Nucleon resonances in Compton scattering

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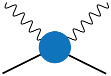
IST Lisboa, Portugal

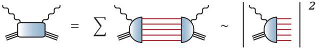
Emergent mass and its consequences in the Standard Model
ECT*, Trento, Italy

September 18, 2018

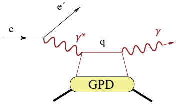
Compton scattering



Structure functions
& PDFs in forward limit

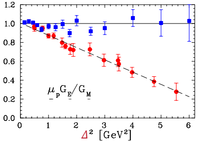


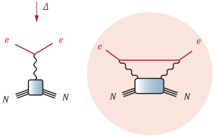
Handbag dominance
& GPDs in DVCS



TPE corrections to form factors

Guichon, Vanderhaeghen, PRL 91 (2003)



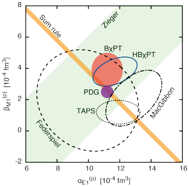


Proton radius puzzle?

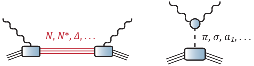
Antonigni et al., 2013, Pohl et al. 2013,
Birse, McGovern 2012, Carlson 2015

Nucleon polarizabilities

Hagelstein, Miskimen, Pascalutsa,
Prog. Part. Nucl. Phys. 88 (2016)

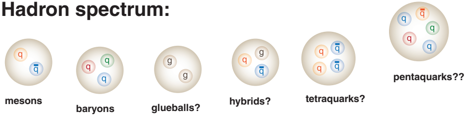


Resonances!



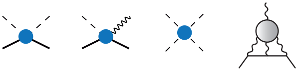
Motivation

Hadron spectrum:

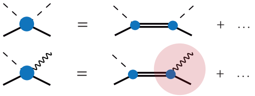


Form factors: resonance transition FFs, spacelike vs. timelike properties

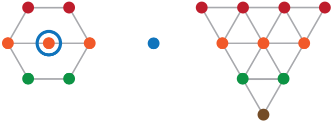
Hadron structure & scattering amplitudes



Extraction of resonances?



$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$	$\frac{5}{2}^+$	$\frac{5}{2}^-$	$\frac{7}{2}^+$
$N(939)$ $N(1440)$ $N(1710)$ $N(1880)$	$N(1535)$ $N(1650)$ $N(1895)$	$N(1720)$ $N(1900)$	$N(1520)$ $N(1700)$ $N(1875)$	$N(1680)$ $N(1860)$ $N(2000)$	$N(1675)$	$N(1990)$
$\Delta(1910)$	$\Delta(1620)$ $\Delta(1900)$	$\Delta(1232)$ $\Delta(1600)$ $\Delta(1920)$	$\Delta(1700)$ $\Delta(1940)$	$\Delta(1905)$ $\Delta(2000)$	$\Delta(1930)$	$\Delta(1950)$
$\Lambda(1116)$ $\Lambda(1600)$ $\Lambda(1810)$	$\Lambda(1405)$ $\Lambda(1670)$ $\Lambda(1800)$	$\Lambda(1890)$	$\Lambda(1520)$ $\Lambda(1690)$	$\Lambda(1820)$	$\Lambda(1830)$	
$\Sigma(1189)$ $\Sigma(1660)$ $\Sigma(1880)$	$\Sigma(1750)$	$\Sigma(1385)$	$\Sigma(1670)$ $\Sigma(1940)$	$\Sigma(1915)$	$\Sigma(1775)$	
$\Xi(1315)$		$\Xi(1530)$	$\Xi(1820)$			
		$\Omega(1672)$				

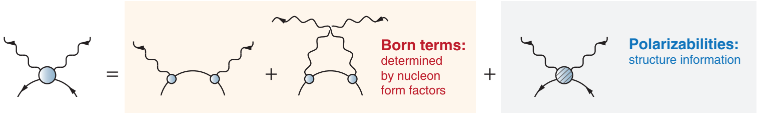


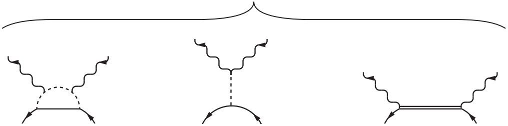
Outline

- **Introduction**
- **DSEs, BSEs:**
  From quarks and gluons to baryon resonances
- **Nucleon resonances** in **Compton scattering,**
  transition form factors
  GE, Ramalho, 1806.04579

Compton scattering

Compton amplitude = sum of **Born terms + 1PI structure part:**

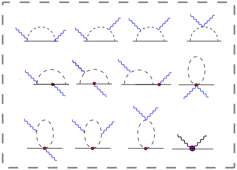




„Pion cloud“ (ChPT)

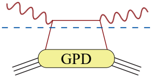
t-channel meson exchange ($\pi, \sigma, a_1, \ldots$)

s/u-channel nucleon resonances ($\Delta, N^*, \ldots$)



Griesshammer, McGovern, Phillips, Feldman, Prog. Part. Nucl. Phys. 67 (2012)

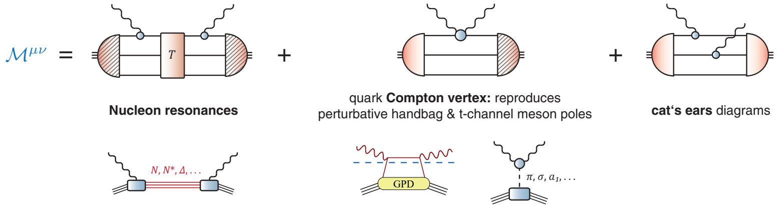
but also:



⇒ is there a common underlying **quark-level description?**

Compton scattering

Scattering amplitude: GE, Fischer, PRD 85 (2012) & PRD 87 (2013)

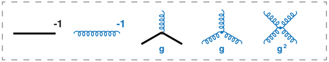


- **Poincaré covariance** and **crossing symmetry** automatic
- **em. gauge invariance** and **chiral symmetry** automatic
  as long as all ingredients calculated from symmetry-preserving kernel
- **perturbative processes** included
- **s, t, u channel poles** dynamically generated,
  no need for "offshell hadrons"

DSEs & BSEs

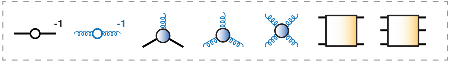
QCD's classical action:

$$S \;=\; \int d^4x\,\left[\bar\psi\,(\partial\!\!\!/ + ig A\!\!\!/ + m)\,\psi + \tfrac{1}{4}\,F^{\,a}_{\mu\nu}\,F^{\mu\nu}_{a}\right]$$

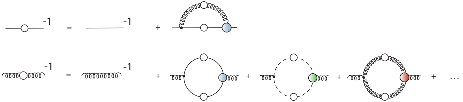
$=$ 

Quantum "effective action":

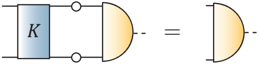
$$\int \mathcal{D}[\psi,\bar\psi,A]\,e^{-S} \;=\; e^{-\Gamma}$$



DSEs = quantum equations of motion:
derived from path integral, relate n-point functions



Bethe-Salpeter equations for hadronic bound states:

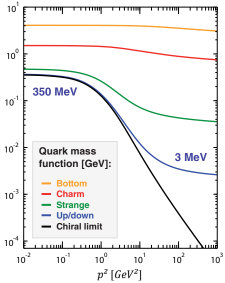


- Poincaré covariance
- Chiral symmetry
- EM gauge invariance
- Only quark & gluon d.o.f.,
  hadron poles generated dynamically
- multiscale problems feasible
- gauge-fixed
- **truncations:** neglect higher n-point functions to obtain closed system

QCD's n-point functions

- **Quark propagator**

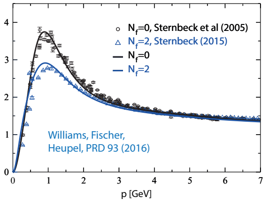
$A(p^2)\,(i\not{p} + M(p^2))$



Dynamical chiral symmetry breaking generates 'constituent-quark masses'

- **Gluon propagator**

$\frac{D(p^2)}{p^2}\left(\delta^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)$



- **Three-gluon vertex**

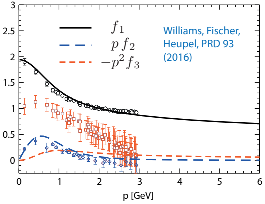
$F_1\,[\,\delta^{\mu\nu}(p_1 - p_2)^\rho + \delta^{\nu\rho}(p_2 - p_3)^\mu + \delta^{\rho\mu}(p_3 - p_1)^\nu] + \dots$

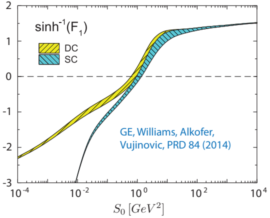
Agreement between lattice, DSE & FRG within reach

Huber, EPJ C77 (2017),
Cyrol, Mitter, Pawlowski, PRD 97 (2018), . . .

