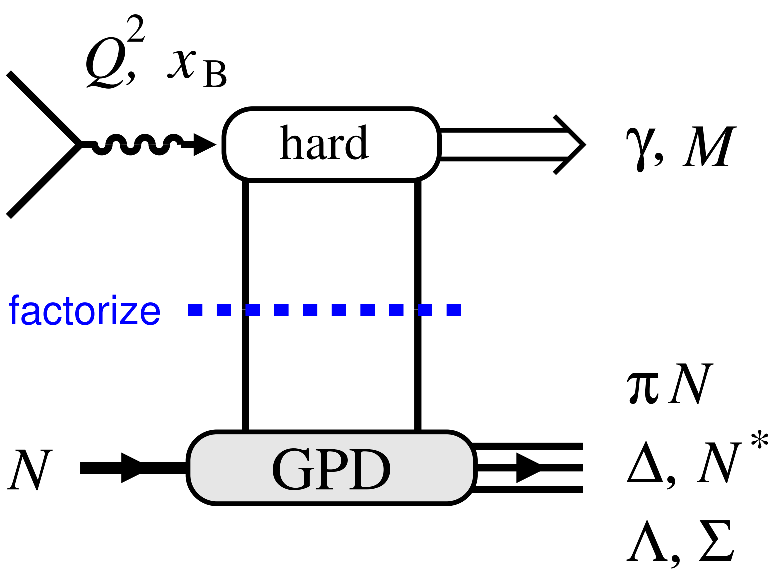
Transition GPDs

C. Weiss (Jefferson Lab), Towards improved hadron femtography with hard exclusive reactions, Jefferson Lab, 7-11 Aug 2023 [Webpage]



This presentation

Overview of concepts, methods, processes

Applications to JLab12+ and EIC

Much progress in theory

First results from JLab12 → **Talk K. Joo**

Motivation

Structure ↔ excitations in QM systems

Transition GPDs

Factorization → QCD operators

Transition matrix elements $N \to \pi N$, resonances

Chiral dynamics, $1/N_c$ expansion ←

EM tensor and mechanical properties ←

Processes

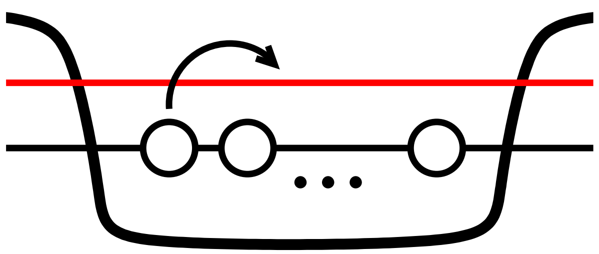
$N \to \Delta$ in DVCS ←

$N \to \Delta, N^*$ in π, η production ←

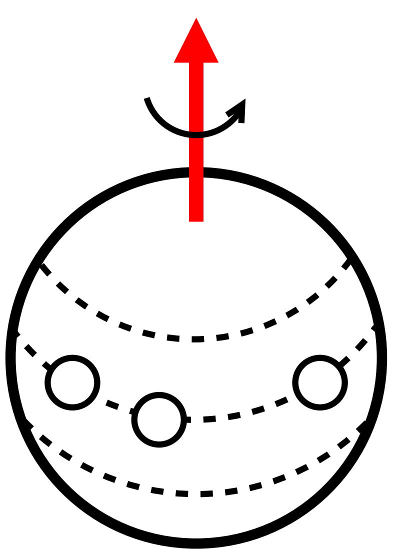
$N \to \Lambda, \Sigma$ in K, K^* production

[$N \to X$ in vector meson production]

Internal structure and excitation spectrum
are closely related aspects of QM systems



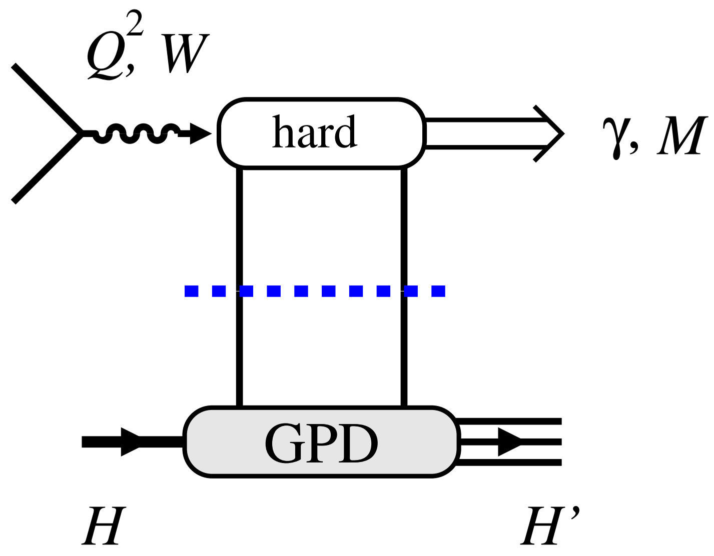
Example: Nuclear shell model
Mean-field structure of ground state ↔
Single-particle excitation spectrum



Example: Collective motion
Semiclassical structure ↔
Rotational excitation spectrum

Same applies to hadron structure in QCD!

