FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

"Mechanical properties of hadrons: structure, dynamics, visualization"

31-04 March/April 2025

ECT* Villa Tambosi, Villazzano

Exclusive reactions: From JLAB to the Electron-Ion Collider

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

UNIVERSITY OF CONNECTICUT 1881

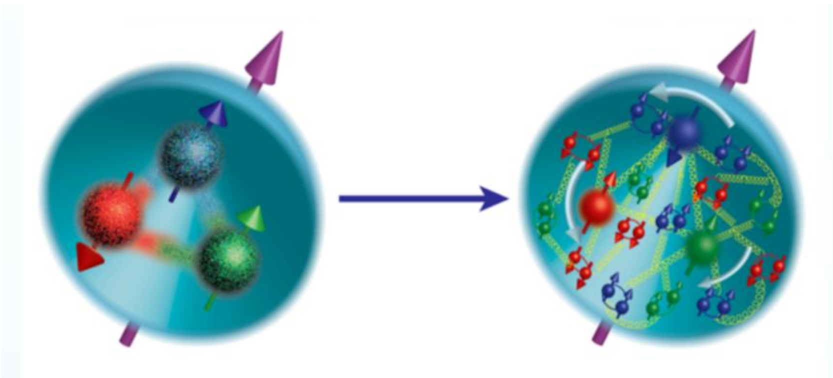
Stefan Diehl

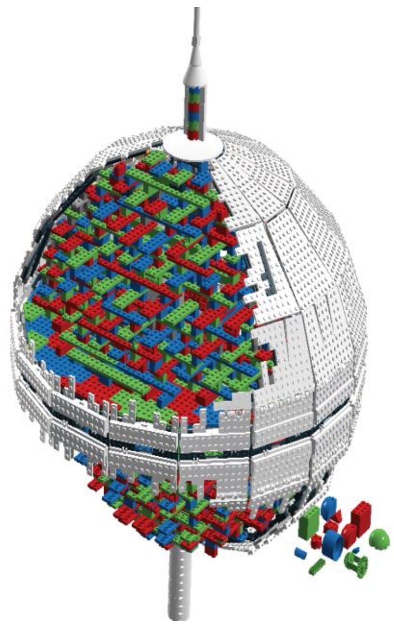
Justus Liebig University Giessen

University of Connecticut

03/31/2025

QCD Science Questions





How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
Charge?
...

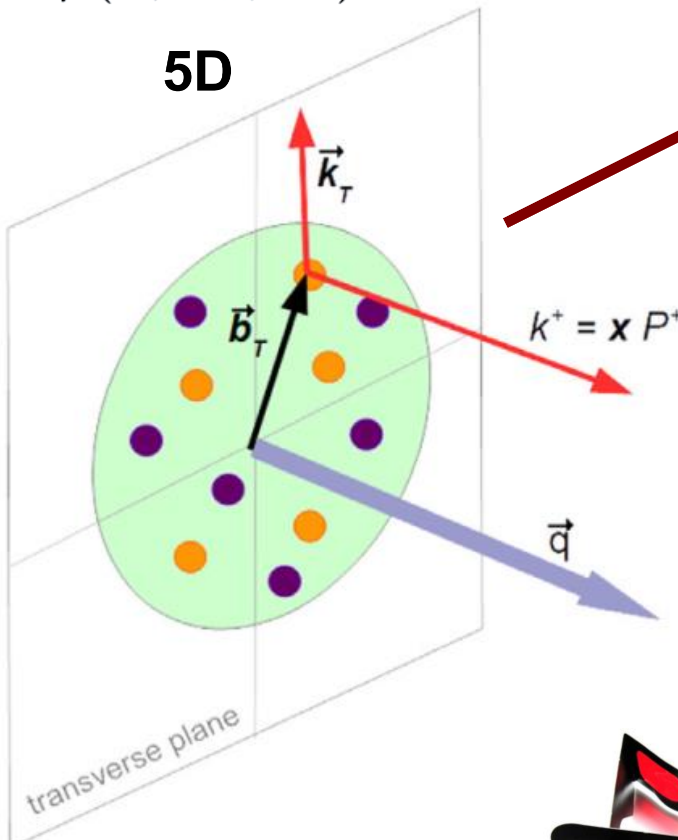
What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?

3D Spatial Imaging of Nucleons and Nuclei

Wigner distributions

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

5D



S. Diehl, Progress in Particle and Nuclear Physics 133, 104069

$$\int d^2 k_T$$

Generalised Parton Distributions (GPDs) **3D**

$$\rho(x, \vec{b}_T)$$

spin-dependent
transverse coordinate and
longitudinal momentum space
images of the nucleon

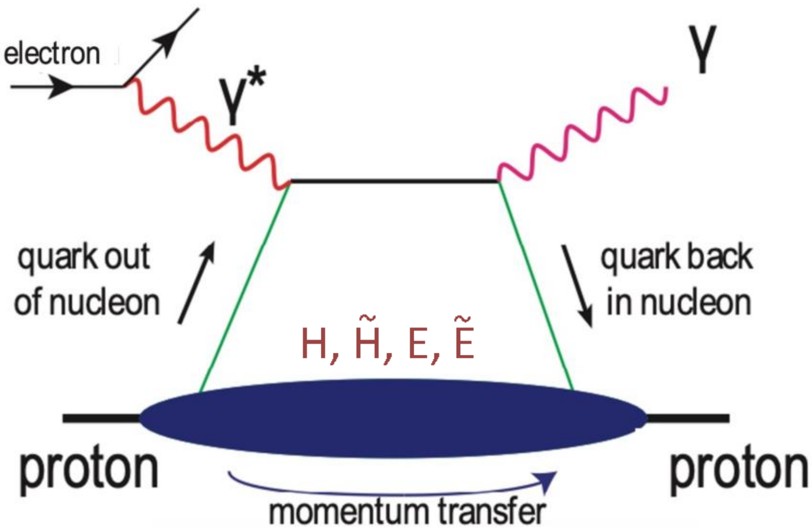
quark pol. / nucleon pol.

N\q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

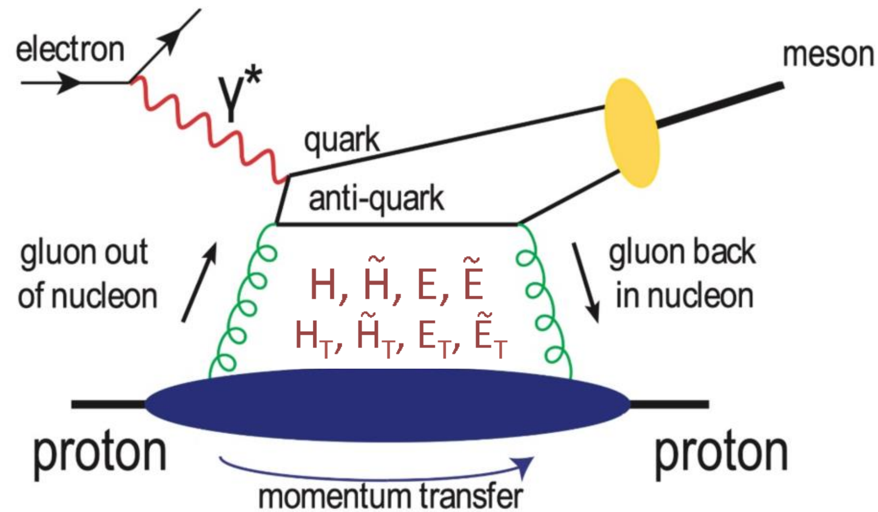
GPDs in Lepton Scattering: Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



Deeply Virtual Compton scattering:
real photon is produced

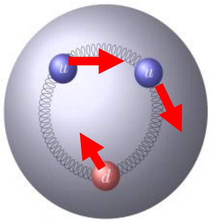
Deeply Virtual Meson Production (DVMP)



Deeply Virtual Meson production:
quark-antiquark bound state is produced

➔ **Access to Generalized Parton Distributions (GPDs)**

Physics Content of GPDs: From GPDs and CFFs to the D-term



- GPDs can not be directly measured with the DVCS and DVMP processes

  DVCS Process: Observables are the Compton-FFs (CFF)

  → Complex integrals over the *x*-dependence of the GPDs

$$\underbrace{\mathrm{Re}\mathcal{H}(\xi,t)}_{\textbf{CFF}} + i\,\underbrace{\mathrm{Im}\mathcal{H}(\xi,t)}_{\textbf{CFF}} = \sum_q e_q^2 \int \mathrm{d}x \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] \underbrace{H^q(x,\xi,t)}_{\textbf{GPD}}$$

GPD, Compton-FFs and the pressure within the nucleon:

- GPDs provide indirect access to mechanical properties of the nucleon ➔ gravitational form factors

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

X. D. Ji, PR**D 55**, 7114-7125 (1997)
M. Polyakov, PL**B 555**, 57-62 (2016)

- Real- and imaginary part of the Compton-FF $\mathcal{H}$ follow the dispersion relation:

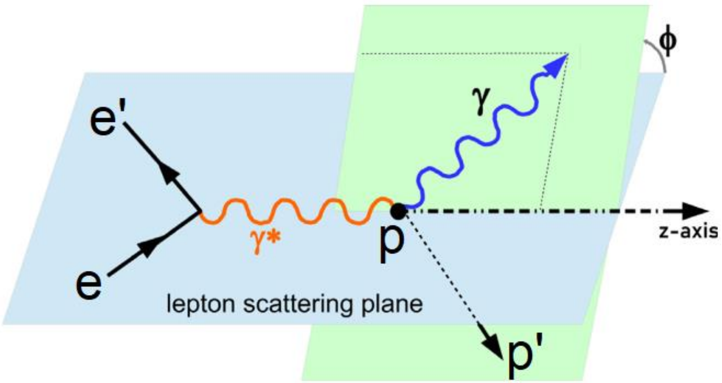
$$\boxed{\mathrm{Re}\mathcal{H}(\xi,t)} \propto \boxed{D(t)} + \frac{2}{\pi}\,\mathcal{P}\!\int \mathrm{d}x \frac{x\,\boxed{\mathrm{Im}\mathcal{H}(x,t)}}{\xi^2 - x^2}$$

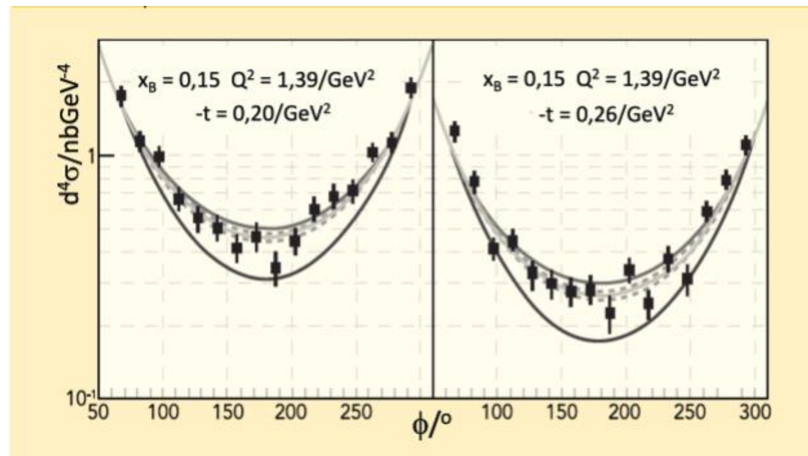
M. Diehl, D. Y. Ivanov, Eur. Phys. J. C 2007, 52, 919

Observables of the DVCS process

How can we measure the CFFs in the DVCS process?

