Intersections of hadronic spectroscopy and partonic structure

C. Weiss (JLab), Future Directions in Spectroscopy Analysis, Mexico City, 09-Nov-17

Jefferson Lab

- How we describe hadron structure in QCD

  QCD operators, matrix elements, measurements, interpretation

- How we can extend the concepts/methods to resonances

  $\langle N^* | \mathcal{O} | N \rangle$, $\langle N^* | \mathcal{O} | N^* \rangle$, $\langle h^* | \mathcal{O} | 0 \rangle$, . . .

- How amplitude analysis methods can contribute to hadron structure extraction and calculation

  Analyticity, dispersion relations, unitarity, . . .

Outline

- Hadron structure in QCD

  Current operators and form factors

  Light-ray operators and generalized parton distributions (GPDs)

  QCD factorization of hard exclusive processes

  Interpretation in light-front quantization

  Extension to resonances

- Form factors and transverse densities

  Nucleon transverse densities

  Dispersion analysis and peripheral structure

  $N \to N^*$ and $N^* \to N^*$ densities

- Exclusive processes and GPDs

  Hard exclusive production of photons/mesons

  $N \to N^*$ transition GPDs

  Meson structure

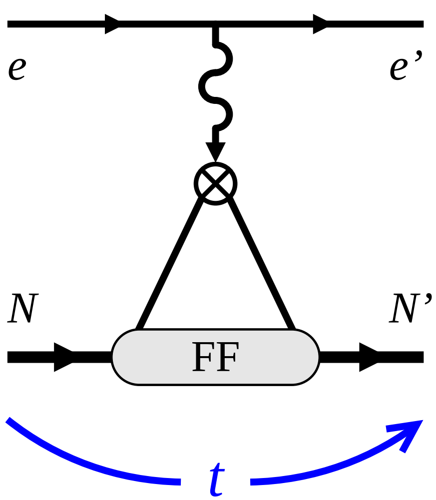
Hadron structure: Current operators

$J^\mu = \bar{\psi}\gamma^\mu\psi \quad (\gamma^\mu\gamma^5)$

Vector/axial current
Local composite operator
Scale-independent (conserved)

$\langle p'|\, J^\mu \,|p\rangle$

$F_i(t)$ form factors
$t = \Delta^2 = (p' - p)^2$



Elastic scattering $eN \to e'N'$
$|t| \sim \mu^2_{\text{had}} \sim 1\,\text{GeV}^2$

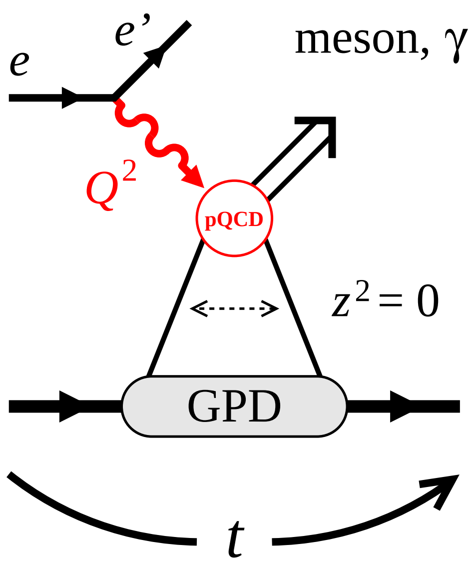
Hadron structure: Light-ray operators

$\mathcal{O}(z) = \bar{\psi}(0)\, z\cdot\gamma \ldots \psi(z)\, |_{z^2=0}$

Light-ray operator, twist-2
Non-local; local limit $z \to 0$ gives current
Logarithmic scale dependence, calculable

$\langle p'|\mathcal{O}(z)|p\rangle$

$F_i(P \cdot z, \Delta \cdot z, t)$
Generalized form factors (or GPDs)



Exclusive production $eN \to e'NM$
Factorization in limit $Q^2, W^2 \gg \mu^2_{\mathrm{had}}$

momenta $\gg \mu^2_{\mathrm{had}}$	in	pQCD subprocess
$\sim \mu^2_{\mathrm{had}}$	in	operator matrix element

Momentum transfer $|t| \sim \mu^2_{\mathrm{had}} \sim 1\,\mathrm{GeV}^2$

Müller et al. 94; Frankfurt Collins Strikman 96; Ji 96; Radyushkin 96

Hadron structure: Factorization

- High-energy, short-distance process only serves to define operator.
  Matrix element at scale $\mu^2_{\rm had}$ describes low-energy, long-distance structure.