Transition GPDs: Hard exclusive processes



Factorization

Asymptotic regime $Q^2, W^2 \gg \mu^2_{\text{had}}, |t| \sim \mu^2_{\text{had}}$

Production process communicates with target through QCD light-ray operators $\mathcal{O}(z) = \bar{\psi}(0) \ldots \psi(z)_{z^2=0}$

Hadronic matrix elements $\langle H' | \mathcal{O}(z) | H \rangle \leftrightarrow$ GPDs

Works for any transition with $m_{H'} - m_H \sim \mu_{\text{had}}$

Physics interest in transitions $H \to H'$

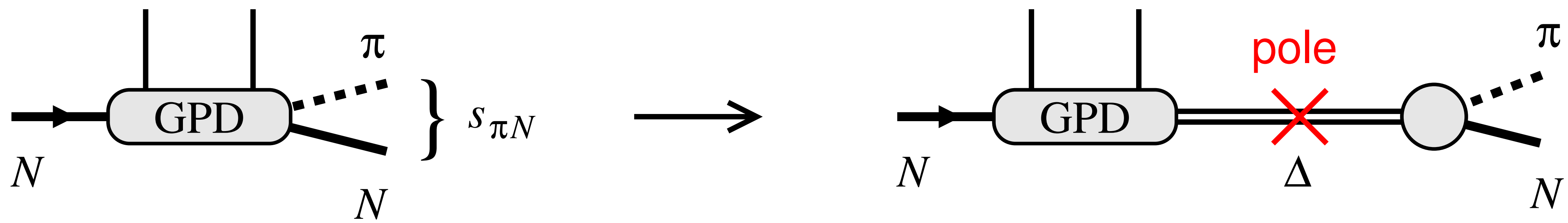
Learn more about operator: Quantum numbers, spin-flavor components?

Learn about structure of excited states:

Use well-defined QCD operators from factorization theorem:
Renormalization, scale dependence, universality → LQCD, nonperturbative methods

Realize operators with quantum numbers not accessible with local vector/axial currents:
Spin ≥ 2 — energy momentum tensor, gluon operators, quarks ↔ antiquarks C-parity

Transition GPDs: Resonances



$$\langle \pi N | \mathcal{O} | N \rangle = \frac{\langle \pi N | \Delta \rangle \, \langle \Delta | \mathcal{O} | N \rangle}{s_{\pi N} - M_\Delta^2} + \text{less singular}$$

Definition of resonance GPDs

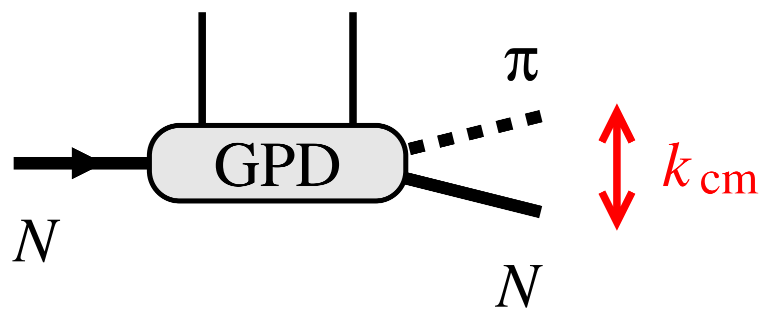
Multihadron final state, e.g. πN

Analytic continuation in invariant mass $s_{\pi N}$:
Pole at $s_{\pi N} = M_\Delta^2$, resonance structure defined at pole, residue factorizes

Rigorous definition of “resonance GPDs” using methods of S-matrix theory

Physical region: Resonant + non-resonant contributions, needs theory

Theoretical methods: Chiral dynamics



Near-threshold region $k_{\rm cm} \sim M_\pi$

Pion emission governed by chiral dynamics

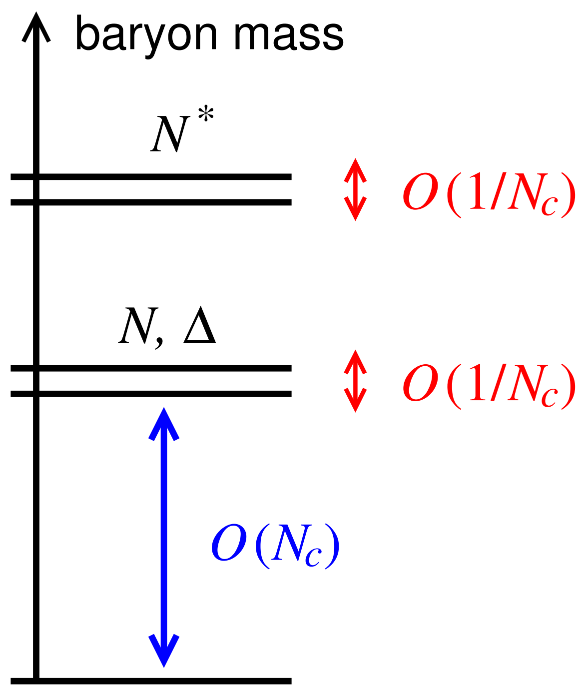
Soft-pion theorems relate $N \rightarrow \pi N$ and $N \rightarrow N$ matrix elements:
$\langle \pi N | \mathcal{O} | N \rangle \leftrightarrow \langle N | \mathcal{O}' | N \rangle, \quad \mathcal{O}' \sim [\mathcal{O}, J_5^\mu]$

