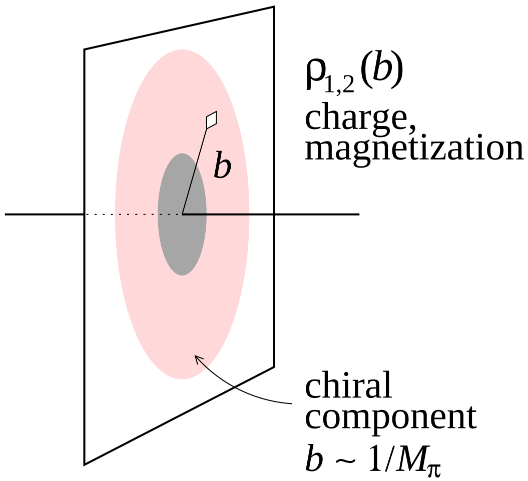
Chiral dynamics and peripheral transverse nucleon structure

C. Weiss (JLab), JLab Theory Seminar, 07–Oct–13 Granados, CW, arXiv:1308.1634



- Light–front view of nucleon
  - Transverse densities from elastic FFs
  - Connection with GPDs
- Peripheral transverse densities
  - Dispersion representation
  - Peripheral densities from chiral EFT
  - Mechanical picture in light–front EFT, charge vs. magnetization
  - Δ isobar and large–N_c QCD
  - Chiral vs. non–chiral component
- Experimental tests and extensions
  - Chiral component in low–$|t|$ FFs
  - GPDs and peripheral high–energy processes

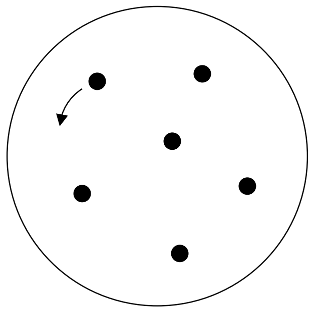
Universal element of nucleon structure!

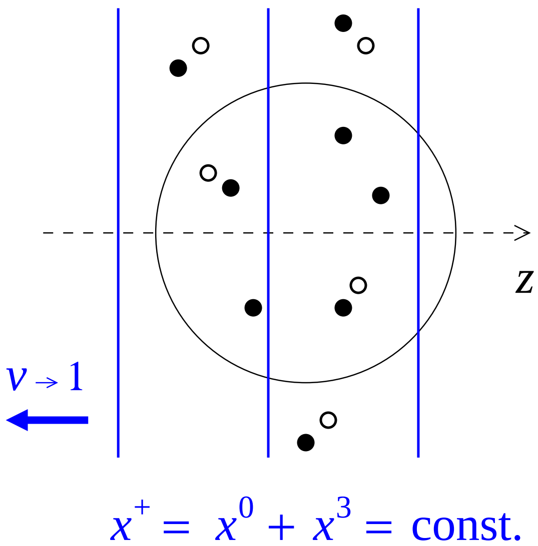
New arena for χEFT: Space–time picture, b as parameter

Low–t elastic FFs
JLab 12 E12-11-106 Gasparian et al.

Connection with GPDs, peripheral ep/pp processes

Nucleon structure: Light–front view





Alt. view: Observer at rest, system moves with $v \to 1$. Infinite–momentum frame

- Non–relativistic quantum system

  Particle number fixed, time absolute

  $\psi(\boldsymbol{x}_1, ..\boldsymbol{x}_N; t)$ Schrödinger WF

  $\rho(\boldsymbol{x}) = \sum \psi^\dagger(..\boldsymbol{x}..; t)\psi(..\boldsymbol{x}..; t)$ Densities

- Relativistic quantum system

  Vacuum fluctuations: Particles appear/disappear

  Time not absolute: How to synchronize clocks?

  Light–front time $x^+ = x^0 + x^3$:
  Observer moving with velocity $v \to 1$

  Wave function at fixed x^+: Components with different particle number

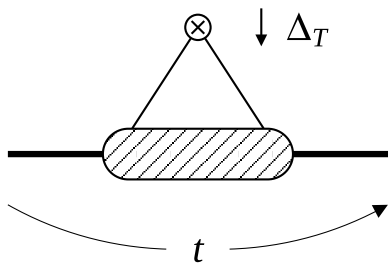
  Densities at fixed x^+: Boost–invariant!

