Nucleon Compton scattering from the Dyson-Schwinger perspective

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Compton scattering off Protons and Light Nuclei: pinning down the nucleon polarizabilities

ECT*, Trento
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Introduction

Goal: compute nucleon’s Compton scattering amplitude (and other things) from quark-gluon substructure in QCD.

- Handbag vs. nucleon (s- and u-channel) and meson (t-channel) resonances?
- Electromagnetic gauge invariance at the quark-gluon level?
- Quark core vs. pion cloud?
- Tensor decomposition for (on- and offshell) fermion two-photon vertex?

QCD’s Green functions ↔ “Dyson-Schwinger approach”:
Nonperturbative, covariant, low and high energies, light and heavy quarks. But: truncations!

- Baryon spectroscopy from three-body Faddeev equation
GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)

- Elastic & transition form factors for N and Δ
GE, PRD 84 (2011); GE, Fischer, EPJ A48 (2012); GE, Nicmorus, PRD 85 (2012); …

- Tetraquark interpretation for σ meson
Heupel, GE, Fischer, PLB 718 (2012)

- Compton scattering
Dyson-Schwinger equations

QCD Lagrangian:
quarks, gluons (+ ghosts)

\[ \mathcal{L} = \bar{\psi}(x) (i \slashed{\partial} + g \slashed{A} - M) \psi(x) - \frac{1}{4} F_{\mu\nu}^a F^{\mu\nu}_a \]

QCD & hadron properties are encoded in QCD’s Green functions. Their quantum equations of motion are the Dyson-Schwinger equations (DSEs):

- **Quark propagator:**

  \[
  = -1 + \quad -1
  \]

- **Quark-gluon vertex:**

  \[
  = 
  \]

- **Gluon propagator:**

  \[
  = -1 + \quad -1
  \]

- **Gluon self-interactions, ghosts, ...**

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Dyson-Schwinger approach

QCD Lagrangian:
quarks, gluons (+ ghosts)

\[ \mathcal{L} = \bar{\psi}(x) \left( i \gamma^\mu \partial_\mu - M \right) \psi(x) - \frac{1}{4} F_{\mu \nu}^a F_a^{\mu \nu} \]

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- **Quark propagator:**
  \[ = \mathbb{1}^{-1} \]

- **Quark-gluon vertex:**
  \[ = \]

- **Gluon propagator:**
  \[ = \]

- **Gluon self-interactions, ghosts, . . .**

- **Truncation** ⇒ closed system, solveable. Ansätze for Green functions that are not solved (based on pQCD, lattice, FRG, ...)

- **Applications:**
  Origin of confinement, QCD phase diagram, Hadron physics
Dynamical quark mass

- Dynamical chiral symmetry breaking: generates “constituent-quark masses”

- Realized in quark Dyson-Schwinger eq:

\[
\begin{align*}
\frac{-1}{\Gamma} &= \frac{-1}{\Gamma_0} + \Gamma \\
\text{If (gluon propagator } \times \text{ quark-gluon vertex)} \\
\text{is strong enough (} \alpha > \alpha_{\text{crit}} \text{): momenta-dependent quark mass } M(p^2) \\
\text{Already visible in simpler models (NJL, Munczek-Nemirovsky)} \\
\text{Mass generation for light hadrons}
\end{align*}
\]


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Hadrons: poles in Green functions

- **Quark four-point function:**
  \[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) \psi(x_3) \bar{\psi}(x_4) | 0 \rangle \]

- **Quark six-point function:**
  \[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) | H \rangle \]

**Bethe-Salpeter WF:**
\[ P^2 \rightarrow -m^2 \]

**Faddeev WF**
Hadrons: poles in Green functions

- **Quark four-point function:**
  \[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) \psi(x_3) \bar{\psi}(x_4) | 0 \rangle \]
  \[ G \quad P^2 \rightarrow -m^2 \]
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  \[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) | H \rangle \]

- **Quark six-point function:**
  \[ G \quad P^2 \rightarrow -m^2 \]
  Faddeev WF

