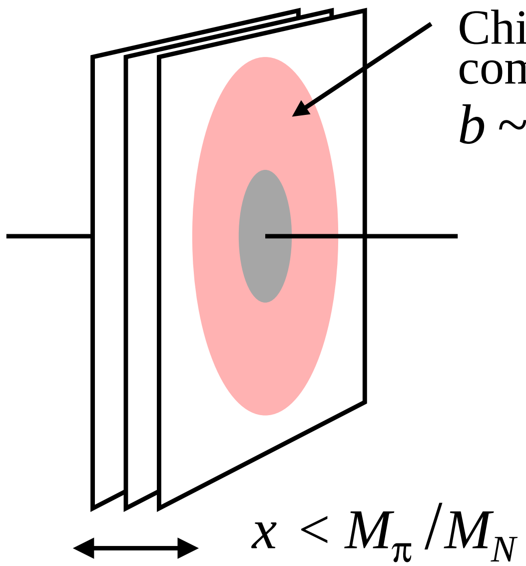
Transverse hadron structure in QCD and chiral dynamics

C. Weiss (JLab), Penn State Theory Seminar, 06-Dec-17

Jefferson Lab



- Spatial structure of nucleon

  Light-front view

  Transverse charge and current densities

  Transverse quark and gluon distributions (GPDs)

- Chiral dynamics at large distances

  Spontaneous symmetry breaking

  Effective field theory

- Peripheral charge and current densities

  Quantum-mechanical interpretation

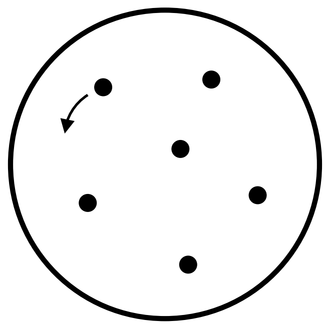
  ρ meson in unitarity-based approach

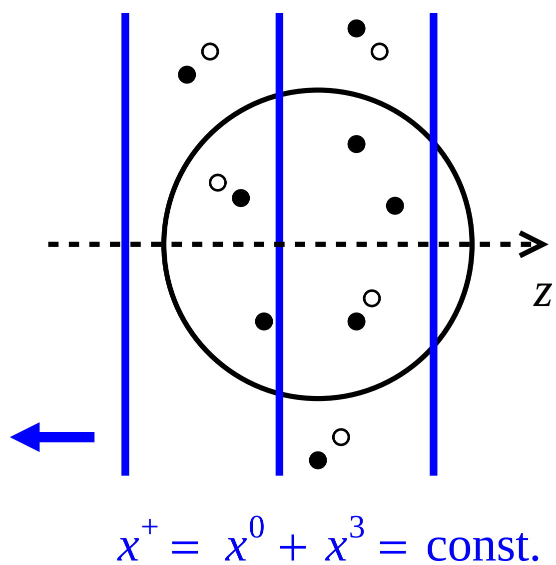
- Peripheral quark/gluon distributions

  Peripheral gluons and nucleon size

  Peripheral high-energy processes in ep at EIC

Spatial structure: Light–front view





- 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 $x^+ = x^0 + x^3$

  Wave function at fixed x^+: boost-invariant
  QCD: UV divergences, renormalization

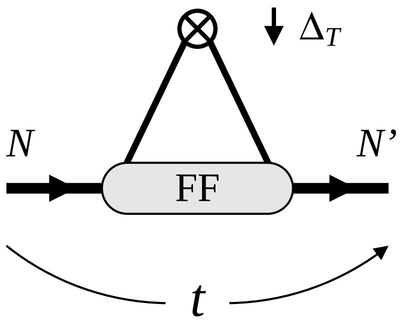
  Densities at fixed x^+: boost-invariant

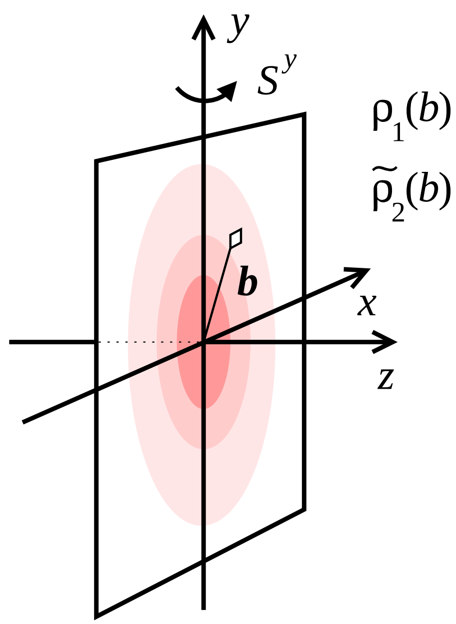
- Light-front view

  Objective notion of spatial structure

  Connection with high–energy scattering:
  Probes system at fixed LF time

Spatial 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 charge/magnetization densities

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

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

Soper 76, Burkardt 00, Miller 07

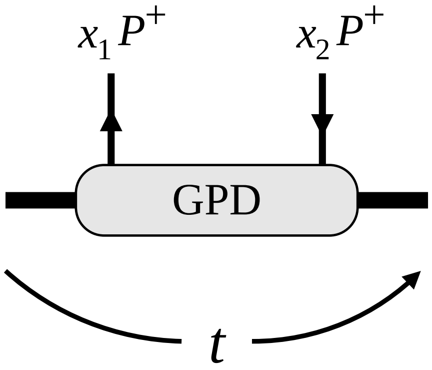
- Interpretation in polarized nucleon state

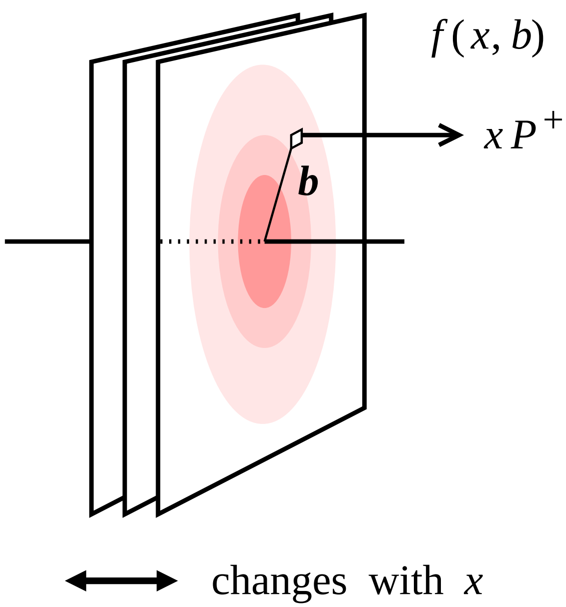
$$\langle J^+(\boldsymbol{b})\rangle_{y-\mathrm{pol}} \;=\; \rho_1(b) + \;(2S^y)\;\cos\phi\;\widetilde{\rho}_2(b)$$

Spin-independent and -dependent current

$\rho_1, \widetilde{\rho}_2 = \langle J^+\rangle_{\mathrm{right}} \pm \langle J^+\rangle_{\mathrm{left}}$ left-right asymmetry

Spatial structure: Transverse parton distributions





- Generalized parton distribution

$$\langle N' | \underbrace{\bar{\psi}(0) \ldots \psi(z)} | N \rangle \;\rightarrow\; H(x_1, x_2; t),\; E(\ldots), \ldots$$