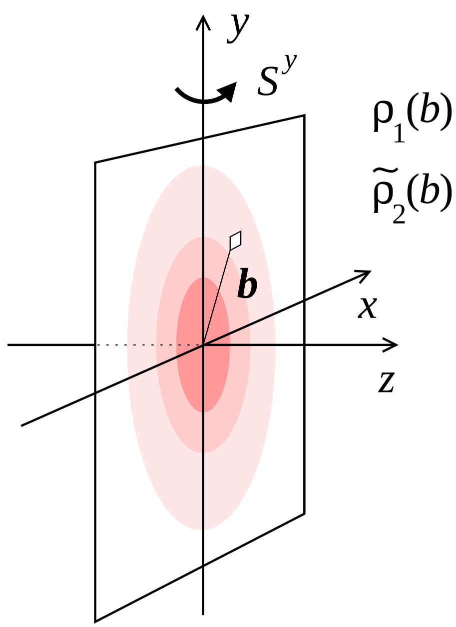
- Advantages of light–front view

  Objective notion of spatial structure

  Connection with high–energy scattering
  Probes system at fixed LF time. Cf. parton picture in QCD

Nucleon structure: Transverse densities





- Current matrix element parametrized by invariant form factors

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

- Transverse densities $t = -\boldsymbol{\Delta}_T^2$
  Soper 76, Burkardt 00, Miller 07

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

$\rho_{1,2}(b)$ charge/magnetization density

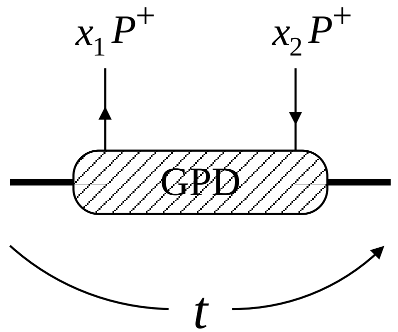
$\boldsymbol{b}$ displacement from transverse C.M.

- Interpretation in polarized nucleon

$$\langle J^+(\boldsymbol{b})\rangle_{y-\mathrm{pol}} \;=\; \rho_1(b) \qquad \text{spin–indep.}$$

$$+\;(2S^y)\;\cos\phi\;\underbrace{\frac{d}{db}\left[\frac{\rho_2(b)}{2M_N}\right]}_{\widetilde{\rho}_2(b)} \qquad \text{spin–dep.}$$

Nucleon structure: Connection with GPDs



- Generalized parton distribution

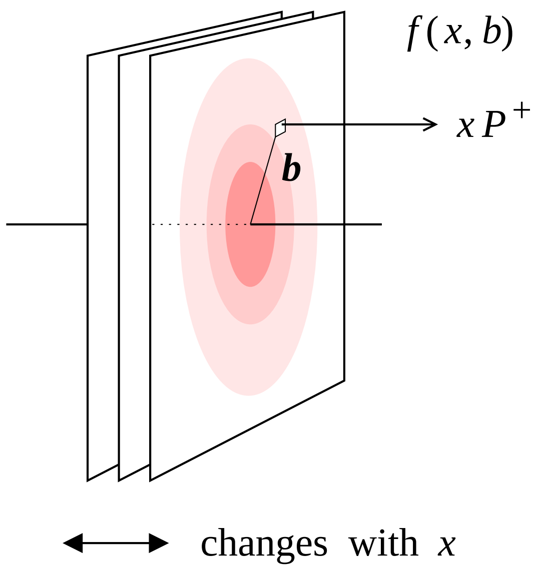
$$\langle N' | \underbrace{\bar{\psi}(0) \ldots \psi(z)}_{\text{QCD light-ray operator, } z^2 = 0} | N \rangle \;\rightarrow\; H(x_1, x_2; t),\; E(\ldots), \ldots$$

- Transverse distribution of partons $\quad x_1 = x_2 = x$

Burkardt 00

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

Transverse spatial distribution of partons with LC momentum xP^+: "Tomography"

