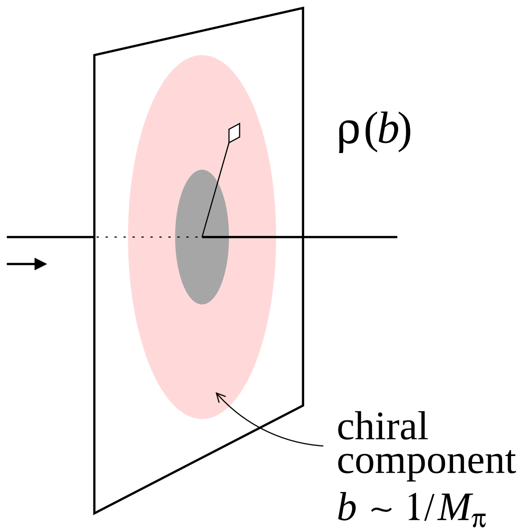
Chiral dynamics in transverse nucleon structure

C. Weiss (JLab), Chiral Dynamics 2012, 08–Aug–12



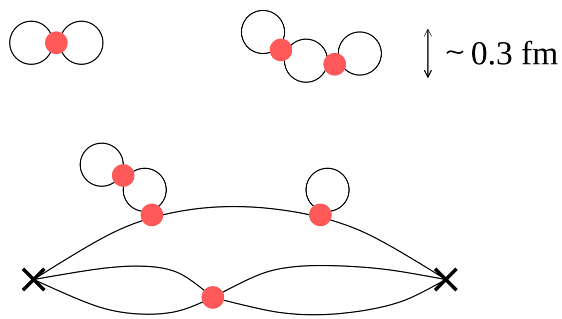
$b \sim 1/M_\pi$ new regime for χPT
universal, model–independent

Chiral and non–chiral components identified by spatial size

Connection with GPDs, peripheral ep/pp processes

- Parton picture of nucleon structure
  - Wave function description
  - Transverse densities from elastic FFs
  - Connection with GPDs
- Chiral component of transverse density
  - Invariant χPT: Spectral function $\mathrm{Im}\, F_{1,2}(t)$
    Strikman, CW, PRC82 (2010) 042201
  - Light–front χPT: πN wave functions
    C. Granados, CW; in progress
  - Chiral vs. non–chiral component
  - Spectral analysis: Vector mesons
    Miller, Strikman, CW, PRC84 (2011) 045205
  - Effect on low–t elastic FFs
    Simple estimates only!
- Chiral dynamics in parton densities
  - x–dependent transverse size of nucleon
  - Peripheral high–energy ep/pp scattering

Nucleon structure: Parton picture



- QCD vacuum not empty

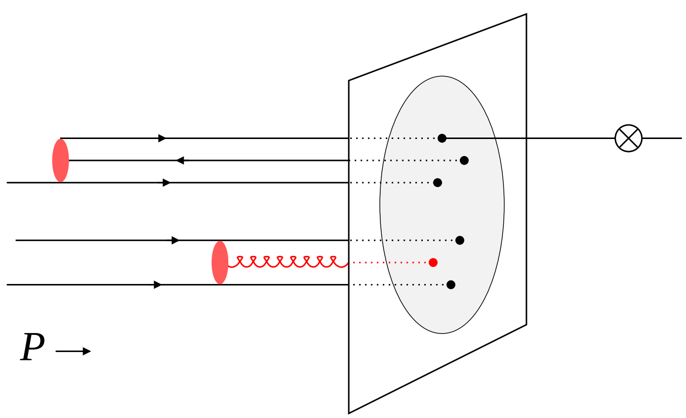
  Strong non-perturbative gluon fields
  of size $\ll 1\,\mathrm{fm}$ ← Lattice QCD, analytic models

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

- Nucleon at rest

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

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



- Fast–moving nucleon $P \gg \mu_{\mathrm{vac}}$

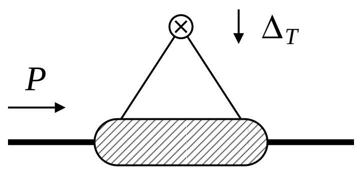
  Closed system: Wave function, Gribov, Feynman
  variable particle number, x_i, $\boldsymbol{k}_{Ti}$

  Current operators "count" particle nr × charge

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

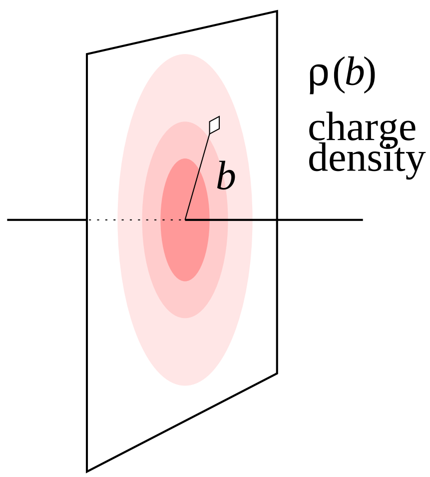
  Alt. view: Observer moves with velocity $v \to 1$.
  Light–front quantization, frame–independent Brodsky et al.