QCD light-ray operator, $z^2 = 0$, scale μ^2

- Transverse distribution of partons

$$H(x, x; t) \;=\; \int d^2 b\, e^{i \boldsymbol{\Delta}_T \boldsymbol{b}}\, f(x, b) \qquad x_1 = x_2 = x$$

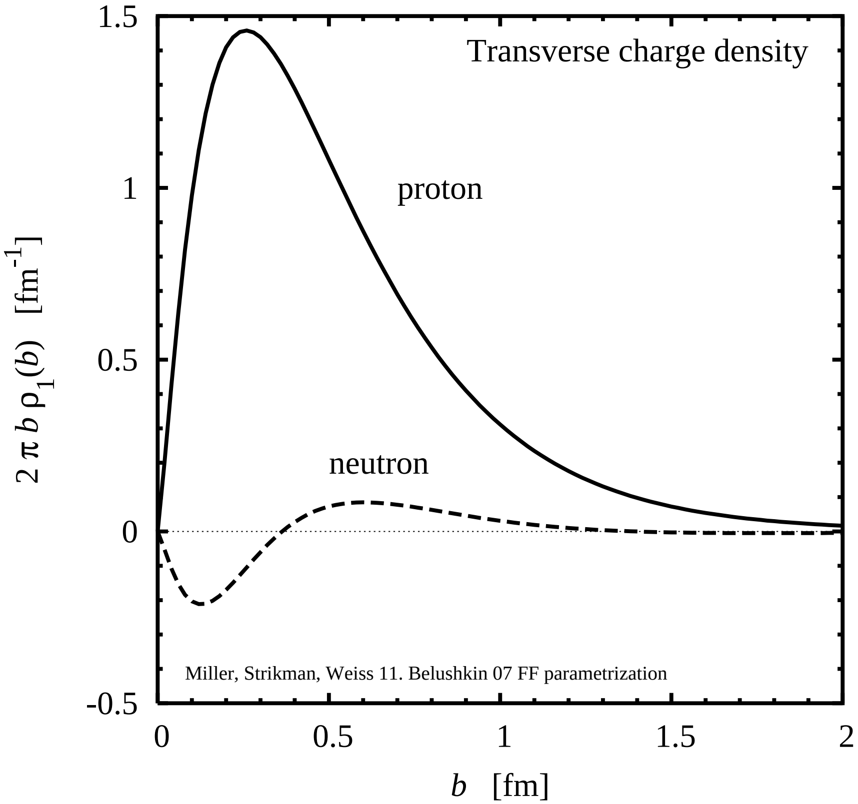
Transverse spatial distribution of partons with LC momentum xP^+: "Tomography"
Burkardt 00

- Transverse charge density 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

Spatial structure: Empirical densities



- Empirical transverse densities

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

  Recent low– and high–$|t|$ FF data
  MAMI Mainz, JLab Hall A

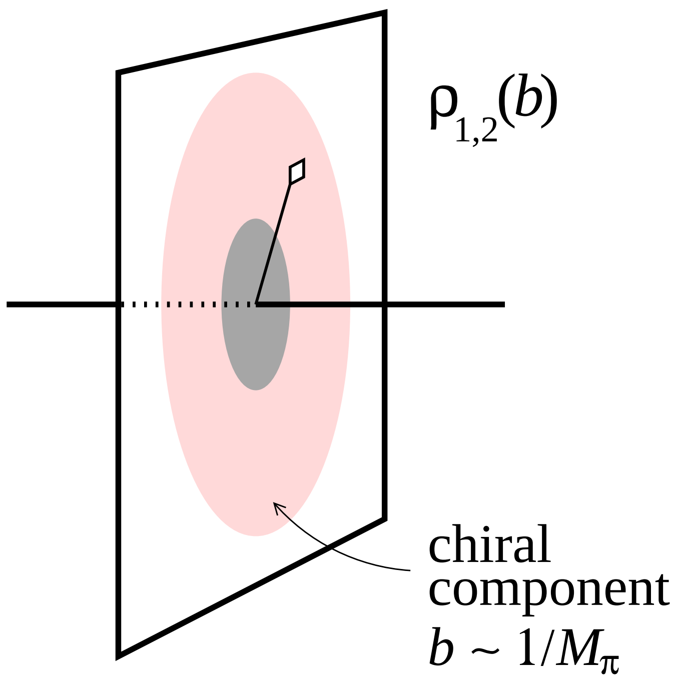
- Many interesting questions

  Neutron charge density

  Flavor/isospin decomposition

  Charge vs. magnetization densities

Spatial structure: Peripheral distances



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

  Densities governed by chiral dynamics

  Calculable from first principles

- Theoretical interest

  Use distance $b \gg R_{\mathrm{had}}$ as parameter

  Study space–time picture of EFT dynamics

  Quantify chiral and non-chiral contributions

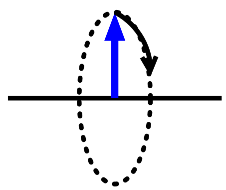
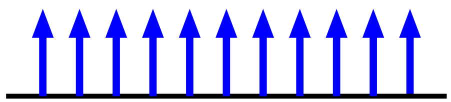
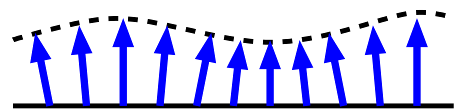
- Practical interest

  Connection with low–$|t|$ form factors,
  proton charge radius
  Atomic physics and electron scattering measurements; much activity

  Peripheral quark/gluon structure
  in high-energy processes

Chiral dynamics: Spontaneous symmetry breaking

- Rotational symmetry in spin system

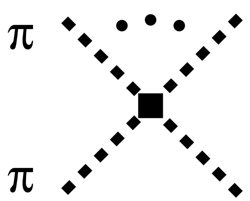
Rotational invariance $O(3)$ | $\boldsymbol{M} = \langle \sum \boldsymbol{S} \rangle \neq 0$ order parameter | spin wave massless excitation

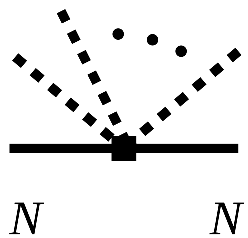
- Chiral symmetry in QCD

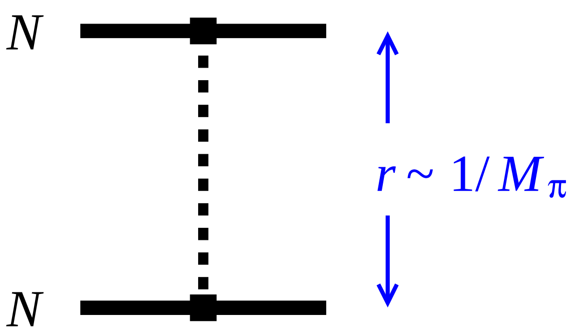
L, R independent flavor rotations $SU(2)_L \times SU(2)_R$ | $\langle \bar{\psi}_L \psi_R \rangle \neq 0$ chiral condensate | $\langle ... \rangle \sim e^{i\boldsymbol{\tau}\boldsymbol{\pi}(x)}$ pion wave

- Determines large-distance, low-energy behavior

Chiral dynamics: Effective dynamics







- Effective dynamics

  Valid at momenta $p_\pi \sim M_\pi \ll \Lambda_\chi \sim 1\,\mathrm{GeV}$

  Structure determined by chiral invariance

  Couplings parametrize short-distance dynamics

  Pions couple weakly $\propto p_\pi^\mu$

  Nucleon as external source

- Constructed and solved using EFT methods

  Parametric expansion in p_π/Λ_χ

  Controled accuracy, uncertainty estimates
  Gasser, Leutwyler 83; Weinberg 90. Extensive work

