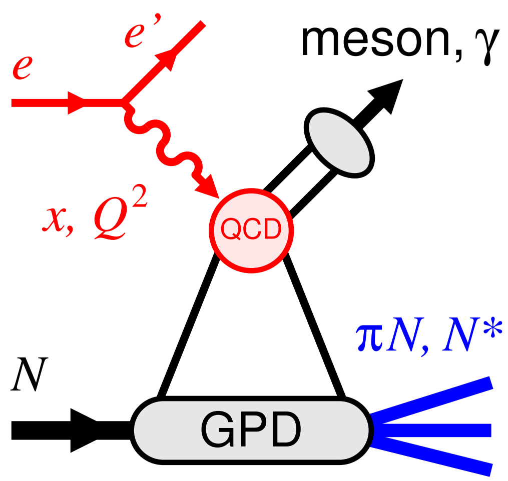
Transition GPDs and mechanical properties of excited baryons

C. Weiss (JLab), Center for Nuclear Femtography Workshop, JLab, 26-27 Mar 2026

Jefferson Lab



Emerging physics program: 2025 White Paper

S. Diehl et al., EPJA 61, 131 (2025) [INSPIRE]

Recent developments in theory

J-Y. Kim, C. Weiss, PLB 870 (2025) 139924 [INSPIRE]

S. Son, K. Semenov-Tian-Shansky, JHEP 01, 119 (2025) [INSPIRE]

J-Y. Kim et al. PRD 111, 114010 (2025) [INSPIRE]

First results from JLab12 experiments

S. Diehl et al. PRL 131 (2023) 021901 [INSPIRE]

Transition GPDs

Exclusive processes $N \to \pi N, N^*$

Resonance transition GPDs

Excited baryon structure

Transition light-front densities

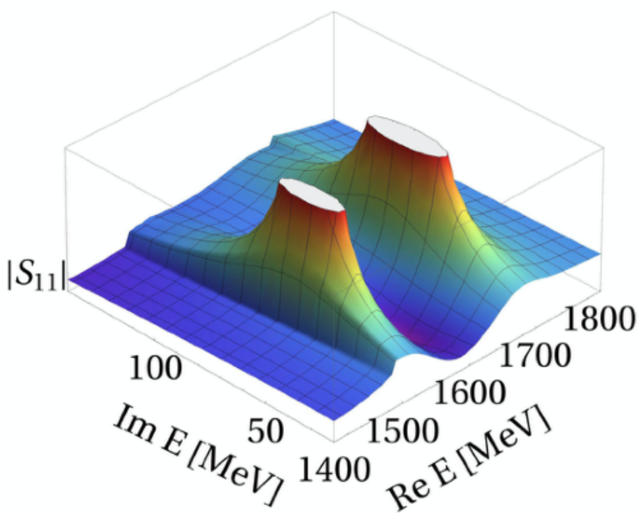
Transition angular momentum: $N \to \Delta$

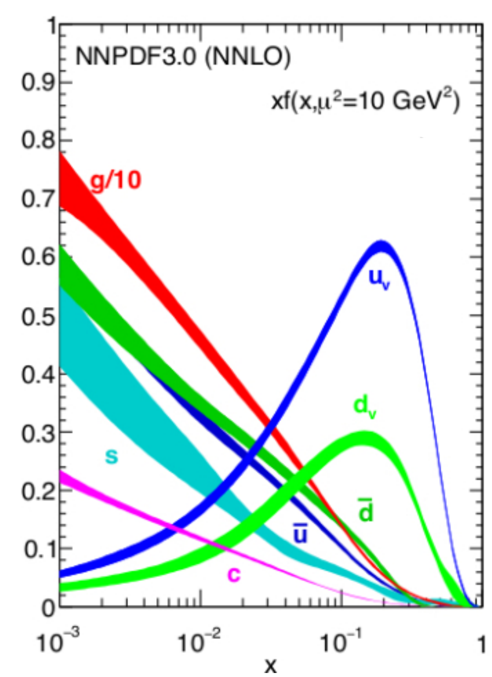
Transition PDFs: $N \to \Delta$ tensor polarized PDF

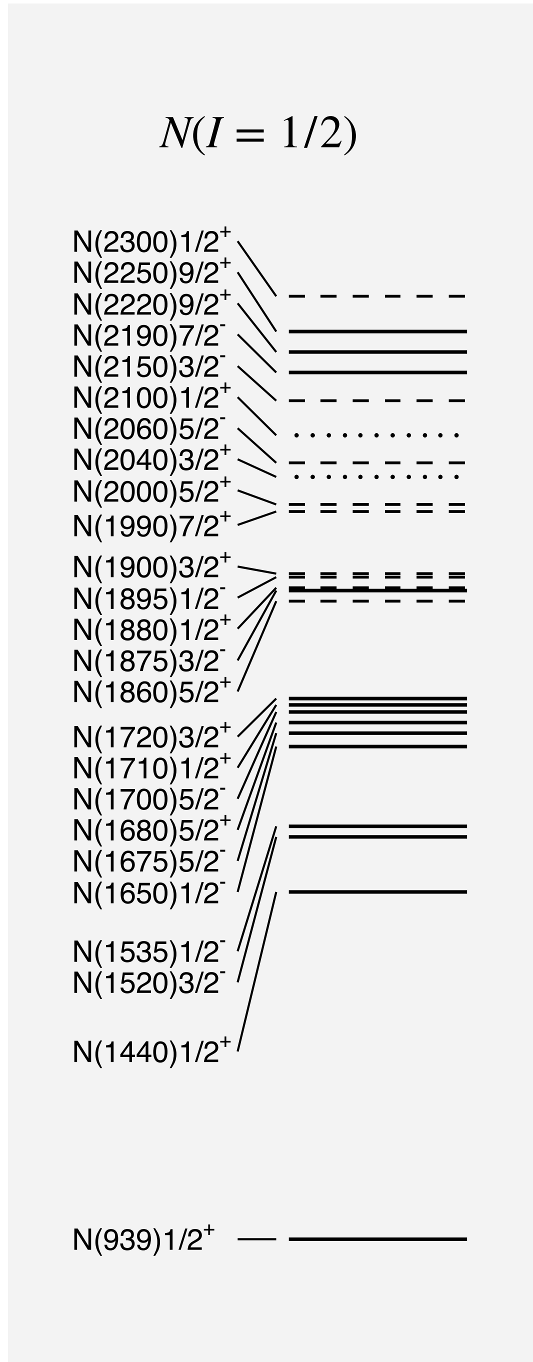
[Processes and experiments

$N \to \Delta$ in pion production and DVCS at JLab12

Baryon transitions with EIC far-forward detectors







[Image credits: NNPDF 3.0, PDG 2016, Roenchen - FZ Jülich]

Structure of ground-state nucleon

High-momentum-transfer processes:
Short-distance probe, “microscope”

Quark/gluon distributions 1D → 3D

Structure of excited baryons?