- **Quark-antiquark vertices:**
  (Currents: \( J^\mu = \bar{\psi} \Gamma^\mu \psi \))
  \[ \langle 0 | T J^\mu(x) \psi(x_1) \bar{\psi}(x_2) | 0 \rangle \]
  \[ \chi \quad P^2 \rightarrow -m^2 \]
  Decay constant:
  \[ \langle 0 | J^\mu | H \rangle \]
  Quark-photon vertex has \( \rho \)-meson poles:
  ‘vector-meson dominance’

- **Current correlators:**
  \[ \langle 0 | T J^\mu(x) J^\nu(y) | 0 \rangle \]
  \[ \chi \quad \chi \]
  \( \rightarrow \) Lattice QCD
Bethe-Salpeter equations

- Inhomogeneous BSE for quark four-point function:
  \[ G = K + G \]

- Homogeneous BSE for bound-state wave function:
  \[ \chi = K \chi \]

- Inhomogeneous BSE for quark-antiquark vertices:
  \[ = K + \]

Analogy: geometric series
\[ f(x) = 1 + xf(x) \quad \Rightarrow \quad f(x) = \frac{1}{1-x} \]
\[ |x| < 1 \quad \Rightarrow \quad f(x) = 1 + x + x^2 + \ldots \]

What’s the kernel $K$?

Related to Green functions via symmetries: CVC, PCAC
\[ \Rightarrow \text{vector, axialvector WTIs} \]

Relate $K$ with quark propagator and quark-gluon vertex
Structure of the kernel

Rainbow-ladder: tree-level vertex + effective coupling

\[ \alpha(k^2) \]

\[ K = \alpha(k^2) \]

\[ \eta \]

\( \eta \) \( \alpha(k^2) \)

\[ k^2 \text{ [GeV}^2] \]

Ansatz for effective coupling:

\[ \alpha(k^2) = \alpha_{\text{IR}}\left(\frac{k^2}{\Lambda^2}, \eta\right) + \alpha_{\text{UV}}(k^2) \]

Adjust infrared scale \( \Lambda \) to physical observable, keep width \( \eta \) as parameter

\( \text{DCSB, CVC, PCAC} \)

\( \Rightarrow \) mass generation

\( \Rightarrow \) Goldstone theorem, massless pion in \( \chi_L \)

\( \Rightarrow \) em. current conservation

\( \Rightarrow \) Goldberger-Treiman

\( \sim \) No pion cloud, no flavor dependence, no \( U_A(1) \) anomaly, no dynamical decay widths

Pion cloud:

need infinite summation of t-channel gluons
**Mesons**

- **Pseudoscalar & vector mesons:** rainbow-ladder is good. Masses, form factors, decays, $\pi\pi$ scattering lengths, PDFs


Pion is Goldstone boson, satisfies GMOR: $m_\pi^2 \sim m_q$

- Need to go **beyond rainbow-ladder** for excited, scalar, axialvector mesons, $\eta$-$\eta'$, etc.

- **Heavy mesons** Blank, Krassnigg, PRD 84 (2011)

![Graph showing mass spectra of mesons including bottomonium and charmonium](image)
**Baryons**

**Covariant Faddeev equation:** kernel contains 2PI and 3PI parts

\[ \langle H | J^\mu | H \rangle = \bar{\chi} (G^{-1})^\mu \chi \]

- Impulse approximation + gauged kernel

\[ (G^{-1})^\mu = (G_0^{-1})^\mu - K^\mu \]

**Current matrix element:**

\[ \langle H | J^\mu | H \rangle = \bar{\chi} (G^{-1})^\mu \chi \]

\[ (G^{-1})^\mu = (G_0^{-1})^\mu - K^\mu \]

**Truncation:**

- Quark-quark correlations only (dominant structure in baryons?)
- Rainbow-ladder gluon exchange
- But full Poincaré-covariant structure of Faddeev amplitude retained

→ Same input as for mesons, quark from DSE, no additional parameters!

