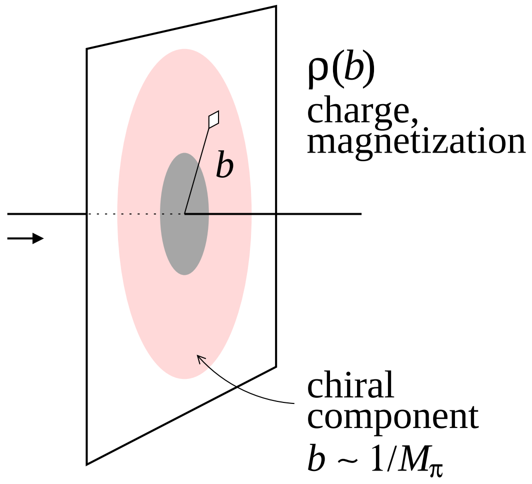
Space-time picture of chiral dynamics with nucleons

C. Weiss (JLab), Nuclear Dynamics with EFTs, Bochum, 01–Jul–13



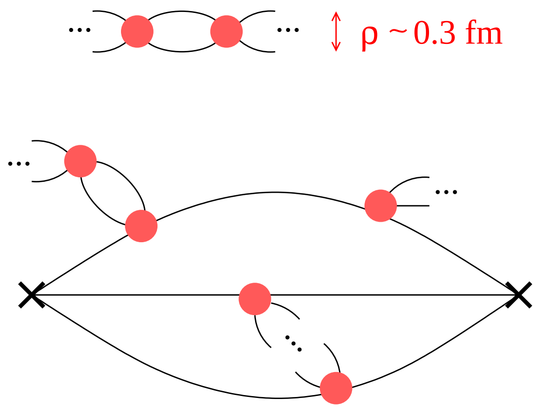
- Parton picture of nucleon structure
  - Fields vs. particles
  - Transverse densities from elastic FFs
- Peripheral transverse densities
  - Dispersion representation
  - Peripheral densities from chiral EFT
  - Chiral vs. non–chiral component
  - Δ isobar and large–N_c QCD
- Time–ordered formulation of chiral EFT
  - Chiral πN light–cone wave functions
  - Particle picture of chiral processes
- Connections and extensions
  - GPDs and peripheral quark/gluon structure
  - Nuclear structure in high–energy processes

Spatial representation of nucleon:
$b \sim 1/M_\pi$ as new parameter
for chiral expansion!

New insights into chiral EFT:
Heavy–baryon expansion,
chiral vs. non–chiral contributions

Connection with QCD structure:
GPDs, peripheral ep/pp processes

Nucleon structure: Parton picture



- QCD vacuum not empty

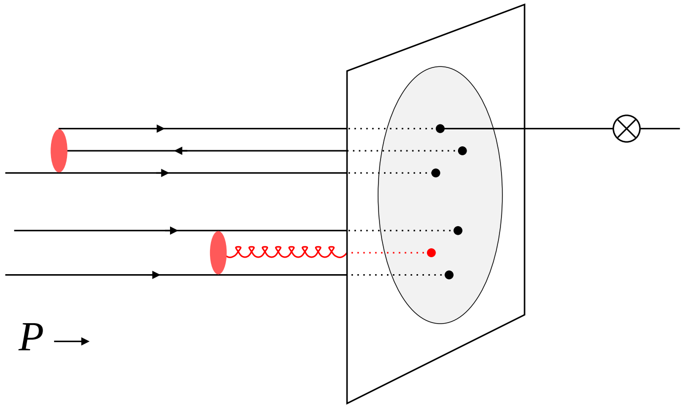
  Strong non-perturbative gluon fields
  of size $\ll 1\,\mathrm{fm}$ ← Lattice QCD, analytic models

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

- Slow–moving nucleon $P \sim \mu_{\mathrm{vac}}$

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

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



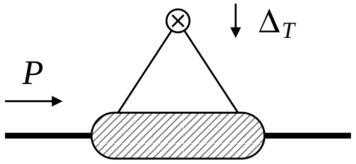
- Fast–moving nucleon $P \gg \mu_{\mathrm{vac}}$

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

  Physical properties:
  Longitudinal momentum densities PDFs
  Transverse distributions → Form factors, GPDs
  QCD operator definitions: Renormalization, scale dependence

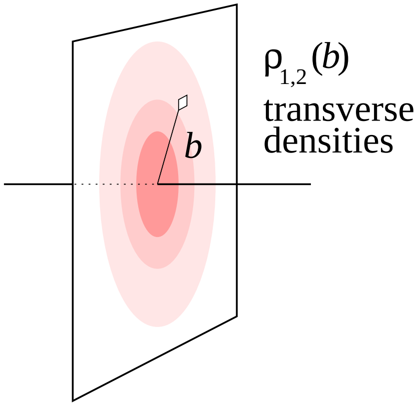
  Alt. view: Observer moves with velocity $v \rightarrow 1$
  Light–front quantization, time $x^+ = x^0 + x^3$

