Nucleon transverse densities from dispersively improved chiral EFT

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Compute transverse charge/current densities at peripheral distances $b = \mathcal{O}(M_\pi^{-1})$ in new approach combining dispersion theory and chiral EFT

- Uses dispersive representation of form factors and transverse densities
- Includes $\pi\pi$ rescattering and ρ resonance through elastic unitarity
- Provides realistic transverse densities down to distances down $b \sim 0.5$ fm
- Enables uncertainty estimates of densities

Method and applications to form factors: J. M. Alarcon, C. Weiss, PLB 784 (2018) 373; PRC **97,** 055203 (2018); J. M. Alarcon, A. N. Hiller Blin, M. Vicente Vacas, C. Weiss, NPA **964**, 18 (2017)

Application to densities: J. M. Alarcon, C. Weiss, in progress ←

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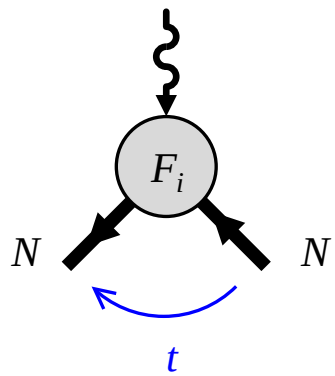
Transverse densities: Concept



- Transverse densities

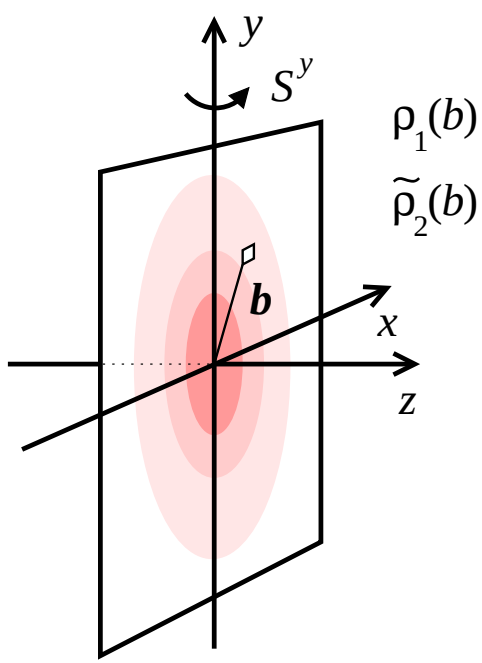
Soper 76, Burkardt 00, Miller 07

$\langle N'|J_\mu|N\rangle \;\rightarrow\; F_{1,2}(t)$ invariant FFs

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

Charge/magnetization densities at light-front time x^+

Frame-independent, appropriate for relativistic systems



- Connection with GPDs/QCD

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

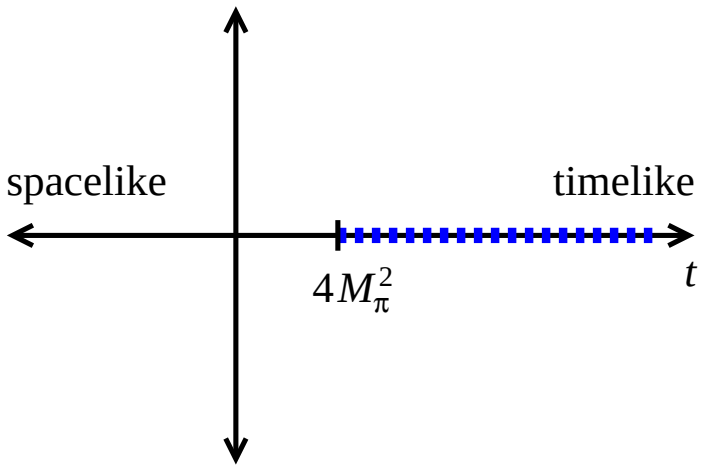
$\tilde{\rho}_2(b)$ spin-dep distortion

- Compute from first principles

Peripheral distances $b=\mathcal{O}(M_\pi^{-1})$: Chiral dynamics?

Quantify/define pionic component of nucleon?

