Two-photon exchange processes in e+-N scattering in resonance region: Analysis using 1/Nc expansion

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Jefferson Lab

Computed target normal single-spin asymmetry from two-photon exchange (TPE) in inclusive scattering $eN \rightarrow e'X$ (and elastic scattering $eN \rightarrow e'N$) in resonance region $\sqrt{s} \lesssim$ 1.5 GeV

Used systematic method based on 1/Nc expansion of QCD: Parametric expansion, controlled accuracy, N and Δ states related by spin-flavor symmetry

Planning several applications/extensions relevant to JLab positron program:
Beam normal spin asymmetry, e+- charge asymmetry, duality DIS — resonance region

J.L. Goity, C. Weiss, C.T. Willemyns, Phys. Lett. B 835, 137580 (2022) [INSPIRE]

J.L. Goity, C. Weiss, C.T. Willemyns, Phys. Rev. D 107, 094026 (2023) [INSPIRE]

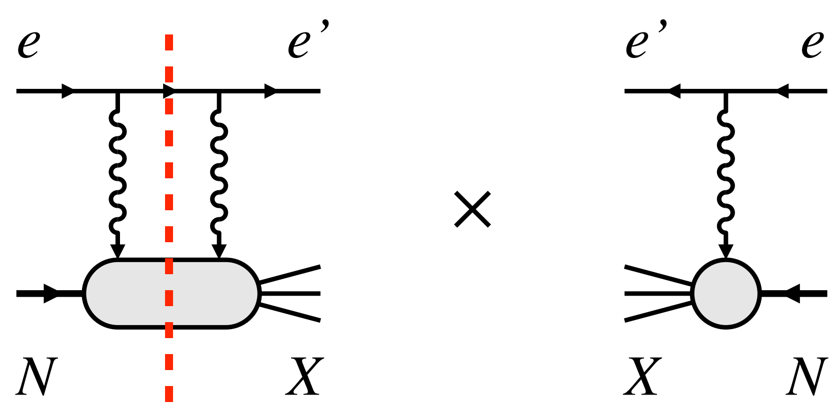
Two-photon exchange

TPE has become field or research in its own right

Elastic ep cross section: TPE as radiative correction, involves Re(TPE) and Im(TPE)
Much theoretical work, situation still inconclusive

Direct measurements: $e^{\pm}N$ charge asymmetry, $eN(\uparrow)$ target normal spin asymmetries

Target normal single-spin asymmetry



$eN \to e'X$ inclusive

$eN \to e'N$ elastic

$$A_N = \frac{\sigma\!\uparrow - \sigma\!\downarrow}{\sigma\!\uparrow + \sigma\!\downarrow}$$

Zero at $O(\alpha^2)$, pure $O(\alpha^3)$ effect

Interference on one- and two-photon exchange
Also contribution from Bethe-Heitler - Virtual Compton interference

Involves only Im(TPE): Finite integral, on-shell amps

Inclusive or elastic scattering

Can be measured in wide kinematic range:
Low-energy — resonance region— DIS

Normal spin asymmetry in inclusive eN scattering

Theoretical calculations

DIS region: QCD mechanism based on vacuum structure. Afanasev, Strikman, Weiss 2008
Various pQCD-based mechanisms. Metz, Schlegel, Goeke 2006; Metz et al. 2012; Schlegel 2013
Large variations $A_N \sim 10^{-4} - 10^{-2}$

A_N(DIS) $\ll$ A_N(low-energy elastic) because anomalous magnetic moment of quark $\ll$ nucleon

How does transition from low-energy to DIS regime happen? Need to explore resonance region!

Experiments

HERMES 2014: p target, $W >$ 2 GeV, $A_N \sim 10^{-2}$

JLab Hall A Katich et al. 2014: 3He target, $W =$ 1.7-2.9 GeV, $A_N \sim 10^{-2}$

Proposal JLab Hall A Grauvogel, Kutz, Schmidt 2021: p target, E_e = 2.2, 4.4, 6.6 GeV