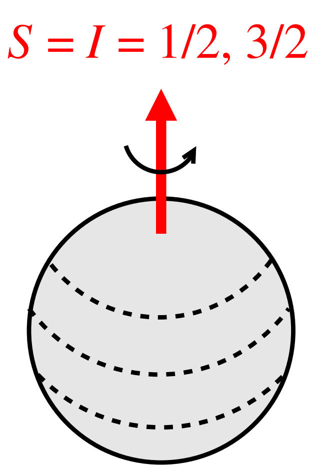
Pobylitsa, Polyakov, Strikman 2001; Guichon, Mossé, Vanderhaeghen 2003; Chen, Savage 2004; Birse 2004

Corrections calculable in ChPT
Kivel, Polyakov 2004

Systematic approach in near-threshold region
Practically applicable in S-wave; limited by Δ resonance in P-wave
Guidal et al 2003

Theoretical methods: 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

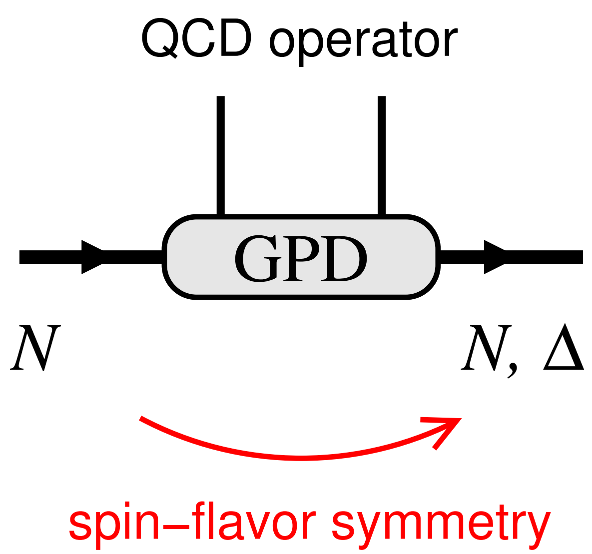
Emerging dynamical spin-flavor symmetry $SU(2N_f)$
Baryons in multiplets with masses $O(N_c)$, splittings $O(1/N_c)$
Gervais, Sakita 1984; Dashen, Manohar, Jenkins 1993

$N \to N$ 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



$1/N_c$ expansion of $N \to N$ GPDs

Hierarchy of spin-flavor components of GPDs
Börnig et al. 1998; Goeke, Polyakov, Vanderhaeghen 2001

Extended to chiral-odd operators
Schweitzer, Weiss 2016

$1/N_c$ expansion of $N \to \Delta$ transition GPDs

$\gamma^+, \gamma^+\gamma_5$	chiral-even
$\sigma^{+T}\gamma_5$	chiral-odd

Leading structures, dynamical predictions from $N \to N$
Frankfurt, Polyakov, Strikman 1998. FPS, Vanderhaeghen 2000

Full $1/N_c$ expansion including subleading corrections can be performed using group-theoretical methods
Goity, Jun-Young Kim, Weiss, planned

Chiral-odd operators
Kroll, Passek-Kumericki 2023

Theoretical methods: Other approaches

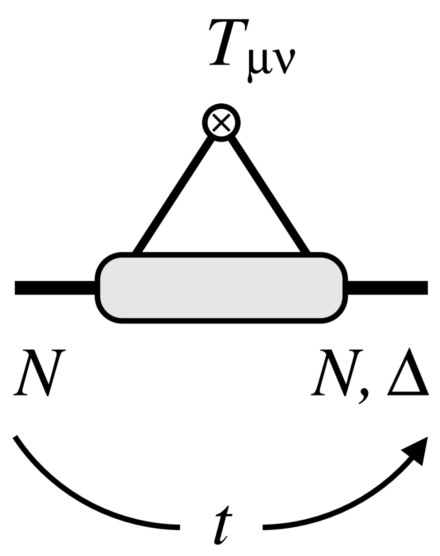
Lattice QCD: Partonic operators using quasi/pseudo PDF approach
Excited states using "distillation" methods developed for hadron spectroscopy
Long-term prospect of calculating $N \to B$ transition GPDs

→ Talks Richards, Zhao

Holography: Models of non-perturbative QCD based on gauge-string duality
Close connection spectrum ↔ structure
First applications to partonic structure and GPDs

→ Talks Mamo, Zahed

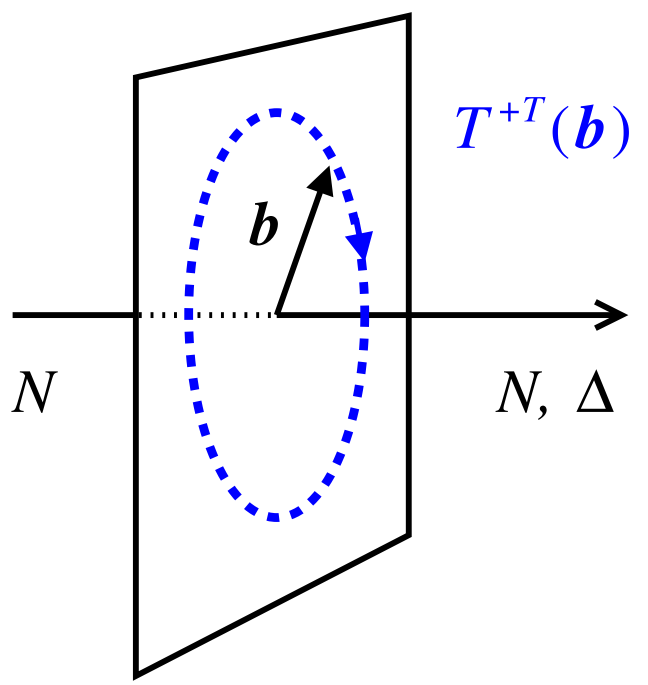
Energy-momentum tensor form factors



EMT operator as 2nd x-moment of light-ray operator

EMT form factors describe distributions of momentum, angular momentum, forces in system
Ji 1996, Polyakov 2003, Lorce et al. 2013+