Nucleon structure: Transverse densities



- Current matrix element parametrized by invariant form factors

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



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

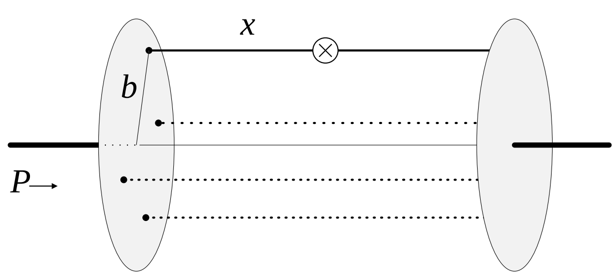
  $$F_1(t) \;=\; \int d^2b \; e^{i\boldsymbol{\Delta}_\mathrm{T}\boldsymbol{b}} \; \rho(b) \quad \text{2D Fourier}$$

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

- Proper density for relativistic system

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

  Cumulative charge of constituents at transv. position $\boldsymbol{b}$
  Breit frame distribution not density: Miller 07

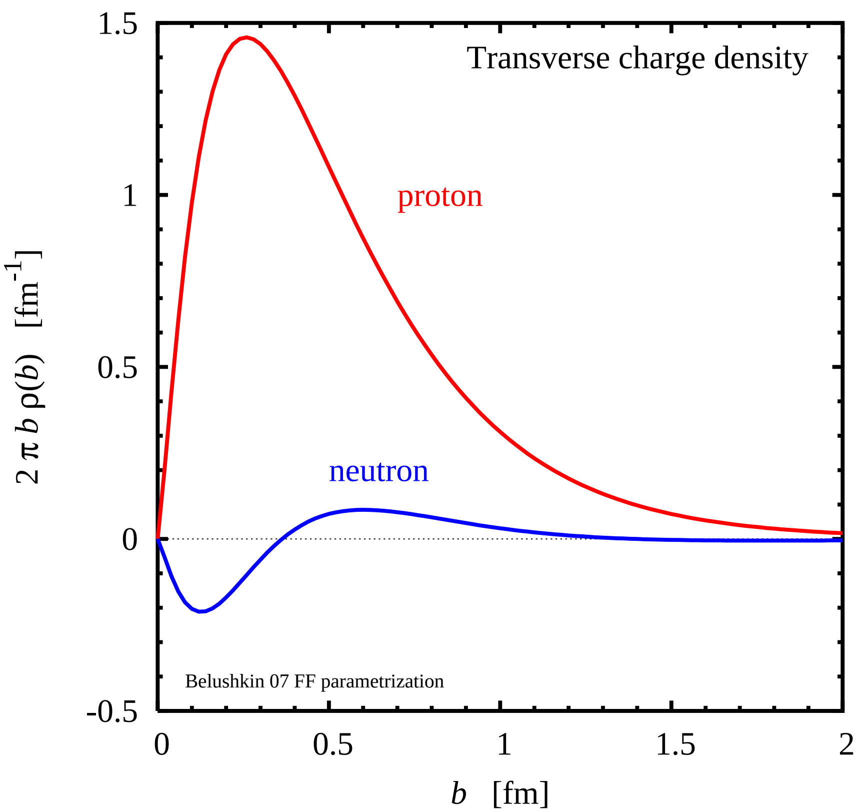


- Reduction of GPDs

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

  Transverse size in hard exclusive processes
  universal, process–independent

Nucleon structure: Densities from FF data



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

- Nucleon transverse charge density from spacelike form factor data

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

  Recent low–$|t|$ data incorporated MAMI: Vanderhaeghen, Walcher 10

  Neutron density positive at distances $b \sim 0.5 - 1$ fm Miller 07. Different theoretical explanations

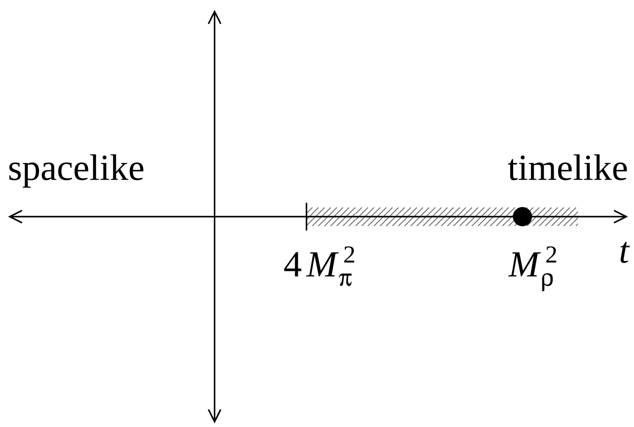
- Large–distance behavior?

  $b \to \infty$ dominated by chiral dynamics: universal, model–independent

  At what distances is the chiral component relevant?