Nucleon structure: Transverse densities



- Current matrix element parametrized by invariant form factors

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



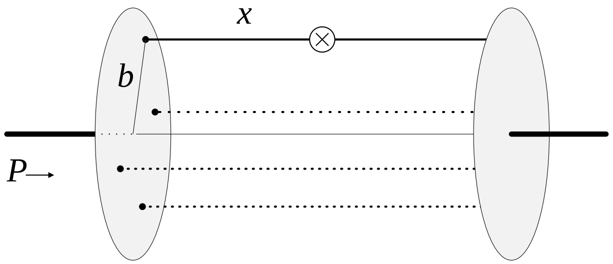
- Transverse densities $t = -\boldsymbol{\Delta}_T^2$ Soper 76, Miller 07

  $$F_{1,2}(t) \;=\; \int d^2b\; e^{i\boldsymbol{\Delta}_\mathrm{T}\boldsymbol{b}}\; \rho_{1,2}(b)$$ 2D Fourier

  $\rho_1(b)$ charge density

  $$\widetilde{\rho}_2(b) = \frac{d}{db}\left[\frac{\rho_2(b)}{2M_N}\right]$$ spin–dependent current density

  $\boldsymbol{b}$ displacement from transverse C.M.



- Proper densities for relativistic system

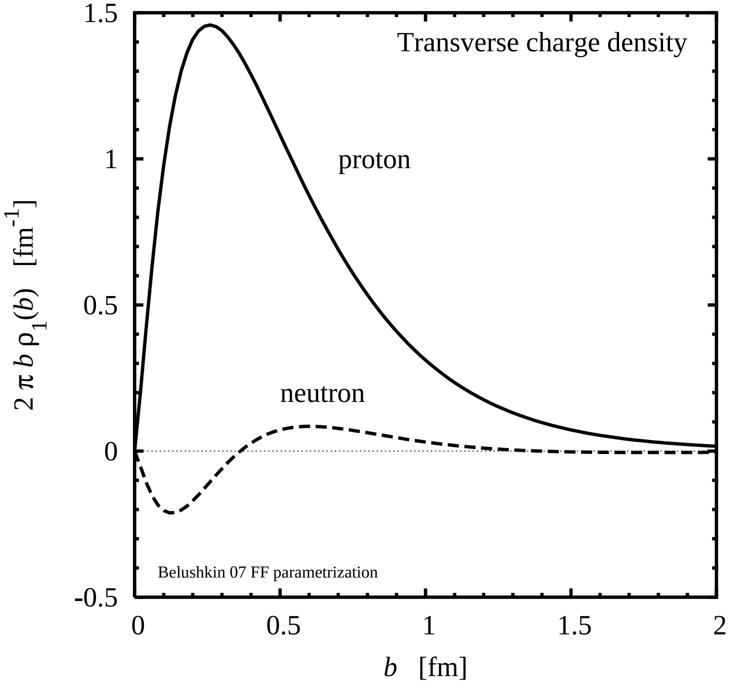
  Overlap of light–front wave functions.
  Breit frame distributions not densities.

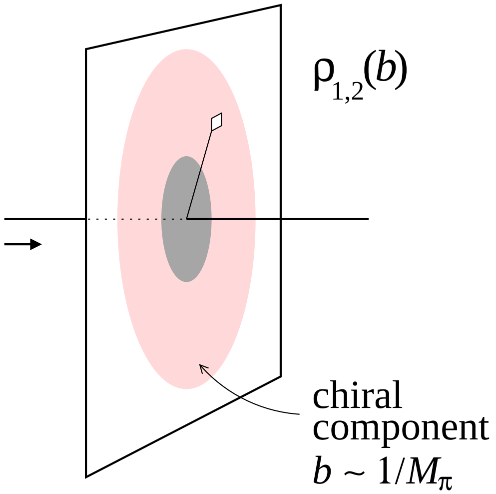
- Reduction of quark GPDs

  $\rho_1(b) = \int dx\, f_{q-\bar{q}}(x, \boldsymbol{b})$

  Elastic FFs ↔ QCD structure, high–energy processes

Nucleon structure: Peripheral densities





- Empirical transverse densities from spacelike form factor data

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

  Recent low– and high–$|t|$ data incorporated MAMI: Vanderhaeghen, Walcher 10. JLab Hall A Riordan et al.

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

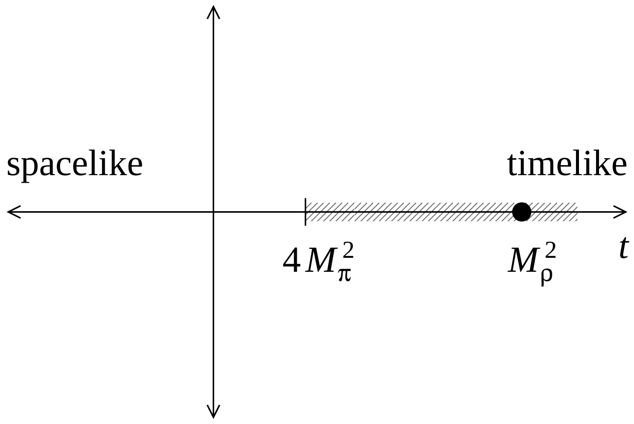
- Peripheral densities $b = O(M_\pi^{-1})$