- Operators with new quantum number available for hadron structure

  $\mathcal{O}(z) = \sum_n z_{\mu_1} \ldots z_{\mu_n} T^{\mu_1 \ldots \mu_n}$ local tensor operators

  Contains QCD energy-momentum tensor $n = 2$: Mass, angular momentum, forces

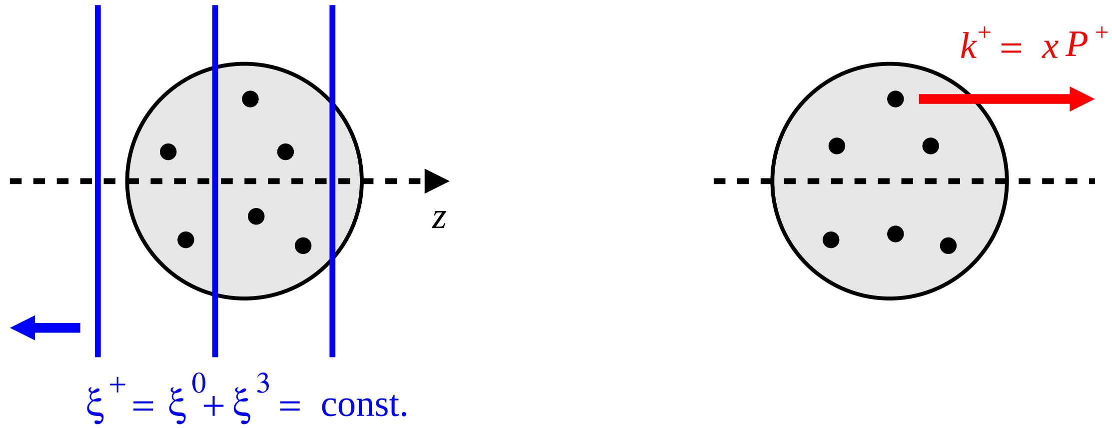
  Ji 96; Polyakov 00

- Similar factorization for heavy quarkonium production with gluonic operators

- Forward matrix elements of some light-ray operators from inclusive electroproduction cross section $eN \to X$ (DIS)

- Factorization is asymptotic expansion. Need to quantify region of applicability, calculate corrections

Hadron structure: Interpretation



- Light-front quantization

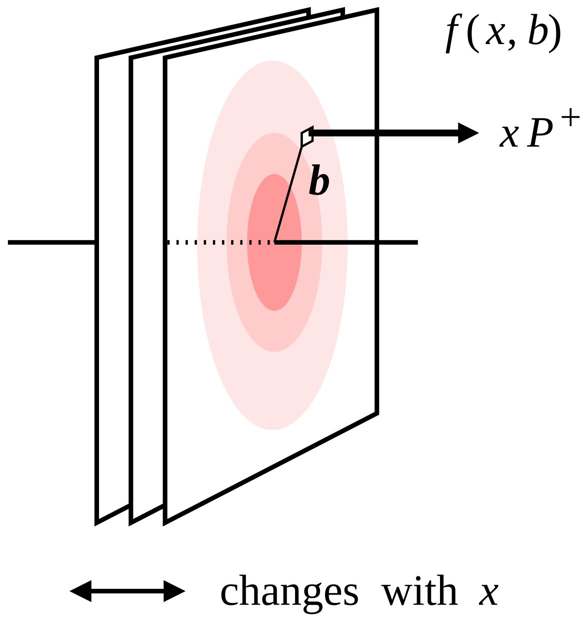
  $\xi^+ = \xi^0 + \xi^3$ — Light-front time, boost-invariant

  $k^+ = k^0 + k^3, \boldsymbol{k}_T$ — Light-front momentum, longitudinal/transverse expressed as $k^+ = xP^+$

- Light-ray operator as number operator

  $\mathcal{O}(z^-) \overset{\text{Fourier}}{\longleftrightarrow} N_{q,\bar{q}}(k^+ = xP^+)$ — Number operator of quarks/antiquarks

Hadron structure: Interpretation II



Burkardt 00

- Transverse density of quarks/antiquarks

$$\langle p'|O(z^-)|p\rangle|_{\Delta^+=0} \quad \overset{\text{Fourier } \Delta_T}{\longleftrightarrow} \quad f_{q,\bar{q}}(x, b)$$

- Transverse density of charge

$$\langle p'|J^+|p\rangle|_{\Delta^+=0} \quad \overset{\text{Fourier } \Delta_T}{\longleftrightarrow} \quad \rho(b)$$

$$\rho(b) = \sum_q e_q \int dx\, [f_q - f_{\bar{q}}](x, b)$$

EM current matrix element (form factor) directly connected with transverse distribution of quarks

- Tomographic images of hadron in $x, \boldsymbol{b}$

  Include spin: Distorted spatial distributions, quark polarization

Hadron structure: Interpretation

- Light-front representation is frame-independent, as appropriate for relativistic systems ($\equiv$ QCD)

  Can consider hadron rest frame: Orbital motion, angular momentum

  No "infinite momentum" is needed

- Light-front representation is used for interpretation, but not needed for calculation/extraction of the matrix elements

  Use invariant methods: χEFT, dispersion theory, amplitude analysis

- Can be extended to resonances!

