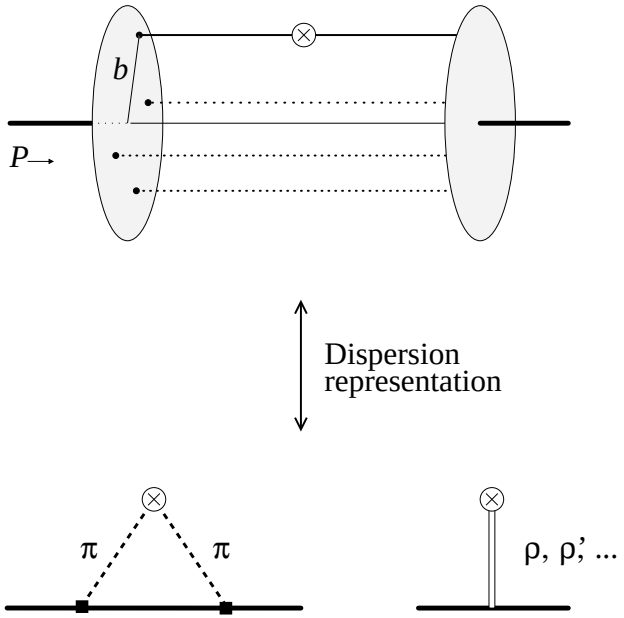
Partons meet spectroscopy: Transverse densities from timelike form factors

C. Weiss (JLab), SUPA Seminar Glasgow University, 03–Dec–10

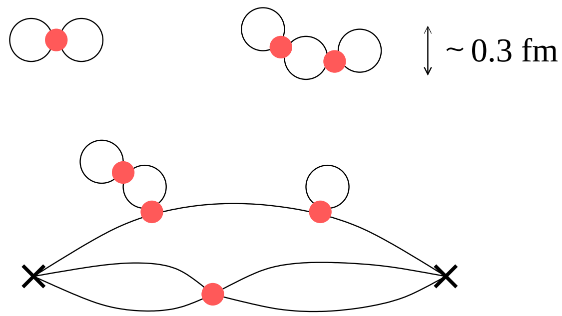


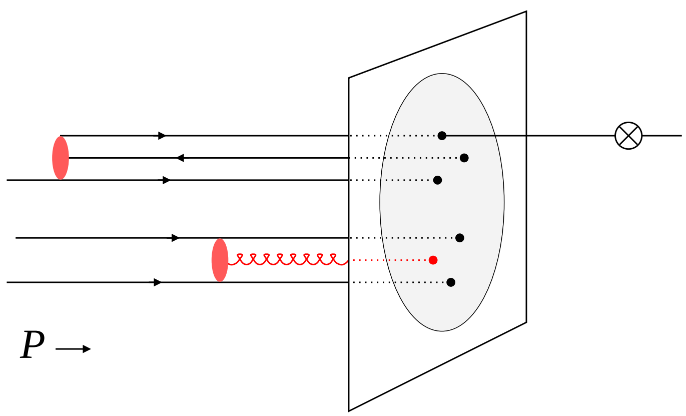
New insights into nucleon's partonic structure

New way to study ρ, ω couplings

- Transverse hadron structure
  - Why partonic description
  - Transverse densities from elastic FFs
  - Connection with GPDs
- Nucleon transverse charge density
  - Dispersion representation of $\rho(b)$
  - Zooming in on exchange mechanisms: Chiral pions, vector mesons, resonances
  - Neutron charge density
- Pion transverse density from timelike FF
  - Timelike pion FF from e^+e^- data
  - Singular charge density at $b \to 0$
  - Pointlike $q\bar{q}$ configurations in pion

Nucleon structure: Partonic description





- QCD vacuum not empty

  Strong non-perturbative gluon fields of size $\rho \ll 1\,\mathrm{fm}$ ← Lattice simulations, analytic models

  Chiral symmetry breaking: $\bar{q}q$ pair condensate, π as collective excitation

- Slow–moving nucleon $P \sim \rho^{-1}$

  $\langle N|J_\mu|N\rangle$ from Euclidean correlation functns

  No concept of particle content
  Cannot separate "constituents" from vacuum fluctuations