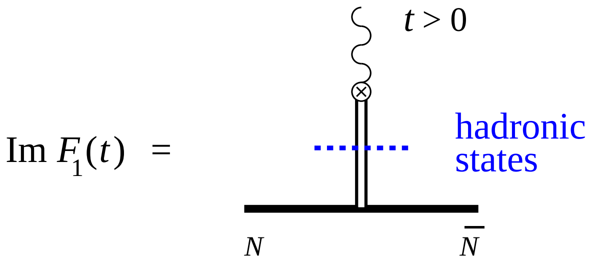
  Governed by chiral dynamics: universal, model–independent, calculable using EFT methods

  Theoretical interest:
  Parametric control,
  space–time picture of EFT dynamics,
  chiral vs. non-chiral contributions

  Practical interest:
  Low–$|t|$ form factors, connection w. peripheral quark/gluon structure

Peripheral densities: Dispersion representation





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

- Dispersion representation of form factor

$$F_{1,2}(t) \;=\; \int\limits_{4\text{m}_\pi^2}^{\infty} \frac{dt'}{t' - t - i0} \, \frac{\text{Im}\, F_{1,2}(t')}{\pi}$$

Spectral function $\text{Im}\, F_{1,2}(t')$ describes "process" current $\rightarrow$ hadronic states $\rightarrow$ $N\bar{N}$

Unphysical region: $\text{Im}\, F_{1,2}(t')$ from theory, FF fits
Höhler et al. 76; Belushkin, Hammer, Meissner 06

- Transverse densities

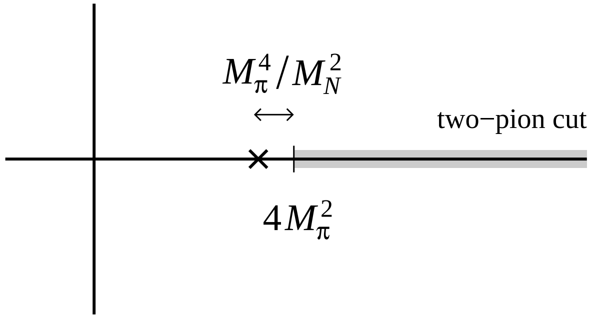
$$\rho_{1,2}(b) \;=\; \int\limits_{4m_\pi^2}^{\infty} \frac{dt}{2\pi} \, K_0(\sqrt{t}b) \, \frac{\text{Im}\, F_{1,2}(t)}{\pi}$$

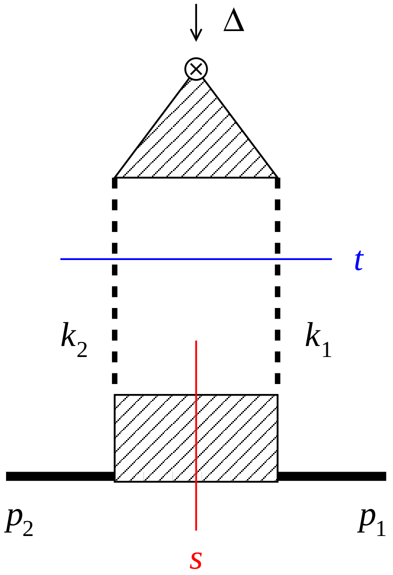
$K_0 \sim e^{-b\sqrt{t}}$ exponential suppression of large t

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

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

Peripheral densities: Spectral function





- Spectral function near threshold

  Two–pion exchange with $t - 4M_\pi^2 = O(M_\pi^2)$

  Subthreshold singularity on unphysical sheet from N pole in πN scattering amplitude

  Anomalously small scale M_π^4/M_N^2

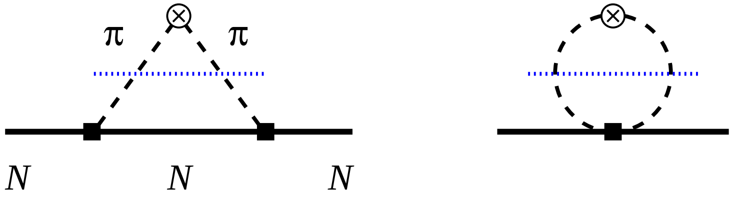
  Dominates behavior of spectral function near threshold!

