Transverse densities from timelike form factors

C. Weiss (JLab), DLS2011 “Spin physics,” 14–Apr–11

- Transverse charge and current densities
  Partonic representation of form factors
  Spectral representation and filtering property  $\sqrt{t} \sim 1/b$

- Nucleon transverse densities
  Chiral large–distance component $e^{-m_\pi b}$
  from $\chi$PT
  Strikman, CW, PRC82 (2010) 042201

  Spectral analysis: Zooming in on vector mesons $\rho, \omega$
  Miller, Strikman, CW; in preparation

- Pion transverse charge density
  Timelike pion form factor from $e^+e^-$ data

  Singular charge density at $b \to 0$:
  Pointlike $q\bar{q}$ configurations in pion
  Miller, Strikman, CW, PRD83 (2011) 013006

New insights in partonic structure!
Quantify pion cloud, vector meson dominance in QCD!
Study vector meson couplings in $t$–channel kinematics!
Transverse densities: Partonic representation

- Elastic form factors
  \[ \langle N' | J_\mu | N \rangle \sim F_{1,2}(t) \]
  Transverse momentum transfer \(|t| = \Delta^2\)

- Transverse charge density \(\rho(b)\) \(\text{Soper 76, Miller 07}\)
  \[ \rho(b) = \int \frac{d^2\Delta}{(2\pi)^2} e^{-i\Delta b} F_1(-\Delta^2) \quad \text{2D Fourier} \]
  Cumulative charge of constituents at distance \(b\) from transverse center-of-mass
  Reduction of GPD \(\rho(b) = \int dx \ f_{q-\bar{q}}(x, b)\)

- Densities from spacelike FF data
  Neutron positive at \(b \sim 0.5 - 1 \text{ fm}\)
  Contradicts naive picture of \(p(\text{center}) + \pi^- (\text{cloud})\) \(\text{Miller 07}\)

  Extension to \(N \rightarrow \Delta, \text{higher-spin} \text{ systems}\)
  Carlson, Vanderhaeghen 07; Lorce et al. 09+
Transverse densities: Dispersion representation

- Dispersion representation of form factor

\[
F(t) = \int_{-\infty}^{\infty} \frac{dt'}{2\pi^2} \frac{\text{Im} F(t')}{t' - t - i0} \frac{1}{\pi}
\]

Spectral function \(\text{Im} F(t')\) describes “process” current \(\rightarrow\) hadronic system \(\rightarrow\) \(N\bar{N}\)

Unphysical region: Spectral function from dispersion analysis, \(\chi\)PT near threshold, pQCD \(t \rightarrow \infty\)

- Transverse density

\[
\rho(b) = \int_{-\infty}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b) \text{Im} F(t)
\]

\(K_0 \sim e^{-b\sqrt{t}}\) exponential suppression of large \(t\)

Distance \(b\) selects masses \(\sqrt{t} \sim 1/b\): “Filter”

Cf. Borel transformation in QCD sum rules, Strikman, CW 10

Analyticity permits study of large-\(b\) asymptotics
Nucleon: Chiral component at large $b$

- Transverse density at $b \sim 1/M_\pi$ from chiral dynamics \textsuperscript{Strikman, CW 10}

\[ \text{Im} F_1(t) \text{ near threshold } t \rightarrow 4M_\pi^2 \]

Isovector two–pion exchange leading

Universal, calculable in $\chi$PT

Heavy–baryon expansion does not converge

Becher, Leutwyler 99; Kaiser 03

Equivalence of invariant and light–front formulations demonstrated

$\Delta$ intermediate states ensure proper $N_c$–scaling of isovector density

- Chiral component dominates only at distances $b > 2 \text{ fm}$

Large non–chiral density from $\rho$ exchange

Contradicts traditional notion of “pion cloud” at distances $\sim 1 \text{ fm}$
Nucleon: Spectral analysis of transverse densities

- Analyze contribution of spectral mass regions to transverse densities
  Model-independent! Miller, Strikman, CW, in preparation

  Empirical spectral functions from FF fits
  Belushkin, Hammer, Meissner 07

  Connect partonic structure with hadronic exchange mechanisms

- Isovector charge density
  Near-threshold $\pi\pi$ relevant only at $b > 2\,\text{fm}$

  Intermediate $b = 0.5 - 1\,\text{fm}$ dominated by $\rho$, with $10 - 15\%$ correction from first $\rho'$
  Perfect “vector dominance,” fully quantitative!

- Isoscalar charge density
  No near-threshold strength, $3\pi$ very small

  $\omega$ dominates at $b \sim 2\,\text{fm}$

  Intermediate $b \sim 1\,\text{fm}$ mostly from $\omega$, with $30\%$ contribution from higher-mass states
  Physical origin uncertain: $\phi, K\bar{K}, \pi\rho$?
  Related to strangeness in nucleon from PVES at JLab
Pion: Transverse density from timelike data

- Spacelike FF poorly known at $|t| > 1 \text{ GeV}^2$
  
  Electroproduction on nucleon, model-dependent. JLab Hall C 6/12 GeV

- Timelike FF from $e^+e^-$ annihilation
  
  $|F_\pi|^2$ from cross secn, phase from models/theory
  
  Resonance–based parametrization from fit to data
  
  Bruch, Khodjamirian, Kuhn 04. CLEO 05 results not included.

- Transverse density from dispersion integral
  
  Miller, Strikman, CW 10

  \[
  \rho_\pi(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{tb}) \text{ Im } F_\pi(t)
  \]

  Fully calculable, precise, error estimates

  Singular charge density at center of pion
Pion: Partonic interpretation

- Singular charge density at center due to point-like configurations in pion wave functn

Confis of size $r \ll R_\pi$, mostly elementary $q\overline{q}$

Observable in other high–momentum transfer processes: $\gamma^*\gamma \rightarrow \pi^0$, $\pi + A \rightarrow 2$ jets, ...

Universal property

Large–size configurations with $x \rightarrow 1$
at scales $Q^2 > 1 \text{ GeV}^2$ cannot account for empirical charge density at $b \rightarrow 0$

Miller, Strikman, CW 10

Detailed modeling with light–cone wave functions Miller, Strikman; in progress

- 2D image of fast–moving pion

First accurate transverse image based on data!
Summary

- Transverse densities connect partonic structure with hadronic spectrum
  - Fully quantitative, consistent with QCD
  - New approach to duality

- Dispersion integral for $\rho(b)$ samples spectral function at energies $\sqrt{t} \sim 1/b$
  - Systematic study of exchange mechanisms
  - Mathematical properties: Asymptotic behavior, error analysis, . . .

- Nucleon charge density at intermediate distances $b = 0.5 - 1.5$ fm governed by vector mesons
  - Chiral component dominant only at $b > 2$ fm
  - Origin of isoscalar strength beyond $\omega$ still unclear

- Pion charge density from timelike form factor data
  - Precise 2D image with controlled accuracy
  - Singular charge density at center attributed to pointlike $q\bar{q}$ configurations