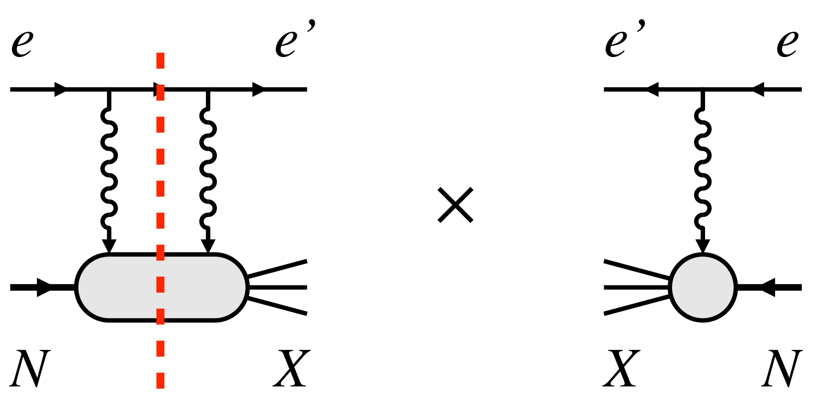
Spin effects in two-photon exchange processes in the resonance and DIS regions

C. Weiss (JLab), Positron Working Group Workshop, GWU, 18-20 March 2024

Jefferson Lab



X inclusive

$X = N$ elastic

$X = \Delta, N^*$ inelastic

J.L. Goity, C. Weiss, C.T. Willemyns,
Phys. Lett. B 835, 137580 (2022) [INSPIRE],
Phys. Rev. D 107, 094026 (2023) [INSPIRE]

A. Afanasev, M. Strikman, C. Weiss,
Phys. Rev. D 77, 014028 (2008) [INSPIRE]

Target normal single-spin asymmetry

Pure two-photon exchange effect

Inclusive or elastic/inelastic scattering

Theoretical analysis

Resonance region Δ, N^*: $1/N_c$ expansion

DIS region: Quark-based mechanisms

Transition: Duality, anomalous magnetic moment

Experimental opportunities

Proposed measurements

Connection with positron program

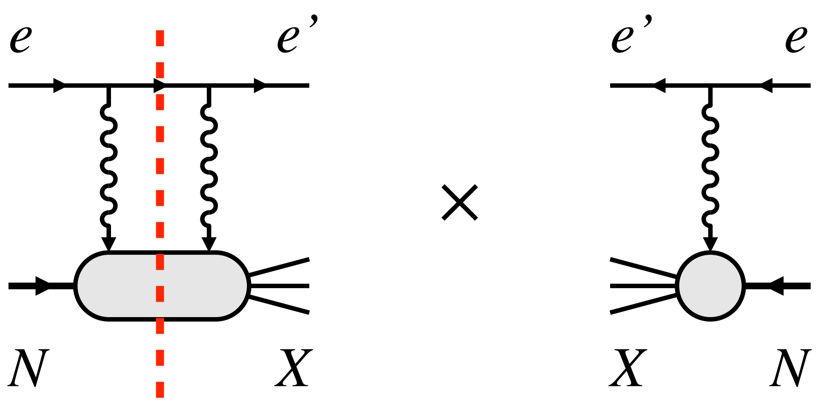
Two-photon exchange and target normal SSA

