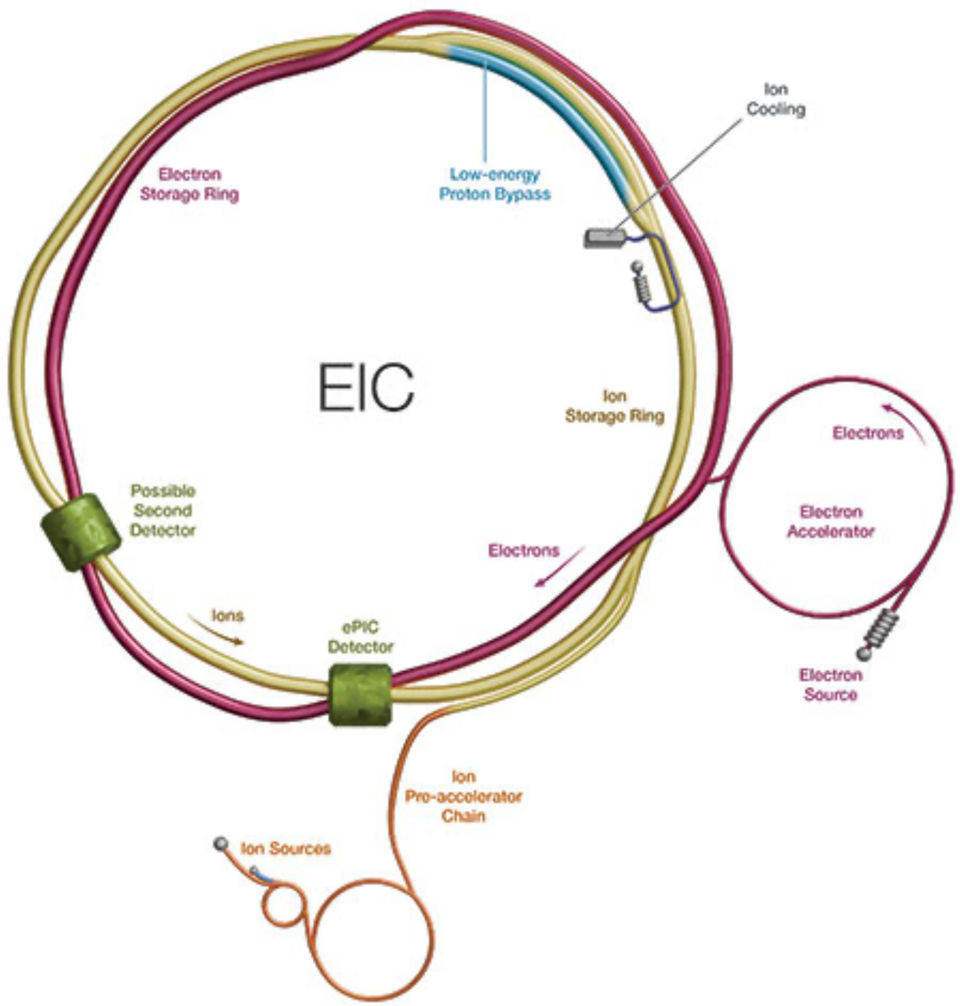
# Emerging topics in EIC science

**C. Weiss (JLab), EIC User Group Early Career Workshop, 11-13 July 2025** [Webpage]

Jefferson Lab




**This presentation**

Informal comments on some emerging topics, based on personal perspective, developments, …

No attempt to review “accepted” EIC program. New topics complementary, natural

Target fragmentation in DIS ←

Transition GPDs ←

Coherent processes with light ions

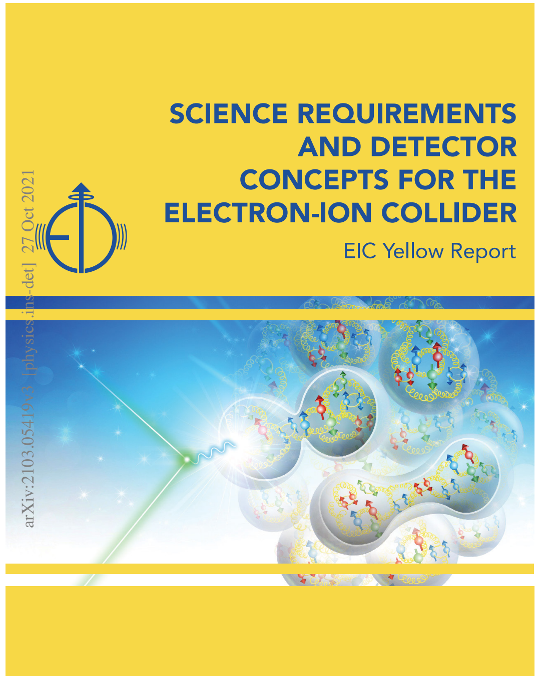
⋮

Interesting: Specific connections with structure and dynamics, open questions

Realistic: Can be studied with expected capabilities - luminosity, detection

Not much developed: Need theoretical modeling and experimental simulations

# EIC science: Program




**Current status: EIC Yellow Report**

R. Abdul Khalek et al, “Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report,” Nucl. Phys. A 1026, 122447 (2022), arXiv:2103.05419 [INSPIRE]

**Main themes**

Global properties of hadrons: Mass, spin, parton distributions

Multidimensional imaging of hadrons: Spatial, momentum

QCD in nuclei: Nuclear partons, interactions, high gluon densities

Hadronization process: Fragmentation, jet physics, medium effects

Eur. Phys. J. C (2023) 83:1125
https://doi.org/10.1140/epjc/s10052-023-11949-2
THE EUROPEAN PHYSICAL JOURNAL C

Review

50 Years of quantum chromodynamics

Introduction and Review

Franz Gross[1,2,a], Eberhard Klempt[3,b], Stanley J. Brodsky[4], Andrzej J. Buras[5], Volker D. Burkert[1], Gudrun Heinrich[6], Karl Jakobs[7], Curtis A. Meyer[8], Kostas Orginos[1,2], Michael Strickland[9], Johanna Stachel[10], Giulia Zanderighi[11,12], Nora Brambilla[5,12,13], Peter Braun-Munzinger[10,14], Daniel Britzger[11], Simon Capstick[15], Tom Cohen[16], Volker Crede[15], Martha Constantinou[17], Christine Davies[18], Luigi Del Debbio[19], Achim Denig[20], Carleton DeTar[21], Alexandre Deur[1], Yuri Dokshitzer[22,23], Hans Günter Dosch[10], Jozef Dudek[1,2], Monica Dunford[24], Evgeny Epelbaum[25], Miguel A. Escobedo[26], Harald Fritzsch[27], Kenji Fukushima[28], Paolo Gambino[11,29], Dag Gillberg[30,31], Steven Gottlieb[32], Per Grafstrom[33,34], Massimiliano Grazzini[35], Boris Grube[1], Alexey Guskov[36], Toru Iijima[37], Xiangdong Ji[16], Frithjof Karsch[38], Stefan Kluth[11], John B. Kogut[39,40], Frank Krauss[41], Shunzo Kumano[42,43], Derek Leinweber[44], Heinrich Leutwyler[45], Hai-Bo Li[46,47], Yang Li[48], Bogdan Malaescu[49], Chiara Mariotti[50], Pieter Maris[51], Simone Marzani[52], Wally Melnitchouk[1], Johan Messchendorp[53], Harvey Meyer[20], Ryan Edward Mitchell[54], Chandan Mondal[55], Frank Nerling[53,56,57], Sebastian Neubert[3], Marco Pappagallo[58], Saori Pastore[59], José R. Peláez[60], Andrew Puckett[61], Jianwei Qiu[1,2], Klaus Rabbertz[33,62], Alberto Ramos[63], Patrizia Rossi[1,64], Anar Rustamov[53,65], Andreas Schäfer[66], Stefan Scherer[67], Matthias Schindler[68], Steven Schramm[69], Mikhail Shifman[70], Edward Shuryak[71], Torbjörn Sjöstrand[72], George Sterman[73], Iain W. Stewart[74], Joachim Stroth[53,56,57], Eric Swanson[75], Guy F. de Téramond[76], Ulrike Thoma[3], Antonio Vairo[77], Danny van Dyk[41], James Vary[51], Javier Virto[78,79], Marcel Vos[80], Christian Weiss[1], Markus Wobisch[81], Sau Lan Wu[82], Christopher Young[83], Feng Yuan[84], Xingbo Zhao[55], Xiaorong Zhou[48]

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Springer

Compact summary available in review article:

F. Gross et al., “50 Years of Quantum Chromodynamics”
Eur. Phys. J. C 83, 1125 (2023), arXiv:2212.11107 [INSPIRE]

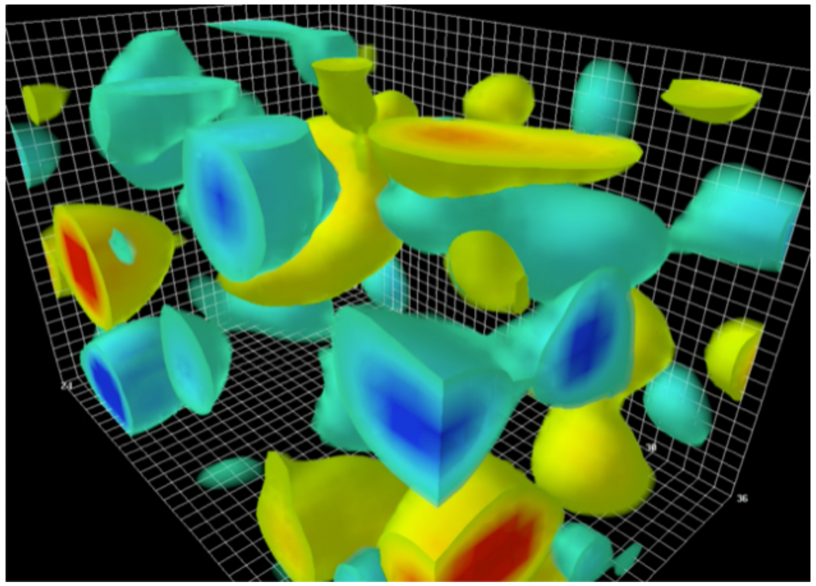
**Program still evolving**

Science: Developments in theory, concepts, methods, processes

Detector: Simulations, design

Facility: Running conditions and staging, 2nd IR/detector, upgrade plans

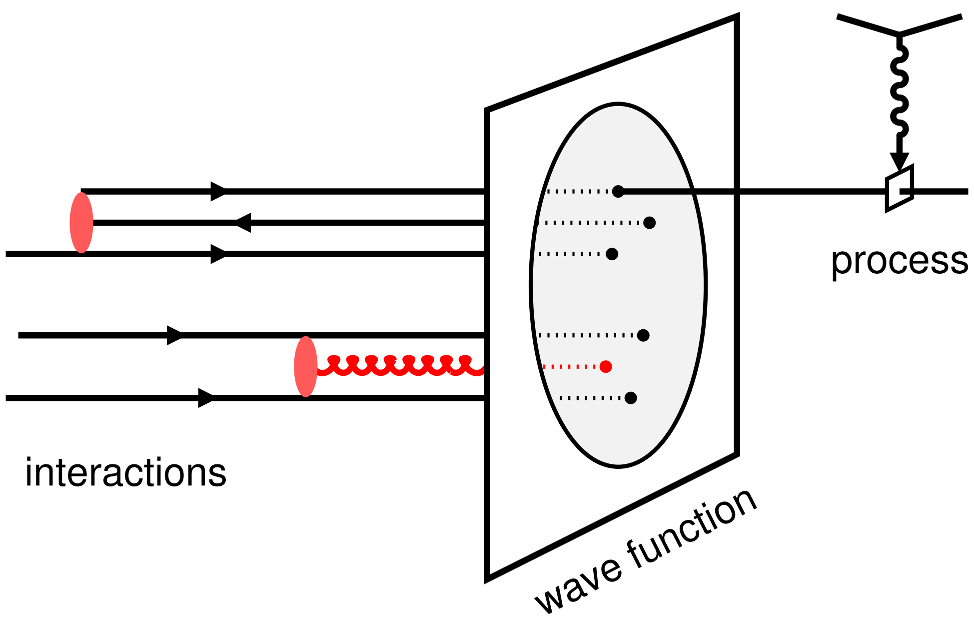
# EIC science: QCD and parton picture



**Hadrons as emergent phenomena of QCD**

Dynamics relativistic, quantum, strongly coupled

Nonperturbative phenomena: Symmetry breaking (chiral, conformal), mass generation, confinement




**Parton picture**

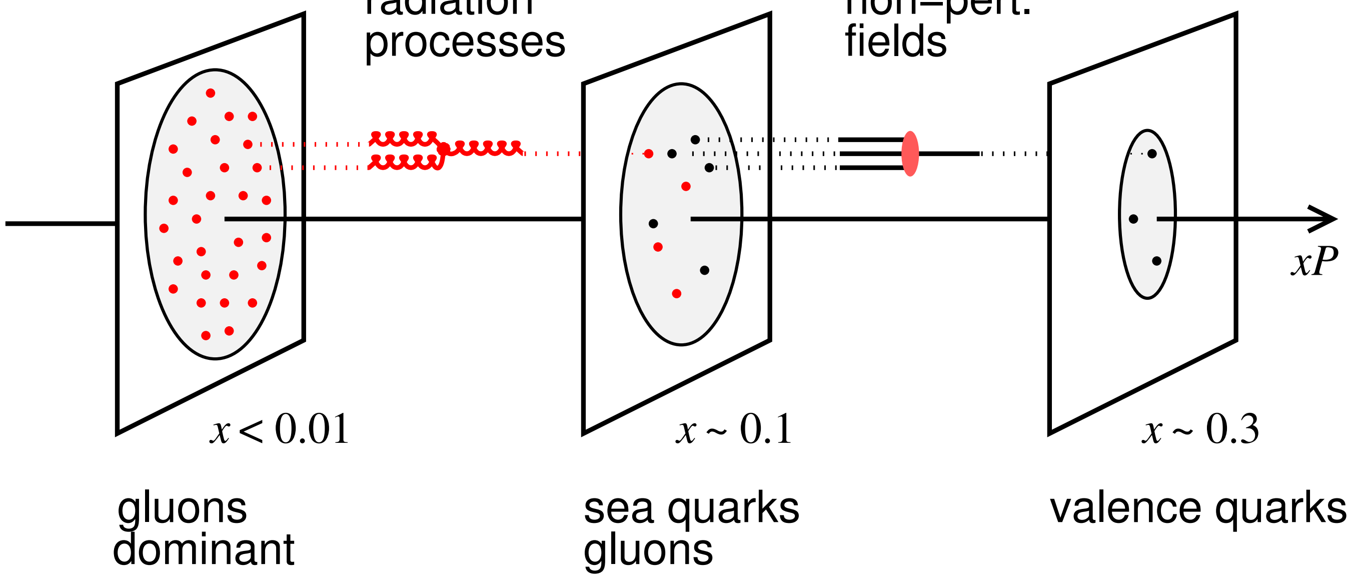
Hadron moves with large momentum $P \gg \mu_{\text{nonpert}}$
QCD radiation: Renormalization, factorization

Field modes regarded as particles

Many-body system: Wave function, configurations, spatial size, internal motion

High-energy process samples instantaneous configurations of system

# EIC science: Many-body system

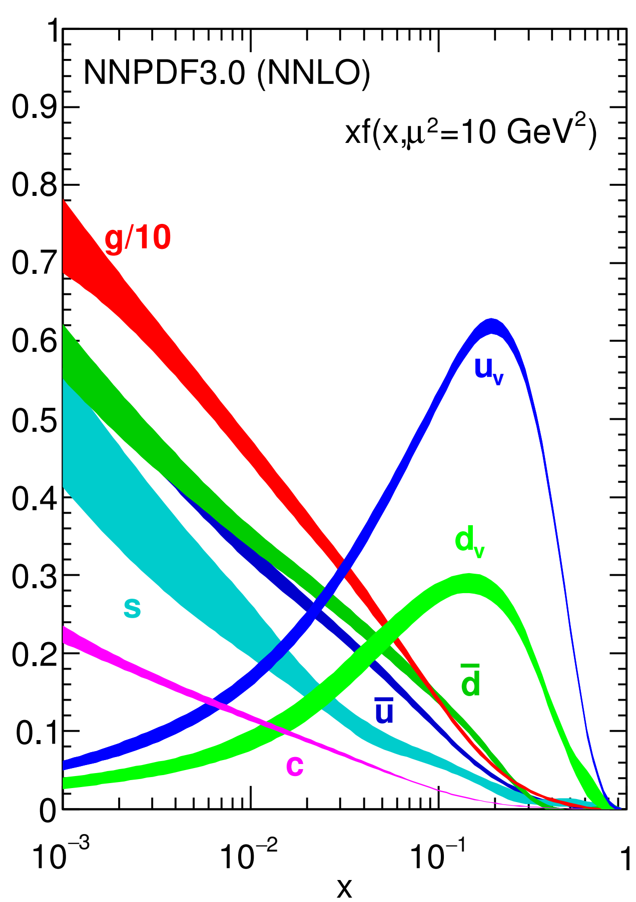



**Components of wave function**

Few particles with large $x = O(1)$

Many particles with small $x \ll 1$

Connected by QCD interactions




**Physical properties**

Particle number densities in $x$, incl. spin/flavor - PDFs

Transverse spatial distributions - GPDs

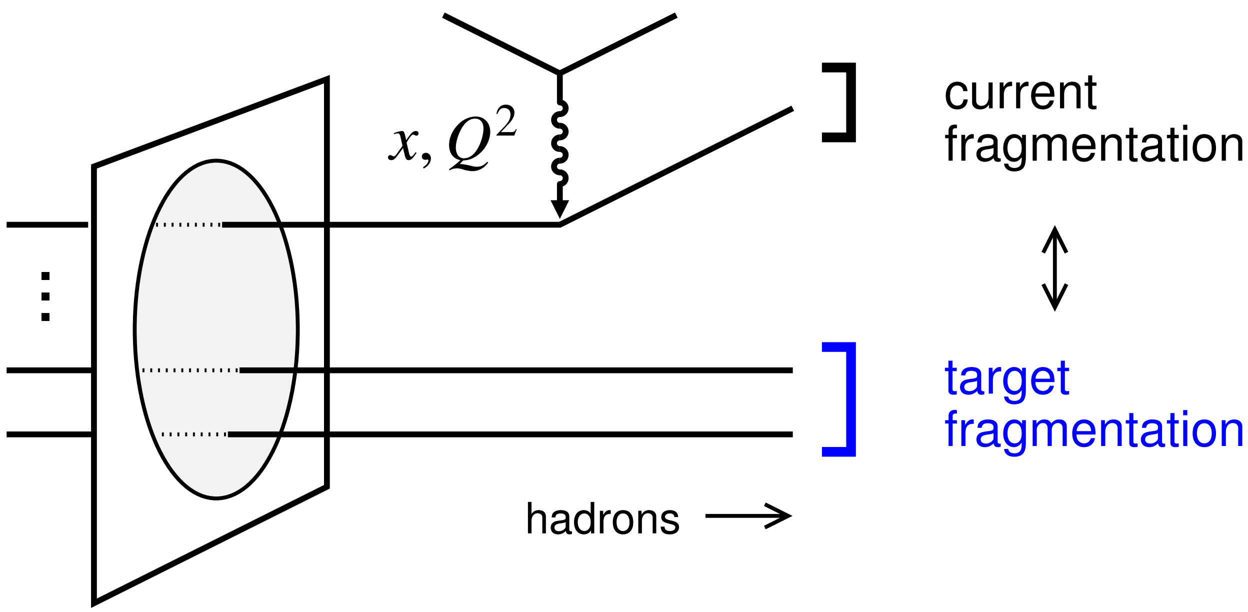
Transverse motion and spin-orbit structures - TMDs

Particle correlations?

Interactions ↔ non-pert. QCD?