Hadron structure: Interpretation

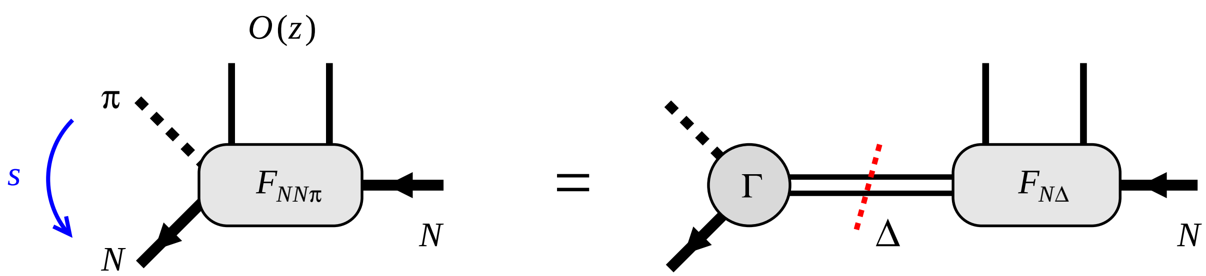
- Matrix elements of light-ray operators between resonance states

$$\langle N^*|\mathcal{O}|N\rangle,\ \langle N^*|\mathcal{O}|N^*\rangle,\ \langle h^*|\mathcal{O}|0\rangle, \ldots$$

$\rightarrow$ QCD structure of resonances

$\rightarrow$ New operators for resonance exciation

- Matrix elements of resonance states



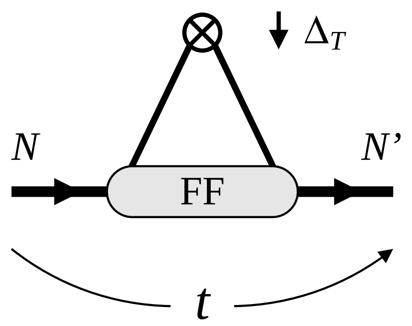
Transition matrix element between stable hadrons

Pole in invariant mass $s = s_{\text{res}}$

Residue factorization gives vertex function at pole

Form factors and transverse densities

Transverse densities: Nucleon



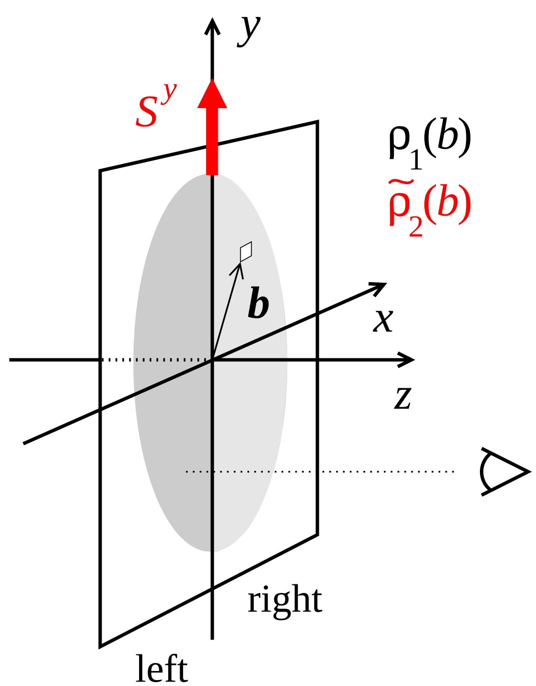
- Current matrix element parametrized by invariant form factors

$$\langle N' | J^\mu | N \rangle \;\rightarrow\; F_1(t), F_2(t)$$ Dirac, Pauli

- Transverse charge/magnetization densities
Soper 76, Burkardt 00, Miller 07

$$\rho_{1,2}(b) \;=\; \int \frac{d^2 \Delta_T}{(2\pi)^2} \; e^{-i\boldsymbol{\Delta}_T \boldsymbol{b}} \; F_i(t = -\boldsymbol{\Delta}_T^2)$$