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



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

X inclusive

$X = N$ elastic, $X = \Delta, N^*$ inelastic

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

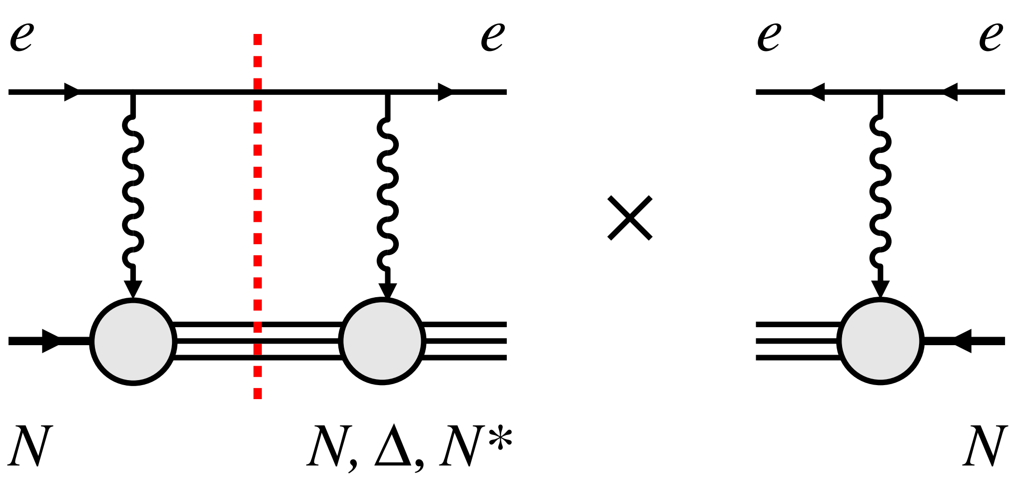
Interference on one- and two-photon exchange
Also contribution from Bethe-Heitler - Virtual Compton interference

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

Inclusive or elastic/inelastic scattering

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

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?

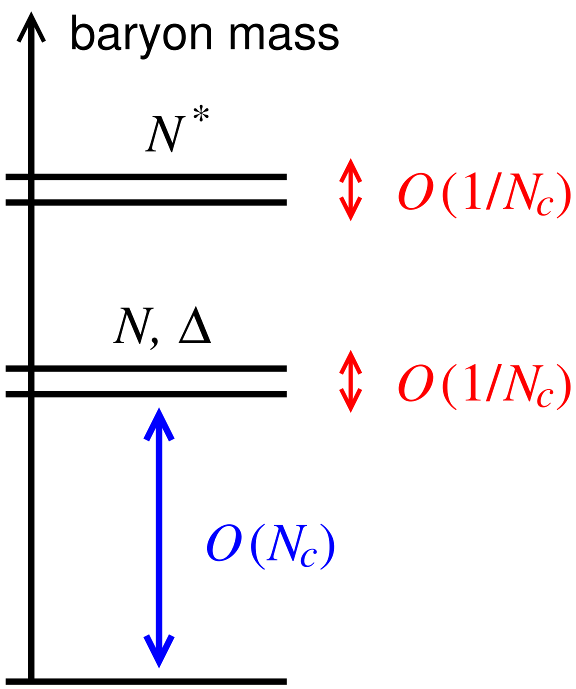
Need transition currents $\langle \Delta \,|\, J \,|\, N \rangle$, $\langle \Delta \,|\, J \,|\, \Delta \rangle$ etc.

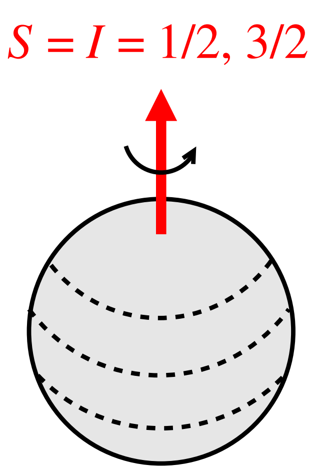
Develop systematic approach based on 1/Nc expansion

J.L. Goity, C. Weiss, C.T. Willemyns 2022/2023

Elastic channel: Calculation using empirical amplitudes Ahmed, Blunden, Melnitchouk 2023

Resonance region: 1/Nc expansion





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

$N \to N$ and $N \to \Delta$ 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

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

Matrix elements between ground-state baryons from symmetry:

$\langle B(S', S'_3, I'_3) \,|\, \dots \,|\, B(S, S_3, I_3) \rangle$ = fun(N_c) × Clebsches $\quad S, S' = 1/2,\ 3/2 \quad B = N, \Delta$

EM current operators expanded in generators:

$$J^0, J^i \;=\; \sum G(q^2) \times \{\hat{S}^i, \hat{I}^a, \hat{G}^{ia}\}$$

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

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

isovector/isoscalar

Expresses parametric expansion in $1/N_c$

Form factors fixed from $N \to N$ matrix elements

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

Resonance region: Kinematic regimes

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

$s = (k+p)^2$	CM energy
$q^2 = (k-k')^2$	momentum transfer
$M_X^2 = p'^2 = (p+q)^2$	final-state mass