1. Cross-section $\sigma^{ep\gamma}(x, Q^2, t, \phi) \propto \boxed{Re\{\mathcal{H}\}}$

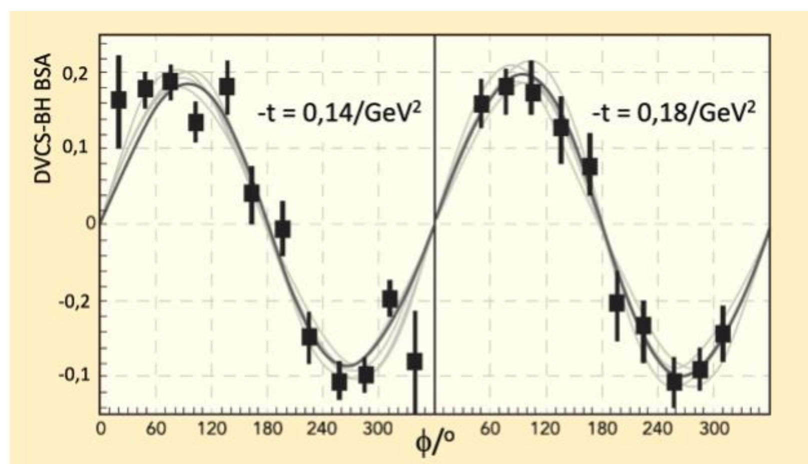




2. Beam-Spin Asymmetry

$$\mathrm{BSA}(x, Q^2, t, \phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

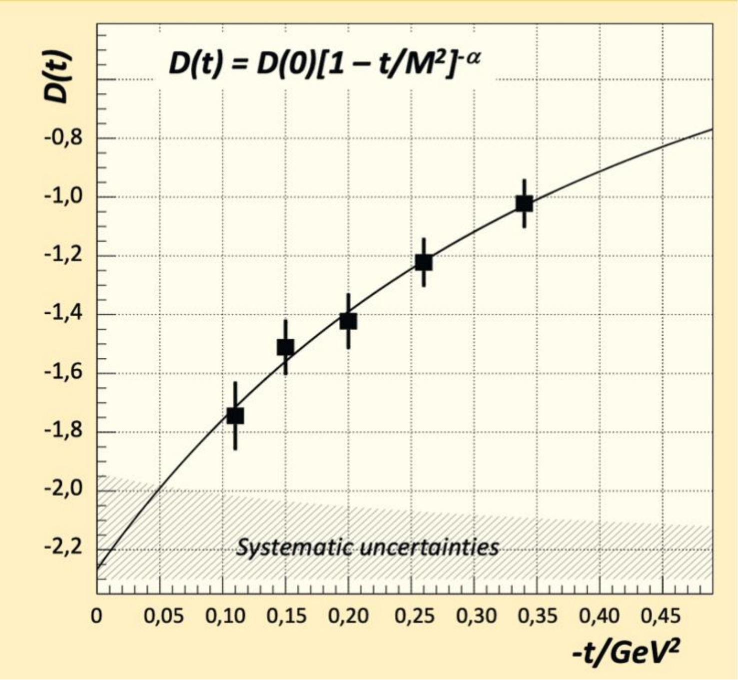
$$\propto \boxed{Im\{\mathcal{H}\}} \sin\phi$$



V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

From the D-term to the pressure distribution

$$\mathrm{Re}\mathcal{H}(\xi,t) \propto D(t) + \frac{2}{\pi}\mathcal{P}\int dx \frac{x\,\mathrm{Im}\mathcal{H}(x,t)}{\xi^2 - x^2}$$



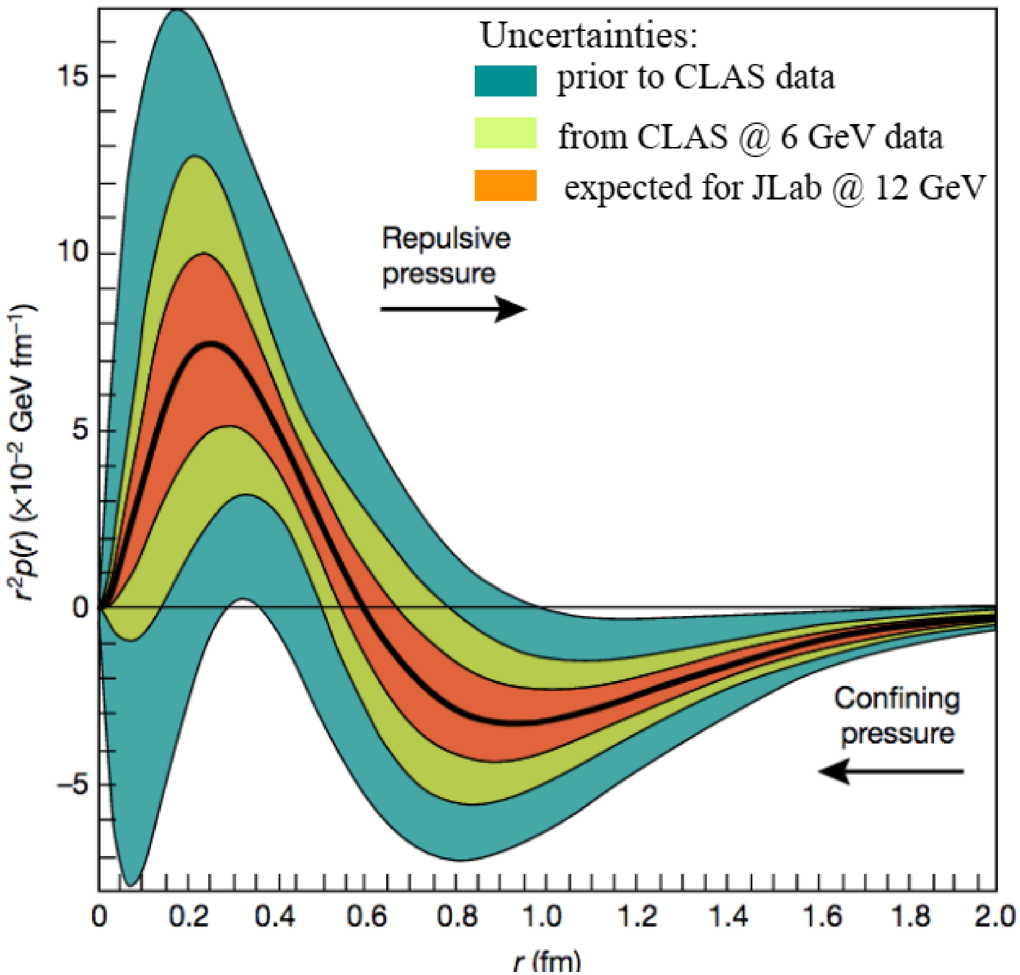
V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

The pressure distribution: $$p(r) = \frac{1}{6m_p}\int \frac{d^3\Delta}{(2\pi)^3}\, t\, D(t)\, e^{-i\Delta r}$$

K. Goeke et al., Phys. Rev. D 75, 094021 (2007)

with $t = -\Delta^2$

Pressure inside the proton



V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

- Positive maximal pressure of 10^{35} Pa in the center at r = 0 fm

  ➔ Highest known pressure in the universe

  ➔ Resulting forces away from the center avoid a collaps of the quark matter

- Negative pressure in the outer areas of the proton, for r > 0,6 fm

  ➔ Forces towards the center stabilize the proton

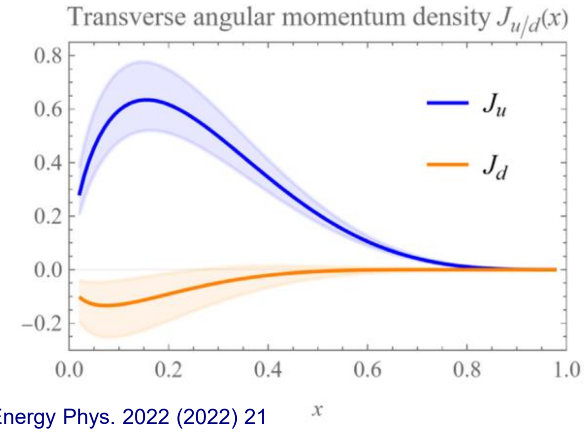
➔ **Interplay of the two regions leads to the stability of the proton**

Physics Content of GPDs

- GPDs are directly related to the nucleon spin

Ji‘s sum rule:

$$J^N = \sum_{q,g} J_{q,g} = \sum_{q,g} \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} x\left[H^{q,g}(x,\xi,t) + E^{q,g}(x,\xi,t)\right] dx$$



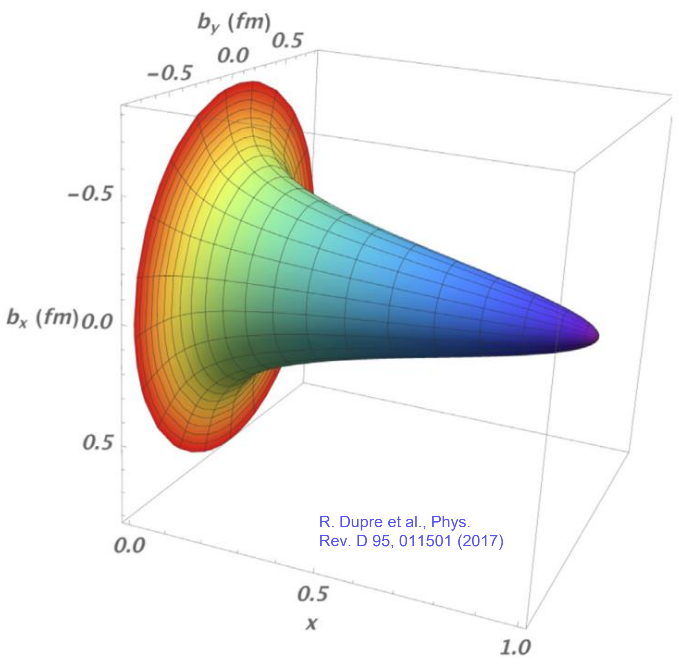
J. High Energy Phys. 2022 (2022) 21

- **GPDs provide a 3D imaging of the nucleon**

Impact parameter space:

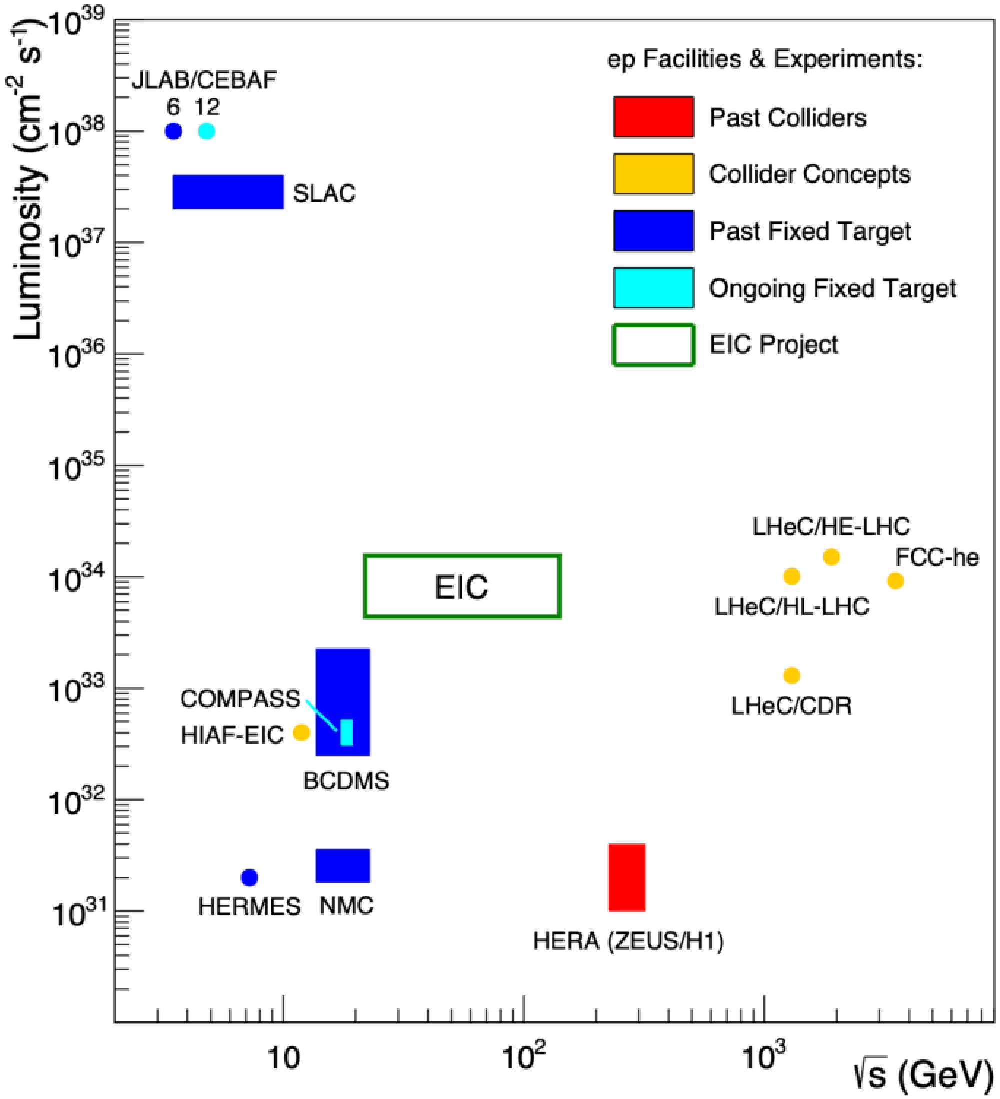
GPDs are a Fourier transform of parton dsitributions

$$q(x, \boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2}\, e^{-i\boldsymbol{\Delta}_\perp \boldsymbol{b}_\perp} H(x, 0, -\boldsymbol{\Delta}_\perp^2)$$



R. Dupre et al., Phys. Rev. D 95, 011501 (2017)

Lepton scattering facilities



EIC Yellow Report: Nuc. Phys. A 1026, 122447 (2022)

Luminosity frontier:

- 12 GeV JLAB (see talk by K. Joo)
- Planned 22 GeV JLAB upgrade

The EIC will be the first …

- High-luminosity e-p collider
- Polarized beam collider
- Electron-nucleus collider

EIC cm energy range:

$$29 < \sqrt{s} < 141\ GeV$$

The Electron Ion Collider

Planned at Brookhaven National Laboratory (Upton, New York, US)

- **Construction start in 2026**

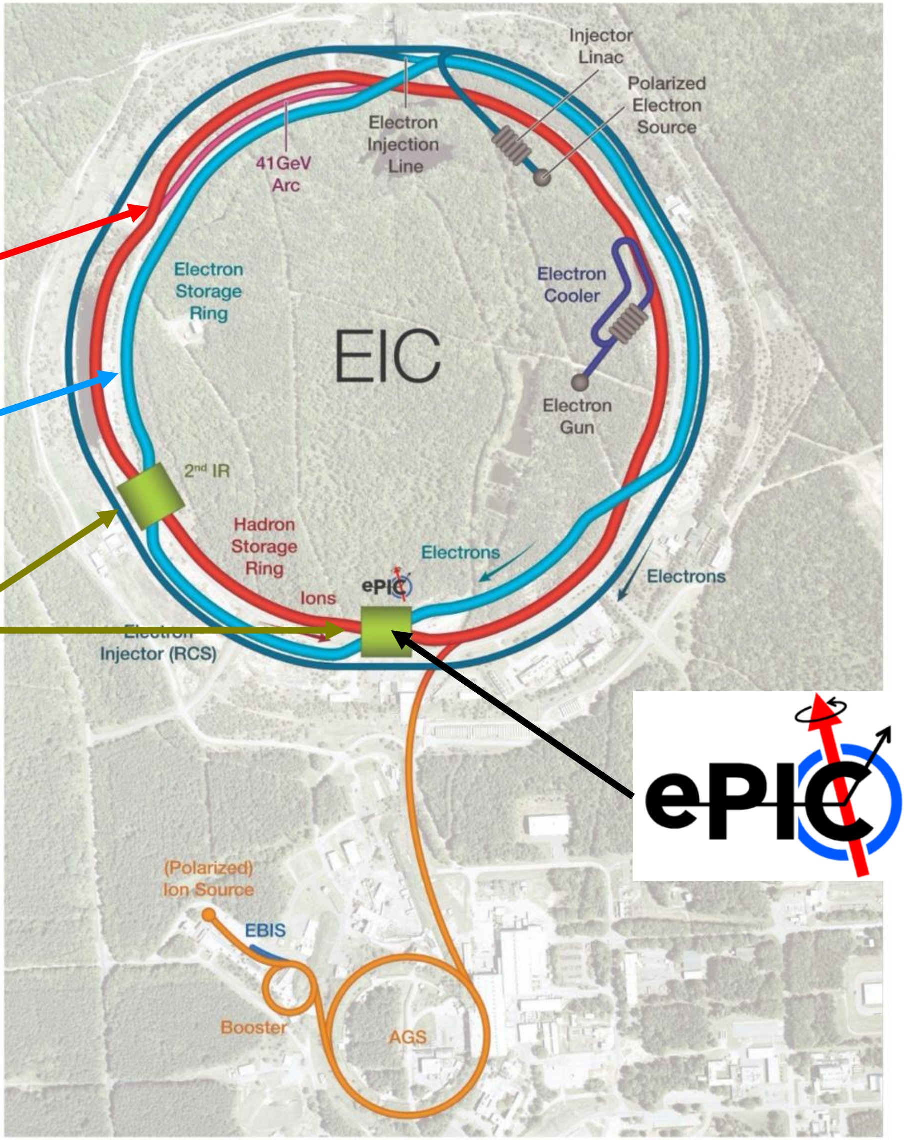
Hadron storage ring (RHIC Rings)
41, 100 - 275 GeV

Electron storage ring **5 - 18 GeV**

High luminosity interaction region(s)