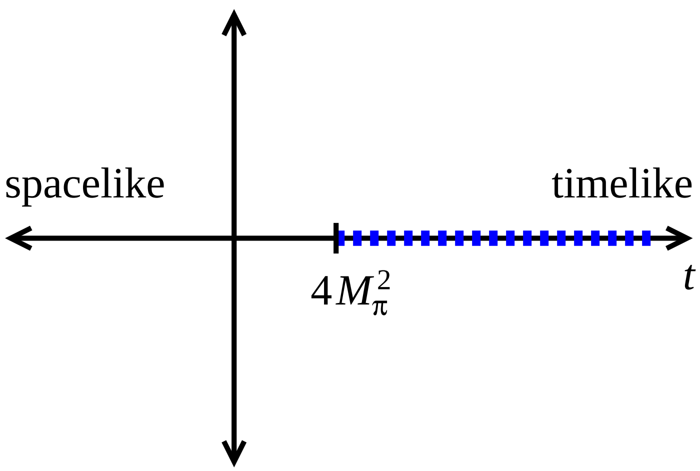
- Large-distance behavior of strong interactions

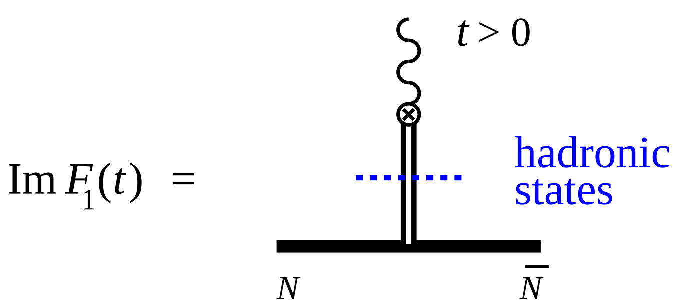
  $\pi\pi$ scattering

  NN interaction at distances $\sim 1/M_\pi$

  πN scattering, EM processes near threshold

Peripheral densities: Dispersive representation





Isovector: $\pi\pi$ (incl. ρ), 4π, ...
Isoscalar: 3π (incl. ω), $K\bar{K}$ (incl. ϕ), ...

- Dispersive representation of form factor

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

Process: Current $\rightarrow$ hadronic states $\rightarrow N\bar{N}$

Unphysical region: $\mathrm{Im}\, F(t')$ from theory
Frazer, Fulco 60; Höhler et al 74

- Transverse densities

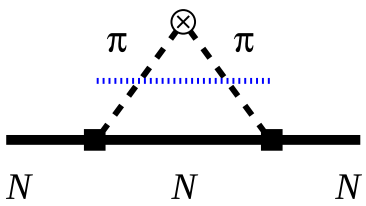
$$\rho(b) = \int_{4M_\pi^2}^{\infty} \frac{dt}{2\pi} K_0(\sqrt{t}b) \frac{\mathrm{Im}\, F(t)}{\pi}$$

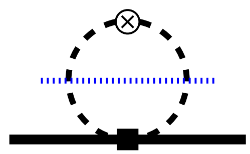
Exponential suppression of large t

Distance b selects masses $\sqrt{t} \lesssim 1/b$

Peripheral densities $\longleftrightarrow$ low–mass states
Strikman, CW 10; Miller, Strikman, CW 11

Peripheral densities: Chiral component



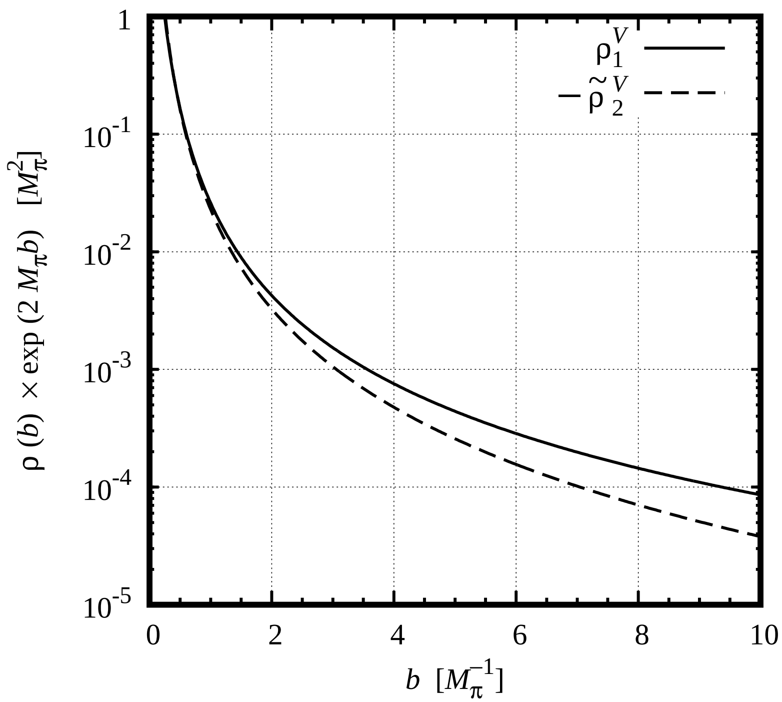


- Spectral functions from χEFT

  $\pi\pi$ exchange, isovector channel

  LO results; higher-order corrections

  Gasser et al. 87; Bernard et al. 96, Kubis, Meissner 00, Kaiser 03



- Chiral component of isovector densities

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

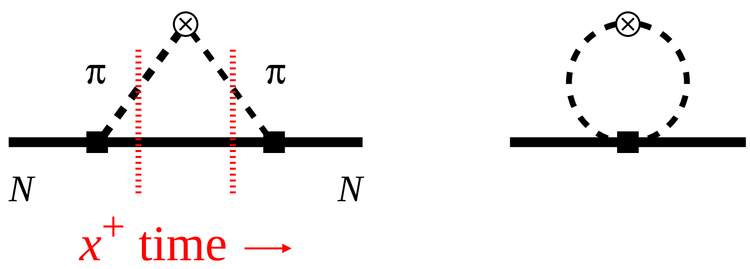
  Yukawa tail with range $2M_\pi$, rich structure

  $\rho_1^V, \widetilde{\rho}_2^V$ of same order in M_π / M_N

  Inequality $\widetilde{\rho}_2^V(b) \leq \rho_1^V(b)$ — explain?