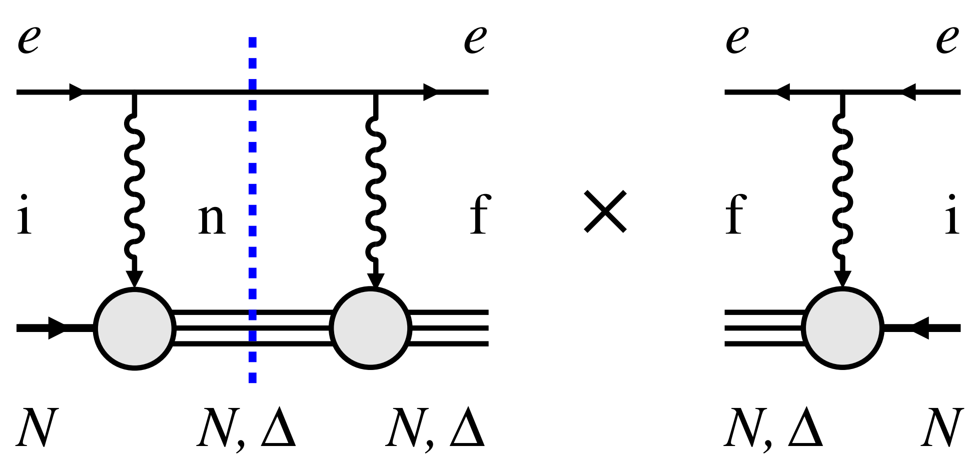
	Energy regime	1/Nc expansion regime	Channels open
"low energy"	$m_\Delta < \sqrt{s} \ll m_{N*}$	$\sqrt{s} - m_N \sim N_c^{-1}, \quad k_{\rm cm} \sim N_c^{-1}$	N, Δ
"intermediate"	$m_\Delta < \sqrt{s} \lesssim m_{N*}$	$\sqrt{s} - m_N \sim N_c^{0}, \quad k_{\rm cm} \sim N_c^{0}$	$N, \Delta, N*$

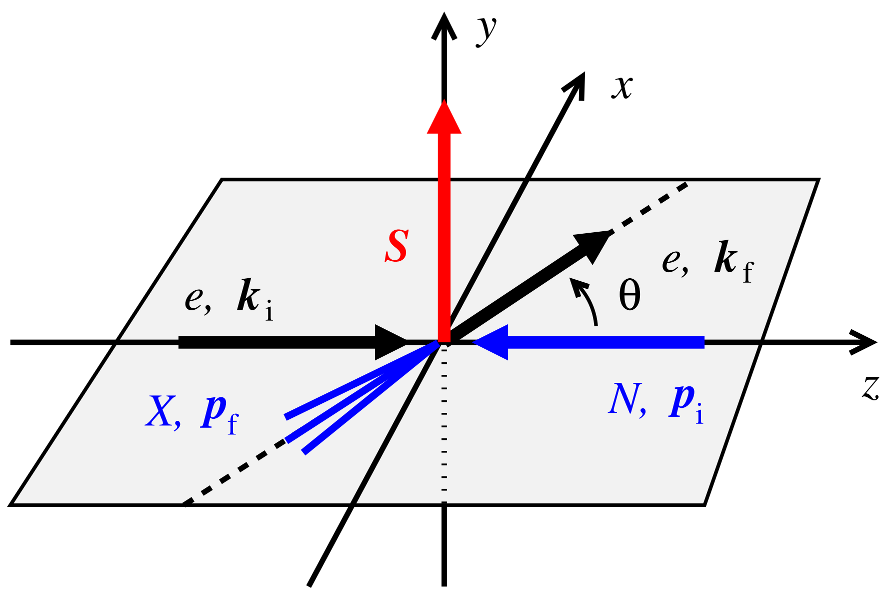
1/Nc expansion can be applied in different kinematic regimes: Different "focus", reach, accuracy