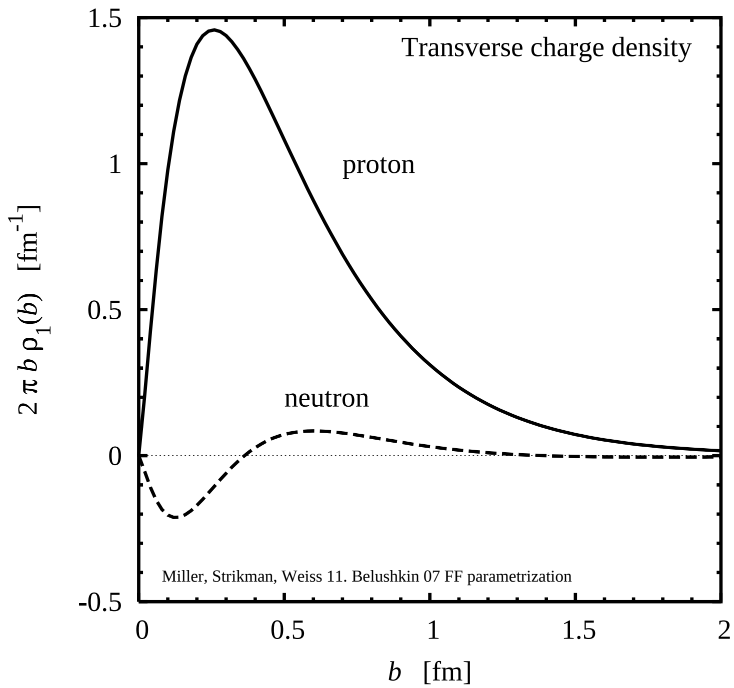


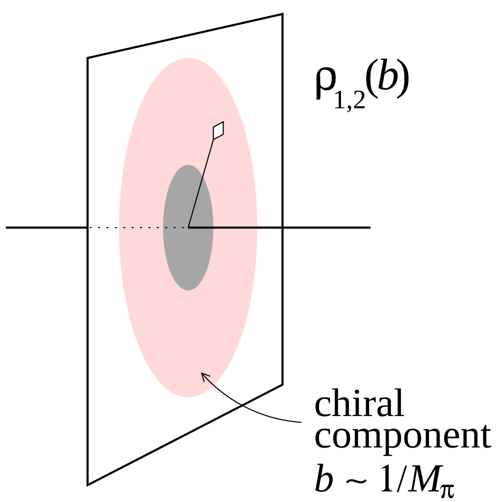
- Transverse densities as reduction

$$\rho_1(b) \;=\; \sum_q e_q \int_0^1 dx \; [f_q(x, b) - f_{\bar{q}}(x, b)] \qquad \text{etc.}$$

Dual role of transverse densities:
Accessible through low–energy elastic FFs,
interpretable in context of QCD partons

Nucleon structure: Peripheral densities





- Empirical transverse densities from elastic 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
  Also $N \to \Delta$, deuteron: Carlson, Vanderhaeghen 08

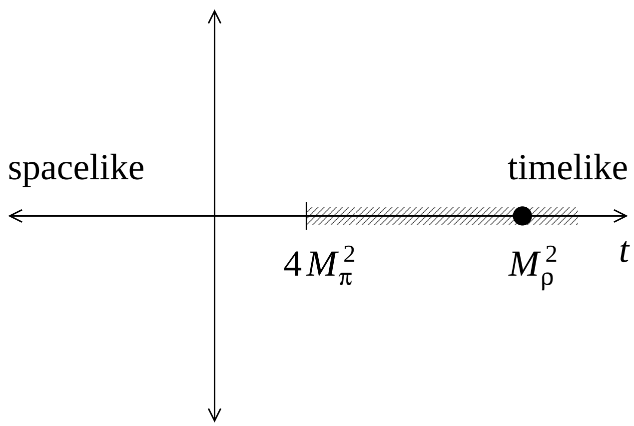
- Peripheral densities $b = O(M_\pi^{-1})$