Resonance region

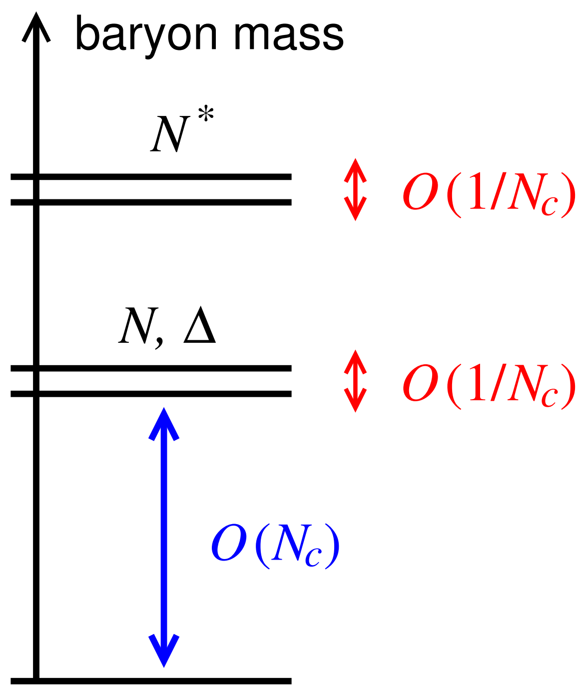
N, Δ, N^* + nonresonant πN as final states and intermediate states in TPE

Need to combine contributions of channels at amplitude level — cancellations?

Need transition currents $\langle \Delta | J | N \rangle$, $\langle \Delta | J | \Delta \rangle$ etc.

Develop systematic approach based on 1/Nc expansion!

1/Nc expansion: Basics



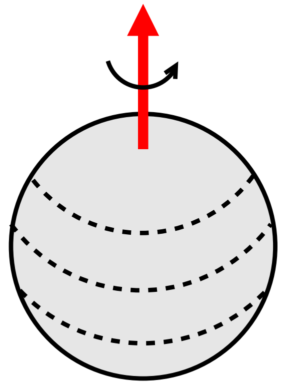
Large-N_c limit of QCD

Semiclassical limit of QCD 'tHooft 1974, Witten 1979

Hadron masses, couplings, matrix elements scale in N_c
"Organization" of non-perturbative dynamics

Emerging dynamical spin-flavor symmetry $SU(2N_f)$
Baryons in multiplets with masses $O(N_c)$, splittings $O(1/N_c)$
Gervais, Sakita 1984; Dashen, Manohar, Jenkins 1993

$N \rightarrow N$ and $N \rightarrow \Delta$ transitions related by symmetry:
$\langle \Delta | \mathcal{O} | N \rangle \;=\;$ [symmetry factor] $\times \langle N | \mathcal{O} | N \rangle$



$1/N_c$ expansion of hadronic matrix elements

Parametric expansion: Systematic, predictive, controlled accuracy

Applied to current matrix elements, hadronic amplitudes
Vector and axial currents: Fernando, Goity 2020

1/Nc expansion: Currents

Generators of spin-flavor group algebra: $\hat{S}^i, \hat{I}^a, \hat{G}^{ia}$

Matrix elements between ground-state baryons from symmetry:

$$\langle B(S', S'_3, I'_3) \,|\, \ldots \,|\, B(S, S_3, I_3) \rangle = \text{fun}(N_c) \times \text{Clebsches} \qquad S, S' = 1/2,\, 3/2 \qquad B = N, \Delta$$

EM current operator expressed through generators:

$$J^\mu_S(q) = G^S_E(q^2)\frac{1}{2}g^{\mu 0} - i\frac{1}{2}\frac{G^S_M(q^2)}{\Lambda}\epsilon^{0\mu ij}q^i\hat{S}^j,$$

$$J^{\mu a}_V(q) = G^V_E(q^2)\hat{I}^a g^{\mu 0} - i\frac{6}{5}\frac{G^V_M(q^2)}{\Lambda}\epsilon^{0\mu ij}q^i\hat{G}^{ja},$$