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

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

Resonance region: Calculation





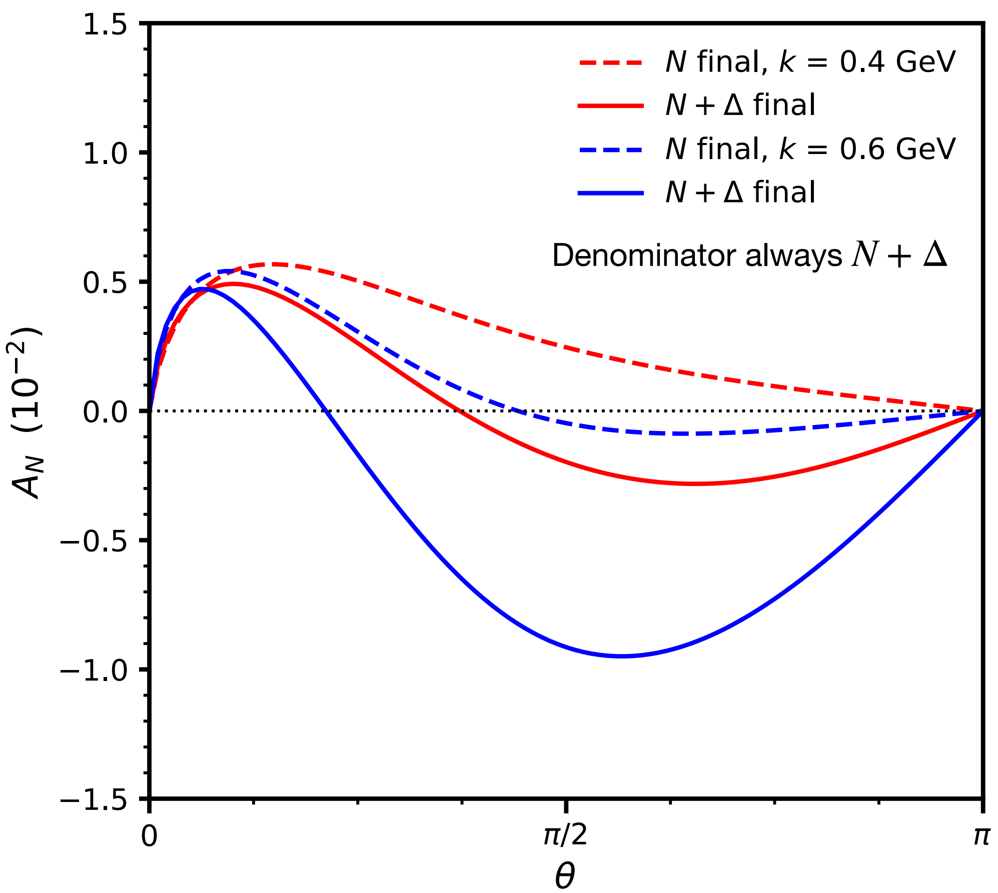
Calculate $eB \to e'B'$ amplitudes for $B, B' = N, \Delta$ with $1/N_c$-expanded currents

Integrate over phase space of intermediate state in TPE

Sum over intermediate and final states

Project out normal-spin dependent part of cross section

Resonance region: Results



A_N at intermediate energies

LO 1/Nc expansion result

Valid for 1.23 GeV $< \sqrt{s} \lesssim$ 1.5 GeV (+ higher)

and $\theta \sim \pi/2$ “large angle”

[Low energies → see supplement]