$\boldsymbol{b}$ displacement from transverse center-of-mass

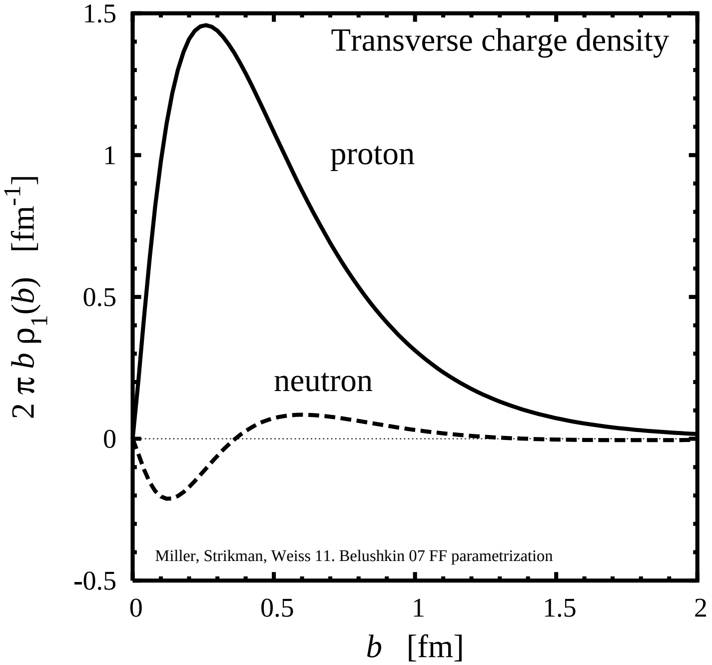


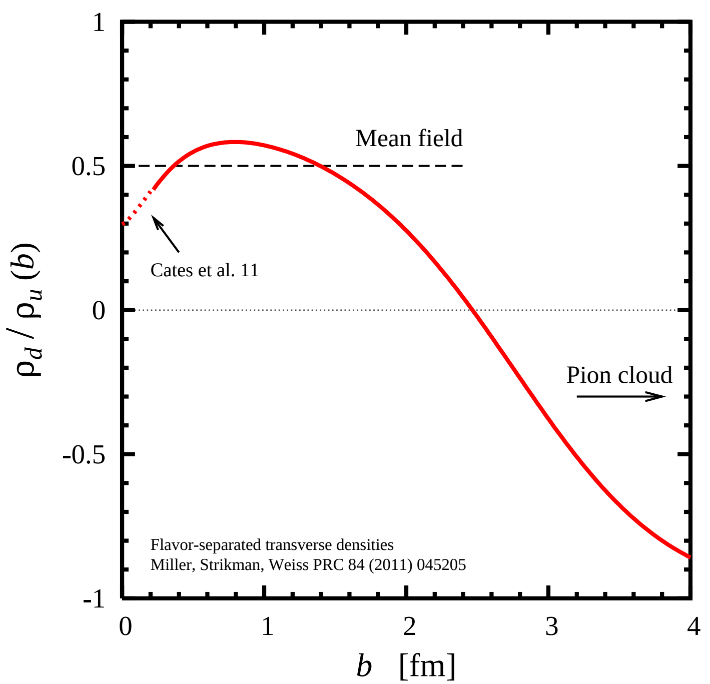
- Connection with quark distributions

$$\rho_1(b) = \sum_q e_q^2 \int dx \, [f_q - f_{\bar{q}}](x, \boldsymbol{b})$$

$\widetilde{\rho}_2(b) =$ distortion due to transverse polarization

Transverse densities: Empirical densities





- Empirical densities from form factor data

  Experimental and incompleteness errors
  Venkat, Arrington, Miller, Zhan 10

  Many interesting questions: Neutron, flavor structure, charge vs. magnetization

- Flavor–separated densities

$$\rho_u(b) = \int dx\, [f_u - f_{\bar{u}}](x, \boldsymbol{b}) \quad \text{etc.}$$

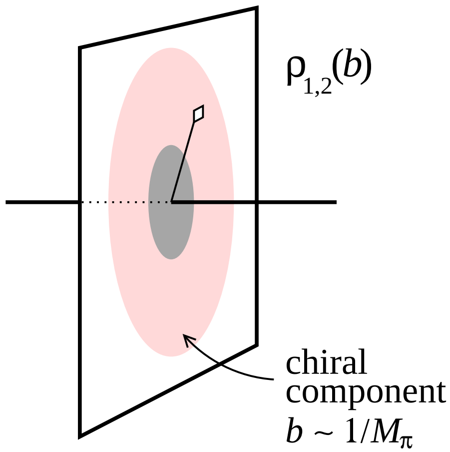
$b \sim 1\,\mathrm{fm}$ — $\rho_d/\rho_u \approx 1/2$