Transverse densities: Dispersive representation

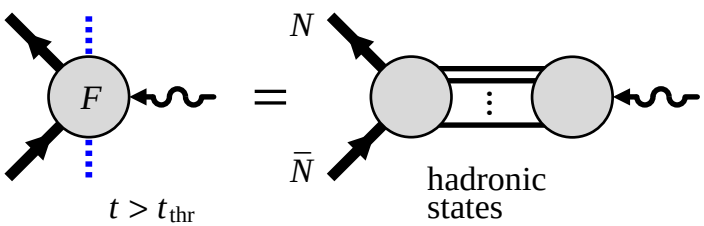


- Dispersive representation of form factor

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

$\mathrm{Im}\, F(t')$ spectral function

Processes current $\longrightarrow$ hadronic states $\longrightarrow N\bar{N}$
Frazer, Fulco 1960; Höhler et al 1975+



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

- Transverse densities

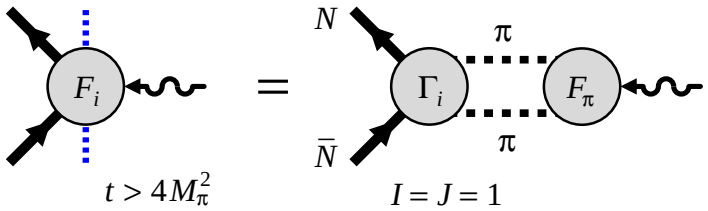
$$\rho(b) \;=\; \int\limits_{4M_\pi^2}^{\infty} \frac{dt}{2\pi^2}\, K_0(\sqrt{t}b)\, \mathrm{Im}\, F(t)$$

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

Large distances b select low masses $\sqrt{t}$

Peripheral densities $\leftrightarrow$ low–mass states
Strikman, Weiss 10; Miller, Strikman, Weiss 11

DIχEFT: Spectral functions



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

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

- Spectral function in $\pi\pi$ region

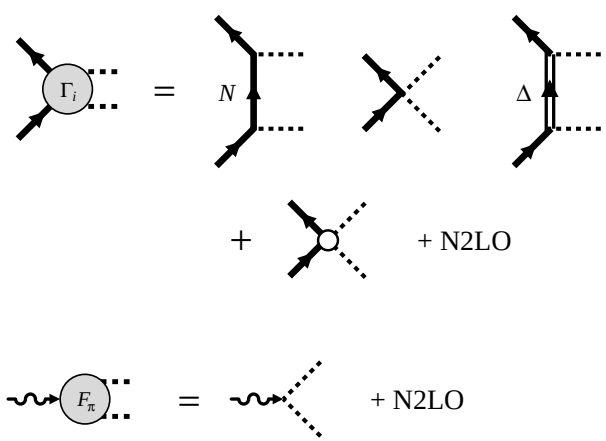
  Elastic unitarity relation
  Frazer, Fulco 1960; Höhler et al 1975+

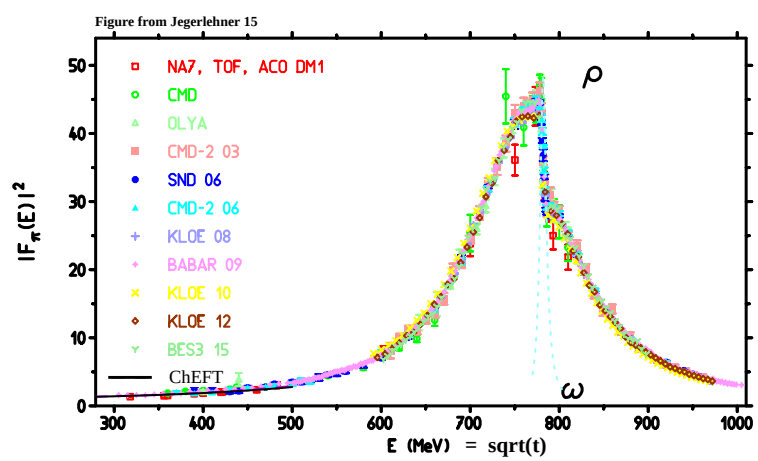
  Factorize $\pi\pi$ rescattering using N/D method