- Parametric regions of distances

$$b \sim M_\pi^{-1} \qquad t - 4M_\pi^2 \sim M_\pi^2 \qquad \text{“chiral”}$$

$$\sim \frac{M_N^2}{M_\pi^3} \qquad \sim \frac{M_\pi^4}{M_N^2} \qquad \text{“molecular”}$$

Peripheral densities: Chiral component

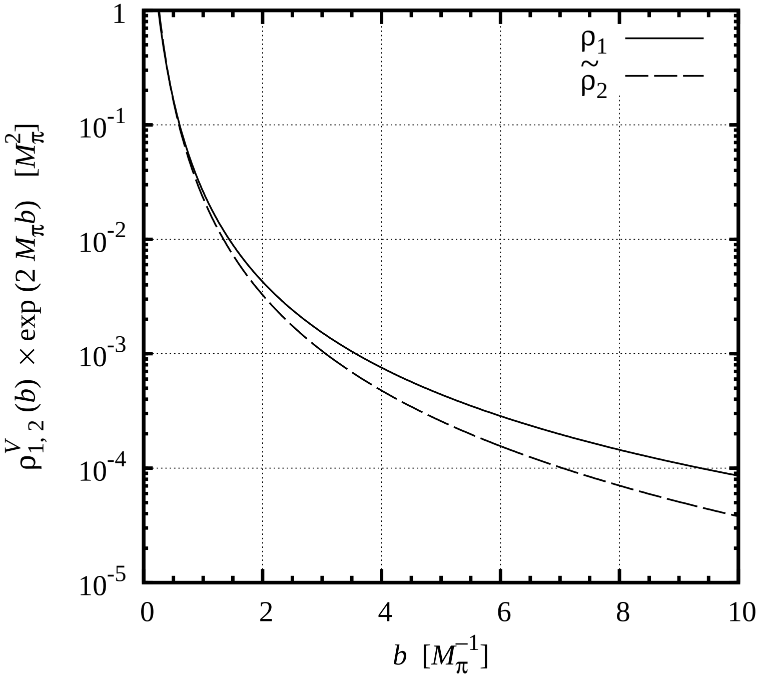


- Spectral function from relativistic χEFT

  Becher, Leutwyler 99; Kubis, Meissner 01; Kaiser 03

  Efficient calculation: t–channel cut only,
  Cutkosky rules, no regularization

  Compact analytic expressions



- Chiral component of isovector densities

  Strikman, CW 10; Granados CW 13

  $$\rho^V_{1,2}(b) = e^{-2M_\pi b}\, P_{1,2}(M_N, M_\pi, b)$$

  Yukawa tail with range $2M_\pi$

  Pre-exponential factor varies strongly,
  exhibits rich structure

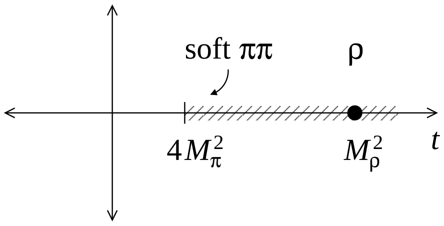
  Heavy–baryon expansion for $b = O(M_\pi^{-1})$:
  Convergence limited by subthreshold singularity,
  but good numerical accuracy $\sim 10\%$

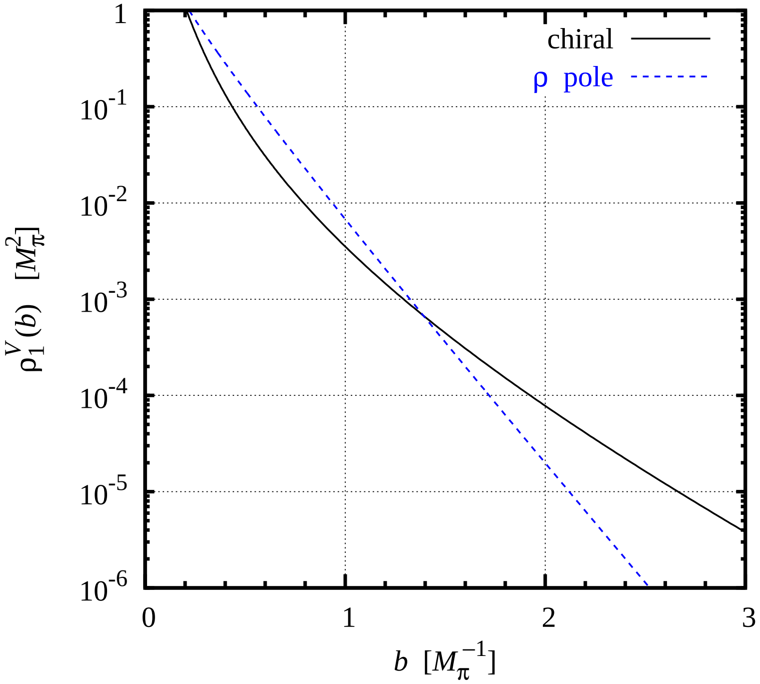
  Granados CW 13. Cf. Becher, Leutwyler 99

  Molecular region $b = O(M_N^2/M_\pi^3)$:
  Asymptotic behavior derived explicitly

  Very large distances ∼ several 10 fm. Practical applications?