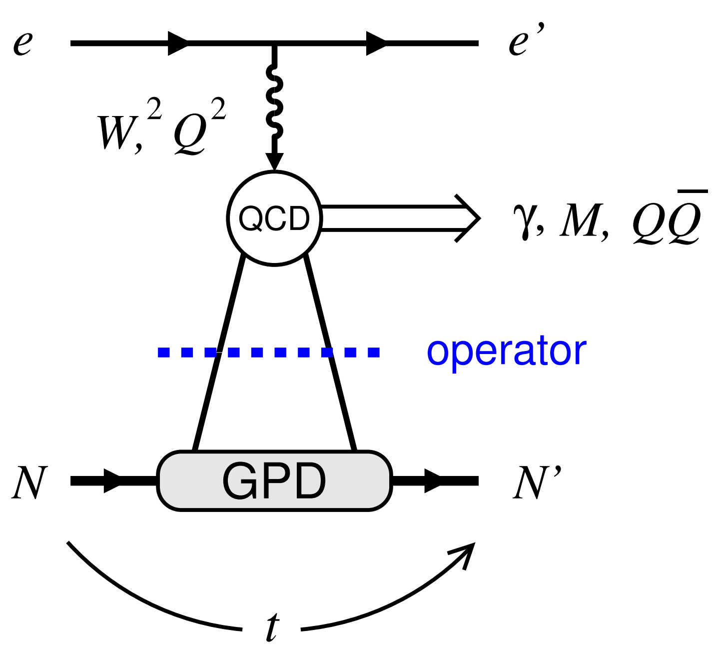
Rich spectrum of excited baryons N^*, Δ:
Resonances, unstable particles

Fundamentals of parton picture:
Structure ↔ excitation spectrum

Relevant for dense matter, astrophysics,
νN interactions

Need short-distance probe suitable for
baryon resonances!

Transition GPDs: Exclusive processes



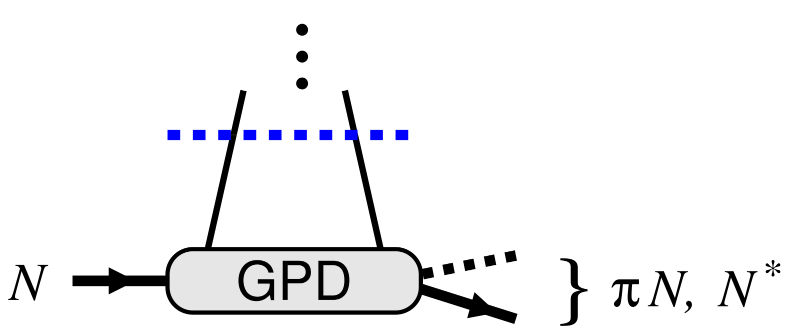
Process with $Q^2, W^2 \gg \mu^2_{\text{had}} \sim 1\ \text{GeV}^2, \quad |t| \sim \mu^2_{\text{had}}$

Scattering takes place on single quark/gluon in nucleon

Amplitude expressed as matrix element of QCD operator between incoming/outgoing nucleon states

$\langle N | \bar{\psi}(z) \ldots \psi(0) | N \rangle \ \leftrightarrow$ nucleon GPDs

Transition GPDs



Same factorization works for scattering processes with $N \to \pi N, N^*$ transitions

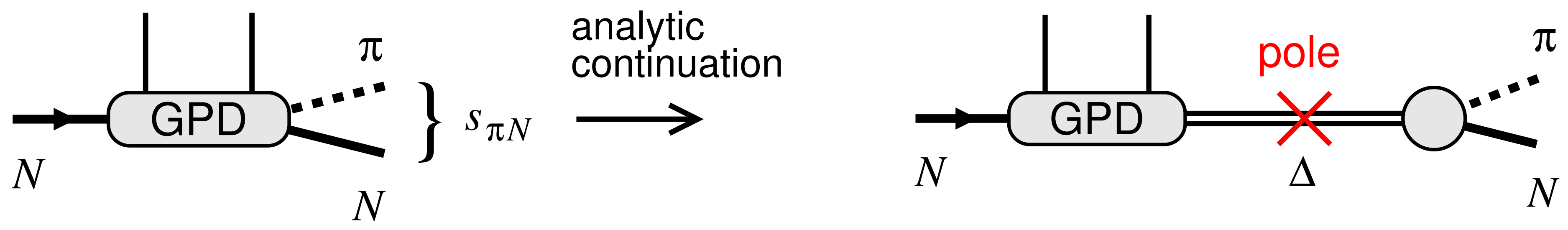
$\langle \pi N | \bar{\psi}(z) \ldots \psi(0) | N \rangle \ \leftrightarrow$ transition GPDs

N^*

Resonance excitation with defined QCD operator, rich set of quantum numbers

Probes quark/gluon structure of N^*

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

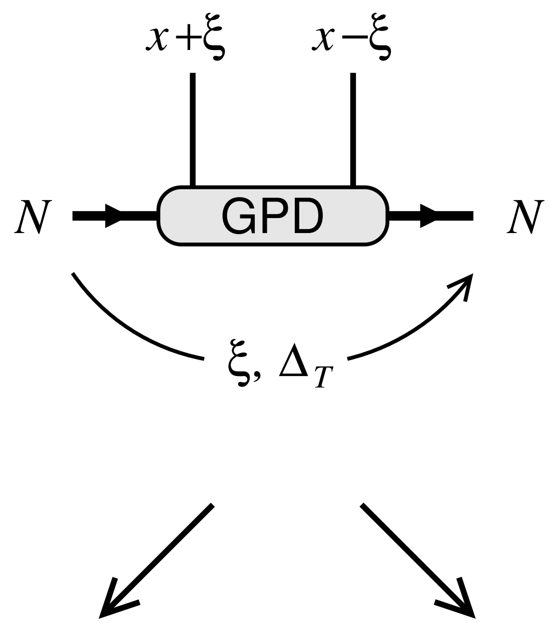
Transition matrix element to multihadron final state, e.g. πN

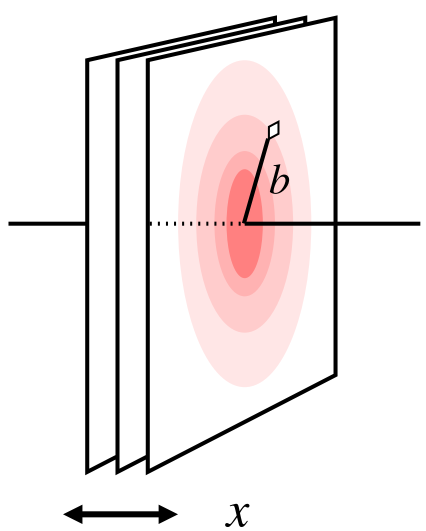
Analytic continuation in invariant mass $s_{\pi N}$: Pole at $s_{\pi N} = M_\Delta^2$, resonance structure defined at pole, residue factorizes

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

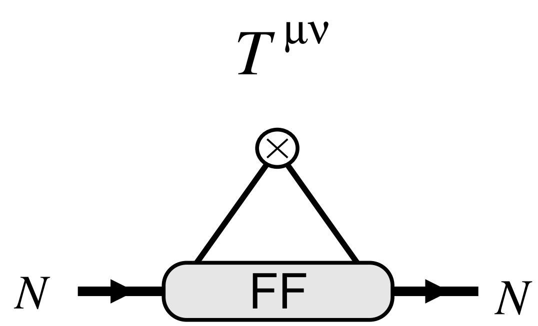
In physical region: Resonant + non-resonant contributions, needs theory

Transition GPDs: Baryon structure

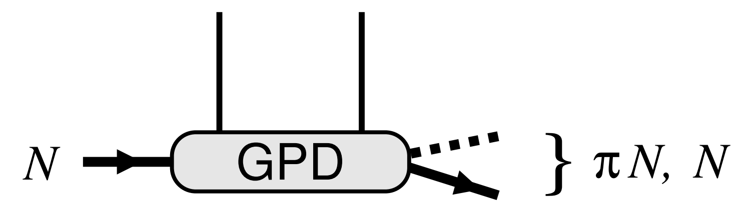




Spatial distribution
of quarks/gluons
“3D imaging”



QCD energy-momentum tensor:
mass, angular momentum, forces
“Mechanical properties”



Concepts can be extended
to $N \rightarrow N^*$ transitions!

