Transverse densities of nucleons and resonances

C. Weiss (JLab), Exploring hadrons with EM probes, JLab, 02-Nov-17
based on work with J.M. Alarcon, A. Hiller Blin, C. Granados

Jefferson Lab

Objective: Explain/predict structure of nucleon and baryon resonances using model-independent methods of strong interaction physics

Chiral effective field theory — large-distance dynamics, controled accuracy, predictive

Dispersion theory — analyticity, global properties, spectrum $\leftrightarrow$ structure

Large-N_c QCD — parametric expansion, $N \leftrightarrow \Delta$, connection with QCD

Structures

EM form factors and transverse densities $N \to N, \; N \to N^*, \; N^* \to N^*$ $\longleftarrow$

Form factors of scalar, axial, twist-2 operators (GPDs)

$\pi N N^*$ vertices, $NN \to NN^*$ amplitudes

Granados, Weiss, JHEP 1401, 092 (2014); PRC 92, 025206 (2015); JHEP 1507, 170 (2015); JHEP 1606, 075 (2016).
Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017)
Alarcon, Weiss, arXiv:1707.07682; arXiv:1710.06430.

Outline

- Form factors and transverse densities

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

  Dispersive representation

  χEFT calculation — Dispersively Improved χEFT (DIχEFT)

  Nucleon EM densities

  $SU(3)$ flavor and octet baryons

  Large-N_c relations

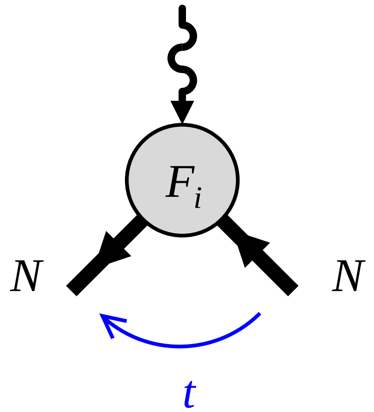
- Resonance form factors and densities

  Unstable particles, $N \to N^*$, $N^* \to N^*$

- Applications and extensions

  Scalar, axial form factor, EM tensor

Form factors and transverse densities



- Current matrix element

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

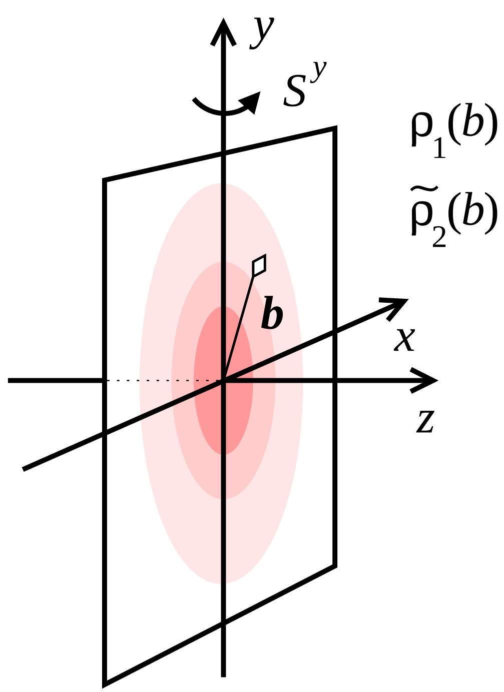
- Transverse densities

Soper 76, Burkardt 00, Miller 07

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

Charge/magnetization density, or spin-indep/dependent

Density at fixed light-front time $x^+ = x^0 + x^3$,
boost-invariant, appropriate for relativistic systems

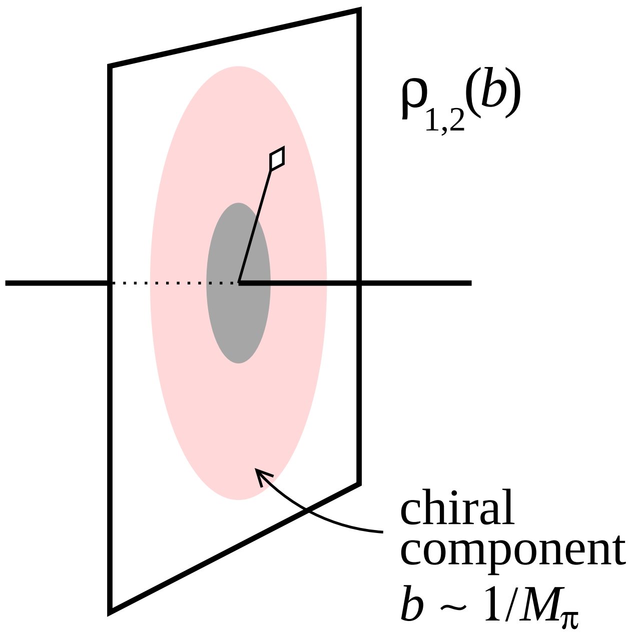


- Connection with GPDs/QCD

$$\rho_1(b) \;=\; \textstyle\sum_q e_q \displaystyle\int_0^1 dx \; [q(x,b) - \bar{q}(x,b)]$$

Dual role of transverse densities:
Accessible through low-energy elastic FFs,
interpretable in terms of QCD DoF

Peripheral densities



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

  Governed by chiral dynamics:
  universal, model–independent

  Calculable using χEFT + dispersion theory
  Strikman, CW 10; Granados CW 13

- Theoretical interest

  Distance as parameter

  Proper definition of mesonic component

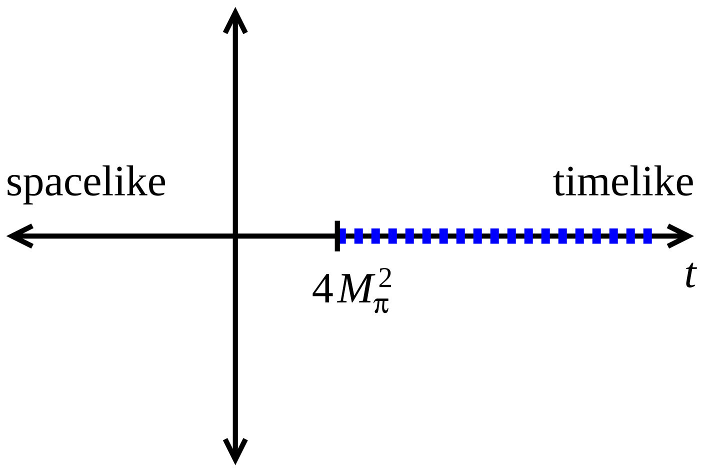
  Space–time picture of chiral dynamics

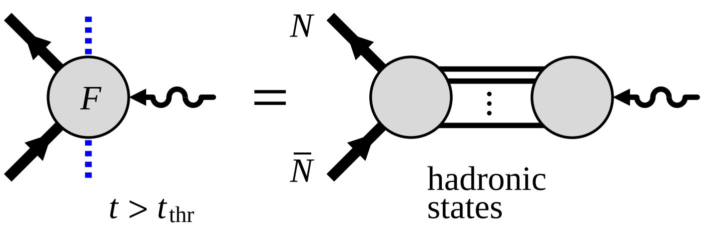
- Practical interest

  Low–$|t|$ form factors, proton size

  Connection w. peripheral quark/gluon structure

Dispersive representation





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

- Dispersive representation of form factor

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

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

Unphysical region: $\text{Im}\, F(t')$ from theory
Frazer, Fulco 60; Höhler et al 74; Hoferichter et al 14

- Transverse densities

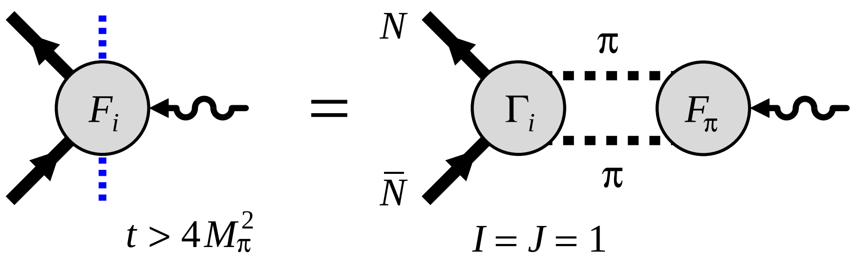
$$\rho(b) = \int_{4M_\pi^2}^{\infty} \frac{dt}{2\pi} K_0(\sqrt{t}b) \frac{\text{Im}\, F(t)}{\pi}$$

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

Distance b selects masses $\sqrt{t} \sim 1/b$: Filter
Strikman, CW 10; Miller, Strikman, CW 11

Peripheral densities $\longleftrightarrow$ low–mass states

Spectral functions



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

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

- Elastic unitarity relation

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

  Functions have same phase — Watson's theorem

  Relation valid up to $t = 16\,M_\pi^2$, in practice up to $t \sim 1$ GeV^2

  Includes ρ as $\pi\pi$ resonance

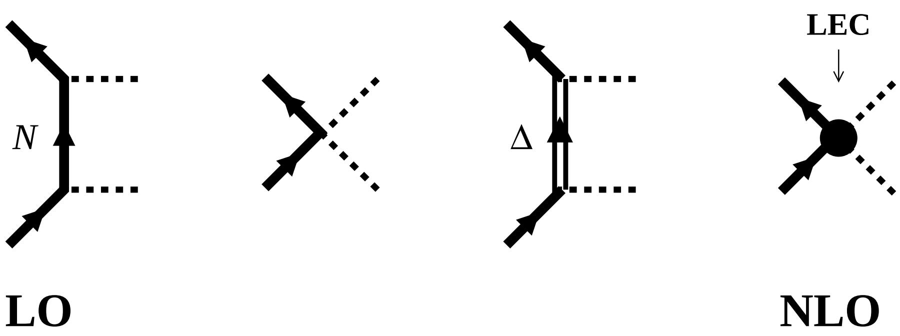
- New χEFT-based approach

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

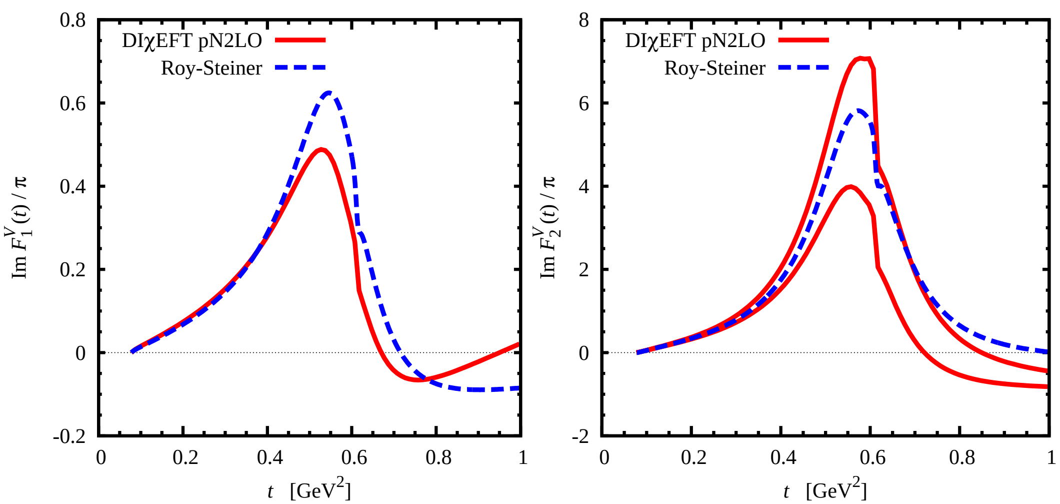
  Multiply with $|F_\pi|^2$ from e^+e^- data — includes $\pi\pi$ rescattering, ρ resonance

  N/D method. Many theoretical advantages. Predictive!

Spectral functions II



$\pi\pi \to N\bar{N}$ amplitude in χEFT



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

- Relativistic χEFT

  Expansion in $(M_\pi, k_\pi)/\Lambda_\chi$

  Controlled accuracy, systematic improvement

  π, N, Δ as effective DoF

- Spectral function results

  New method includes $\pi\pi$ rescattering, ρ resonance

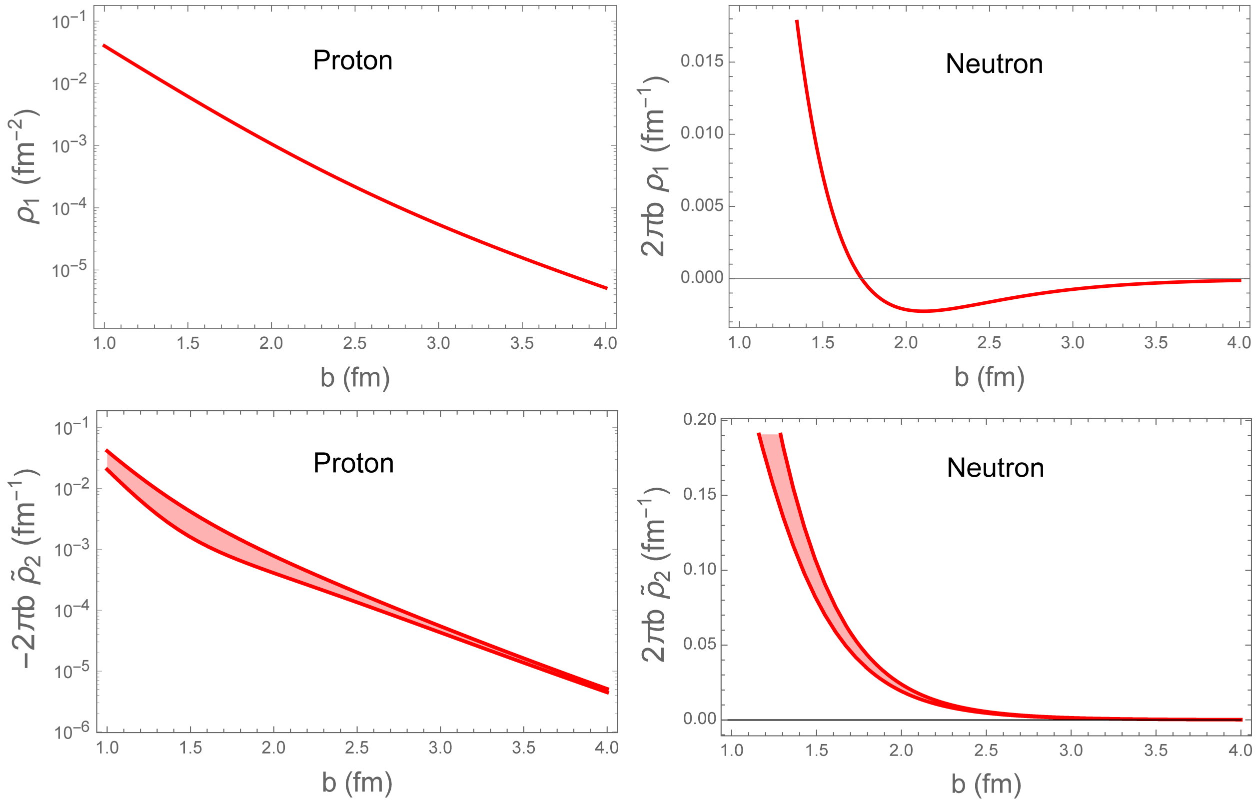
  Dramatic improvement over conventional χEFT calculations

  Good convergence in higher orders

  Possible to compute spectral functions up to ~ 1 GeV^2

  Many applications!

Peripheral densities in nucleon

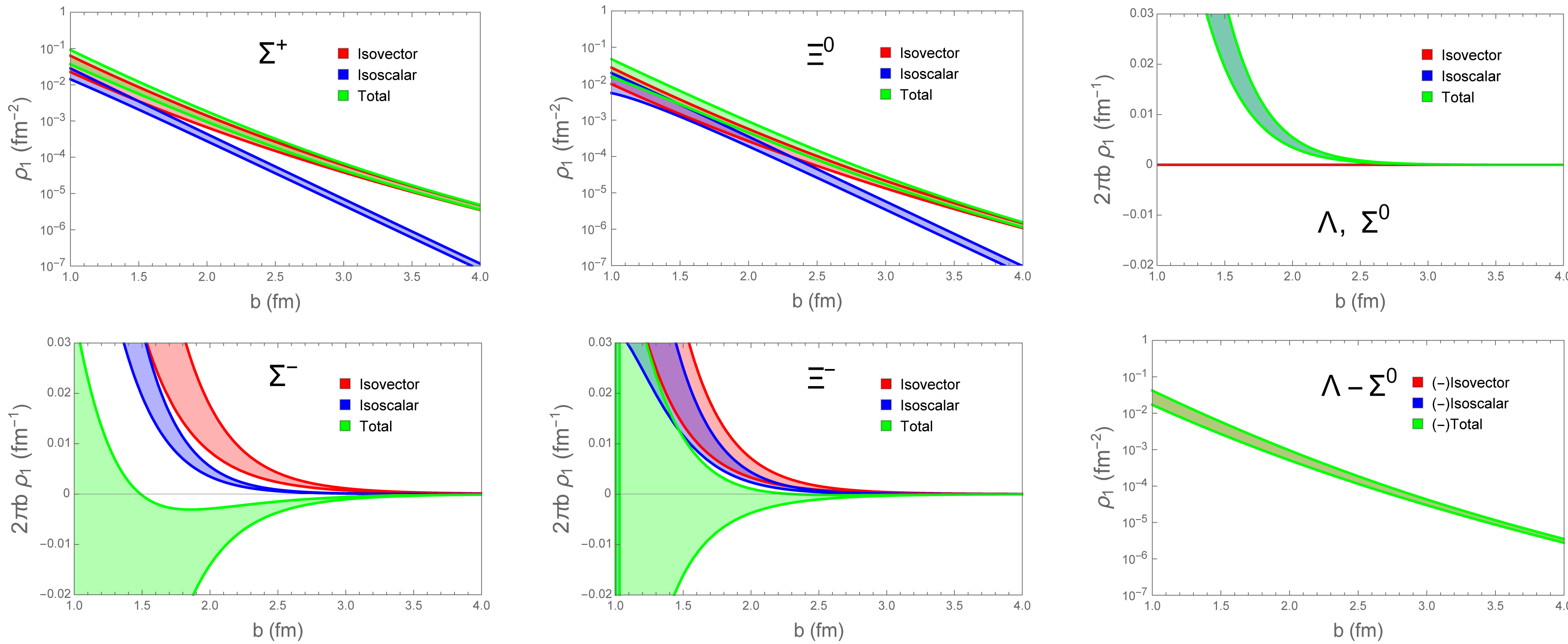


- Use DIχEFT spectral functions to calculate peripheral transverse densities

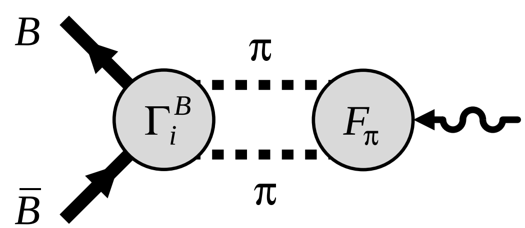
- Peripheral isovector densities predicted down to $b \sim 1$ fm with controled accuracy
  Isoscalar densities from empirical parametrization with ω, ϕ

- Peripheral nucleon structure can be computed from first principles!
  Alarcon, Blin, Vicente Vacas, Weiss, NPA 964 18 (2017). NLO: Alarcon, Weiss, arXiv:1710.06430; in progress.

SU3 flavor and octet baryons



- DIχEFT extended to $SU(3)$ flavor
- $\pi\pi$ spectral functions of octet baryon FFs
  $K\bar{K}$ negligible at peripheral distances
- Peripheral densities of octet baryons,
  quark flavor separation $u/d/s$
  Alarcon, Blin, Vicente Vacas, CW, 2017



Large-N_c limit of QCD

- Study scaling behavior of non-perturbative QCD quantities with N_c:
  Meson and baryon masses, current matrix elements, hadronic couplings, ...
  'tHooft 73, Witten 79

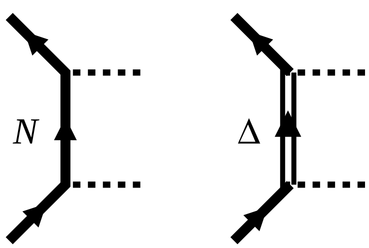
  N_c scaling can be established on general grounds

  Parametric classification, hierarchy of structures, qualitative insight

- N_c scaling of nucleon transverse densities

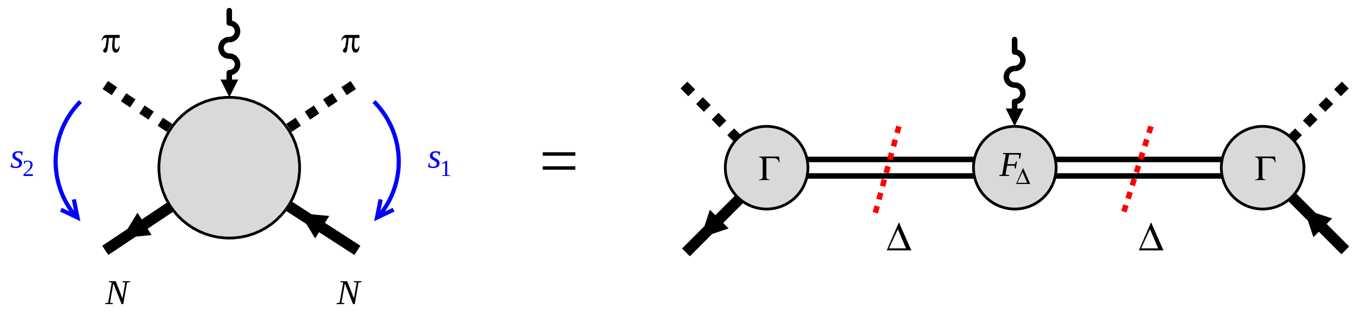
$$\rho_1(b) = \mathcal{O}(N_c^0), \quad \widetilde{\rho}_2(b) = \mathcal{O}(N_c), \quad \text{for} \;\; b = \mathcal{O}(N_c^0)$$

- χEFT results have correct N_c scaling if Δ isobar included as dynamical DoF
  Cohen, Broniowski 92. Transverse densities and GPDs: Strikman CW 04, 09, 11; Granados, CW 13



N, Δ	cancel	in	$\rho_1(b)$
	amplify		$\widetilde{\rho}_2(b)$

Resonance form factors and densities



- Structure of unstable particle

  S-matrix theory: Stable-particle amplitude $\pi N \to \pi N$, Δ as pole in 2-particle channels $s_{1,2} = M_\Delta^2$ complex, residue factorizes