Peripheral densities: Chiral vs. non-chiral





- At what distances does the chiral component of densities become numerically dominant?
  Strikman, CW 10

  Model higher mass states in spectral function by ρ meson pole
  Refined estimates w. empirical spectral functions
  Miller, Strikman, CW 11

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

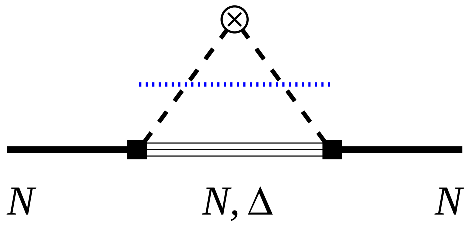
  Reasons are strength of ρ, suppression of $\pi\pi$ near threshold

- Spatial representation as new way of identifying chiral component

  Model–independent, fully relativistic

  Impact parameter b objectively defined, observable in exclusive processes
  ↔ Breit frame radius

Peripheral densities: Δ isobar



- Two–pion component with intermediate Δ

  Large coupling due to spin/isospin

  N and Δ degenerate in large–N_c limit of QCD:
  $M_\Delta - M_N = O(N_c^{-1})$

  Δ contribution to spectral functions and densities calculated in relativistic Rarita–Schwinger formalism
  Strikman, CW 10, Granados, CW 13

- Peripheral densities in large–N_c limit of QCD

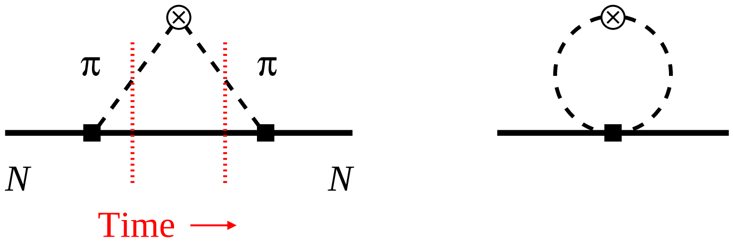
  Transverse distances $b = O(M_\pi^{-1}) = O(N_c^0)$

  $\rho_1(N \text{ alone}) \;=\; O(N_c^2)$ too large!
  $\rho_1(N + \Delta) \;=\; O(N_c)$ correct
  Δ restores proper N_c–scaling of isovector charge density

  $\rho_2(N + \Delta) \;=\; O(N_c^2) \;=\; \frac{3}{2}\rho_2(N \text{ alone})$
  Δ enhances isovector magnetization density by 3/2

  Agrees with findings for isovector electric/magnetic radii
  Cohen, Broniowski 92; Cohen 96

Time–ordered formulation: Wave functions



$$\psi_{\pi N}(y, \boldsymbol{r}_T) = \lim_{P\to\infty} \frac{\langle \pi N | \mathcal{L}_\chi | N\rangle}{E_{N\mathrm{f}} + E_\pi - E_{N\mathrm{i}}}$$

$$\rho_1^V(b) = \int_0^1 dy \sum_{L=0,1} \psi^{L*}_{\pi N}\psi^L_{\pi N}(y, b/\bar{y})$$

$+$ contact term

$\rho_2^V(b)$ $\Delta L = 1$

- Time–ordered formulation of χEFT

  $$\left.\begin{array}{l}\text{Infinite–mom. frame } P \to \infty \\ \text{Light–front time } x^+ = x^0 + x^3\end{array}\right\}\text{ equivalent!}$$

- Wave function of chiral πN system

  Describe transition $N \to N\pi$,
  calculable from chiral Lagrangian

  Universal, frame–independent,
  also in high–energy processes, $\bar{u} - \bar{d}$

  Pion momentum fraction $y \sim M_\pi / M_N$,
  parametrically small

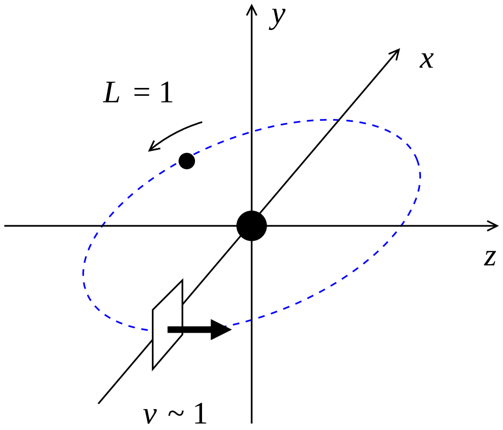
  Orbital angular momentum $L = 0, 1$

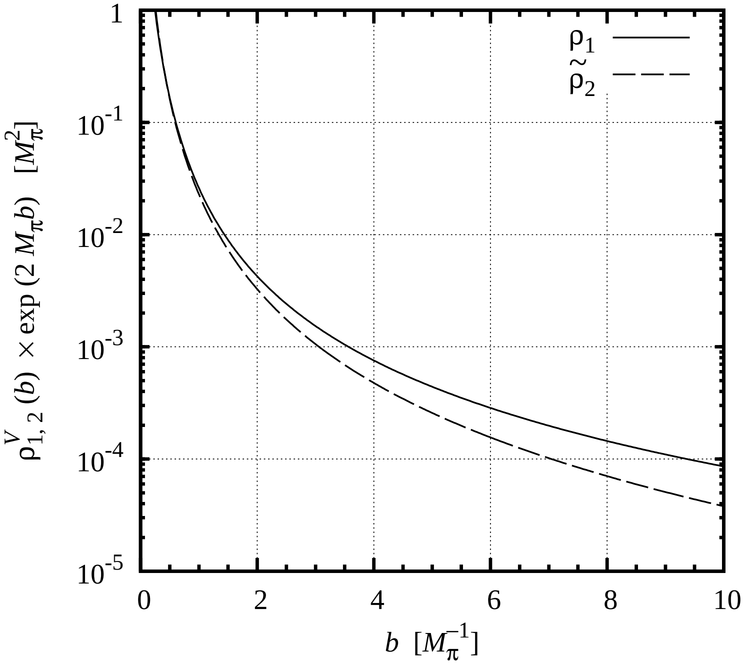
- Densities as overlap integrals

  Contact terms $\delta(y)$ represent
  high–mass intermediate states in TOPT.
  Coefficient $(1 - g_A^2)$ reflects
  "compositeness" of nucleon