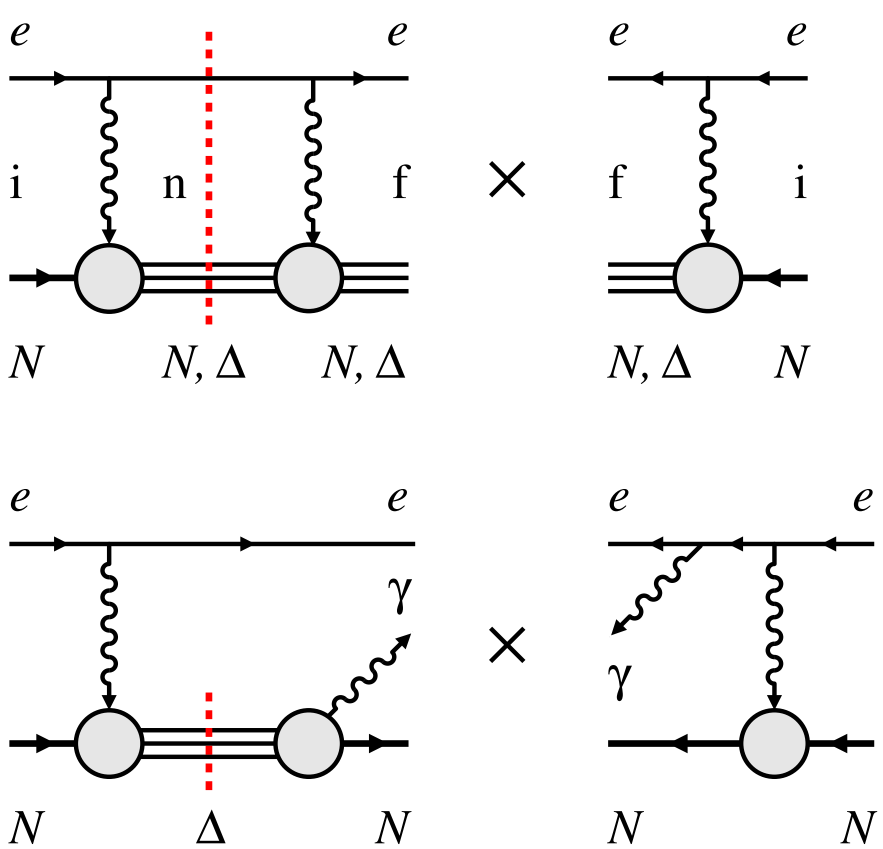
$A_N \sim 10^{-2}$ predicted in intermediate-energy regime

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)

Resonance region: Real photon emission



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

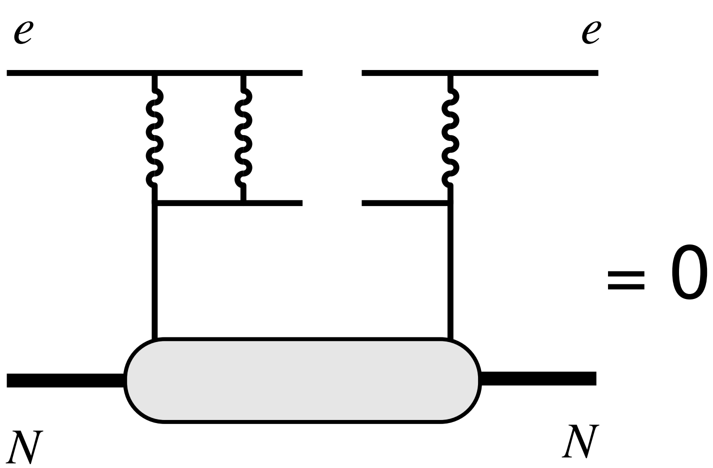
Interference of Virtual Compton Scattering and Bethe-Heitler amplitudes

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

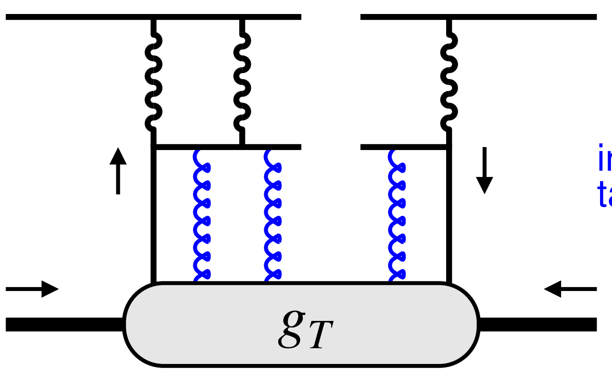
DIS region: Mechanisms for SSA



Unpolarized DIS cross section from high-momentum scattering on single quark: Factorization, PDF