  Strikman, CW 10; Granados CW 13

Peripheral densities: Time–ordered formulation



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

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

$+$ contact term

$$\widetilde{\rho}^V_2(b) = \; \ldots \qquad \psi_0^* \psi_1 + \psi_1^* \psi_0$$

- 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 $L_z = 0, 1$

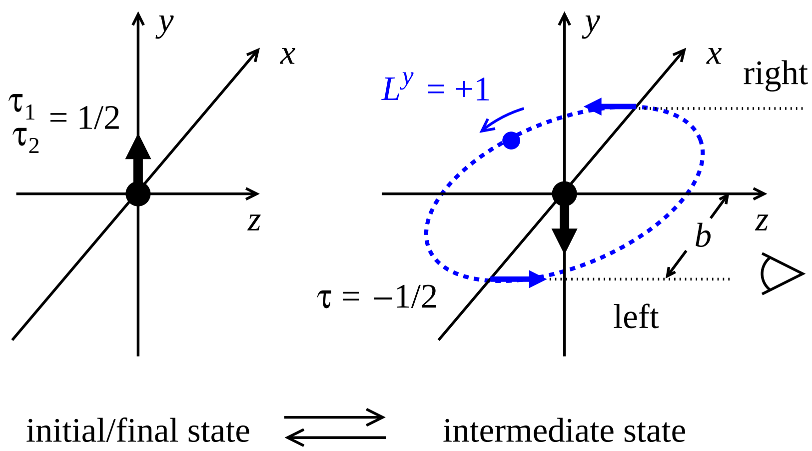
- Densities as wave function overlap

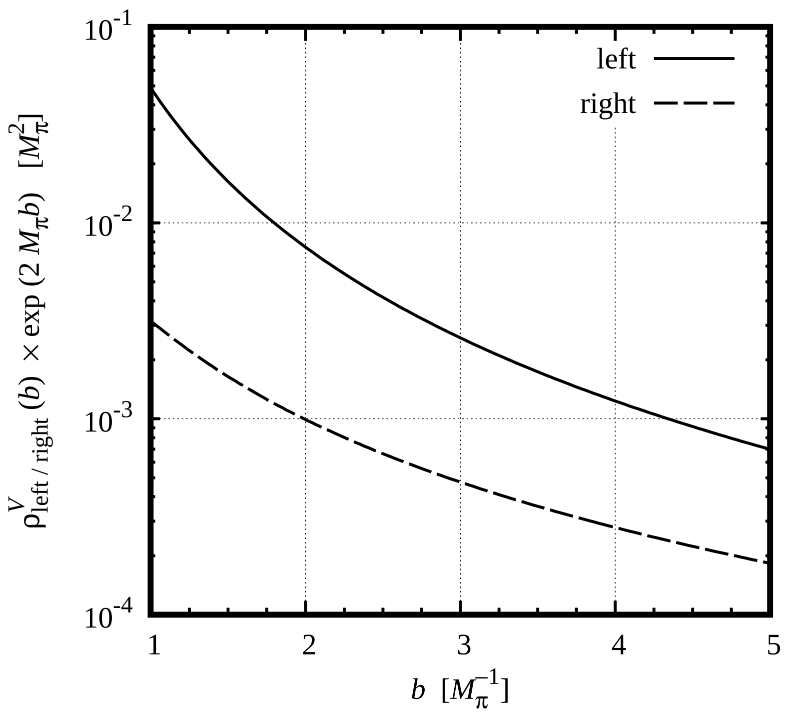
  Explains inequality $|\rho^V_2| < \rho^V_1$ Granados, CW 13

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

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

Peripheral densities: Mechanical picture





- χEFT process as time sequence

  Rest frame, nucleon polarized in y–direction

  Bare N fluctuates into πN system via χEFT interaction

  Peripheral densities result from J^+ current carried by orbiting pion

- Explains peripheral densities

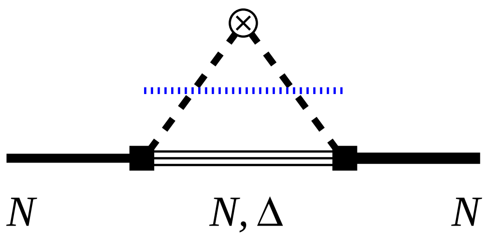
  $$\rho_1, \widetilde{\rho}_2 \;=\; \langle J^+\rangle_{\text{right}} \;\pm\; \langle J^+\rangle_{\text{left}}$$

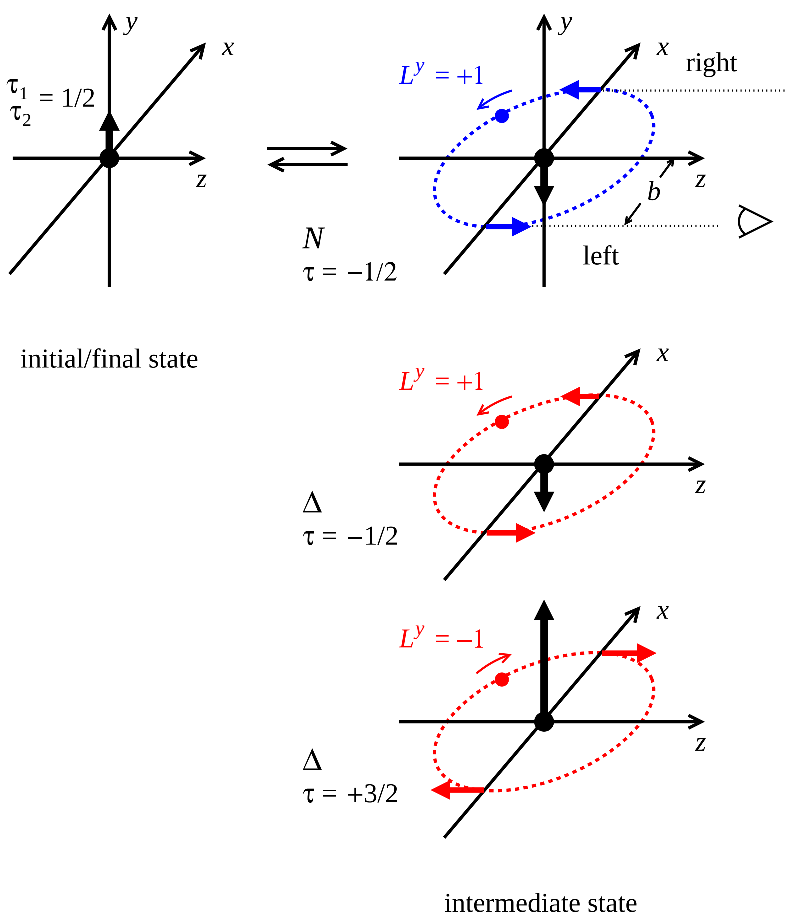
  $\langle J^+\rangle_{\text{left}} \gg \langle J^+\rangle_{\text{right}}$ large asymmetry

  Pion motion relativistic $k_\pi \sim M_\pi$

- Quantitative picture based on χEFT

Peripheral densities: Δ isobar





- Intermediate Δ isobar

  Large coupling to πN, low mass

  Included in relativistic χEFT
  Rarita-Schwinger formalism, small-scale expansion

  Contributes to peripheral transverse densities
  Strikman, CW 10, Granados, CW 13

- Mechanical picture with Δ

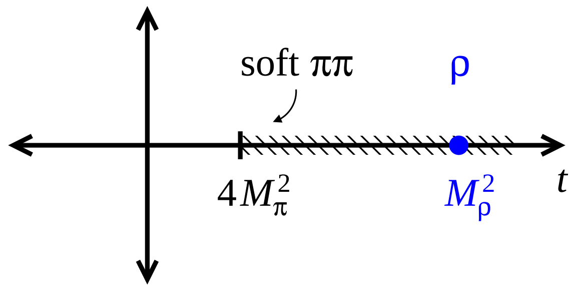
  More spin-isospin states, reverse pion motion