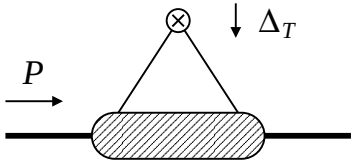
- Fast–moving nucleon $P \gg \rho^{-1}$

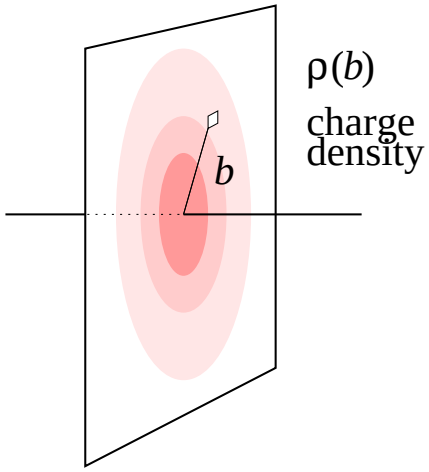
  Closed system: Wave function description variable particle number, x_i, $\boldsymbol{k}_{Ti}$ Gribov, Feynman

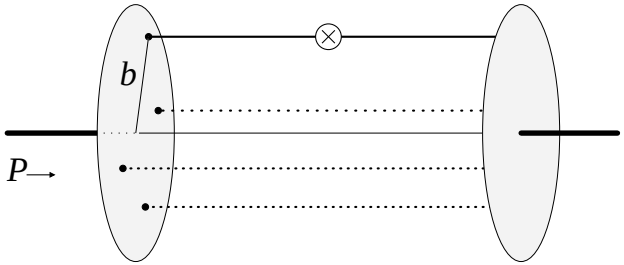
  Current operators "count" particle nr × charge

  Physical properties:
  Longitudinal momentum densities — PDFs
  Transverse distributions — → Form factors, GPDs
  Orbital motion — TMDs

Nucleon structure: Transverse densities







- Current matrix element parametrized by invariant form factors

  $\langle N'|J_\mu|N\rangle \;\rightarrow\; F_1(t), F_2(2)$ Dirac, Pauli

- Transverse charge density $t = -\boldsymbol{\Delta}_T^2$

  $F_1(t) \;=\; \int d^2b\; e^{i\boldsymbol{\Delta}_\mathrm{T}\boldsymbol{b}}\; \rho(b)$ 2D Fourier

  Transverse density of charge in fast–moving nucleon
  $\boldsymbol{b}$ displacement from transverse C.M.

- Proper density for relativistic system

  $$\rho(b) = \sum_N \text{charge} \int dx\; \psi^*(x, \boldsymbol{b}/\bar{x}, ..)\psi(x, \boldsymbol{b}/\bar{x}, ..)$$

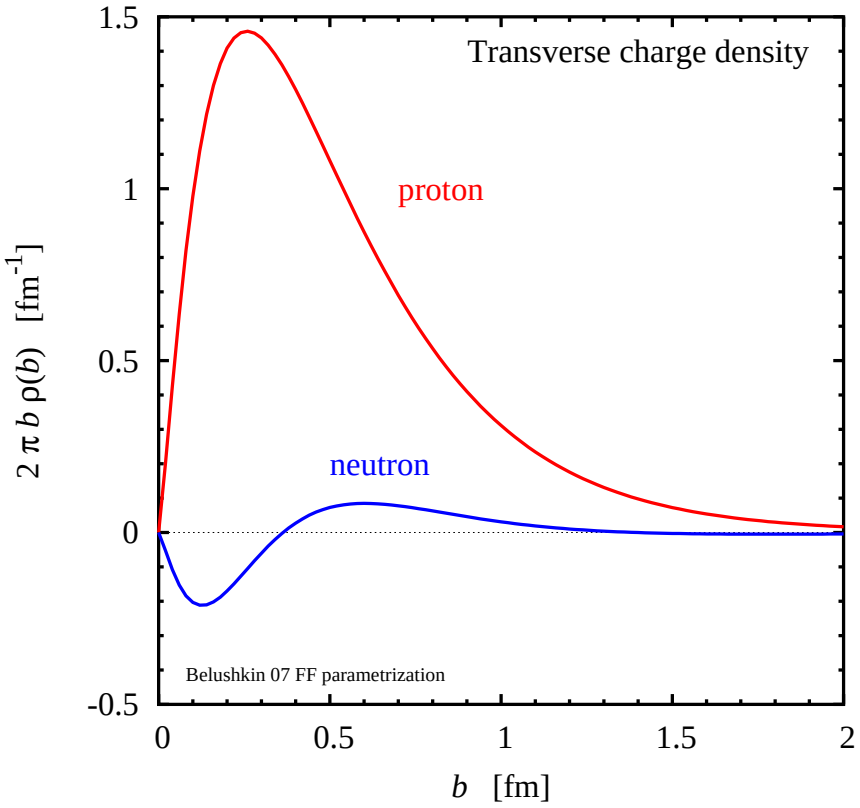
  Cumulative effect of constituents at transv. position $\boldsymbol{b}$