  Γ_i/F_π: $\pi\pi$–NN coupling, calculated in χEFT
  good convergence

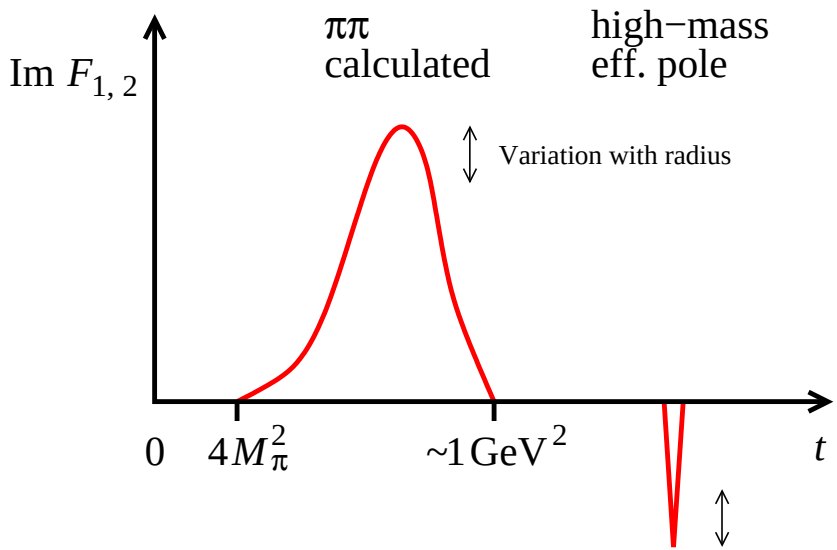
  $|F_\pi|^2$: $\pi\pi$ rescattering, taken from e^+e^- data

  Presently implemented LO + NLO + partial N2LO
  Alarcon, Weiss, PLB 784 (2018) 373; PRC 97 (2018) 055203





DIχEFT: Sum rules and parameters



$$\frac{1}{\pi}\int_{t_{\rm thr}}^{\infty} dt\, \frac{{\rm Im}F_1(t)}{t} = Q$$

$$\frac{1}{\pi}\int_{t_{\rm thr}}^{\infty} dt\, \frac{{\rm Im}F_1(t)}{t^2} = \frac{1}{6}\langle r^2\rangle_1$$

$$\frac{1}{\pi}\int_{t_{\rm thr}}^{\infty} dt\, \frac{{\rm Im}F_2(t)}{t} = \kappa$$

$$\frac{1}{\pi}\int_{t_{\rm thr}}^{\infty} dt\, \frac{{\rm Im}F_2(t)}{t^2} = \frac{1}{6}\kappa\langle r^2\rangle_2$$

$+$ asymptotics $t \to \infty$

- Spectral function in high-mass region

  Parameterized by effective pole

  Sufficient for low-Q^2 form factors, uncertainty quantified
  Alarcon, Weiss PLB 784 (2018) 373