Baryon structure: Transition light-front densities

$$|\mathbf{X}_T\rangle = \int \frac{d^2P_T}{(2\pi)^2}\, e^{i\mathbf{P}_T\mathbf{X}_T}\, |\mathbf{P}_T\rangle$$

LF dynamics: Transverse motion independent of mass of state. Galilean, same as nonrelativistic

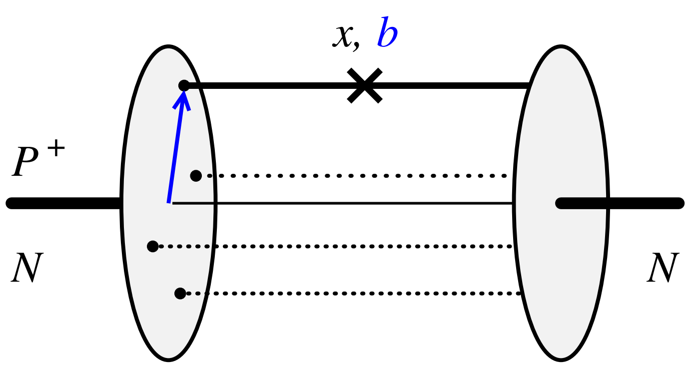
Transversely localized states defined independently of mass

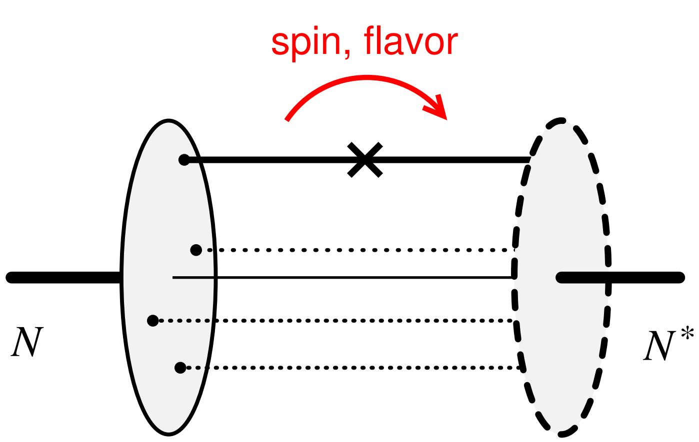
$$\rho_{N\to N^*}(\mathbf{b}) = \int \frac{d^2\Delta_T}{(2\pi)^2} e^{-i\mathbf{\Delta}_T\mathbf{b}} \langle N^*(-\mathbf{\Delta}_T/2)\,|\,\mathcal{O}\,|\,N(\mathbf{\Delta}_T/2)\rangle$$

Transition densities $N \to N^*$

same P^+, momentum transfer $\mathbf{\Delta}_T$, $\Delta^- \neq 0$

Cf. instant form: Motion depends on mass of state, definition of transition density ambiguous





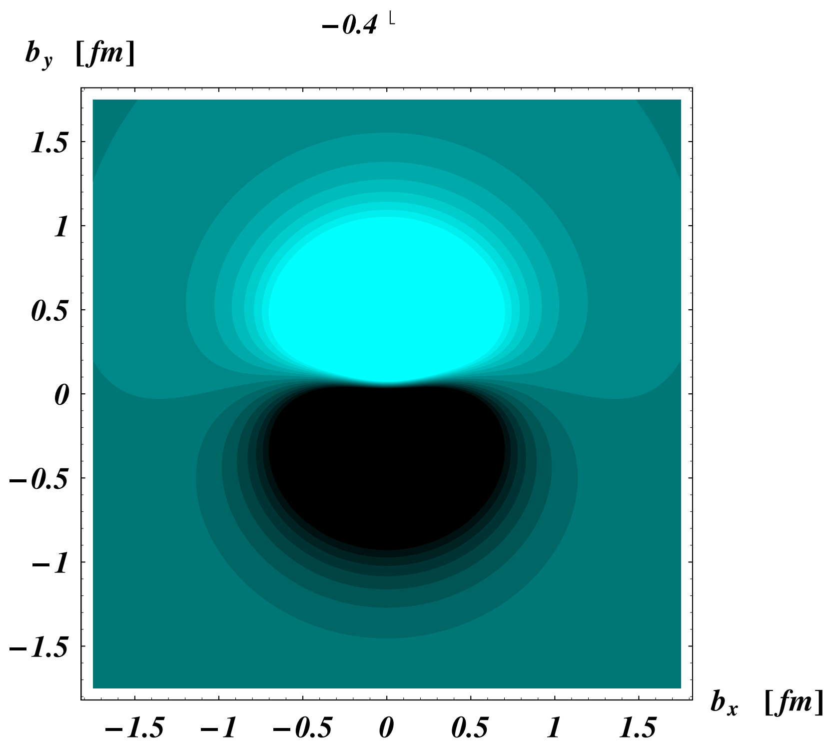
Interpretation

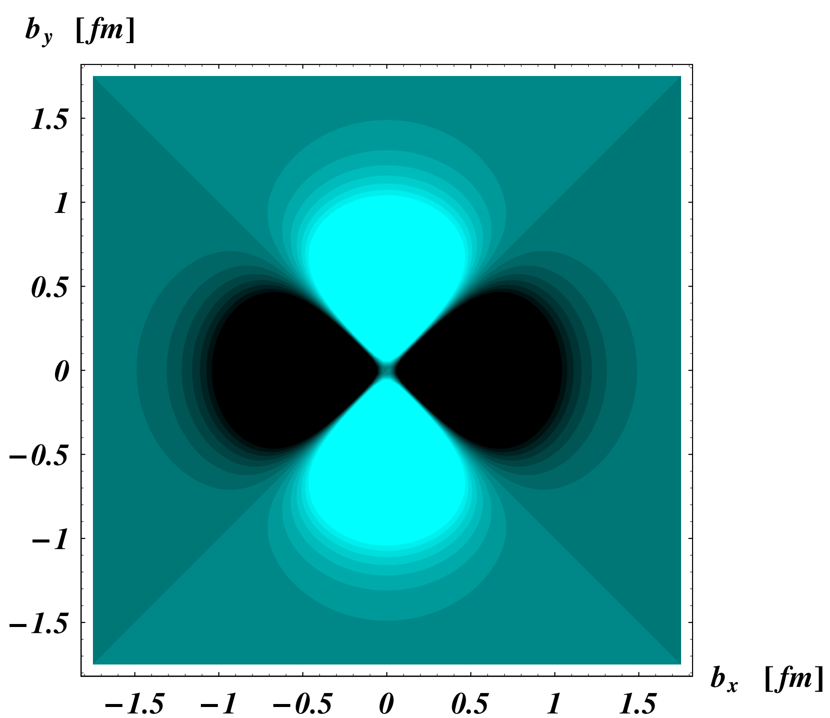
LF wave function overlap $N \to N^*$

Operator localized in transverse position, measures charge/current of constituents