  Can it be seen experimentally?

Transverse density: Dispersion representation

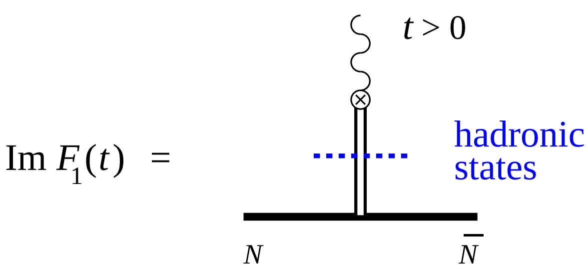


- Dispersion representation of form factor

$$F_1(t) = \int_{4m_\pi^2}^{\infty} \frac{dt'}{t' - t - i0} \frac{\mathrm{Im}\, F_1(t')}{\pi}$$

Spectral function $\mathrm{Im}\, F_1(t')$ describes "process" current $\rightarrow$ hadronic states $\rightarrow N\bar{N}$

$\mathrm{Im}\, F_1(t')$ from form factor fits and theory: χPT near threshold, dispersion rels, pQCD $t \rightarrow \infty$
Höhler et al. 76; Belushkin, Hammer, Meissner 06



- Transverse density

$$\rho(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b)\, \mathrm{Im}\, F_1(t)$$

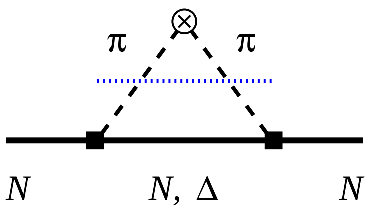
$K_0 \sim e^{-b\sqrt{t}}$ exponential suppression of large t

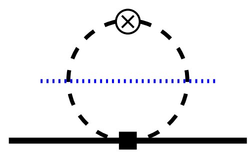
Distance b selects masses $\sqrt{t} \sim 1/b$: "Filter"
Cf. Borel transformation in QCD sum rules. Strikman, CW 10

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

Peripheral $\rho(b) \longleftrightarrow$ low–mass hadronic states

Chiral component: Spectral function





$$\rho^V(b) \quad \propto \quad \frac{\exp(-2M_\pi b)}{(2M_\pi b)^3}$$

$$\times \quad \left(1 + \text{terms} \, \frac{M_N^2}{M_\pi^3 b} + \ldots \right)$$

Limits $b \to \infty$ and $M_\pi / M_N \to 0$ do not commute: Do not expand in M_π / M_N

- Spectral function near threshold $t - 4M_\pi^2 \sim$ few M_π^2 from χPT   Isovector

  Relativistic chiral Lagrangian
  Becher, Leutwyler 99

  Heavy–baryon expansion not convergent due to subthreshold singularity
  Becher, Leutwyler 99; Kaiser 03

- Asymptotic behavior for $b \to \infty$
  Strikman, CW 10

  Yukawa tail with range $2M_\pi$

  Pre-exponential factor strongly varying

- Include intermediate Δ

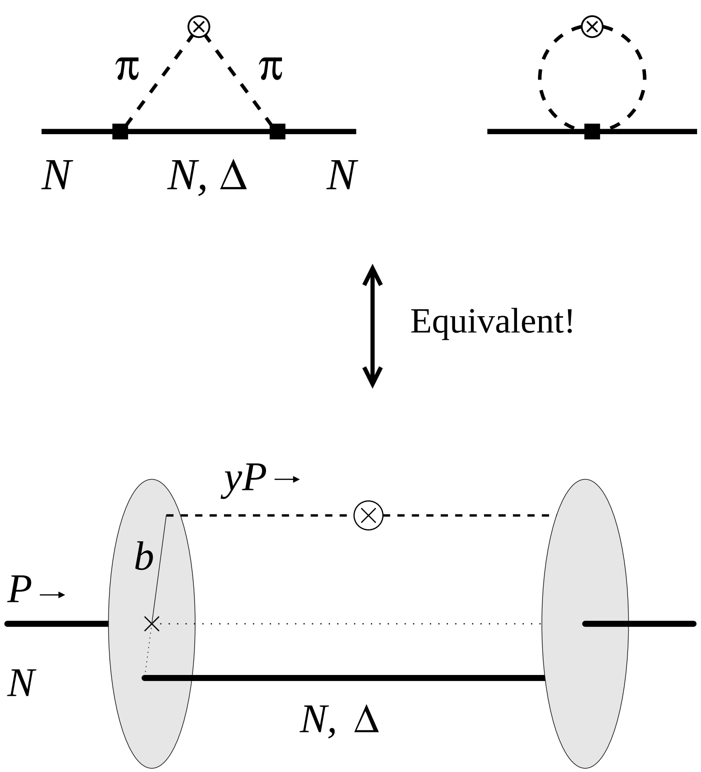
  Large coupling!