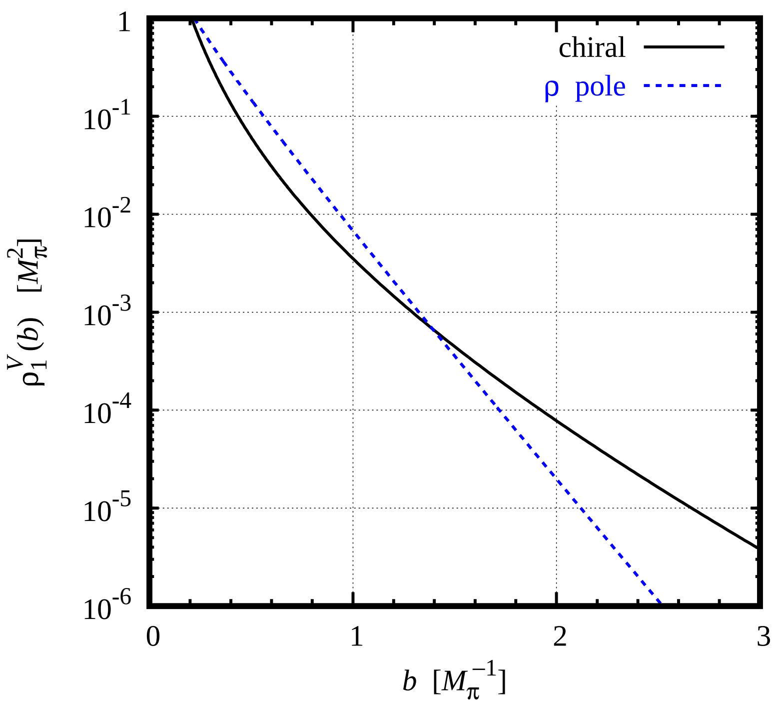
- Large-N_c limit of QCD

  N, Δ degenerate, $M_\Delta - M_N = O(N_c^{-1})$

  $N + \Delta$ χEFT densities have correct N_c-scaling
  Granados, CW 13; see also Cohen, Broniowski 92; Cohen 96

Peripheral densities: Vector meson





- Region of applicability of χEFT?

  Corrections?

- Dispersive representation

  Density $\rho(b) \leftrightarrow$ spectral function $\mathrm{Im}F(t)$

  Soft $\pi\pi$ exchange near threshold $t \sim 4\, M_\pi^2$

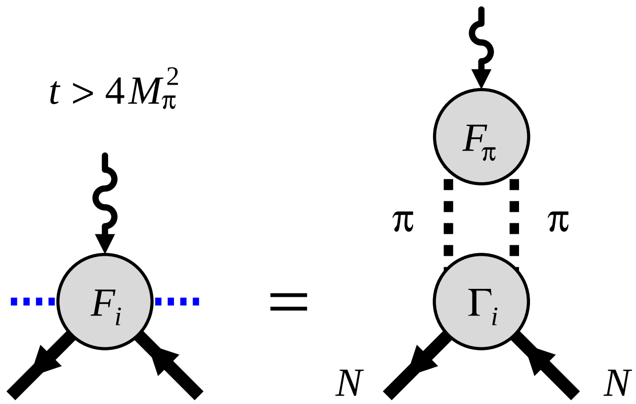
  ρ resonance at $t \sim 30\, M_\pi^2$

  ρ dominates peripheral densities up to distances $b \sim 1.5 M_\pi^{-1} \sim 2\,\mathrm{fm}$

- Include ρ in systematic fashion

  New unitarity-based approach
  Alarcon, Blin, Vicente Vacas, Weiss, NPA 964 18 (2017)
  NLO: Alarcon, Weiss, arXiv:1710.06430; in progress.

Peripheral densities: Elastic unitarity



$$\mathrm{Im}F_i(t) = \frac{k_{\mathrm{cm}}^3}{\sqrt{t}}\,\Gamma_i(t)\;\;F_\pi^*(t)$$

$$= \frac{k_{\mathrm{cm}}^3}{\sqrt{t}}\,\underbrace{\frac{\Gamma_i(t)}{F_\pi(t)}}_{\chi\text{EFT}}\;\;\underbrace{|F_\pi(t)|^2}_{\text{Data}}$$

- Elastic unitarity relation

  Timelike pion FF $F_\pi(t)$, $\pi\pi \rightarrow N\bar{N}$ partial-wave amplitude Γ_i

  Functions have same phase — Watson's theorem

  Includes ρ as $\pi\pi$ resonance

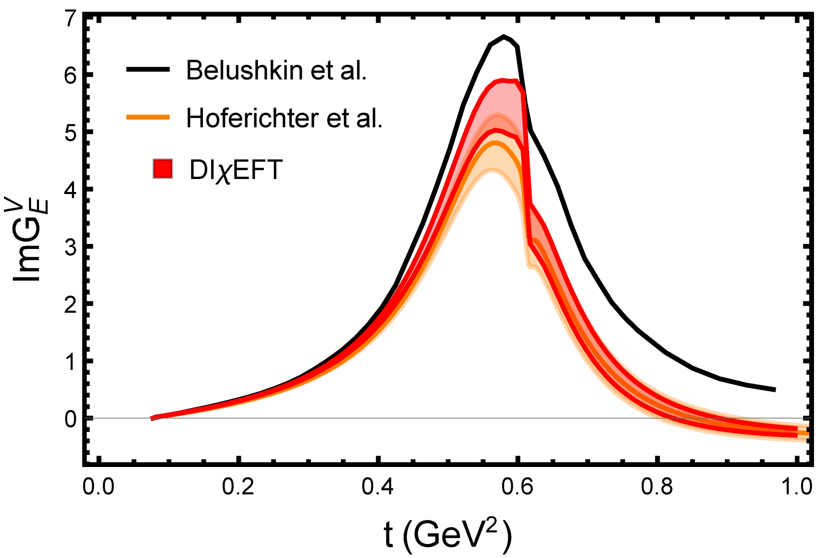
- Combine unitarity and χEFT

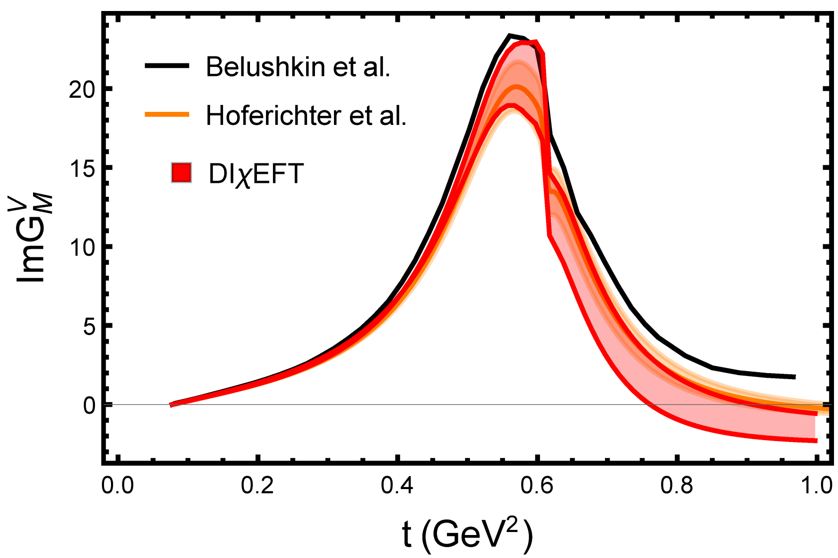
  Calculate Γ_i/F_π in χEFT — free of $\pi\pi$ rescattering, well convergent

  Multiply with $|F_\pi|^2$ from e^+e^- data — includes $\pi\pi$ rescattering, ρ resonance

  N/D method. Frazer, Fulco 60; Höhler et al 74. Many theoretical advantages. Predictive!
  Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017); Alarcon, Weiss, arXiv:1707.07682; arXiv:1710.06430.