Hadron undergoes excitation $N \to N^*$ (LF energy transfer $\Delta^- \neq 0$)

Operator can transfer quantum numbers: Spin, flavor/isospin





Example: Transverse charge density in $p \to \Delta^+$ transition (J^+ current density) from empirical transition form factors

Carlson, Vanderhaeghen 2007

Dipole and quadrupole patterns

Baryon structure: Transition EMT densities

$$T^{\mu\nu} = \sum_q T_q^{\mu\nu} + T_g^{\mu\nu} \qquad \partial_\mu T^{\mu\nu}(x) = 0$$

Total EMT of QCD, conserved current (Noether thm)

$$T_u^{\mu\nu}, T_d^{\mu\nu} \qquad T_{u\pm d}^{\mu\nu}$$

Individual quark flavor or gluon terms, not conserved

$$\rho_{N\to N^*}(\mathbf{b}) \quad \leftrightarrow \quad \langle N^*(-\mathbf{\Delta}_T/2)\,|\,T_q^{++}\,|\,N(\mathbf{\Delta}_T/2)\rangle$$

$$T_q^{+T}$$

LF transition densities from transition matrix elements of EMT terms

Transitions must be allowed by quantum numbers, e.g. $\langle \Delta \,|\, T_{u-d} \,|\, N \rangle$ by isospin

Conserved currents can have nonzero transition densities: see EM current

Conserved charges (= integrals of EMT) leave hadronic states unchanged and have no transitions

$$\hat{Q}\,|\,N\rangle = q\,|\,N\rangle \qquad \langle N^*\,|\,\hat{Q}\,|\,N\rangle = q\,\langle N^*\,|\,N\rangle = 0$$

e.g. $\hat{Q} = P^+ \equiv \int dx^- d^2x_T \, T^{++}(x)$

total LF momentum

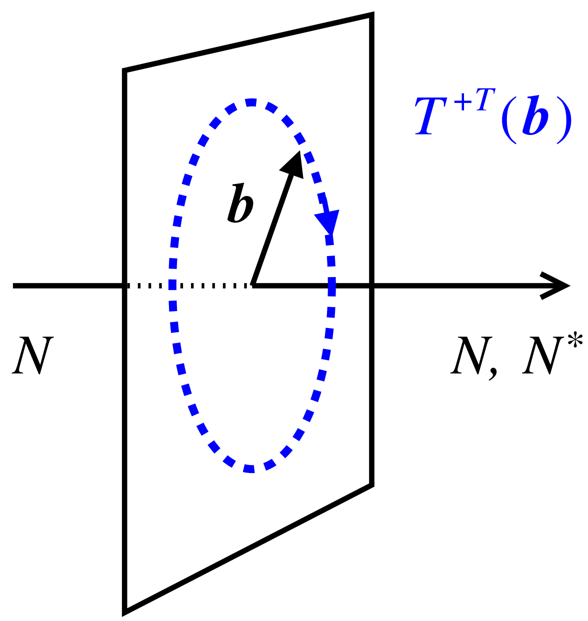
$\mathbf{T}^{+T}_{N\to N^*}(\mathbf{b}) \leftrightarrow \langle N^*(-\Delta_T/2)\,|\,\mathbf{T}^{+T}\,|\,N(\Delta_T/2)\rangle$

Transverse density of T momentum in hadron

$J^z_{N\to N^*} = C_{\text{spin}} \int d^2b\ \left[\mathbf{b}\times\mathbf{T}^{+T}(\mathbf{b})\right]$

Angular momentum as integral of transverse density
Kim, Won, Goity, Weiss, PLB 844,138083 (2023) [INSPIRE]

For AM definitions see e.g. Lorce, Mantovani, Pasquini 2017



$N \to \Delta$ transition angular momentum

Isovector quark angular momentum $u-d$

$1/N_c$ expansion: $J^{u-d}_{p\to p} = \frac{1}{\sqrt{2}} J^{u-d}_{p\to\Delta^+}$

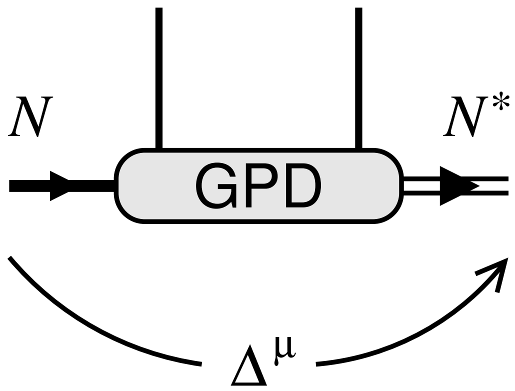
$p\to\Delta$ estimated using LQCD results for $p\to p$

Other gravitational form factors in $N\to\Delta$
Kim 2022; Alharazin et al. 2024

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

Baryon structure: Transition PDFs



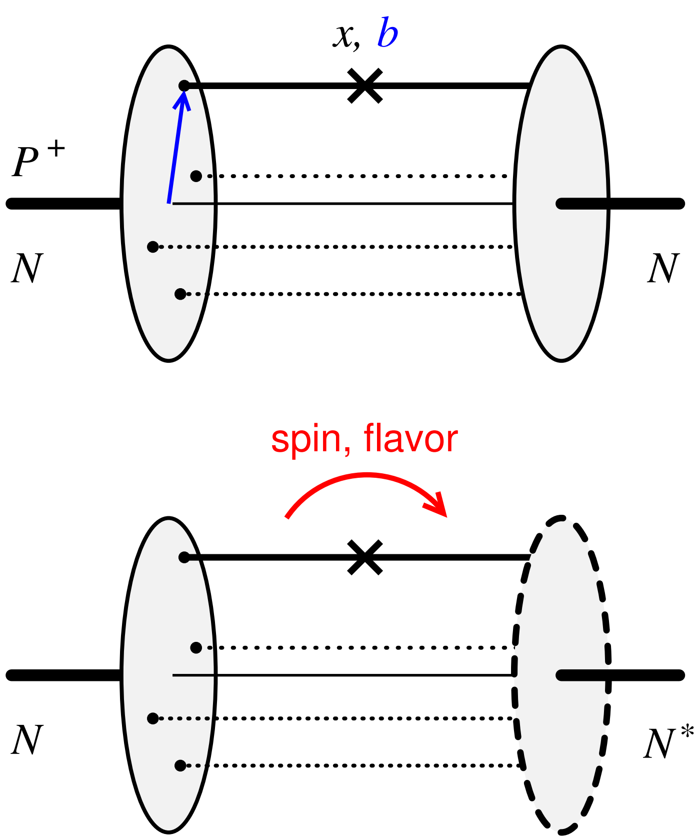
Forward limit of transition GPDs

$$\Delta^+ = -2\xi P^+ \to 0, \quad \Delta_T \to 0$$ light-front momentum transfer

$$\Delta^- = \frac{m_{N*}^2 - m_N^2}{2P^+} \neq 0$$ light-front energy transfer

Zero light-front momentum transfer, only energy transfer

J-Y. Kim, C. Weiss, PLB 870 (2025) 139924 [INSPIRE]