mean field picture
cf. quark model

$b > 3\,\mathrm{fm}$ — $\rho_d/\rho_u \to -1$

pion cloud
peripheral π^+

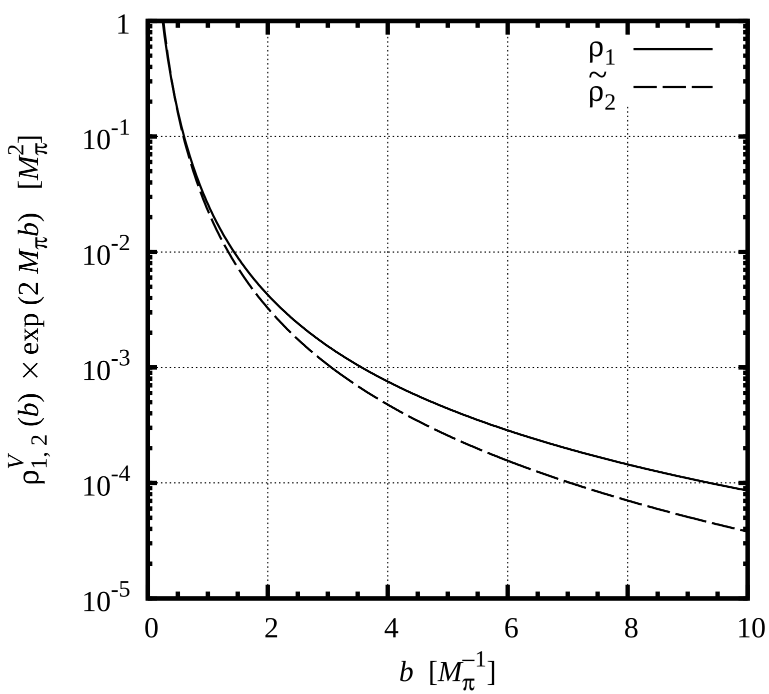
Transverse densities: Chiral periphery



- Peripheral densities at $b = O(M_\pi^{-1})$

  Governed by chiral dynamics, universal

  Calculable in chiral EFT + dispersion theory
  Strikman, Weiss PRC 82, 042201 (2010); Granados, Weiss, JHEP 1401, 092 (2014). New N/D method for $\pi\pi$ rescattering: Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017)

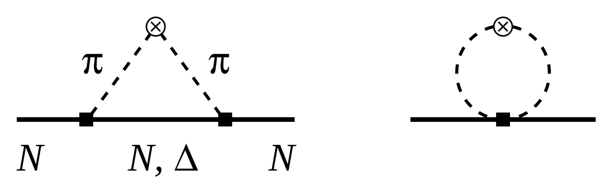


- Interesting insights

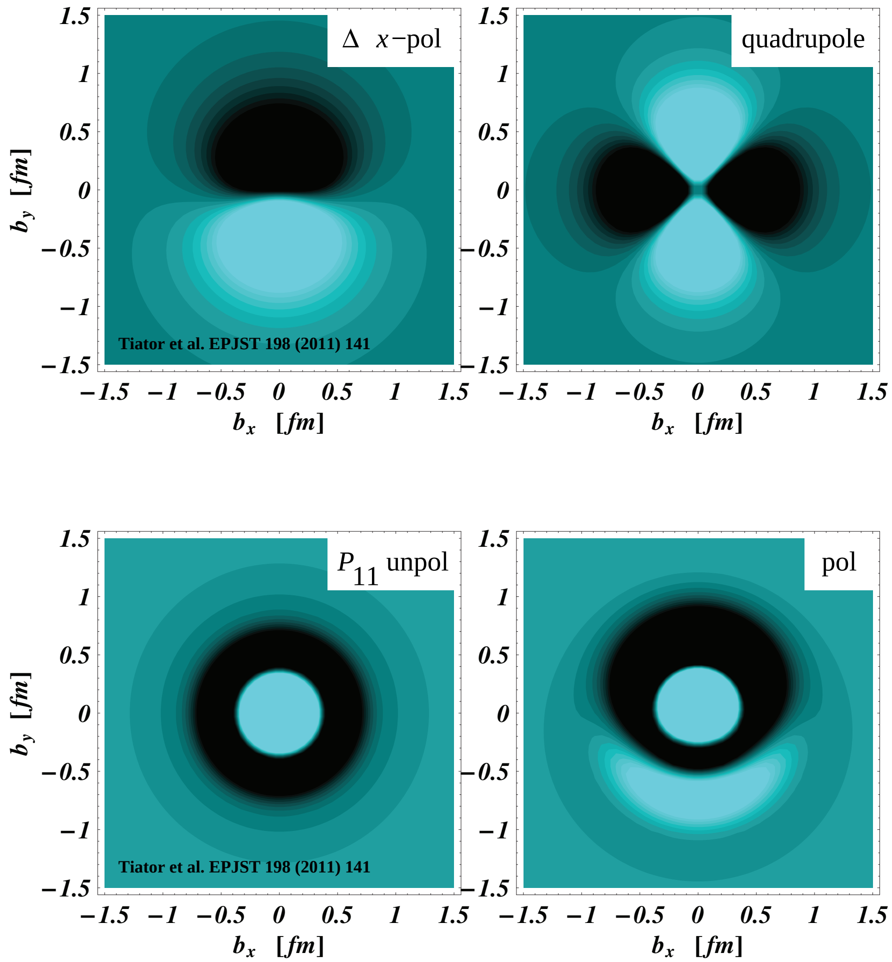
  "Yukawa tail," rich structure

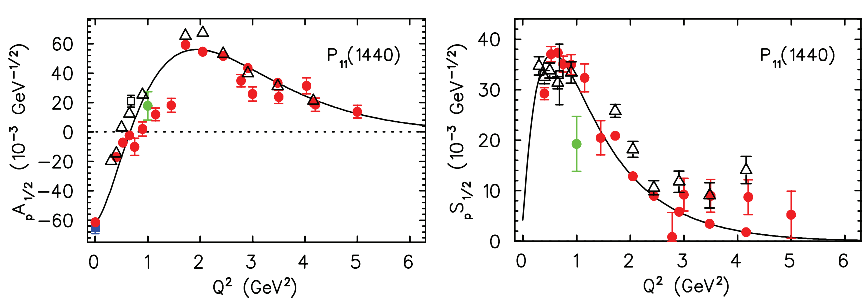
  Relation between spin-independent and -dependent densities $\widetilde{\rho}_2(b) < \rho_1(b)$
  Granados, Weiss JHEP 1507, 170 (2015); JHEP 1606, 075 (2016)