$$J^\mu_{\text{EM}}(q) = J^\mu_S(q) + J^{\mu 3}_V(q),$$

$q^0 = \mathcal{O}(N_c^{-1}),\ q^i = \mathcal{O}(N_c^0)$ momentum transfer

$G^{V,S}_{E,M}(q^2)$ form factors

Expresses parametric expansion in $1/N_c$

Charges/form factors fixed from $N \to N$ matrix elements

Predicts $N \to \Delta$ and $\Delta \to \Delta$ matrix elements

Kinematic variables in inclusive electron scattering

$$e(k) + N(p) \to e(k') + X(p')$$

$s = (k+p)^2$ CM energy

$q^2 = (k-k')^2$ momentum transfer

$M_X^2 = p'^2 = (p+q)^2$ final-state mass

Kinematic regimes in 1/Nc expansion

	Energy regime	$1/N_c$ expansion regime	Channels open	Final states possible
I	$m_N < \sqrt{s} < m_\Delta$	$\sqrt{s} - m_N \sim N_c^{-1}, \; k \sim N_c^{-1}$	N	elastic
II	$m_\Delta < \sqrt{s} \ll m_{N*}$	$\sqrt{s} - m_N \sim N_c^{-1}, \; k \sim N_c^{-1}$	N, Δ	elastic or inelastic
III	$m_\Delta < \sqrt{s} \lesssim m_{N*}$	$\sqrt{s} - m_N \sim N_c^{0}, \quad k \sim N_c^{0}$	N, Δ, N^*(suppr)	elastic or inelastic

"low energies" (I, II)

"intermediate energies" (III)

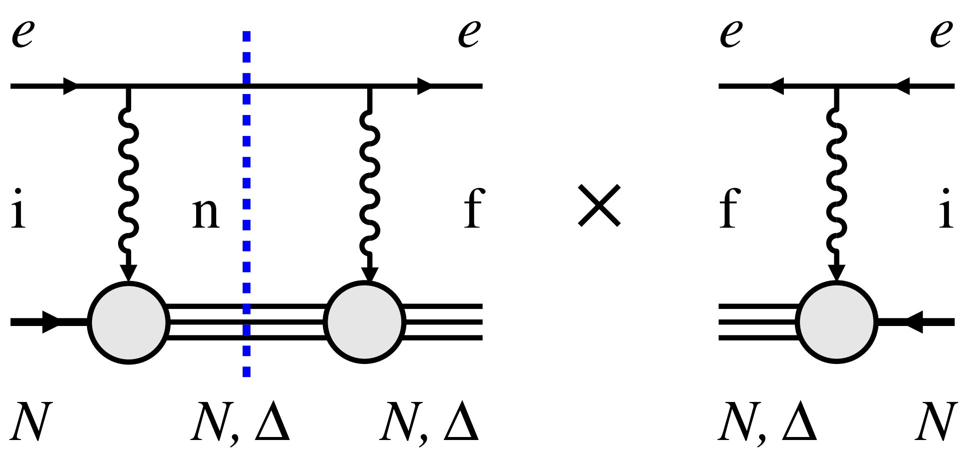
$k = (s - m^2)/2\sqrt{s}$ CM momentum

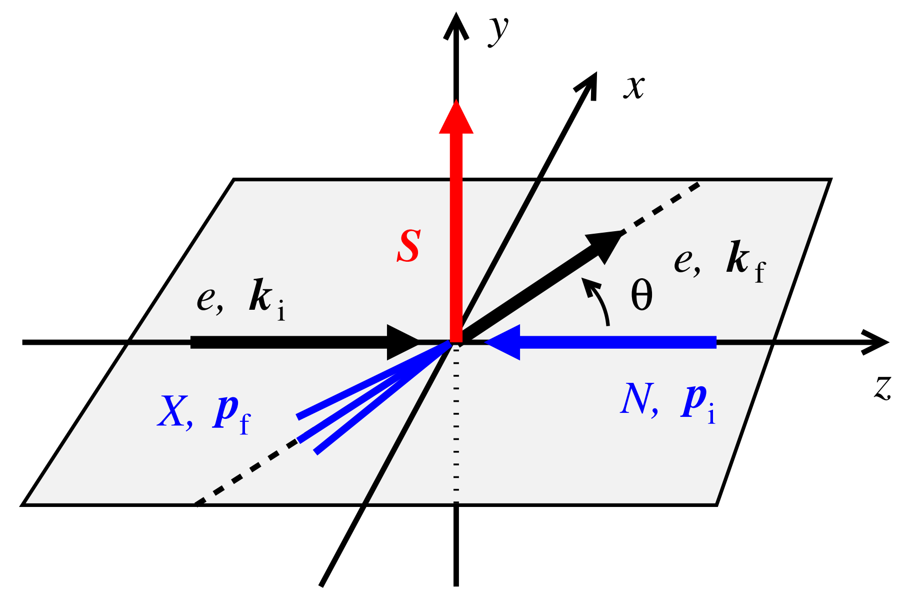
Expansion can be applied in different kinematic regimes: Different "focus", reach, accuracy