  Large–N_c limit of QCD: $g_V \sim N_c^0$ requires cancellation between N and Δ Cohen 95

  $M_N, M_\Delta \sim N_c$

  $M_N - M_\Delta \sim 1/N_c$ degenerate

Chiral component: Partonic formulation



Equivalence of invariant and partonic formulation of χPT

- Partonic representation of chiral component

$$\rho^V(b) \;=\; \int_0^1 dy\,\left[\tfrac{2}{3} f_{\pi N}(y,b) - \tfrac{1}{3} f_{\pi\Delta}(y,b)\right]$$

$f_{\pi B}(y,b)$ pion longitudinal momentum and transverse coordinate density
Strikman, CW 09: Chiral contributions to parton densities

$y \sim M_\pi / M_N$ parametrically small

- Overlap of light–front wave functions

$$f_{\pi N}(y,b) = \sum_{L=0,1} \psi^{L*}_{\pi N}(y, b/\bar{y}) \psi^{L}_{\pi N}(y, b/\bar{y}) + \delta(y) \text{ term}$$

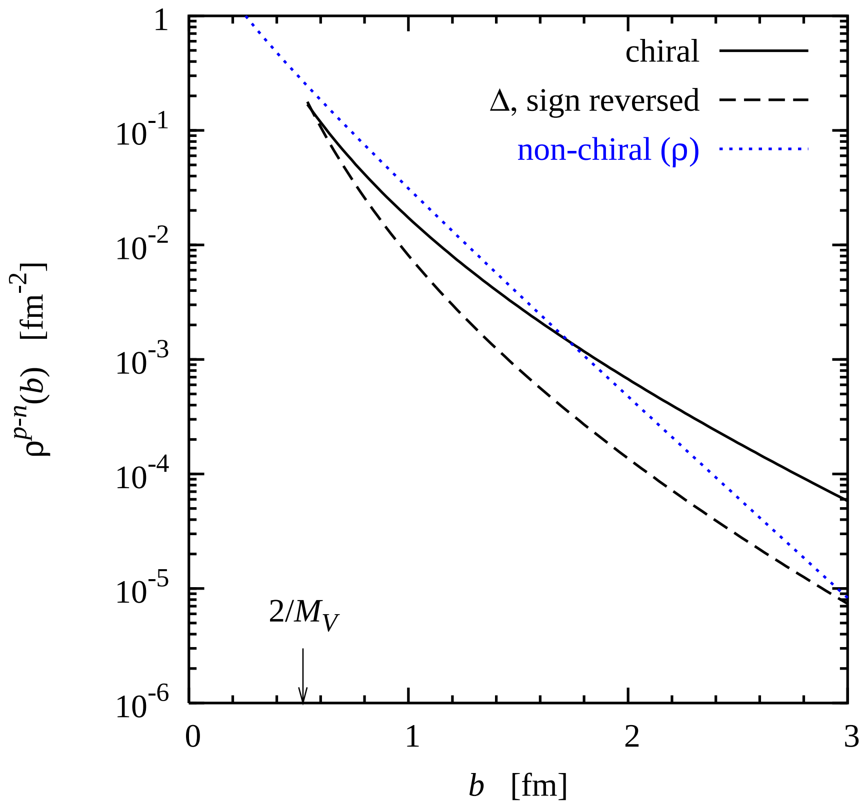
Orbital angluar momentum of πN system!
Also magnetic density: $\Delta L = 1$. Granados, CW 12

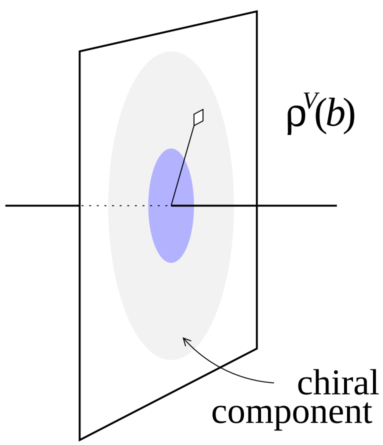
- Contact terms $\delta(y)$ "Light–front zero modes"

Represent effect of high–mass intermediate states in time–ordered PT Granados, CW 12