'Gauging of equations':
Kvinikhidze, Blankleider, PRC 60 (1999)
Oettel, Pichowsky, von Smekal, EPJ A 8 (2000)
Baryons

**Covariant Faddeev equation:** kernel contains 2PI and 3PI parts

\[
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\]

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‘Gauging of equations’:
Kvinikhidze, Blankleider, PRC 60 (1999)
Oettel, Pichowsky, von Smekal, EPJ A 8 (2000)
Faddeev wave function

\[
\chi(x_1, x_2, x_3) = \langle 0 | T \psi(x_1) \psi(x_2) \psi(x_3) | N \rangle
\]

**Momentum space:**
Jacobi coordinates \( p, q, P \)  
\( \Rightarrow \) 5 Lorentz invariants  
\( \Rightarrow \) 64 Dirac basis elements

\[
\chi(p, q, P) = \sum_k f_k(p^2, q^2, p \cdot q, p \cdot P, q \cdot P) \quad \text{Momentum}
\]

\[
\tau^k_{\alpha\beta\gamma\delta}(p, q, P) \quad \text{Dirac} \otimes \text{Flavor} \otimes \text{Color}
\]

Complete, orthogonal **Dirac tensor basis**  
(partial-wave decomposition in nucleon rest frame):  
GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)

\[
T_{ij} (\Lambda_+ \gamma_5 C \otimes \Lambda_+) \\
(\gamma_5 \otimes \gamma_5) T_{ij} (\Lambda_+ \gamma_5 C \otimes \Lambda_+)
\]

\( (A \otimes B)_{\alpha\beta\gamma\delta} = A_{\alpha\beta} B_{\gamma\delta} \)
Baryon masses

- Good agreement with experiment & lattice. Pion mass is also calculated.
- Same kernel as for mesons, scale set by $f_\pi$. Full covariant wave functions, no further parameters or approximations.
- Masses not sensitive to effective interaction.

**Diquark clustering in baryons:**
similar results in quark-diquark approach

Oettel, Alkofer, von Smekal, EPJ A8 (2000)
GE, Cloet, Alkofer, Krassnigg, Roberts, PRC 79 (2009)

- **Excited baryons** (e.g. Roper): also quark-diquark structure?

**Delta mass:**
Sanchis-Alepuz et al., PRD 84 (2011)

**Nucleon mass:**
GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010); GE, PRD 84 (2011)

**$\rho$-meson mass:**
Maris & Tandy, PRC 60 (1999)

Pion mass is also calculated.
Electromagnetic form factors

Nucleon em. FFs vs. momentum transfer
GE, PRD 84 (2011)

- Agreement with data at larger $Q^2$ and lattice at larger quark masses

- Missing pion cloud below 1–2 GeV$^2$, in chiral region

~ nucleon quark core without pion effects
Electromagnetic form factors

Nucleon charge radii:
isovector (p-n) Dirac (F1) radius

\[(r_1^v)^2 \ [fm^2]\]

- Pion-cloud effects missing in chiral region (⇒ divergence!), agreement with lattice at larger quark masses.

Nucleon magnetic moments:
isovector (p-n), isoscalar (p+n)

\[\kappa^v \ [\mu_N]\]

\[\kappa^s \ [\mu_N]\]

- But: pion-cloud cancels in \(\kappa^s \leftrightarrow quark \text{ core}\)
  
  Exp: \(\kappa^s = -0.12\)
  
  Calc: \(\kappa^s = -0.12(1)\)
Nucleon-Δ-γ transition

- **Magnetic dipole form factor** \( G^*_M \) dominant, quark spin flip. As expected: “Core + 25% pion cloud”

- **Electric quadrupole transition** \( R_{EM} \) small & negative, encodes deformation. Perturbative QCD: \( R_{EM} \rightarrow 1 \), Quark model: need d waves or pion cloud.