Systematic calculation, defined accuracy, could be improved by higher-order corrections

Non-resonant πN states suppressed in $1/N_c$ relative to Δ

1/Nc expansion: Calculation





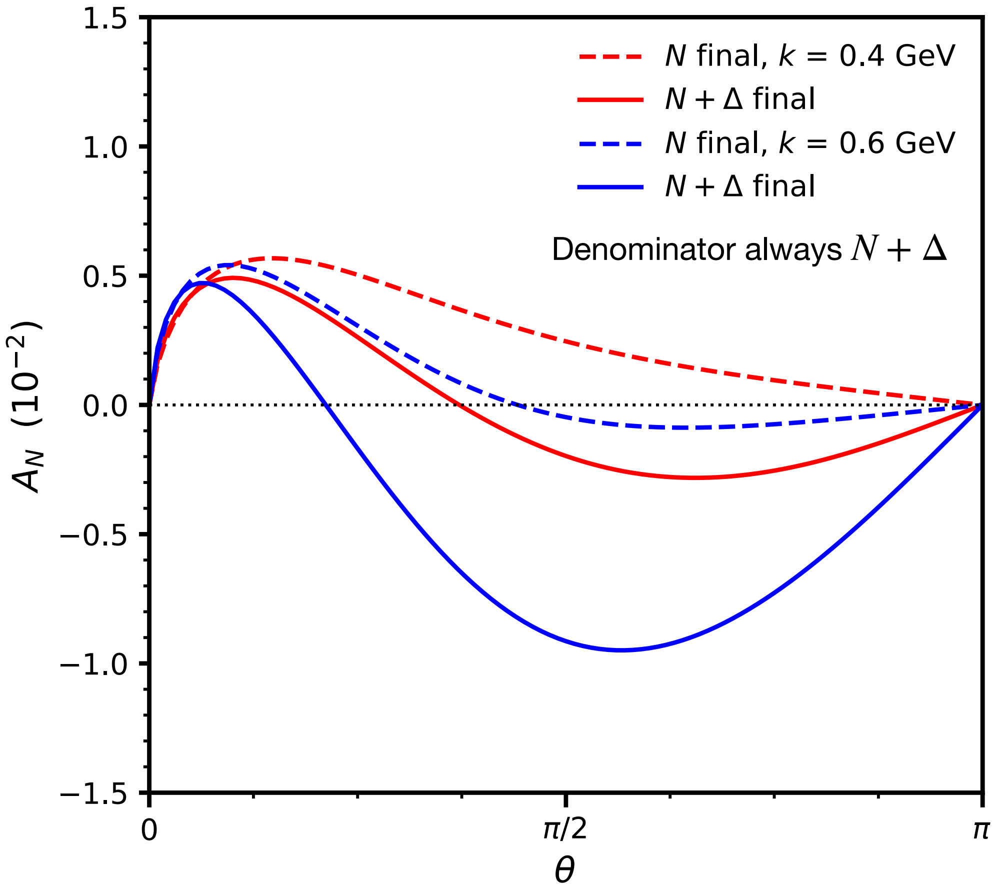
Calculate $eB \to e'B'$ amplitudes for $B, B' = N, \Delta$ with $1/N_c$-expanded currents

Integrate over phase space of intermediate state in TPE

Sum over intermediate and final states

Project out normal-spin dependent part of cross section

Results: A_N at intermediate energies



A_N at intermediate energies (regime III)
LO 1/Nc expansion result

Valid for 1.23 GeV $< \sqrt{s} \lesssim$ 1.5 GeV

or 0.3 GeV $< k \lesssim$ 0.6 GeV,

and $\theta \sim \pi/2$ "large angle"

