Low-Q2 nucleon form factors from dispersion theory and chiral EFT

C. Weiss (JLab), NREC 2026 Workshop, Stony Brook U., 13-17 April 2026 [Webpage]

Jefferson Lab

Dispersion theory

Analyticity

Unitarity

×

Chiral EFT dynamics

$\pi\pi$ cut

πN interactns

LECs

Analytic structure of form factors

Correlations $Q^2 = 0 \longleftrightarrow Q^2$ finite

Two-pion cut and spectral functions

DIChEFT: Dispersion theory × chiral EFT

Radius extraction

ep Mainz electric + magnetic

$\mu p / ep$ MUSE ←

Further applications

Peripheral charge/current densities

Gravitational form factors ←

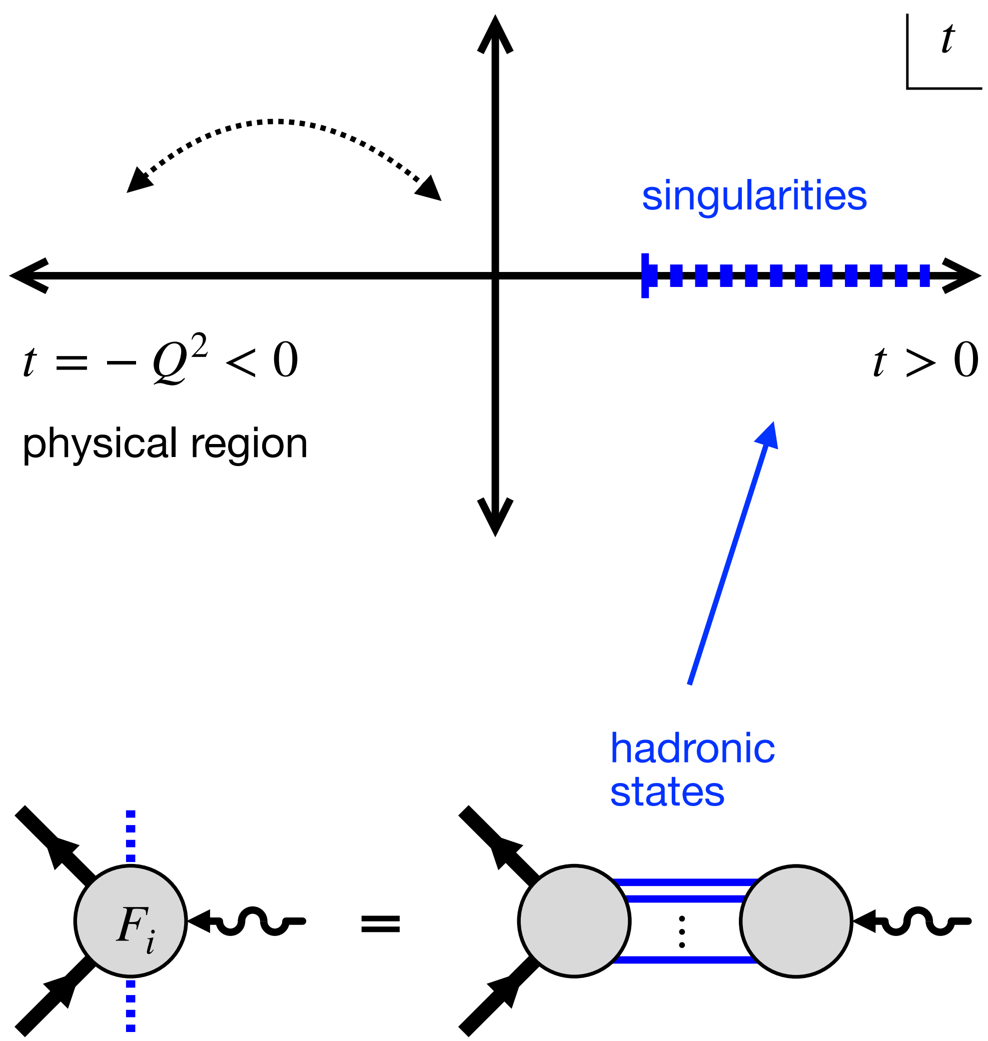
F. Gil-Dominguez, J.M. Alarcon, C. Weiss PRD 108, 074026 (2023) [INSPIRE]

J.M Alarcon, C. Weiss PRD 106, 054005 (2022) [INSPIRE]

J.M. Alarcon, D. Higinbotham, C. Weiss, PRC 102, 035203 (2020) [INSPIRE]

J.M. Alarcon, C. Weiss, PRC 96, 055206 (2017) [INSPIRE], PRC97, 055203 (2018) [INSPIRE], PLB784, 373 (2018) [INSPIRE]

Analyticity: Motivation



Here: Discuss electromagnetic FFs;
arguments can be extended to gravitational FFs

FFs analytic functions of $t = -Q^2$

Singularities: Branch cuts at $t > 0$
from hadronic exchanges

Position of singularities: Hadron masses
Strength of singularities: Amplitudes → Theory

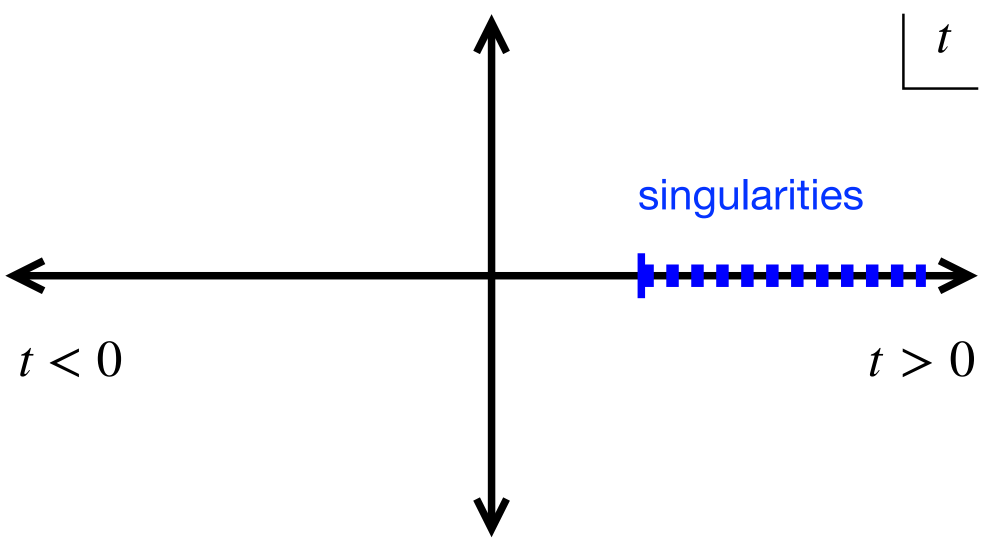
Implications for radius extraction

Correlates FF at $Q^2 > 0$ with derivatives at $Q^2 = 0$

Allows to use data at finite Q^2 for radius extraction, avoids "extrapolation to zero"

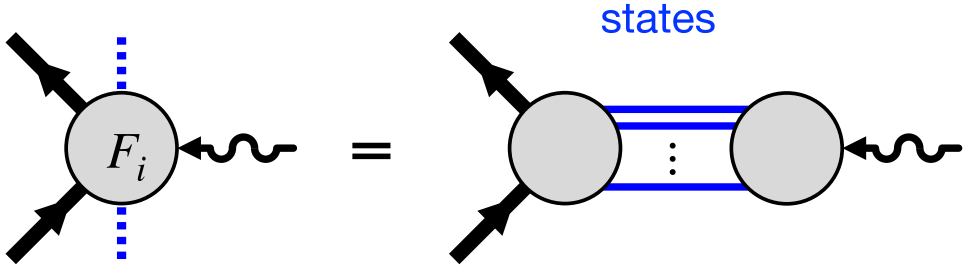
Necessary for magnetic radius extraction

Predicts size and pattern of higher derivatives from singularities



$$F_i(t) = \int_{t_{\rm thr}}^{\infty} \frac{dt'}{\pi} \frac{\text{Im}\, F_i(t')}{t' - t - i0}$$

Expresses analytic structure of $F_i(t)$ on physical sheet



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

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

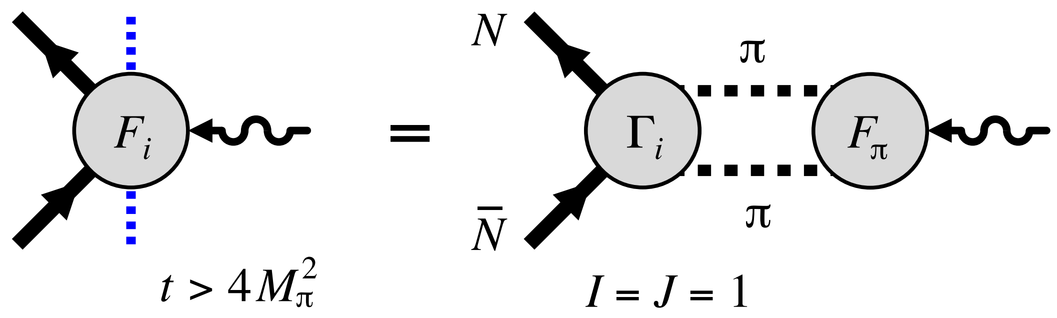
Spectral functions Im $F_i(t)$

Transition amplitude
current $\rightarrow$ hadronic states $\rightarrow N\bar{N}$

Processes in unphysical region $t < 4m_N^2$
below $N\bar{N}$ threshold

Needs to be calculated theoretically
Frazer, Fulco 1960; Höhler et al 1975+

Analyticity: Two-pion cut



Two-pion cut

Appears in isovector vector form factors

Lowest-mass state, dominates low-Q^2 spacelike form factors, peripheral densities

