high-energy $pp$ collisions
Supplementary material
Chiral symmetry breaking: Dynamical model

- Effective description of $\chi_{SB}$
  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 $\chi_{SB}$ scale $\rho^{-2}$:
  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” $\pi \parallel r$ 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+

\[
f^q(x, p_T) = \langle N| a^\dagger a(xP, p_T) |N\rangle_{P \to \infty}
\]

\[
f^{q^c}(x, p_T) = b^\dagger b
\]

Equivalent to quark field correlation function
\[
\langle N| \bar{\psi}(0) \ldots \psi(z) |N\rangle \text{ in rest frame}
\]

\[p_T\] integral convergent due to UV cutoff \(\rho^{-2}\)
No final-state interaction. Model extension possible

- Interpretation
  \(x\) and \(p_T\) distribution of effective DOF:
  Constituent quarks and antiquarks

  Matching with QCD \(q, \bar{q}, g\) at scale \(\rho^{-2}\)

  PDF fits at \(\mu^2 \sim 0.5 \text{ GeV}^2\) 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 \(W \rightarrow \text{Talk Surrow}\)