  Equivalent to invariant formulation
  Granados, CW 13

Time–ordered formulation: Few–body picture





- Light–front time evolution of χEFT

  Bare N fluctuates into πN system
  via χEFT interaction

  Peripheral densities result from charge/current
  carried by pion at $b = O(M_\pi)$

  Light–front formulation frame–independent:
  Interpretation in rest frame

  "Few–body picture" of chiral nucleon
  Fully relativistic!

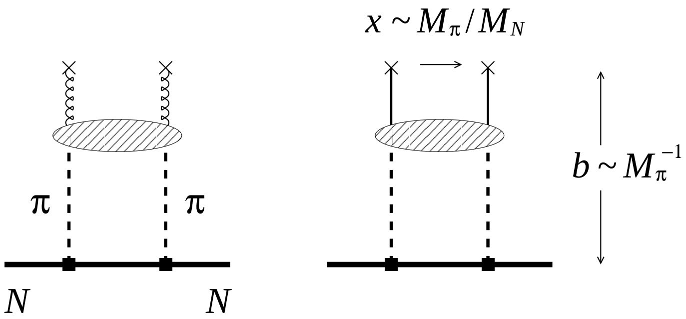
- Explains peripheral densities

  Nucleon polarized in y–direction

  $\langle J^+(\boldsymbol{b})\rangle = \rho_1(b) + (2S^y)\,\cos\phi\,\widetilde{\rho}_2(b) \geq 0$
  for current carried by quasi–real pion,
  therefore $|\widetilde{\rho}_2| \leq \rho_1$

  $\widetilde{\rho}_2/\rho_1 \sim v_\pi$ pion velocity

Outlook: Quark/gluon structure, nuclei

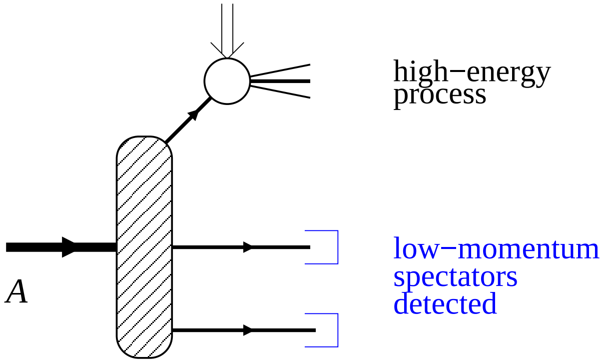


- Peripheral quark/gluon structure of nucleon

  Parton densities at $b \sim M_\pi^{-1}$ and $x \sim M_\pi / M_N$

  Calculable from χEFT πN wave functions
  and empirical quark/gluon densities in pion
  Same πN WFs as in transverse charge/current densities!

  Experimental probes: x–dependent transverse size,
  peripheral pion knockout in high–energy ep/pp



"Conditional"
LF spectral function

- Light–front structure of light nuclei in χEFT

  High–energy eA/hA scattering processes
  sensitive to low–energy nuclear structure

  Light–front formulation essential: Factorization,
  momentum conservation, sum rules

  I) Inclusive quark/gluon structure:
  EMC effect, antishadowing

  II) High–energy processes with detected spectators:
  Neutron structure, nuclear modifications
  Becomes feasible with medium–energy Electron–Ion Collider

  New application of nuclear EFT?
  Great need for theoretical control

Summary

- Light–front (or partonic) formulation provides concise spatial representation of relativistic system

