Resonance structure from chiral EFT and dispersion theory

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based on work with J.M. Alarcon, A. Hiller Blin, C. Granados

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

- Chiral effective field theory (large-distance dynamics, controlled accuracy, predictive)
- Dispersion theory (analyticity, global properties, spectrum ↔ structure)
- Large-$N_c$ QCD (parametric expansion, $N \leftrightarrow \Delta$, connection with QCD)

Structures

- EM form factors and densities $N \rightarrow N$, $N \rightarrow N^*$, $N^* \rightarrow N^*$
- Other operators: Scalar, axial, twist-2 operators (GPDs)
- $\pi NN^*$ vertices, $NN \rightarrow NN^*$ amplitudes

Here: Describe methods for $N \rightarrow N$, discuss extension to $N^*$
Outline

• Baryon EM form factors and densities
  
  Transverse densities

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

  Dispersive representation

  \( \chiEFT \) calculations — Dispersively improved \( \chiEFT \) (DI\( \chiEFT \))

  \( SU(3) \) flavor extension

  Other operators: Scalar

• Resonance form factors and densities

  Properties of unstable particles

  Interest for resonance structure

• Large-\( N_c \) QCD

  \( N \leftrightarrow \Delta \) connection, spin/flavor components
Form factors and transverse densities

- Current matrix element
  \[ \langle N' | J_\mu | N \rangle \rightarrow F_1(t), F_2(t) \]  
  invariant FFs

- Transverse densities
  Soper 76, Burkardt 00, Miller 07
  \[ F_{1,2}(t = -\Delta_T^2) = \int d^2b \ e^{i\Delta_T b} \ \rho_{1,2}(b) \]  
  Fourier
  Charge/magnetization density, spin indep/dep
  Fixed light-front time \( x^+ = x^0 + x^3 = \text{const} \), appropriate for relativistic systems

- Connection with GPDs/QCD
  \[ \rho_1(b) = \sum_q e_q \int_0^1 dx \ [q - \bar{q}](x, b) \]
Peripheral densities

- Peripheral densities $b = \mathcal{O}(M_\pi^{-1})$
  - Governed by chiral dynamics: universal, model-independent
  - Calculable using $\chi$EFT + dispersion theory

- 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

- Dispersive representation of form factor

\[
F(t) = \int_{4M^2_\pi}^{\infty} \frac{dt'}{t' - t - i0} \frac{\text{Im} F(t')}{\pi}
\]

“Process” current $\rightarrow$ hadronic states $\rightarrow N \bar{N}$

Unphysical region: $\text{Im} F(t')$ from theory, FF fits
Höhler et al 76; Belushkin, Hammer, Meissner 06; Lorenz et al 12

- Transverse densities

\[
\rho(b) = \int_{4M^2_\pi}^{\infty} \frac{dt}{2\pi} K_0(\sqrt{tb}) \frac{\text{Im} F(t)}{\pi}
\]

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

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

Peripheral densities $\leftrightarrow$ low–mass states

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

\[ I = J = 1 \]

\[ t > 4M_\pi^2 \]

\[ \text{Im} F_i(t) = \frac{k_{\text{cm}}^3}{\sqrt{t}} \frac{\Gamma_i(t)}{F_\pi(t)} \left| F_\pi(t) \right|^2 \]

- **Elastic unitarity relation**

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

  Functions have same phase — Watson’s theorem

  Relation valid up to \( t = 16M_\pi^2 \), in practice up to \( t \sim 1 \text{ GeV}^2 \)

  Includes \( \rho \) as \( \pi\pi \) resonance

- **New \( \chi \text{EFT}-based approach**

  Calculate \( \Gamma_i/F_\pi \) in \( \chi \text{EFT} \) — free of \( \pi\pi \) rescattering, well convergent

  Multiply with \( |F_\pi|^2 \) from \( e^+e^- \) data — includes \( \pi\pi \) rescattering, \( \rho \) resonance

  Version of \( N/D \) method. Many theoretical advantages. Predictive!
Spectral functions II

- Relativistic $\chi$EFT
  
  Expansion in $(M_\pi, k_\pi)/\Lambda_\chi$
  
  Controlled accuracy, systematic improvement

  $\pi, N, \Delta$ as effective DoF

- Spectral function results
  
  New method includes $\pi\pi$ rescattering, $\rho$ resonance

  Dramatic improvement over conventional $\chi$EFT calculations

  Good convergence in higher orders

  Alarcon, CW, in progress

  Possible to compute spectral functions up to $\sim 1$ GeV$^2$

  Many applications!
Peripheral densities

- Use DIχEFT spectral functions to calculate peripheral transverse densities

- Peripheral isovector densities predicted down to $b \sim 1$ fm with controlled accuracy
  Isoscalar densities from empirical parametrization with $\omega, \phi$

- Peripheral nucleon structure can be computed from first principles!
  
  *Alarcon, Blin, Vicente Vacas, CW, 2017*
SU3 flavor extension

- DI\chi EFT 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
Present directions

- Higher-order corrections in DIχEFT
  Alarcon, CW, in progress. See also Granados, Leupold, Perotti 2017.

- Nucleon FFs of scalar operators, EM tensor — nucleon mass and spin

- Anomalous threshold effects in FFs and densities

- Extension to $N \rightarrow N^*$ and $N^* \rightarrow N^*$ FFs
  Alarcon, Blin, CW in progress
• Structure of unstable particle

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

Resonance structure defined at complex pole

Can be implemented in $\chi$EFT

Ledwig et al 10

• Form factors and densities of $\Delta$ isobar

New spin structures because of $S = \frac{3}{2}$

Lorce 09

LQCD results

Alexandrou et al 08; Aubin, Orginos, Pascalutsa, Vanderhaegehen 08
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
  Very successful phenomenology
  $N_c \to \infty$ corresponds to semiclassical limit of QCD

- Great potential for resonance physics

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

  $g_{\pi N\Delta} = \frac{3}{2} g_{\pi NN}$

  $\langle B'|J^\mu|B\rangle = \text{common function}$

  $N, \Delta$ almost degenerate
  Pion couplings simply related
  $N$ and $\Delta$ current MEs related

- $\chi$EFT results have correct $N_c$-scaling if $\Delta$ isobar included as dynamical DoF
  Cohen, Broniowski 90’s. Transverse densities and GPDs: Strikman CW 04/09/11, Granados, CW 13
Summary

- Model-independent methods have much to contribute to understanding resonance structure and production mechanism
  
  Chiral effective field theory
  Dispersion theory
  Large-$N_c$ QCD

- Peripheral baryon structure can be computed with controlled accuracy by combining $\chi$EFT and dispersion theory (DI$\chi$EFT)

- Extension to resonance structure in progress