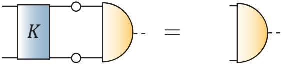
- **Quark-gluon vertex**

$f_1\,\gamma^\mu + f_2\, ip^\mu + f_3\, p^\mu \not{p} + \dots$



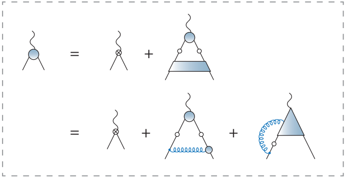


Truncations



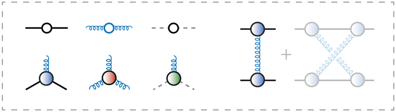
- **Beyond rainbow-ladder** using symmetries and quark-gluon vertex ansätze

  Chang, Roberts, PRL 103 (2009),
  Binosi, Chang, Papavassiliou, Qin, Roberts, PRD 93 (2016)

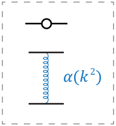


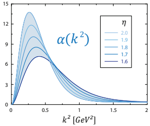
- **3PI system:** all 2 & 3-point functions calculated

  Williams, Fischer, Heupel, PRD 93 (2016)



- **Rainbow-ladder:** quark propagator calculated, kernel = effective gluon exchange



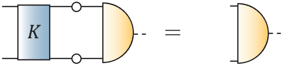


$$\alpha(k^2) = \alpha_{\text{IR}}\left(k^2/\Lambda^2, \eta\right) + \alpha_{\text{UV}}(k^2)$$

adjust scale Λ to observable,
keep width η as parameter

Maris, Tandy, PRC 60 (1999),
Qin et al., PRC 84 (2011)

Truncations



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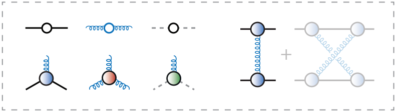

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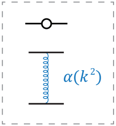

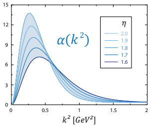

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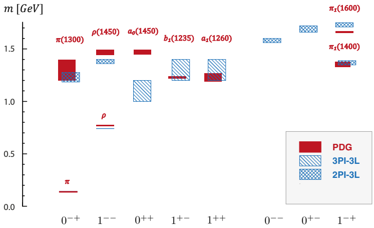
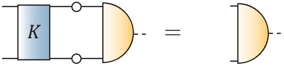
Light meson spectrum beyond rainbow-ladder:



GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016)

Truncations



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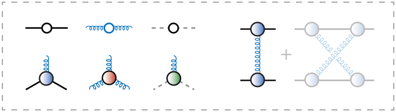

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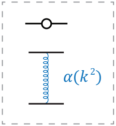

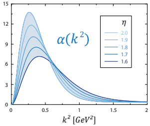

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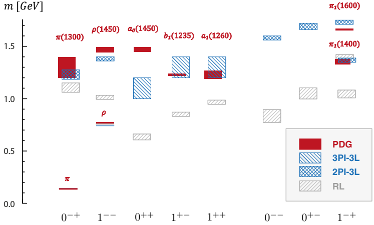

GE, Sanchis-Alepuz, Williams,
Alkofer, Fischer, PPNP 91 (2016)

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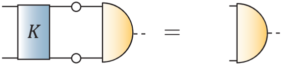

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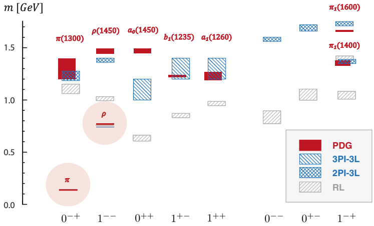

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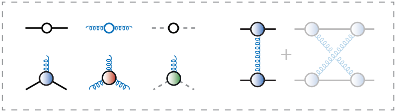

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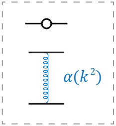

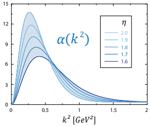

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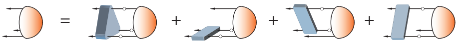
Baryons

Covariant Faddeev equation for baryons:

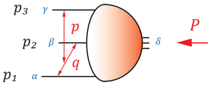
GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)



- 3-gluon diagram vanishes ⇒ **3-body effects small?**

  Sanchis-Alepuz, Williams, PLB 749 (2015)

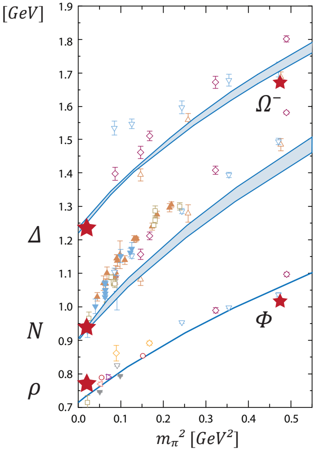
- 2-body kernels same as for mesons, no further approximations:



$$\Psi_{\alpha\beta\gamma\delta}(p,q,P) = \sum_i f_i(p^2, q^2, p\cdot q, p\cdot P, q\cdot P)\;\tau_i(p,q,P)_{\alpha\beta\gamma\delta}$$

Lorentz-invariant dressing functions

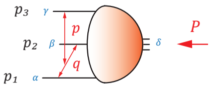
Dirac-Lorentz tensors carry OAM: s, p, d,...



Review: GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016), 1606.09602

The role of diquarks

Three-body equation knows nothing of **diquarks**,
but dynamically generates them in iteration



Group Lorentz invariants into
multiplets of permutation group S3:
GE, Fischer, Heupel, PRD 92 (2015), GE, Sanchis-Alepuz, in preparation

- **Singlet:**
  symmetric variable,
  carries overall scale:

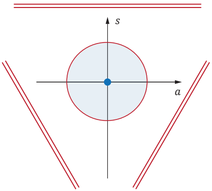
$$\mathcal{S}_0 \sim p_1^2 + p_2^2 + p_3^2 + \frac{M^2}{3}$$

- **Doublet:**

$$\mathcal{D}_0 \sim \frac{1}{\mathcal{S}_0} \begin{bmatrix} -\sqrt{3}\,(\delta x + 2\delta\omega) \\ x + 2\omega \end{bmatrix}$$

- Second **doublet:**

$$\mathcal{D}_1 \sim \frac{1}{\sqrt{\mathcal{S}_0}} \begin{bmatrix} -\sqrt{3}\,(\delta x - \delta\omega) \\ x - \omega \end{bmatrix}$$



Mandelstam plane,
outside: **diquark poles!**

The role of diquarks

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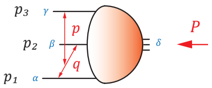

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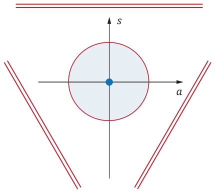
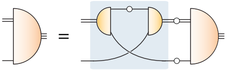
- Second **doublet:**

$$\mathcal{D}_1 \sim \frac{1}{\sqrt{\mathcal{S}_0}} \begin{bmatrix} -\sqrt{3}\,(\delta x - \delta\omega) \\ x - \omega \end{bmatrix}$$



⇒ Simplify 3-body equation to **quark-diquark BSE**



Oettel, Alkofer, Hellstern Reinhardt, PRC 58 (1998),

Cloet, GE, El-Bennich, Klähn, Roberts, FBS 46 (2009)

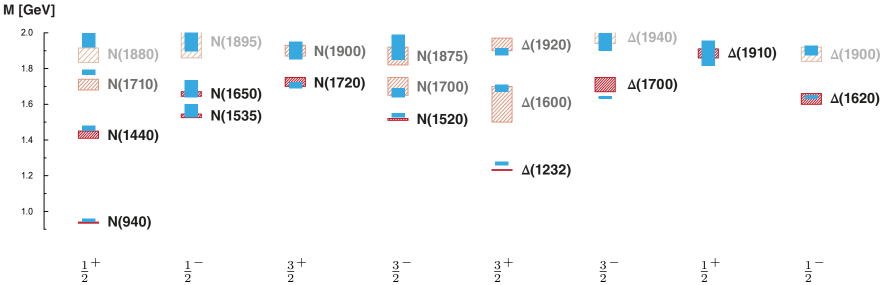
GE, Krassnigg, Schwinzerl, Alkofer, Ann. Phys. 323 (2008)

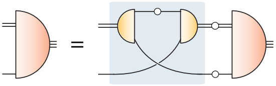
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu, Zong, PRL 115 (2015)

...