Peripheral densities: Improved spectral functions

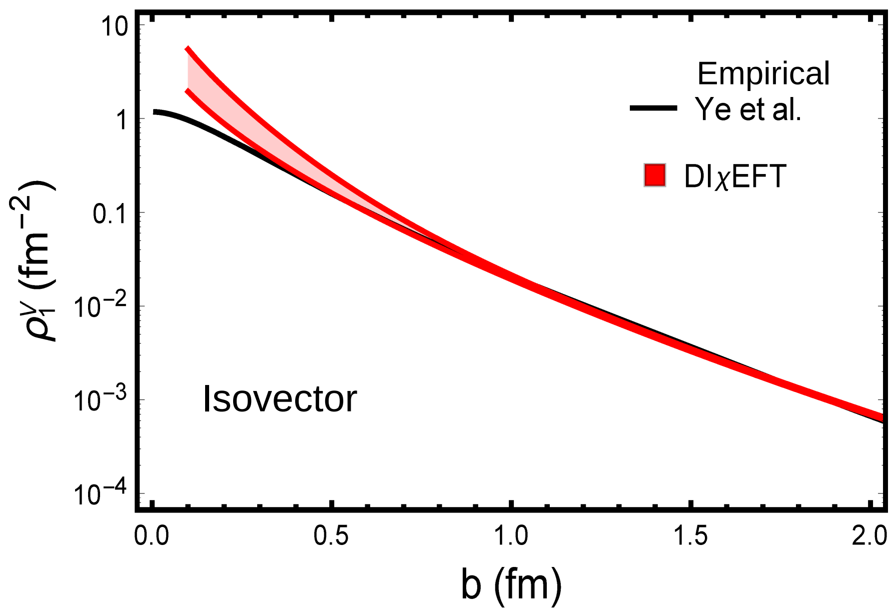


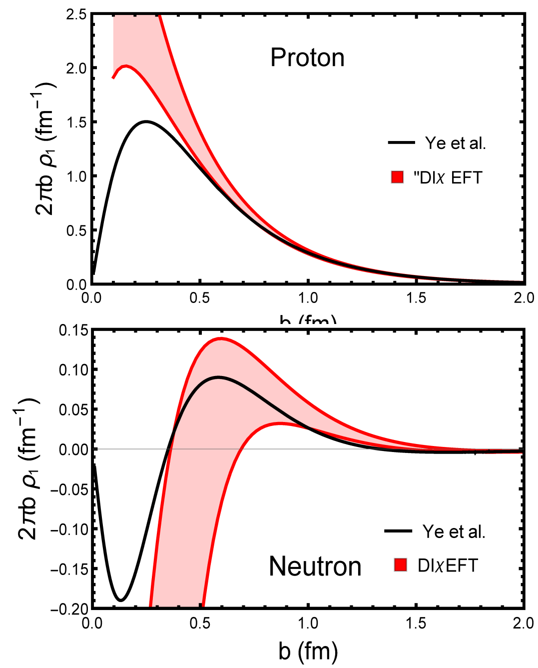


LO Alarcon, Blin, Vicente Vacas, Weiss, NPA 964 18 (2017). NLO: Alarcon, Weiss, arXiv:1710.06430; in progress.

- Spectral functions computed in DIχEFT
- Method includes $\pi\pi$ rescattering, ρ resonance, applicable up to ~ 1 GeV^2
- Dramatic improvement over conventional χEFT calculations
- Good convergence in higher orders (NLO, partial N2LO), uncertainty estimates

Peripheral densities: Improved densities





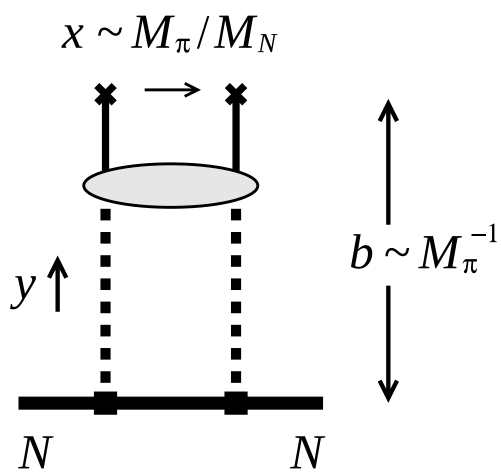
NLO + partial N2LO: Alarcon, Weiss, arXiv:1710.06430; in progress.

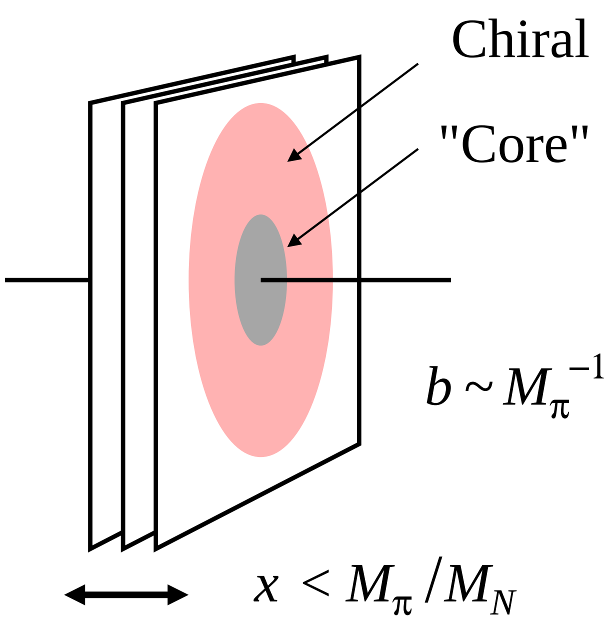
- Use DIχEFT spectral functions to calculate peripheral transverse densities

- Peripheral isovector densities predicted down to $b < 1$ fm with controled accuracy
  Isoscalar densities from empirical parametrization with ω, ϕ

- Peripheral transverse nucleon structure can be computed from first principles!

Peripheral partons: Chiral component





- Transverse spatial distribution (GPD)