$N \to N$: Extensive studies, "mechanical properties"



$N \to \Delta$ transition EMT form factors

Transition matrix elements: Form factors, multipoles
J-Y Kim 2022 + in progress

Transition angular momentum formulated as light-front density
J-Y Kim, H-Y Won, Goity, Weiss, 2023

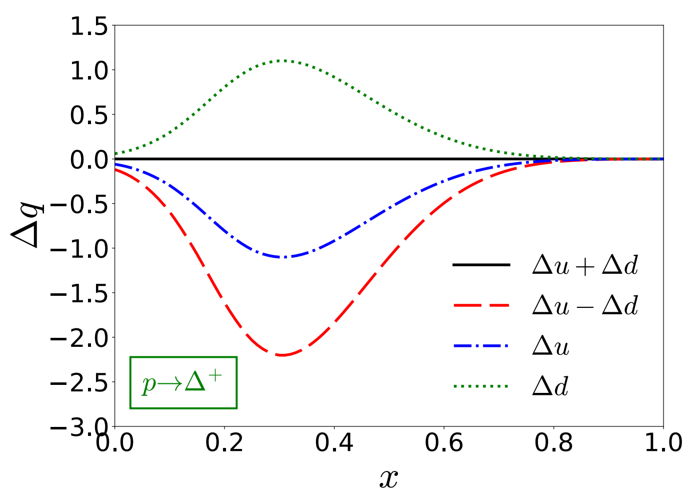
$$J^z(N \to \Delta) = \int d^2b\ \mathbf{b} \times \langle \Delta \,|\, \mathbf{T}^{+T} \,|\, N \rangle$$

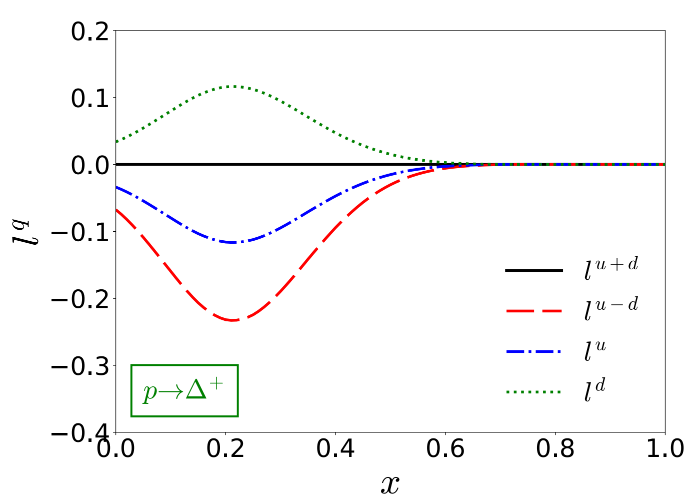
Probes isovector quark angular momentum $u - d$

Energy-momentum tensor form factors

Lattice QCD	$J^S_{p\to p}$	$J^S_{\Delta^+\to\Delta^+}$	$J^V_{p\to p}$	$J^V_{p\to\Delta^+}$	$J^V_{\Delta^+\to\Delta^+}$
[9] $\mu^2 = 4\,\text{GeV}^2$	0.33^*	0.33	0.41^*	0.58	0.08
[10] $\mu^2 = 4\,\text{GeV}^2$	0.21^*	0.21	0.22^*	0.30	0.04
[11] $\mu^2 = 4\,\text{GeV}^2$	0.24^*	0.24	0.23^*	0.33	0.05
[12] $\mu^2 = 1\,\text{GeV}^2$	–	–	0.23^*	0.33	0.05
[13] $\mu^2 = 4\,\text{GeV}^2$	–	–	0.17^*	0.24	0.03

[9] Göckeler 2004. [10] Hägler 2008. [11] Bratt 2010.
[12] Bali 2019. [13] Alexandrou 2020





$1/N_c$ expansion connects AM in $N \to \Delta$ and $N \to N$

Goeke, Vanderhaeghen, Polyakov 2000; Kim, Won, Goity, Weiss, 2023

$$J^V(p \to p) = \frac{1}{\sqrt{2}} J^V(p \to \Delta^+) = 5J^V(\Delta^+ \to \Delta^+)$$

$$V \equiv u - d$$

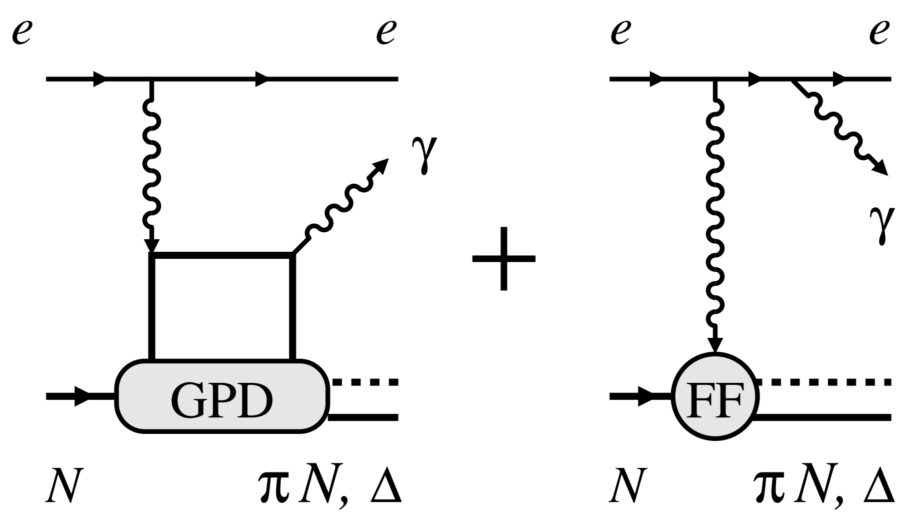
$N \to \Delta$ transition AM estimated using lattice QCD results for $p \to p$