  Resonance structure defined at complex pole

  Can be implemented in χEFT — Ledwig et al 10. Alarcon, Blin, CW, in progress

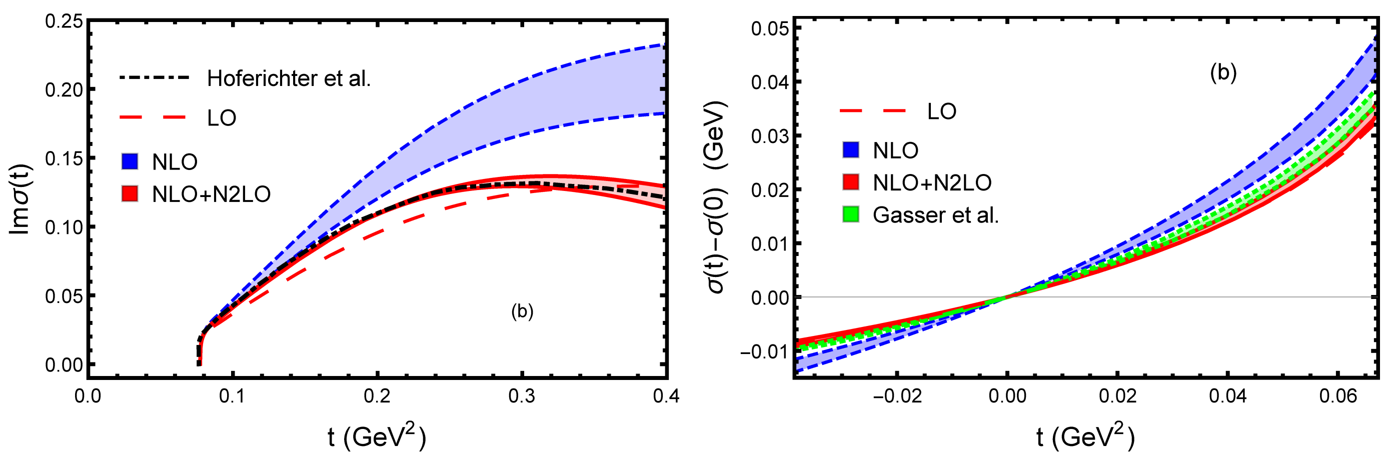
- Form factors and densities of Δ isobar

  New spin structures beacuse of $S = \frac{3}{2}$ — Lorce 09

  LQCD results — Alexandrou et al 08; Aubin, Orginos, Pascalutsa, Vanderhaegehen 08

Applications and extensions

- Electromagnetic form factors at low $t < 0$ and derivatives — Alarcon, CW, arXiv:1710.06430
- Scalar form factor and mass distribution in nucleon — Alarcon, CW, arXiv:1707.07682
- Energy-momentum tensor form factors and angular momentum — Granados, CW 2017
- Peripheral GPDs and high-energy processes — Strikman, CW 04
- Isoscalar-vector form factor from 3-body unitarity — Alarcon, Passemar, Pilloni, CW; in progress



Scalar spectral function and form factor from DIχEFT. Alarcon, CW, arXiv:1707.07682

Summary

- Transverse densities are an essential tool for hadron structure studies

    Provide objective spatial representation of relativistic system

    Connect low-energy dynamics with partonic structure in QCD

- Peripheral transverse densities can be computed with controled accuracy by combining χEFT and dispersion theory (DIχEFT)

    Includes $\pi\pi$ rescattering and ρ resonance

- Numerous applications and extensions

[• Not covered here: Light-front time-ordered formulation of chiral dynamics, chiral $N \rightarrow \pi N$ wave functions, quantum-mechanical interpretation]
Granados, Weiss, PRC 92, 025206 (2015); JHEP 1507, 170 (2015); JHEP 1606, 075 (2016).