Peripheral transverse densities from chiral EFT and dispersion analysis

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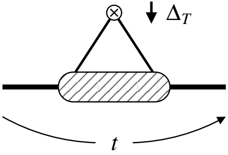
Form factors and spatial densities

Spatial distribution of charge given by **form factors**

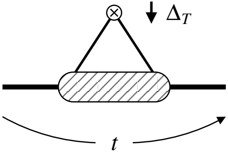
$$\langle N'|J_\mu|N\rangle \longrightarrow F_1(t), F_2(t)$$



Form factors and spatial densities

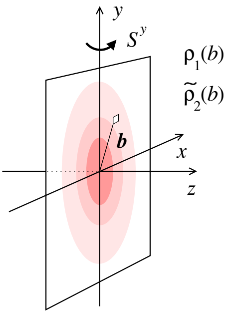
Spatial distribution of charge given by **form factors**

$$\langle N' | J_\mu | N \rangle \longrightarrow F_1(t), F_2(t)$$



- **Non-relativistic systems:**
  Fourier transforms of 3-dimensional spatial densities
- **Relativistic systems:** vacuum fluctuations!
  The number of particles in the system is not a constant

Transverse densities



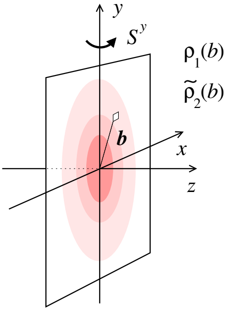
- **Fixed light-front time:** $x^+ = x^0 + x^3$

  Soper, PRD15 1141 (1977); Burkardt, PRD62 071503 (2000);
  Miller, PRC76 065209 (2007)

  For momentum transfer $\Delta^+ = \Delta^0 + \Delta^3 = 0$
  current not affected by vacuum fluctuations!

- Connection with general parton distributions

Transverse densities



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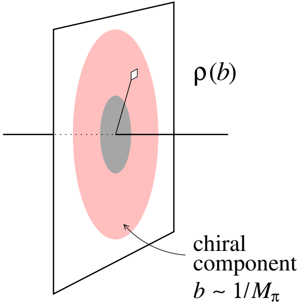
- Connection with general parton distributions

- Pure **transverse** momentum transfer $\boldsymbol{\Delta}_T = (\Delta^1, \Delta^2)$

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

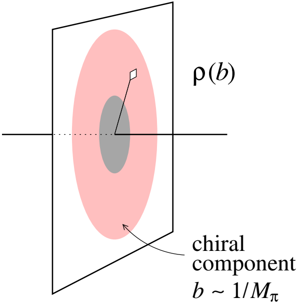
$$\langle J^+(\boldsymbol{b})\rangle_{y-\mathrm{pol}} \sim \underbrace{\rho_1(b)}_{\text{spin-independent}} + \underbrace{(2S^y)\cos\phi \overbrace{\frac{d}{db}\left[\frac{\rho_2(b)}{2M_N}\right]}^{\widetilde{\rho}_2(b)}}_{\text{spin-dependent}}$$

Peripheral densities



- Distances $b \sim M_\pi^{-1}$: densities governed by low-energy chiral dynamics

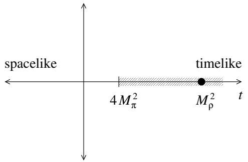
Peripheral densities



- Distances $b \sim M_\pi^{-1}$: densities governed by low-energy chiral dynamics

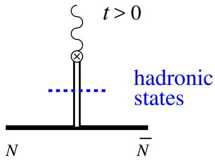
- Can be computed model-independently
  $\Longrightarrow$ **chiral effective field theory** and dispersion analysis
  Strikman and Weiss PRC82 042201 (2010); Granados and Weiss JHEP1401 092 (2014)
- **Predictive!**

Dispersive representation



$$F_{1,2}(t) = \int_{4m_\pi^2}^{\infty} \frac{dt'}{t' - t - i0} \frac{\operatorname{Im} F_{1,2}(t')}{\pi}$$

$\operatorname{Im} F_1(t) =$

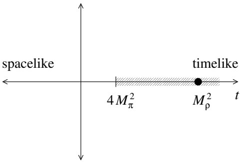


Unphysical region from theory

Hohler et al., NPB114 505 (1976);

Belushkin et al., PRC75 035202 (2007)

Dispersive representation



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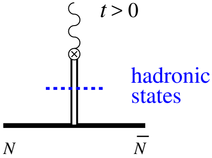