Baryon spectrum

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)

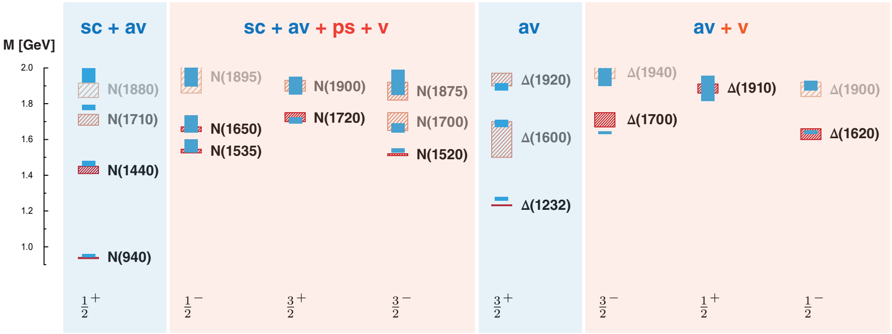


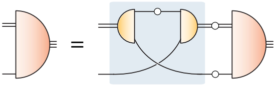


- Scale Λ set by f_π
- Current-quark mass m_q set by m_π
- c adjusted to ρ–a_1 splitting
- η doesn't change much

Baryon spectrum

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)





- Scale Λ set by f_π
- Current-quark mass m_q set by m_π
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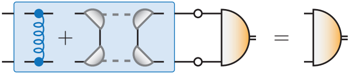
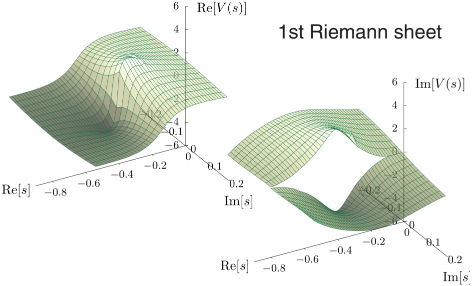
- η doesn't change much

Resonances!

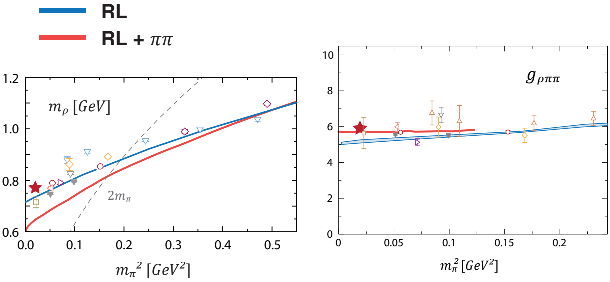
ρ meson as a dynamical resonance

Williams, 1804.11161





1st Riemann sheet



Lattice references: GE et al., PPNP 91 (2016) 1606.09602

Resonances!

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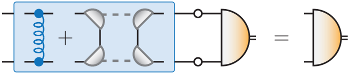
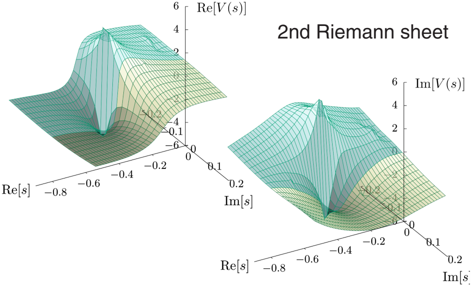
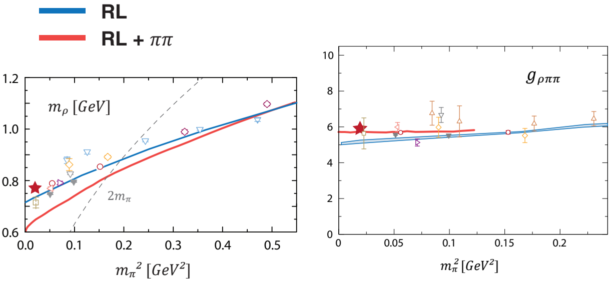


2nd Riemann sheet

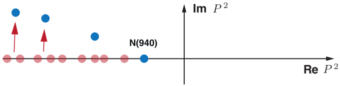




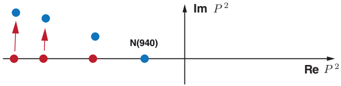
Lattice references: GE et al., PPNP 91 (2016) 1606.09602

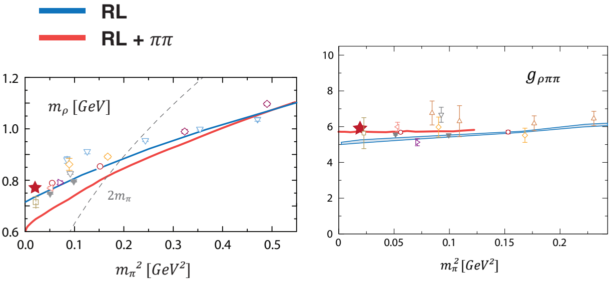
Resonances!

Lattice:
Proper treatment of
resonances essential



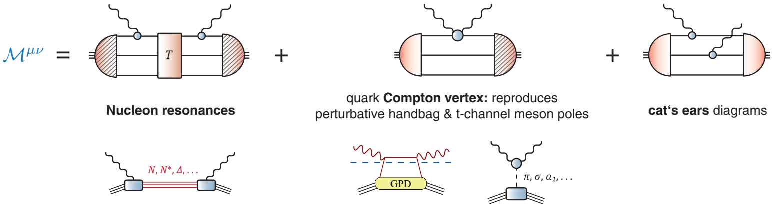
DSE / BSE:
Resonance dynamics
"on top of" quark-gluon dynamics





Compton scattering

Scattering amplitude: GE, Fischer, PRD 85 (2012) & PRD 87 (2013)



- **Poincaré covariance** and **crossing symmetry** automatic
- **em. gauge invariance** and **chiral symmetry** automatic
  as long as all ingredients calculated from symmetry-preserving kernel
- **perturbative processes** included
- **s, t, u channel poles** dynamically generated,
  no need for "offshell hadrons"

Nucleon resonances

$\sum$ 

$J^P = \frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
N(940)	**N(1720)**	**N(1535)**	**N(1520)**
N(1440)	$N(1900)$	**N(1650)**	$N(1700)$
$N(1710)$		$N(1895)$	$N(1875)$
$N(1880)$			
Δ(1910)	**Δ(1232)**	**Δ(1620)**	**Δ(1700)**
	Δ(1600)	Δ(1900)	Δ(1940)
	Δ(1920)		

Need **em. transition FFs**

But vertices are half offshell:
need 'consistent couplings'
Pascalutsa, Timmermans, PRC 60 (1999)

- **em gauge invariance:** $Q^\mu \, \Gamma^{\alpha\mu} = 0$
- **spin-3/2 gauge invariance:** $k^\alpha \, \Gamma^{\alpha\mu} = 0$
- invariance under **point transformations:** $\gamma^\alpha \, \Gamma^{\alpha\mu} = 0$
- no kinematic dependencies, **"minimal" basis**

E.g. Jones-Scadron current **cannot be used offshell:**

$$\Gamma^{\alpha\mu} \sim \bar{u}^\alpha(k) \Big[m^2 \lambda_- (G_M^* - G_E^*) \, \varepsilon^{\alpha\mu}_{kQ} - G_E^* \, \varepsilon^{\alpha\beta}_{kQ} \, \varepsilon^{\beta\mu}_{kQ} - \tfrac{1}{2} \, G_C^* \, Q^\alpha k^\beta t^{\beta\mu}_{QQ} \Big] \, u(k')$$

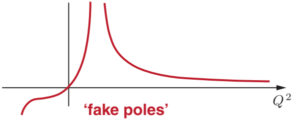
$$t^{\alpha\beta}_{AB} = A \cdot B \, \delta^{\alpha\beta} - B^\alpha A^\beta$$
$$\varepsilon^{\alpha\beta}_{AB} = \gamma_5 \, \varepsilon^{\alpha\beta\gamma\delta} A^\gamma B^\delta$$