  ↯ Breit frame distribution not density Miller 07

- More general: Reduction of GPDs

  $\rho(b) \leftrightarrow$ transverse size in hard exclusive processes

Nucleon: Transverse density from spacelike FF



$$\rho(b) = \int_0^\infty \frac{d\Delta}{2\pi}\, \Delta\, J_0(\Delta b)\; F_1(t = -\Delta^2)$$

- Nucleon transverse charge density from spacelike form factor data

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

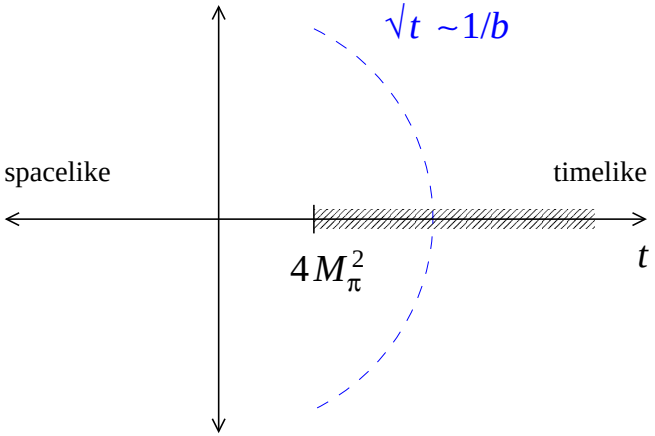
- Neutron density positive at distances $b \sim 0.5 - 1\,\text{fm}$ Miller 07

  Contradicts naive picture of $n = p(\text{center}) + \pi^-(\text{cloud})$

  Dynamical explanation?

  Nucleon periphery
  $\leftrightarrow$ exchange mechanisms?

Nucleon: Dispersion representation

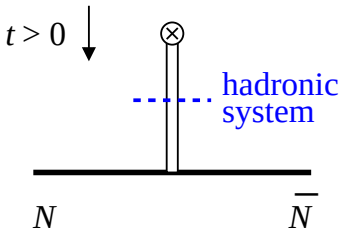


- Dispersion representation of form factor

$$F(t) = \int_{4\mathrm{m}_\pi^2}^{\infty} \frac{dt'}{t' - t + i0} \frac{\mathrm{Im}\, F(t')}{\pi}$$

Spectral function $\mathrm{Im}\, F(t')$ describes "process"
$\gamma^* \to$ hadronic system $\to N\bar{N}$

Unphysical region: Spectral function from dispersion analysis, χPT near threshold, pQCD $t \to \infty$



- Transverse density

$$\rho(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b)\, \mathrm{Im}\, F(t)$$

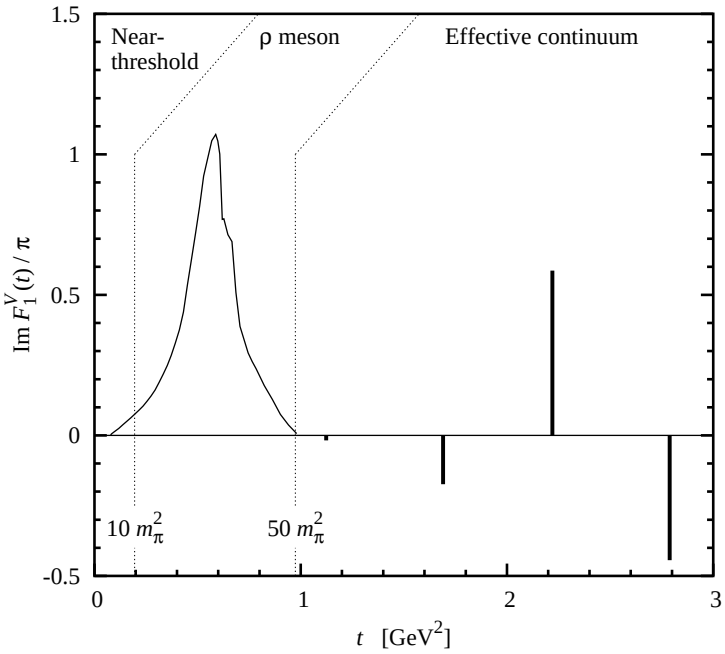
$K_0 \sim e^{-b\sqrt{t}}$ exponential suppression of large t