# Target fragmentation: Process






DIS process removes parton with $x$ at scale $Q^2$

Observe hadrons from fragmentation of target remnant

Measure hadron distribution in longitudinal/ transverse momentum, correlation with high-energy process

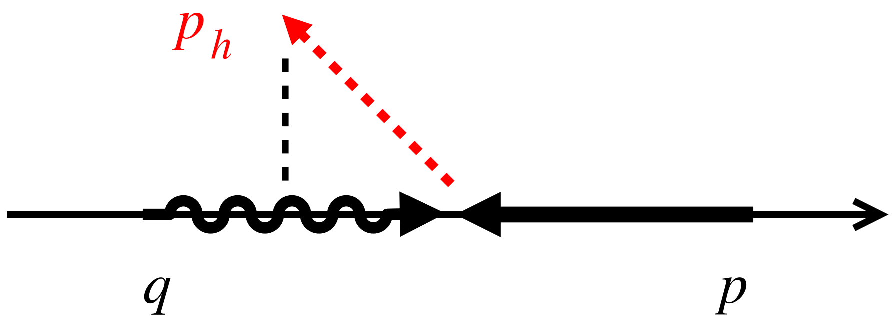
**Physics interest**

Configurations: What configurations in wave function give rise to the PDFs?
How do the typical configurations in the PDFs change with $x$ and parton type?

Correlations: How are the partons in wave function correlated?
Momentum - spin - quark/antiquark - flavor?

Hadronization dynamics: How does “diquark-type” system hadronize?
Where/how does baryon number materialize in final state?

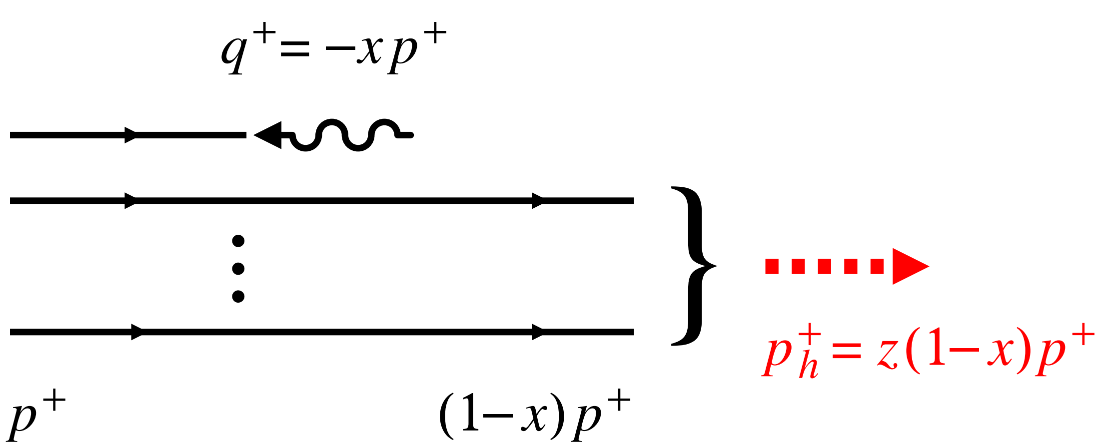
# Target fragmentation: Kinematic variables




**Feynman variable**

$$x_F = \frac{p_h^z}{p_h^z(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \quad -1 < x_F < 1$$

Natural for hadron-hadron collisions




**Light-cone fraction**

$$z = \frac{p_h^+}{(1-x)p^+} = \frac{\text{hadron}}{\text{remnant}} \qquad 0 < z < 1$$

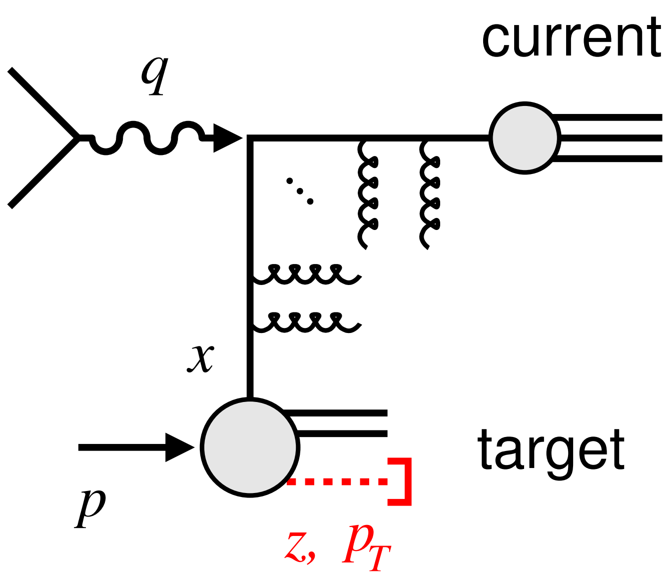
Natural for parton picture, QCD factorization

$z \approx -x_F$ in target fragmentation region $z = O(1)$

Photon-proton collinear frame

[Alt variable: Rapidity]

# Target fragmentation: QCD factorization




**QCD factorization** $\gamma^* + N \to X + h(\text{target})$

Trentadue, Veneziano 1994: $p_T$-integrated
Collins 1998: Fixed $p_T$

QCD radiation: DGLAP, same as inclusive DIS

Predicts $Q^2$-scaling for fixed $z, p_T \ll Q$

**Fracture functions / Conditional PDFs**

Describe probability to find hadron with $z, p_T$ in target after removing parton with $x$

Universal, independent of hard process

Leading-twist structures

Combine aspects of parton distribution and fragmentation functions

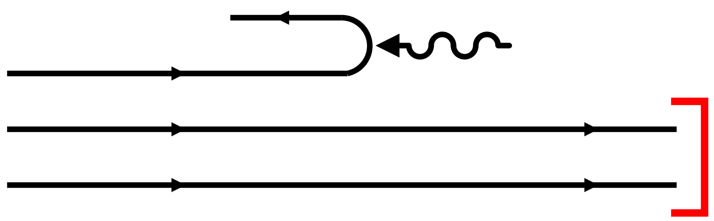
$$f_h(x, z, p_T; \mu_{\text{fact}}) = \sum_{X'} \int d^2 k_T$$

$$\langle p \,|\, a^\dagger(k) \,|\, hX' \rangle \langle hX' \,|\, a(k) \,|\, p \rangle_{k^+ = xp^+}$$

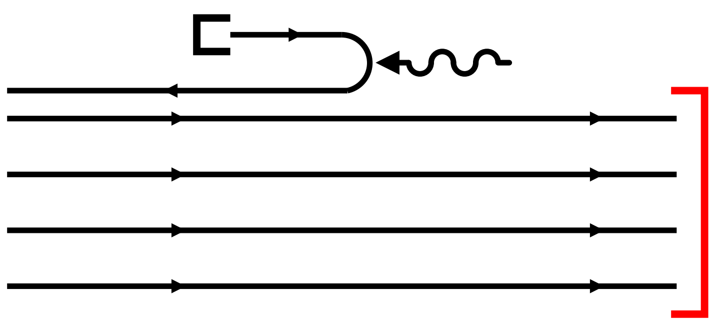
[Naive expression: Gauge link, renormalization]

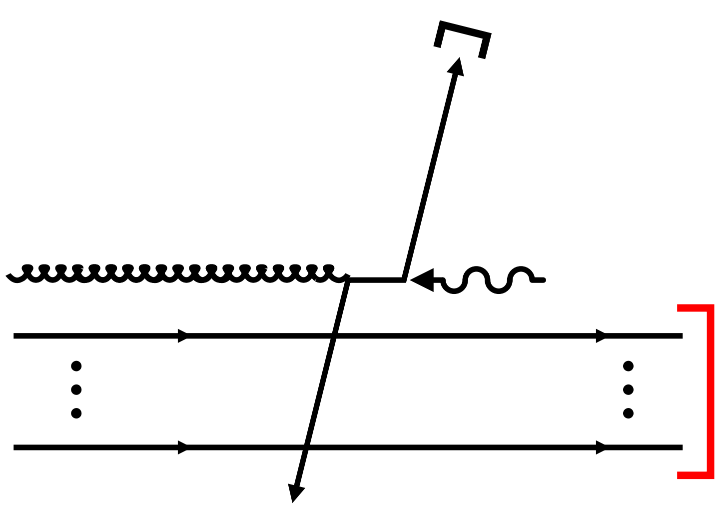
# Target fragmentation: Dependences 

$x > 0.3$



$x < 0.1$





**$x$-dependence of target fragmentation**

Remove parton from different configurations in wave fn

$x > 0.3$: remove valence quark

$x < 0.1$: remove sea quark/gluon in multiparticle config

**Dependence on charge/flavor of removed parton**

Tag flavor or removed quark/antiquark:
Correlation between current and target fragmentation

Remove gluon through charm production process

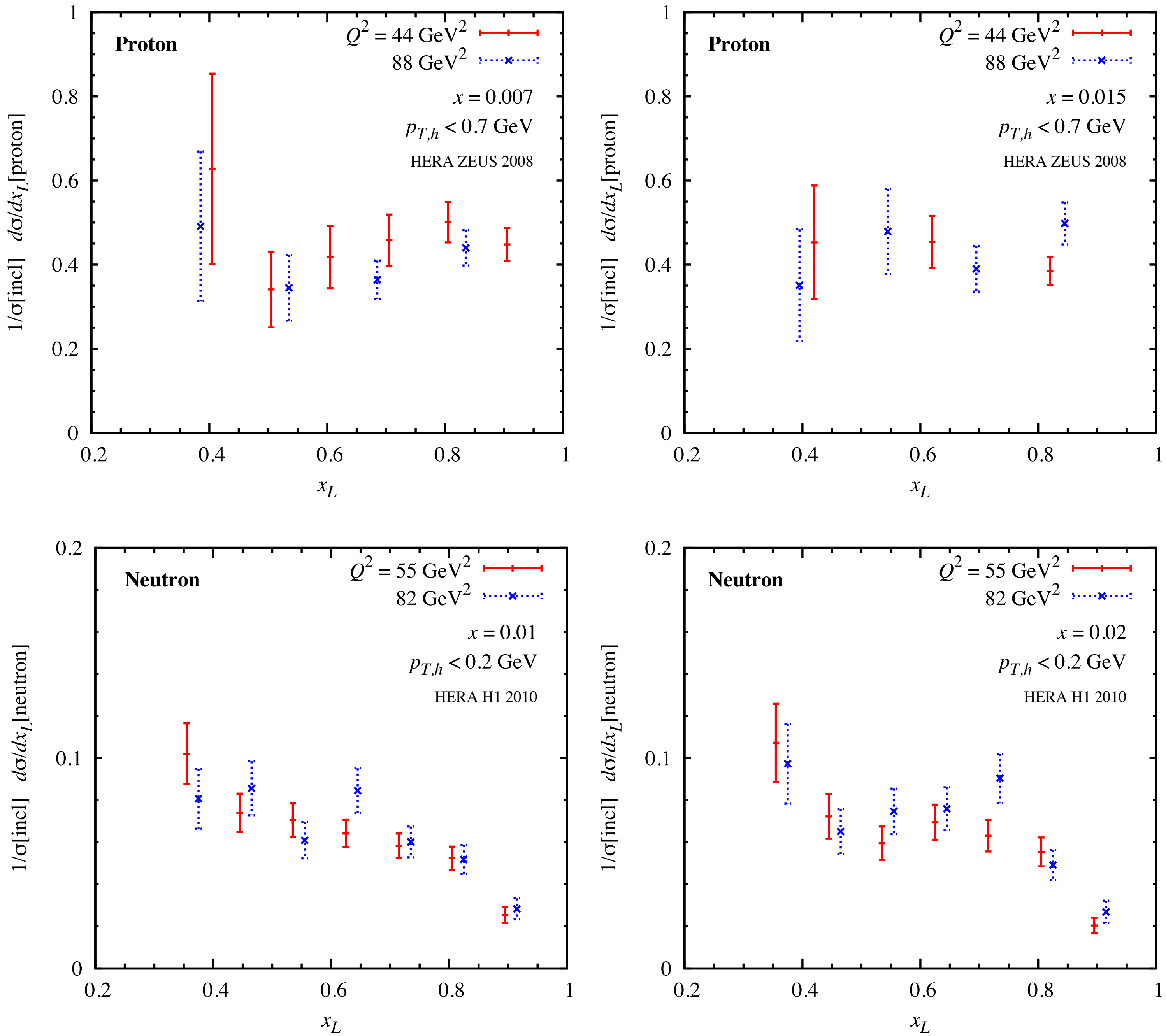
**$z$-dependence of target fragmentation**