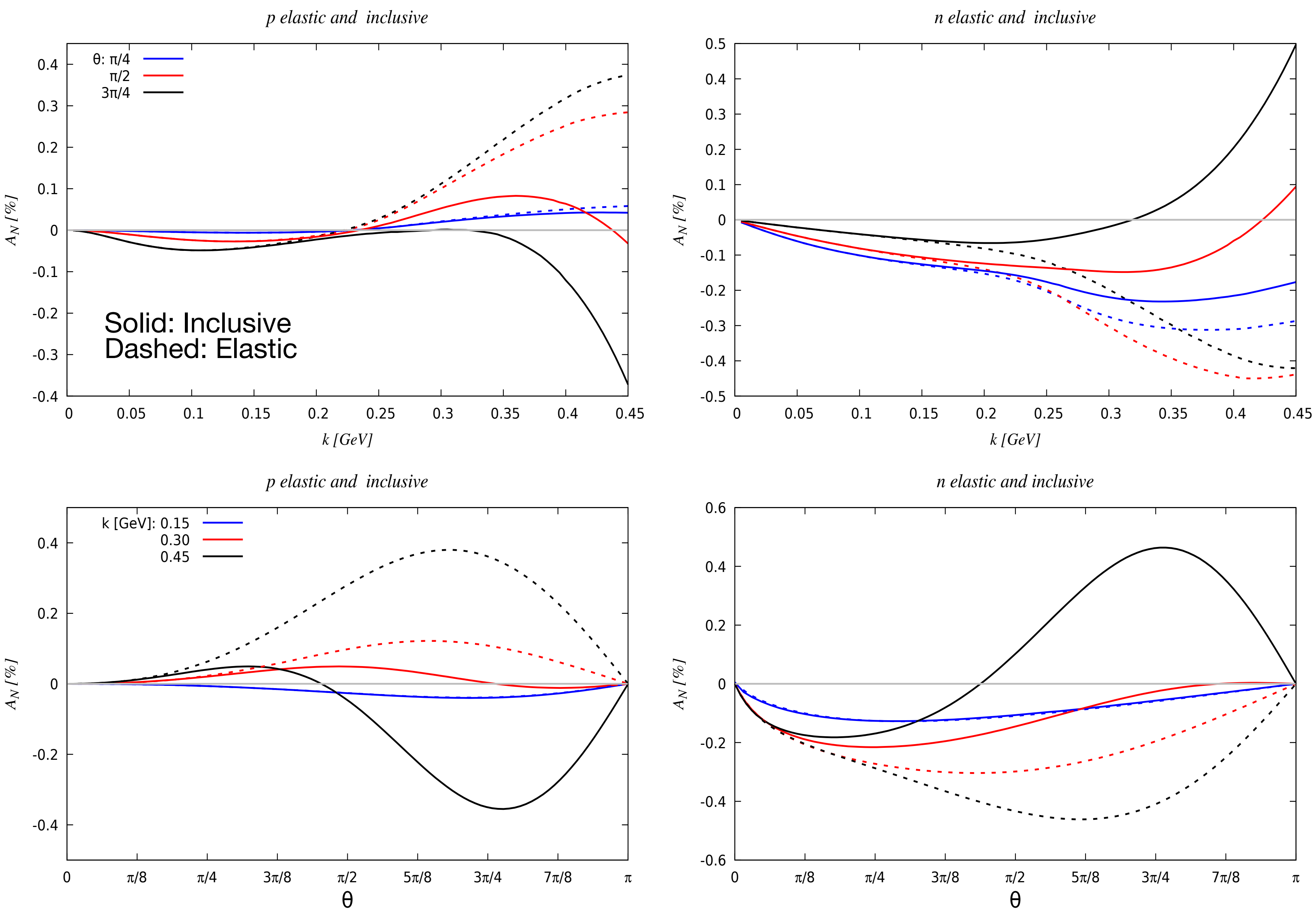
$A_N \sim 10^{-2}$ predicted in intermediate-energy regime

Large contribution of Δ final states at angles $\theta \sim \pi/2$, could be tested experimentally!