Transition PDFs

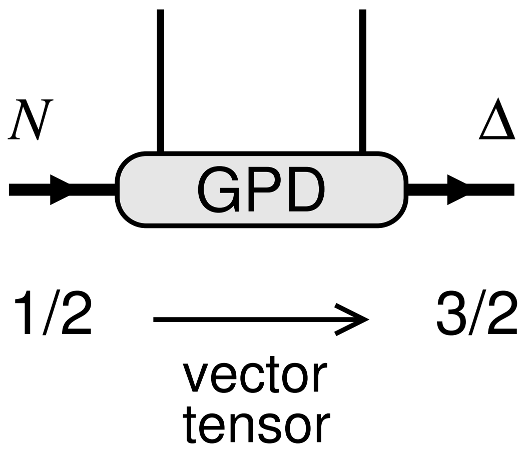
Describe excitation of baryon at rest (in LF momentum)

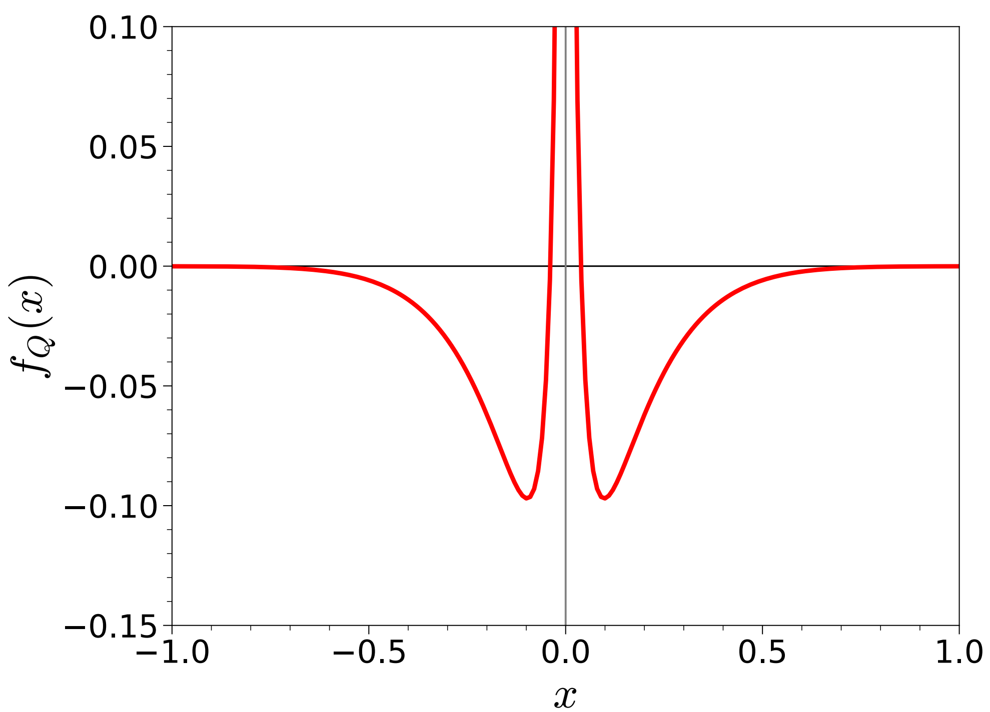
Represented as LF wave function overlap $N \to N^*$

Realize spin-isospin quantum numbers not accessible in $N \to N$

Also: Impact parameter dependence: $\Delta_T \neq 0 \to b$

Baryon structure: $N \to \Delta$ spin tensor PDF





J-Y. Kim, C. Weiss, PLB 870 (2025) 139924 [INSPIRE]

$N \to \Delta$ spin transition

Transition vector and tensor

$\psi^*_{3/2} [\ldots] \psi_{1/2} \to V^i, Q^{ij}$ in 3D rest frame

$N \to \Delta$ spin tensor PDF

Structure $\sim Q^{ij} n^i n^j$ 3D part of light-like 4-vector n

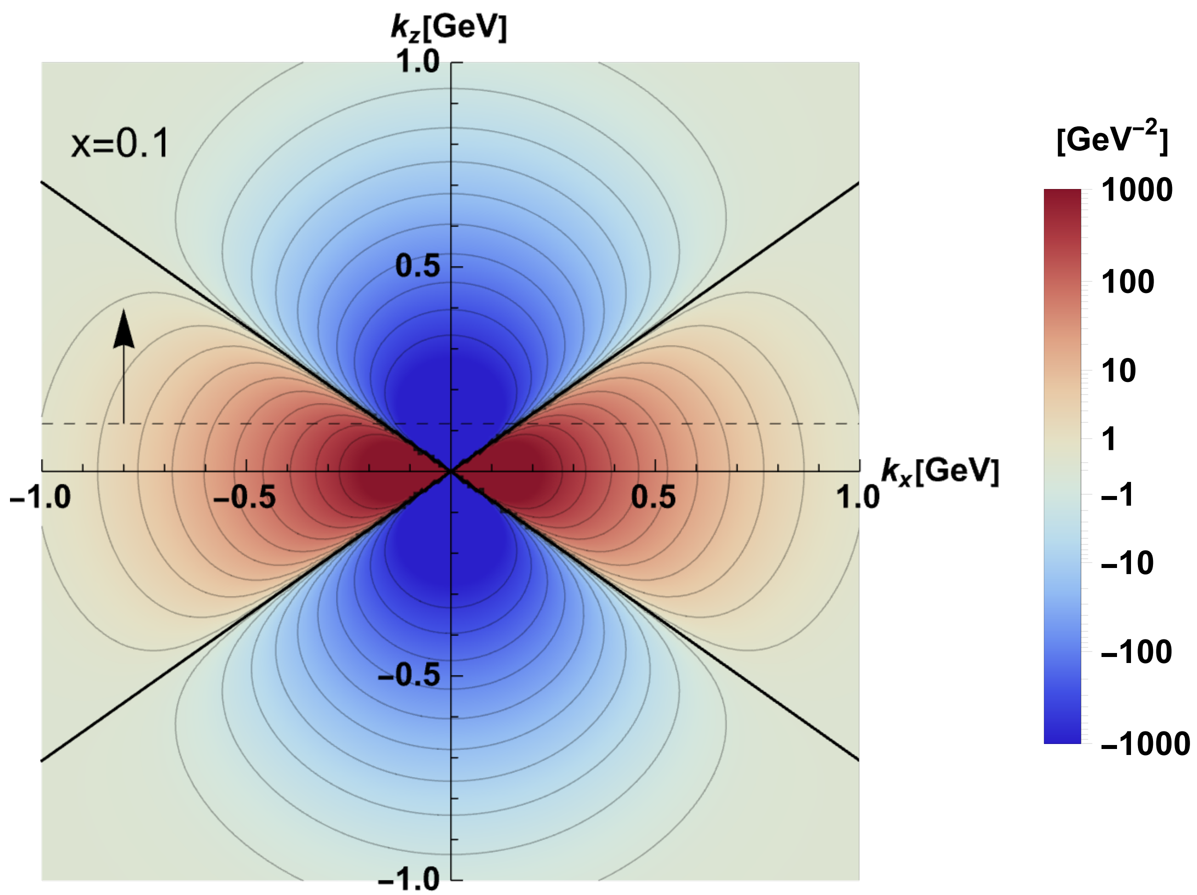
Unique to 1/2 →3/2 transition matrix element of nonlocal partonic operator, absent in local vector current

$$\int_{-1}^{1} dx\, f_Q(x) = 0$$ zero sum rule

Subleading in $1/N_c$ expansion
Estimated in chiral quark-soliton model

Complete spin structure of $N \to \Delta$ transition GPDs
J-Y. Kim et al. PRD 111, 114010 (2025) [INSPIRE]