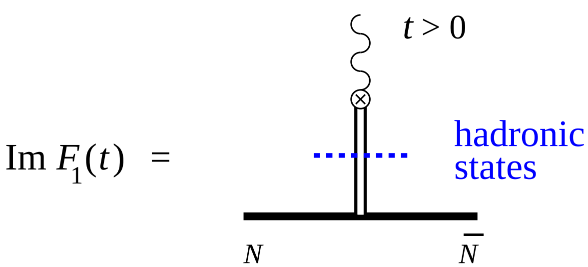
  Governed by chiral dynamics: universal, model–independent, calculable using EFT methods

  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

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

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

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

- Transverse densities

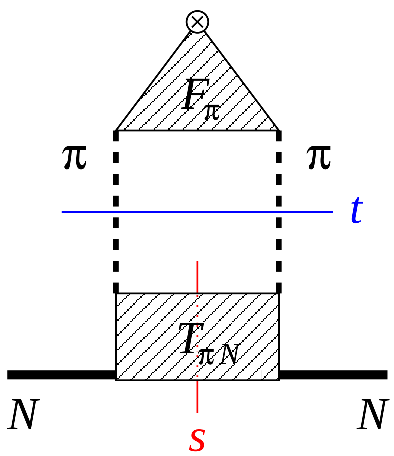
$$\rho_{1,2}(b) \ = \int\limits_{4m_\pi^2}^{\infty} \frac{dt}{2\pi} \, K_0(\sqrt{t}b) \, \frac{\mathrm{Im}\, F_{1,2}(t)}{\pi}$$

$K_0 \sim e^{-b\sqrt{t}}$ 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



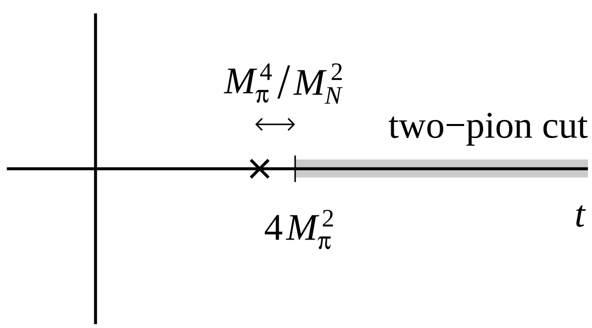
- Spectral function near threshold

  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!



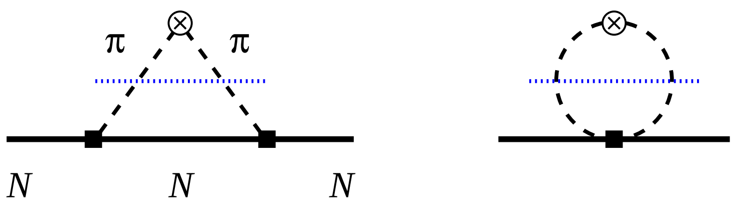
- Parametric regions of distances

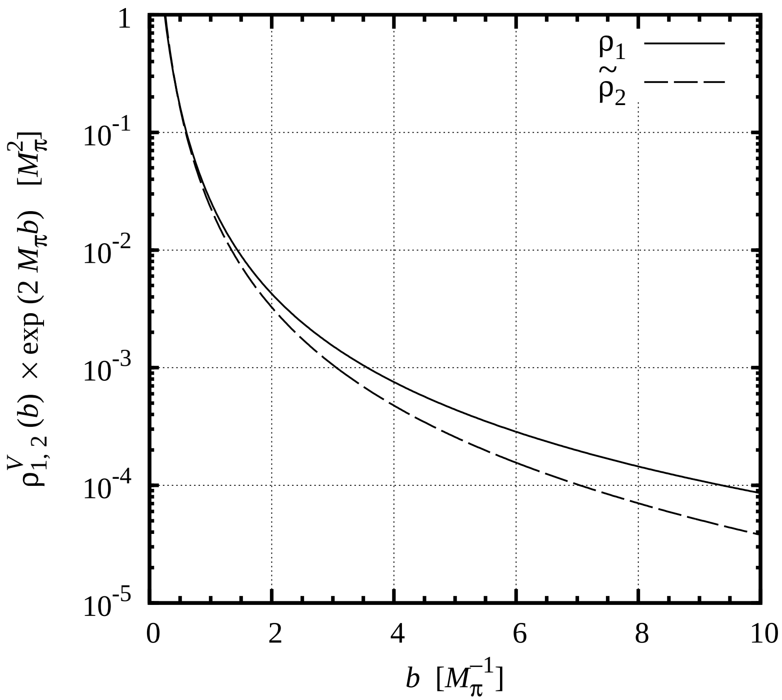
$b \sim M_\pi^{-1}$	$t - 4M_\pi^2 \sim M_\pi^2$	"chiral" $\leftarrow$
$\sim \dfrac{M_N^2}{M_\pi^3}$	$\sim \dfrac{M_\pi^4}{M_N^2}$	"molecular"