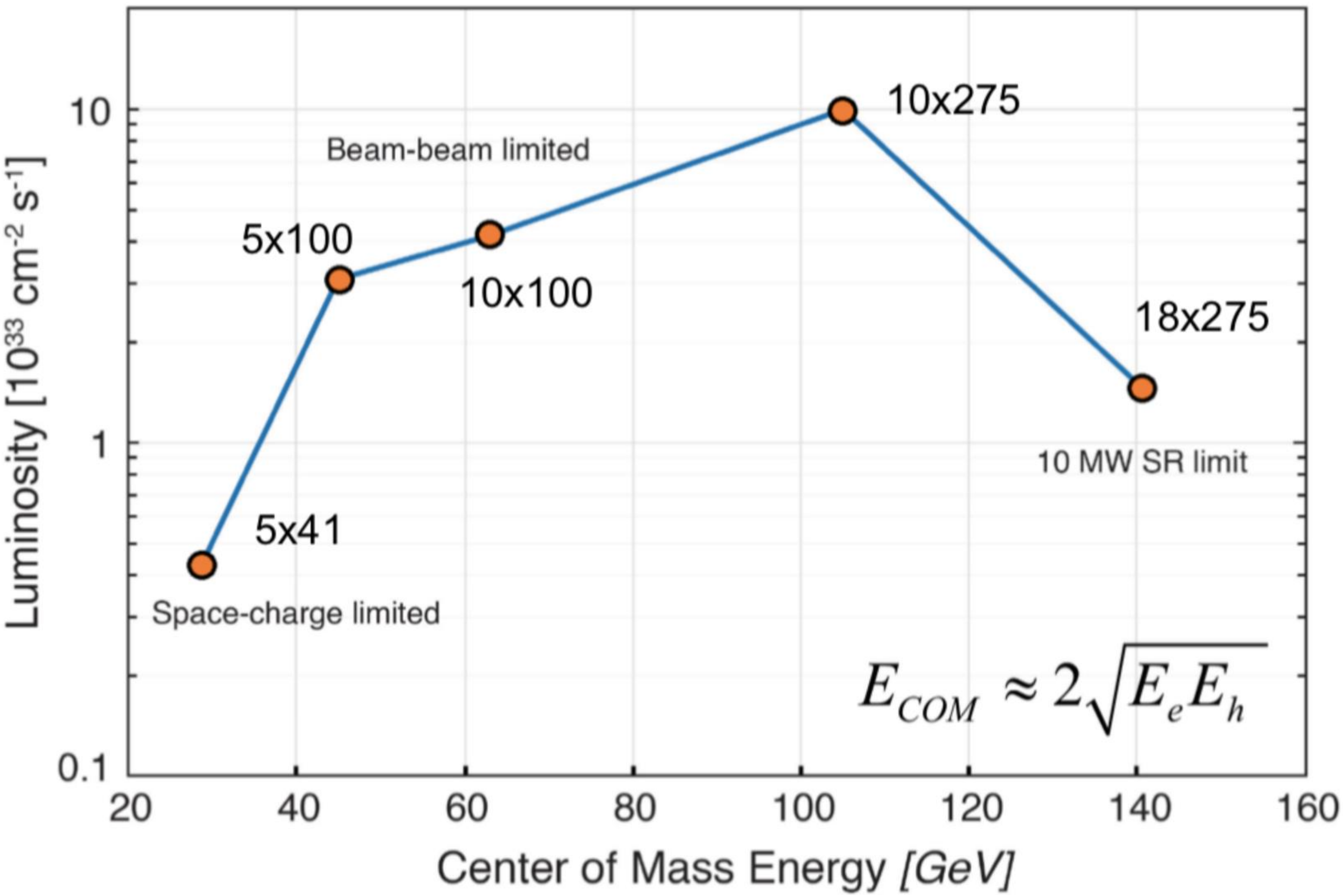
● **Luminosity:** L= 10^{33} - 10^{34} $cm^{-2}s^{-1}$
→ 10 - 100 fb^{-1}/year

● **Highly polarized beams:** ~ 70%



EIC White Paper: Eur. Phy. J. A 52, 9 (2016)
EIC Yellow Report: Nuc. Phys. A 1026, 122447 (2022)

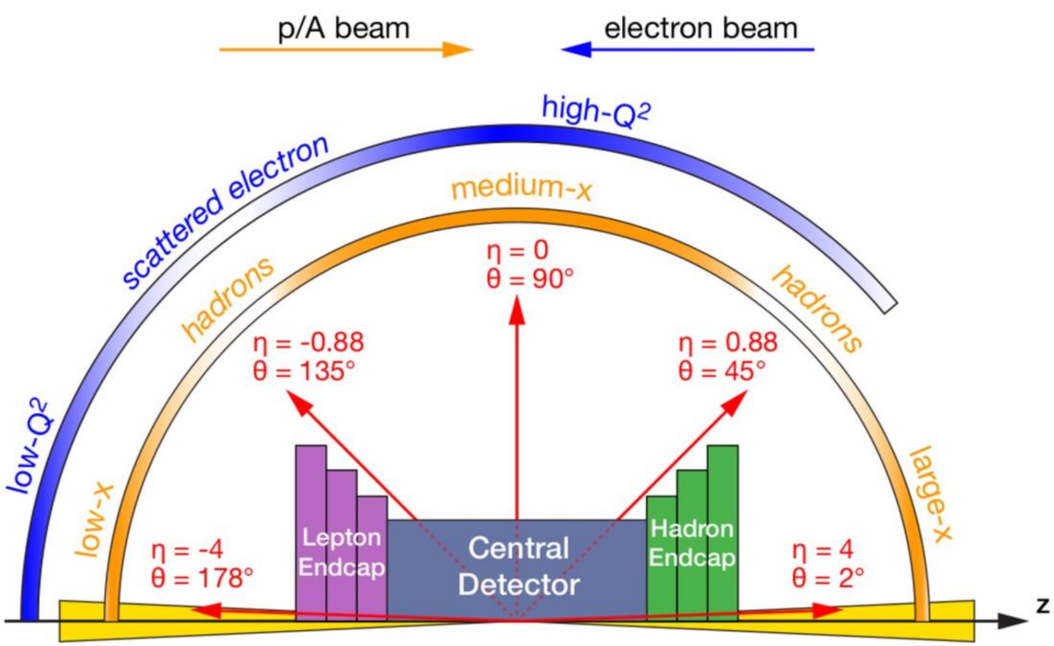
EIC peak luminosities



EIC Yellow Report: Nuc. Phys. A 1026, 122447 (2022)

Detector challenges and requirements for the EIC

p: 41, 100 - 275 GeV **e:** 5 - 18 GeV



$$\eta = -\ln\tan(\theta/2)$$

Large center-of-mass energy range:
29 - 141 GeV

- Large detector acceptance

Asymmetric beams

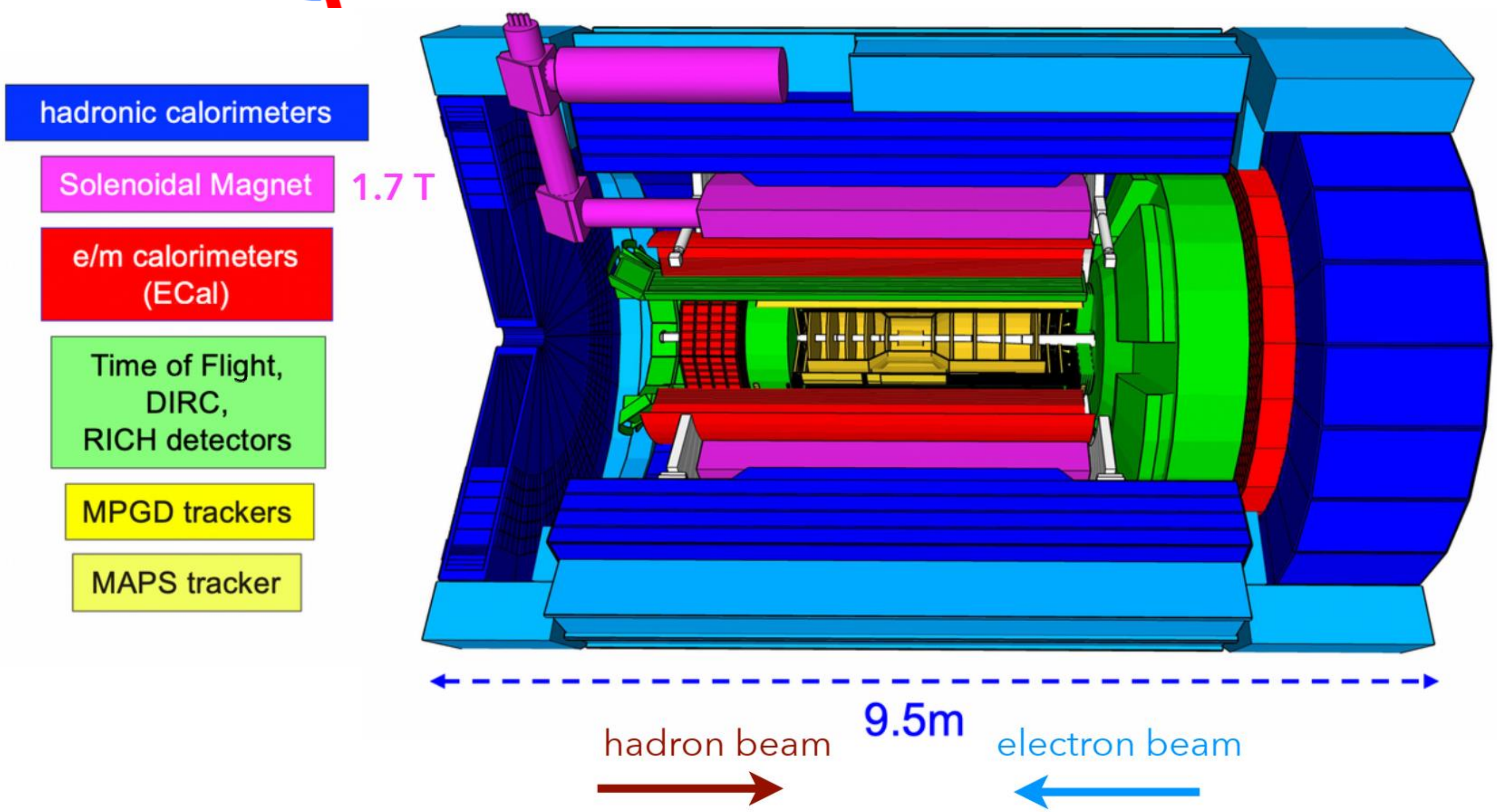
- **Asymmetric detector**: Barrel + electron and hadron end-caps
- Large central coverage ($-4 < \eta < 4$) in **tracking**, **particle identification**, em and hadronic **calorimetry**
  - High precision low mass tracking
  - Good e/h separation critical for scattered electron ID
  - Good separation of e, p, π, K over a wide momentum range

EIC Yellow Report: Nuc. Phys. A 1026, 122447 (2022)

The ePIC detector

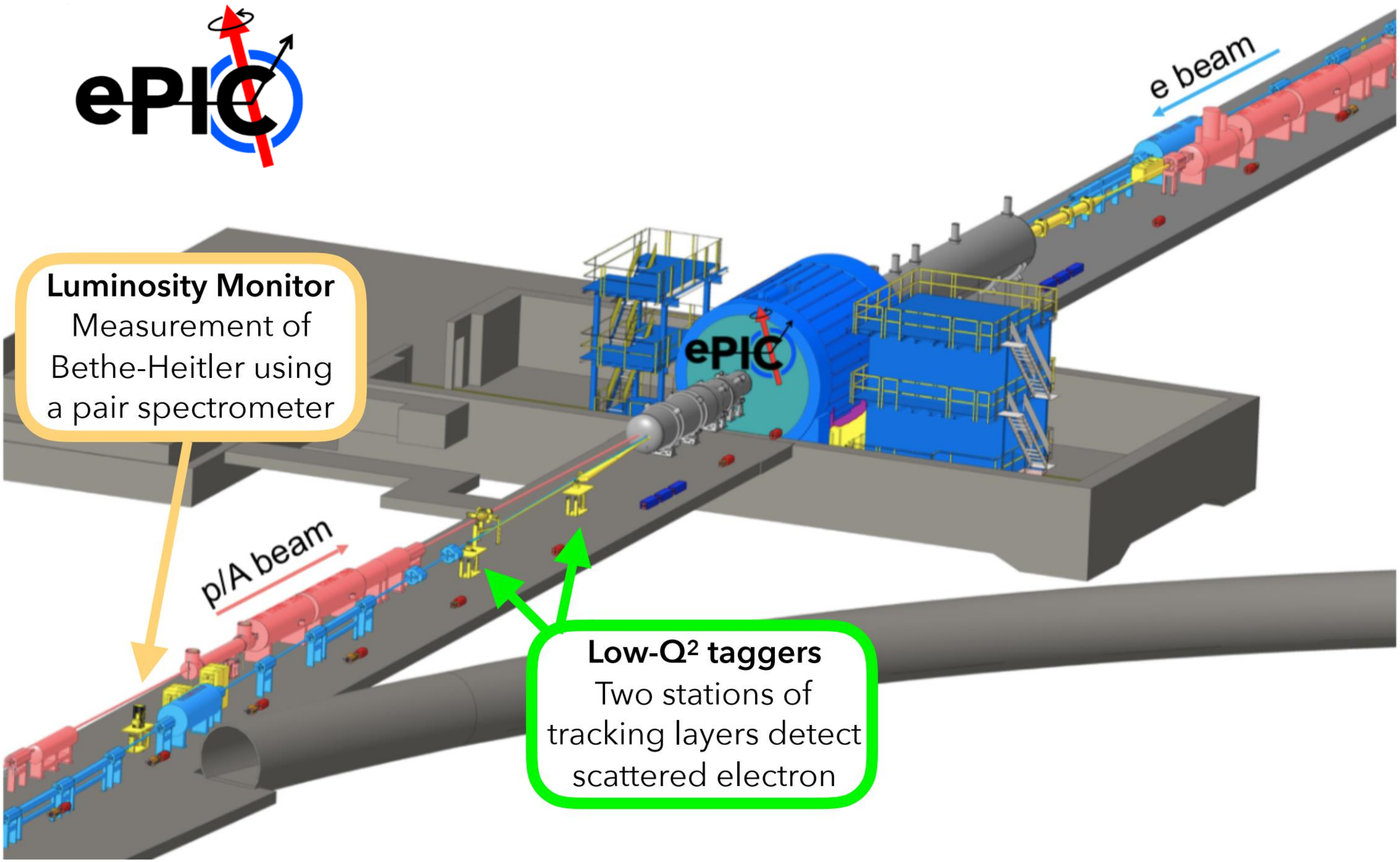
Electron-Proton and -Ion Collider detector

- Hermetic detectors within a central solenoid

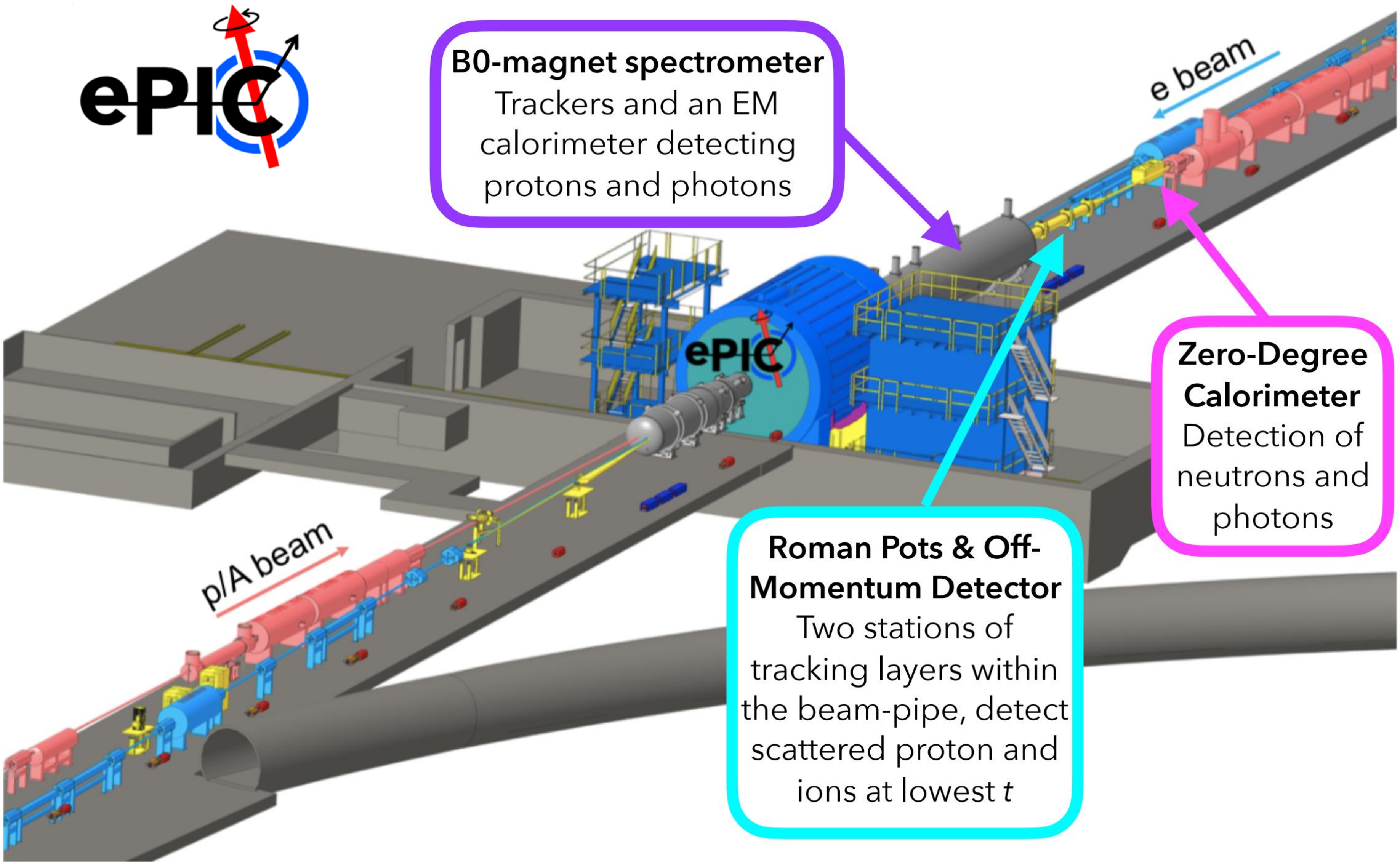


The **ePIC Collaboration** formed in July 2022 > 177 Institutions, 26 countries > 850 collaborators

ePIC far-backward detectors

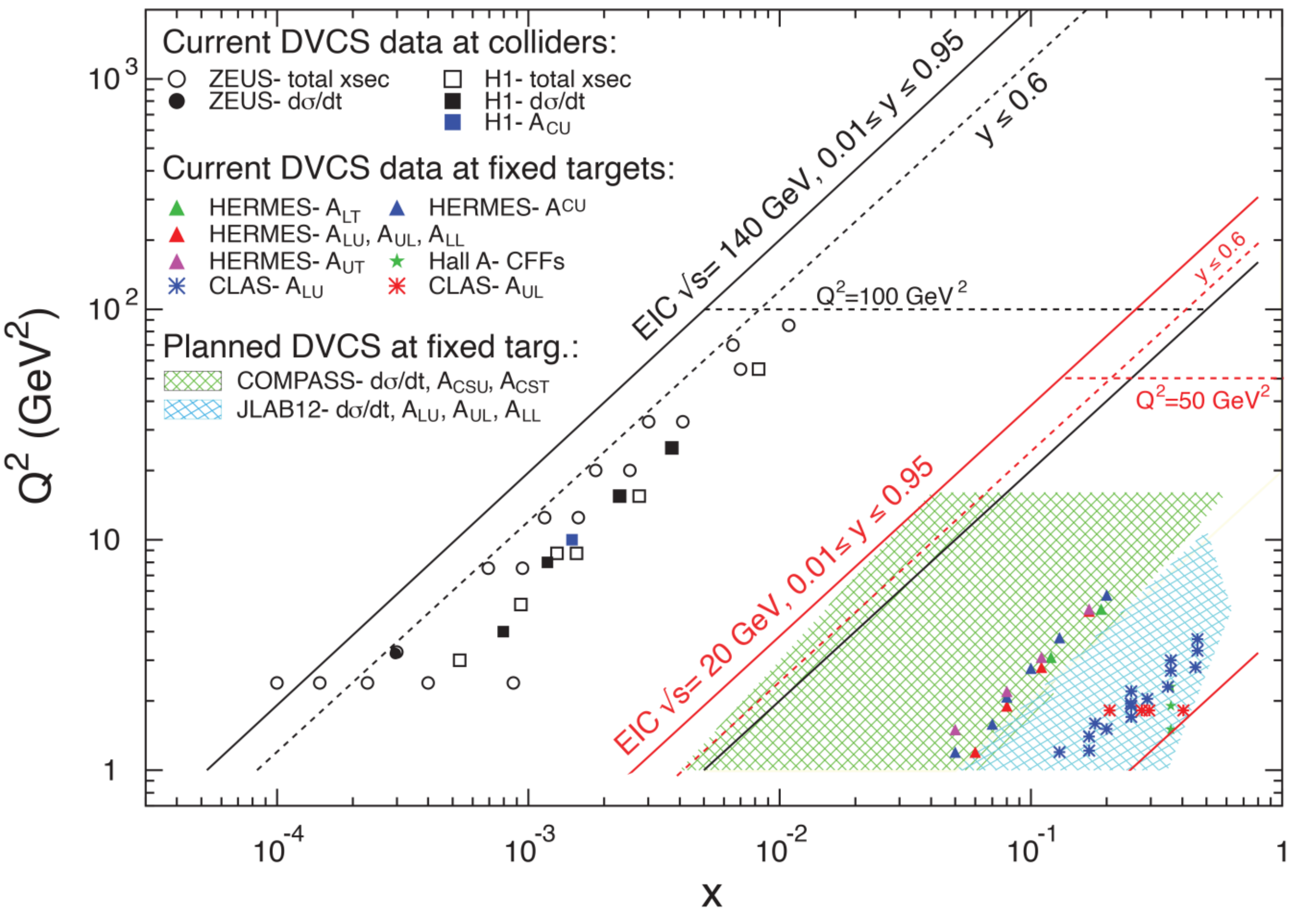


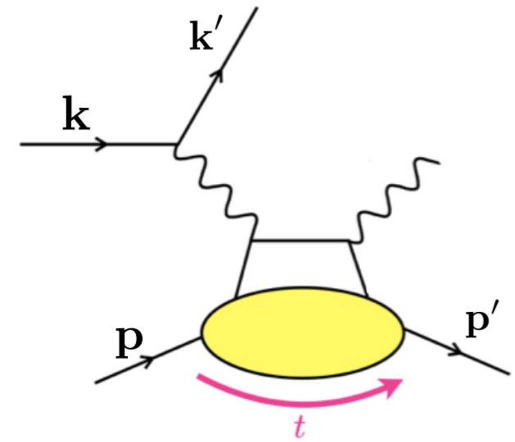
ePIC far-forward detectors



The DVCS process – Kinematic coverage

The DVCS process at the EIC:





$$\mathbf{q} = \mathbf{k} - \mathbf{k}'$$

$$Q^2 = -\mathbf{q}^2$$

$$x_B = \frac{Q^2}{2\mathbf{p}\cdot\mathbf{q}}$$

$$t = (\mathbf{p}' - \mathbf{p})^2$$

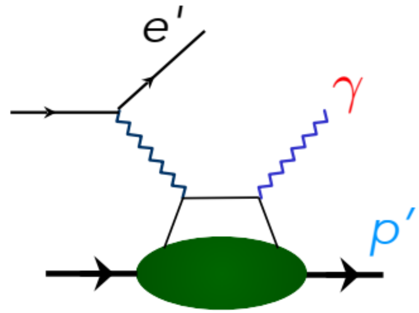
$$y = \frac{\mathbf{p}\cdot\mathbf{q}}{\mathbf{p}\cdot\mathbf{k}}$$

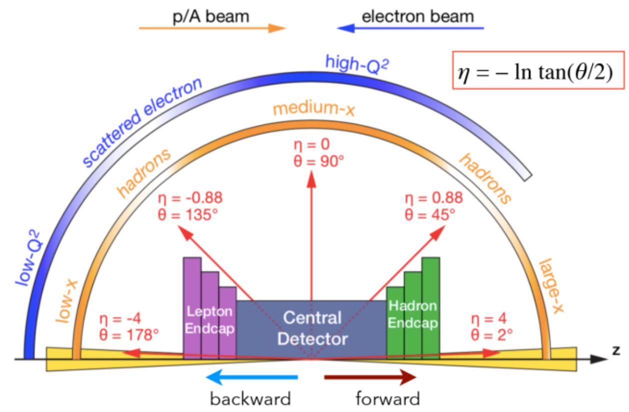
https://arxiv.org/abs/2103.05419

The DVCS process with ePIC

DVCS:

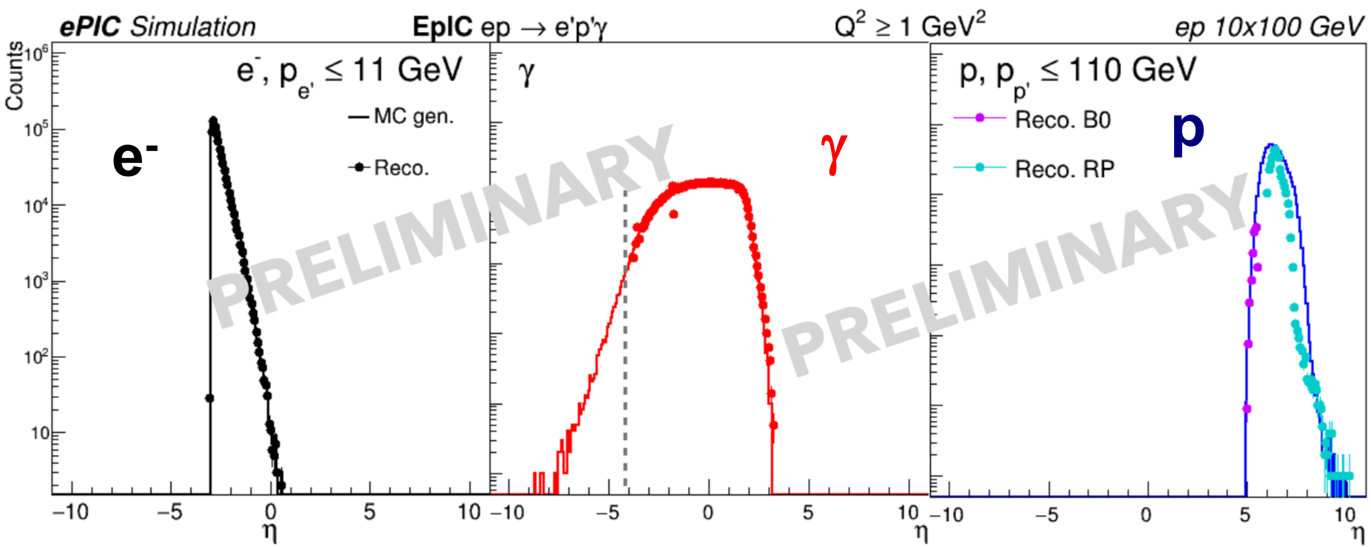
- ePIC has excellent acceptance for the scattered electron and proton + good acceptance for the produced photon





η: pseudorapidity

- Simulation using a realistic DCVS MC generator and a reconstruction with ePIC geometry and resolutions

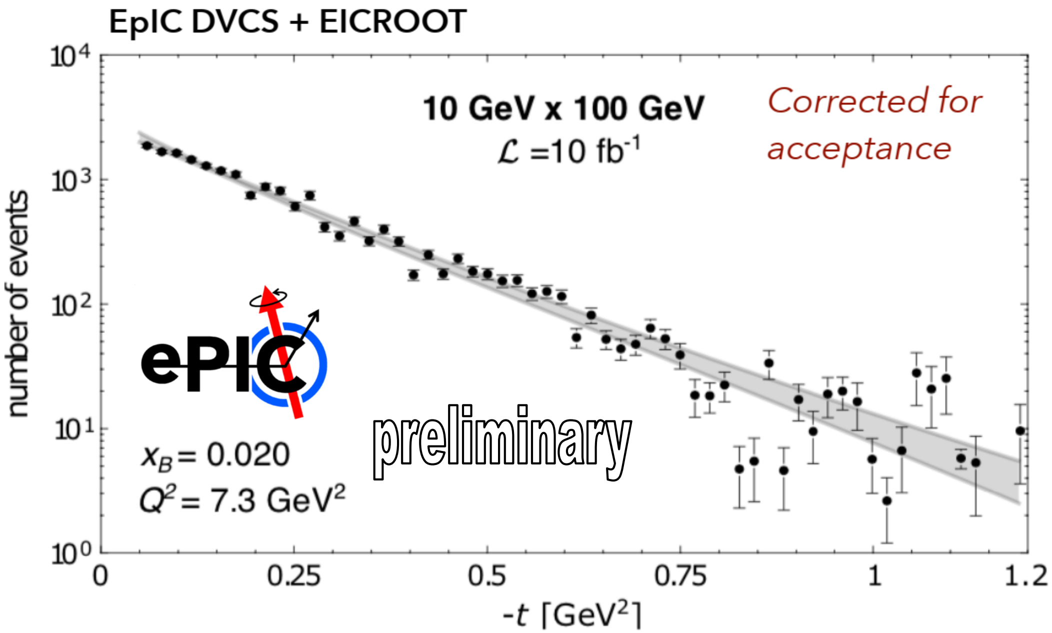


Generator:
EpIC *EPJ C* **82**, 819 (2022)

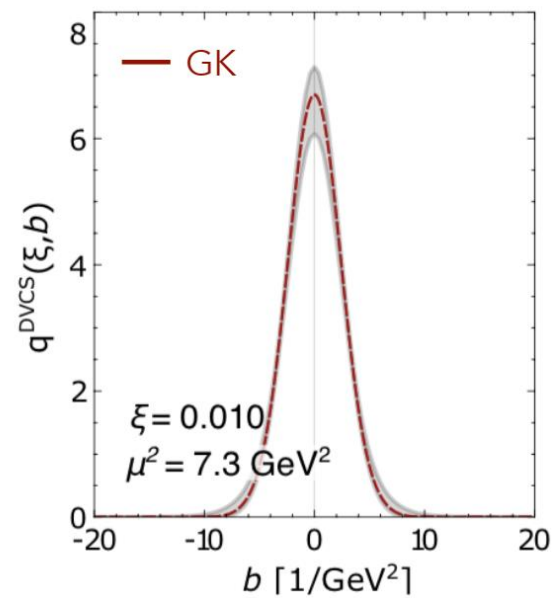
O. Jevons (Glasgow)

EIC - Towards nucleon femtography

Extracted momentum transfer distribution ~ cross section



Impact parameter distribution extracted from a Fourier transform of the t-distribution