Unphysical region from theory

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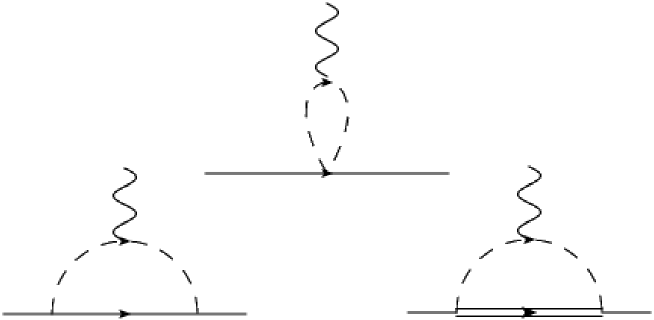
$$\rho_{1,2}(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi} K_0(\sqrt{t}b) \frac{\mathrm{Im}\, F_{1,2}(t)}{\pi}$$

Bessel function $K_0 \sim e^{-b\sqrt{t}}$: **suppression at large *t***

Distance b as filter of masses $\sqrt{t} \sim 1/b$

Spectral functions – low-energy cut

Two-pion cut: low-mass states $\rightarrow$ **peripheral** density



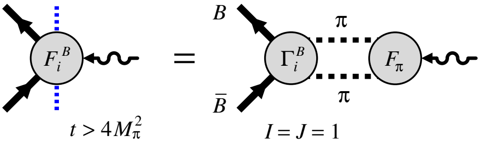
Diagrams with **imaginary parts** at the 2π cut

Dispersive improvement

- Chiral EFT works well for densities down to distances of 3 fm
- We want a good description down to 1 fm

Dispersive improvement

- Chiral EFT works well for densities down to distances of 3 fm
- We want a good description down to 1 fm
- Include $\pi\pi$ rescattering effects — manifest in ρ resonance



$$\mathrm{Im}F_i^B(t) = \frac{k_{\rm cm}^3}{\sqrt{t}}\,\Gamma_i^B(t)\,F_\pi^*(t) = \frac{k_{\rm cm}^3}{\sqrt{t}}\,\frac{\Gamma_i^B(t)}{F_\pi(t)}\,|F_\pi(t)|^2$$

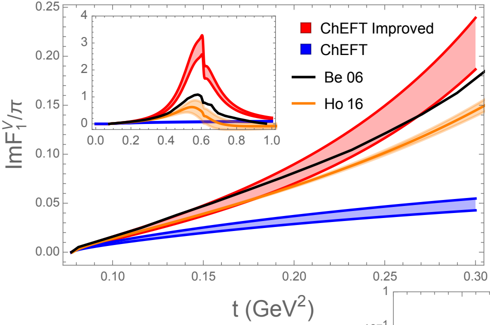
Computed with χEFT

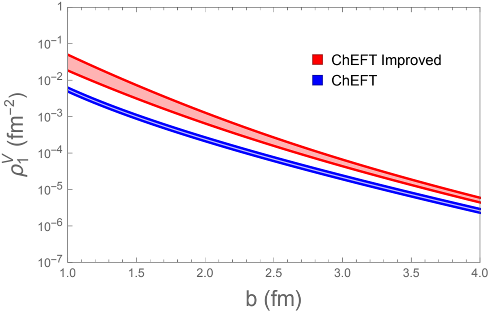
Empirical pion form factor

Gounaris and Sakurai, Phys. Rev. Lett. 21 (1968) 244

Similar approach for Λ-Σ^0 transition FF: Granados et al., arXiv:1701.09130 [hep-ph] (2017)

Sneak preview





Improvement by **one order of magnitude!**

Chiral effective field theory

- Effective theory of strong interactions at distances $b \sim M_\pi^{-1}$
- Small masses, momenta ($M_\pi / \Lambda_{\text{chiral}} \ll 1$):
  systematic combined expansion!