Minimal tensor bases

$$\Gamma^{\mu\nu} = \sum_i c_i K_i^{\mu\nu} = \underbrace{\sum_i g_i G_i^{\mu\nu}}_{\mathbf{G}} + \underbrace{\sum_j f_j X_j^{\mu\nu}}_{\mathbf{T}}$$

Minimal basis: neither g_i, f_j nor G_i, X_j become singular

Without minimal basis:



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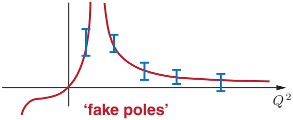

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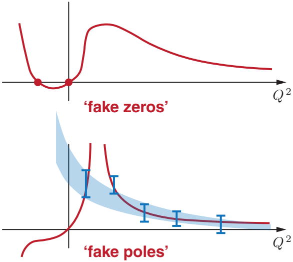

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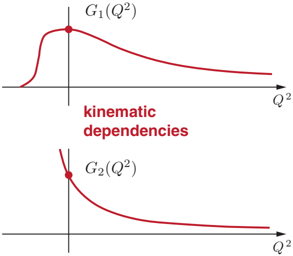

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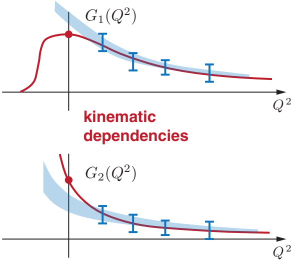

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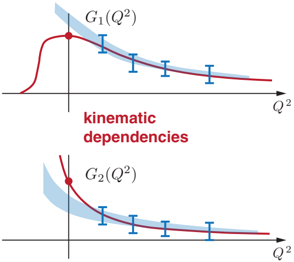
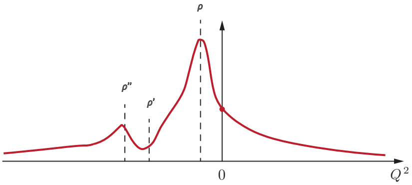
Without minimal basis:



With minimal basis:
no kinematic dependencies,
only 'physical' poles and cuts!



Minimal tensor bases

$$\Gamma^{\mu\nu} = \sum_i c_i\, K_i^{\mu\nu} = \underbrace{\sum_i g_i\, G_i^{\mu\nu}}_{\textbf{G}} + \underbrace{\sum_j f_j\, X_j^{\mu\nu}}_{\textbf{T}}$$

Minimal basis: neither g_i, f_j nor G_i, X_j become singular

Transversality constraints:

$$\begin{aligned} Q'^{\mu}\,\Gamma^{\mu\nu} &= 0 \\ Q^{\nu}\,\Gamma^{\mu\nu} &= 0 \end{aligned} \quad \Rightarrow \quad \begin{bmatrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} c_1 \\ \vdots \\ \\ c_n \end{bmatrix} = 0$$

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Row-reduced echelon form:

$$\begin{bmatrix} \overbrace{\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}}^{\text{dim G}} & \overbrace{\begin{matrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{matrix}}^{\text{dim T}} \\ \begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{matrix} & \begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{matrix} \end{bmatrix} \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} = 0$$

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A **minimal basis** exists, if

- by swapping columns (= renaming basis tensors)
- adding / subtracting rows, multiplying rows with scalars (Gauss-Jordan elimination)

one can find a **row-reduced echelon form** where $\begin{smallmatrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{smallmatrix}$ is nonsingular in any kinematic limit

$$\Big[\overbrace{\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{matrix}}^{\textbf{dim G}} \;\Big|\; \overbrace{\begin{matrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}}^{\textbf{dim T}}\Big] \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} = 0$$

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Minimal basis: neither g_i, f_j nor G_i, X_j become singular

Prerequisites:

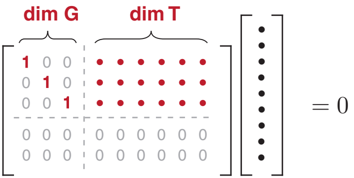
- K_i must be **linearly** and **kinematically** independent
- symmetries should be exploited beforehand $\Rightarrow$ arrange K_i in **singlets**

e.g. $K_1 \dots K_5$, but $k \cdot Q\, K_3 = Q^2\, K_4 + k^2\, K_5$ **?**

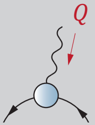
A **minimal basis** exists, if

- by swapping columns (= renaming basis tensors)
- adding / subtracting rows, multiplying rows with scalars (Gauss-Jordan elimination)

one can find a **row-reduced echelon form** where  is nonsingular in any kinematic limit



An example



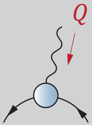
3 variables:

$k^2,\ Q^2,\ w = k\cdot Q$

$$\Gamma^\mu(k,Q) = c_1\, k^\mu + c_2\, Q^\mu$$

$$\overline{\Gamma}^\mu(k,Q) := \Gamma^\mu(-k,-Q) \stackrel{!}{=} -\Gamma^\mu(k,-Q) \qquad \text{(charge conjugation)}$$

An example



$k_+ = k + \frac{Q}{2}$ $\quad k_- = k - \frac{Q}{2}$

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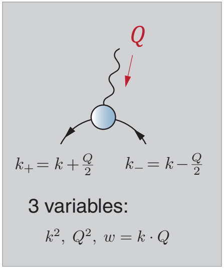

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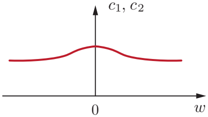

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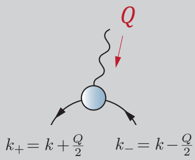

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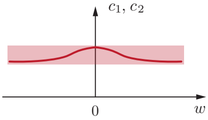

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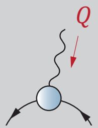

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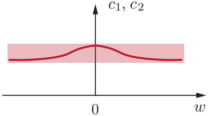
Transversality:

$$Q^\mu\, \Gamma^\mu = c_1\, w + c_2\, w\, Q^2 = 0$$



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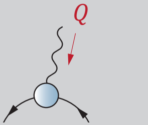

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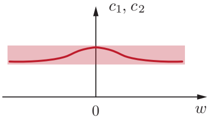
$$\Rightarrow \begin{bmatrix} w & w\,Q^2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = 0$$



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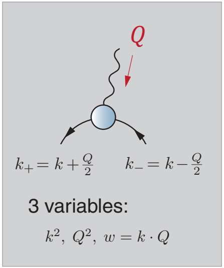

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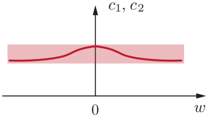


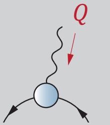
Transversality:

$$Q^\mu\, \Gamma^\mu = c_1\, w + c_2\, w\, Q^2 = 0$$

$$\Rightarrow \begin{bmatrix} w & w\,Q^2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = 0$$

$$\Rightarrow \begin{bmatrix} 1 & Q^2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = 0$$

An example



$k_+ = k + \frac{Q}{2}$ $\quad$ $k_- = k - \frac{Q}{2}$

3 variables:

$k^2,\ Q^2,\ w = k \cdot Q$

$$\Gamma^\mu(k,Q) = c_1\, k^\mu + c_2\, (k\cdot Q)\, Q^\mu$$

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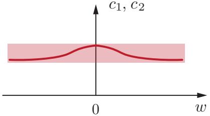
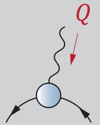


but **not**

$$\begin{bmatrix} 1 & \frac{1}{Q^2} \end{bmatrix} \begin{bmatrix} c_2 \\ c_1 \end{bmatrix} = 0$$ **!!**

An example



3 variables:

$k^2, \; Q^2, \; w = k\cdot Q$

$$\Gamma^\mu(k,Q) = c_1\, k^\mu + c_2\, (k\cdot Q)\, Q^\mu$$

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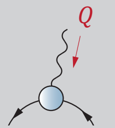
Transversality:

$$Q^\mu\, \Gamma^\mu = c_1\, w + c_2\, w\, Q^2 = 0$$

$$c_1 = -c_2\, Q^2 \quad \Rightarrow \quad \Gamma^\mu = -c_2\, (Q^2\, k^\mu - w\, Q^\mu) = -c_2\, (Q^2\, \delta^{\mu\nu} - Q^\mu Q^\nu)\, k^\nu = -c_2\, t^{\mu\nu}_{QQ}\, k^\nu$$

$$\Rightarrow \quad \Gamma^\mu(k,Q) = \underbrace{g_1\, k^\mu}_{\mathbf{G}} + \underbrace{f_1\, t^{\mu\nu}_{QQ}\, k^\nu}_{\mathbf{T}}$$