Coefficient $(1 - g_A^2)$: Compositeness of nucleon

Chiral component: Numerical evaluation





- Numerical evaluation

  Contact term $\delta(y)$ in πN contributes $< 10\%$ at $b > 1\,\mathrm{fm}$

  $\pi\Delta$ negative, suppressed at large b

- Compare with "non–chiral" density

  Simple estimate: ρ meson pole

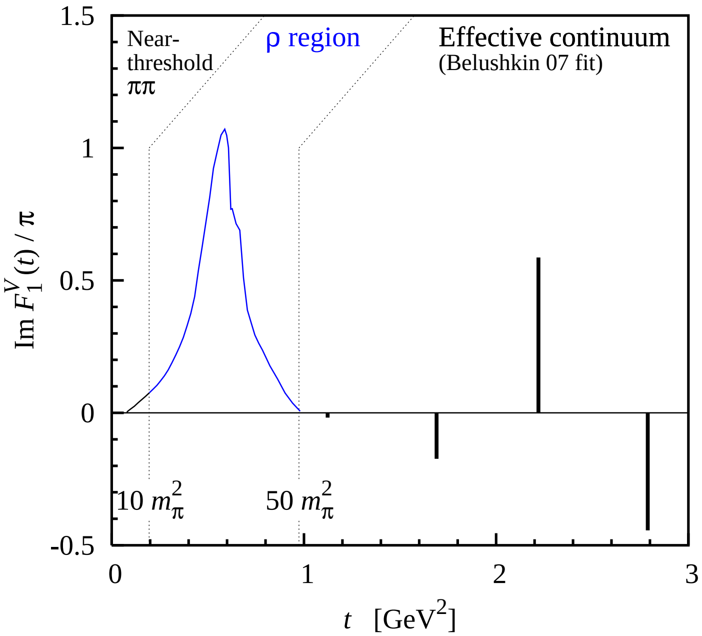
  Chiral component dominates only at $b > 2\,\mathrm{fm}$ . . . surprisingly large!

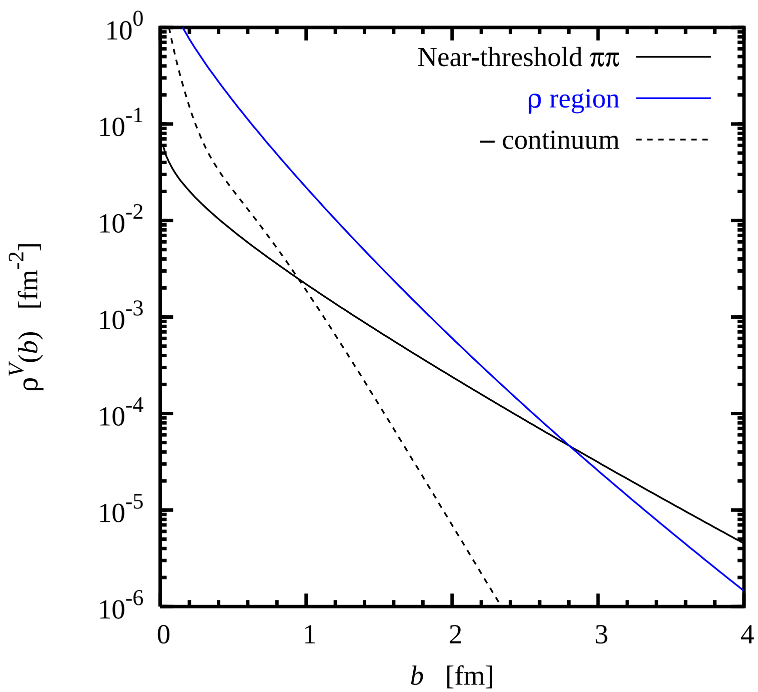
- Impact parameter b as new way of identifying chiral component

  Model–independent!

  b observable in exclusive processes, objectively defined $\leftrightarrow$ Breit frame radius

Chiral component: Spectral analysis





- Empirical isovector spectral function

  Near–threshold $\pi\pi$ from chiral dynamics
  ρ region from $\pi\pi$ phase shifts Höhler 76
  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07

- Spectral analysis of isovector density
  Strikman, CW 10; Miller, Strikman, CW 11

  Near–threshold $\pi\pi$ relevant only at $b > 2\,\mathrm{fm}$

  Intermediate $b = 0.5 - 1\,\mathrm{fm}$ dominated by ρ, with $\sim 10\%$ correction from higher masses
  "Vector dominance" quantified

- Isoscalar density

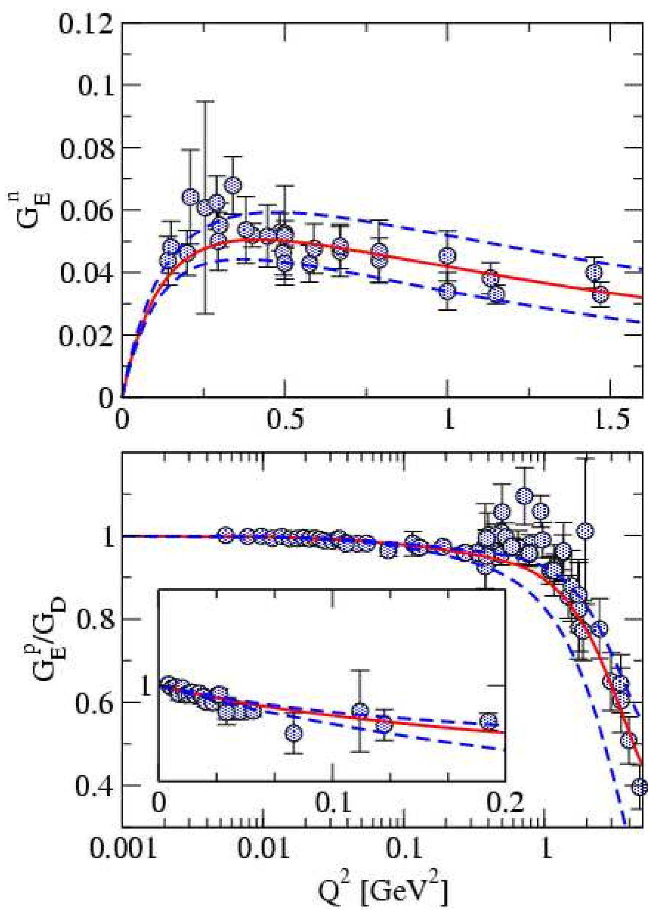
  ω dominates at $b > 1.5\,\mathrm{fm}$.

  Large cancellations between ω and higher–mass states at $b = 0.5 - 1\,\mathrm{fm}$

Model–independent identification of chiral component, "vector dominance" in QCD

Chiral component: Effect on form factors

Simple estimates!



Dispersion fit Belushkin, Hammer, Meissner 07
New data from Bates, MAMI, JLab

- Moments of transverse charge density

$$\langle b^2 \rangle = \int d^2b\, b^2 \rho(b) = 4\, F_1'(0)$$

$$\langle b^4 \rangle = 32\, F_1''(0)$$

- Contribution of chiral component isovector

$$\langle b^2 \rangle_{\text{chiral}} \approx 0.2 \times \langle b^2 \rangle_{\text{fit}} \qquad \text{small}$$

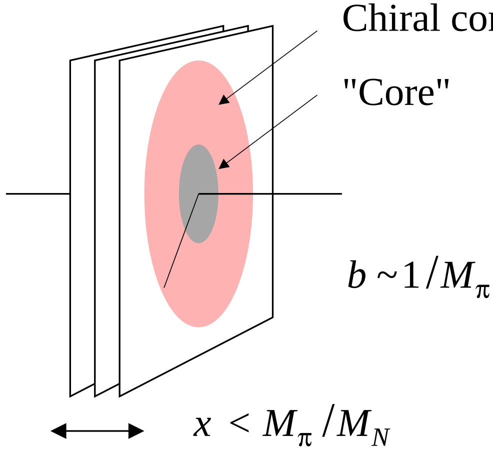
$$\langle b^4 \rangle_{\text{chiral}} \approx 1.5 \times \langle b^2 \rangle_{\text{fit}}^2 \qquad \text{sizable}$$

Chiral component should be visible in "unnatural" second and higher derivatives of FF at $Q^2 = 0$
Can we extract it?

- Analyticity of form factor fit is essential
Needs dispersion analysis: Belushkin et al. 07

- Affects extrapolation to $t \to 0$
CLAS/PRIMEX 12 GeV experiment at $Q^2 = 10^{-4} - 10^{-2}\text{GeV}^2$
PR12-11-106 Gasparian et al.

Parton distributions: Chiral component

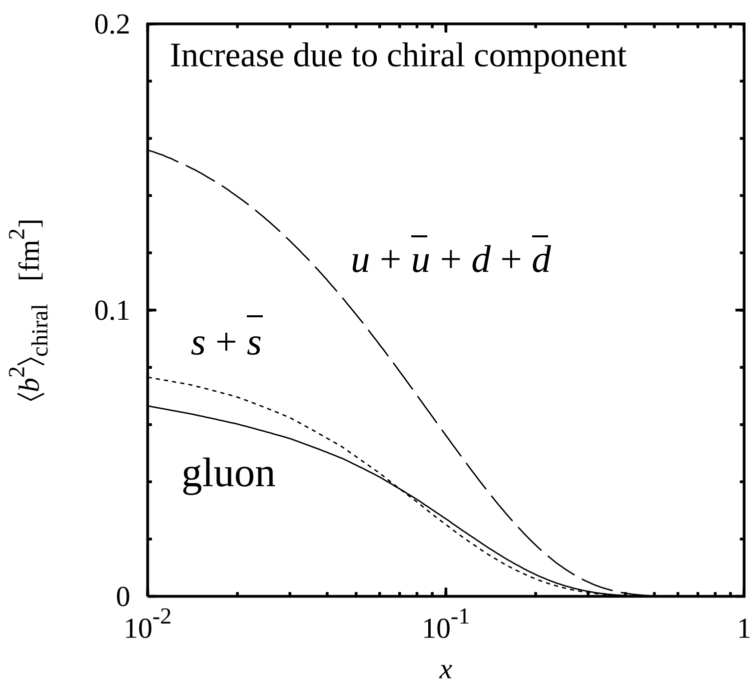


- Large–distance component of quark/gluon densities at $b \sim M_\pi^{-1}$ and $x < M_\pi/M_N$
  Strikman, CW PRD69:054012,2004; PRD80:114029,2009

  Model–independent, calculable: "Yukawa tail"

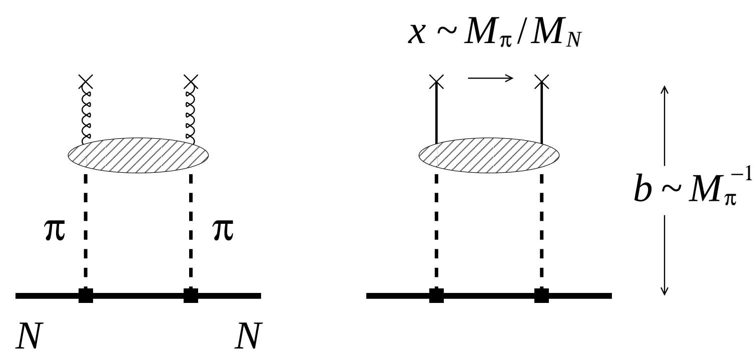
  Strong in isoscalar quarks and gluons, suppressed in isovector $\bar{d} - \bar{u}$

  Small fraction of total number: Most partons sit at distances $b \lesssim 0.5\,\text{fm}$

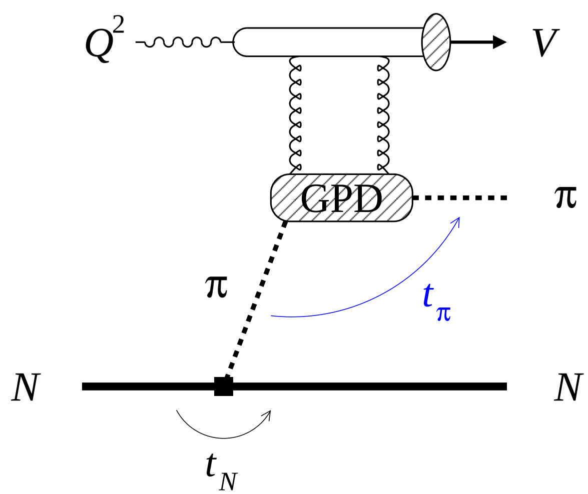


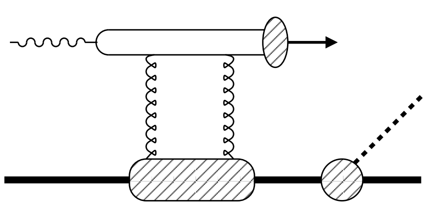
- Increase of nucleon's transverse radius below $x \sim M_\pi/M_N$

  Larger for quarks than for gluons!



Parton distributions: Peripheral hard processes





suppressed!

- Hard exclusive process on peripheral pion
  Strikman, CW PRD69:054012,2004

  $k_\pi^2 \sim M_\pi^2$ quasi-real

  Requires $x \ll M_\pi / M_N \sim 0.1$

- Kinematics with $p_T(\pi) \gg p_T(N)$ suppresses production on nucleon

  $F_{\pi NN}(t)$ softer than $\mathrm{GPD}_\pi(t)$

- Probe gluon GPD in pion at $|t_\pi| \sim 1\,\mathrm{GeV}^2$

  Fundamental interest

  Moments calculable in Lattice QCD

- Requires detection of forward nucleon and moderate–p_T pion
  Feasible with Electron–Ion Collider EIC

Direct probe of chiral component of nucleon's partonic structure!

Summary

- Transverse densities relate elastic FFs to universal partonic structure

  Impact parameter b "observable" unlike Breit frame radius

  Dispersion representation connects partonic structure at given b with hadronic exchange mechanisms

- Chiral component of transverse densities at large b

  Chiral expansion justified by $b \sim M_\pi^{-1}$. . . new arena for χPT

  Equivalence of invariant and light–front formulations of χPT

  Chiral and non–chiral components identified by spatial size

  Chiral component dominant only at large $b \gtrsim 2\,\mathrm{fm}$

- Dispersion fits to FF data contain much interesting information

  Correct analyticity crucial for studying peripheral densities

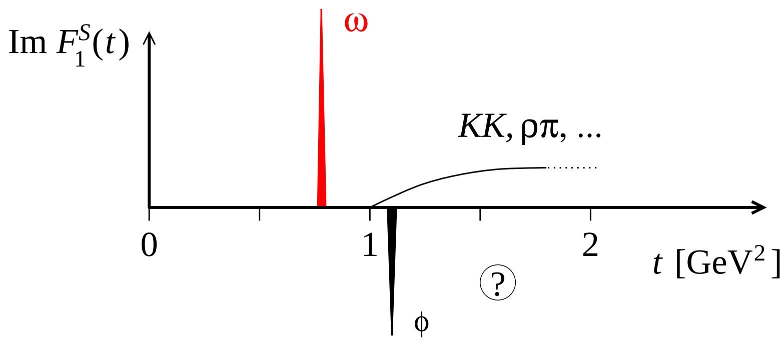
  Should be updated with new data JLab 6/12 GeV

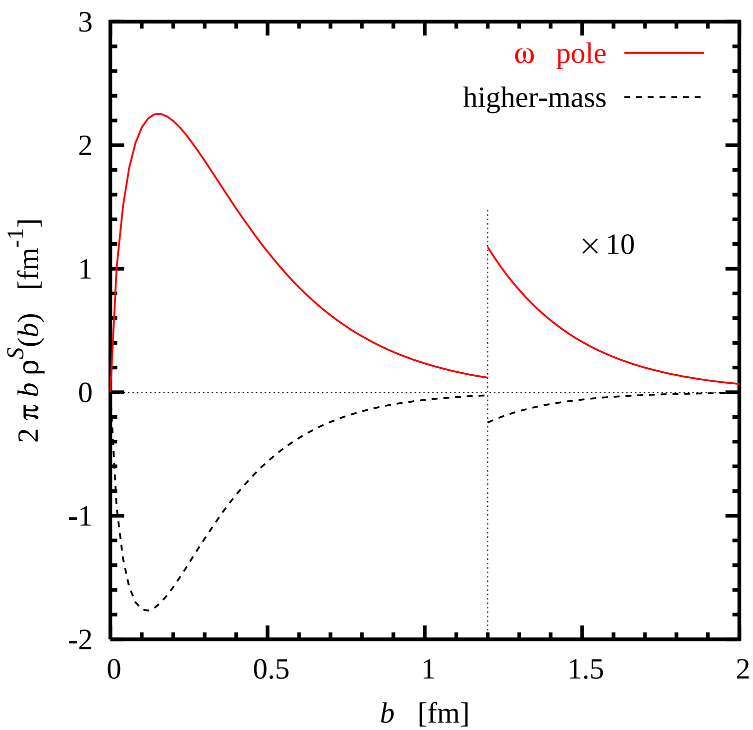
- Many interesting extensions

  Current vs. charge densities, x–dependent structures

Supplementary material

Spectral analysis: Isoscalar density





- Isoscalar spectral function

  ω exhausts strength below $1\,\mathrm{GeV}^2$
  Non-resonant 3π negligible

  Large negative strength above $1\,\mathrm{GeV}^2$, dynamical origin unclear
  ϕNN coupling $\leftrightarrow$ $s\bar{s}$ content of nucleon

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07

- Spectral analysis of isoscalar density
  Miller, Strikman, CW 11

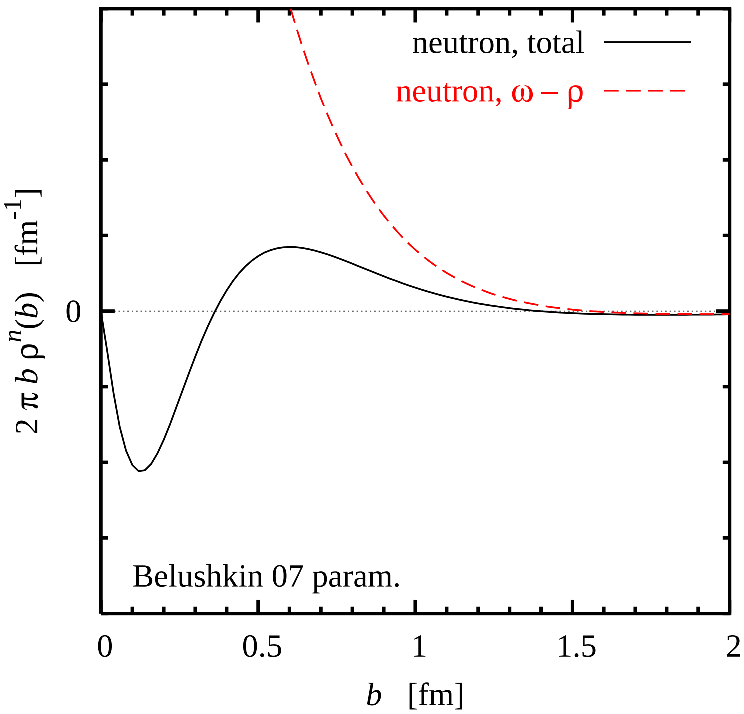
  ω dominates at $b > 1.5\,\mathrm{fm}$
  Fit uncertainty in ωNN coupling $\pm 15\%$

  Large cancellations between ω and higher–mass states at $b = 0.5 - 1\,\mathrm{fm}$

- Impact of future form factor data

  Sensitivity to ωNN coupling broadly distributed at spacelike $|t| \lesssim 1\,\mathrm{GeV}^2$
  Does not require measurements at extemely small $|t|$

Spectral analysis: Neutron density



- Spectral analysis of neutron density

  $\omega - \rho$ alone gives large positive density!

  Substantially reduced by higher–mass states in isoscalar spectral function

  Neutron form factor measurements can help to determine isoscalar spectral function $\rightarrow$ ϕNN coupling, $s\bar{s}$ in nucleon