  $f(x, b)$ longitudinal momentum
  transverse position

- Chiral component

  $b \sim M_\pi^{-1}$ transverse distance

  $y \sim M_\pi / M_N$ momentum fraction of soft pion

  $x < y$ quark/gluon in pion

  Peripheral, slow partons

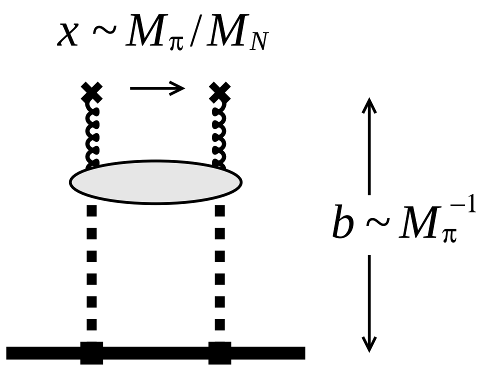
- Calculable model-independently

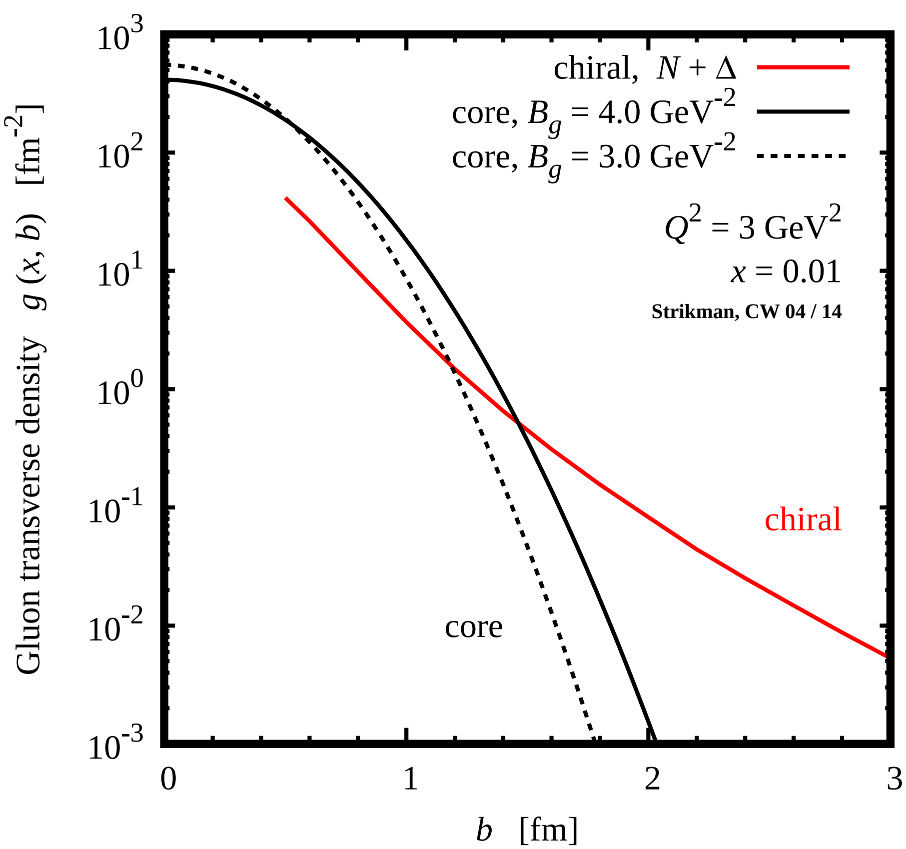
  Pion distribution in nucleon
  from chiral dynamics

  Parton distribution in pion
  from independent measurements

Strikman, CW, PRD 69, 054012 (2004); PRD 80, 114029 (2009)

Peripheral partons: Gluon density





- Gluon transverse density

  Chiral component calculated
  Strikman, CW 04

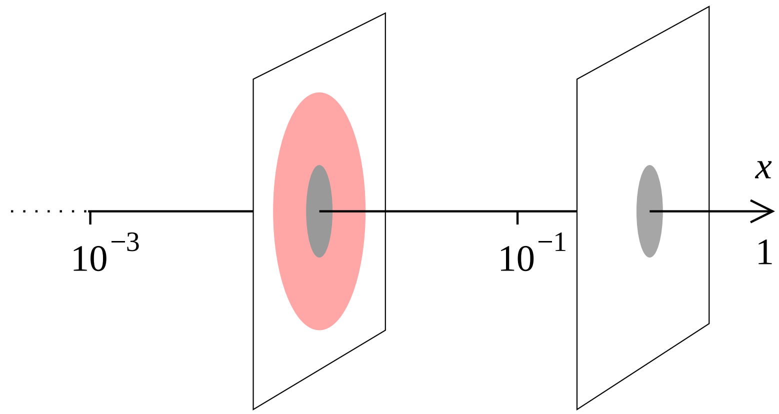
  Nonchiral core modeled empirically using J/ψ data
  HERA, FNAL

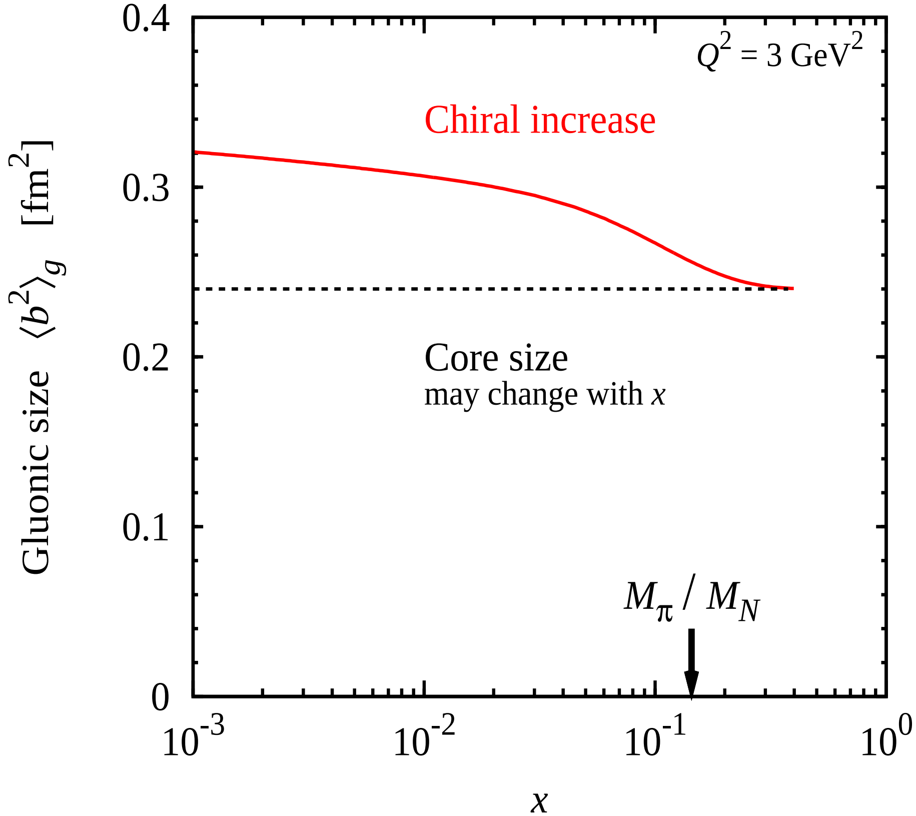
- Chiral component is distinct only at distances $b \gtrsim 2$ fm

- $O(1\%)$ contribution to overall gluon density in nucleon

  Model-independent feature!

Peripheral partons: Gluonic transverse size





- Average transverse size

$$\langle b^2 \rangle_f(x) \;=\; \frac{\int d^2b\; b^2\;\; f(x,b)}{\int d^2b\;\, f(x,b)}$$

  cf. EM charge radius

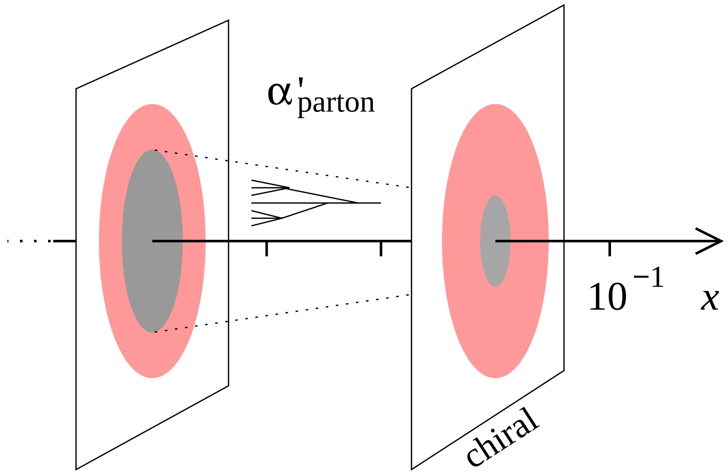
  Changes with x and Q^2 (DGLAP)