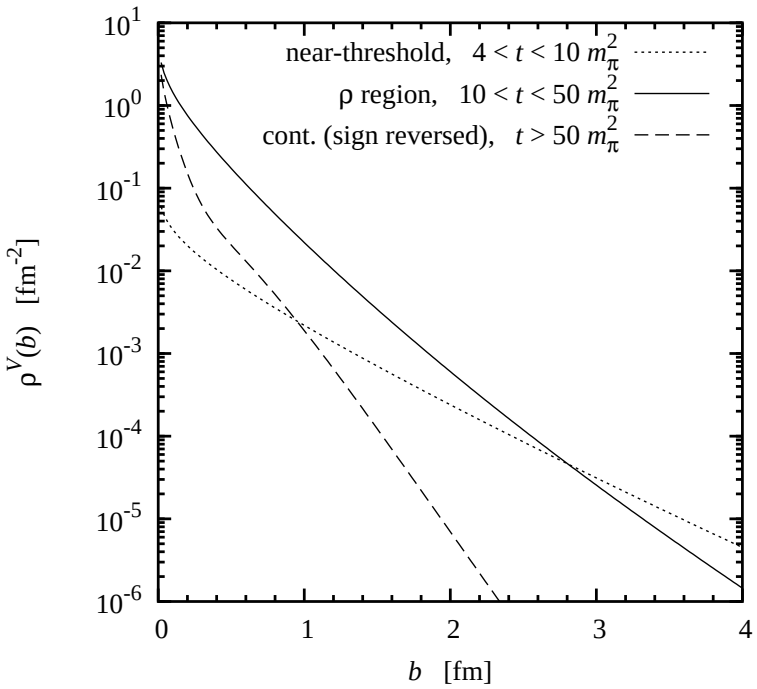
Dispersion integral selects $\sqrt{t} \sim 1/b$:
"Filter" for spectral density Strikman, CW 10

New tool to analyze exchange mechanisms!

Isovector: $\pi\pi, \rho, \rho', \ldots$
Isoscalar: $\omega, \phi, K\bar{K}, \ldots$

Nucleon: Spectral analysis of charge density





- Analyze contributions of spectral mass regions to transverse charge density

  Quantitative, model–independent. Miller, Strikman, CW, in preparation.
  Spectral densities from Belushkin, Hammer, Meissner 07

- Isovector density

  Near–threshold $\pi\pi$ relevant only at $b > 2\,\mathrm{fm}$
  Chiral dynamics applicable only at very large distances! SW10

  Intermediate $b = 0.5 - 1\,\mathrm{fm}$ dominated by ρ, with $10 - 15\%$ correction from first ρ'