Dynamics of “diquark” hadronization

Counting rules $(1 - z)^n$ for leading hadrons

Frankfurt, Strikman 81

# Target fragmentation: Baryon number transport




**$x_L$ distributions of leading baryons**

Here $x_L \approx -x_F$

$Q^2$-scaling supports QCD factorization

**Baryon number transport**

Integrated baryon number at $x_L > 0.1$ is only ~0.6-0.7

Significant baryon number transported away from TF region

Surprising because at $x \lesssim 0.01$ the DIS process removes mostly sea quarks/gluons, not valence quarks
Strikman 2021

Dynamical mechanism of baryon number transport?
Baryon junctions: Magdy, Deshpande, Lacey, Li, Tribedy, Xu 2024

[Proton distribution does not contain diffractive peak $x_L \approx 1$]

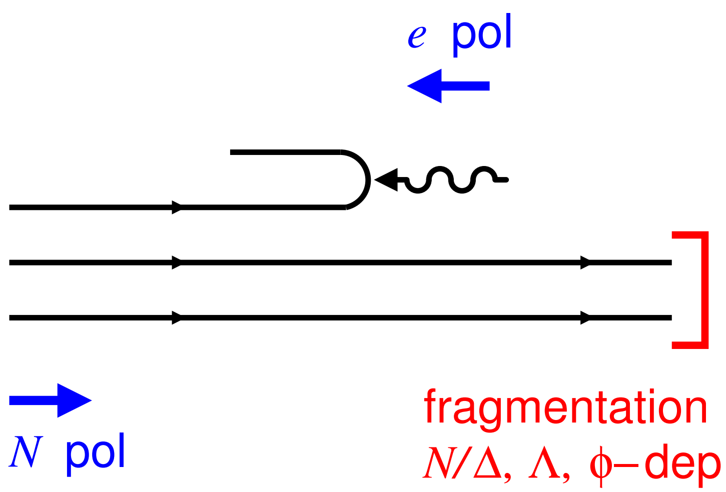
ZEUS: S. Chekanov et al., JHEP 06, 074 (2009) [INSPIRE]

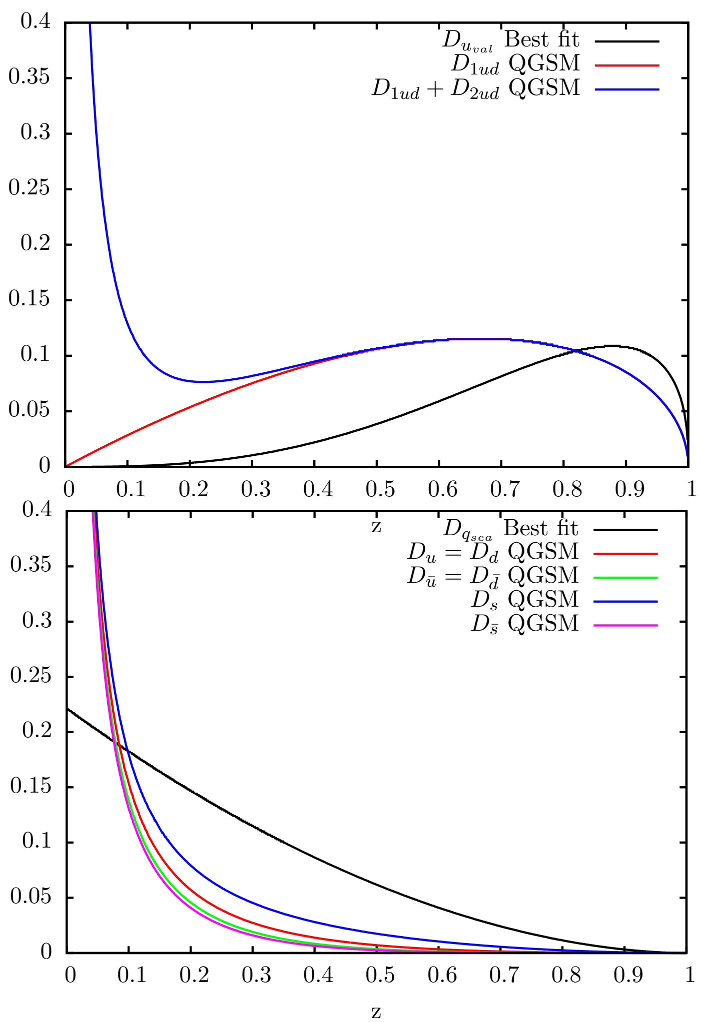
H1: F. Aaron et al., Eur.Phys.J.C 68, 381 (2010) [INSPIRE]

Connected with “color entanglement”of nucleon WF

Relevant for final states of heavy-ion collisions

# Target fragmentation: Spin correlations




**Target fragmentation in polarized DIS**

Polarized DIS leaves remnant system with definite spin

Study spin dependence of target fragmentation

**Fragmentation observables sensitive to spin**

$N - \Delta$ production ratio

$\Lambda$ production: Polarization transfer

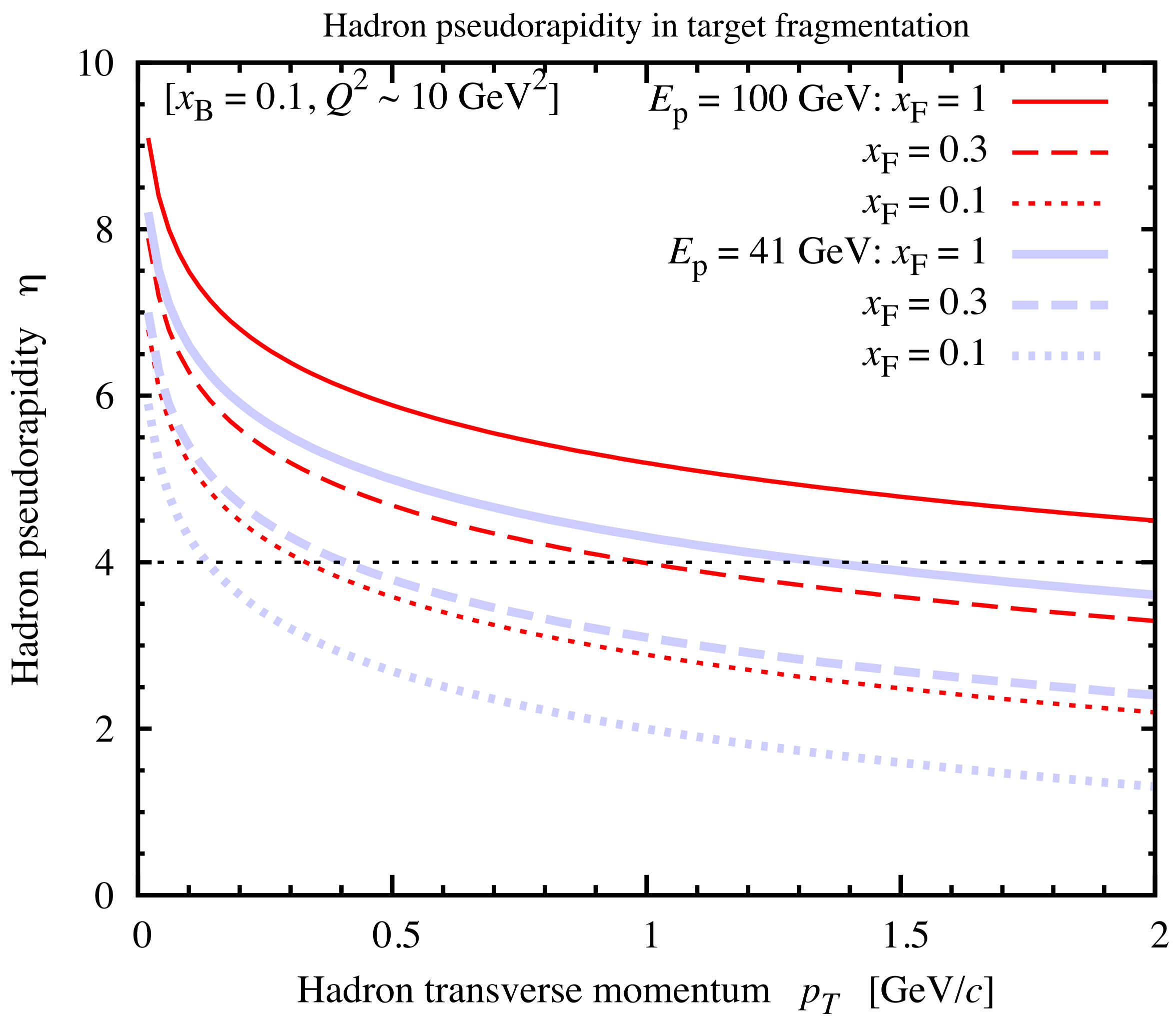
Ceccopieri, Mancusi 2012: Neutrino + DIS data