An example



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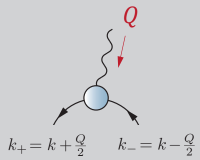
Ward-Takahashi identity only affects **G:**

$$Q^\mu\, \Gamma^\mu = D(k_+)^{-1} - D(k_-)^{-1} = g_1\, w$$

$$\Rightarrow \quad g_1 = 2\, \frac{D(k_+)^{-1} - D(k_-)^{-1}}{k_+^2 - k_-^2} = 2\Delta$$

$$\Rightarrow \quad \Gamma^\mu(k,Q) = \underbrace{g_1\, k^\mu}_{\textbf{G}} + \underbrace{f_1\, t^{\mu\nu}_{QQ}\, k^\nu}_{\textbf{T}}$$

An example



3 variables:

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Transverse-longitudinal separation?

$$\Gamma^\mu(k,Q) = \tilde{g}_1\, w\, Q^\mu + \tilde{f}_1\, t^{\mu\nu}_{QQ}\, k^\nu$$

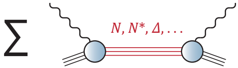
$$Q^\mu\,\Gamma^\mu = D(k_+)^{-1} - D(k_-)^{-1} = \tilde{g}_1 w\, Q^2$$

$$\Rightarrow \quad \Gamma^\mu(k,Q) = \underbrace{g_1\, k^\mu}_{\mathbf{G}} + \underbrace{f_1\, t^{\mu\nu}_{QQ}\, k^\nu}_{\mathbf{T}}$$

$$\Rightarrow\quad \tilde{g}_1 = \frac{2\Delta}{Q^2} \quad\Rightarrow\quad \tilde{f}_1 = f_1 + \frac{2\Delta}{Q^2} \quad\Rightarrow$$

both **kinematically dependent** and **singular!**

Nucleon resonances



$J^P = \frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
N(940) **N(1440)** N(1710) N(1880)	**N(1720)** N(1900)	**N(1535)** **N(1650)** N(1895)	**N(1520)** N(1700) N(1875)
Δ(1910)	**Δ(1232)** Δ(1600) Δ(1920)	**Δ(1620)** Δ(1900)	**Δ(1700)** Δ(1940)

Need **em. transition FFs**

But vertices are half offshell:
need 'consistent couplings'
Pascalutsa, Timmermans, PRC 60 (1999)

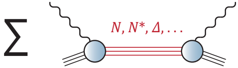
- **em gauge invariance:** $Q^\mu\,\Gamma^{\alpha\mu} = 0$
- **spin-3/2 gauge invariance:** $k^\alpha\,\Gamma^{\alpha\mu} = 0$
- invariance under **point transformations:** $\gamma^\alpha\,\Gamma^{\alpha\mu} = 0$
- no kinematic dependencies, **"minimal" basis**

Most general **offshell vertices** satisfying these constraints:
GE, Ramalho, 1806.04579

$$\frac{1}{2}^+ \to \frac{1}{2}^\pm : \quad \Gamma^\mu = \begin{bmatrix} \mathbf{1} \\ \gamma_5 \end{bmatrix} \sum_{i=1}^{8} F_i\, T_i^\mu \qquad \begin{cases} t^{\mu\nu}_{QQ}\gamma^\nu \\ [\gamma^\mu, \not{Q}] \\ \dots \end{cases}$$

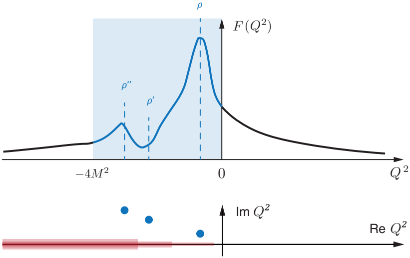
$$\frac{1}{2}^+ \to \frac{3}{2}^\pm : \quad \Gamma^{\alpha\mu} = \begin{bmatrix} \gamma_5 \\ \mathbf{1} \end{bmatrix} \sum_{i=1}^{12} F_i\, T_i^{\alpha\mu} \qquad \begin{cases} \varepsilon^{\alpha\mu}_{kQ} \\ t^{\alpha\mu}_{kQ} \\ i t^{\alpha\beta}_{k\gamma} t^{\beta\mu}_{QQ} \\ \dots \end{cases}$$

Nucleon resonances

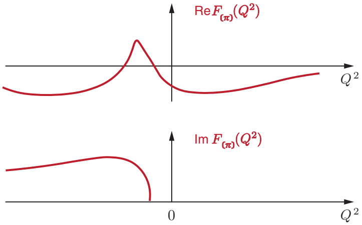


Constraint-free transition FFs:
only physical poles and cuts

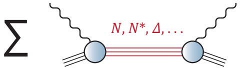
- ρ **poles** $\rightsquigarrow$ monotonous behavior
(+ zero crossings for excited states)



- Non-monotonicity at low Q2
$\rightsquigarrow$ signature for cuts ($\rho \to \pi\pi$, etc.):
meson cloud



Nucleon resonances



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N(940) **N(1440)** $N(1710)$ $N(1880)$	**N(1720)** $N(1900)$	**N(1535)** **N(1650)** $N(1895)$	**N(1520)** $N(1700)$ $N(1875)$
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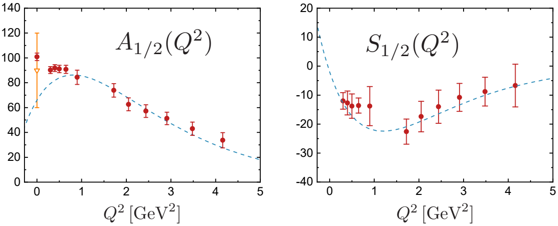


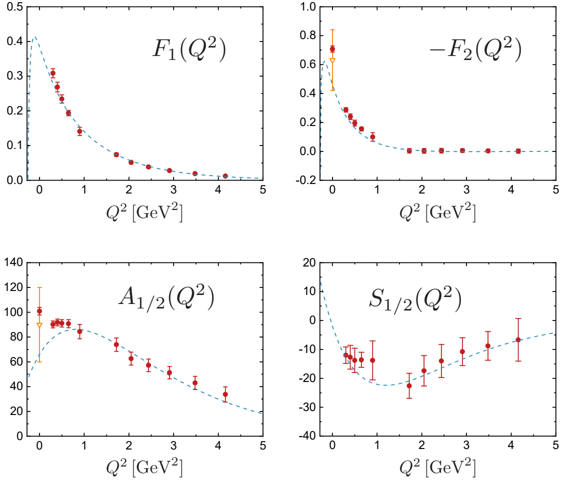
Example:
N(1535) helicity amplitudes

PDG

CLAS data
userweb.jlab.org/~mokeev/resonance_electrocouplings

MAID
Tiator, Drechsel, Kamalov, Vanderhaeghen, EPJ 198 (2011)

Nucleon resonances



N(1535) transition FFs:
no kinematic constraints

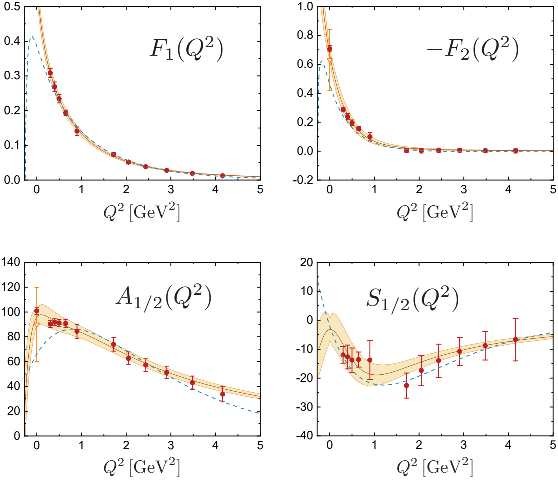
Example:
N(1535) helicity amplitudes

PDG

CLAS data
userweb.jlab.org/~mokeev/resonance_electrocouplings

MAID
Tiator, Drechsel, Kamalov, Vanderhaeghen, EPJ 198 (2011)