Measurements of $N \to \Delta$ transition AM could explain/constrain flavor asymmetry of proton AM J^{u-d}

Many interesting questions: Separation of spin and orbital AM in $N \to \Delta$ transition — dynamics?

Large-Nc light-front chiral quark-soliton model: J-Y Kim 2023

Processes: $N \to \pi N$ and Δ in DVCS

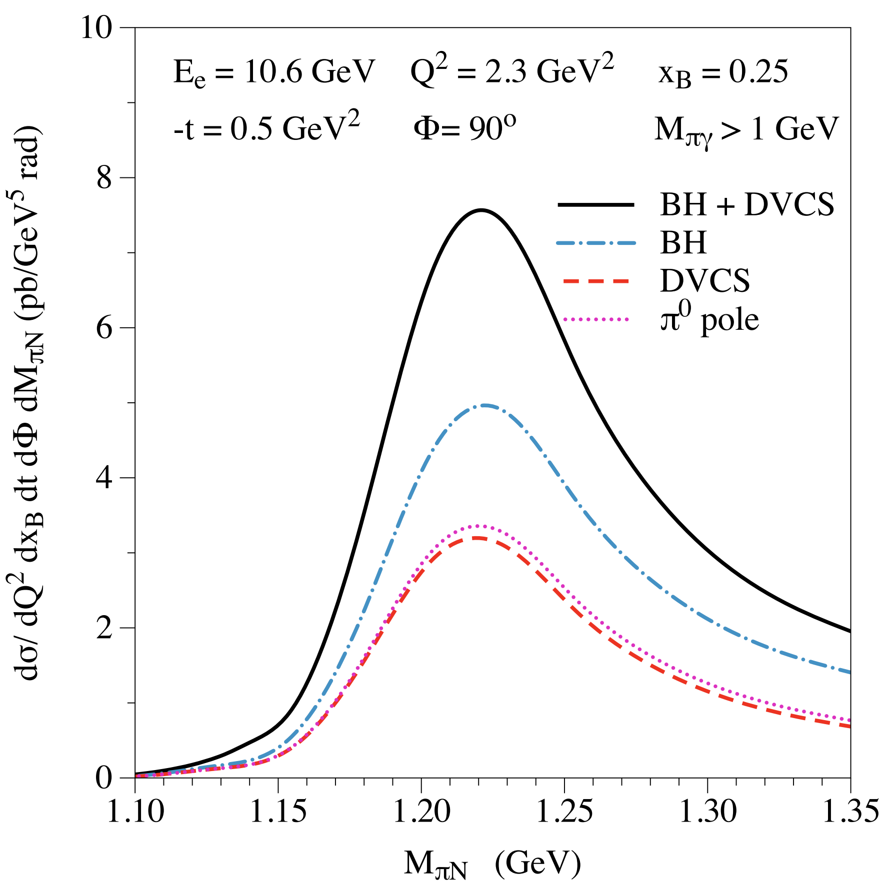


$$e + p \to e' + \gamma + \pi^0 p,\ \pi^+ n \quad (\Delta^+ \text{ resonance})$$

$$e + n \to e' + \gamma + \pi^0 n,\ \pi^- p \quad (\Delta^0 \text{ resonance})$$

Probes chiral-even GPDs

Detailed modeling: Semenov-Tian-Shansky, Vanderhaeghen 2023

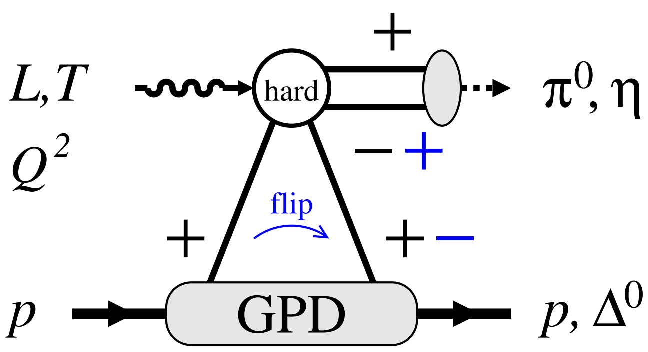


Experiments

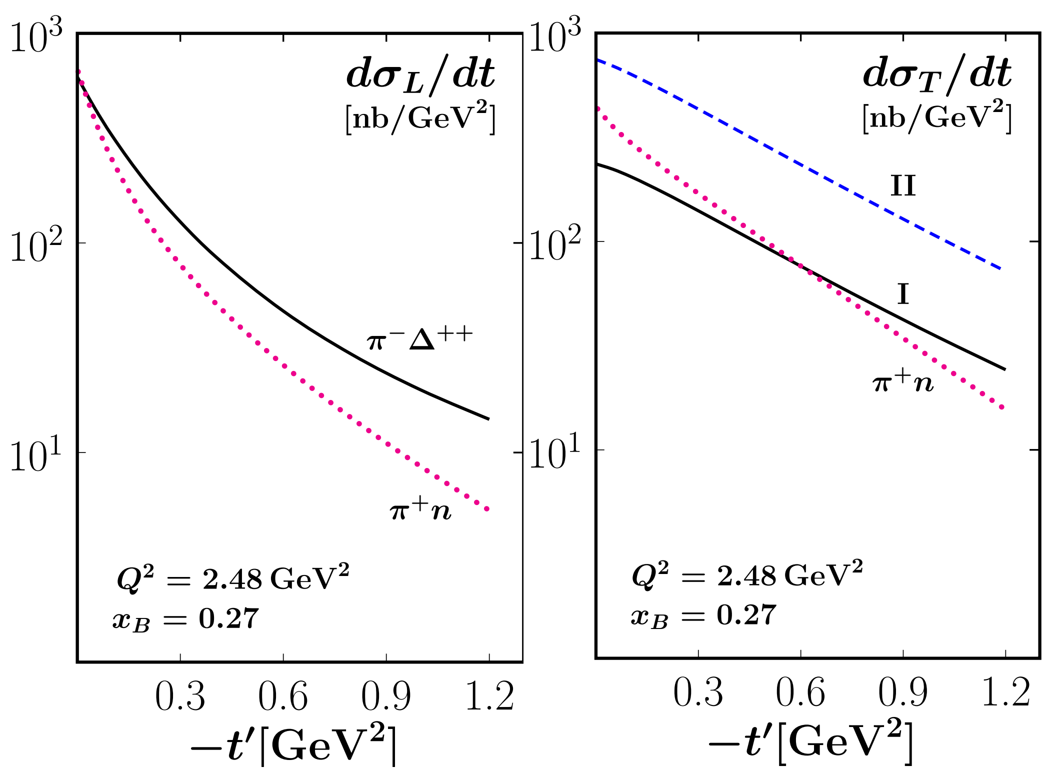
HERMES: Beam spin asymmetry A_{LU}, large exp. uncertainties

JLab12: First results from CLAS12 Δ^+ → **Talk K. Joo**

EIC: Far-forward Delta reconstruction?
Various channels, should be simulated
→ Discussion



$\langle H_T \rangle$: $u - d$ leading in $1/N_c$
$\langle \bar{E}_T \rangle$: $u + d$ leading



Twist-2 mechanism: Chiral-even helicity-conserving GPDs + DA, L photon