Azimuthal asymmetries with beam and target spin:
T-even/odd structures, as in current fragmentation SIDIS

Anselmino, Barone, Kotzinian 2011

$$\frac{d\sigma}{dx dQ^2 dz dp_T d\phi_h} = [\ldots] + \sum_n [\ldots] \cos n\phi_h + \sum_n [\ldots] \sin n\phi_h$$

# Target fragmentation: EIC detector coverage




[CW 2021, prepared for EIC Yellow Report [INSPIRE]]

Pseudorapidity $\eta$ covered in proton target fragmentation measurements at various $x_F$ and $p_T$

Uses mostly hadron endcap of central detector

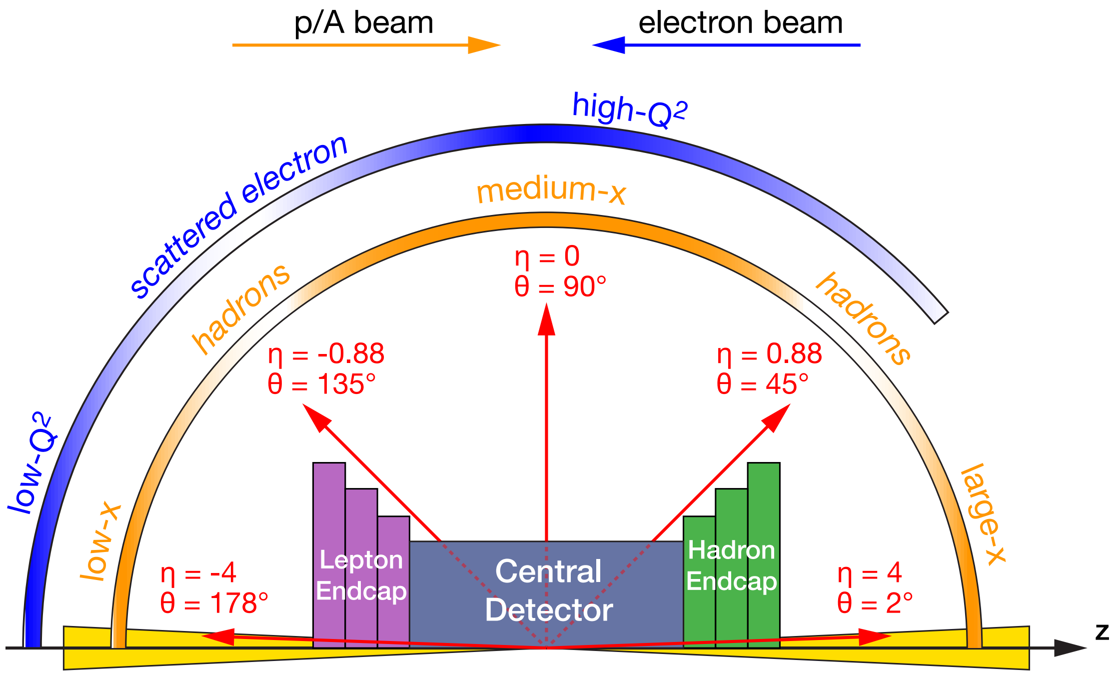
Some target fragmentation hadrons appear between central detector $\eta \gtrsim 3.5$ and forward detectors $\eta \gtrsim 4.5$

Coverage for target fragmentation hadrons depends on proton beam energy

**Production rates**

Standard semiinclusive DIS rates.
Every DIS event has target fragments!

Target fragmentation studies can be done with moderate luminosity



# Target fragmentation: Future EIC studies



**Theory**

Develop realistic models of nucleon fracture function combining partonic structure in initial state and fragmentation dynamics in final state (→ discussion)

Identify observables testing specific hypotheses about partonic structure in initial state, e.g. spin and flavor correlations between partons

Use jet physics concepts to describe target fragmentation?
Yang-Ting Chien 2022

**Simulations**

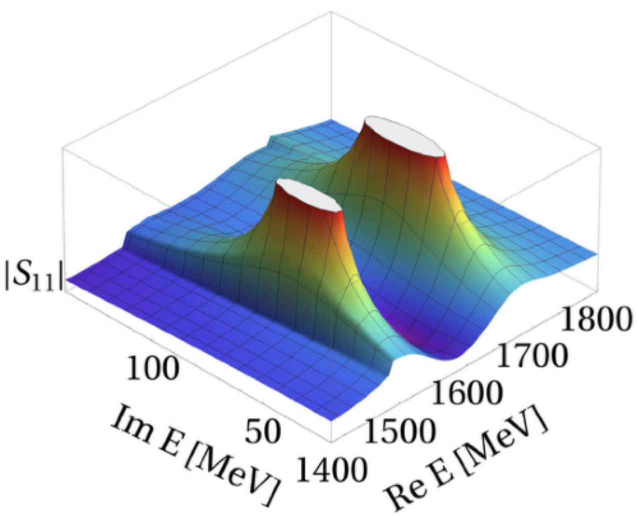
Simulate detection of target fragmentation hadrons in DIS at EIC with ePIC: Charged $p, \pi^{\pm}, K^{\pm}$, neutral $n, \pi^0, \Lambda$
Explore role of hadron endcap and far-forward detectors in various regions of $x_F, p_T$

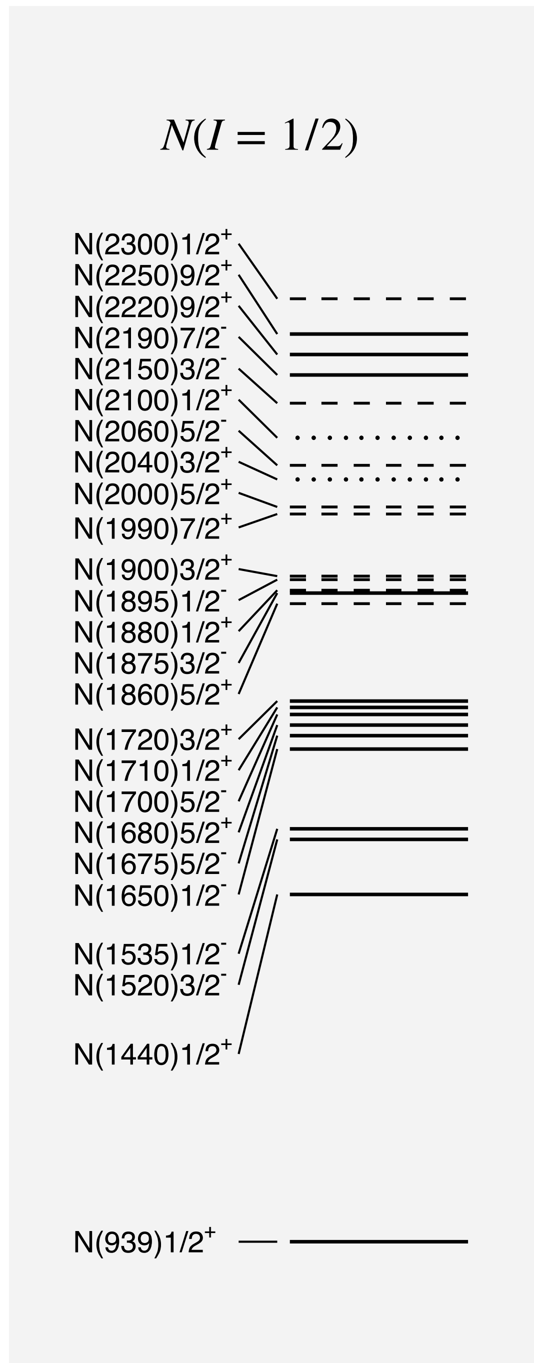
Study target fragmentation at various proton beam energies

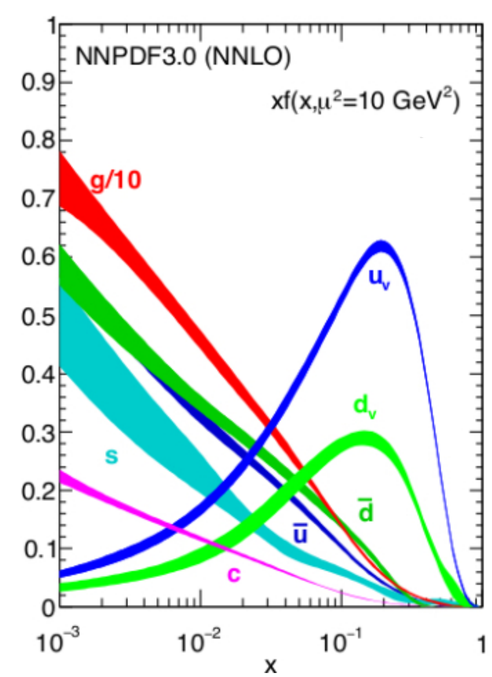
Could be done with fragmentation MC before dedicated models of fracture functions become available

Explore feasibility of measurement of azimuthal angle dependence ($\phi$ harmonics) of target fragmentation

# Transition GPDs: Excited baryons in QCD




[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 $N^*$, $\Delta$:
Resonances, unstable particles