  Distances in molecular region extremely large, $\sim$ several 10 fm. Practical use?

  Cf. NN potential Robilotta 96. Review Epelbaum

Peripheral densities: Chiral component





- Spectral functions from chiral EFT
  Gasser et al. 87; Bernard et al. 96, Kubis, Meissner 00, Kaiser 03

  Expansion in $k_\pi/\Lambda_\chi \ll 1$. Lagrangian from chiral symmetry + phenom. constants

  Relativistic nucleon: Analytic structure, subthreshold singularity Becher, Leutwyler 99

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

- Chiral component of isovector densities
  Strikman, CW 10; Granados CW 13

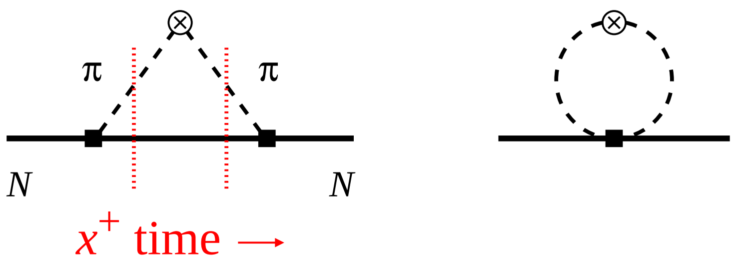
  $$\rho_1^V, \widetilde{\rho}_2^V(b) = e^{-2M_\pi b} \times \text{function}(M_N, M_\pi; b)$$

  "Yukawa tail" with range $2M_\pi$, pre-exponential factor with rich structure

  Heavy–baryon expansion:
  $\rho_1, \widetilde{\rho}_2$ of same order in M_π/M_N
  Convergence, numerical accuracy of HBE: Granados CW 13.

  Interesting inequality: $\widetilde{\rho}_2^V(b) < \rho_1(b)$
  Explanation?

Peripheral densities: Time–ordered formulation



$$\psi^{\pi N}_{L=0,1}(y, \boldsymbol{r}_T) = \underbrace{\frac{\langle \pi N | \mathcal{L}_\chi | N \rangle}{p^-_\pi + p^-_{N'} - p^-_N}}_{\text{energy denominator}}$$

$$\rho^V_1(b) = \int_0^1 dy \left[|\psi_0|^2 + |\psi_1|^2 \right]_{r_T = b/\bar{y}}$$

$+$ contact term

$$\widetilde{\rho}^V_2(b) = \ \ldots \quad \psi^*_0 \psi_1 + \psi^*_1 \psi_0$$

- Time–ordered formulation of χEFT

  Follow evolution in LF time $x^+ = x^0 + x^3$

- Wave function of chiral πN system

  Describes transition $N \to N\pi$ in χEFT, calculable from chiral Lagrangian

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

  Pion momentum fraction $y \sim M_\pi / M_N$, transverse distance $r_T \sim M_\pi^{-1}$