- Sum rules and parameters

  Sum rules for $F(0)$, $F'(0)$ = charges, radii

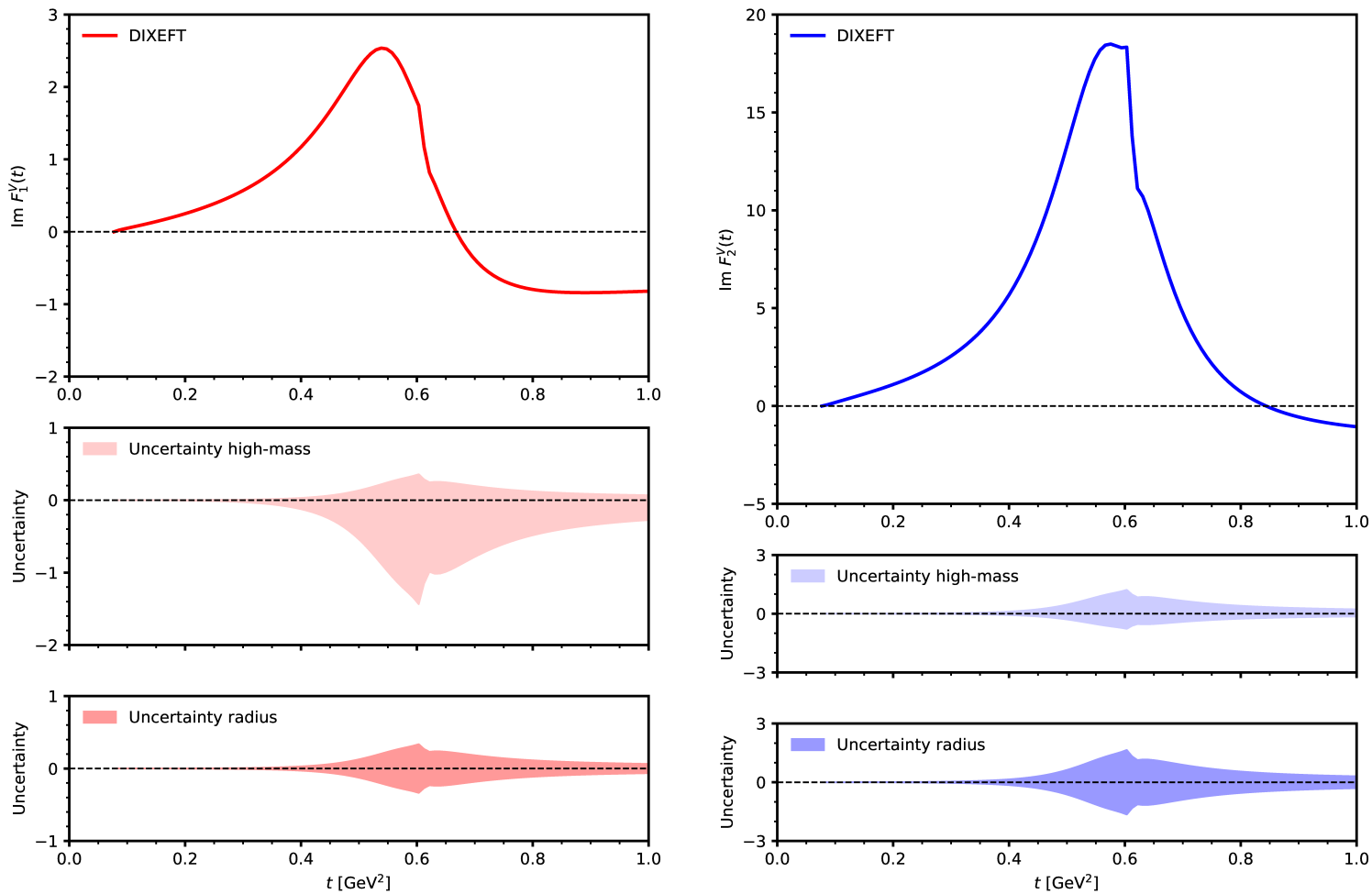
  Express χEFT LEC in terms of radii

  Radii appear directly as parameters of spectral functions, control behavior