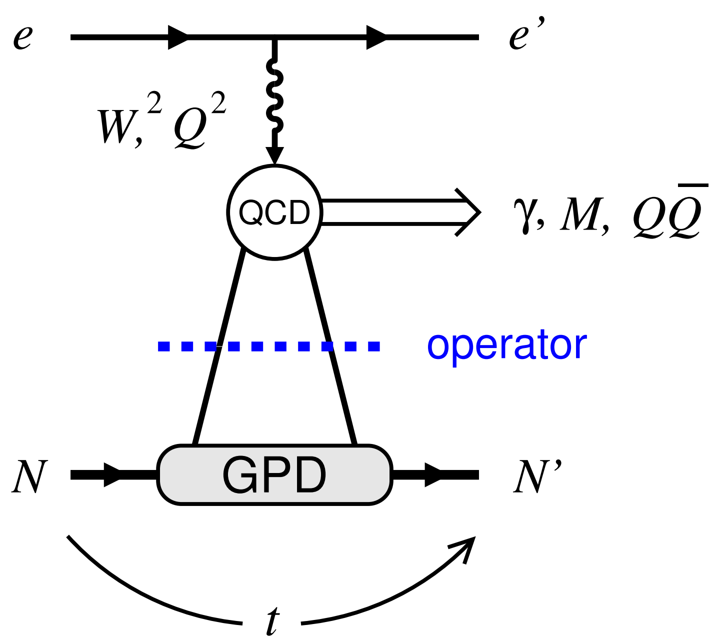
Quark/gluon structure relevant for

→ Dense matter, neutron stars, early universe

→ Neutrino-nucleus interactions

Need short-distance probe suitable
for baryon resonances

# Transition GPDs: Exclusive processes



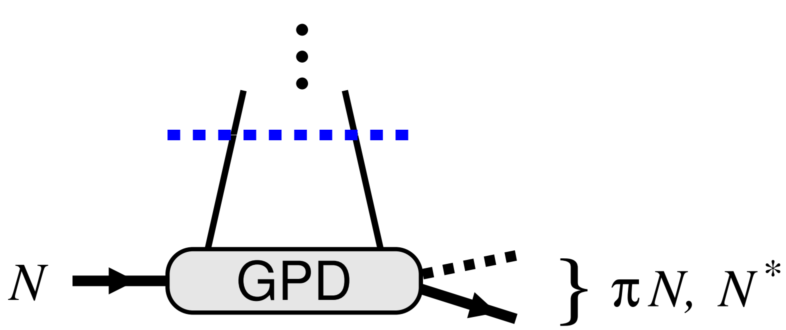

Process with $Q^2, W^2 \gg \mu^2_{\text{had}} \sim 1\ \text{GeV}^2, \quad |t| \sim \mu^2_{\text{had}}$

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**




$N^*$ from $s_{\pi N}$(pole)

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

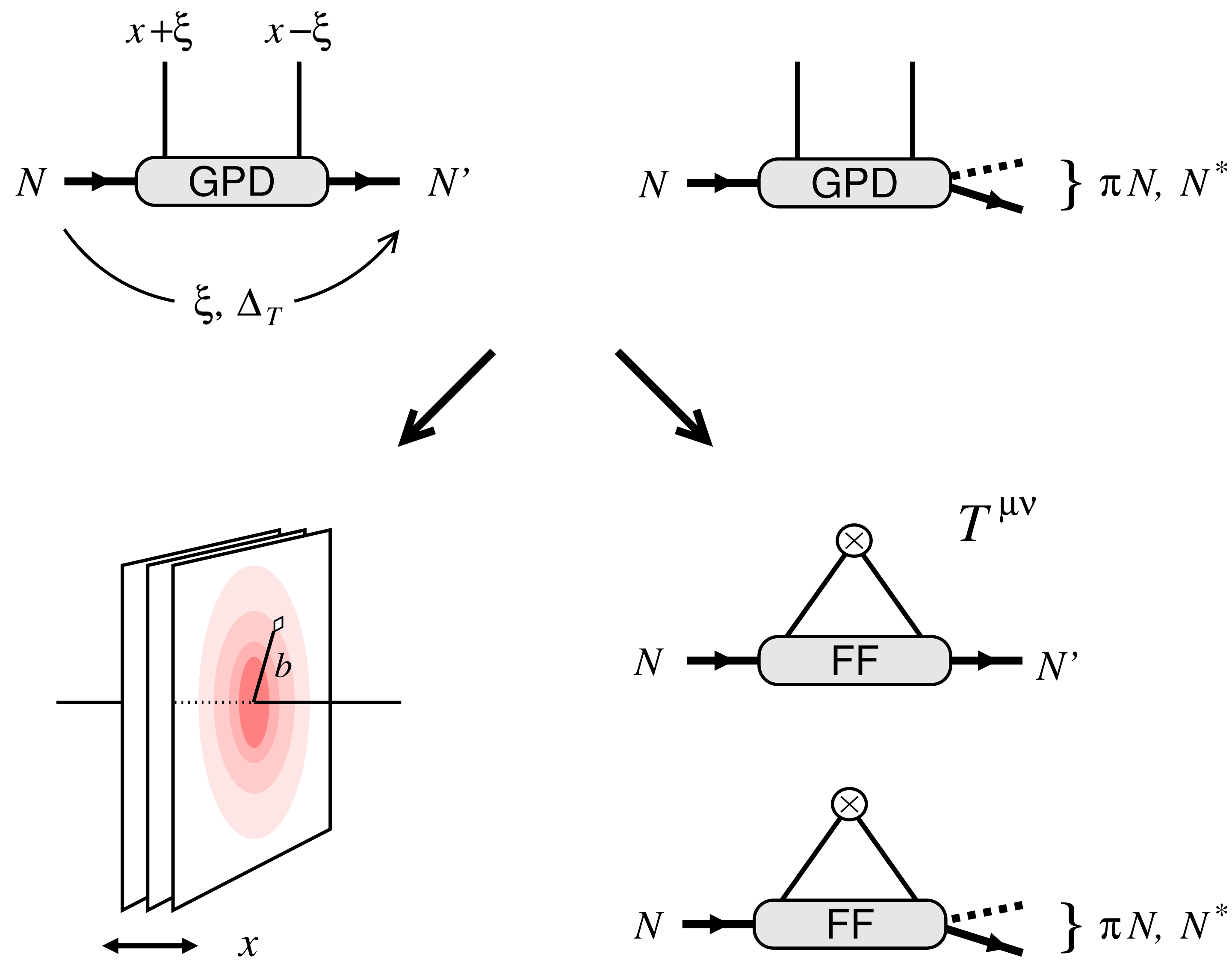
$\langle \pi N | \bar{\psi}(z) \ldots \psi(0) | N \rangle \;\leftrightarrow\;$ transition GPDs

$N^*$

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

Probes quark/gluon structure of $N^*$

# Transition GPDs: Baryon structure




Spatial distribution
of quarks/gluons
“3D imaging”

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

Can be extended
to $N \to N^*$ transitions

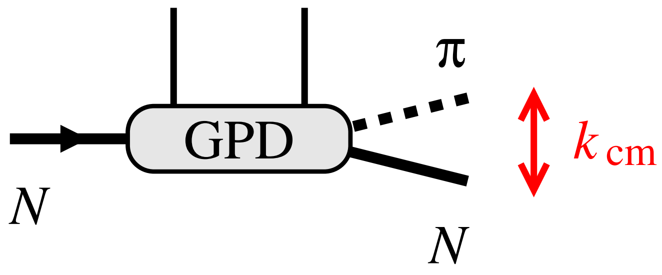
# Transition GPDs: Nonperturbative methods



**Chiral dynamics**

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

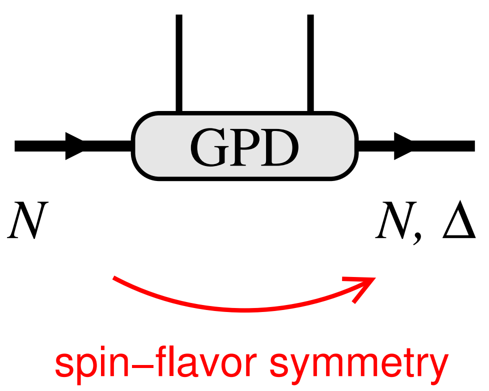
Pobylitsa, Polyakov, Strikman 2001; Guichon, Mossé, Vanderhaeghen 2003; Chen, Savage 2004; Birse 2004




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

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

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



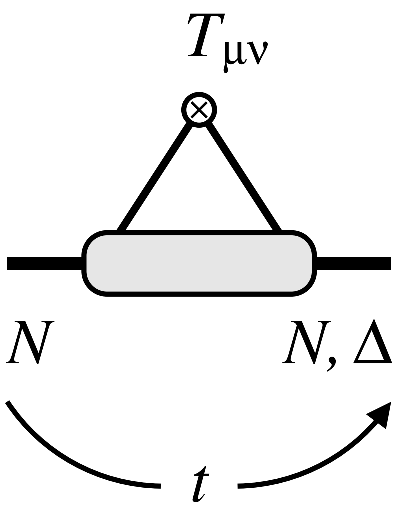

**Effective degrees of freedom**

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

**Lattice QCD**

Partonic structure from Euclidean correlation functions

# Transition GPDs: Quark angular momentum

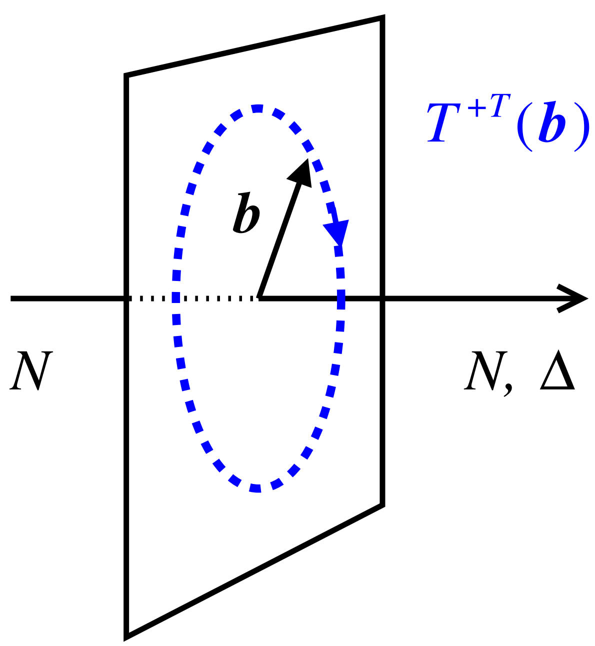



Concept of quark angular momentum formulated for $N \to \Delta$ transitions

Kim, Won, Goity, Weiss, 2023

$N \to \Delta$ transition angular momentum connected with flavor asymmetry $J^{u-d}$ of quark angular momentum in proton