Frankfurt, Pobylitsa, Polyakov, Strikman 1998

Large twist-3 mechanism: Chiral-odd helicity-flip GPD + DA, T photon
Goldstein, Liuti et al 08+, Goloskokov, Kroll 09+

Describes well JLab 6 GeV $N \to N$ data
CLAS6 2017 Bedlinskiy et al. π^0, η

$1/N_c$ expansion correctly predicts flavor structure
Schweitzer, Weiss 2016; Kubarovsky 2019

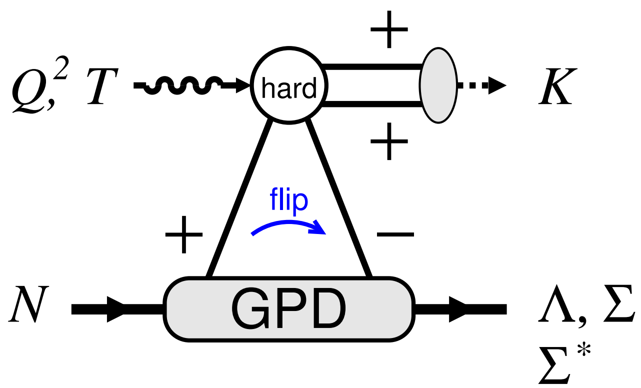
$N \to \Delta$ transitions

Predictions for $\pi^- \Delta^{++}$ final states using $1/N_c$
Kroll, Passek-Kumericki 2023

CLAS12: Beam spin asymmetry $\pi^- \Delta^{++}$ → Talk K. Joo

Distinguish chiral-odd/even GPDs through $N \to \Delta$?

Processes: $N \to \Lambda, \Sigma, \Sigma^*$ in K production



Same twist-3 mechanism with chiral-odd structures as π, η production

Symmetry relations for strange chiral-odd GPDs

$N \to \Lambda, \Sigma$ related to $N \to N$
by conventional SU(3) flavor symmetry

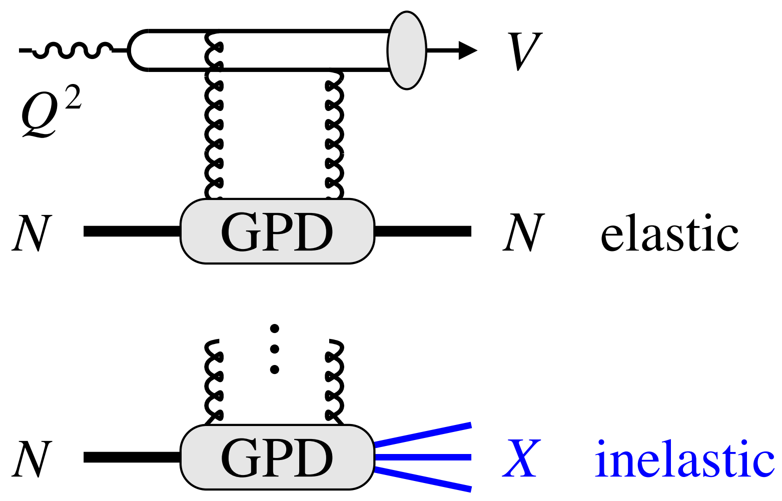
$N \to \Sigma^*$ related to $N \to N, \Lambda, \Sigma$
by SU(6) spin-flavor symmetry in large-N_c limit

Predictive power; quantitative modeling possible

JLab12

$p \to \Lambda, \Sigma, \Sigma^*$ in CLAS12 K production data, to be analyzed → **Talk K. Joo**

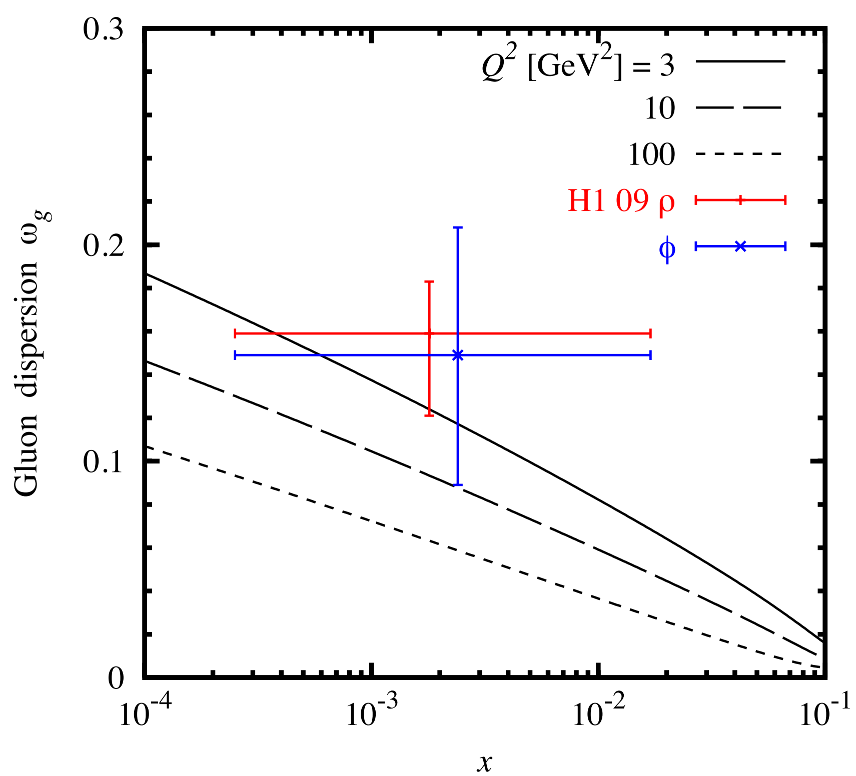
Processes: Vector meson production at small x



Diffractive vector meson production ($V = J/\psi, \phi, \rho^0$) with $N \to X$(low-mass) transitions

Probes quantum fluctuations of gluon density in nucleon:
Frankfurt, Strikman, Treleani, Weiss PRL 101:202003, 2008

$$\omega_g \equiv \frac{\langle G^2 \rangle - \langle G \rangle^2}{\langle G \rangle^2} = \left. \frac{d\sigma/dt\ (\gamma^* N \to VX)}{d\sigma/dt\ (\gamma^* N \to VN)} \right|_{t=0}$$



Fluctuations formulated in context of collinear factorization and transition GPDs. Alt formulation in dipole model
Schlichting, Schenke 2014; Mäntisaari, Schenke 2016

Discussed as part of diffraction at HERA and EIC: Inelastic diffraction

High rates at EIC; detection being simulated

Summary

- Factorization theorem for hard exclusive processes as "source" of new operators for studying hadronic transitions: well-defined, simple, new spin/charge quantum numbers

- $1/N_c$ expansion relates $N \to N$ and $N \to \Delta$ transitions [or $8 \to 8$ and $8 \to 10$ for strange] through dynamical spin-flavor symmetry: systematic, predictive

- Energy-momentum tensor form factors and "mechanical properties" can be generalized to $N \to \Delta, N^*$ transitions

- $N \to \Delta$ transitions generally as large as $N \to N$ where allowed, similar rates

- First results on $N \to \Delta$ in DVCS and π, η production from JLab12 → Talk K. Joo

- Δ reconstruction with EIC far-forward detectors should be simulated. Different decay modes of same Δ activate different detectors — charged-neutral, neutral-neutral, charged-charged. Could be used for tests and calibration, besides physics interest.

Announcement: ECT* Workshop on Transition GPDs

ECT* - APCTP Joint Workshop:
Exploring resonance structure with transition GPDs

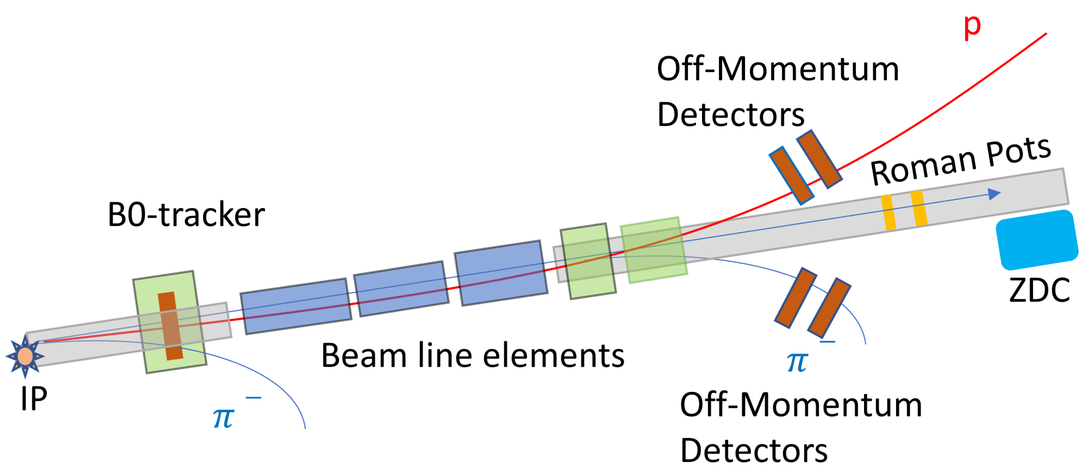
ECT* Trento, 21-25 August 2023 [Webpage]

Organizers:

Stefan Diehl (Justus Liebig Unversity Giessen, Germany)
Charlotte Van Hulse (University of Alcala, Madrid Region, Spain)
Vladimir Braun (University Regensburg, Germany)
Seung-il Nam, (Pukyong National University, Republic of Korea)
Kyungseon Joo (University of Connecticut, United States)
Christian Weiss (Jefferson Lab, United States)

Supplemental material

Processes: Forward Δ at EIC



EIC → **Talk Jentsch**

Far-forward detection system
Charged hadrons: Forward spectrometer
Neutral hadrons: Zero-Degree Calorimeter

Decay pion carries small fraction of Δ longit. momentum: $p_{L\pi}/p_{L\Delta} \approx M_\pi/m_\Delta \approx 1/9$

Forward Δ reconstruction at EIC?

Forward p detection (with rigidity $\gtrsim$ 1/2 beam) and forward n detection have been simulated for $p \to p, n$ exclusive processes, are well understood

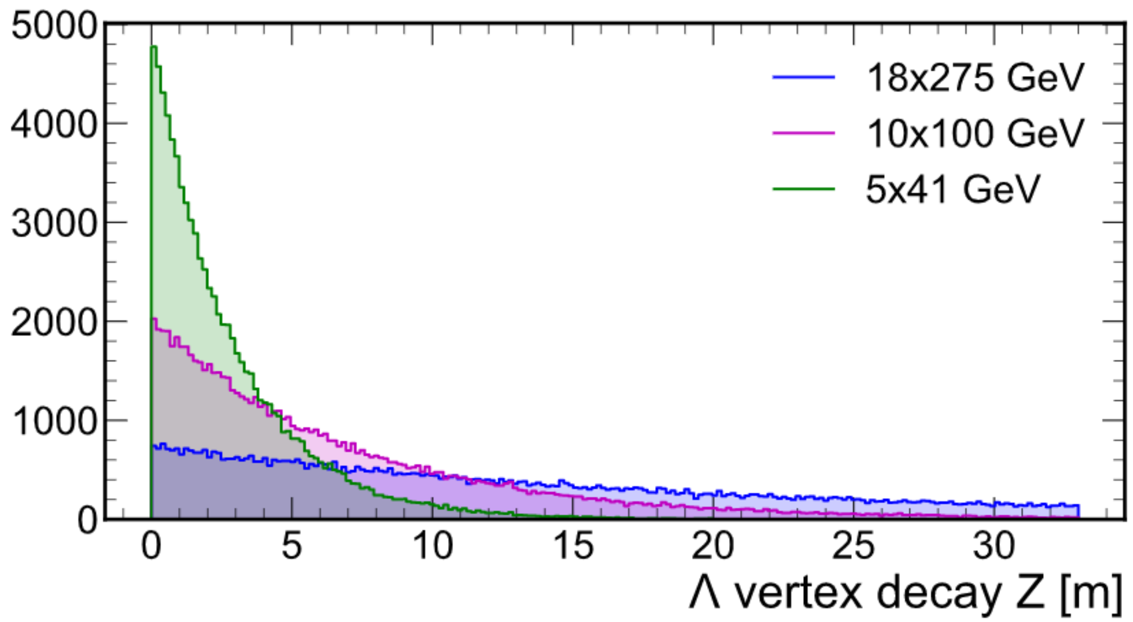
Forward π^0 detection with ZDC has been explored in connection with u-channel processes [A. Jentsch, Wenliang Li et al.]

Forward $\pi^\pm$ detection with rigidity $\ll$ beam might be possible with B0 tracker [A. Jentsch, private communication]

Would be very interesting to simulate Δ reconstruction at EIC!
Comparison of decay channels can serve as cross-check and detector calibration
$\Delta^+ \to \pi^+ n$ or $\pi^0 p$. $\Delta^0 \to \pi^0 n$ or $\pi^- p$

Processes: Forward Λ at EIC

J. Arrington et al.,J.Phys.G 48 (2021) 7, 075106



Λ decays $\sim 1 - 10$ meters from IP, depending on ion beam energy

Vertex position unknown, wide range of possibilities

Simulations of Λ reconstruction $(p\pi^-, n\pi^0)$ performed in context of K structure studies
J. Arrington et al.,J.Phys.G 48 (2021) 7, 075106

Would be interesting to simulate Σ reconstruction, Σ^* resonance — “strange Δ”