- Isoscalar spectral function

  ω + high-mass pole

DIχEFT: Spectral functions



Red: Im $F_1^V(t)$
Blue: Im $F_2^V(t)$

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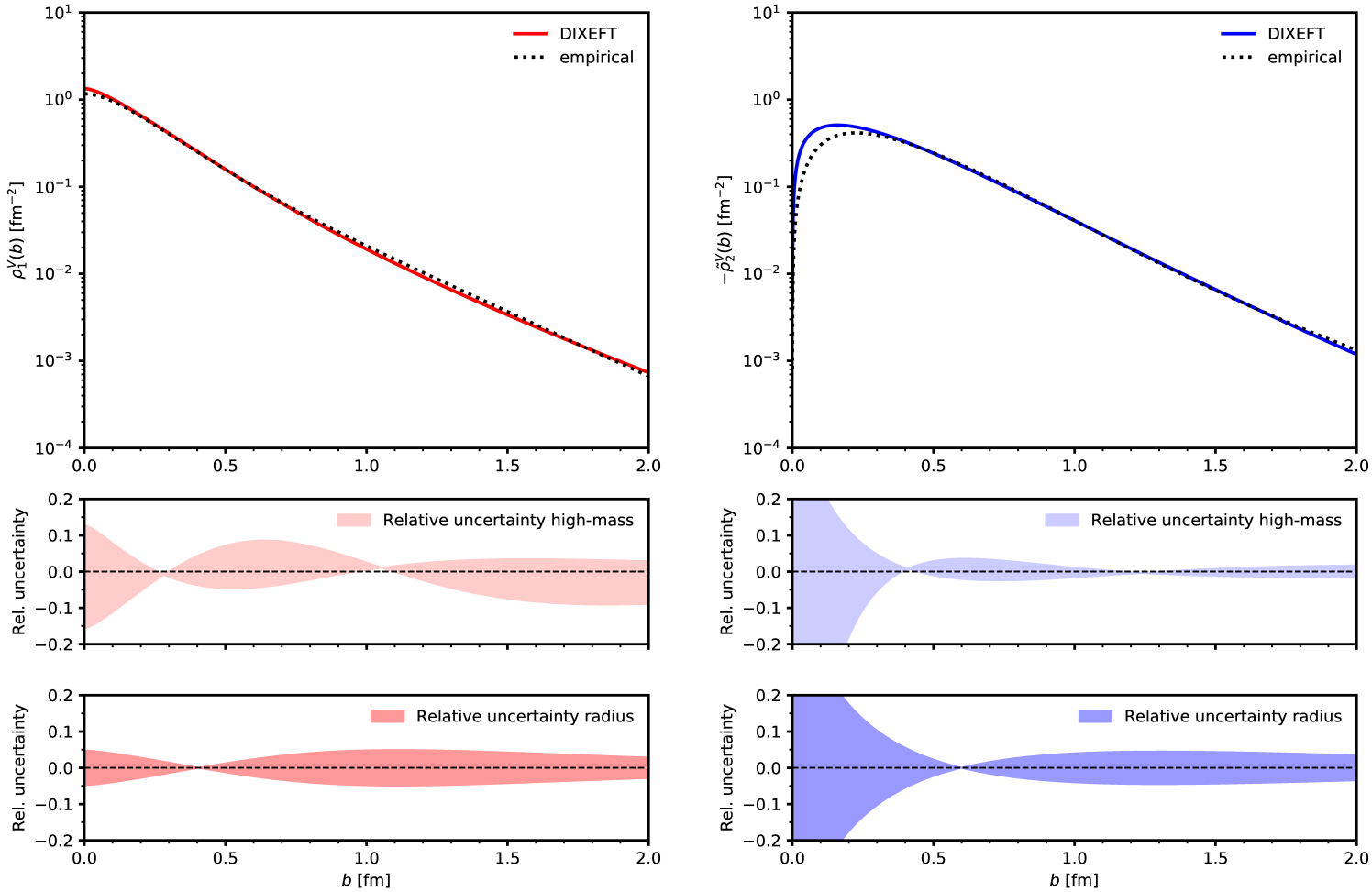
ρ peak from $\pi\pi$ rescattering