  Space–time picture of chiral dynamics



Transverse densities: Resonances





- Transition densities $N \to \Delta, N^*$

  $$\langle N^* | J^\mu | N \rangle \;\sim\; \rho^S_{N^* N}(b)$$

  Spin components

  Empirical densities extracted from transition form factors
  Carlson, Vanderhaeghen 09; Tiator et al. 11

- Resonance structure in QCD

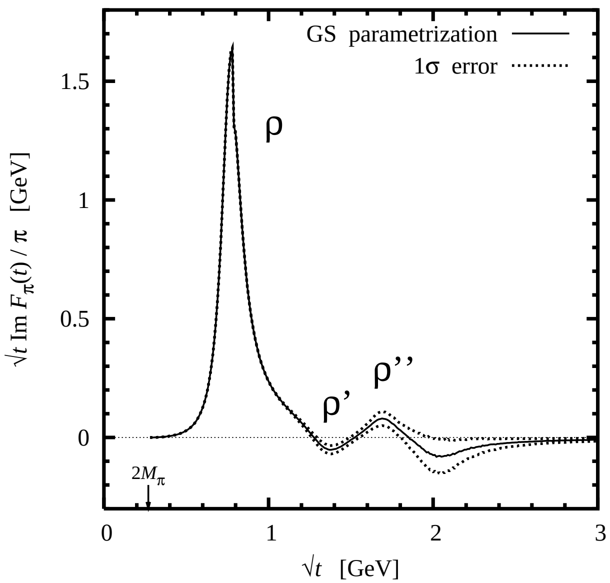
  Polarization effects: Spin–orbit interactions, deformation

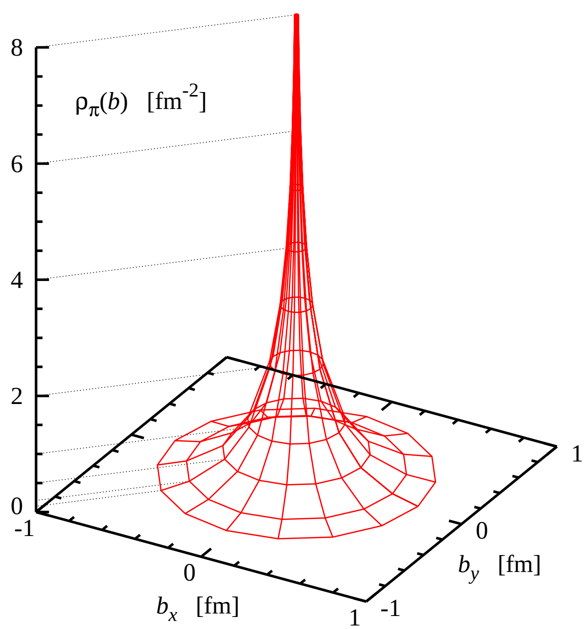
  Comparison of N and N^*: More central or more peripheral?

  Lattice QCD results
  Alexandrou et al. 08; Aubin et al 08

  Effective models: Quark orbital angular momentum Lorce, Pasquini et al.

Transverse densities: Pion





- Timelike pion FF from $e^+e^- \to \pi^+\pi^-$

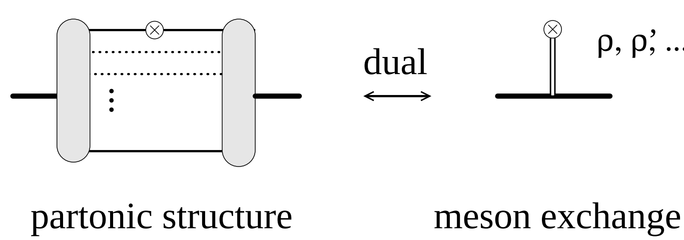
  Precise data on $|F_\pi|^2$, phase from fits/theory
  Bruch, Khodjamirian, Kuhn 04. New data CLEO 05+

- Transverse density as dispersion integral
  Miller, Strikman, Weiss, PRD 83, 013006 (2011)

$$\rho_\pi(b) = \int_{4M_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b) \, \mathrm{Im} \, F_\pi(t)$$