  Elastic FFs reveal transverse densities

  Independent of dynamics; can be applied to QCD, χEFT

- Peripheral transverse densities from χEFT

  Chiral expansion justified by $b = O(M_\pi^{-1})$, new parameter

  Chiral and non–chiral components identified by spatial size

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

  Inclusion of Δ ensures proper N_c scaling of densities

- Light–front time evolution of χEFT

  "Few–body picture" of low–energy chiral nucleon structure

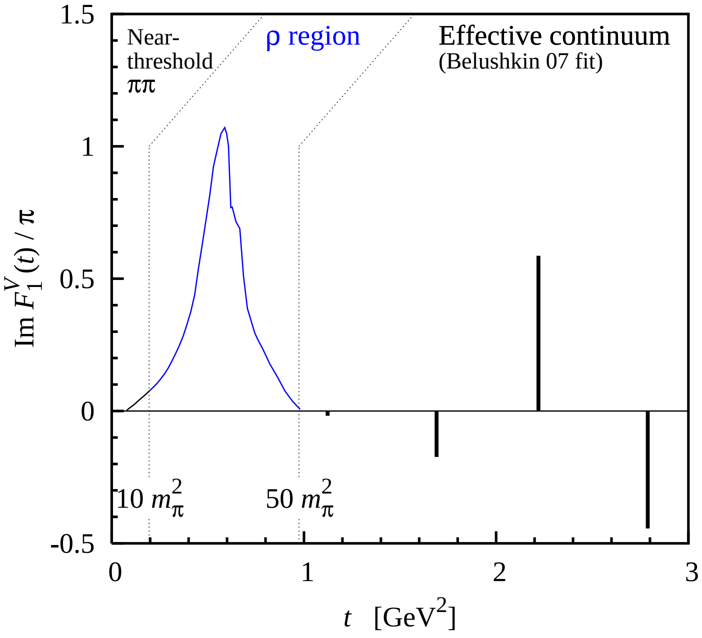
  Connection with quark/gluon structure, high–energy processes

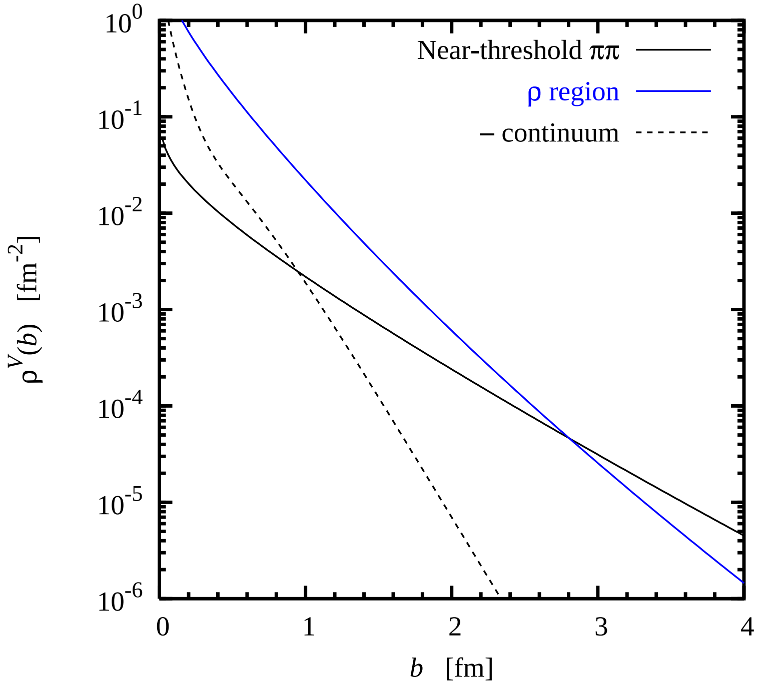
- Light–front nuclear structure new challenge for nuclear χEFT

  High–energy processes with tagged spectators: Great potential, need theoretical control

Supplementary material

Spectral analysis: Isovector charge density





- 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

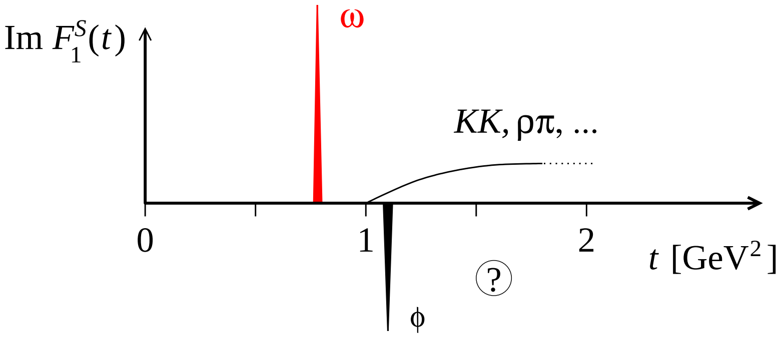
- Isoscalar density

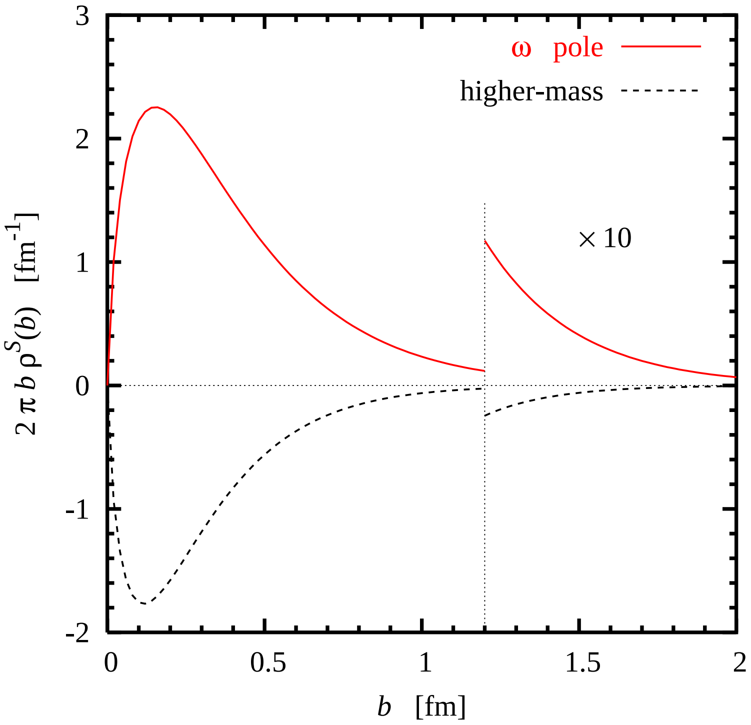
  ω dominates at $b > 1.5\,\mathrm{fm}$.