Nucleon resonances



N(1535) transition FFs:
no kinematic constraints

Fit

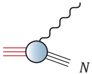
Example:
N(1535) helicity amplitudes

PDG

CLAS data
userweb.jlab.org/~mokeev/resonance_electrocouplings

MAID
Tiator, Drechsel, Kamalov, Vanderhaeghen, EPJ 198 (2011)

Nucleon resonances



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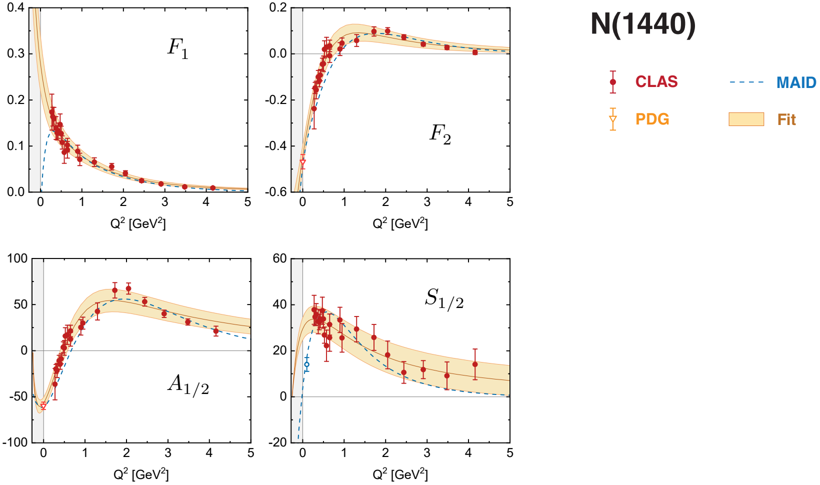
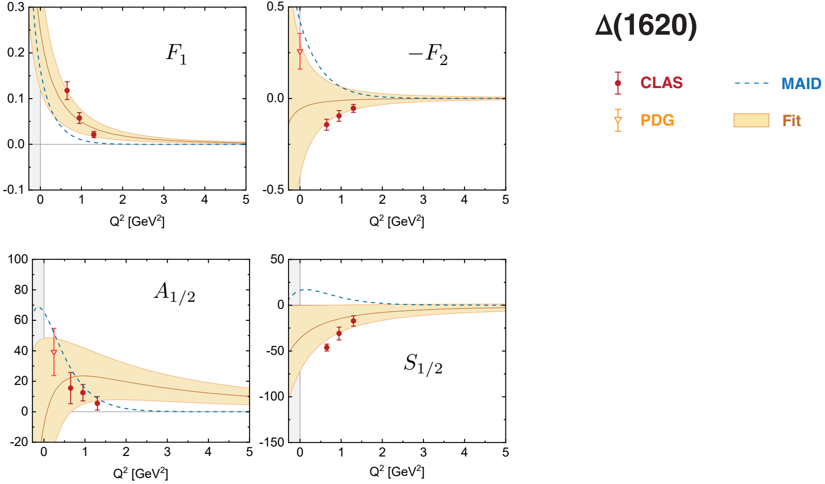
$\mathbf{N(940)}$	$\mathbf{N(1720)}$	$\mathbf{N(1535)}$	$\mathbf{N(1520)}$
$\mathbf{N(1440)}$	$N(1900)$	$\mathbf{N(1650)}$	$N(1700)$
$N(1710)$		$N(1895)$	$N(1875)$
$N(1880)$			
$\mathbf{\Delta(1910)}$	$\mathbf{\Delta(1232)}$	$\mathbf{\Delta(1620)}$	$\mathbf{\Delta(1700)}$
	$\Delta(1600)$	$\Delta(1900)$	$\Delta(1940)$
	$\Delta(1920)$		

Nucleon resonances

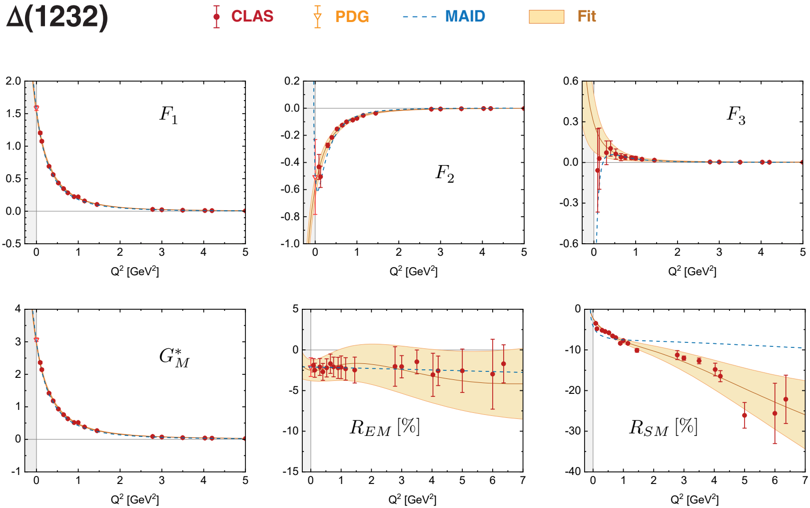


Nucleon resonances

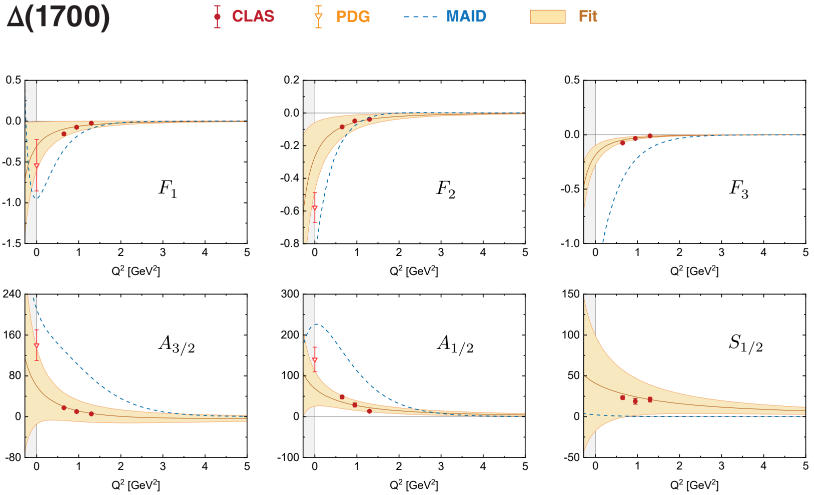


Nucleon resonances

Δ(1232)

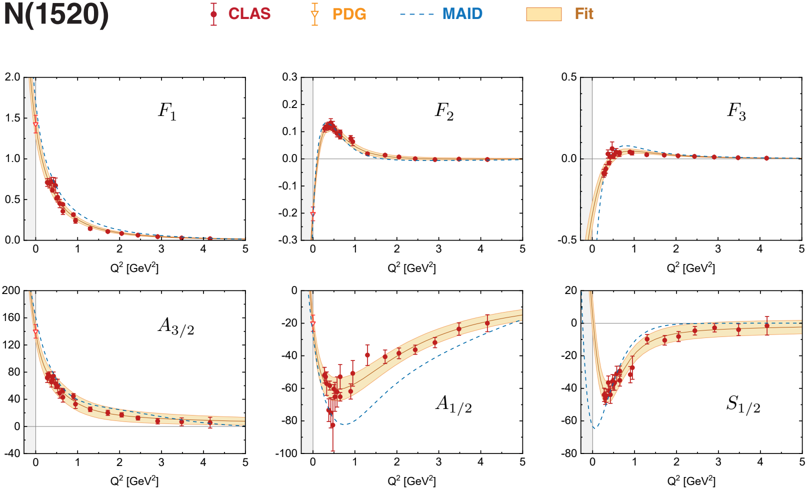


Nucleon resonances

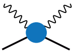


Nucleon resonances

N(1520)



Kinematics



$$= \sum_{i=1}^{18} c_i(\eta_+, \eta_-, \omega, \lambda)\, \bar{u}(p_f)\, X_i^{\mu\nu}(p, Q, Q')\, u(p_i)$$

18 CFFs

4 kinematic variables:

$$\eta_+ = \frac{Q^2+Q'^2}{2m^2}$$
$$\eta_- = \frac{Q\cdot Q'}{m^2}$$
$$\omega = \frac{Q^2-Q'^2}{2m^2}$$
$$\lambda = -\frac{p\cdot Q}{m^2}$$