But: subleading tensor structures important, Quark OAM (p waves) by Poincaré covariance!

\[ G^*_M(Q^2) \]

\[ R_{EM} \]
Quark-photon vertex

Current matrix element: \[ \langle H | J^\mu | H \rangle = \Gamma^\mu(k, Q) + \Delta^\mu(k, Q) \]

Vector WTI \[ Q^\mu \Gamma^\mu(k, Q) = S^{-1}(k_+) - S^{-1}(k_-) \]
determines vertex up to transverse parts:

\[ \Gamma^\mu(k, Q) = \Gamma^\mu_{BC}(k, Q) + \Gamma^\mu_T(k, Q) \]

- **Ball-Chiu vertex**, completely specified by dressed fermion propagator:  
  Ball, Chiu, PRD 22 (1980)

\[ \Gamma^\mu_{BC}(k, Q) = i\gamma^\mu \Sigma_A + 2k^\mu(i\kappa) \Delta_A + \Delta_B \]

- **Transverse part**: free of kinematic singularities, tensor structures \( \sim Q, Q^2, Q^3 \), contains meson poles
  Kizilersu, Reenders, Pennington, PRD 92 (1995); GE Fischer, PRD 87 (2013)

\[ \tau^\mu_{ab} := a \cdot b \delta^{\mu\nu} - b^\mu a^\nu \]

<table>
<thead>
<tr>
<th>Dominant</th>
<th>Anomalous magnetic moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_1^\mu = t^\mu QQ \gamma^\nu )</td>
<td>( \tau_3^\mu = \frac{i}{2} \left[ \gamma^\mu, Q \right] )</td>
</tr>
<tr>
<td>( \tau_2^\mu = t^\mu QQ k \cdot Q \frac{i}{2} \left[ \gamma^\nu, k \right] )</td>
<td>( \tau_4^\mu = \frac{1}{6} \left[ \gamma^\mu, k, Q \right] )</td>
</tr>
<tr>
<td>( \tau_5^\mu = t^\mu QQ i k^\nu )</td>
<td>( \tau_6^\mu = t^\mu QQ k^\nu k )</td>
</tr>
<tr>
<td>( \tau_7^\mu = t^\mu Qk k \cdot Q \gamma^\nu )</td>
<td>( \tau_8^\mu = t^\mu Qk \frac{i}{2} \left[ \gamma^\nu, k \right] )</td>
</tr>
</tbody>
</table>
Can we extend this to **four-body scattering** processes?

GE, Fischer, PRD 85 (2012)

- Compton scattering, DVCS, $2\gamma$ physics
- Meson photo- and electroproduction
- Nucleon-pion scattering
- $\bar{p}p \rightarrow \gamma\gamma^*$ annihilation
- Meson production
- Pion Compton scattering

$\Rightarrow$ Nonperturbative description of hadron-photon and hadron-meson scattering
Nucleon Compton scattering

- **RCS, VCS:** nucleon (generalized) polarizabilities
- **DVCS:** factorization & handbag dominance, GPDs
- **Forward limit:** structure functions in DIS
- **Timelike region:** p\(\bar{p}\) annihilation at PANDA@FAIR
- **Spacelike region:** two-photon corrections to nucleon form factors

\[
\tau = \frac{Q^2}{4M^2}, \quad \tau' = \frac{Q'^2}{4M^2}, \quad t = \frac{\Delta^2}{4M^2}, \quad \nu = \frac{s-u}{4M^2} = -\frac{\Sigma \cdot P}{M^2}
\]
Nucleon Compton scattering

\[
\frac{\Delta^2}{4M^2} = t, \quad \frac{\Sigma^2}{M^2} = tX, \quad \widehat{P} \cdot \widehat{\Sigma} = Y, \quad \hat{\Sigma} \cdot \hat{\Delta} = Z
\]

4-dim phase space simpler in Lorentz-invariant hyperspherical variables \( t, X, Y, Z \):

- **\( VCS \)**: \( Q^2 = 0 \)
- **\( VVCS \)**: \( Q^2 = Q'^2 \)
- **\( TCS \)**: \( Q^2 = 0 \)
- **\( RCS \)**: \( X = -1 \)

\[
\tau = \frac{Q^2}{4M^2}, \quad \tau' = \frac{Q'^2}{4M^2}, \quad t = \frac{\Delta^2}{4M^2}, \quad v = \frac{s-u}{4M^2} = -\frac{\Sigma \cdot P}{M^2}
\]