  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

Spectral analysis: Isoscalar charge 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

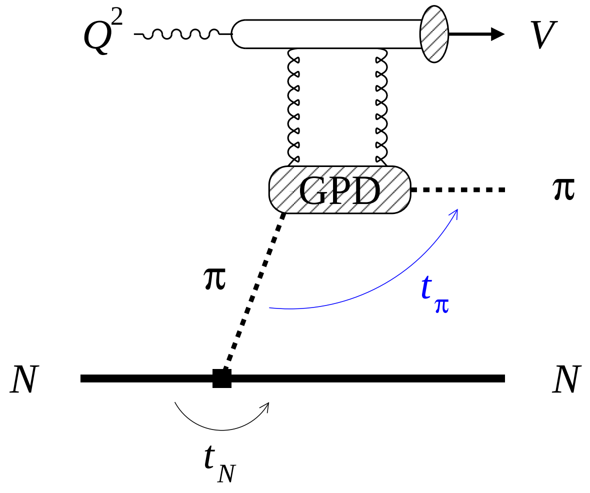
  ω dominates at $b > 1.5\,\mathrm{fm}$
  Fit uncertainty in ωNN coupling $\pm 15\%$

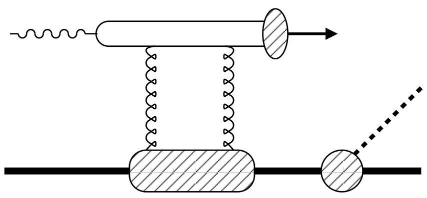
  Large cancellations between ω and higher–mass states at $b = 0.5 - 1\,\mathrm{fm}$

- 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 $|t|$

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

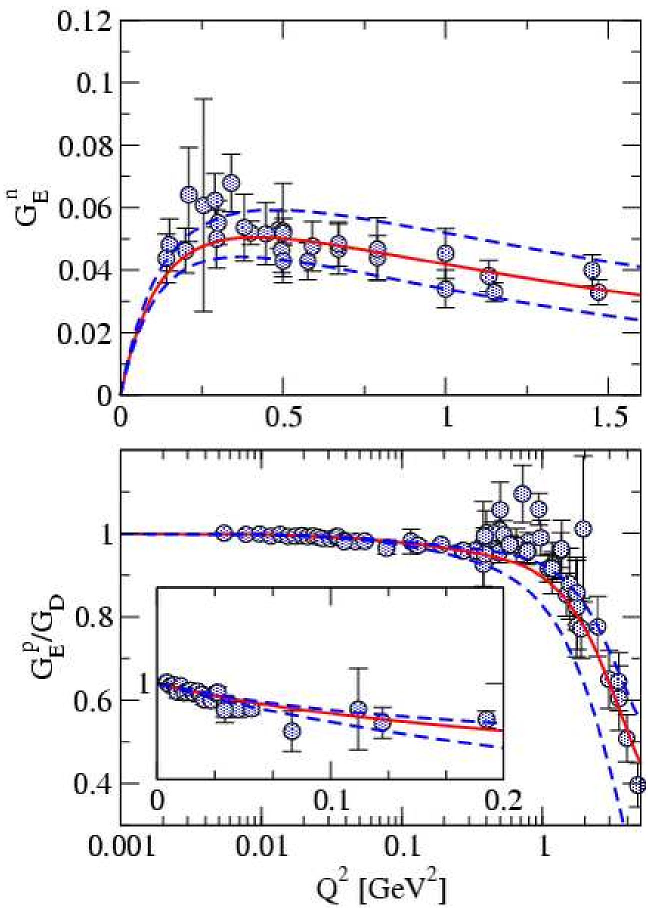
  Moments calculable in Lattice QCD

- 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!

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

$$\begin{aligned} \langle b^2 \rangle &= \int d^2 b\, b^2 \rho(b) = 4\, F_1'(0) \\ \langle b^4 \rangle &= 32\, F_1''(0) \end{aligned}$$

- Contribution of chiral component isovector

$$\begin{aligned} \langle b^2 \rangle_{\text{chiral}} &\approx 0.2 \times \langle b^2 \rangle_{\text{fit}} && \text{small} \\ \langle b^4 \rangle_{\text{chiral}} &\approx 1.5 \times \langle b^2 \rangle_{\text{fit}}^2 && \text{sizable} \end{aligned}$$

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.