$\pi\pi$ system strongly interacting, ρ resonance

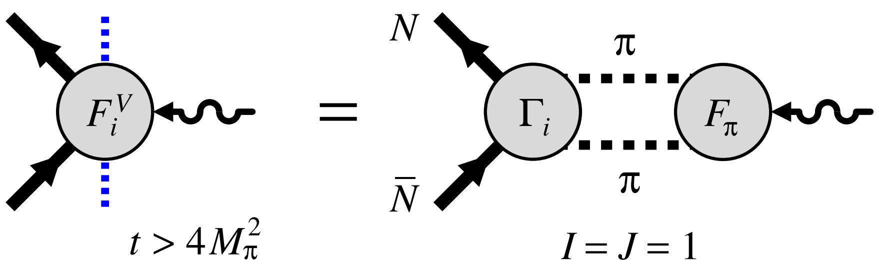
Spectral functions on two-pion cut

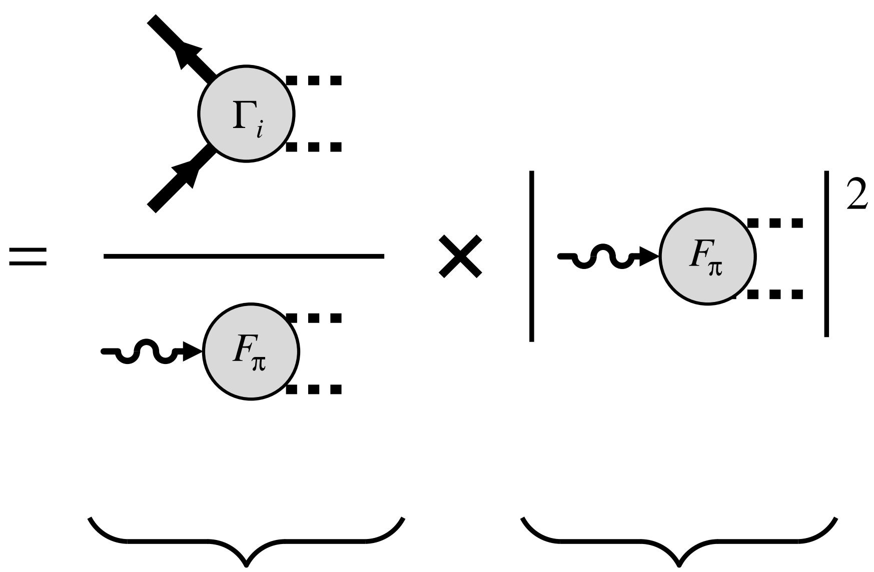
Analytic continuation of πN scattering data
Frazer, Fulco 1960; Höhler et al 1975+

Roy-Steiner equations for πN scattering
Hoferichter, Kubis, Ruiz de Elvira, Hammer, Meissner 2016

Chiral EFT? Direct calculations poorly convergent because of strong $\pi\pi$ interactions
Gasser, Sainio, Svarc 1988; Becher, Leutwyler 1999; Kubis, Meissner 2001; Kaiser 2003; ...

Need different approach!





calculated in chiral EFT

measured in $e^+e^- \to \pi^+\pi^-$

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

$$= \frac{k_{\text{cm}}^3}{\sqrt{t}}\, \frac{\Gamma_i(t)}{F_\pi(t)}\, |F_\pi(t)|^2$$

Elastic unitarity relation

$F_\pi(t)$ current $\to$ $\pi\pi$ amplitude = pion timelike FF

$\Gamma_i(t)$ $\pi\pi \to N\bar{N}$ partial-wave amplitude

Amplitudes have same phase from $\pi\pi$ interactions: Watson theorem

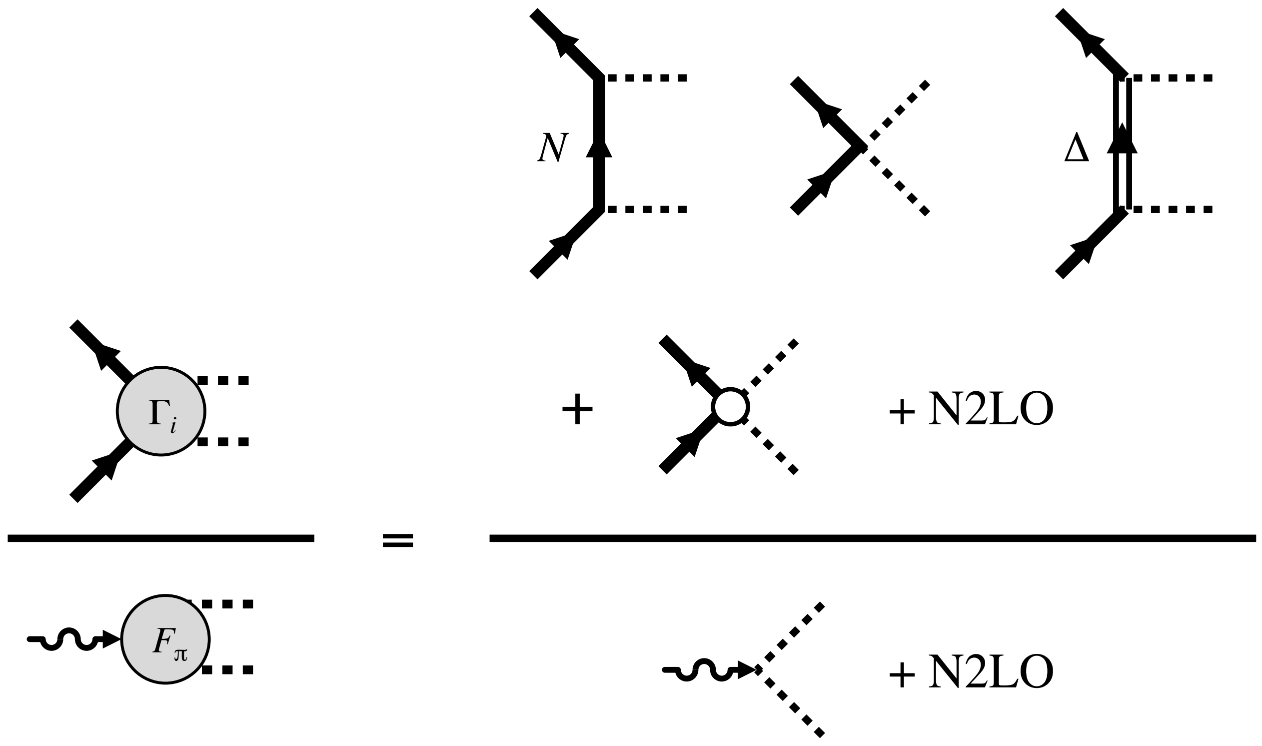
Factorize $\pi\pi$ interactions (N/D representation)

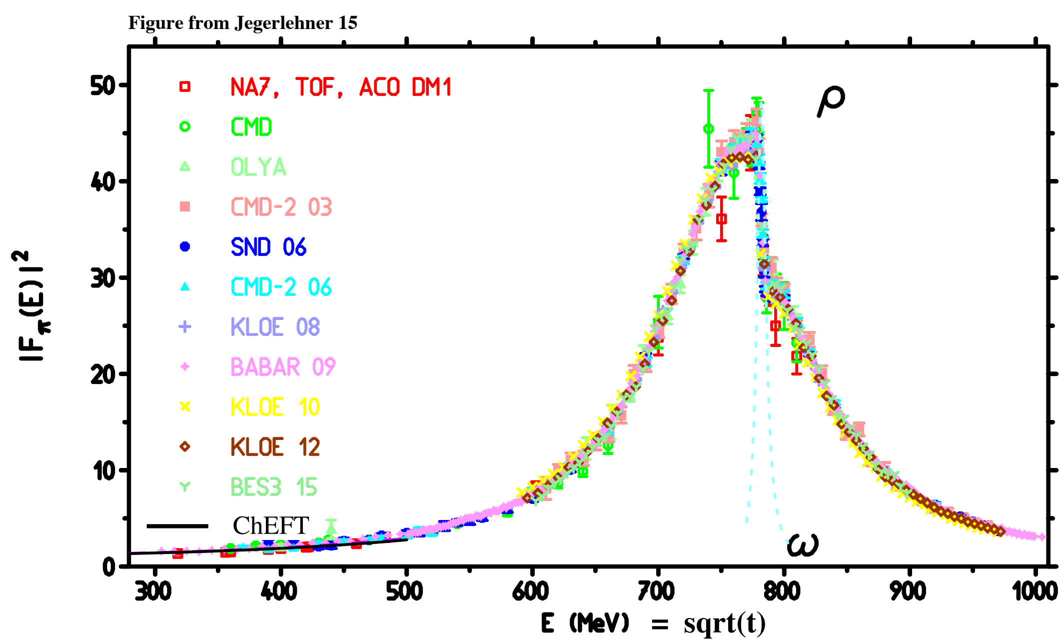
Γ_i/F_π free of $\pi\pi$ interactions
$\to$ calculated in ChEFT with good convergence

$|F_\pi|^2$ contains $\pi\pi$ interactions
$\to$ measured in e^+e^- annihilation

Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 96, 18 (2017)
Alarcon, Weiss, PLB 784 (2018) 373; PRC 97 (2018) 055203
Alt. formulation: Granados, Leupold, Perotti 2017

DIChEFT: Calculation





Relativistic ChEFT

Expansion in $\{M_\pi, k_\pi\}/\Lambda_{\text{chiral}}$

Include Δ isobar

ChEFT calculation of Γ_i/F_π

LO: Born terms + Weinberg-Tomozawa

NLO: Contact term in Γ_i $(i = 2)$

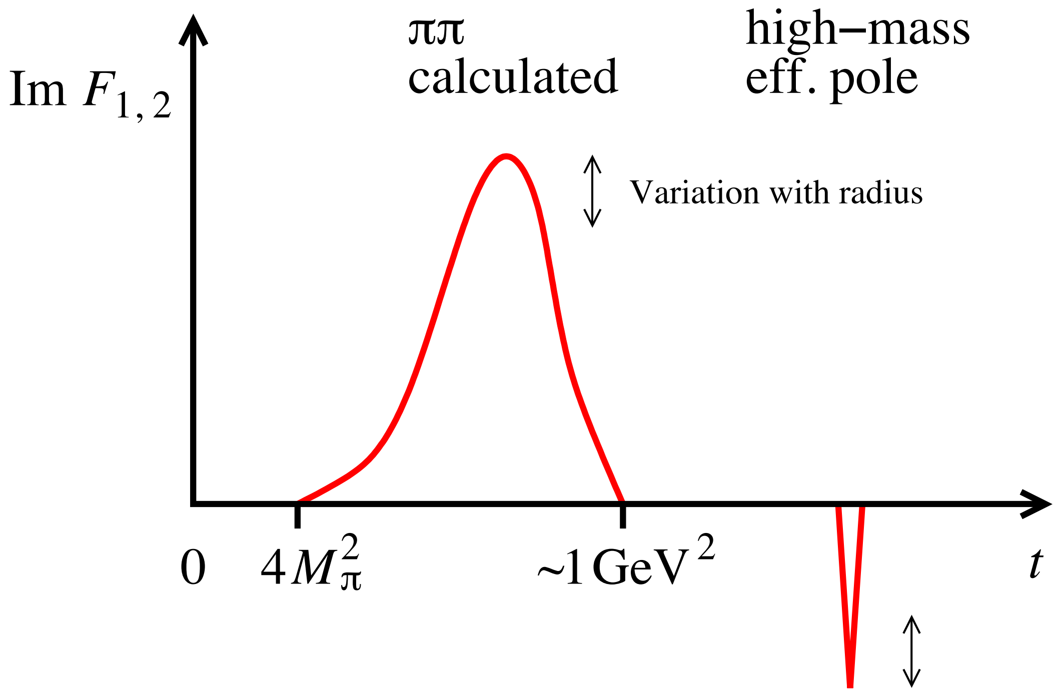
N2LO: Contact term and pion loops
Presently use partial result
Contains LEC, to be determined

Good convergence

Pion timelike form factor $|F_\pi|^2$

Measured accurately in $e^+e^- \to \pi^+\pi^-$

DIChEFT: Sum rules and parameters



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

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

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

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

[+ asymptotic conditions]

Spectral functions

$\pi\pi$ region calculated from unitarity + ChEFT

High-mass region parametrized by effective poles
Pole positions → theoretical uncertainty

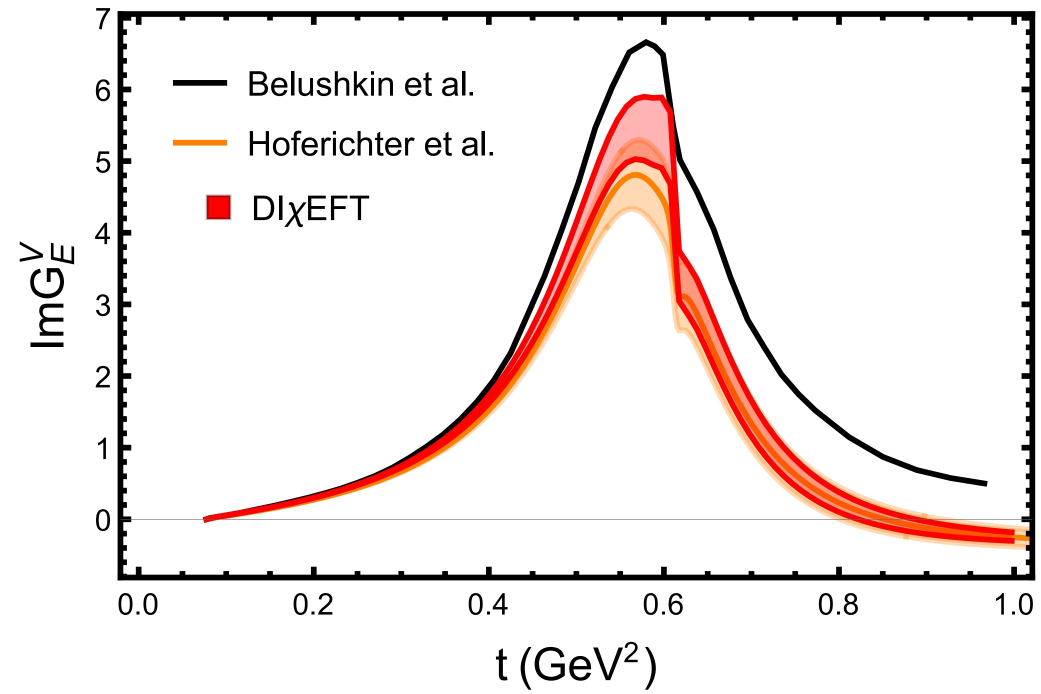
Sufficient for low-Q^2 form factors

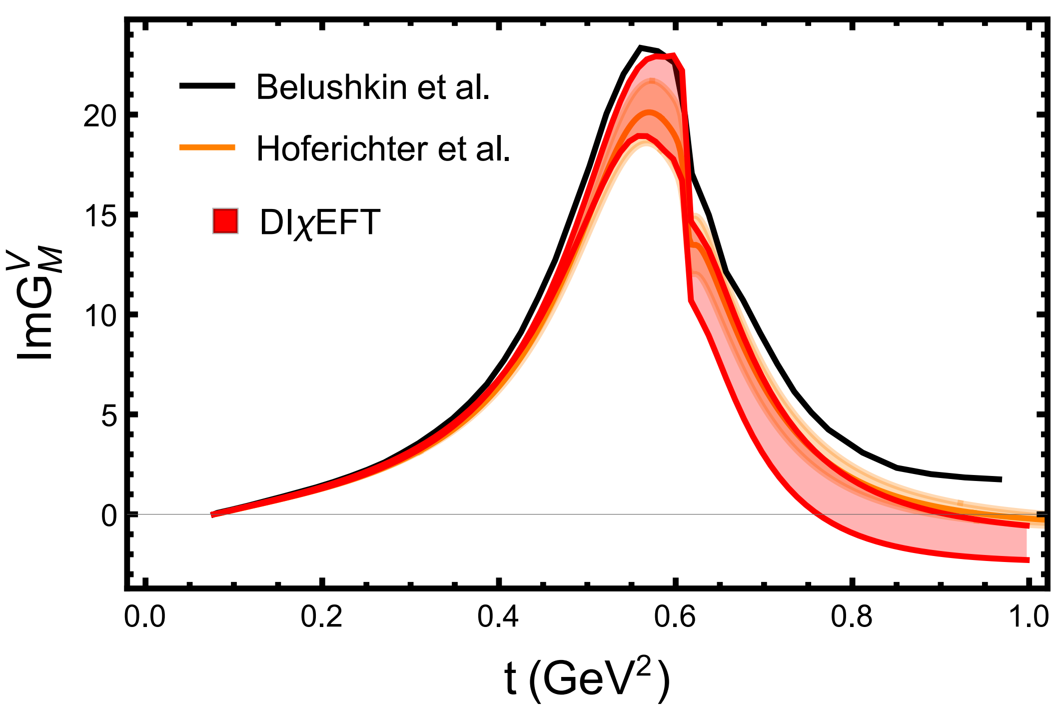
Sum rules and parameters

Spectral functions constrained by sum rules
for $F(0), F'(0)$ = charges, radii

Sum rules connect ChEFT LECs ↔ nucleon radii

Nucleon radii appear directly as parameters,
control finite-Q^2 behavior of form factors





Alarcon, Weiss, PLB784, 373 (2018) [INSPIRE]

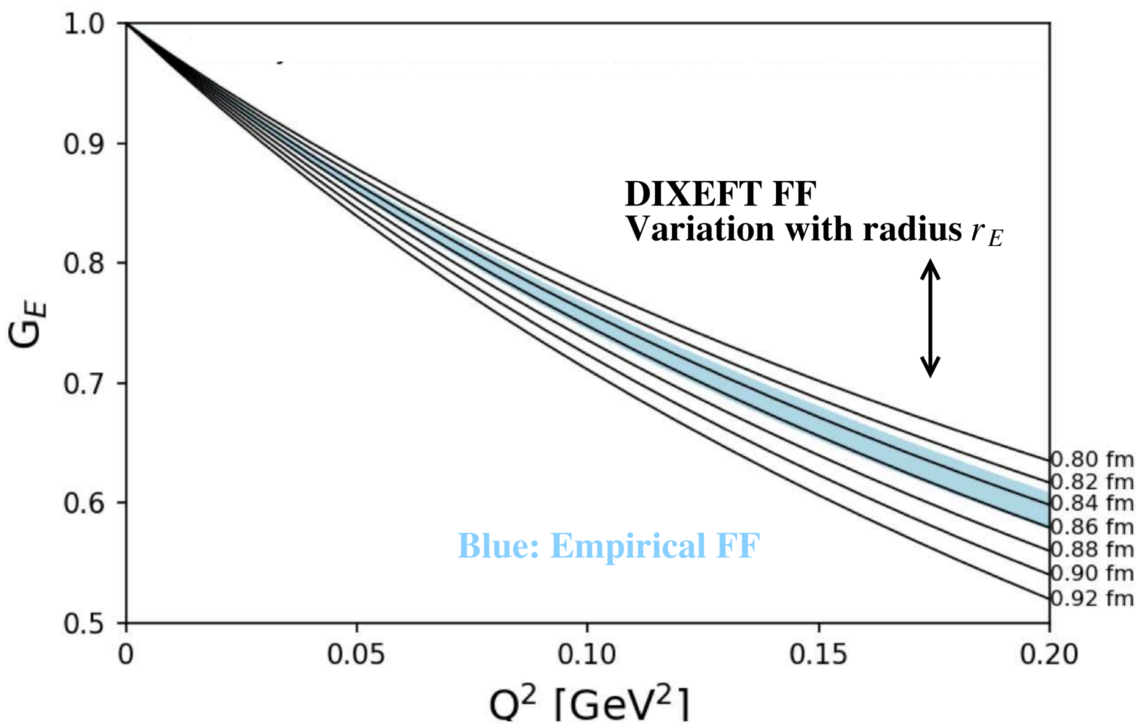
Spectral functions depend on radii as parameters

Bands show uncertainty from radii (PDG range)
Uncertainty from high-mass pole position → later

Good agreement with Roy-Steiner results
Hoferichter et al. 2017

Here: $G_E, G_M \leftrightarrow F_1, F_2$

DIChEFT: Form factors



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

Family of FF predictions depending on radii as parameters

Each member respects analyticity, sum rules

Each member has intrinsic theoretical uncertainty from high-mass states

Radius correlated with finite-Q^2 behavior!

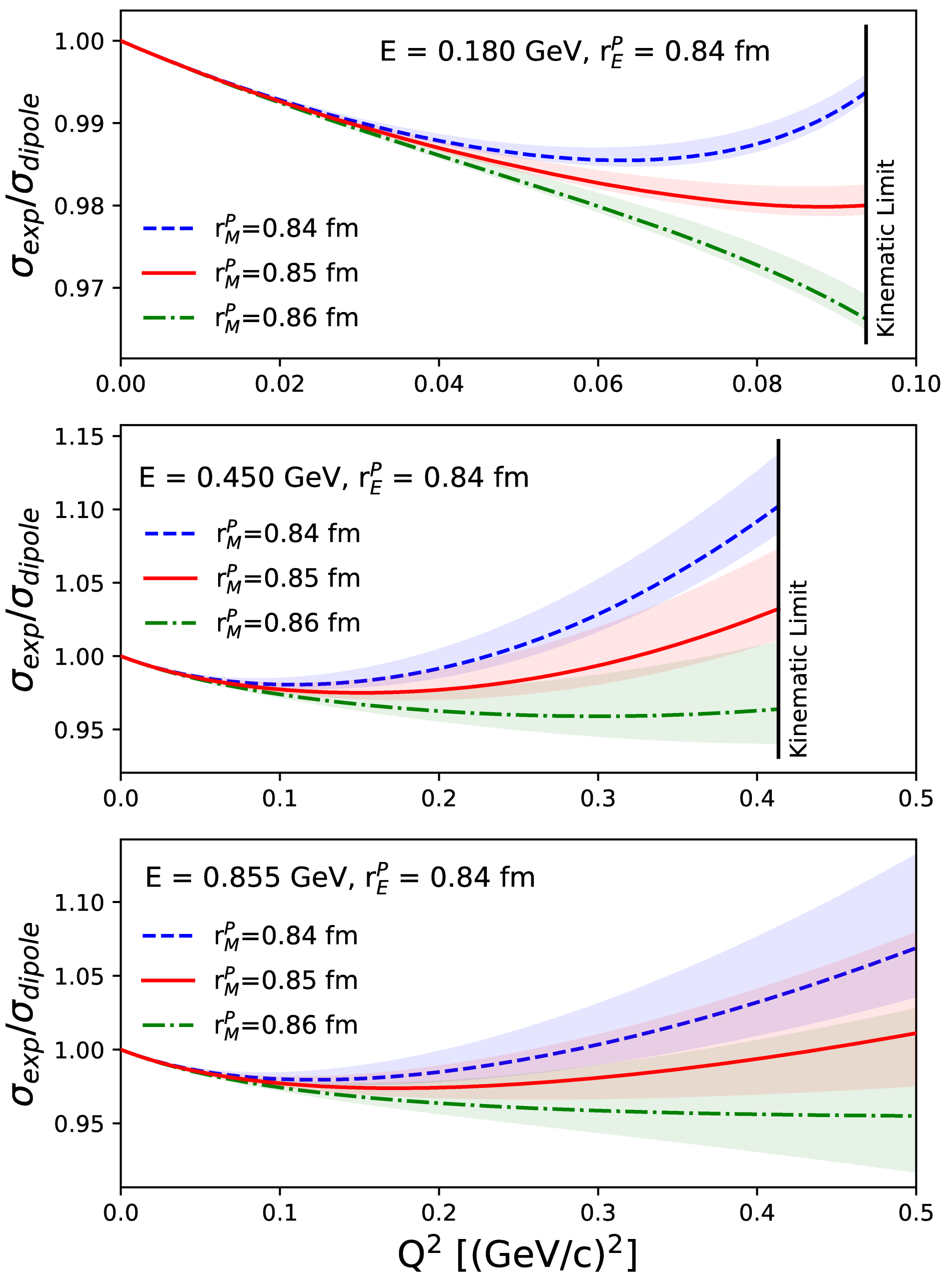
Radius extraction using DIChEFT

Compare DIChEFT FF predictions with data, for various values of radius parameter

Radius constrained by finite-Q2 data

Optimal Q2 range determined by interplay of radius sensitivity and exp+thy uncertainties

Alarcon, Higinbotham, Weiss, Ye PRC 99, 044303 (2019) [INSPIRE].
Fit to FF data up to Q2 ~ 0.5 GeV2, uncertainties estimated



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\epsilon\,[G_E^p]^2 + \tau[G_M^p]^2}{\epsilon(1+\tau)}$$

Alarcon, Higinbotham, Weiss, PRC 102, 035203 (2020) [INSPIRE]

Extracted electric + magnetic radii from cross section fit

Used DIChEFT $G_{E,M}$ depending on r_E^p, r_M^p

Fitted cross sections with floating normalizations

Quantified fit and theoretical uncertainties

$r_E^p = 0.842 \pm 0.002$ (fit 1σ) $^{+0.005}_{-0.002}$ (theory full-range) fm

$r_M^p = 0.850 \pm 0.001$ (fit 1σ) $^{+0.009}_{-0.004}$ (theory full-range) fm

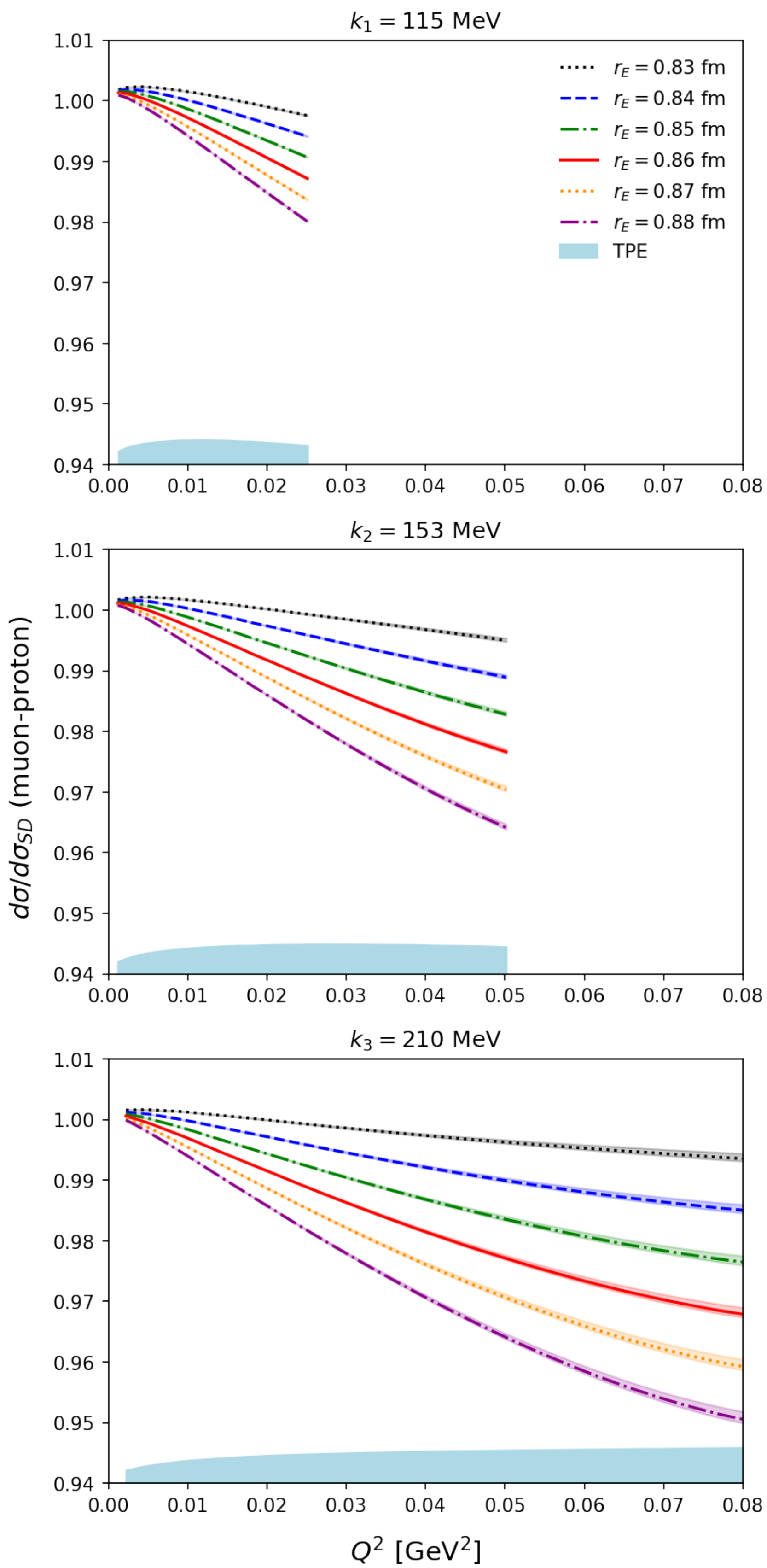
Sensitivity to G_M only at $Q^2 > 0$, needs theory

DIChEFT enables accurate magnetic radius extraction

Conventional dispersion analysis: Lorenz, Hammer, Meissner 2012

Actual fits, chi2 → Supplement

Radius extraction: μp/ep MUSE



First measurement of proton radius in $\mu p + ep$ scattering
k = 115—210 MeV, Q2 = 0.001—0.08 GeV2 → Talk Krahulik

Studied radius extraction with DIChEFT

What kinematics has most impact on radius?
What is the overall uncertainty including theory?

Tradeoff between:
Sensitivity of cross section to radius
Theoretical uncertainty
Two-photon exchange corrections

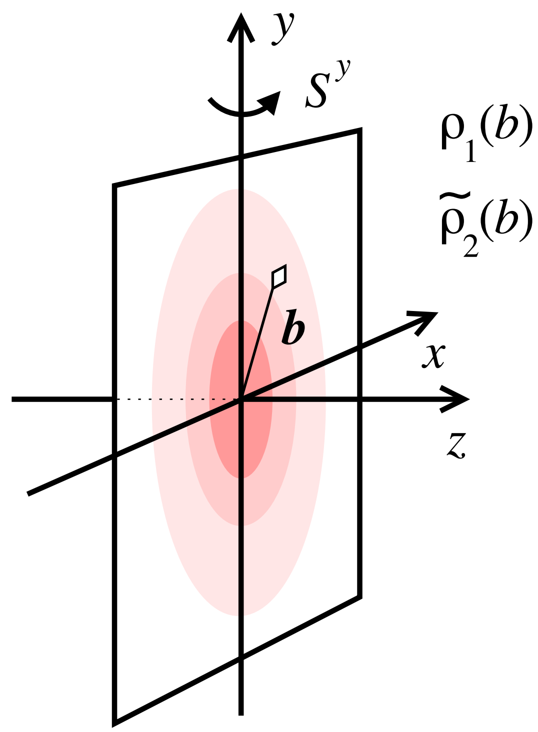
Findings

Influence of TPE on radius extraction diminished at higher Q2

Optimal kinematics for radius extraction
k = 210 GeV, Q2 = 0.05–0.08 GeV2

F. Gil-Dominguez, J.M. Alarcon, C. Weiss PRD 108 074026 (2023) [INSPIRE]

Two-photon exchange: Tomalak, Vanderhaeghen 2016



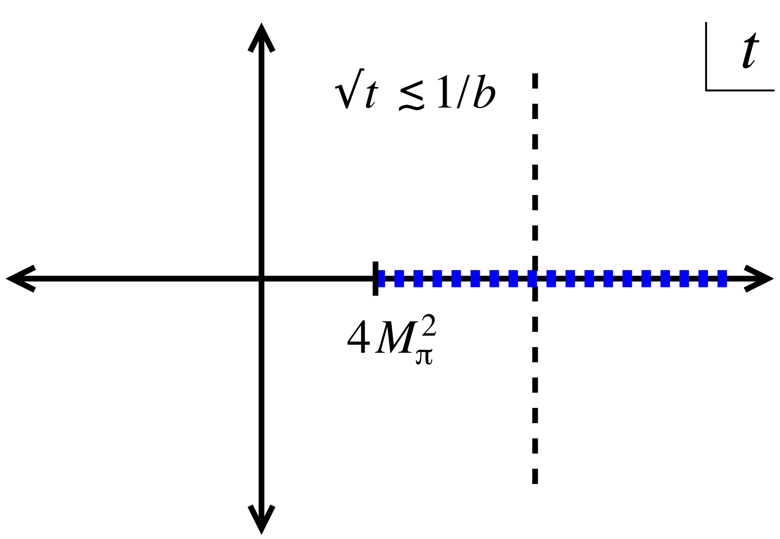
$$F_{1,2}(t = -\boldsymbol{\Delta}_T^2) = \int d^2b \, e^{i\boldsymbol{\Delta}_T \mathbf{b}} \rho_{1,2}(b)$$

Charge/magnetization densities at light-front time x^+,
Frame-independent, appropriate for relativistic systems
Soper 1976, Burkardt 2000, Miller 2007

Fourier transform of form factor data
Miller 2007; Carlson Vanderhaeghen 2008; Venkat, Arrington, Miller, Zhan 2010