Quantified uncertainties resulting from high-mass states and radius

Good agreement with Roy-Steiner results Hoferichter et al 2017

DIχEFT: Isovector transverse densities



Red: $\rho_1^V(b)$
Blue: $\tilde{\rho}_2^V(b)$

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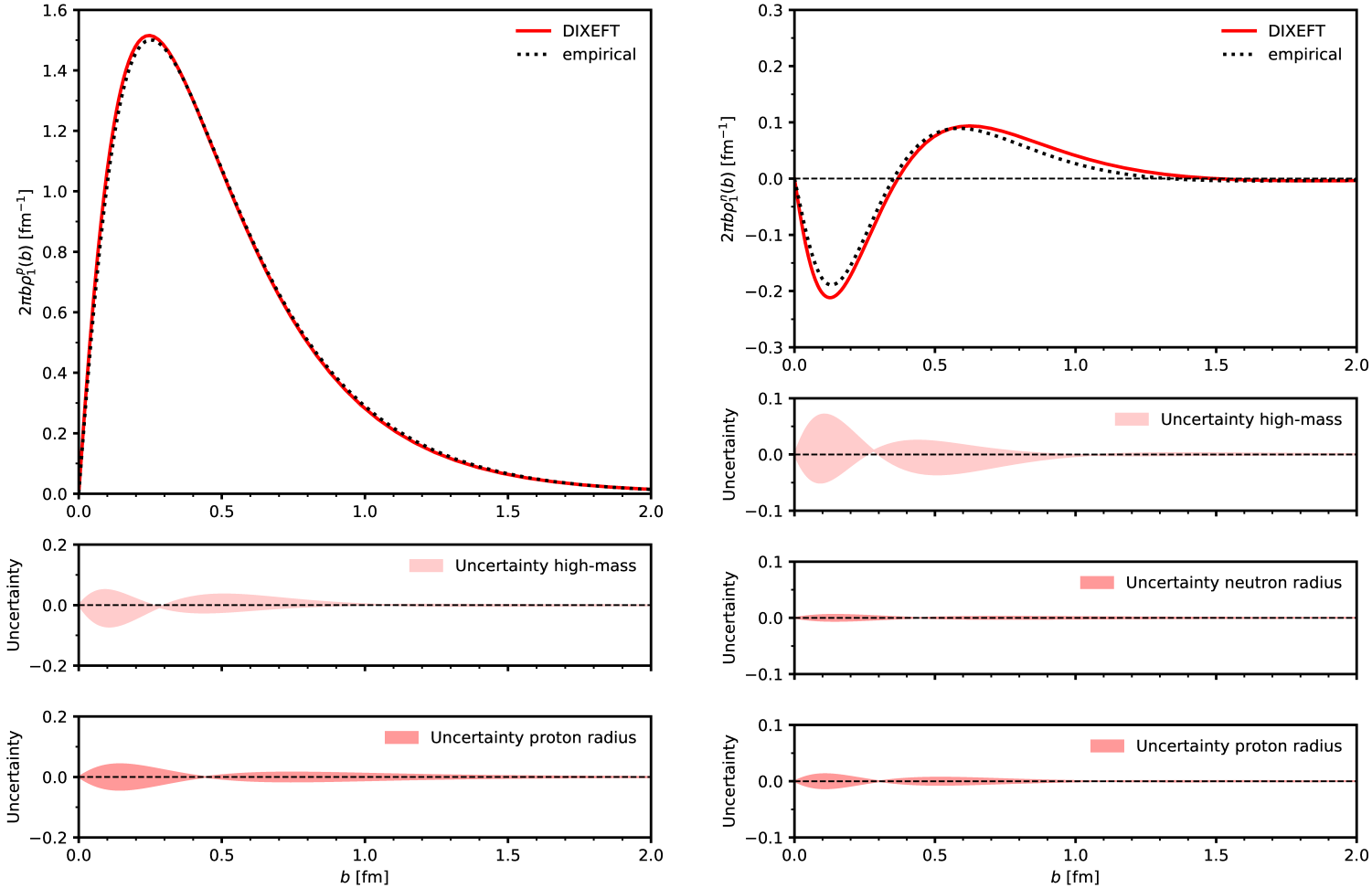
Large-b asymptotics governed by spectral properties
Difficult to obtain from Fourier transform. Requires proper analyticity of FF!

Relative uncertainties in $\rho_{1,2}(b) \lesssim 10\%$ for $b > 0.3$ fm

Excellent agreement with empirical densities for $b > 0.3$ fm

DIχEFT: Proton and neutron charge densities



Radial densities $2\pi b\rho_1(b)$

Left: Proton
Right: Neutron

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Realistic nucleon charge densities with controled uncertainties

Reproduced positive neutron charge densit at intermediate $b \approx 0.5 - 1$ fm Miller 2007

Summary

- Peripheral nucleon structure successfully described in DIχEFT

  $\pi\pi$ rescattering in isovector spectral function (ρ resonance) essential at peripheral distances

  Nucleon center summarily described by effective pole + sum rules

  Insight gained: EFT-based approach, dynamical information in LECs, deconstruction

- Applications and extensions

  Nucleon form factors of energy-momentum tensor
  Granados, Weiss, PLB 797 (2019) 134847

  Light-front representation of chiral processes in transverse densities
  Granados, Weiss JHEP 1401, 092 (2014); JHEP 1507, 170 (2015)

  x-dependent partonic structure and GPDs