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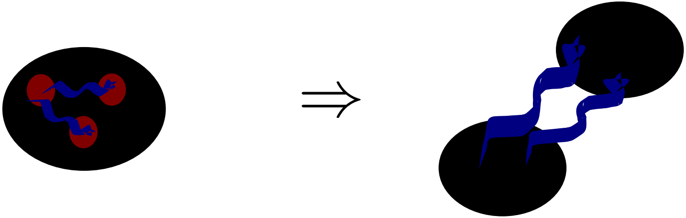
- Effective theory of strong interactions at distances $b \sim M_\pi^{-1}$
- Small masses, momenta ($M_\pi/\Lambda_{\text{chiral}} \ll 1$): systematic combined expansion!
- Hadronic degrees of freedom:

~~quarks and gluons~~ $\Longrightarrow$ mesons and baryons



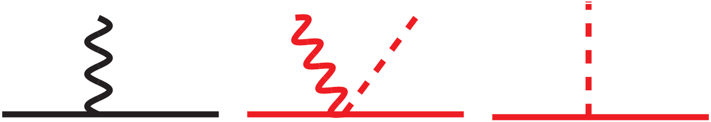
The Lagrangian

Lowest-order **meson** Lagrangian $\sim p_{\text{ext}}^2,\ m_\pi^2$

$$\mathcal{L}^{(2)}_{\phi\phi\gamma} = \frac{F_0^2}{4}\mathrm{Tr}\left(\nabla_\mu U \nabla^\mu U^\dagger + \chi_+\right)$$

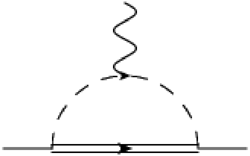
Lowest-order **baryon** Lagrangian $\sim p_{\text{ext}}$

$$\mathcal{L}^{(1)}_{\phi B\gamma} = \mathrm{Tr}\left(\bar{B}(\mathrm{i}\not{D} - m)B\right) + \frac{D}{2}\mathrm{Tr}\left(\bar{B}\gamma^\mu \left\{u_\mu, B\right\}\gamma_5\right) + \frac{F}{2}\mathrm{Tr}\left(\bar{B}\gamma^\mu \left[u_\mu, B\right]\gamma_5\right)$$



Inclusion of the decuplet

Experiment: Strong coupling to octet baryons
Theory: Correct large N_c behaviour recovered

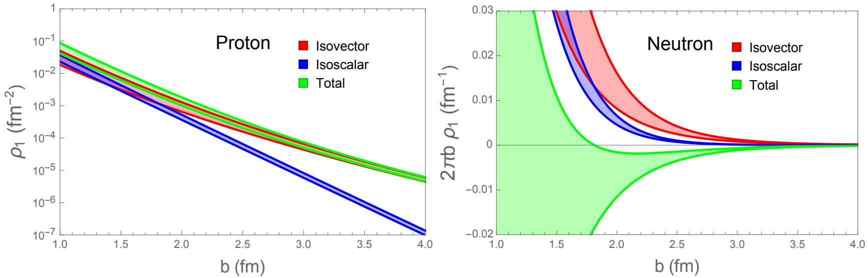


Geng et al., Phys. Lett. B 676 (2009) 63

$$\mathcal{L}^{(1)}_{\Delta\phi B} = \frac{-\mathrm{i}\sqrt{2}\mathcal{C}}{F_0 M_\Delta} \bar{B}^{ab} \varepsilon^{cda} \gamma^{\mu\nu\lambda} (\partial_\mu \Delta_\nu)^{dbe} (\mathrm{D}_\lambda \phi)^{ce} + \text{H.c.}$$

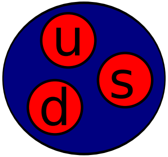
Nucleon charge densities

- Isovector component: 2π contributions (includes chiral piece and ρ-meson effects)
- Isoscalar component: $2K$ contributions, ω and ϕ mesons



$$\rho_1^p = \rho_1^S + \rho_1^V \qquad \rho_1^n = \rho_1^S - \rho_1^V$$

Hyperons



$$SU(2) \longrightarrow SU(3)$$

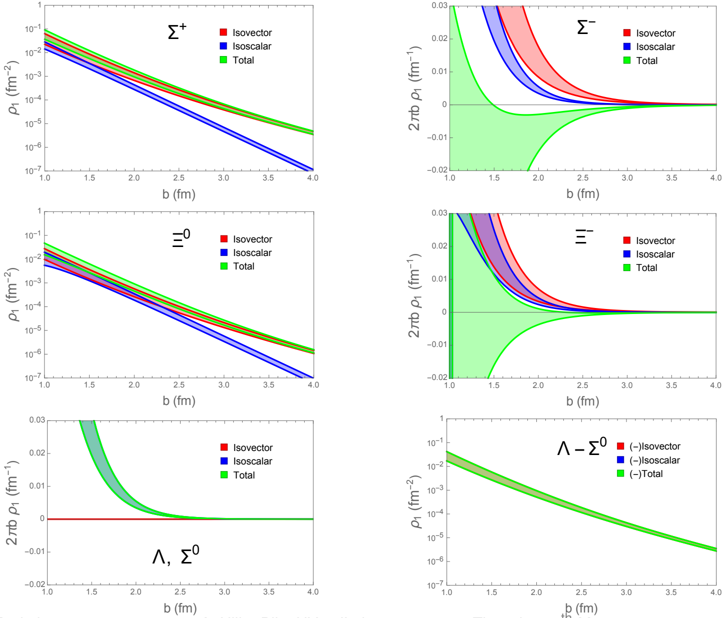
$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