TPE amplitude needs to “interfere” - same final state

Possible mechanisms for SSA

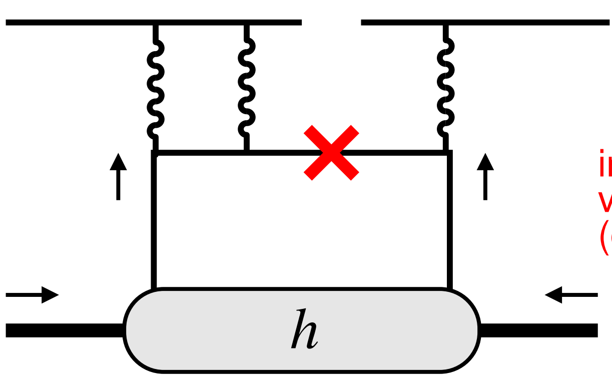


TPE with interaction of quark with target fields: $g_T(x)$ twist-3

Metz, Schlegel, Goeke 2006

TPE with chirality flip of quark through interaction with vacuum fields: $h(x)$ transversity + quark mass

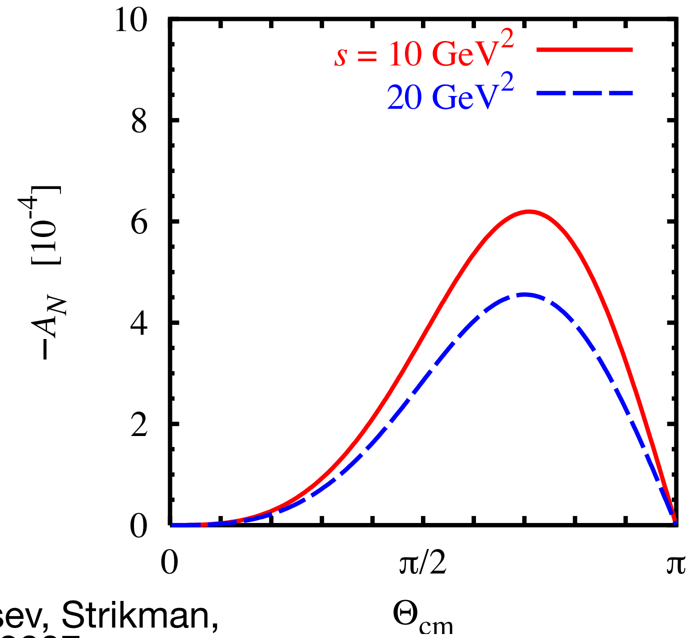
Afanasev, Strikman, Weiss 2007



TPE involving multiple quarks: Multiquark distributions

Schlegel 2013

DIS region: Predictions and measurements



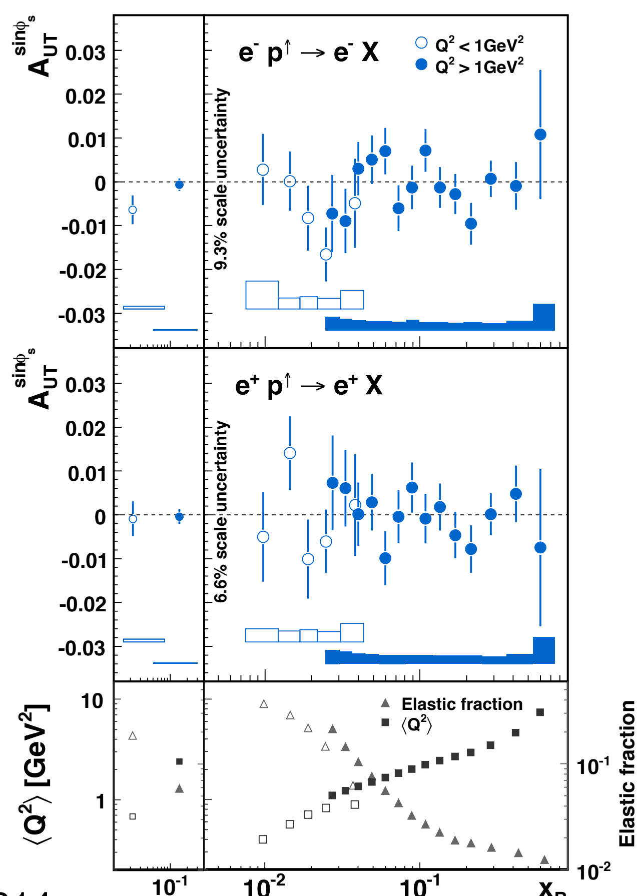
Afanasev, Strikman, Weiss 2007

Predictions for SSA

Quark chirality-flip mechanism $A_N \lesssim 10^{-3}$

Multiquark mechanism $A_N \sim 10^{-2}$

Wide range of numerical predictions



HERMES 2014

Measurements

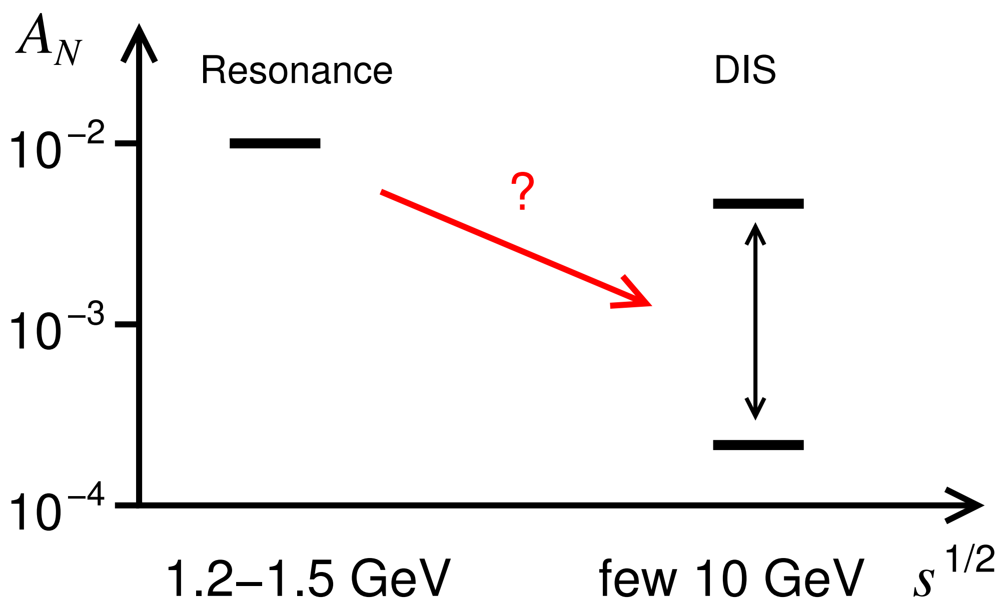
HERMES 2014: p target, $W > 2$ GeV,
$A_N \sim 10^{-2}$, consistent with zero

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

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

Proposal JLab CLAS12: Schmidt et al 2023

DIS region: Predictions and measurements



Resonance region: $A_N \sim 10^{-2}$, solid predictions

DIS region: $A_N \sim 10^{-2} - 10^{-4}$, large uncertainties

Follow transition!

Experiments should measure

Contributions of Δ, N^* final states to A_N; M_X evolution at fixed s, Q^2: Elastic → inelastic

s and Q^2 dependence of A_N: Low → high energies/momenta

Isospin dependence?

New area of quark-hadron duality

Quark single-particle scattering — resonance excitation

Emergence of anomalous magnetic moment: Quark << Nucleon

Summary

A_N as pure TPE observable, in inclusive or elastic/inelastic scattering

Resonance region analyzed in 1/Nc expansion: Systematic, controlled accuracy.
$A_N \sim 10^{-2}$, large contribution from Δ final state

DIS region: Various quark-based mechanisms, wide range of predictions
$A_N \sim 10^{-3} - 10^{-2}$

Experiment should measure M_X and s, Q^2 evolution!
Test proposed mechanisms in DIS region; new area of quark-hadron duality