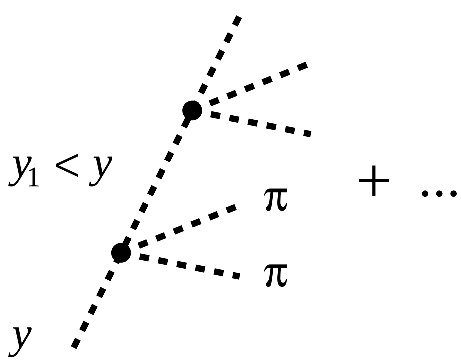
- Chiral component causes increase below $x \sim M_\pi / M_N$
  Strikman, CW 04 / 09

- Faster increase for quarks than for gluons $\langle b^2 \rangle_{q+\bar{q}} > \langle b^2 \rangle_g$

- Size changes also due to non-chiral effects, $\langle b^2 \rangle$ cannot discriminate

Peripheral partons: Chiral vs. small–x dynamics





- Non–chiral core size grows due to Gribov diffusion

  Slow because $\alpha'_{\mathrm{gluon}}(Q^2) \ll \alpha'_{\mathrm{soft}}$ if $Q^2 \sim \mathrm{few\ GeV}^2$

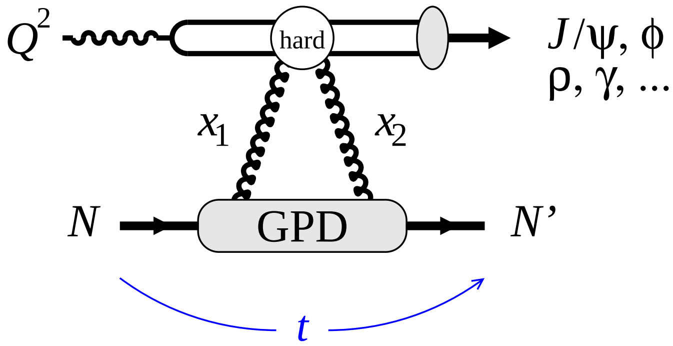
- Pion size can grow due to higher–order chiral effects

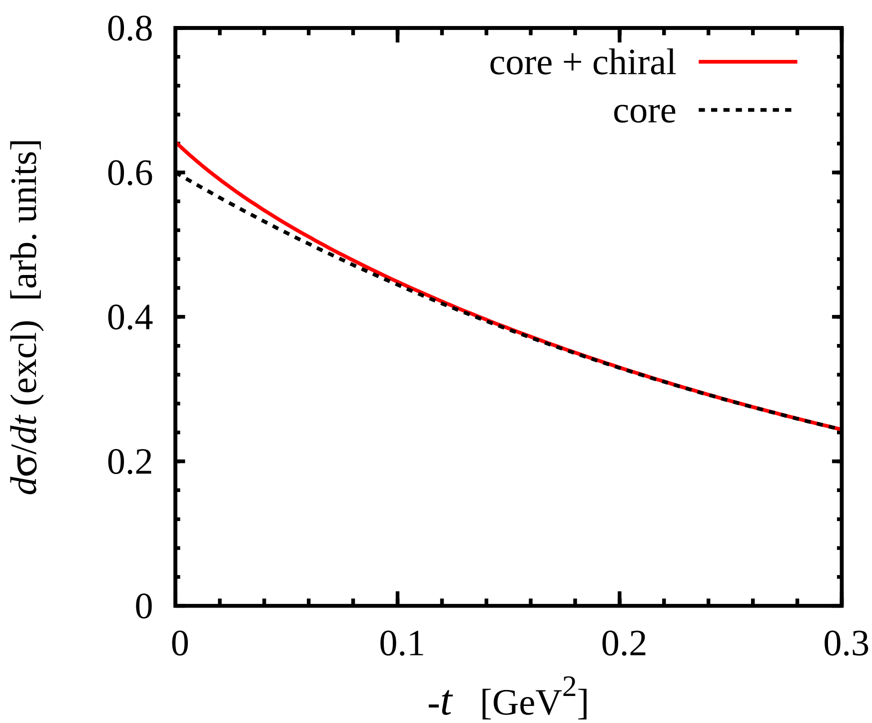
  Logarithmic terms resummed using functional methods
  Polyakov, Kivel 08; PK + Vladimirov 09; Perevalova et al 11

  Could become important at $x \ll 10^{-2}$

- "Single–step" chiral component should be safe for $x > 10^{-3}$

Peripheral partons: Hard exclusive processes





- Hard exclusive processes: Transverse imaging of nucleon

$$\frac{d\sigma}{dt} \;\rightarrow\; H_f(x_1, x_2, t) \;\xrightarrow[x1=x2]{\text{Fourier}}\; f(x, b)$$

$$\langle b^2 \rangle_f \;=\; 4 \frac{\partial}{\partial t} \left. \frac{H_f(x, x, t)}{H_f(x, 0)} \right|_{t=0}$$

- Effect of chiral component

  Numerically small

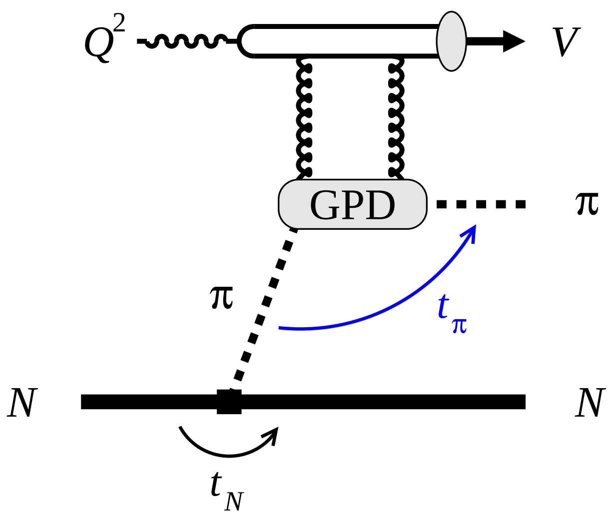
  Visible at $-t < 0.1\,\mathrm{GeV}^2$

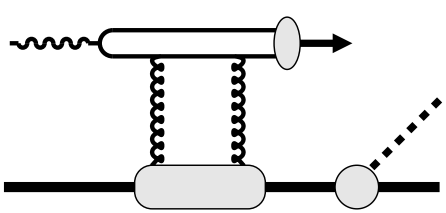
  Simple model estimate, needs detailed simulation!

- Caution when extracting $\langle b^2 \rangle$ from measurements at finite $-t$

  Very challenging!

Peripheral partons: Pion knockout processes





suppressed!

- Hard exclusive process on soft pion

  $k_\pi^2 = O(M_\pi^2)$ pion soft

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

  Fundamental interest

  Moments calculable in LQCD

- Detection requirements

  Forward nucleon $p_T \sim 100\,\mathrm{MeV}$
  Forward pion $p_T \lesssim 1\,\mathrm{GeV}$

Direct probe of chiral component!
Needs detailed simulation...
Strikman, CW PRD69, 054012 (2004)

Summary

- Light–front view provides 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

  Quantum-mechanical picture of low–energy chiral nucleon structure

  New unitarity-based approach includes $\pi\pi$ rescattering, predicts densities at $b \gtrsim 1$ fm

  Many applications and extensions: Form factors of energy-momentum tensor 2π, isoscalar vector current 3π, axial current 3π

- Peripheral partons in nucleon

  Chiral dynamics expressed in partonic structure

  Could be probed in pion knockout processes at EIC