LO 1/Nc expansion result: All transition currents magnetic isovector G^{ia}, simple structure.
Electric currents come in at higher orders

A_N is overall isovector: A_N(proton) = $-A_N$(neutron)

Results: A_N at low energies



A_N at low energies (regimes I and II)

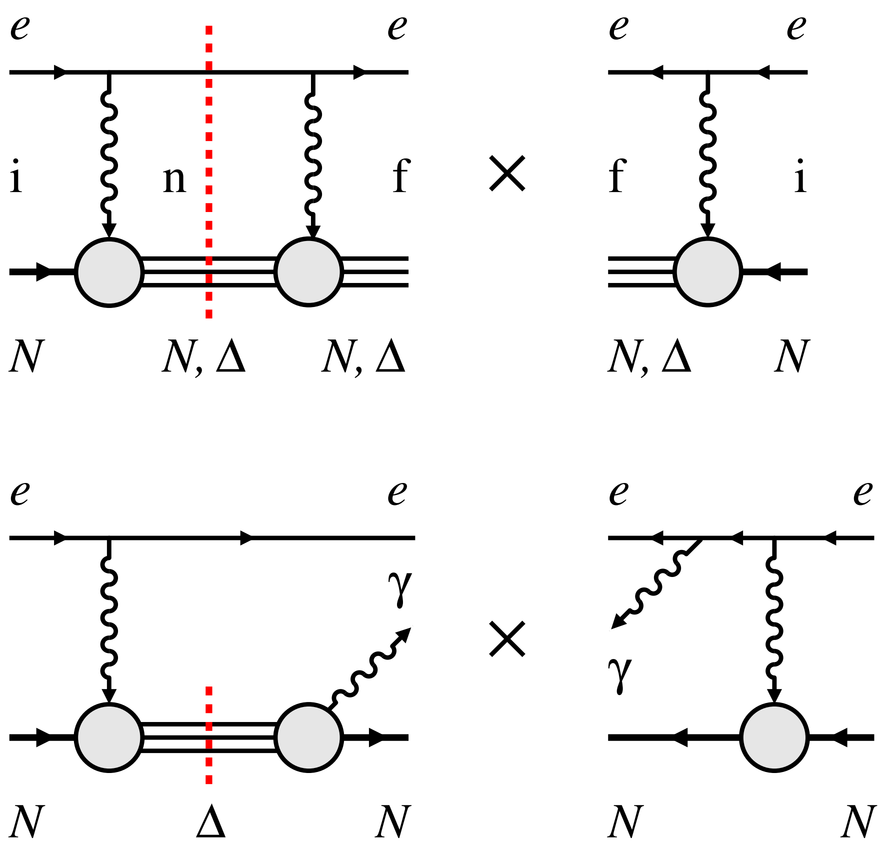
LO + NLO $1/N_c$ expansion result

Includes finite Δ width

A_N rises steeply as function of energy above Δ threshold (here: CM momentum k)

Large contribution of Δ final states

Results: Real photon emission



A_N in inclusive eN scattering also receives contribution from real photon emission channel

Interference of Virtual Compton Scattering and Bethe-Heitler amplitudes

Im (VCS) $\neq 0$ above Δ threshold

$1/N_c$ expansion: Real photon emission process suppressed by $1/N_c$ relative to TPE

$1/N_c$ expansion guides analysis and interpretation of TPE processes

Summary

Computed/analyzed A_N from TPE in eN scattering in resonance region
in systematic approach based on $1/N_c$ expansion

A_N predicted to be $\sim 10^{-2}$, should be measurable

Interesting features that could be studied experimentally

→ Discussion

Separate contributions of N and Δ final states in spin-dependent cross section (= numerator)

Energy and angular dependence of spin-dependent cross section and A_N

Isospin dependence proton-neutron of spin-dependent cross section and A_N

Transition from resonance to DIS region - qualitative changes?

Possible theoretical improvements

Higher-order $1/N_c$ corrections in intermediate-energy regime → N^* states, real γ emission

Combined chiral and $1/N_c$ expansion in low-energy regime → πN states

Applications and extensions

$1/N_c$ expansion enables systematic approach to eN scattering in resonance region:
Organizes kinematics, channels $\Delta \leftrightarrow \pi N$, currents, calculation

Applications to TPE and positron physics

Beam normal spin asymmetry: Pure TPE effect, $\propto m_{\text{lepton}}$, enhanced by collinear logarithm

Charge asymmetry of $e^{\pm}N$ cross section: Involves also Re(TPE), obtained dispersion integral

Electroweak processes, γZ exchange

Applications to hadronic physics

Transition between resonance and DIS regions, quark-hadron duality

Spin effects in intermediate-energy eN scattering