  Orbital angular momentum $L_z = 0, 1$

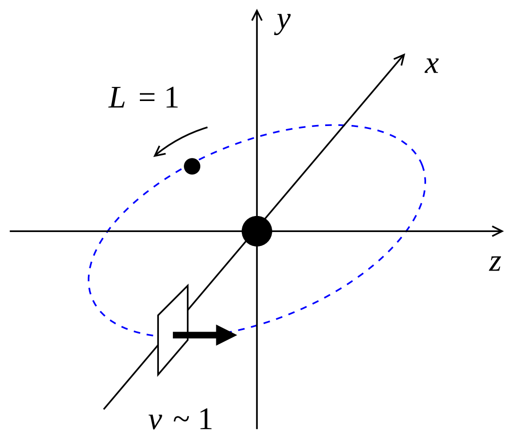
- Densities as wave function overlap

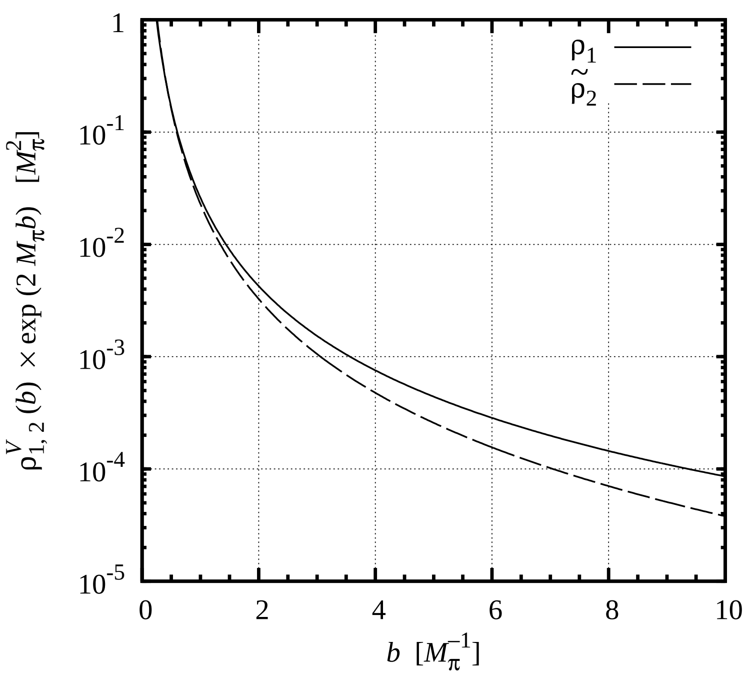
  Explains inequality $|\rho^V_2| < \rho_1$ Granados, CW 13

  Contact terms $\delta(y)$ represent high–mass interm. states. Coefficient $(1 - g_A^2)$

  Equivalent to invariant formulation
  Granados, CW 13. Cf. also Ji, Melnitchouk et al. 09+

Perpheral densities: Rest frame





- Rest frame picture Granados, CW 13

  LF formulation boost-invariant!

  Nucleon state polarized in y–direction.
  Intermediate pion orbits with $L_y = 1$

- Explains peripheral densities

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

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

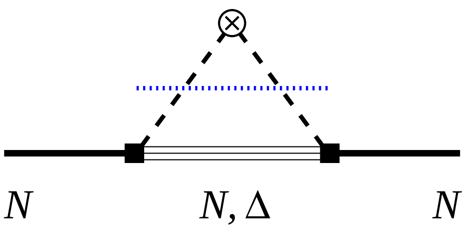
- Mechanical interpretation of χEFT

  Bare N fluctuates into πN system
  via χEFT interaction

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

  Fully relativistic! Model-independent dynamics!

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 peripheral densities calculated in relativistic Rarita–Schwinger formalism
  Strikman, CW 10, Granados, CW 13

- Peripheral densities in large–N_c limit of QCD

$\rho_1^V(b) \sim N_c^0$ — General N_c-scaling in QCD, $b = O(N_c^0)$

$\widetilde{\rho}_2^V(b) \sim N_c$

$\rho_1^V(N \text{ alone}) \sim N_c$ — Wrong... too large!