Dispersive representation

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

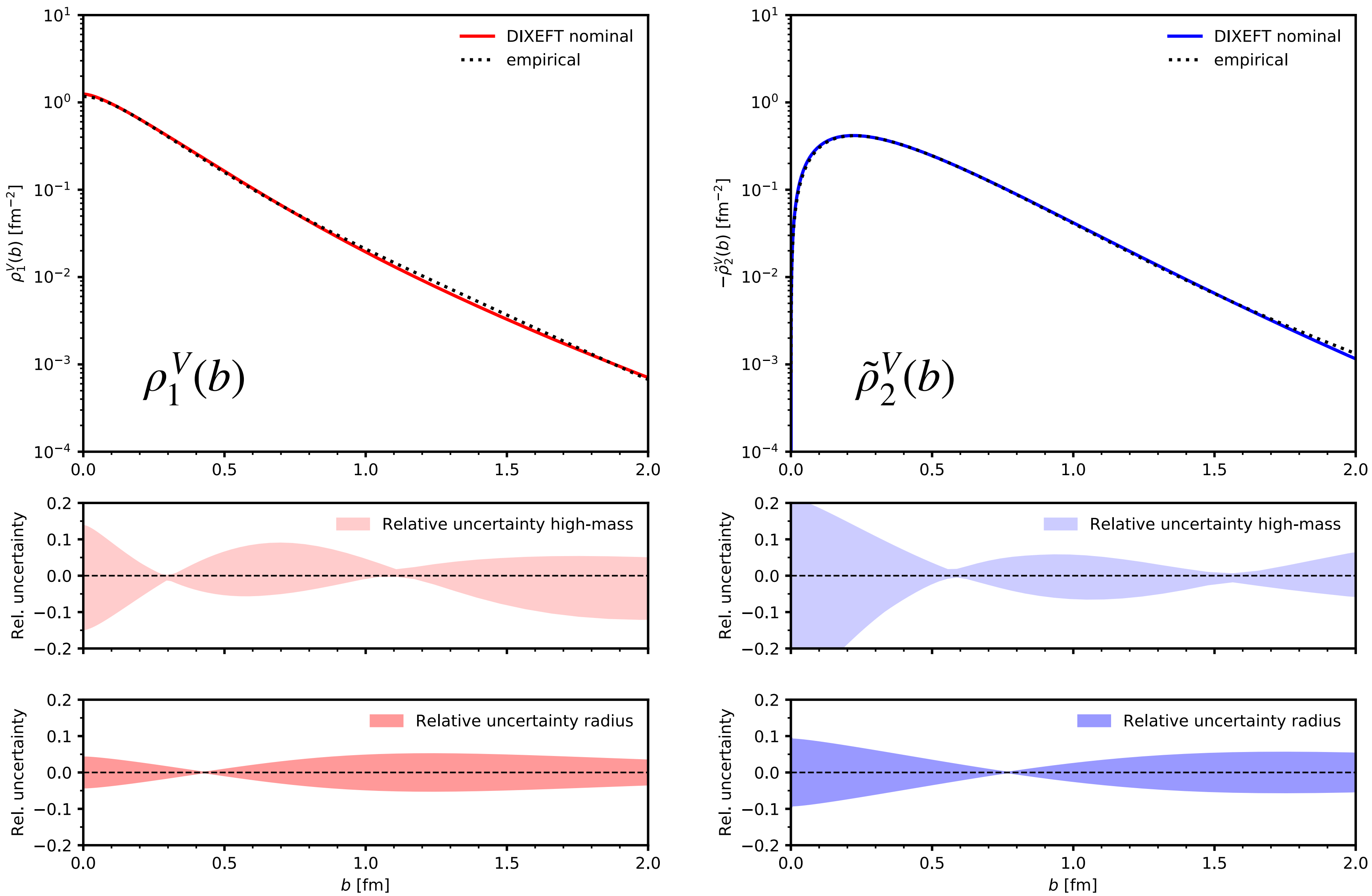


Exponentially convergent, acts as filter $\sqrt{t} \lesssim 1/b$
Large distances $b \leftrightarrow$ low masses $\sqrt{t}$

Peripheral densities
Uncertainty quantification } with analyticity

Strikman, Weiss PRC 82, 042201 (2010) [INSPIRE]; Miller, Strikman, Weiss PRC 84 , 045205 (2011) [INSPIRE]; Granados, Weiss JHEP 01, 092 (2014) [INSPIRE]

Transverse densities: DIChEFT results



Transverse densities and uncertainties computed from DIChEFT spectral functions

Alarcon, Weiss PRD 106, 054005 (2022) [INSPIRE]

Large-b asymptotics governed by analyticity

Difficult to obtain from Fourier transform. Requires proper analyticity of form factor!

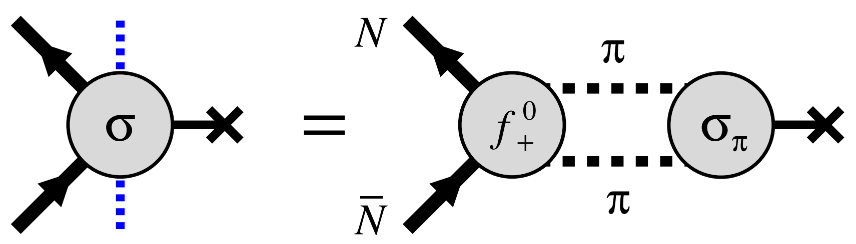
Densities predicted with relative uncertainties $\lesssim 10\,\%$ at $b > 0.3$ fm

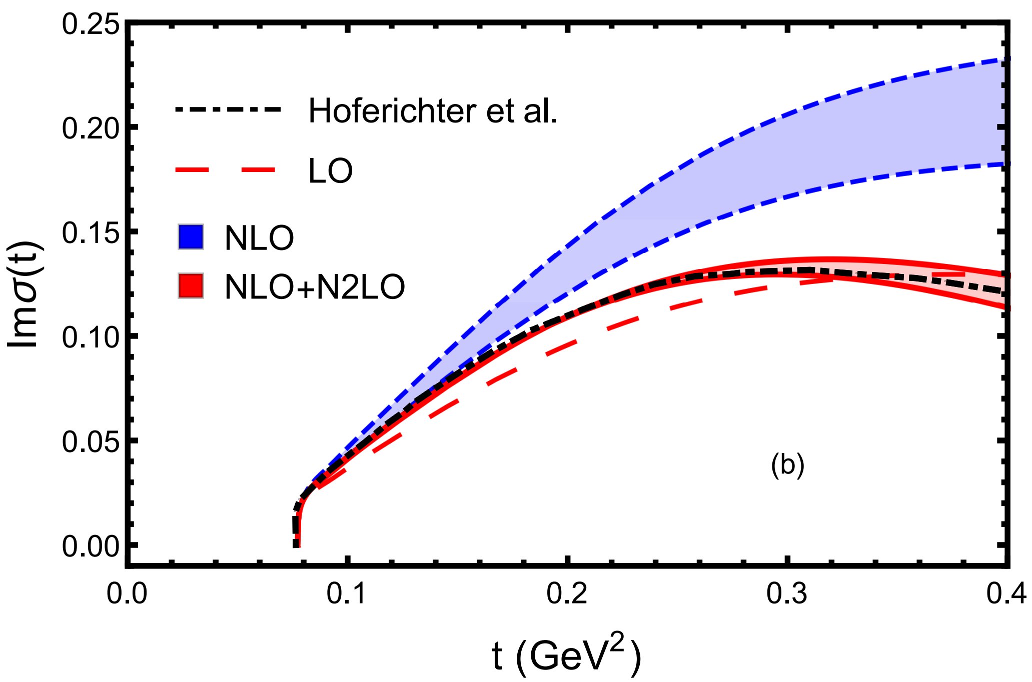
Excellent agreement with empirical densities

Uncertainty quantification using analyticity: Spectral functions → densities

→ Supplement

Gravitational form factors





Nucleon FFs of QCD energy-momentum tensor

Contain multipoles J = 2, 1, 0

Describe distributions of momentum, spin, forces, mass: Much interest → Talk Schweitzer

Can be analyzed using DIChEFT

Nucleon scalar form factor (J = 0)

$\sigma(t) = \langle N' | m\bar{\psi}\psi | N \rangle$ sigma term

$\sigma_\pi(t)$ from empirical dispersion analysis
Colangelo et al 04; Celis, Cirigliano, Passemar 14

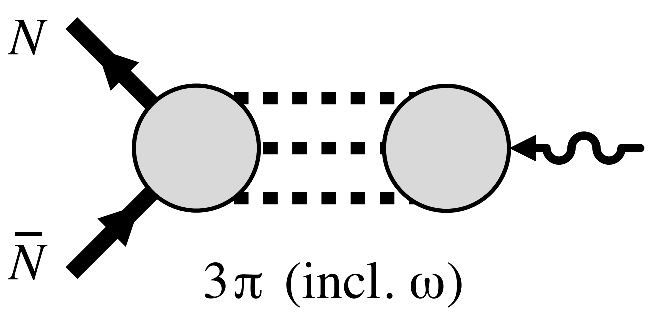
Used subtracted dispersion relation

$\langle r^2 \rangle_\sigma$ = 1.03 - 1.13 fm^2 nucleon scalar radius predicted

Gravitational form factors (J = 2)

Possible with pion timelike FF as input: Constrained by LQCD, instanton vacuum
χQCD Collab B. Wang et al. 2024; Hackett et al. 2023. Liu, Shuryak, Weiss, Zahed, PRD 110, 054021 (2024)

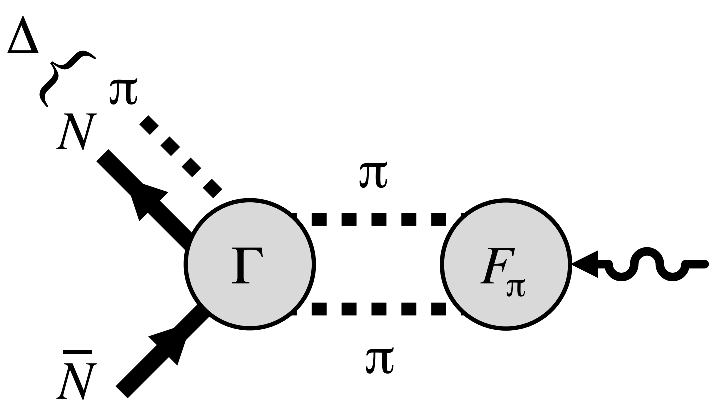
Other operators and transitions



Nucleon FFs with 3π cut

Isoscalar vector current, isovector axial current

Use methods of 3-body unitarity
Szczepaniak, Jackura, Pilloni, Doering et al.



$N \to \Delta$ transition form factors

Compute transition matrix element $\langle N\pi \,|\, J^\mu \,|\, N \rangle$
Continue to pole in $s_{\pi N} = m_\Delta^2$, extract residue

ChEFT calculations
Ledwig et al. 2010

LQCD results
Alexandrou et al. 08; Aubin, Orginos, Pascalutsa, Vanderhaeghen 08

Large-N_c spin-flavor symmetry connects $N \to N$ and $N \to \Delta$
→ Talk Paolone

Summary

- Analyticity correlates FF at Q2 = 0 and finite Q2, plays essential role in radius extraction

- DIChEFT: Combines dispersion theory (analyticity, unitarity) with ChEFT (long-range dynamics), permits first-principles calculations of ππ spectral functions and low-Q2 form factors

- DIChEFT-based radius extraction implements analyticity and resulting "information flow"

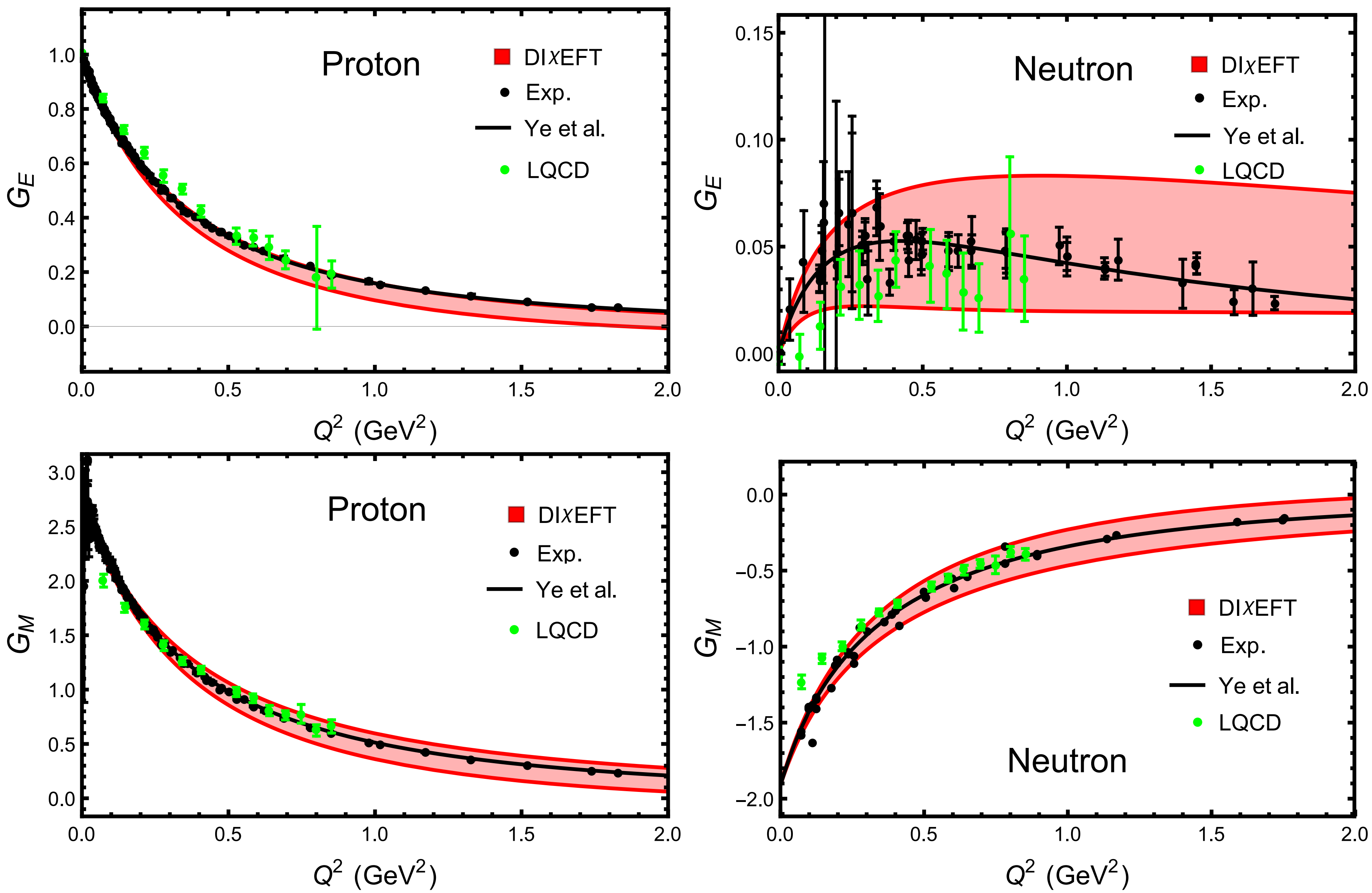
- Highest impact on radius from finite Q2 data, no need for “extrapolation to zero”. Assessments depend on actual exp + thy uncertainties, can be updated

- DIChEFT determines peripheral densities with quantified uncertainties, analyticity essential

- DIChEFT can be extended to gravitational form factors: Pion input needed

Supplemental material

DIChEFT: Form factor results



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

Isovector: DIChEFT

Isoscalar: ω+high-mass

Alarcon, Weiss,
PLB784, 373 (2018)

LQCD: Alexandrou et al. 2017

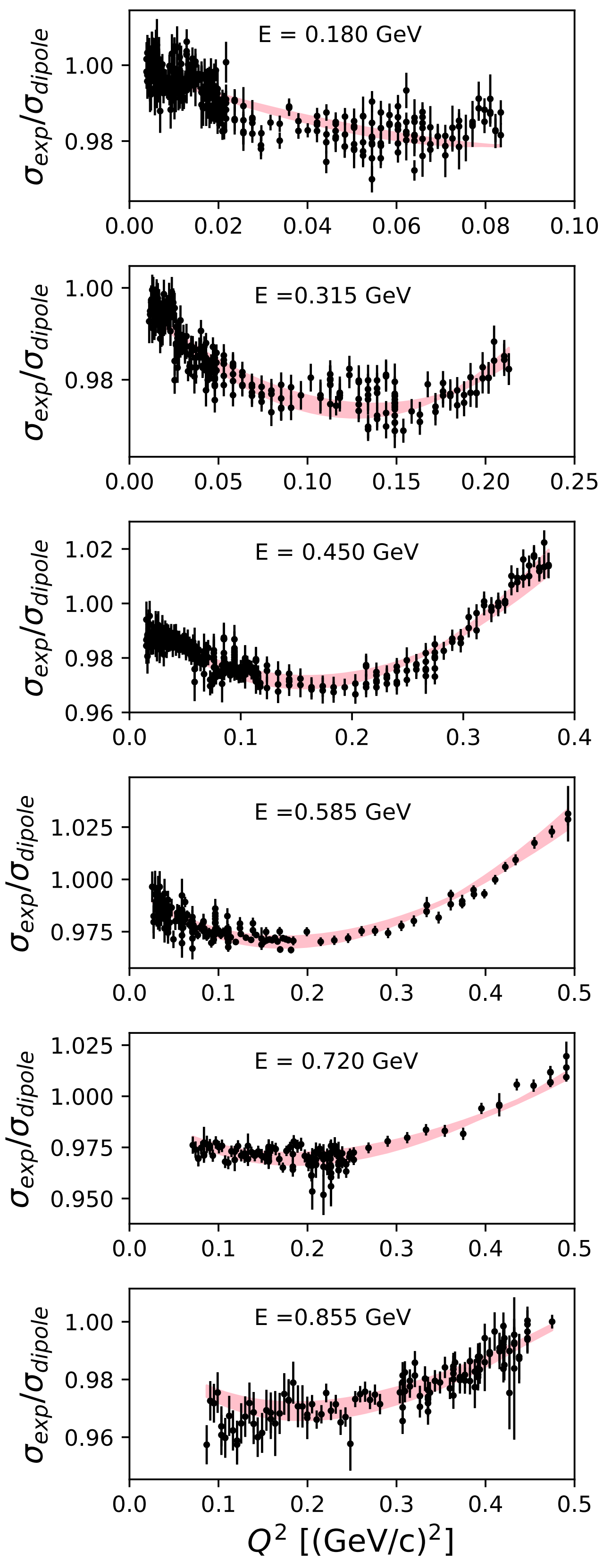
Form factors

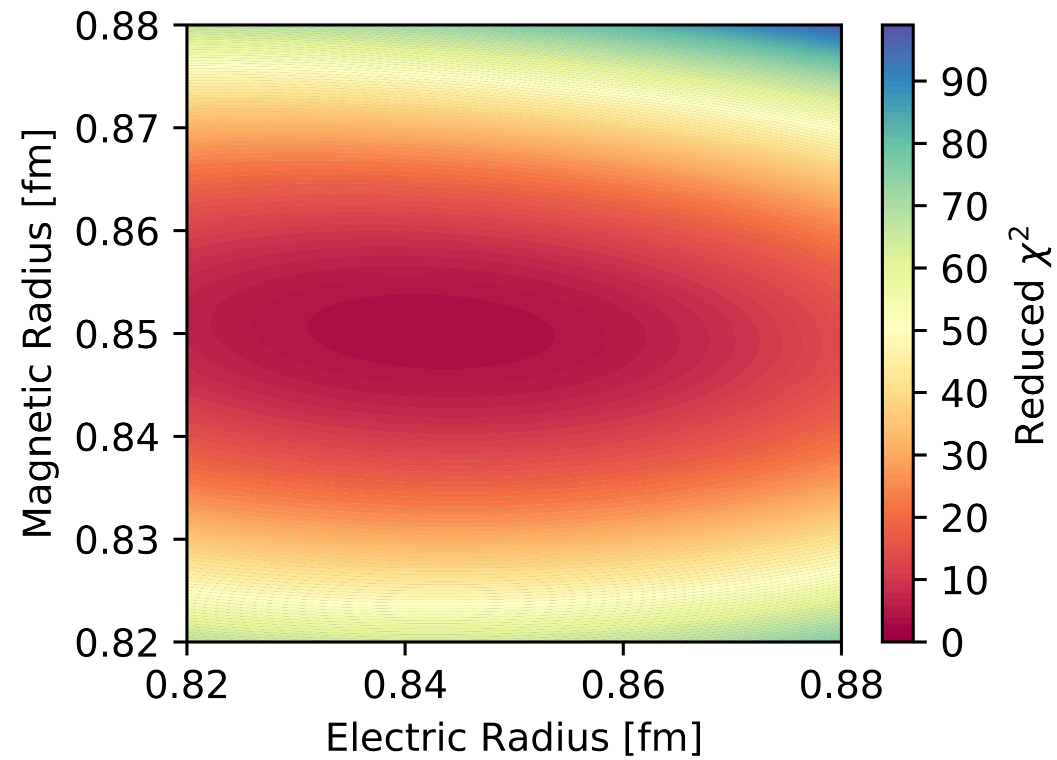
Dispersion integral evaluated with spectral functions (including $\pi\pi$ and high-mass part)

Band shows uncertainty from radii (uncertainty from high-mass pole position → later)

Excellent agreement with data. No fit, but prediction based on dynamics

Radius extraction: ep Mainz



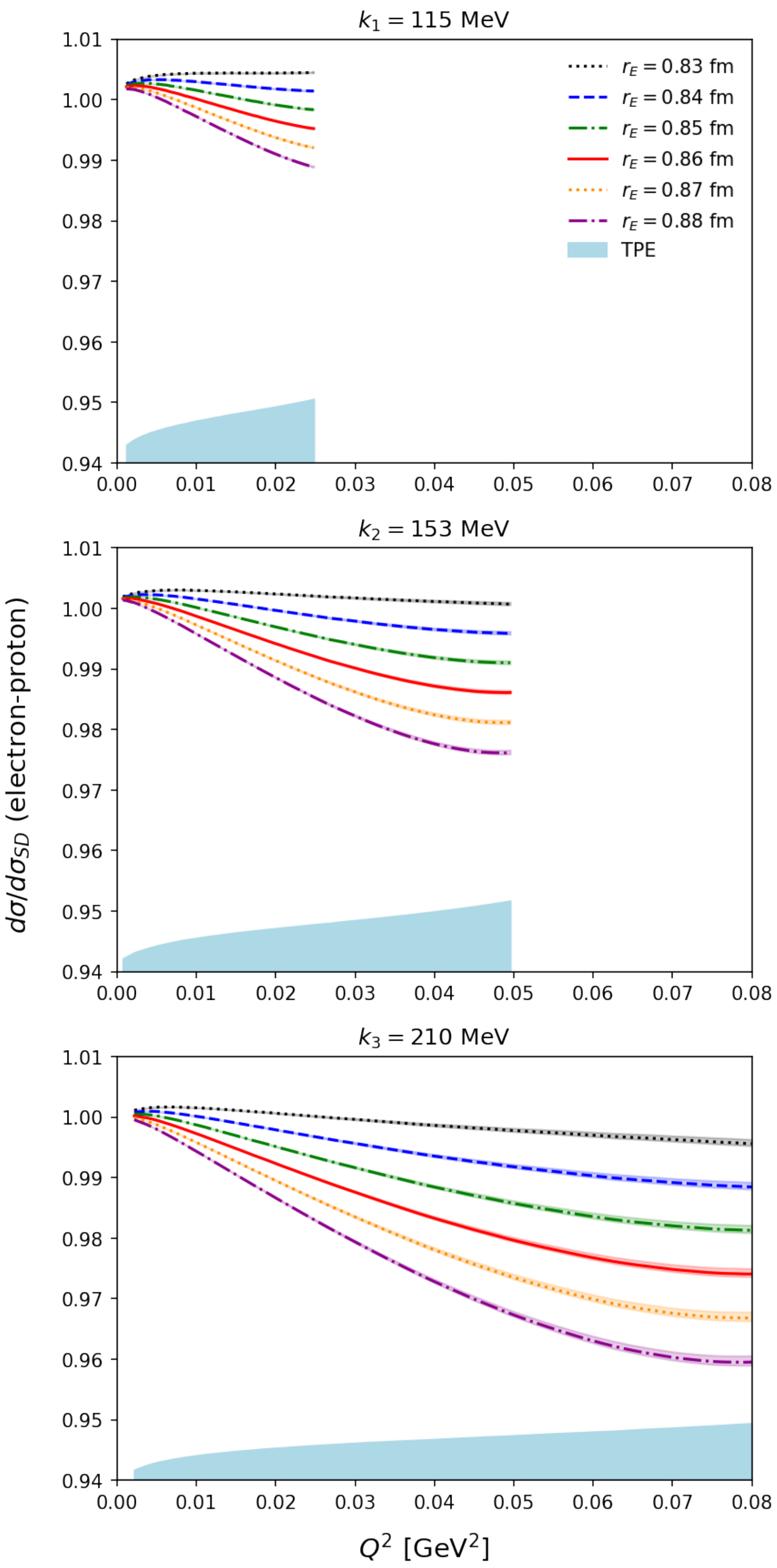


χ^2 profile in electric and magnetic radius

Mainz A1 data and DIχEFT fit
Bands: Fit uncertainty

Alarcon, Higinbotham, Weiss, PRC 102, 035203 (2020) [INSPIRE]

Radius extraction: μp/ep MUSE



Here: MUSE ep scattering (for μp see above)

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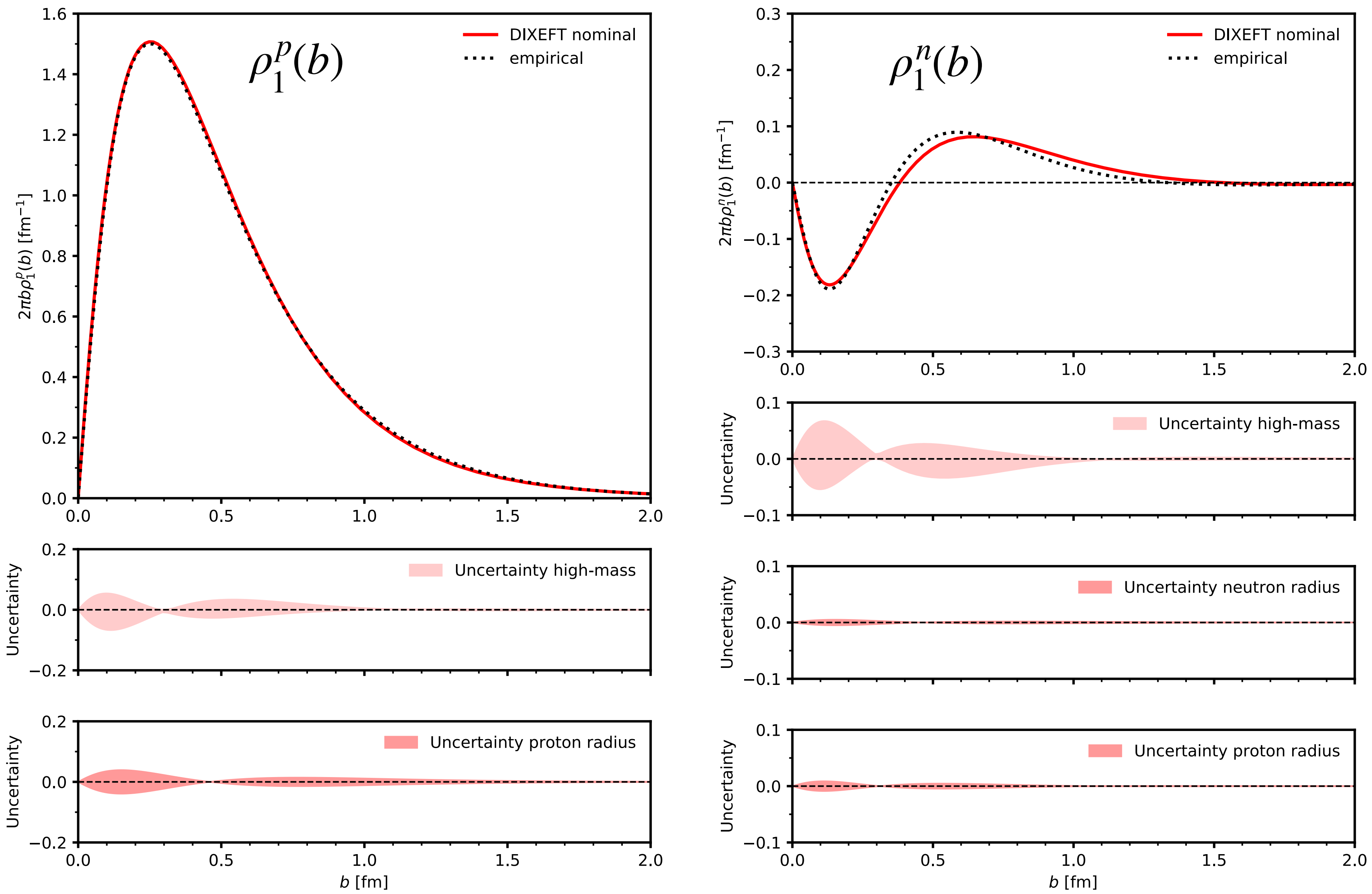
Two-photon exchange: Tomalak, Vanderhaeghen 2016

Transverse densities: DIChEFT results



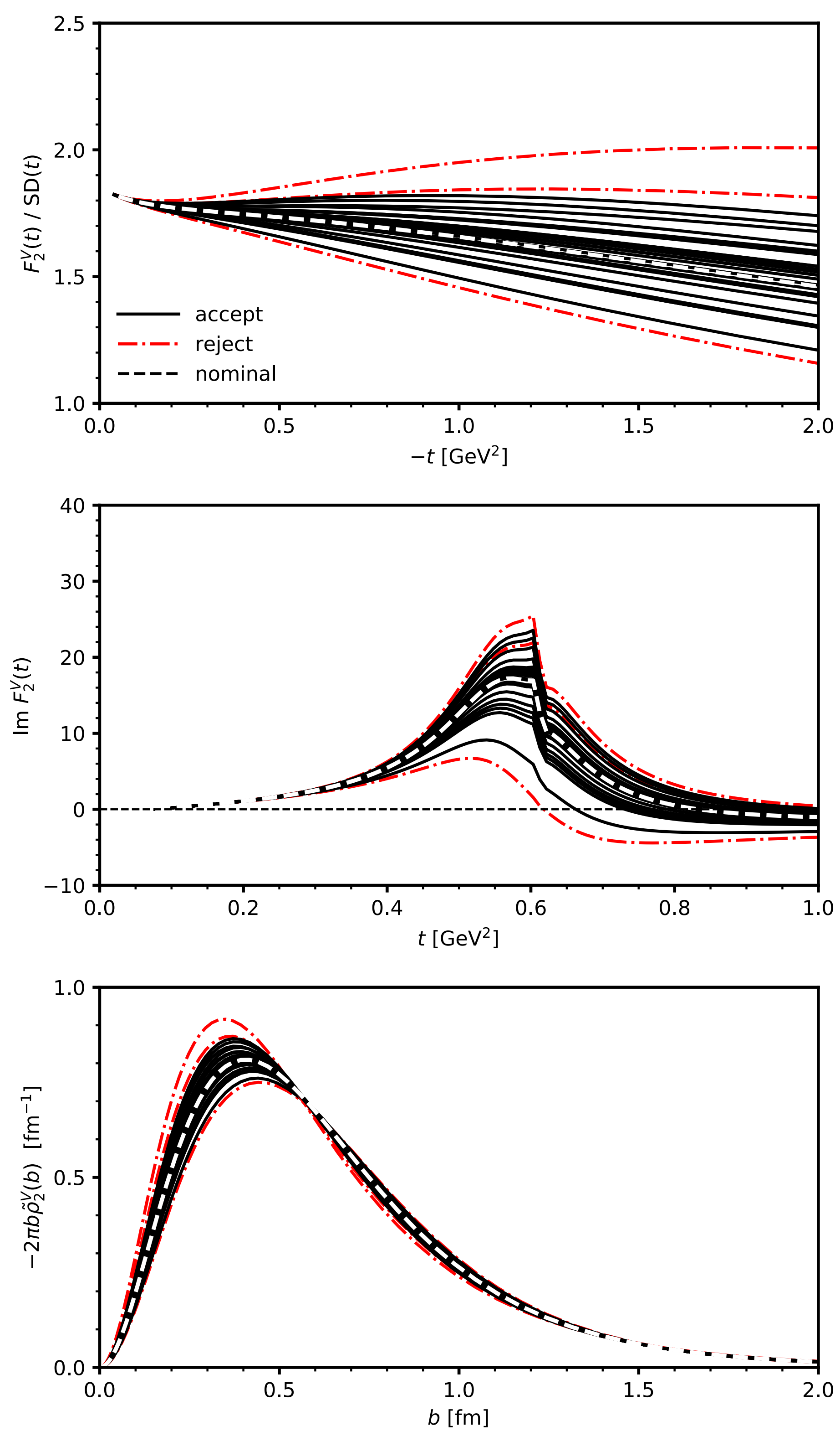
Alarcon, Weiss PRD 106, 054005 (2022)