Predictions from $1/N_c$ expansion and LQCD

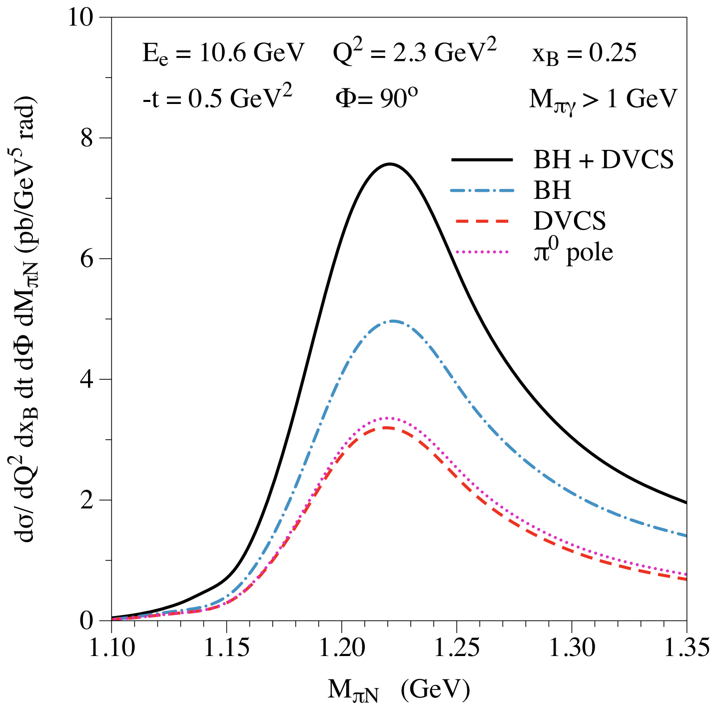



$$J^z(N \to \Delta) = \int d^2b \; \mathbf{b} \times \langle \Delta \,|\, \mathbf{T}^{+T} \,|\, N \rangle$$

