Probing nucleons with photons at the quark level

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Excited QCD, Bjelasnica Mountain, Sarajevo
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Motivation

**Goal:** compute **hadron properties** (ground state & excitations, form factors, scattering amplitudes, etc.) from **quark-gluon substructure in QCD.**

**QCD’s Green functions** $\leftrightarrow$ “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 $\Delta$
  GE, PRD 84 (2011); GE, Fischer, EPJ A48 (2012);
  GE, Nicmorus, PRD 85 (2012); Sanchis-Alepuz et al., PRD 87 (2013), . . .

- **Nucleon Compton scattering**

- **Tetraquark** interpretation for $\sigma$ meson
  Heupel, GE, Fischer, PLB 718 (2012)

- **Three-gluon vertex** from its DSE
  GE, Williams, Alkofer, Vujinovic, 1402.1365
  $\rightarrow$ **see talk by Milan Vujinovic**

- **Quark-gluon vertex** from its DSE
  Hopfer, Windisch, GE, Alkofer, in preparation
  $\rightarrow$ **see talk by Markus Hopfer**
**Dyson-Schwinger equations**

**QCD Lagrangian:**
quarks, gluons (+ ghosts)

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

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

- **Quark propagator:**
  \[ \begin{array}{c}
  \text{Quark propagator:} \\
  \end{array} \begin{array}{c}
  \quad -1
  \end{array} \]

- **Quark-gluon vertex:**

- **Gluon propagator:**
  \[ \begin{array}{c}
  \quad -1
  \end{array} \]

- **Gluon self-interactions, ghosts, . . .**
Dyson-Schwinger approach
QCD Lagrangian:
quarks, gluons (+ ghosts)

Quark propagator:
Gluon propagator:
Quark-gluon vertex:
Gluon self-interactions, ghosts, . . .

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

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- **Quark propagator:**
  \[ = \quad -1 \]

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

- **Gluon propagator:**
  \[ = \quad -1 \]

- **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:

\[
\begin{align*}
D^{-1} &= D_{0}^{-1} + \text{vertex}\text{-dependent mass}\text{ term} \\
\int (\text{gluon propagator} \times \text{quark-gluon vertex}) &\text{ is strong enough } (\alpha > \alpha_{\text{crit}}) \\
\text{momentum-dependent quark mass } M(p^2)
\end{align*}
\]

- Already visible in simpler models (NJL, Munczek-Nemirovsky)

- Mass generation for light hadrons

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:**
\[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) | H \rangle \]

**Faddeev WF**

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Hadrons: poles in Green functions

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- **Quark six-point function**:

- **Quark-antiquark vertices**: (Currents: \( J^\mu = \bar{\psi} \Gamma^\mu \psi \))
  \[ \langle 0 | T J^\mu(x) \psi(x_1) \bar{\psi}(x_2) | 0 \rangle \]

- **Current correlators**:
  \[ \langle 0 | T J^\mu(x) J^\nu(y) | 0 \rangle \]

**Bethe-Salpeter WF**: 
\[ \langle 0 | T \psi(x_1) \bar{\psi}(x_2) | H \rangle \]

**Faddeev WF**

**Decay constant**: 
\[ \langle 0 | J^\mu | H \rangle \]

Quark-photon vertex has \( \rho \)-meson poles: ‘vector-meson dominance’

\( \rightarrow \) Lattice QCD
Bethe-Salpeter equations

- Inhomogeneous BSE for **quark four-point function:**
  \[
  G = \frac{\chi}{f \chi} + K G
  \]

- Homogeneous BSE for **bound-state wave function:**
  \[
  \chi = \frac{1}{f} \chi
  \]

- Inhomogeneous BSE for **quark-antiquark vertices:**
  \[
  = + \frac{1}{f} K
  \]

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

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

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

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

\( \eta \)

- 2.0
- 1.9
- 1.8
- 1.7
- 1.6

\( k^2 \) [GeV^2]

- 15
- 12
- 9
- 6
- 3
- 0

- 2.0
- 1.9
- 1.8
- 1.7
- 1.6

DCSB, CVC, PCAC
- mass generation
- Goldstone theorem, massless pion in \( \chi L \)
- em. current conservation
- Goldberger-Treiman

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

Pion cloud:
need infinite summation of t-channel gluons

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Mesons

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

Maris, Roberts, Tandy, PRC 56 (1997), PRC 60 (1999);

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.
  