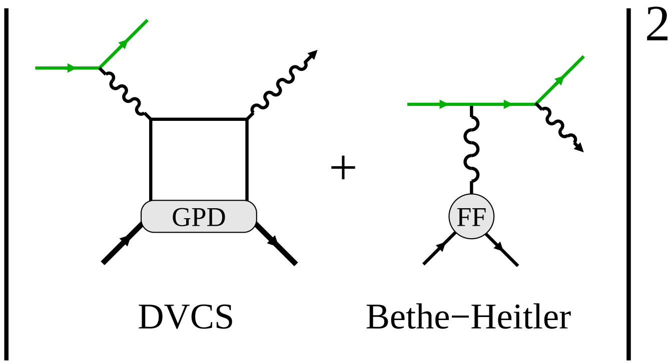
Singular charge density at center of pion:
Small–size $q\bar{q}$ configurations

Dual to vector meson exchange



Exclusive processes and GPDs

GPDs: Deeply-virtual Compton scattering

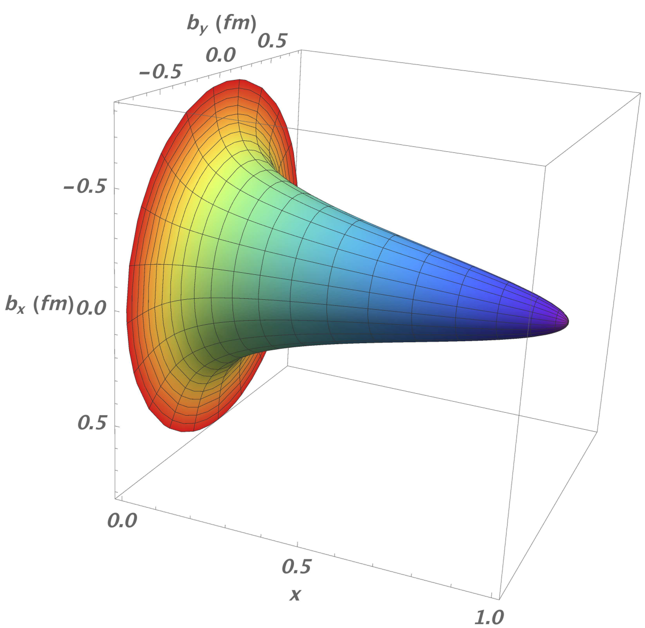


- Exclusive electroproduction $eN \to e'N'\gamma$

  Interference of DVCS and Bethe-Heitler procs

  QCD factorization extensively studied

  Experiments at HERMES, COMPASS, JLab6; dedicated program with JLab12



- First tomographic images of nucleon

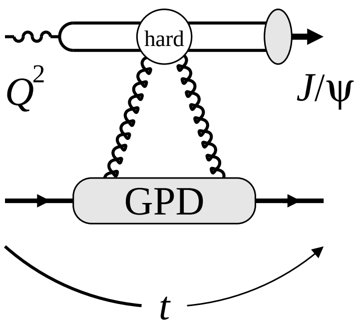
  Valence quark region $x > 0.2$
  Combined analysis of JLab6 Hall A and CLAS data.
  Dupre, Guidal, Niccolai, Vanderhaeghen 17.

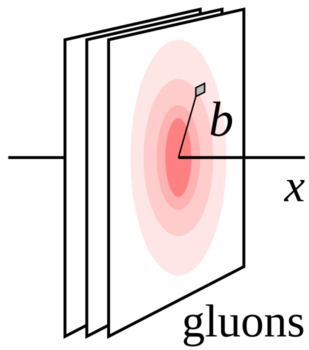
- Could be extended to $N \to \Delta$

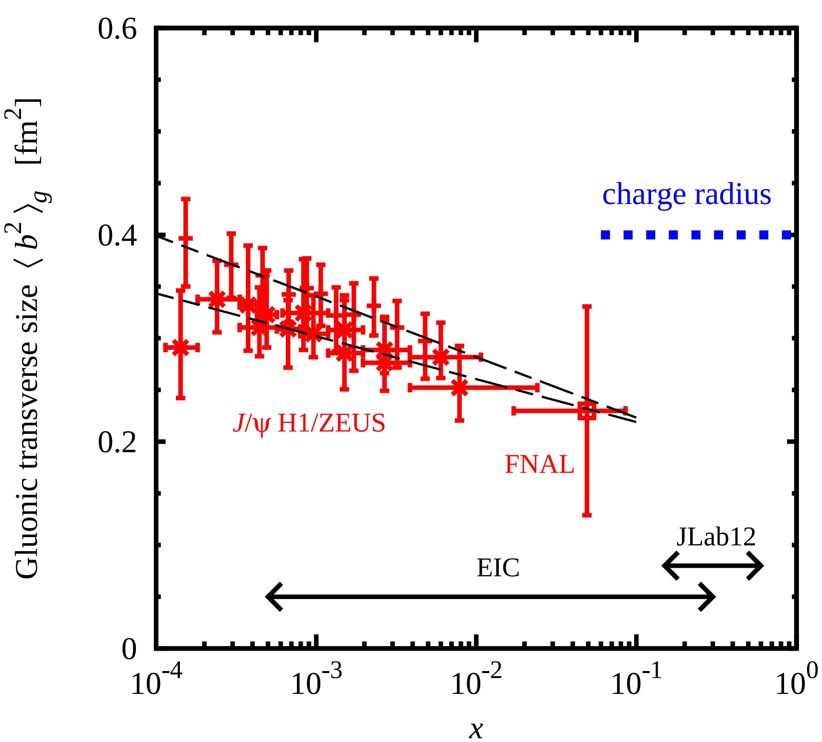
  Quark structure of $N \to \Delta$ transition