| 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

# Transition GPDs: Processes




### Deeply-virtual Compton scattering

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

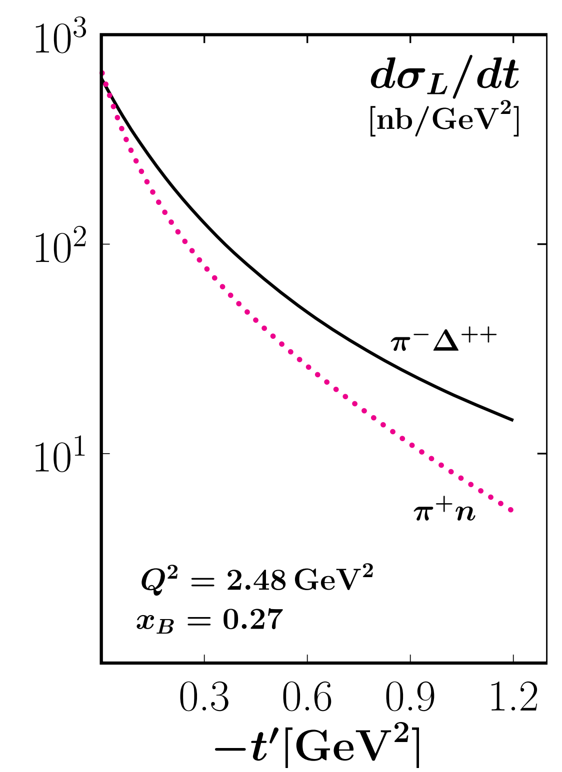
Probes chiral-even GPDs

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

### Pseudoscalar meson production

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

also $\eta, K$ mesons

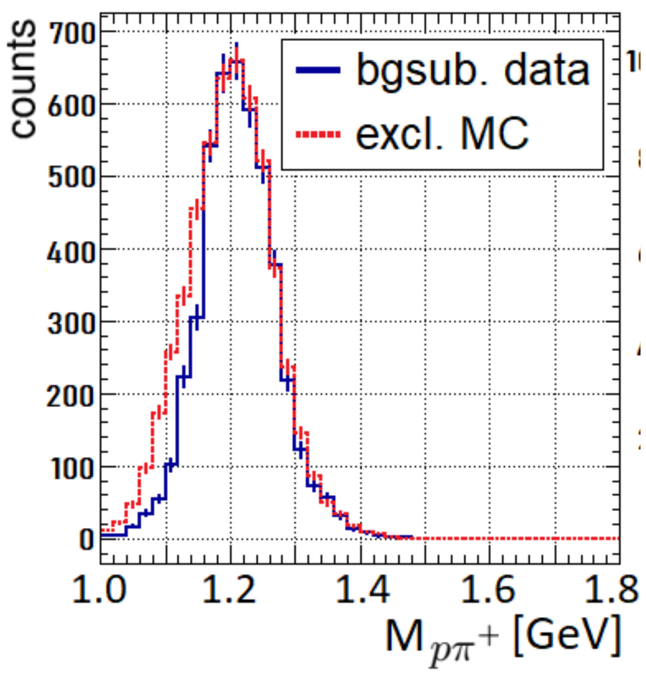


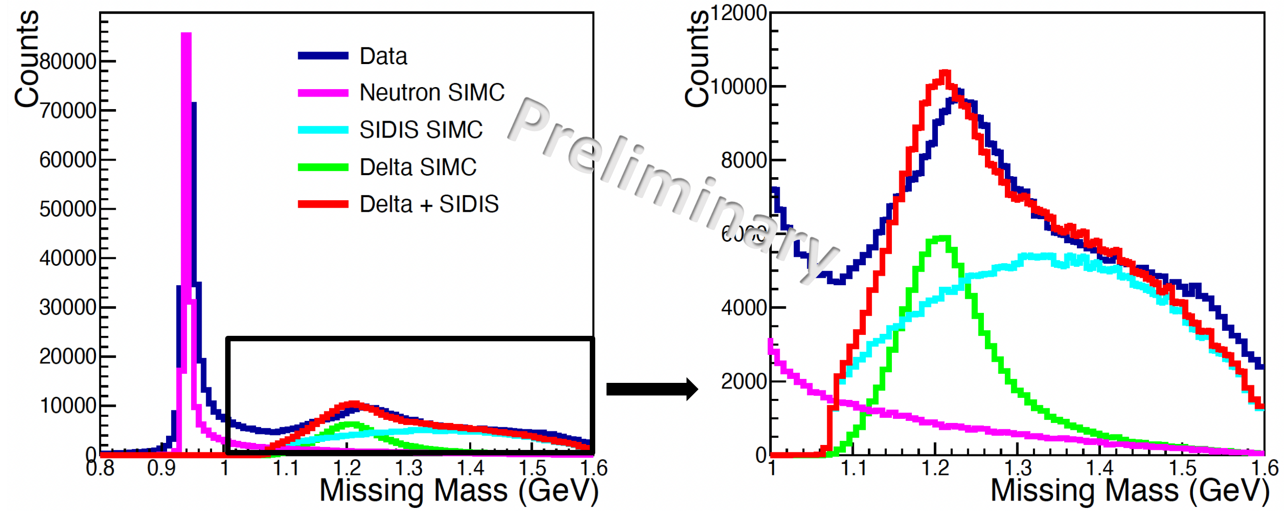

Probes chiral-odd GPDs ($x \gtrsim 0.1$), mechanism tested in $p \to p$

Cross section predictions: Kroll, Passek-Kumericki 2023

**[Diffractive vector meson production → separate]**

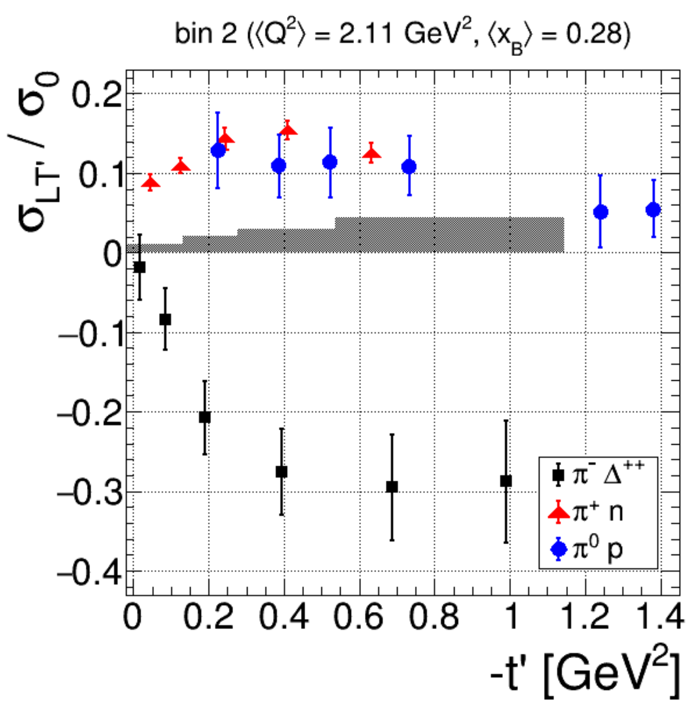
# Transition GPDs: First JLab12 results



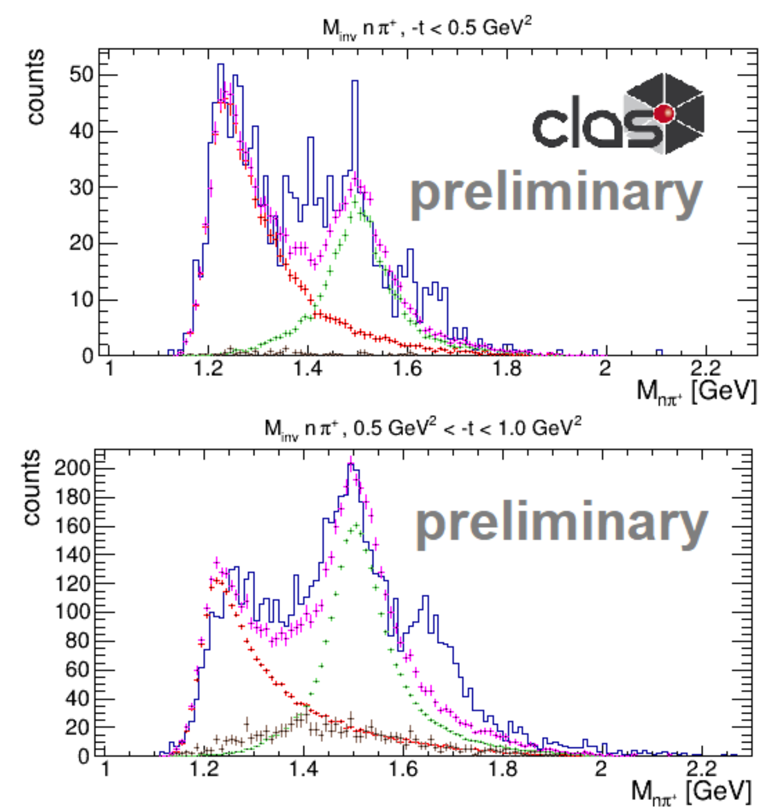

Hall C $ep \rightarrow e'\pi^+\Delta^0$

A. Usman, ECT* Trento Workshop Aug 2023




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

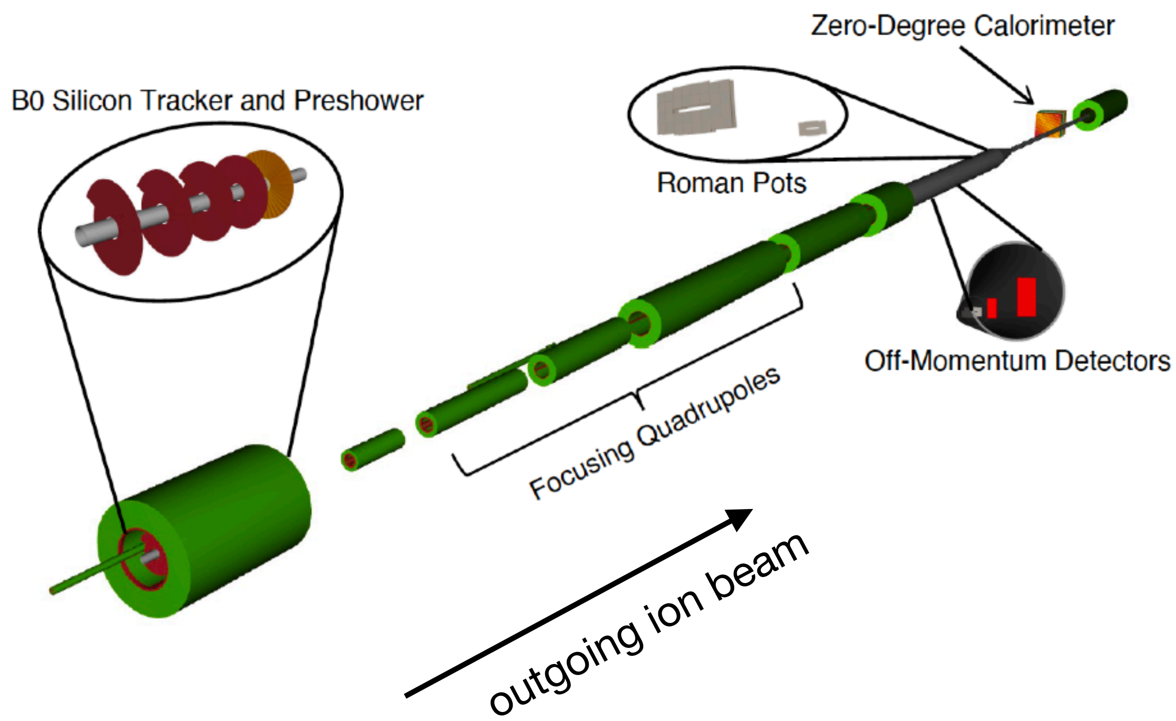
S. Diehl et al. PRL 131 (2023) 021901 [INSPIRE]




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

# Transition GPDs: EIC far-forward detector






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

Designed/simulated mostly for
forward protons and neutrons

Transition GPDs present “new” forward hadrons

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

# Transition GPDs: Future EIC studies



**DVCS with $N \to \Delta$**

$ep \to e'\gamma\Delta^+$ 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 $\Delta$ activate different detectors — charged-neutral, neutral-neutral, charged-charged. Could be used for tests and calibration besides physics interest

Can we reconstruct forward $\Delta's$ at EIC?

Cross section of $N \to \Delta$ DVCS comparable to $N \to N$ DVCS at $x > 0.1$,
drops at small $x$ (non-diffractive process)

Cross section models for MC generators can be developed

**DVCS with $N \to N^*$**

Cross section models can be developed

# Transition GPDs: Future EIC studies



**Pion production with $N \to \Delta$**

$ep \to e'\pi^+\Delta^0,\ \pi^0\Delta^+,\ \pi^-\Delta^{++}$ variety of final states charged/neutral

**Kaon production with $N \to \Lambda, \Sigma$**

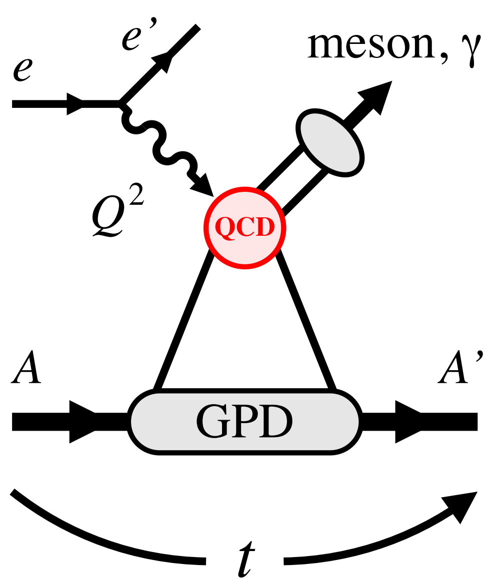
First simulations of forward $\Lambda$ detection have been performed

**Vector meson production with $N \to N^*$**

Non-diffractive channels $\rho^\pm, K^*$: Cross sections drop at small $x$

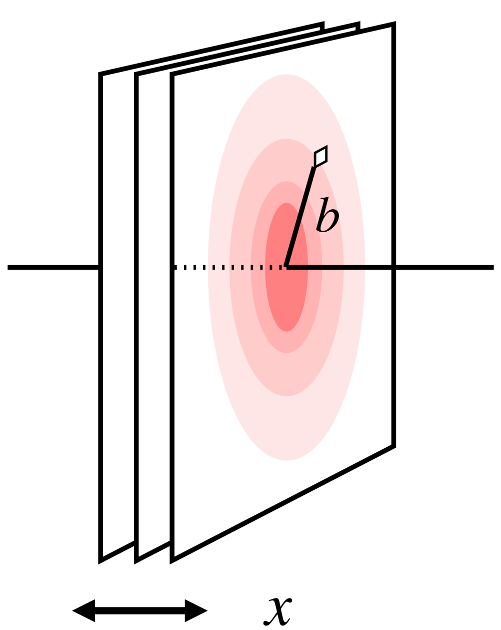
Diffractive channels $\rho^0, \omega, \phi, J/\psi$: Diffraction dissociation of nucleon, connected with fluctuations of gluon density

# Coherent processes: Physics




$e + A \rightarrow e' + M + A'$ $M =$ meson, $\gamma$ coherent scattering

Light nuclei: D, 3He, 4He, …




**Physics interest**

Measure nuclear GPDs $\langle A' | \hat{\mathcal{O}}_{\text{QCD}} | A \rangle$
Obtain images of nucleus in QCD degrees of freedom
Compare quark ↔ gluon, charge ↔ matter distributions

Variable target spin: D - Spin 1, 3He - Spin 1/2, 4 He - Spin 0

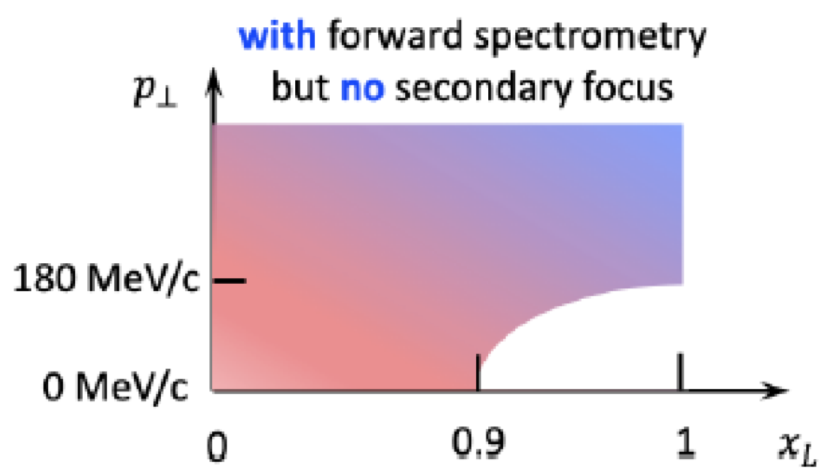
Probe gluon shadowing in few-nucleon system ($J/\psi$ production)
New approach, complementary to measurements with heavy nuclei
Gluon shadowing governs approach to saturation at small $x$

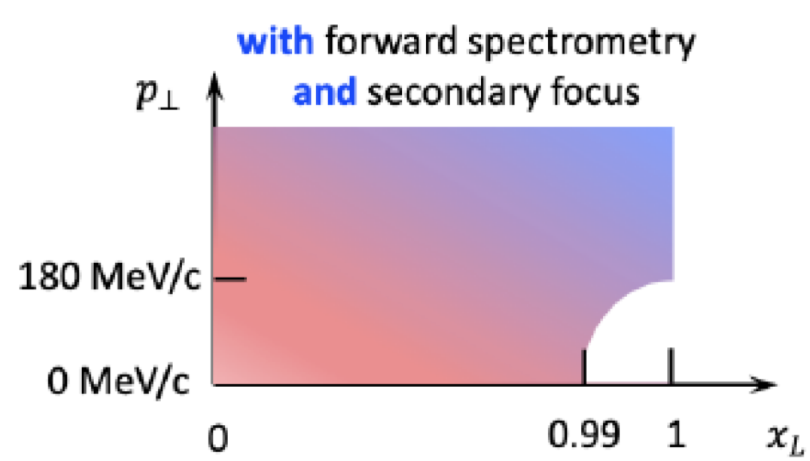
Guzey, Rinaldi, Scopetta, Strikman, Viviani 2022

# Coherent processes: EIC studies

Far-forward detection of recoiling nucleus $x_B \lesssim 0.1$, $p_T \sim$ few 10 MeV

Use active detection, complementary to veto detection for heavy nuclei




**Challenge for far-forward acceptance**

Rigidity(recoil) ≈ Rigidity(beam)

$x_B \approx 1 - x_L$ longitudinal momentum loss

Need acceptance at $x_L \to 1$

**Secondary focus**

Acceptance limited by accelerator; can be improved by secondary focus $\beta_x \approx 0$ at Roman Pots location

Discussed for IR8; possible also at IR6

Critical benefits for coherent processes with light ions

# Summary



EIC science program still developing

Examples of “emerging” topics:

- Target fragmentation: Inspect configurations in partonic wave function
- Transition GPDs: Explore QCD structure of excited baryons
- Coherent nuclear processes: Image nucleus in QCD degrees of freedom
- others not covered here…

Realistic, can be studied with projected capabilities

Many opportunities to pursue new ideas, lead developments, build communities