  Fischer, Williams & Chang, Roberts, PRL 103 (2009)
  Alkofer et al., EPJ A38 (2008), Bhagwat et al., PRC 76 (2007)

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

\[
\begin{align*}
M [GeV] & \\
\end{align*}
\]

\[
\begin{align*}
\eta_1(1S) & \eta_1(1P) \quad \eta_1(1S) \\
\eta_1(1P) & \eta_1(1S) \quad \eta_1(1P) \\
\eta_1(1S) & \eta_1(1P) \quad \eta_1(1P)
\end{align*}
\]

**Bottomonium**

**Charmonium**

- **Figures:**
  - \( m_\rho [MeV] \)
  - \( m_\pi [MeV] \)

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

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

- Impulse approximation + gauged kernel \( (G^{-1})^\mu = (G_0^{-1})^\mu - K^\mu \)

**Current matrix element:**

- 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!
**Baryons**

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

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- But full **Poincaré-covariant structure** of Faddeev amplitude retained

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

- Role of **pion cloud**?
  Sanchis-Alepuz, Fischer, Kubrak, 1401.3183

- Role of **three-gluon vertex**?
  GE, Williams, Alkofer, Vujinovic, 1402.1365

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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)
Electromagnetic form factors

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

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

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

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

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

- **But**: pion-cloud cancels in \( \kappa^s \) ⇔ quark core
  
  \[ \text{Exp: } \kappa^s = -0.12 \]
  \[ \text{Calc: } \kappa^s = -0.12(1) \]

GE, PRD 84 (2011)
Nucleon-Δ-γ transition

- **Magnetic dipole transition** ($G_M^*$) dominant: quark spin flip (s wave). “Core + 25% pion cloud”

- **Electric & Coulomb quadrupole transitions** small & negative, encode deformation.

Ratios reproduced without pion cloud: OAM from relativistic p waves in the quark core!

Eichmann & Nicmorus, PRD 85 (2012)
Quark-photon vertex

Current matrix element: \[ \langle H | J^\mu | H \rangle = \tau_1 + \tau_2 \]

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

- **Ball-Chiu vertex**, completely specified by
dressed fermion propagator: \( \text{Ball, Chiu, PRD 22 (1980)} \)
\[ \Gamma^\mu_{\text{BC}}(k, Q) = i\gamma^\mu \Sigma_A + 2k^\mu (i\gamma^\nu \Delta_A + \Delta_B) \]

- **Transverse part**: free of kinematic singularities,
tensor structures \( \sim Q^2, Q^3 \), contains meson poles
\( \text{Kizilersu, Reenders, Pennington, PRD 92 (1995)}; \quad \text{GE Fischer, PRD 87 (2013)} \)
\[ t^\mu_{\nu ab} := a \cdot b \delta^\mu_{\nu} - b^\mu a^\nu \]

<table>
<thead>
<tr>
<th>Dominant</th>
<th>[ \tau_1^\mu = t^\mu_{QQ} \gamma^\nu, ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ \tau_2^\mu = t^\mu_{QQ} k \cdot Q \gamma^\nu, ]</td>
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<table>
<thead>
<tr>
<th>Anomalous magnetic moment</th>
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<tr>
<td>[ \tau_3^\mu = \frac{i}{2} [\gamma^\mu, Q], ]</td>
</tr>
<tr>
<td>[ \tau_4^\mu = \frac{1}{6} [\gamma^\mu, k, Q], ]</td>
</tr>
</tbody>
</table>

\[ \Sigma_A := \frac{A(k_+^2) + A(k_-^2)}{2}, \]
\[ \Delta_A := \frac{A(k_+^2) - A(k_-^2)}{k_+^2 - k_-^2}, \]
\[ \Delta_B := \frac{B(k_+^2) - B(k_-^2)}{k_+^2 - k_-^2}, \]
\[ \text{Curtis, Pennington, PRD 42 (1990)} \]
\[ \tau_5^\mu = t^\mu_{QQ} i k^\nu, \]
\[ \tau_6^\mu = t^\mu_{QQ} k^\nu k, \]
\[ \tau_7^\mu = t^\mu_{Qk} k \cdot Q \gamma^\nu, \]
\[ \tau_8^\mu = t^\mu_{Qk} \frac{i}{2} [\gamma^\nu, k]. \]
Quark-photon vertex

Structure of quark-photon vertex is reflected in form factors. Experimentally (sketch):

Calculated:
(Sketch)

- Ball-Chiu part is dominant (em. gauge invariance): charge, magnetic moments
- Transverse part changes slope and charge radii. No pion cloud in RL \( \Rightarrow \) timelike \( \rho \)-meson poles
Quark-photon vertex

Structure of quark-photon vertex is reflected in form factors. Experimentally (sketch):