Mandelstam plane in RCS:
Compton scattering

- All direct measurements in kinematic limits (RCS, VCS, forward limit).
- Em. gauge invariance $\Rightarrow$ Compton amplitude is fully transverse. Analyticity constrains 1PI part in these limits (low-energy theorem).
- Polarizabilities = coefficients of tensor structures that vanish like $\sim Q^\mu Q^\nu, Q^\mu Q^\nu, Q'^\mu Q'^\nu, \ldots$
- Need tensor basis free of kinematic singularities (18 elements). Complicated...

Bardeen, Tung, Phys. Rev. 173 (1968)
Tarrach, Nuovo Cim. 28 A (1975)
Drechsel et al., PRC 57 (1998)
L'vov et al., PRC 64 (2001)
Gorchtein, PRC 81 (2010)
Belitsky, Mueller, Ji, 1212.6674 [hep-ph]
Transversality, analyticity and Bose symmetry makes the construction extremely difficult...

\[
\begin{align*}
\tau_1 &= \gamma^\mu \\
\tau_2 &= \sigma^{\mu
\nu} Q^\nu
\end{align*}
\]

Tarrach, Nuovo Cim. 28 (1975)
**Transverse tensor basis for** $\Gamma^{\mu\nu}(p, Q, Q')$

- **Generalize transverse projectors:**
  \[ t_{ab}^{\mu\nu} := a \cdot b \delta^{\mu\nu} - b^{\mu} a^{\nu} \]
  \[ \varepsilon_{ab}^{\mu\nu} := \gamma_5 \varepsilon^{\mu\nu\alpha\beta} a^\alpha b^\beta \]
  \( a, b \in \{ p, Q, Q' \} \)
  (exhausts all possibilities)

- **Apply Bose-(anti-)symmetric combinations**
  \[ E_{\pm}^{\mu\alpha,\beta\nu}(a, b) := \frac{1}{2} \left( \varepsilon_{Q'a'}^{\mu\alpha} \varepsilon_{b'Q'}^{\beta\nu} \pm \varepsilon_{Q'Q'}^{\mu\alpha} \varepsilon_{a'a}^{\beta\nu} \right) \]
  \[ F_{\pm}^{\mu\alpha,\beta\nu}(a, b) := \frac{1}{2} \left( t_{Q'a'}^{\mu\alpha} s_{b'Q'}^{\beta\nu} \mp t_{Q'Q'}^{\mu\alpha} s_{a'a}^{\beta\nu} \right) \]
  \[ G_{\pm}^{\mu\alpha,\beta\nu}(a, b) := \frac{1}{2} \left( t_{Q'a'}^{\mu\alpha} t_{b'Q'}^{\beta\nu} \mp t_{Q'Q'}^{\mu\alpha} t_{a'a}^{\beta\nu} \right) \]

- **Transverse onshell basis:**
  - Simple
  - analytic in all limits
  - manifest crossing and charge-conjugation symmetry
  - scalar & pion pole only
  - in a few Compton form factors
  - Tarrach’s basis can be cast in a similar form

\[ \begin{array}{c|c|c}
E_+(P,P) & (++) & E_+(P,P) & (--) \\
F_+(P,P) & (++) & F_+(P,P) & (--) \\
G_+(P,P) & (++) & G_+(P,P) & (--) \\
G_-(P,P) & (--) & G_-(P,P) & (++)
\end{array} \]

\[ \begin{array}{c|c|c}
F_-(P,Q) & (--) & F_+(P,Q) & (++) \\
G_+(P,Q) & (--) & G_+(P,Q) & (++) \\
F_-(P,Q) & (--) & F_+(P,Q) & (++) \\
G_-(P,Q) & (--) & G_+(P,Q) & (++)
\end{array} \]
Compton amplitude at quark level