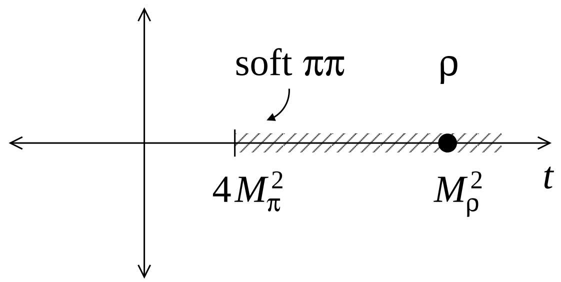
$\widetilde{\rho}_2^V(N \text{ alone}) \sim N_c$

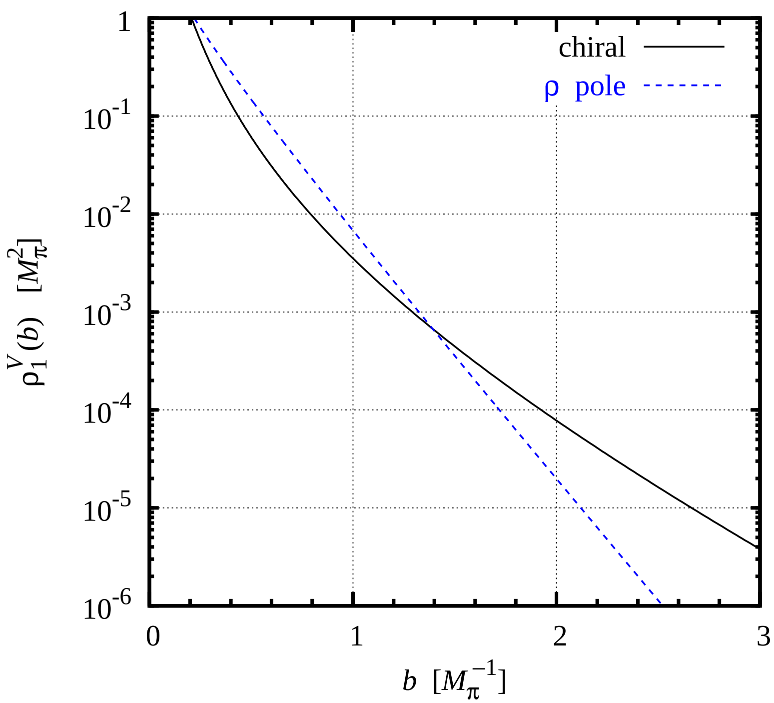
$\rho_1^V(N + \Delta) \sim N_c^0$ — Δ restores correct N_c–scaling of ρ_1^V

$\widetilde{\rho}_2^V(N + \Delta) \sim N_c$

Two-pion component has correct N_c scaling if Δ included
Cf. Isovector electric/magnetic radii. Cohen, Broniowski 92; Cohen 96

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 $b > 2$ fm. Surprisingly large!

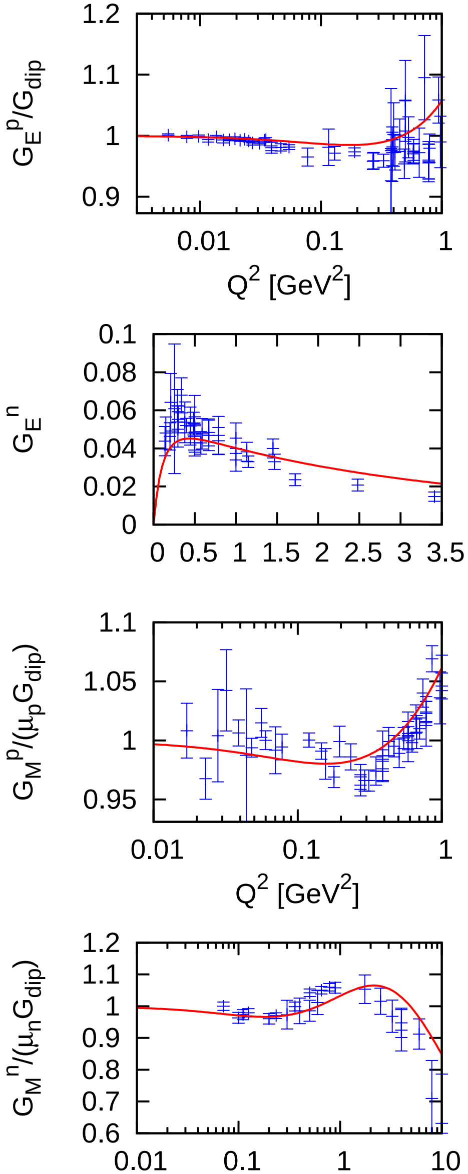
  Reasons are strength of ρ, suppression of $\pi\pi$ near threshold