- **Timelike:** $e^+e^- \rightarrow N\bar{N}$
  - Not accessible

- **Spacelike:** $e^-N \rightarrow e^-N$
  - Charge, magnetic moment, ...
  - Radius

**Calculated:**
(Sketch)

- **Ball-Chiu part** is dominant (em. gauge invariance): charge, magnetic moments
- Transverse part changes slope and charge radii. No pion cloud in RL $\Rightarrow$ timelike $\rho$-meson poles
Pion form factor

Spacelike and timelike region:

A. Krassnigg (Schladming 2010)
extension of Maris & Tandy,

Include pion cloud:
Kubrak et al., in preparation
Hadron scattering

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
- $pp \rightarrow \gamma\gamma^*$ annihilation
- Meson production
- Pion Compton scattering

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

- RCS, VCS: nucleon polarizabilities
- DVCS: handbag dominance, GPDs
- Forward limit: structure functions in DIS
- Timelike region: $\bar{p}p$ annihilation at PANDA
- Spacelike region: two-photon corrections to nucleon form factors, proton radius puzzle?
Two-photon corrections

- **Proton form factor ratio:**
  Rosenbluth extraction suggested $G_E/G_M = \text{const.}$, in agreement with perturbative scaling.
  Polarization data from JLAB showed falloff in $G_E/G_M$ with possible zero crossing.
  Modified pQCD predictions: OAM.
  Difference likely due to two-photon corrections.

- **Proton radius puzzle:**
  Proton radius extracted from Lamb shift in $\mu H$ 4% smaller than that from $eH$, would need additional $\Delta E \sim 300 \text{ \mu eV}$ to agree
  Pohl et al., Nature 466, 213 (2010)
  Can two-photon offshell corrections explain discrepancy?
  Miller, Thomas, Carroll, Rafelski; Carlson, Vanderhaeghen; Birse, McGovern; …
Handbag dominance

- **Handbag dominance in DVCS**
  
  large $Q^2$ & $s$, small $t$: factorization, extract **GPDs** from handbag diagram

- **p$\bar{p}$ annihilation at PANDA@FAIR**
  
  Are the concepts developed for lepton scattering (factorization, handbag dominance, GPDs) applicable?

- **Is it possible to calculate these processes directly within nonperturbative QCD?**
  
  Wishlist:
  
  - Em. gauge invariance
  - Crossing symmetry
  - Poincare invariance
  - Recover parton picture (handbag, ...)
  - Recover hadronic structure (s, u, t-channel resonances)
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 $\sim Q^\mu Q'^\nu$, $Q^\mu Q^\nu$, $Q'^\mu Q'^\nu$, ...
- 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]

...
Tensor basis?

Transversality, analyticity and Bose symmetry makes the construction extremely difficult...

\[ T_1 = \gamma^\mu \]
\[ T_2 = \sigma^{\mu \nu} Q^\nu \]
Transverse tensor basis for $\Gamma^{\mu \nu}(p, Q, Q')$

- **Generalize transverse projectors:**
  
  \[
  t^{\mu \nu}_{ab} := a \cdot b \delta^{\mu \nu} - b^{\mu} a^{\nu} \\
  \varepsilon^{\mu \nu}_{ab} := \gamma_5 \varepsilon^{\mu \nu \alpha \beta} a^\alpha b^\beta
  \]
  
  \[a, b \in \{p, Q, Q'\}\]
  
  (exhausts all possibilities)

- **Apply Bose-(anti-)symmetric combinations**

  \[
  E_{\pm}^{\mu \alpha, \beta \nu}(a, b) := \frac{1}{2} \left( \varepsilon_{Q' a}^{\mu \alpha} \varepsilon_{bQ}^{\nu \beta} \pm \varepsilon_{Q' b}^{\mu \alpha} \varepsilon_{aQ}^{\nu \beta} \right)
  \]

  \[
  F_{\pm}^{\mu \alpha, \beta \nu}(a, b) := \frac{1}{2} \left( t_{Q' a}^{\mu \alpha} t_{bQ}^{\nu \beta} \pm t_{Q' b}^{\mu \alpha} t_{aQ}^{\nu \beta} \right)
  \]

  \[
  G_{\pm}^{\mu \alpha, \beta \nu}(a, b) := \frac{1}{2} \left( \varepsilon_{Q' a}^{\mu \alpha} t_{bQ}^{\nu \beta} \pm t_{Q' b}^{\mu \alpha} \varepsilon_{aQ}^{\nu \beta} \right)
  \]

  to structures independent of $Q, Q'$:

  \[p^\alpha \gamma^\beta + \gamma^\alpha p^\beta \]

  \[p^\alpha \gamma^\beta - \gamma^\alpha p^\beta \]

  \[\gamma^\alpha, \gamma^\beta \]

  \[\gamma^\alpha, \gamma^\beta, \gamma \]