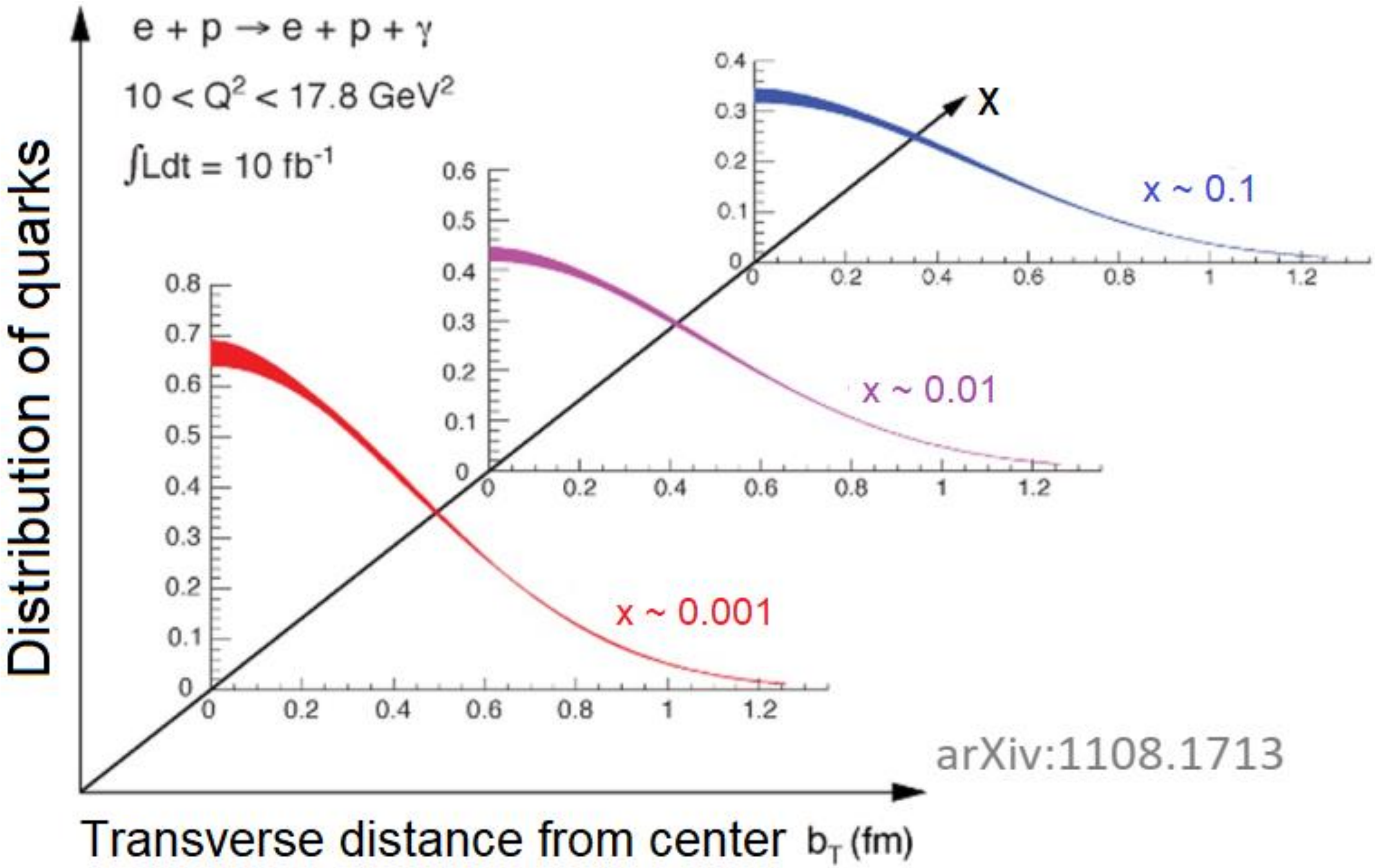
➔ Low -t region can be well reconstructed

➔ Extraction returns the curve of the Goloskokov-Kroll (GK) model used in the EpIC generator with low uncertainties

E. Aschenauer, V. Batozskaya, S. Fazio, A. Jentsch, K. Kumerički, H. Moutarde, K. Passek-K., D. Sokhan, H. Spiesberger, P. Sznajder, K. Tezgin: on arXiv soon

Spatial parton distributions

Extracted spatial parton distributions:



➔ **Excellent extraction of spatial distributions down to the lowest x values**

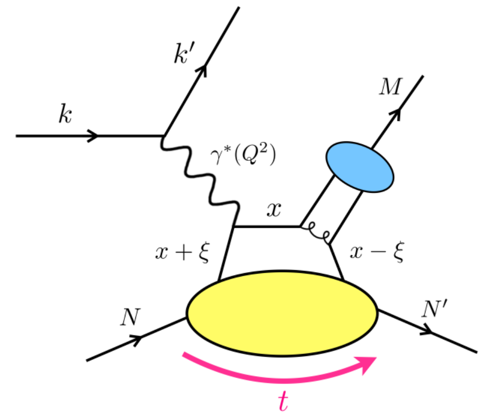
The DVMP process with ePIC

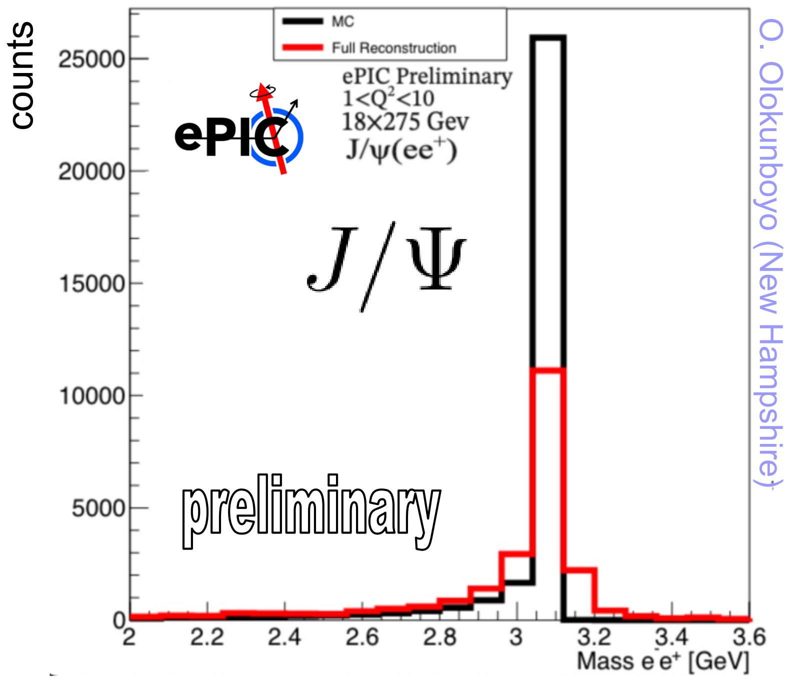
- **Hard exclusive electro-production of vector-mesons** gives access to gluon GPDs

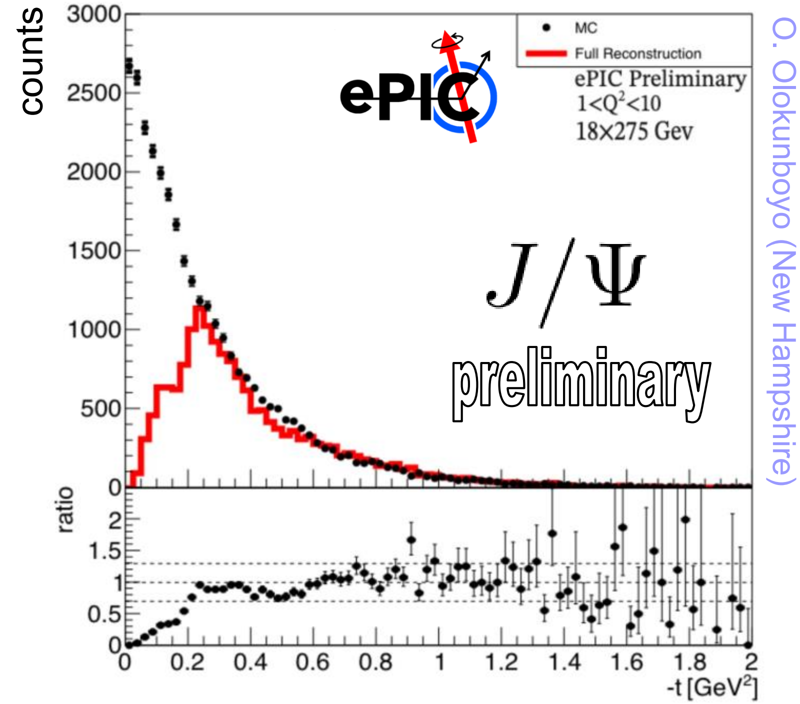
  → Quark-antiquark bound state ($s\bar{s},\ c\bar{c},\ b\bar{b}$) is produced