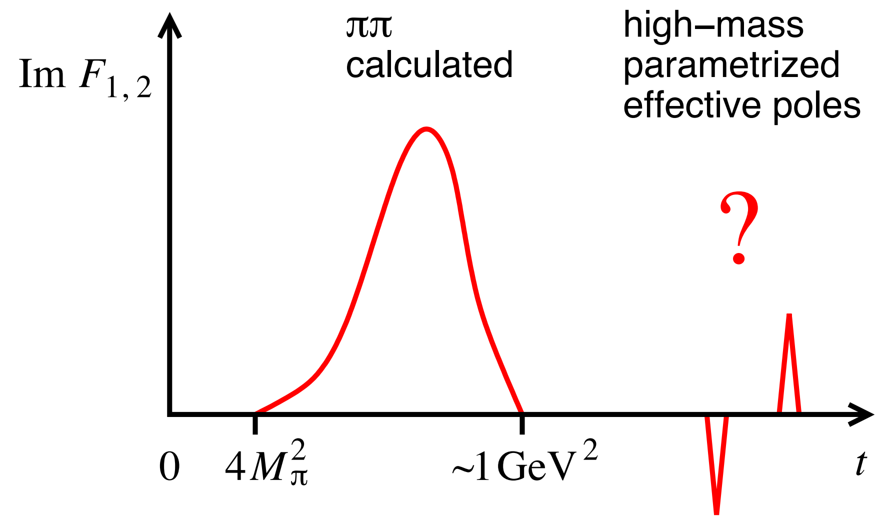
Radial charge densities $2\pi b\, \rho_1^{p,n}$ of proton and neutron

Obtained realistic nucleon densities with controlled uncertainties

Reproduced positive charge density in neutron at intermediate $b \sim 0.5 - 1$ fm
Miller 2007

Transverse densities: Uncertainty quantification





Shape of high-mass spectral function unknown
→ treat as theoretical uncertainty

Parametrize through effective poles
Im F_1[high-mass] $= a_0\delta(t - t_0) + a_1\delta'(t - t_1)$

Pole positions considered unknown (in reasonable range)
Pole coefficients fixed by sum rules

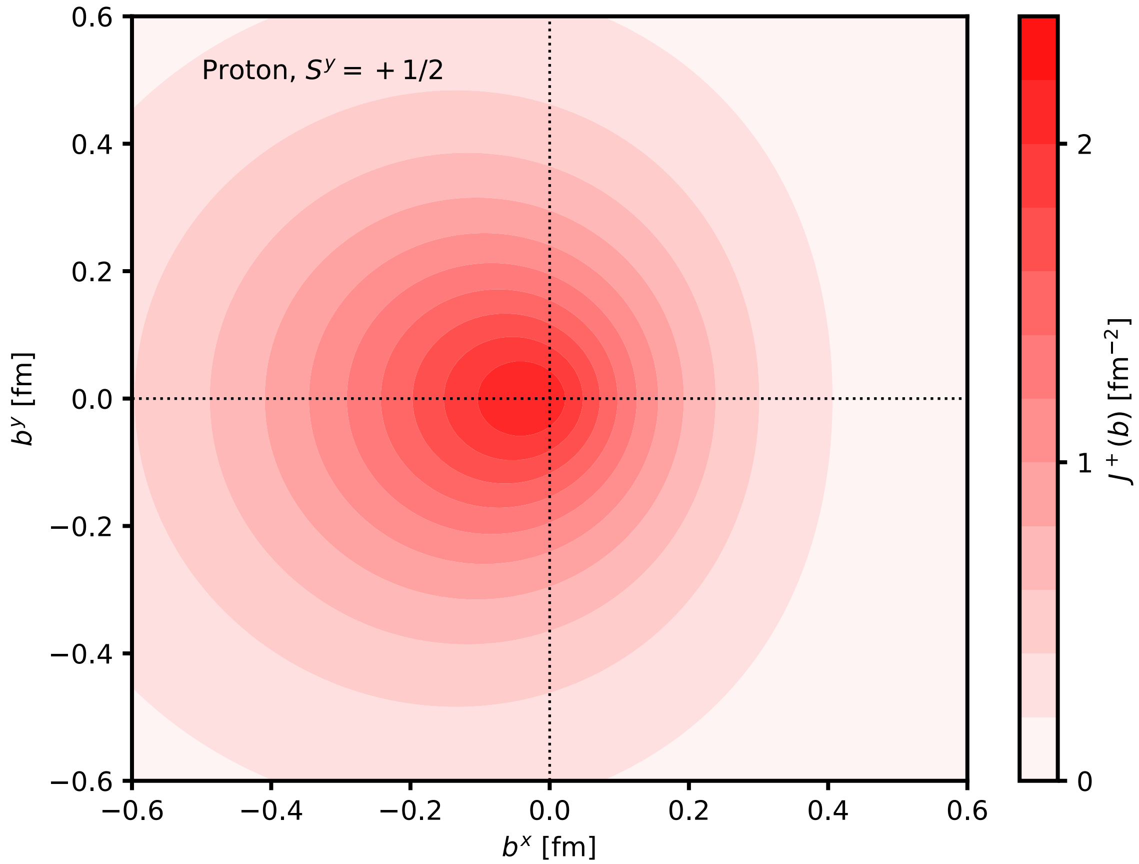
Generate MC ensemble of spectral functions
Propagate variation into form factors, densities, etc.

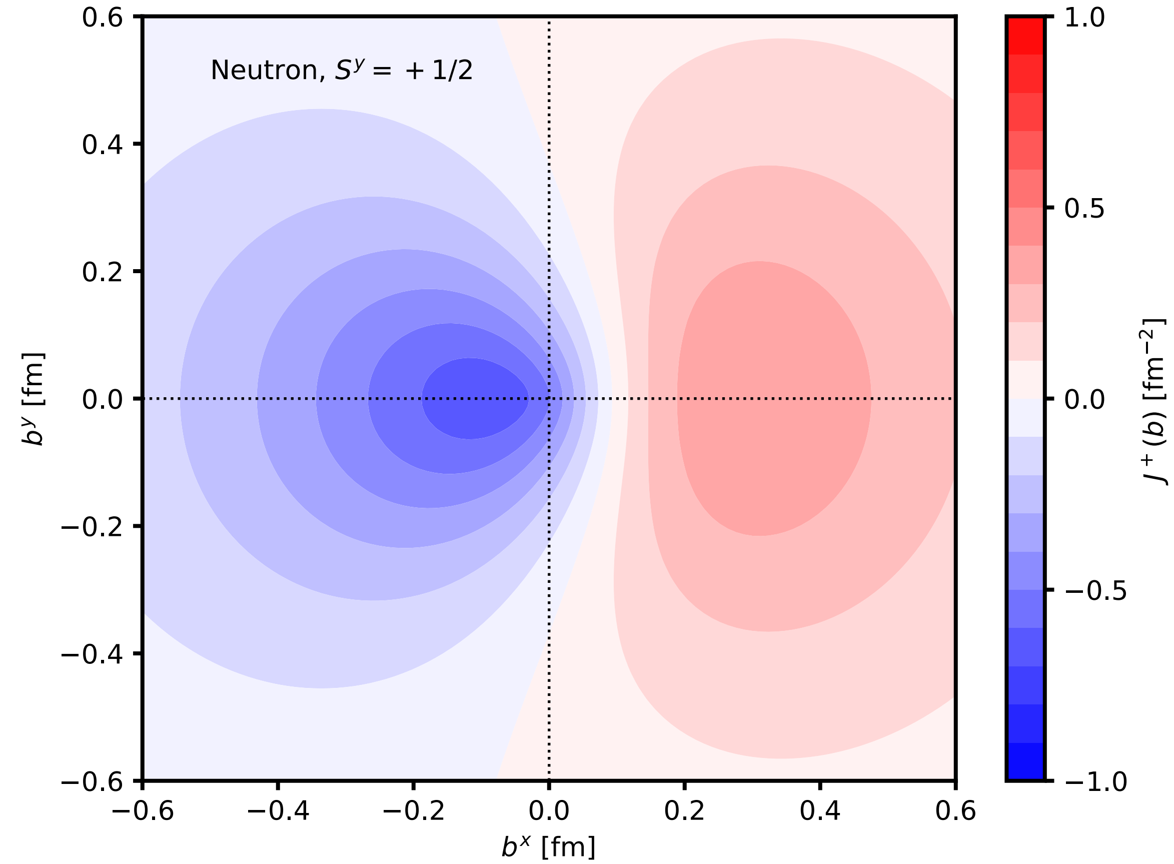
Uncertainty quantification consistent with analyticity!

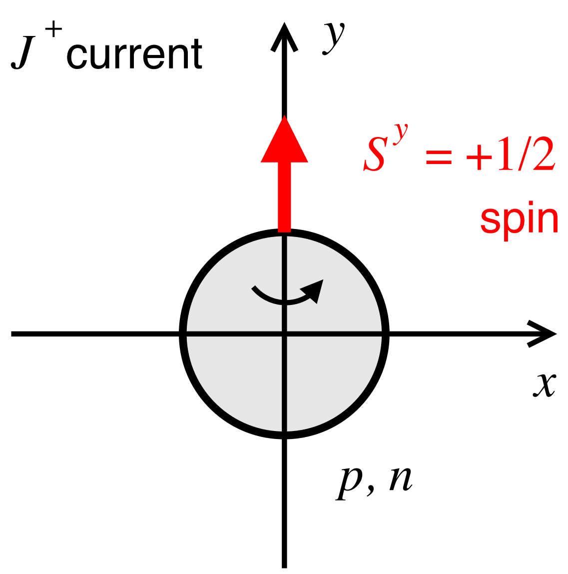
Peripheral densities not sensitive to unknown
high-mass spectral function - robust predictions!

Alarcon, Weiss PRD 106, 054005 (2022) [INSPIRE]

Transverse densities: J+ current in polarized nucleon







Alarcon, Weiss PRD 106, 054005 (2022)

Plus current density in transversely polarized nucleon localized at $x = y = 0$

$$\langle J^+(\mathbf{b})\rangle = \rho_1(b) + (2S^y) \cos\phi\, \tilde{\rho}_2(b)$$

This is how an electromagnetic probe coupling to J^+ "sees" the nucleon in transverse space

Computed from DIChEFT results