18 Compton tensors,
form minimal basis

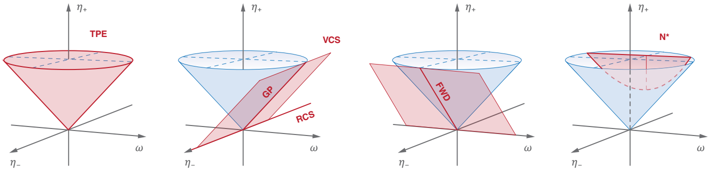
- systematic derivation
- similar to Tarrach basis
  Tarrach, Nuovo Cim. A28 (1975)

$$X_i' = U_{ij}\, X_j\,, \qquad \det U = const.$$

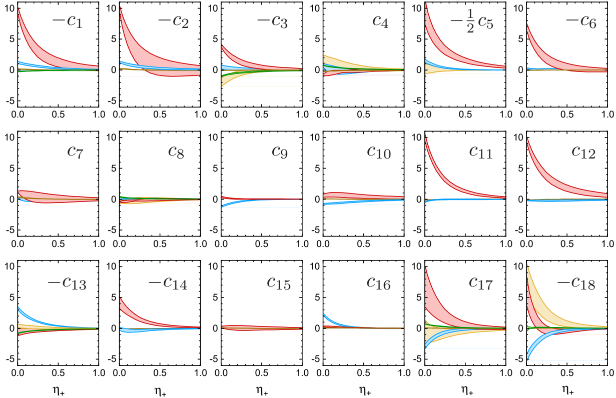
- CFFs free of kinematics

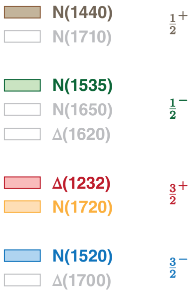
$$X_1^{\mu\nu} = \frac{1}{m^4}\, t^{\mu\alpha}_{Q'p}\, t^{\alpha\nu}_{pQ}\,,$$
$$X_2^{\mu\nu} = \frac{1}{m^2}\, t^{\mu\nu}_{Q'Q}\,,$$
$$X_3^{\mu\nu} = \frac{1}{m^4}\, t^{\mu\alpha}_{Q'Q'}\, t^{\alpha\nu}_{QQ}\,,$$
$$X_4^{\mu\nu} = \frac{1}{m^6}\, t^{\mu\alpha}_{Q'Q'}\, p^\alpha p^\beta\, t^{\beta\nu}_{QQ}\,,$$
$$X_5^{\mu\nu} = \frac{\lambda}{m^4}\left(t^{\mu\alpha}_{Q'Q'}\, t^{\alpha\nu}_{pQ} + t^{\mu\alpha}_{Q'p}\, t^{\alpha\nu}_{QQ}\right),$$
$$X_6^{\mu\nu} = \frac{1}{m^2}\, \varepsilon^{\mu\nu}_{Q'Q}\,,$$
$$X_7^{\mu\nu} = \frac{1}{im^3}\left(t^{\mu\alpha}_{Q'Q'}\, \varepsilon^{\alpha\nu}_{\gamma Q} - \varepsilon^{\mu\alpha}_{Q'\gamma}\, t^{\alpha\nu}_{QQ}\right),$$
$$X_8^{\mu\nu} = \frac{\omega}{im^3}\left(t^{\mu\alpha}_{Q'Q'}\, \varepsilon^{\alpha\nu}_{\gamma Q} + \varepsilon^{\mu\alpha}_{Q'\gamma}\, t^{\alpha\nu}_{QQ}\right),$$
$$\vdots$$

GE, Ramalho, 1806.04579

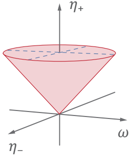


Compton form factors

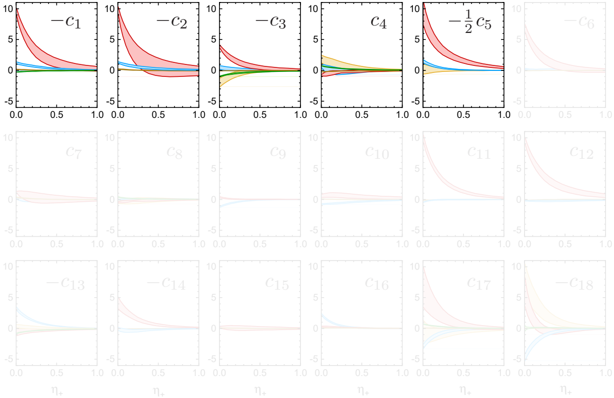




To be multiplied with $\dfrac{(m_R^2 - m^2)^2}{(s-m_R^2)(u-m_R^2)} = \dfrac{\delta^2}{(\eta_- + \delta)^2 - 4\lambda^2}$

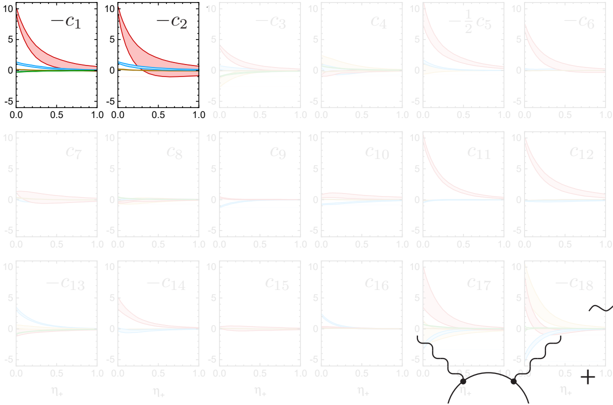


Compton form factors

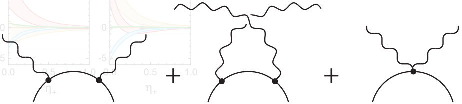


- CS on **scalar particle**

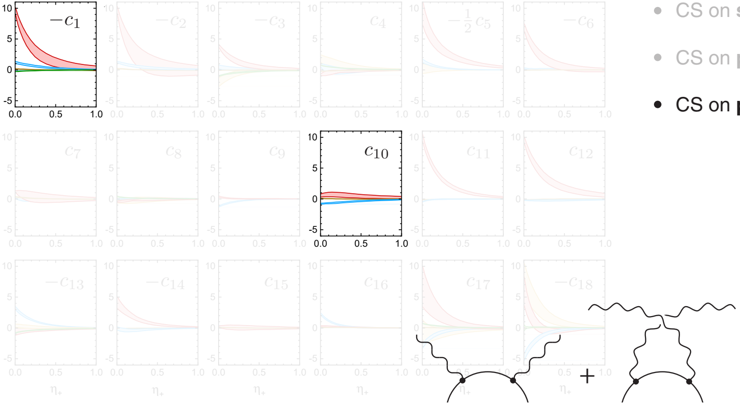
Compton form factors



- CS on **scalar particle**
- CS on **pointlike scalar**

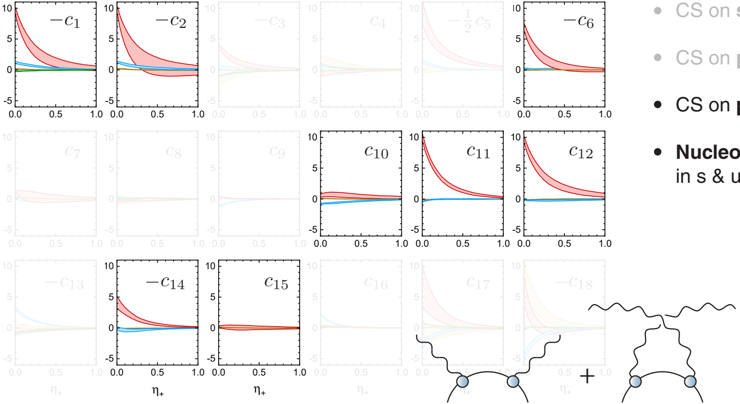


Compton form factors



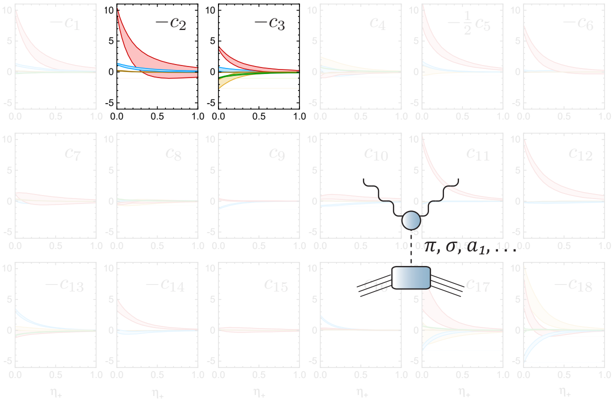
- CS on **scalar particle**
- CS on **pointlike scalar**
- CS on **pointlike fermion**