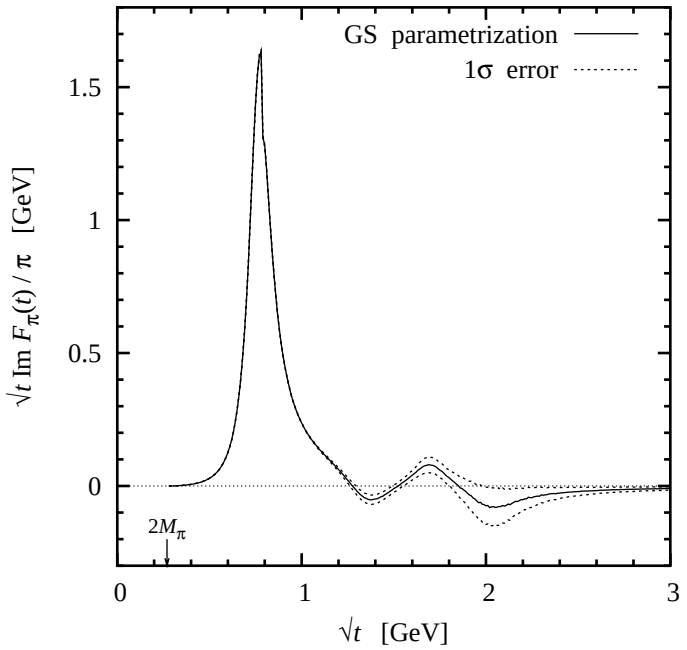
- Isoscalar density

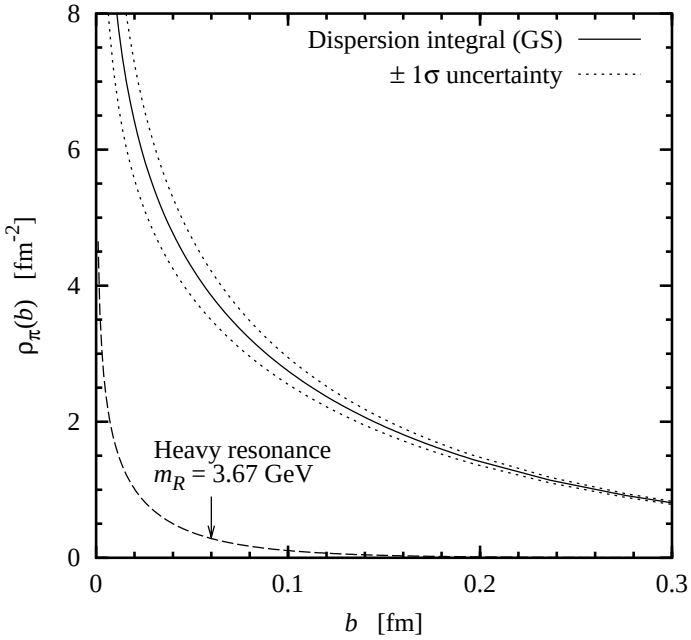
  No chiral contribution, 3π extremely small

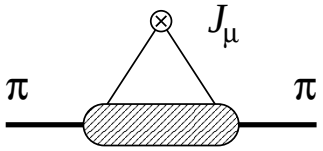
  Intermediate $b = 0.5 - 1\,\mathrm{fm}$ from ω, with $20 - 50\%$ contribution from $K\bar{K}, \pi\rho$

Neutron charge density at intermediate b unrelated to pion cloud! Explained instead by effective dynamics in vector meson mass region

Pion: Transverse density from timelike FF







- Spacelike FF poorly known at $|t| > 1\,\mathrm{GeV}^2$
  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.

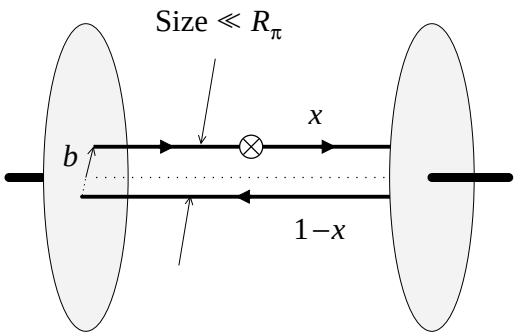
- Transverse density from dispersion integral
  Miller, Strikman, CW 10

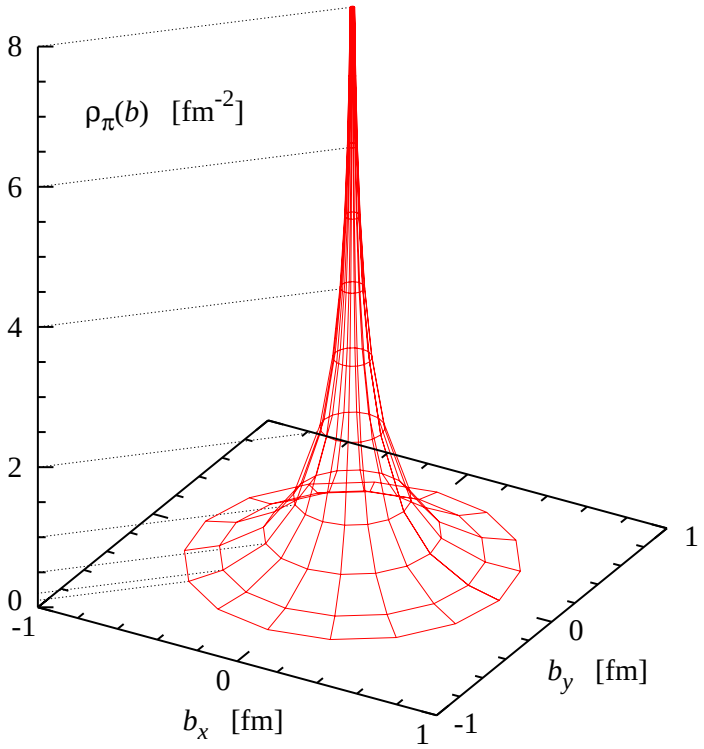
$$\rho_\pi(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2}\, K_0(\sqrt{t}b)\, \mathrm{Im}\, F_\pi(t)$$