  Large-N_c relations for $N \to \{N, \Delta\}$ GPDs
  Polyakov, Vanderhaeghen 00

GPDs: Gluons with heavy vector mesons







- Gluon GPD with J/ψ and ϕ

  $x < 10^{-1}$ HERA, COMPASS, EIC

  $x > 0.2$ JLab 12 GeV ϕ

- Gluonic size of nucleon

  Increases with $x \to 0$

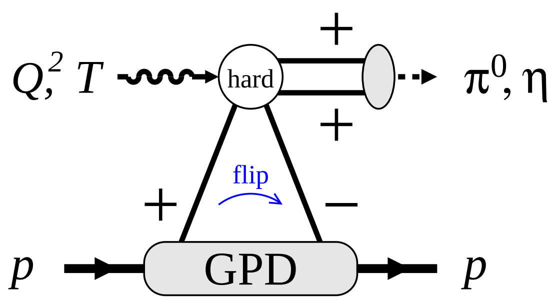
  $\langle b^2 \rangle_g < \langle b^2 \rangle_{q+\bar{q}}$ at $x > 10^{-2}$
  Gluons more central than valence quarks

  Input for pp@LHC, saturation models

- Could be extended to $N \to N^*$

  Gluonic structure of resonance transition?

Hard exclusive processes: Transversity with π, η

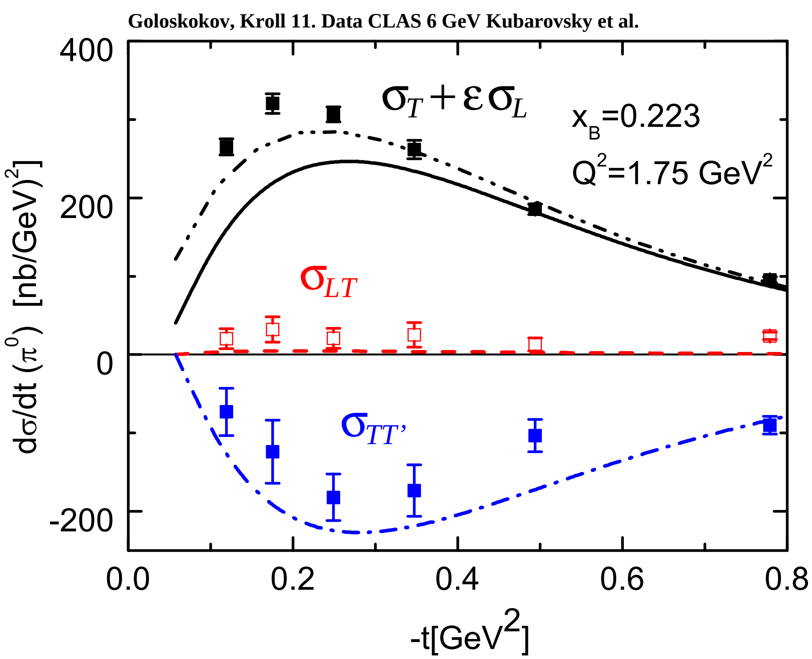


- Quark helicity flip in pion WF

  Chiral symmetry breaking in QCD

  Dominates σ_T at $W \sim$ few GeV
  Goldstein Liuti 08, Goloskokov, Kroll 11

  Probes quark transversity GPD
  cf. transversity in SIDIS, Drell–Yan



- π^0, η production at JLab6/12

  Flavor separation of transversity GPDs
  Kubarovsky 16

  Large-N_c predictions
  Schweitzer, Weiss PRC94, 045202 (2016)

- Could be extended to $N \to N^*$

  Chirality flip in resonance excitation?

Summary

- Light-ray operators are an essential tool for hadron structure

  Generalization of local current operators

  Measured in hard processes thanks to factorization

  Interpretation in terms of QCD DoF at fixed light-front time

- Tomographic images of hadron structure

  Current operators/FFs $\rightarrow$ transverse densities $\rho(b)$, $\quad \int dx$

  Light-ray operators $\rightarrow$ transverse parton densities $f(x, b)$

- Concepts and methods can be extended to resonances

  Rigorous definition of resonance structure in QCD

  Calculable theoretically: EFT, dispersion theory

  Accessible experimentally