Compton form factors



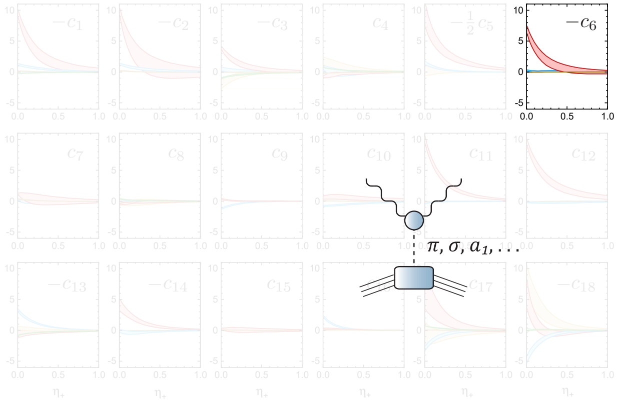
- CS on **scalar particle**
- CS on **pointlike scalar**
- CS on **pointlike fermion**
- **Nucleon Born poles** in s & u channel

Compton form factors

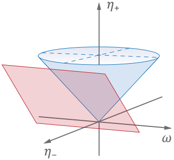


- CS on **scalar particle**
- CS on **pointlike scalar**
- CS on **pointlike fermion**
- **Nucleon Born poles** in s & u channel
- **Scalar pole** in t channel

Compton form factors

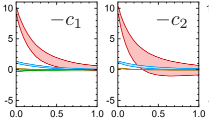


- CS on **scalar particle**
- CS on **pointlike scalar**
- CS on **pointlike fermion**
- **Nucleon Born poles** in s & u channel
- **Scalar pole** in t channel
- **Pion pole** in t channel ($\pi^0 \to \gamma^* \gamma^*$)



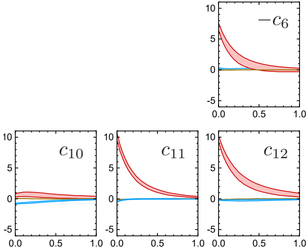
GE, Fischer, Weil, Williams, PLB 774 (2017)

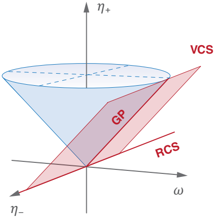
Polarizabilities



Scalar polarizabilities:

$$\begin{bmatrix} \alpha+\beta \\ \beta \end{bmatrix} = -\frac{\alpha_{\text{em}}}{m^3} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$



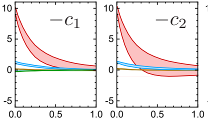


Spin polarizabilities:

$$\begin{bmatrix} \gamma_{E1E1} \\ \gamma_{M1M1} \\ \gamma_{E1M2} \\ \gamma_{M1E2} \end{bmatrix} = \frac{\alpha_{\text{em}}}{2m^4} \begin{bmatrix} c_6 + 4c_{11} - 4c_{12} \\ -c_6 - 2c_{10} + 4c_{12} \\ c_6 + 2c_{10} \\ -c_6 \end{bmatrix}$$

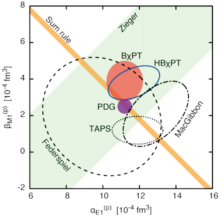
$$\begin{bmatrix} \gamma_0 \\ \gamma_\pi \end{bmatrix} = -\frac{2\alpha_{\text{em}}}{m^4} \begin{bmatrix} c_{11} \\ c_6 + c_{10} + c_{11} - 2c_{12} \end{bmatrix}$$

Polarizabilities

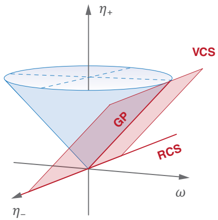


Scalar polarizabilities:

$$\begin{bmatrix} \alpha+\beta \\ \beta \end{bmatrix} = -\frac{\alpha_{\text{em}}}{m^3} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$



Hagelstein, Miskimen, Pascalutsa,
Prog. Part. Nucl. Phys. 88 (2016)

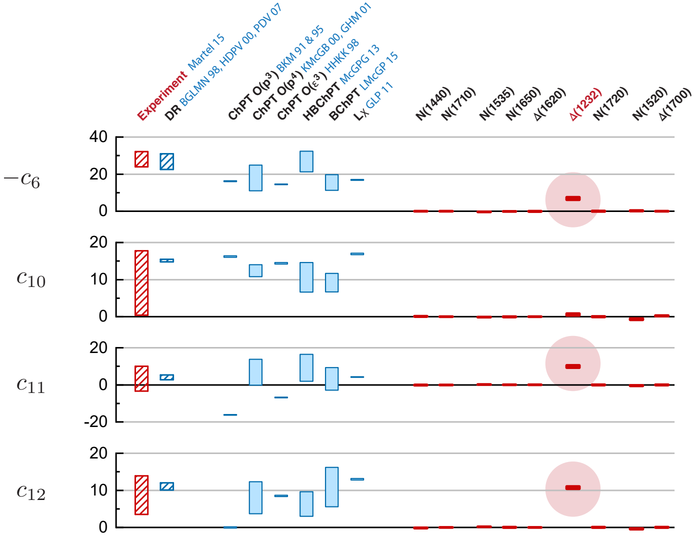


PDG:

$-c_1 = 20.3(4)$
$-c_2 = \ \ 3.7(6)$

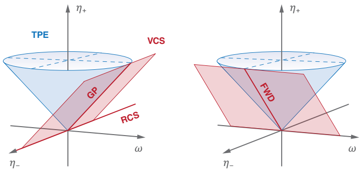
Large **Δ(1232)** contribution,
but also **N(1520)** non-negligible

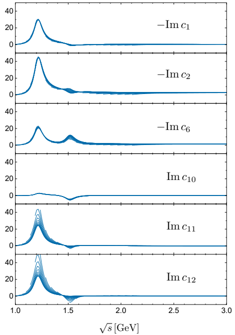
Spin polarizabilities



Only $\Delta(1232)$ important

General kinematics

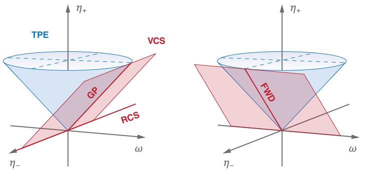




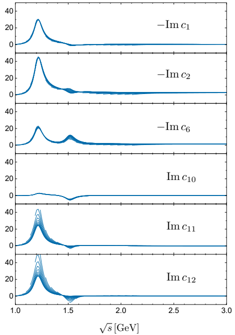
Resonance contributions in **RCS**

- Lorentz-invariant PW analyses?

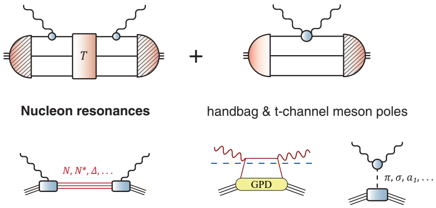
General kinematics



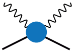
- Lorentz-invariant PW analyses?
- With minimal basis, only physical singularities; if no physical singularities, no momentum dependence!



Resonance contributions in **RCS**

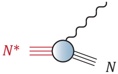


Compton scattering



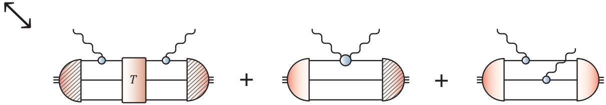
- kinematic variables
- tensor basis
- constraint-free **Compton FFs**

GE, Ramalho, 1806.04579

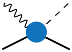


- general offshell transition vertices
- constraint-free **transition FFs**
- fits for transition FFs

- impact of higher resonances on Compton FFs
- only **Δ(1232)** and **N(1520)** relevant for polarizabilities



Meson electroproduction?



- kinematic variables
- tensor basis
- constraint-free **electroproduction amplitudes**
  GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016)

How important is the **“QCD background”**?