- 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

Chiral component: Effect on low–t form factors



Dispersion fit: Lorenz, Hammer, Meissner 12.
Includes recent MAMI data

- 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

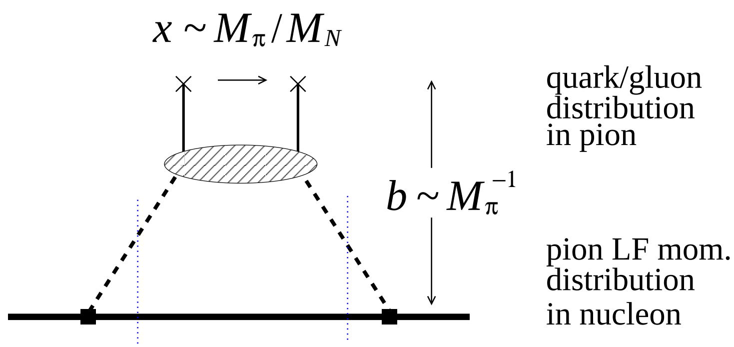
$$\langle b^2 \rangle_{\text{chiral}} \approx 0.2 \times \langle b^2 \rangle_{\text{fit}} \qquad \text{small}$$
$$\langle b^4 \rangle_{\text{chiral}} \approx 1.5 \times \langle b^2 \rangle_{\text{fit}}^2 \qquad \text{sizable}$$

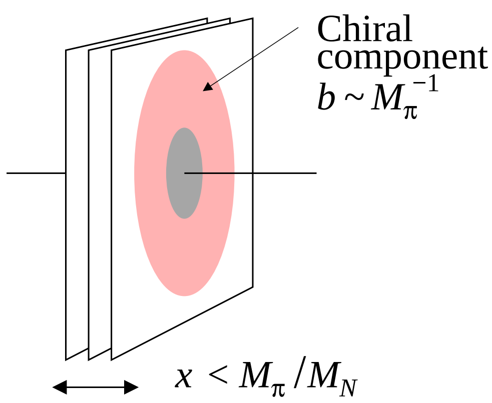
Chiral component should be visible in "unnatural" second and higher derivatives of FF at $Q^2 = 0$
Can we extract it?

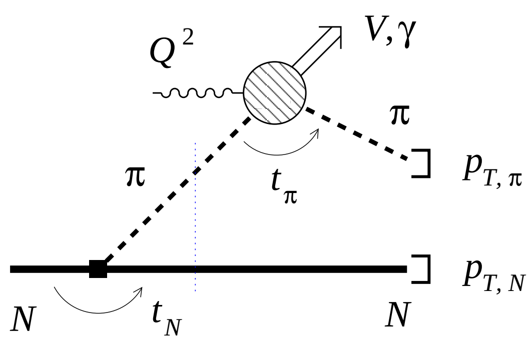
- Analyticity of form factor fit is essential
Needs dispersion analysis: Belushkin et al. 07; Lorenz et al. 12

- 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.

Chiral component: Partonic structure







- Peripheral quark/gluon structure of nucleon
  Strikman, CW PRD69:054012,2004; PRD80:114029,2009

  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!

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

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

- Exclusive processes on peripheral pion

  Soft peripheral pion requires $x \ll M_\pi / M_N \sim 0.1$

  $p_{T,\pi} \sim 1\,\mathrm{GeV} \gg p_{T,N} \sim 100\,\mathrm{MeV}$ suppresses production on nucleon

  Probes GPDs in pion at $|t_\pi| \sim 1\,\mathrm{GeV}^2$
  Fundamental interest. Moments calculable in Lattice QCD

  Detection of low–p_T forward nucleon and moderate–p_T pion

Summary

- Light–front view 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 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 offers new insights

  Mechanical picture of low–energy chiral nucleon structure

  Connection with quark/gluon structure and high–energy processes

- Many extensions and applications

  FFs of energy–momentum tensor — transverse densities of mass, momentum, forces
  Granados, CW, in preparation

  Axial and pseudoscalar FFs — constraining spin–dependent quark GPDs

  Transverse densities from amplitude analysis