- **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

\[\begin{array}{c|c|c}
E_+(P, P) & (+ +) & \tilde{E}_+(P, P) \quad (- +) \\
F_+(P, P) & (+ +) & \tilde{F}_+(P, P) \quad (- +) \\
G_+(P, P) & (+ +) & \tilde{G}_+(P, P) \quad (- +) \\
G_-(P, P) & (- -) & \tilde{G}_-(P, P) \quad (+ +) \\
\end{array}\]

\[\begin{array}{c|c|c}
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\end{array}\]

\[\begin{array}{c|c|c}
F_+(Q, Q) & (+ +) & \tilde{F}_+(Q, Q) \quad (- +) \\
\end{array}\]
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:** \( N, \Delta \)
- **1PI quark 2-photon vertex:** all t-channel meson poles
- **cat’s ears diagrams**

\( \square \) crossing symmetry
\( \square \) em. gauge invariance
\( \square \) perturbative processes included
\( \square \) s, t, u channel poles generated in QCD
Compton amplitude at quark level

Collect all (nonperturbative!) ‘handbag’ diagrams: no nucleon resonances, no cat’s ears

- **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! (scalar, pion, ... )
- represented by full **quark Compton vertex**, including Born terms. Satisfies inhomogeneous BSE, solved in RL (128 tensor structures)
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Residues at pion pole recover **$\pi\gamma\gamma$ transition form factor $\checkmark$**

GE & Fischer, PRD 87 (2013)

Rainbow-ladder result: Maris & Tandy, PRC 65 (2002)
Compton amplitude at quark level

- Quark Compton vertex has **extremely** rich structure:
  \[
  \Gamma^{\mu\nu}(p, Q, Q') = \sum_{i=1}^{72} f_i \left( p^2, Q^2, Q'^2, Q \cdot Q', p \cdot Q, p \cdot Q' \right) \tau_i^{\mu\nu}(p, Q, Q')
  \]

- Exploit **em. gauge invariance**: general **offshell quark Compton vertex** can be written as

  \[
  \Gamma^{\mu\nu} = \Gamma_B^{\mu\nu} + \Gamma_{BC}^{\mu\nu} + \Gamma_T^{\mu\nu}
  \]

  - Born
  - WTI
  - WTI-T
  - **Transverse**
    - 2-photon equivalent of **Ball-Chiu vertex**, fixed by quark propagator & quark-photon vertex
    - **no kinematic singularities**
    - not constrained by WTI, calculated from BSE
    - no kinematic singularities
    - contains **t-channel poles**
    - 72 elements offshell
    - (18 elements onshell)

  - All these will contribute to Compton form factors (⇒ polarizabilities, structure functions, GPDs, etc.)
  - Dominant contributions?
    - Born (pure handbag)?
    - WTI, WTI-T (em. gauge invariance)?
    - Fully transverse part (t-channel poles)?
Here be dragons

• **Gauge invariance ↔ transversality:**
  when inserted in nucleon Compton amplitude, non-transverse terms in quark Compton vertex (in Born, WTI, WTI-T) must be cancelled by those in remaining diagrams (cat’s ears, 6pt function)

• But handbag alone is **not gauge-invariant**, incomplete calculation can produce **singularities** in \( Q^2, Q'^2, Q \cdot Q', P \cdot Q \)

\[ F(Q^2) = \alpha(Q^2) Q^2 \]

\[ \alpha(Q^2): \text{Polarizability} \]
Here be dragons

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Polarizabilities: a first look

- \(\alpha + \beta\): dominated by quark Born terms (pure handbag) (here: \(1 / Q \cdot Q^\prime\) singularity not yet removed)
- \(\beta\): cancellation between Born and t-channel poles? no singularity in \(\beta\)
Summary

So far:

- Structure analysis of **Compton scattering**
- Nonperturbative calculation of **handbag part** (Born + t-channel)

Next:

- Extract **polarizabilities**
- **Two-photon exchange** contribution to form factors
- GPDs & nucleon PDFs
- **Pion electroproduction** at quark level
- **Nucleon resonances**
- **Timelike form factors & processes**

Need to improve:

- **Go beyond rainbow-ladder!** (Pion cloud, decay channels, higher n-point functions, ...)
- Deal with quark singularities ⇒ access high $Q^2$, timelike region etc.  

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Thanks for your attention.

Cheers to my collaborators: