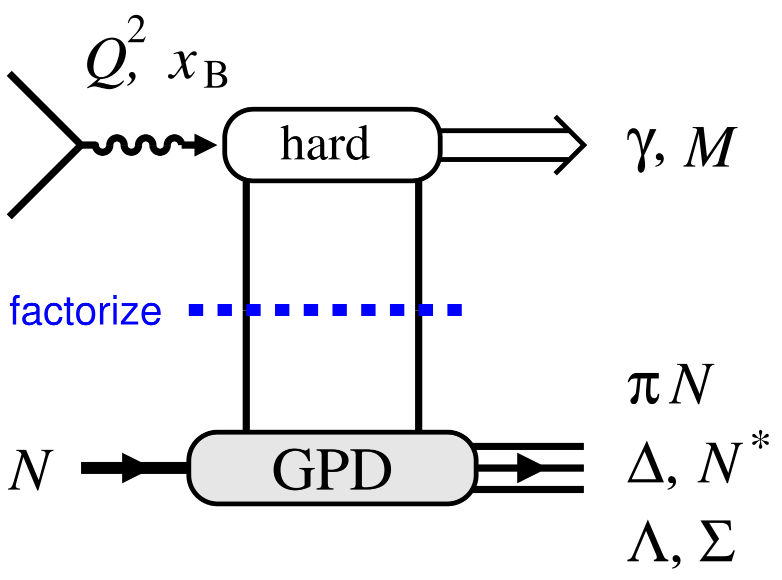
Exploring resonance structure with transition GPDs

C. Weiss (JLab), SPIN 2023, Durham NC, 26 Sep 2023

Jefferson Lab



Overview of concepts, methods, processes

Applications to JLab12+ and EIC

Much progress in theory

First results from JLab12

More resources: Workshop ECT* Trento, 21-25 Aug 2023 [Webpage]

Transition GPDs

Factorization → QCD operators

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

Dynamics and interpretation

Chiral dynamics, $1/N_c$ expansion

EM tensor and mechanical properties

Processes

$N \to \Delta, N^*$ in DVCS

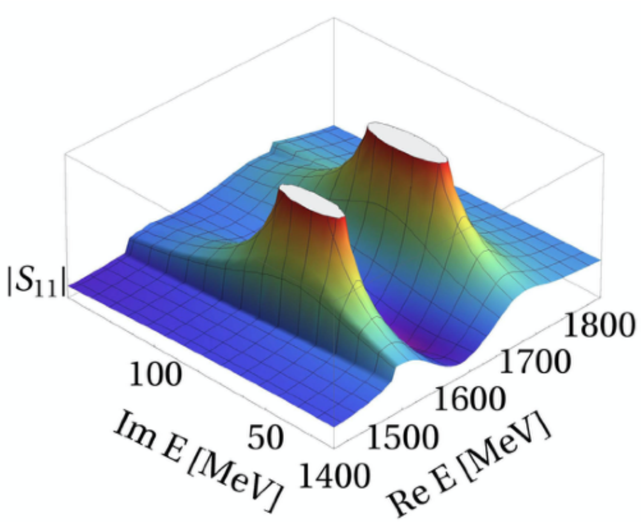
$N \to \Delta$ in π production at JLab12

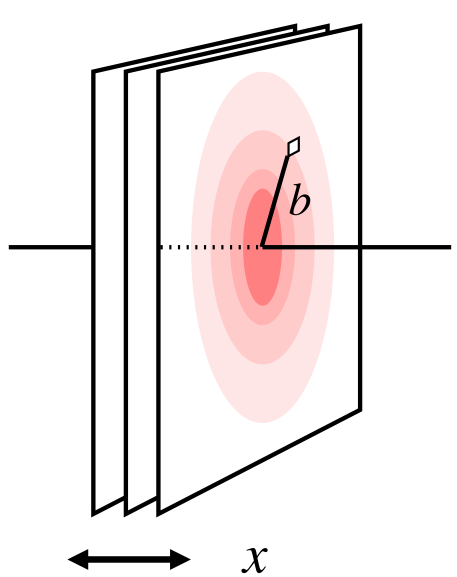
$N \to \Lambda, \Sigma$ in K, K^* production

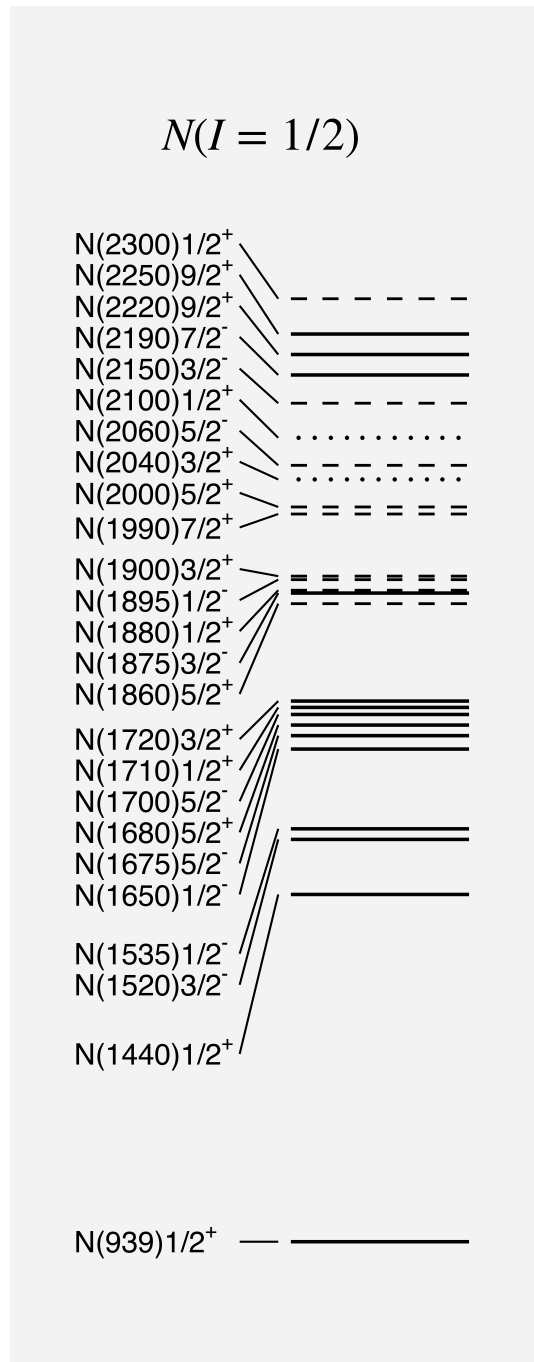
[$N \to X$ in vector meson production at small x]

Measurements with EIC far-forward detectors

Motivation: QCD structure of excited states







[Image credits: 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 interacting/excited states?

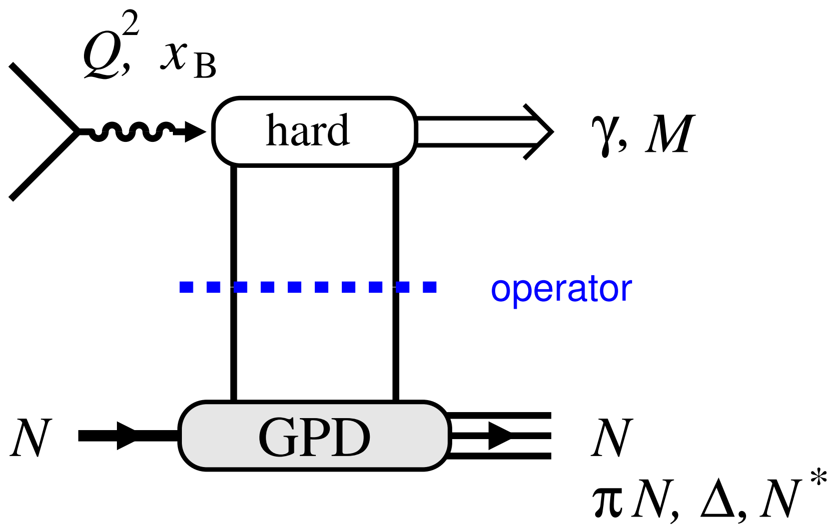
Multihadron states $\pi N, \pi\pi N, KY$

Baryon resonances N^*, Δ, Y^*

Limited information available from
vector/axial currents $\langle N^* \,|\, V^\mu, A^\mu \,|\, N \rangle$

Need other short-distance probes…

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 $\langle N' | \mathcal{O}(z) | N \rangle$ $\leftrightarrow$ GPDs

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

Interest in transitions $N \to N'$

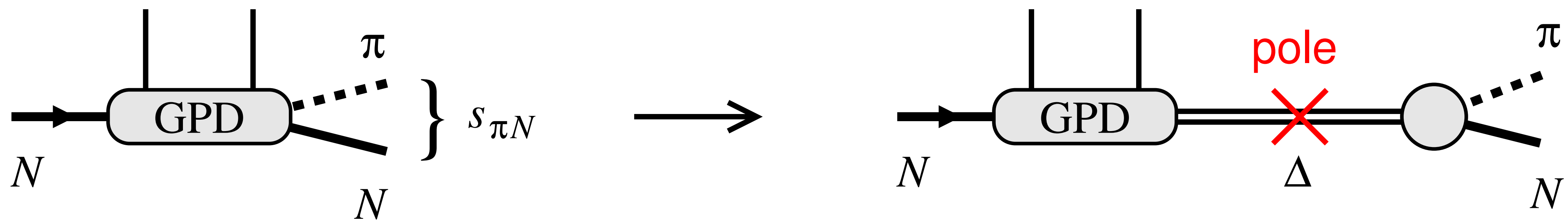
Learn more about operator: Quantum numbers, spin-flavor components?

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

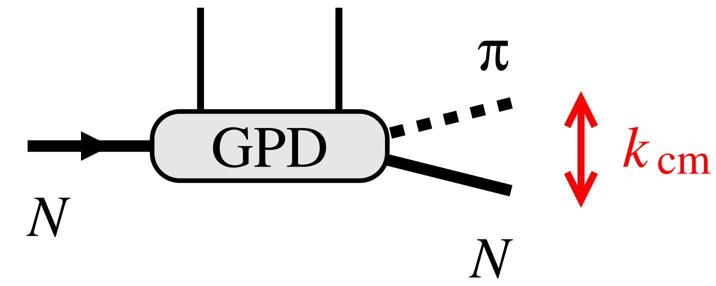
Rigorous definition of “resonance GPDs” using methods of S-matrix theory

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

Chiral dynamics

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

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

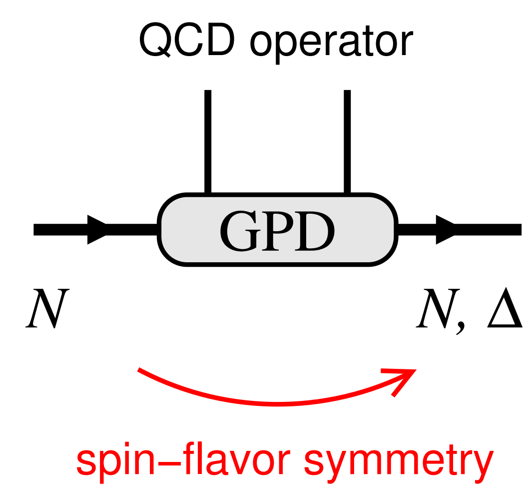


$1/N_c$ expansion of QCD

Organization scheme for non-perturbative dynamics

Spin-flavor symmetry relates $N \to N$ and $N \to \Delta$ transitions:
$\langle \Delta | \mathcal{O} | N \rangle \;=\;$ [symmetry factor] $\times \langle N | \mathcal{O} | N \rangle$

Predictions for transition GPDs
Frankfurt, Polyakov, Strikman 1998. FPS, Vanderhaeghen 2000

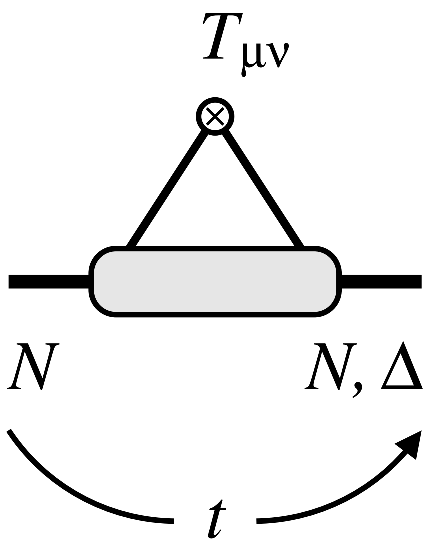


Effective degrees of freedom

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

Lattice QCD → Talks

Energy-momentum tensor form factors

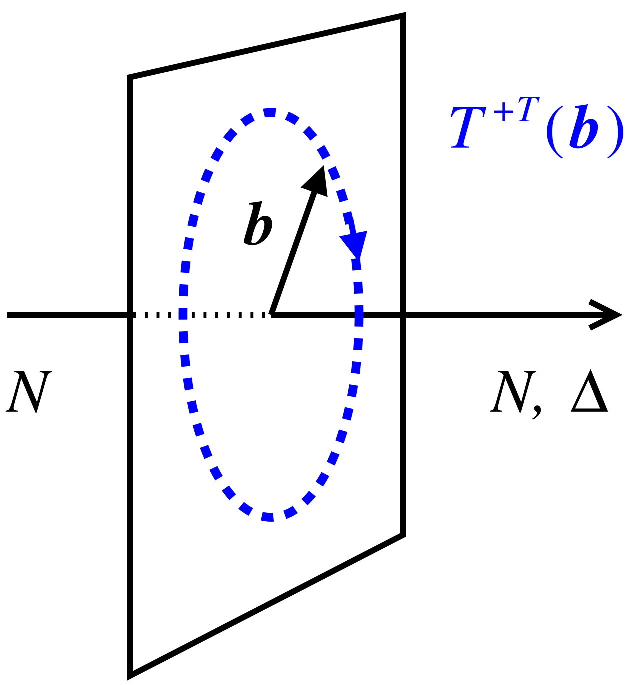


EMT operator as 2nd x-moment of light-ray operator

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

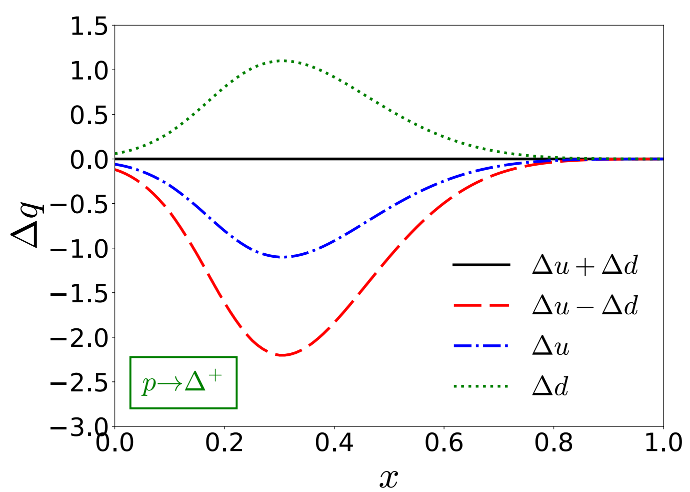
$$J^z(N \to \Delta) = \int d^2b \, \mathbf{b} \times \langle \Delta \,|\, \mathbf{T}^{+T} \,|\, N \rangle$$

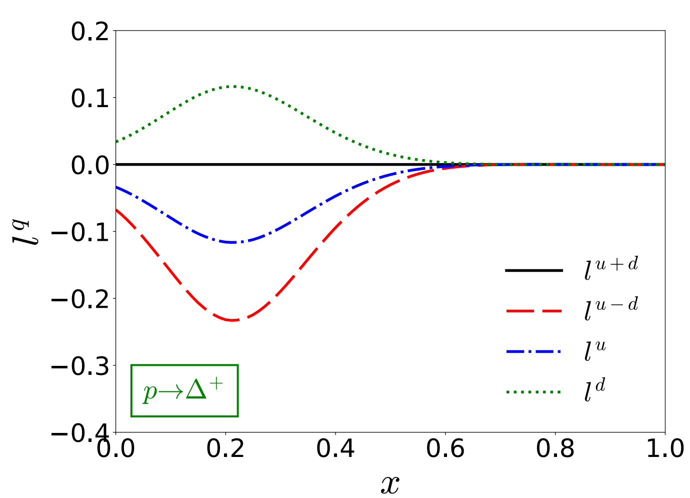
Probes isovector quark angular momentum $u - d$

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] $\mu^2 = 4\,\mathrm{GeV}^2$	0.33^*	0.33	0.41^*	0.58	0.08
[10] $\mu^2 = 4\,\mathrm{GeV}^2$	0.21^*	0.21	0.22^*	0.30	0.04
[11] $\mu^2 = 4\,\mathrm{GeV}^2$	0.24^*	0.24	0.23^*	0.33	0.05
[12] $\mu^2 = 1\,\mathrm{GeV}^2$	–	–	0.23^*	0.33	0.05
[13] $\mu^2 = 4\,\mathrm{GeV}^2$	–	–	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

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

$$V \equiv u - d$$

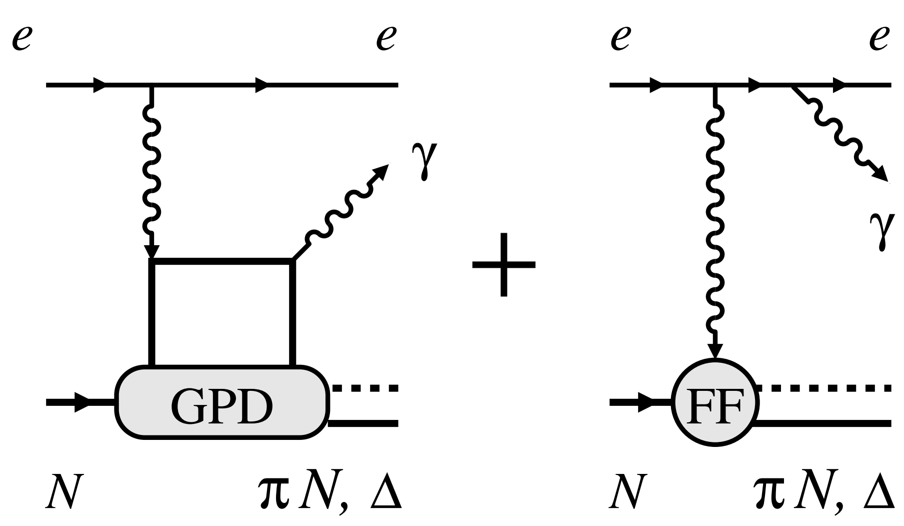
$N \to \Delta$ transition AM estimated using lattice QCD results for $p \to p$

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: $N \to \Delta$ in DVCS

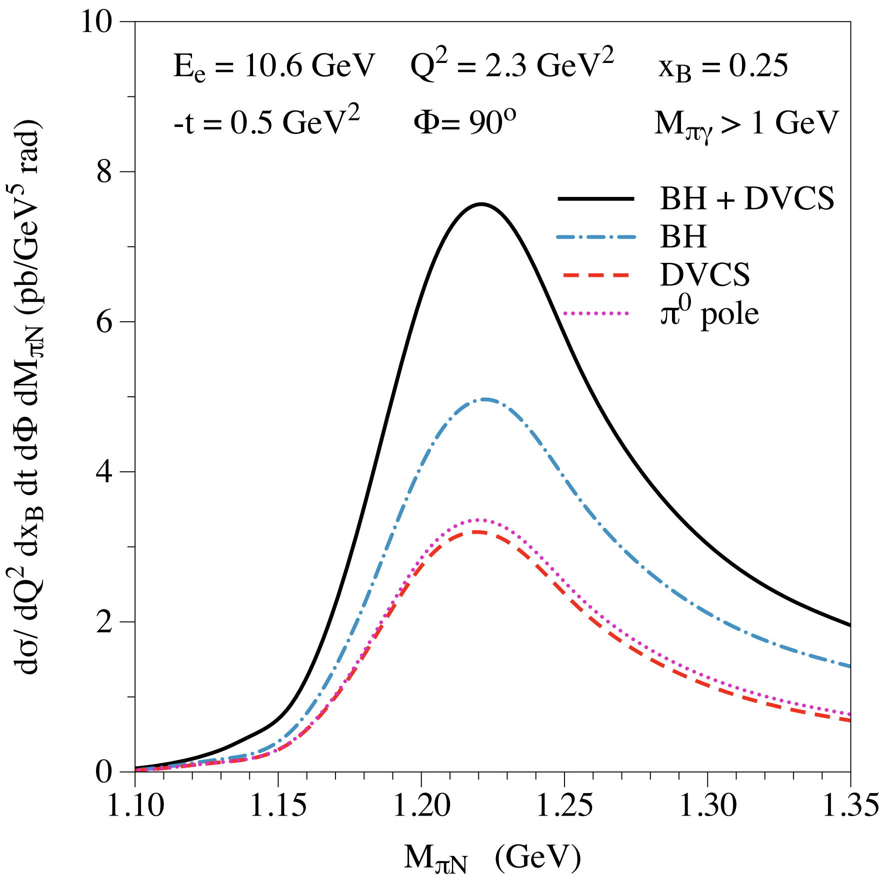


$$e + p \to e' + \gamma + \pi^0 p,\ \pi^+ n \quad (\Delta^+ \text{ resonance})$$

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

Probes chiral-even GPDs

Detailed modeling: Semenov-Tian-Shansky, Vanderhaeghen 2023



Semenov-Tian-Shansky, Vanderhaeghen 2023

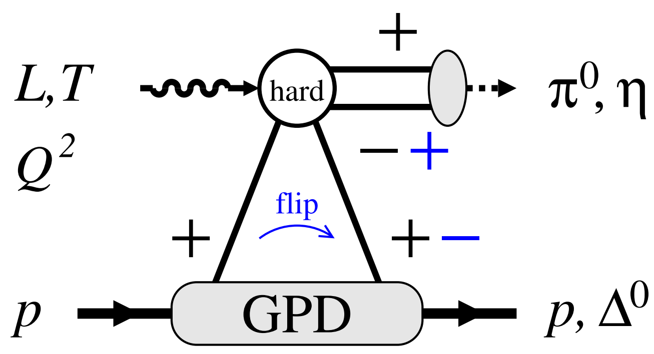
Experiments

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

JLab12: First results from CLAS12 Δ^+

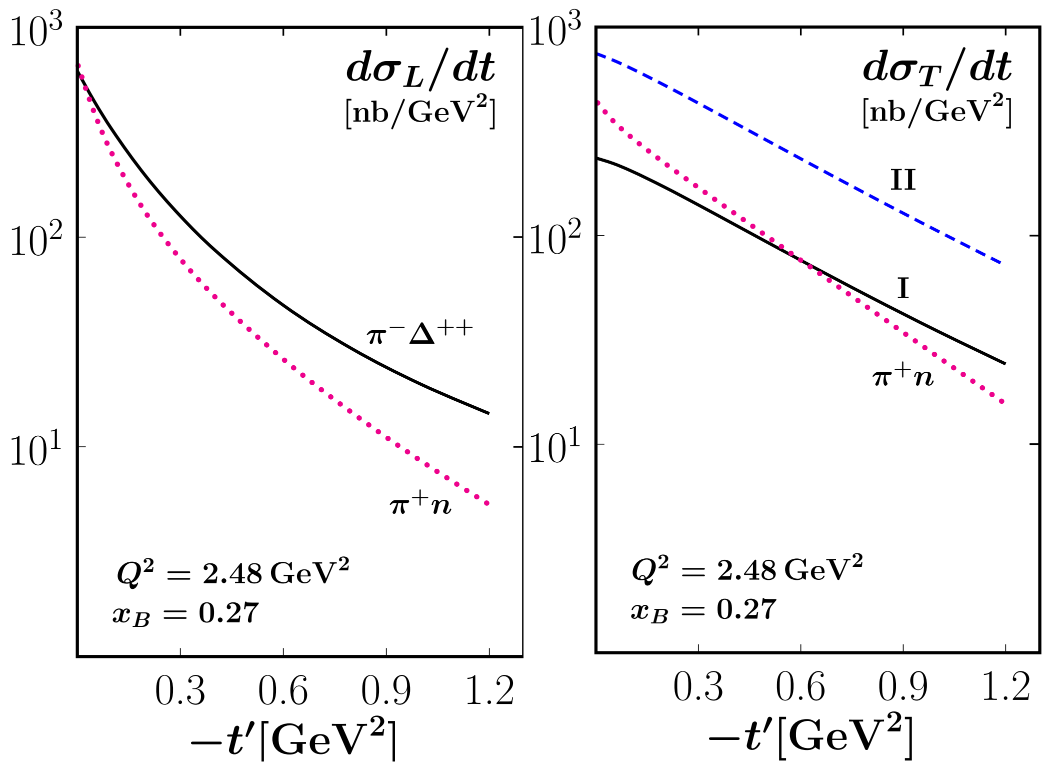
EIC: Far-forward Delta reconstruction?
Various channels, should be simulated

Processes: $N \to \Delta$ in pion production



$\langle H_T \rangle$: $u-d$ 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

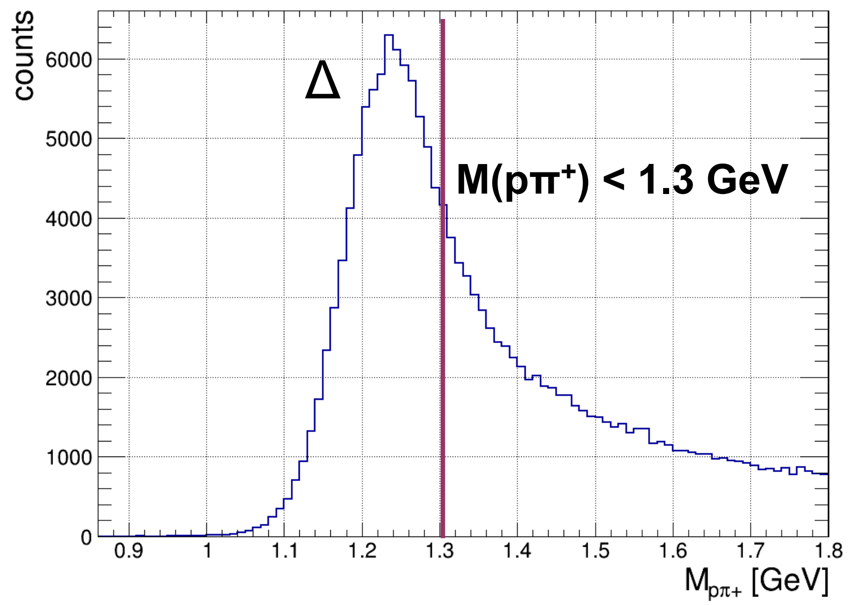
$1/N_c$ expansion predicts/explains flavor structure
Schweitzer, Weiss 2016; Kubarovsky 2019

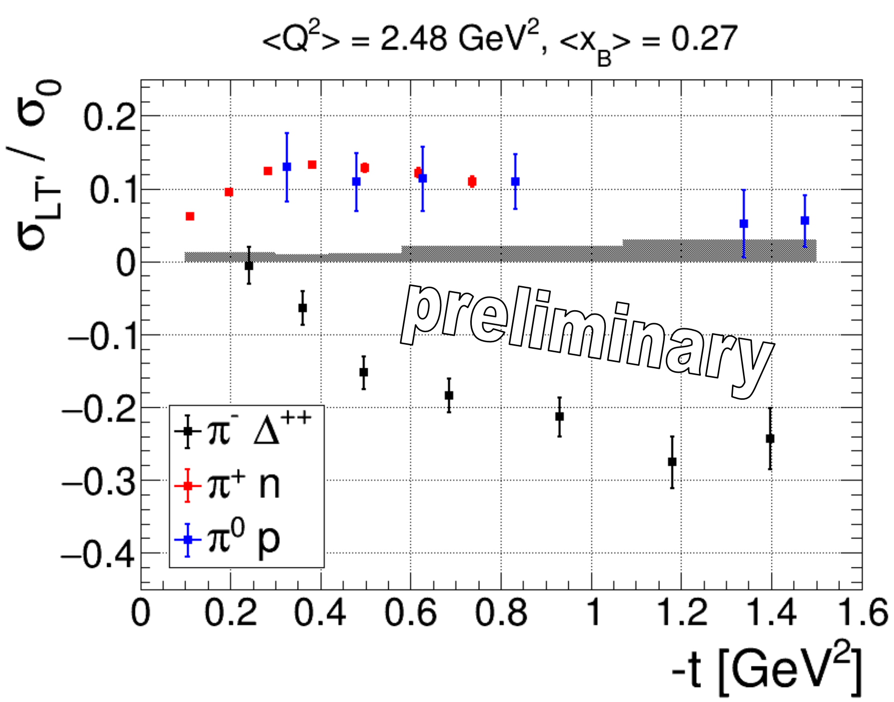
$N \to \Delta$ transitions

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

JLab12: First results from CLAS12 and Hall C

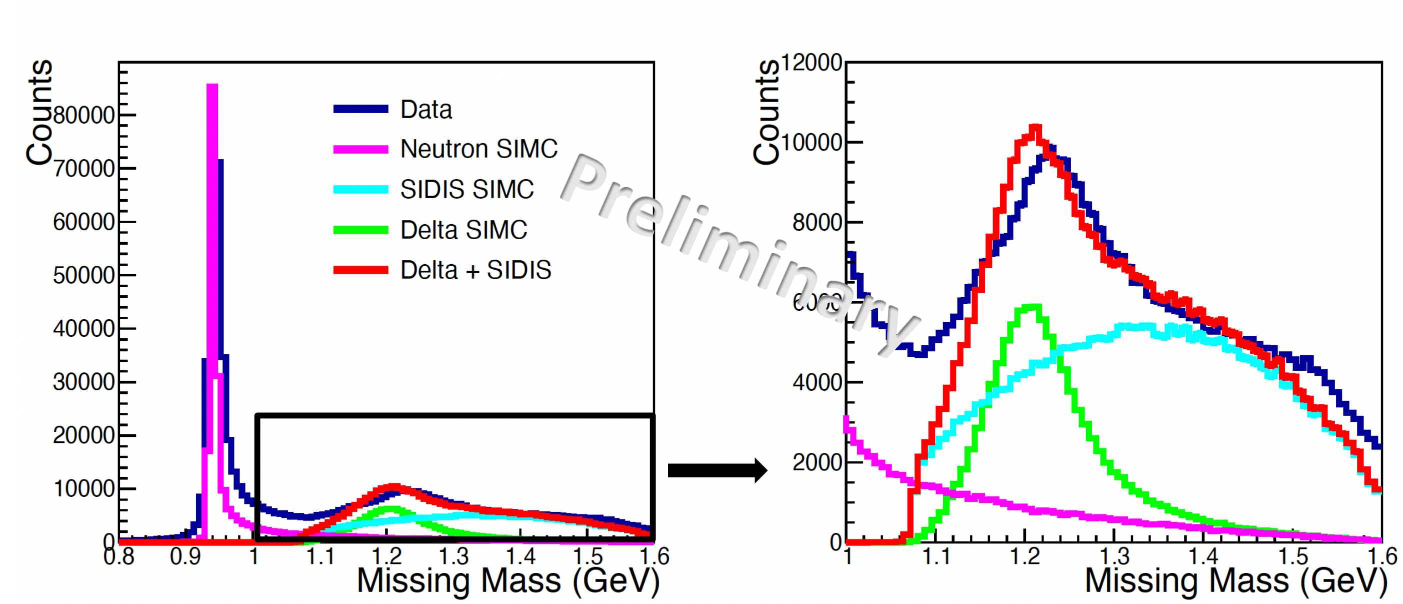
Processes: First JLab12 results

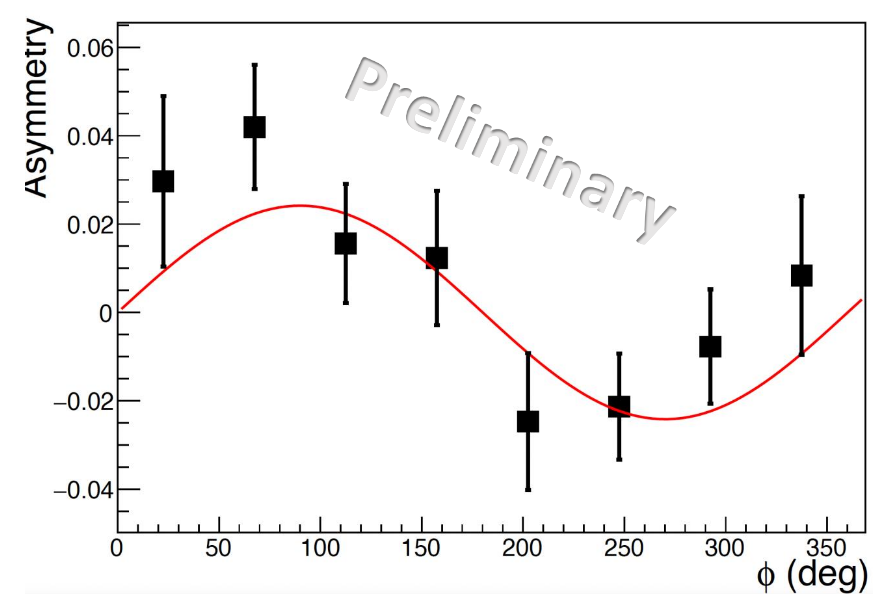




CLAS12 $ep \rightarrow e'\pi^-\Delta^{++}$

S. Diehl, ECT* Trento Workshop Aug 2023





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

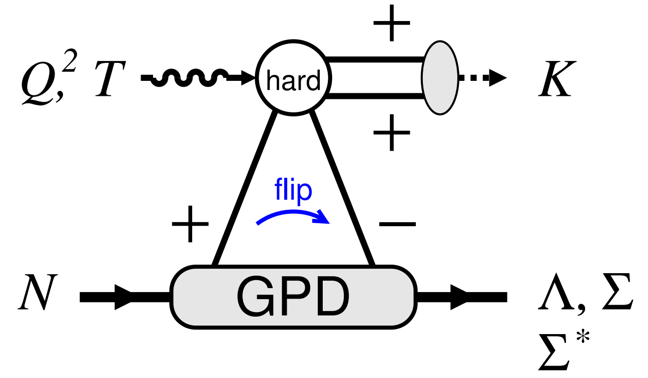
A. Usman, ECT* Trento Workshop Aug 2023

Processes: Other transitions

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

Transition GPDs from SU(3) flavor symmetry and $1/N_c$

Experiments JLab12, esp CLAS12



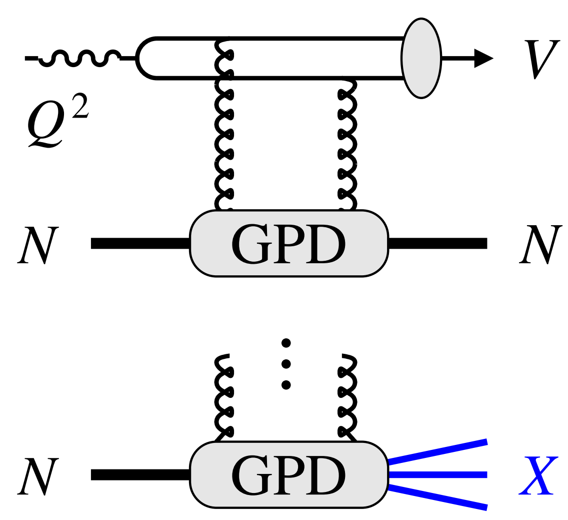
$N \to X$ in vector meson production at small x

Transitions $p \to X$(low-mass): Inelastic diffraction

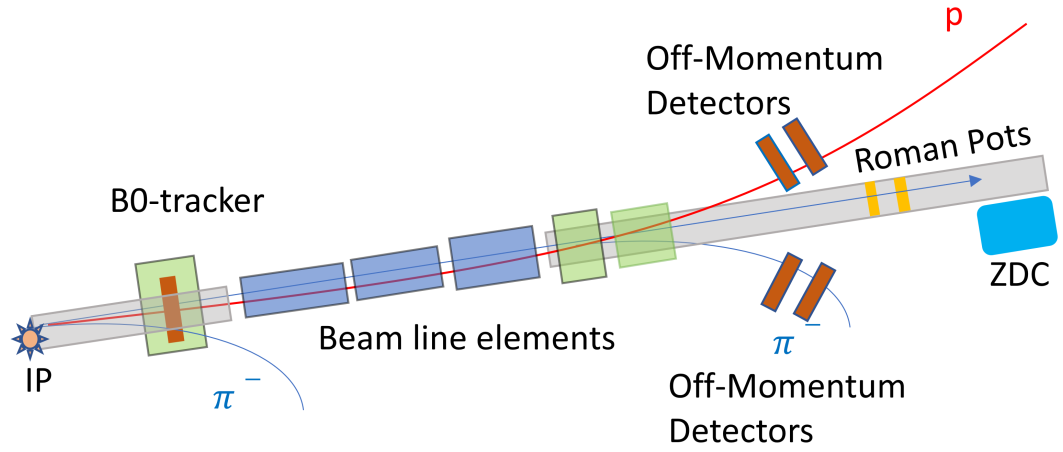
Connected with quantum fluctuations of gluon density
Frankfurt, Strikman, Treleani, Weiss 2008; Schlichting, Schenke, Mäntisaari 2014/2016

Can be viewed/analyzed in context of transition GPDs

Experiments HERA, LHC ultraperipheral, EIC



EIC: Far-forward detection



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

Channels that should be simulated

$ep \to e'\gamma\Delta^+$ DVCS	$\Delta^+ \to \pi^+ n,\, \pi^0 p$	Strong decay, at vertex
$ep \to e'\pi^+\Delta^0$	$\Delta^0 \to \pi^- p,\, \pi^0 n$	
$ep \to e'K^+\Lambda$	$\Lambda \to \pi^- p,\, \pi^0 n$	Weak decay, downstream

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

Cross section models for MC generators can be developed

Summary

- Factorization of hard exclusive processes as "source" of new operators for studying resonance structure: 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

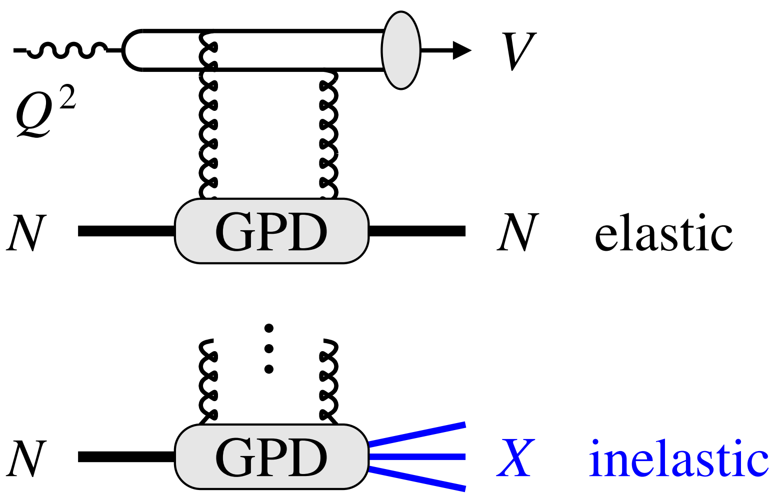
- First results on $N \to \Delta$ in pion production at JLab CLAS12 and Hall C

- Δ reconstruction with EIC far-forward detectors should be simulated.

- Emerging field of study… major opportunities

Supplemental material

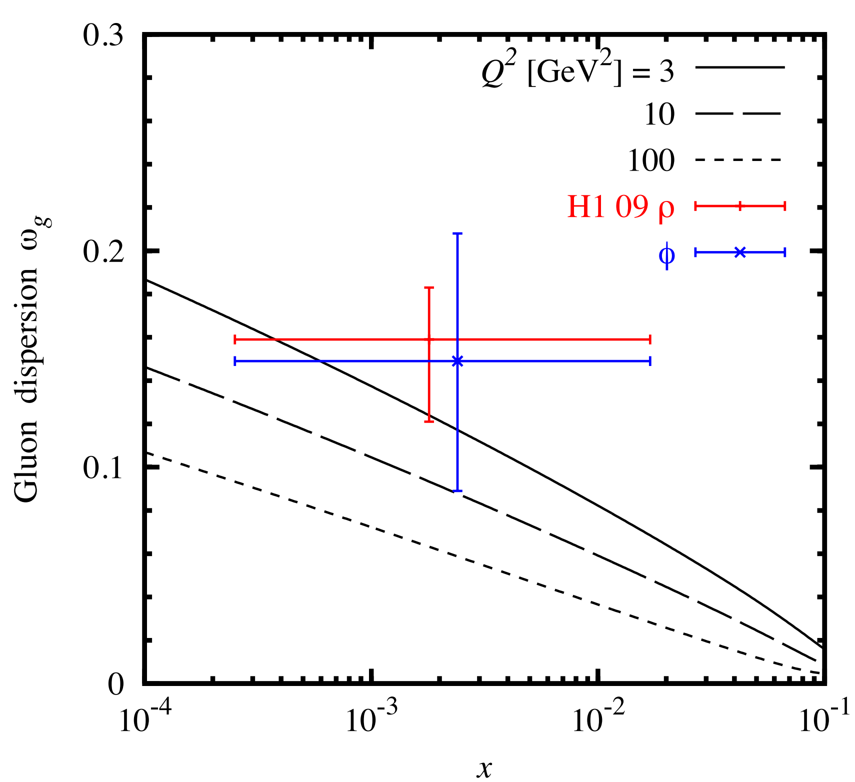
Processes: Vector meson production at small x



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

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

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



Frankfurt, Strikman, Treleani, Weiss 2008

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