  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

  Configs of size $r \ll R_\pi$, mostly elementary $q\bar{q}$

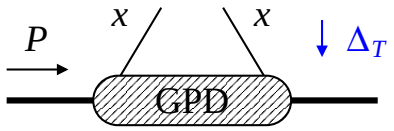
  Observable in other high–momentum transfer processes: $\gamma^*\gamma \to \pi^0$, $\pi + A \to 2\,\text{jets}, \ldots$
  Universal property

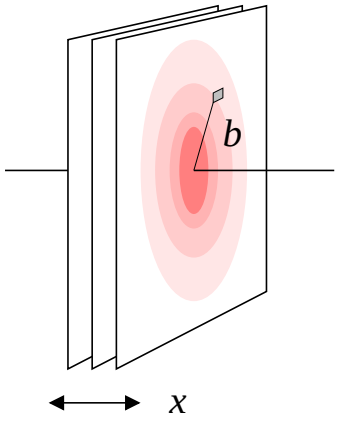
  Large–size configs with $x \to 1$ cannot account for empirical charge density at $b \to 0$
  Miller, Strikman, CW 10

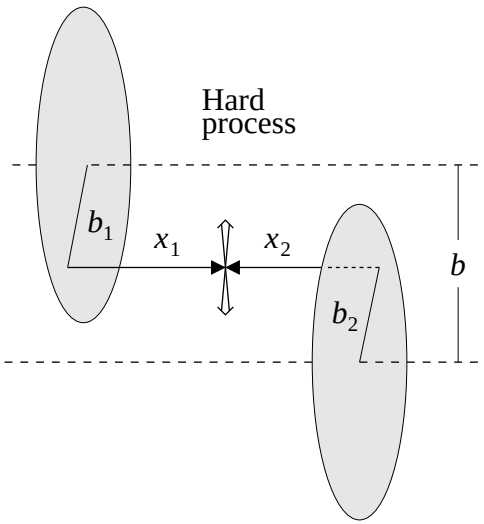
- 2D image of fast–moving pion

  First accurate transverse image based on data!

More general: GPDs







- Generalized parton distribution

  Form factor of partons with longit. momentum xP

  QCD operator definition $\langle N'|\,\text{twist-2}\,|N\rangle$, universal

  Probed in hard exclusive processes in $ep/\gamma p$:
  Factorization theorems, kinematics $x' \neq x$
  J/ψ, vector mesons at HERA, DVCS at HERMES, COMPASS, JLab 6/12 GeV

- Transverse spatial distribution of partons

  $$\text{GPD}(x,t) \;=\; \int d^2b\; e^{i\boldsymbol{b}\boldsymbol{\Delta}_T}\; f(x,b)$$

  Tomographic image of hadron at fixed x, changes with x, Q^2

  $$\rho(b) \;=\; \int dx\; f_{q-\bar{q}}(x,b)$$ Reduction of GPD

- Essential input to pp@LHC

  Impact parameter dependence of cross secn for hard processes
  Underlying event, multiparton processes, gap survival in diffraction → MPI@LHC2010 Glasgow

Summary

- Elastic form factors provide important information on partonic structure through transverse charge/current densities

- Dispersion integral for $\rho(b)$ samples spectral function at energies $\sqrt{t} \sim 1/b$, allows for systematic study of the various exchange mechanism

- Nucleon charge densities at intermediate distances $b = 0.5 - 1.5\,\text{fm}$ governed by vector mesons; pion cloud relevant only at $b > 2\,\text{fm}$

- Singular charge density in pion reveals pointlike $q\bar{q}$ configurations in partonic wave function