Complementary to positron measurements

Theoretical improvements in 1/Nc analysis of resonance region

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

1/Nc expansion: Further applications

$1/N_c$ 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

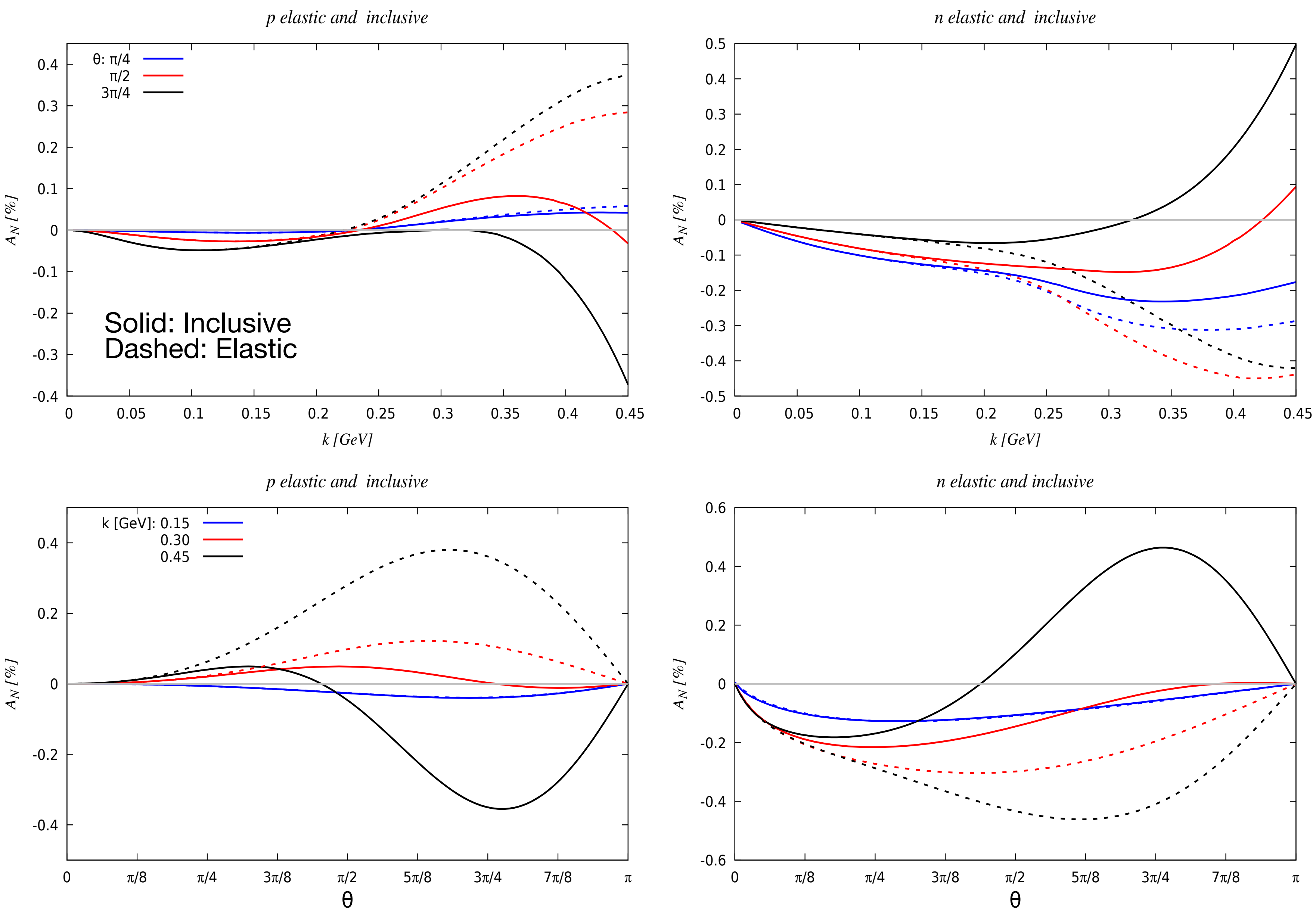
Electroweak processes, γZ exchange

Applications to hadronic physics

Transition between resonance and DIS regions, quark-hadron duality

Spin effects in intermediate-energy eN scattering

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