$$\pi^\pm\ (\pi^0) \longrightarrow \pi^\pm, K^\pm\ (\pi^0, K^0, \eta)$$

$$\Delta(1232) \longrightarrow \Delta^\pm, \Delta^{++}, \Delta^0, \Sigma^{*\pm}, \Sigma^{*0}, \Xi^{*-}, \Xi^{*0}, \Omega$$

- Hyperons: baryons with **strangeness** $\mathcal{S} \neq 0$
- Short lifetimes $\Longrightarrow$ properties computed on the lattice
- Gives space for theoretical predictions

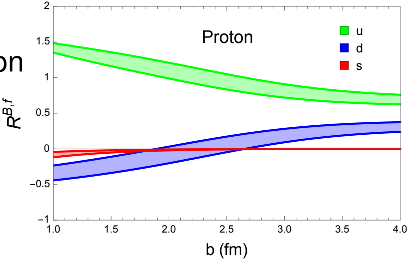
Hyperon charge densities

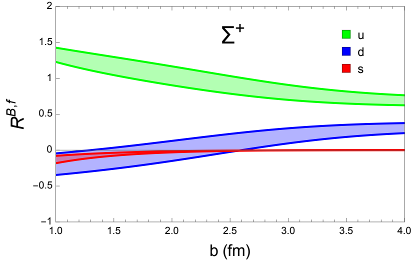


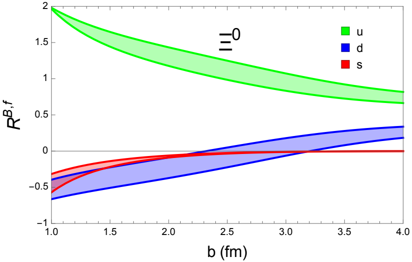
Quark contributions

Charge-weighted contribution of quark flavor to $\rho(b)$

$\sum_f R^{B,f} = 1$







Summary and outlook

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- **Peripheral** transverse densities can be computed **model-independently** using χEFT and dispersion analysis
- New formulation includes $\pi\pi$ **rescattering** (ρ resonance) and results in major improvement
- **Decuplet** intermediate states make essential contributions

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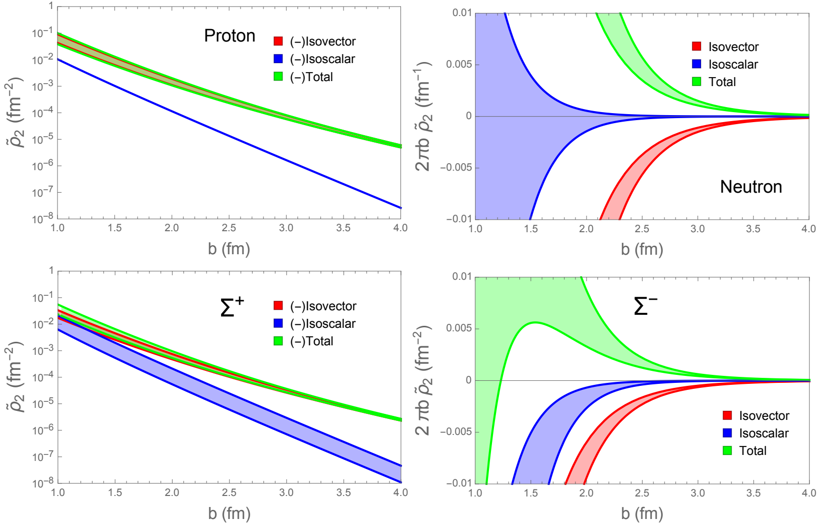
Outlook

- Study of anomalous-threshold effects
- Extension to decuplet-baryon densities
- Transition form factors

Additional material

Baryon magnetic densities I



Baryon magnetic densities II