Baryon’s **Compton scattering amplitude**, consistent with Faddeev equation:

GE, Fischer, PRD 85 (2012)

\[ \langle H | J^\mu J^\nu | H \rangle = \bar{\chi} \left( G^{-1\mu} G G^{-1\nu} + G^{-1\nu} G G^{-1\mu} - (G^{-1})^{\mu\nu} \right) \chi \]

In rainbow-ladder (+ crossing & permutation):

- Born (handbag) diagrams: \( G = 1 + T \)
- all s- and u-channel nucleon resonances:
- 1PI quark 2-photon vertex: all t-channel meson poles
- cat’s ears diagrams

\( G \)
Represented by full **quark Compton vertex**, including Born terms.
Satisfies inhomogeneous BSE:

\[
\begin{align*}
\Delta Q' & = Q \\
\mu & \quad Q' \\
\Sigma & \quad p \\
\Sigma & \quad p + \Sigma \\
\Sigma & \quad \Sigma \\
\Sigma & \quad \Sigma \\
\end{align*}
\]

Solved in rainbow-ladder: 128 tensor structures (72 transverse).
Simplifies dramatically by choice of convenient basis!

- **not electromagnetically gauge invariant**, but comparable to 1PI 'structure part' at nucleon level?
- reduces to **perturbative handbag** at large photon momenta
- but also all **t-channel poles** included!
Compton amplitude at quark level

Quark Compton vertex: recovers t-channel poles, e.g. scalar and pion √

\begin{align*}
\bar{f}_{11}(t) \ [GeV^{-1}] \\
-\bar{f}_{41}(t) \ [GeV^{-1}]
\end{align*}

GE & Fischer, PRD 87 (2013)

Quark Compton vertex and nucleon Compton amplitude: residues at pion pole recover \(\pi\gamma\gamma\) transition form factor √

\begin{align*}
F_{\pi\gamma\gamma}(Q^2=Q'^2) & \\
F_{\pi\gamma\gamma}(Q^2=Q'^2)
\end{align*}

(extracted from quark Compton vertex) (extracted from nucleon Compton amplitude)

Rainbow-ladder result:
Maris & Tandy, PRC 65 (2002)

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Fermion Compton vertex

2-photon WTI $\Rightarrow$ general **offshell fermion Compton vertex** can be written as

$$\Gamma_{\mu\nu} = \Gamma_{B_{\mu\nu}} + \Gamma_{BC_{\mu\nu}} + \Gamma_{TT_{\mu\nu}}$$

- **Born**
- **WTI**
- **WTI-T**

- 2-photon equivalent of Ball-Chiu vertex, fixed by quark propagator & quark-photon vertex
- no kinematic singularities

**Transverse**

- not constrained by WTI, calculated from BSE
- contains t-channel poles
- no kinematic singularities
- 72 elements offshell
- (18 elements onshell)

General **structure** of fermion two-photon vertex (both offshell and onshell) determined.

- Onshell amplitude: gauge-invariant separation!
- Quark Compton vertex: all these will contribute to Compton form factors
  ($\Rightarrow$ polarizabilities, structure functions, GPDs, etc.). Dominant contributions?
  - $\Rightarrow$ Born (**handbag**)?
  - $\Rightarrow$ WTI, WTI-T (**em. gauge invariance**) ?
  - $\Rightarrow$ Fully transverse part (**t-channel poles**) ?
Summary

So far:

- Structure analysis of nucleon Compton amplitude & quark Compton vertex
- Nonperturbative calculation of handbag part (quark Compton vertex = Born + t-channel), t-channel pole behavior reproduced.

Next:

- Extract polarizabilities (subtraction needed to restore gauge invariance)
- Two-photon exchange contribution to form factors
- GPDs & nucleon PDFs
- Study offshell effects at nucleon level

Long term:

- Improve truncations (pion cloud, decay channels, quark six-point function)
- Access larger phase space (e.g. timelike region in $p\bar{p} \rightarrow \gamma\gamma$)
Thanks for your attention.

Cheers to my collaborators:


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