Baryon structure: $N \to \Delta$ spin tensor PDF



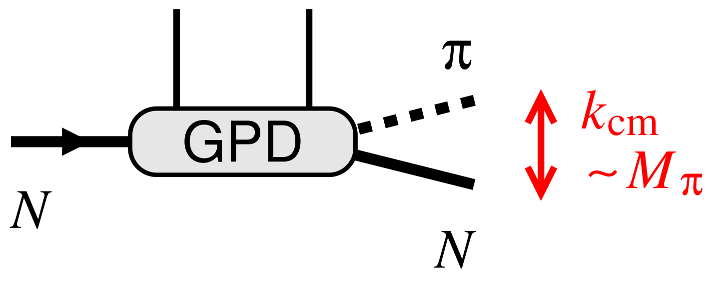
Rest-frame momentum distribution of quarks giving rise to $N \to \Delta$ spin tensor PDF (chiral quark-soliton model, large N_c-limit)

J-Y. Kim, C. Weiss, PLB 870 (2025) 139924 [INSPIRE]

Chiral dynamics

Soft-pion theorems relate $N \to \pi N$ and $N \to N$ matrix elements

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

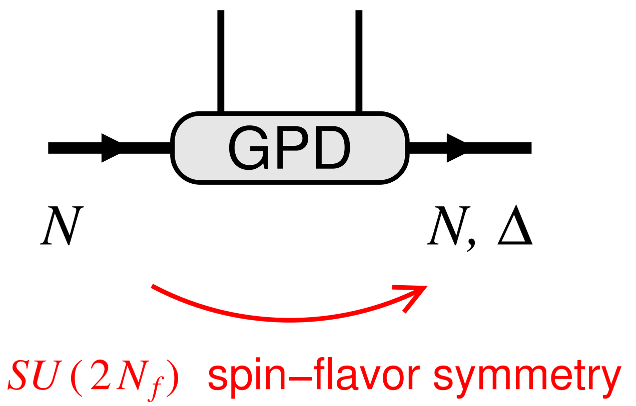


$1/N_c$ **expansion of QCD**

Spin-flavor symmetry relates $N \to N$ and $N \to \Delta$ transitions:

$\langle \Delta | \mathcal{O} | N \rangle \;=\;$ [symmetry factor] $\times \langle N | \mathcal{O} | N \rangle$

Frankfurt, Polyakov, Strikman 1998. FPS, Vanderhaeghen 2000; Kim, Won, Goity, Weiss 2023



Effective degrees of freedom

Chiral soliton model, light-front quark models, holographic models, instanton vacuum

→ Talk Mamo

Lattice QCD

Partonic structure from Euclidean correlation functions

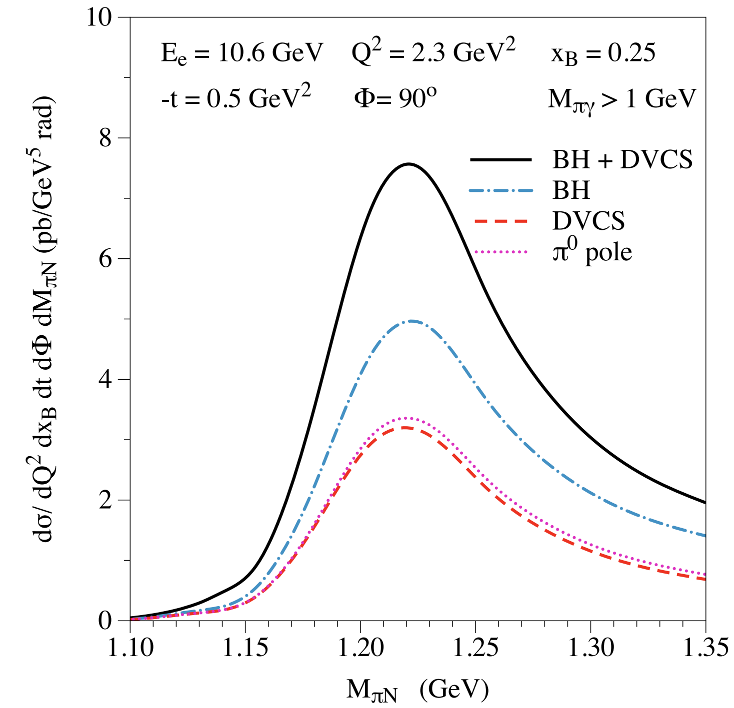
Deeply-virtual Compton scattering

$$e + p \to e' + \gamma + \Delta^+ \;\; (\to \pi^0 p, \pi^+ n)$$

also higher N^*

Probes chiral-even GPDs

Cross section predictions: Semenov-Tian-Shansky, Vanderhaeghen 2023



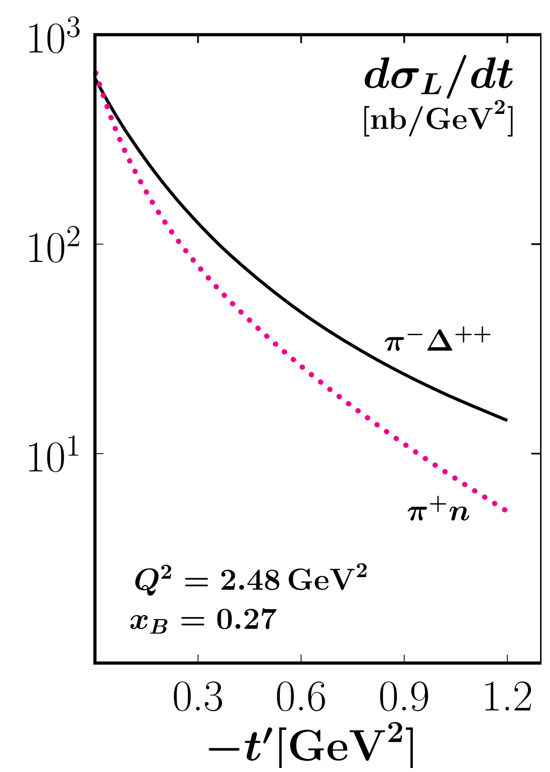
Pseudoscalar meson production

$$e + p \to e' + \pi^+ + \Delta^0$$
$$\pi^0 + \Delta^+$$
$$\pi^- + \Delta^{++}$$

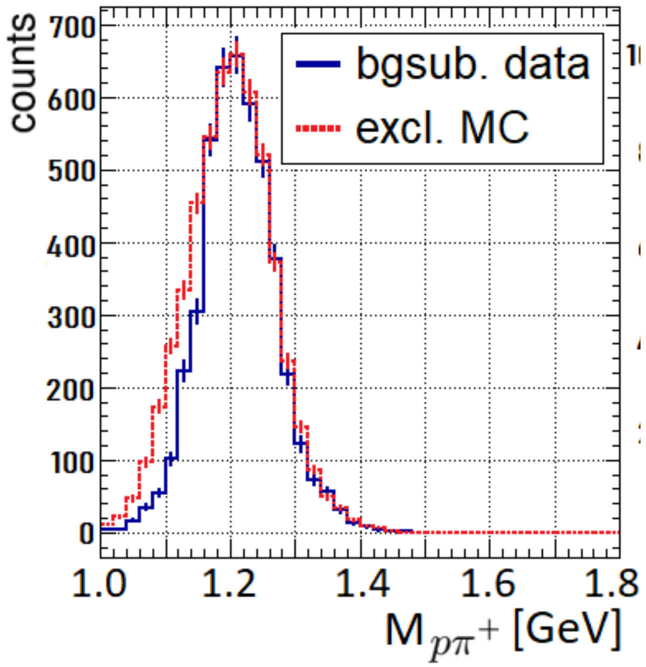
also η, K mesons

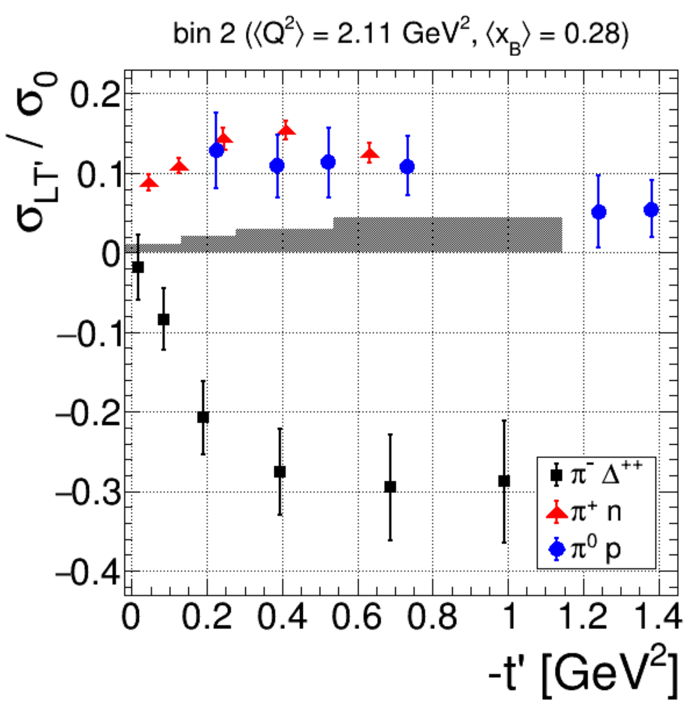
Probes chiral-odd GPDs ($x \gtrsim 0.1$), mechanism tested in $p \to p$

Cross section predictions: Kroll, Passek-Kumericki 2023



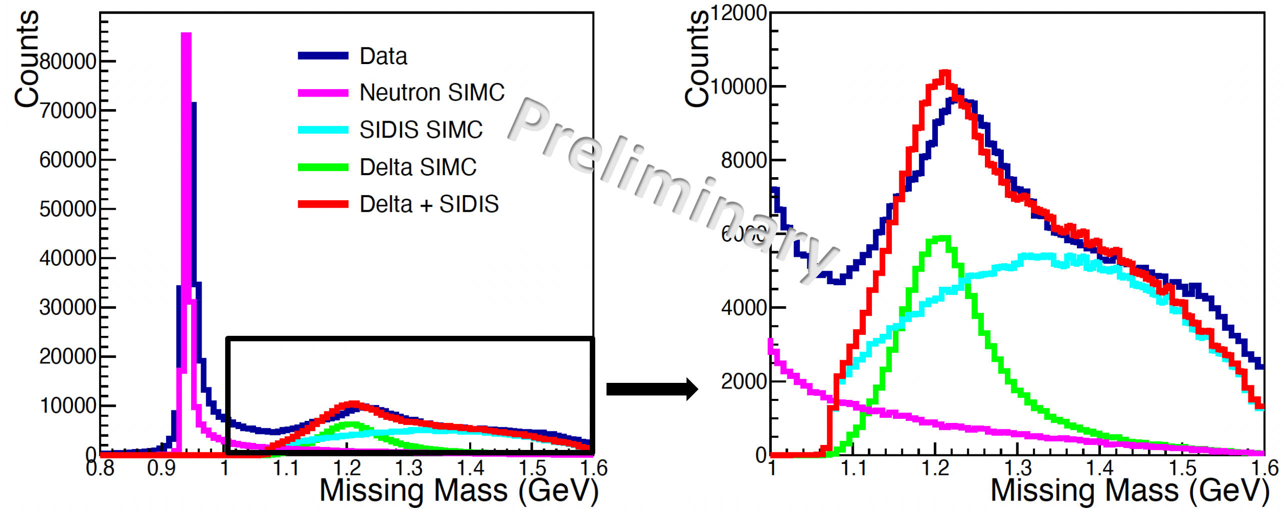
Experiments: First JLab12 results





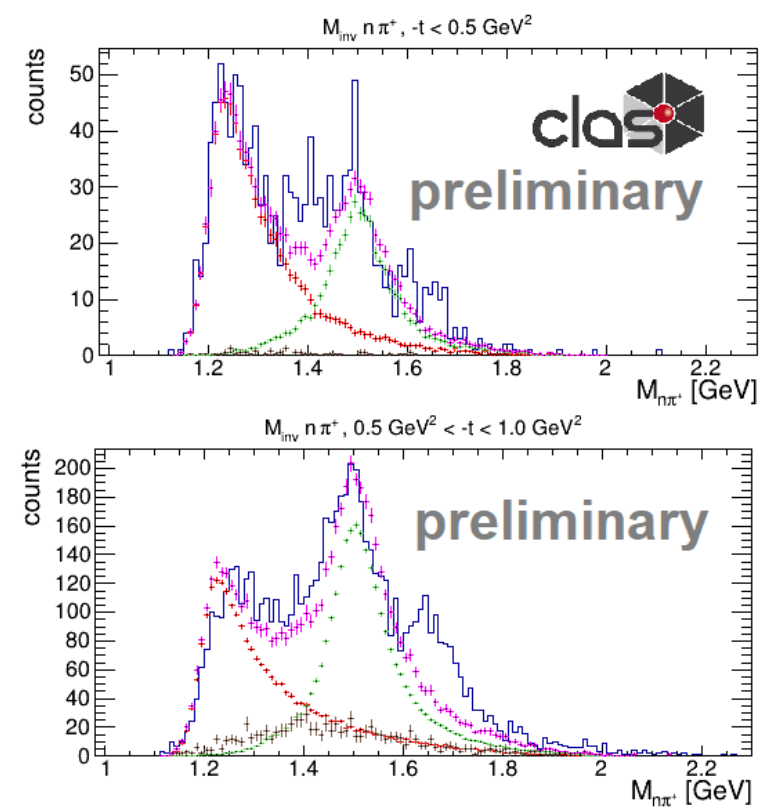
CLAS12 $ep \rightarrow e'\pi^-\Delta^{++}$

S. Diehl et al. PRL 131 (2023) 021901 [INSPIRE]



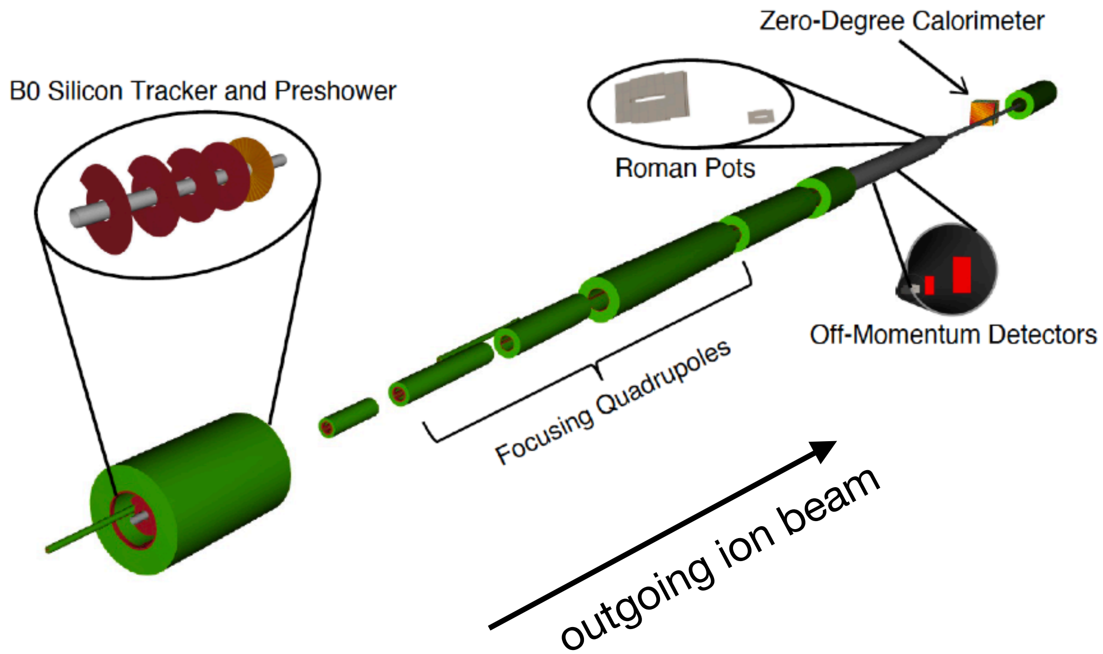
Hall C $ep \rightarrow e'\pi^+\Delta^0$

A. Usman, ECT* Trento Workshop Aug 2023



CLAS12 $ep \rightarrow e'\gamma n\pi^+$
DVCS

Experiments: EIC far-forward detection



Charged hadrons: Forward spectrometer
Neutral hadrons: Zero-Degree Calorimeter

Transition GPDs present “new” final states, complement/extend elastic channels

E.g. forward π^0, forward $\pi^\pm$ rigidity $\ll$ beam

Transition channels that should be simulated

$ep \to e'\gamma\Delta^+$ DVCS $\quad \Delta^+ \to \pi^+ n,\, \pi^0 p$ $\quad$ Strong decay, happens at vertex

$ep \to e'\pi^+\Delta^0$ $\quad \Delta^0 \to \pi^- p,\, \pi^0 n$

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

Also: $ep \to e'K\Lambda, \Sigma$ $\quad$ Can we reconstruct forward baryon resonances at EIC?

Summary

- Transition GPDs present new probe of excited baryon structure: Well-defined QCD operator, various quantum numbers accessible
- Transverse densities can be extended to $N \to N^*$ transitions with unequal masses
- EMT densities and mechanical properties can be formulated for $N \to N^*$ transitions
- Transition PDFs defined as forward limit of GPDs: Simple interpretation, new quantum numbers
- Theoretical methods for nonperturbative dynamics, experimental results
- Emerging field of study… many opportunities

Related topics

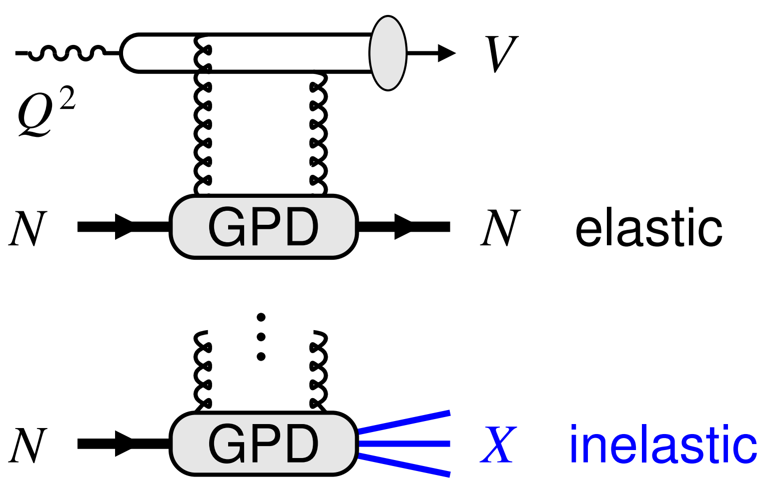
Transition GPDs in diffractive vector meson production $N \to X$ at small x

Transition GPDs in hadron-induced exclusive processes → S. Diehl et al., EPJA 61, 131 (2025) [INSPIRE]

Transition GPDs with JLab 22 GeV → A. Accardi et al. EPJA 60, 173 (2024) [INSPIRE]

Supplemental material

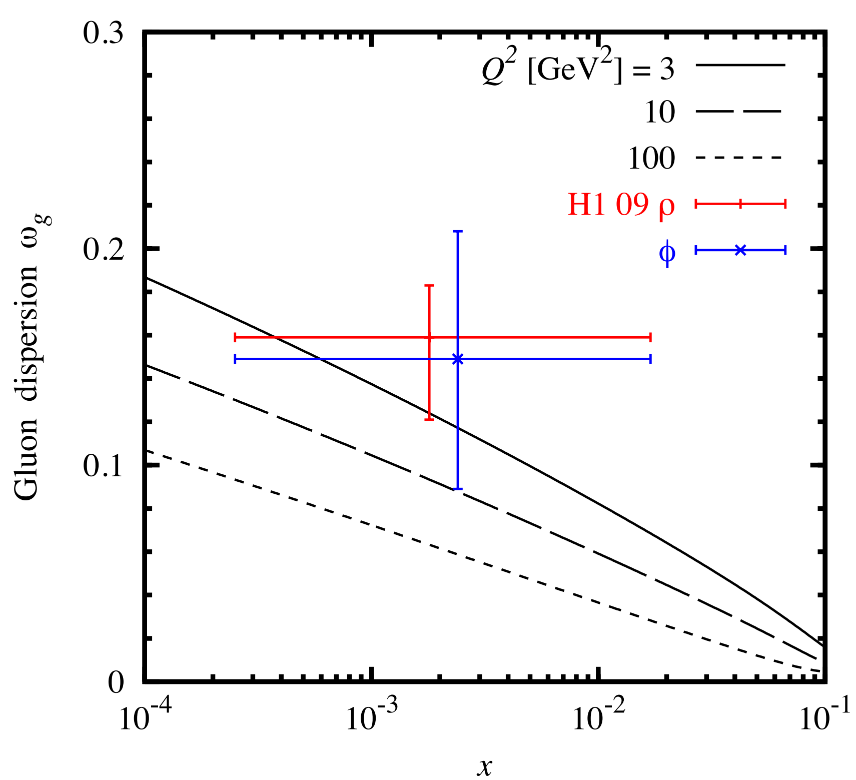
Transition GPDs: Vector meson production at small x



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) [INSPIRE]

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



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

Connection: Diffraction ↔ transition GPDs