ePIC: Particularly clean reconstruction for heavy mesons

J/Ψ and Υ

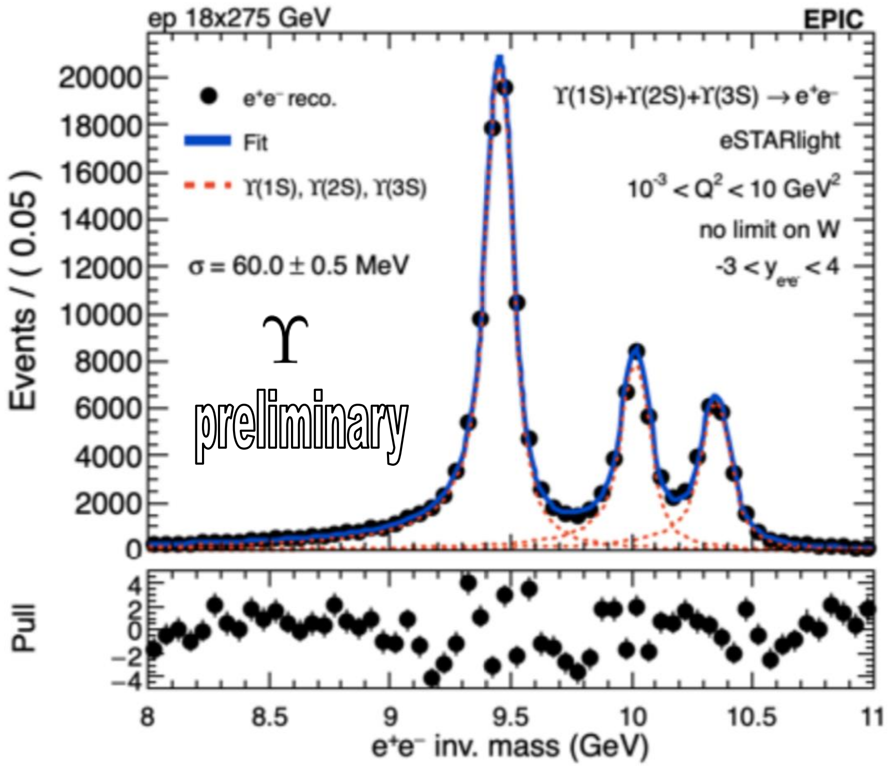


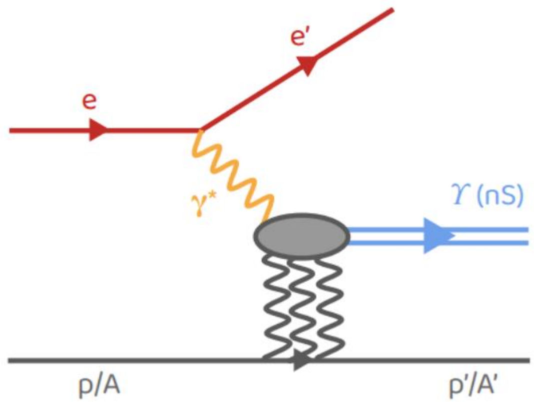




➔ Good resolution based on the di-lepton final state

The DVMP process with ePIC



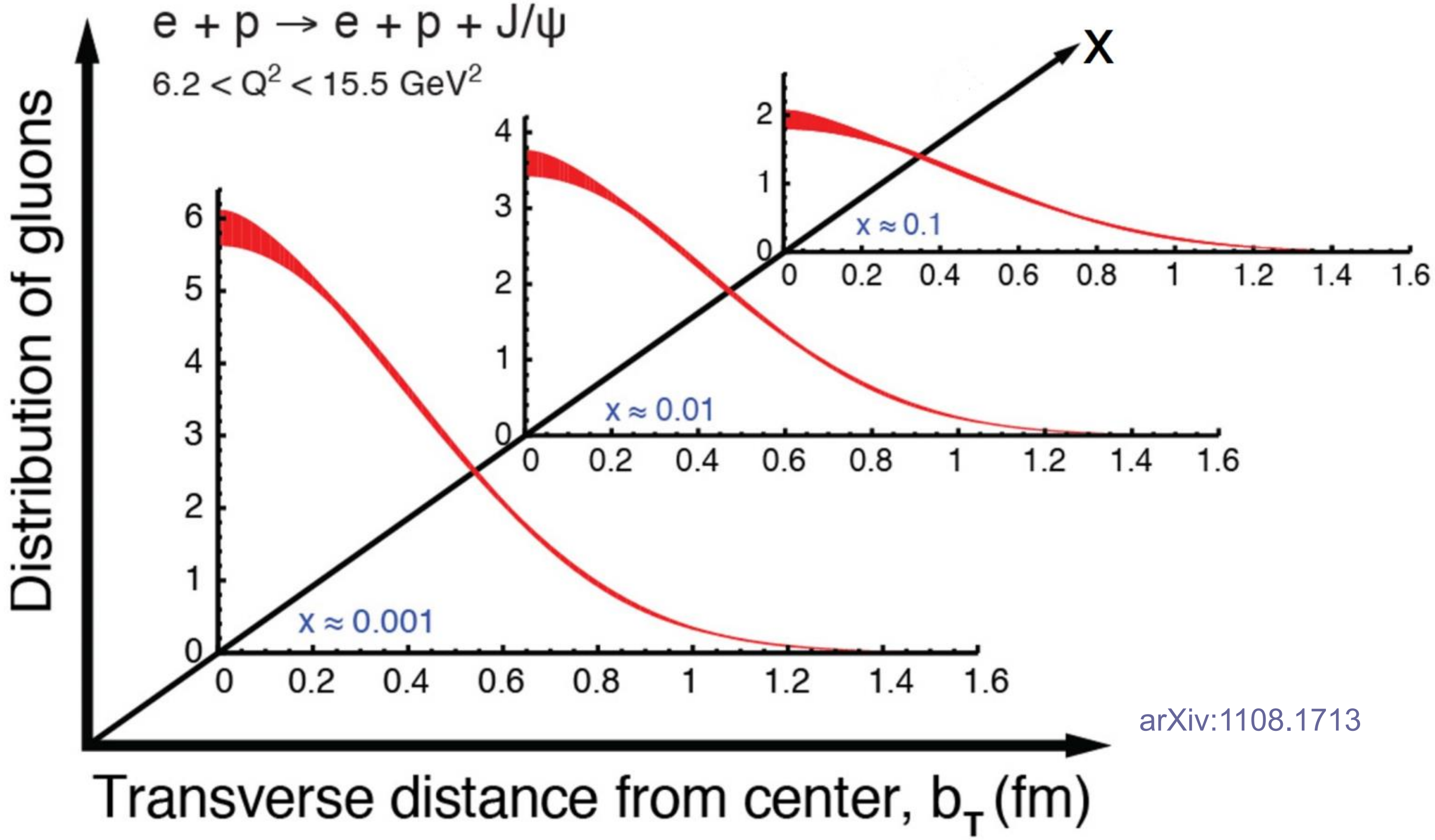


S. Yoo (Davis), M. Kim (Berkeley), S. Klein (Berkeley), D. Cebra (Davis)

➔ Good separation of the three states through most of the rapidity region

- Sensitivity to gluon distributions
- Information on colour correlations
- Upsilon-proton scattering lengths
- Near-threshold production: Littleknown, twist-4 effects contribute significantly

DVMP: Towards nucleon femtography

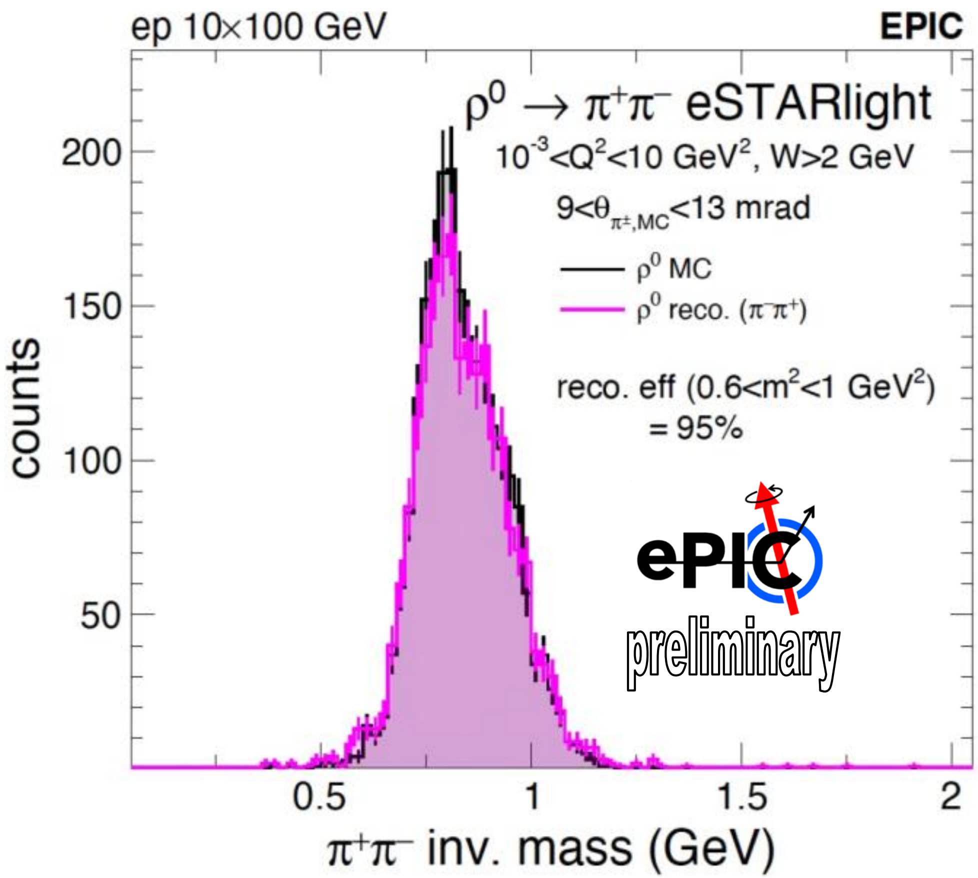


arXiv:1108.1713

➔ **The EIC will provide the first ever tomographic images of the ocean of gluons within the nucleon**

Access to TDAs: Backward production of ρ

$$\rho \to \pi^+\pi^-$$



Z. Sweger (UC Davis), S. Klein (Berkeley)

- Meson photo-production, but proton at mid-rapidity and meson goes forward with high momentum

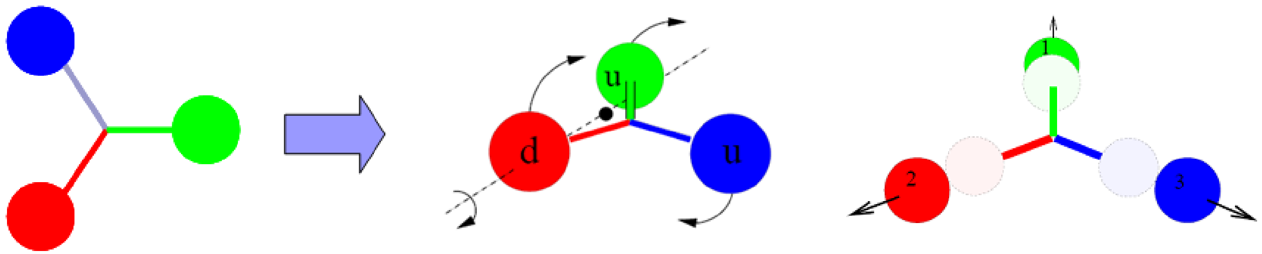
  ➔ **u-channel**

- Proton (a few hundred MeV) detected in central detector.

➔ Sensitivity to Transition Distribution Amplitudes (TDA)

+ Many more exclusive channels sensitive to GPDs!

From the Ground State Nucleon to Resonances



How does the excitation affect the **3D structure** of the resonance?

→ Pressure distributions, tensor charge, … of resonances?

→ Gluon contribution to the excitation process!

→ 3D images of the excitation process

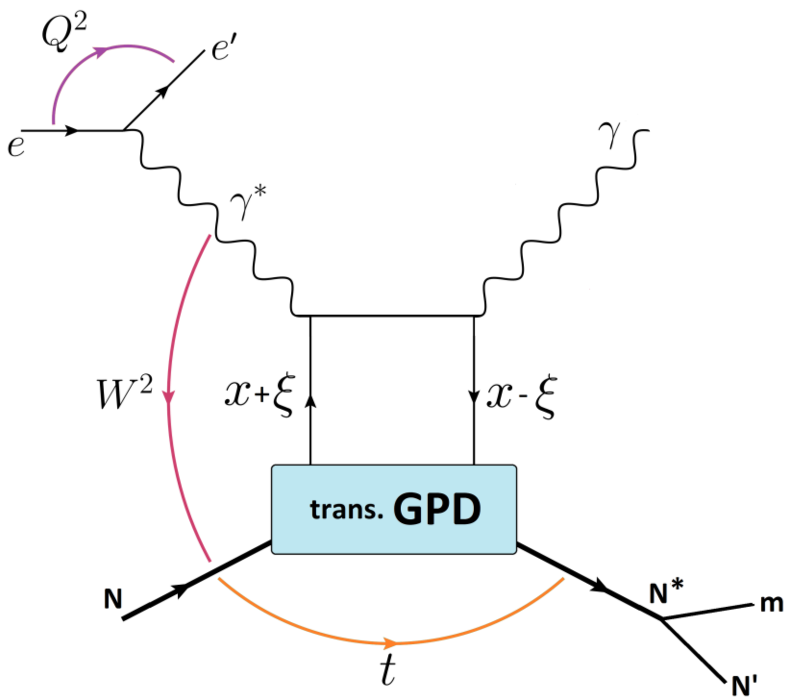
➔ Information encoded in **transition GPDs**

N→Δ: 8 helicity non-flip trans. GPDs (Related to the Jones-Scardon and Adler FFs)
+ 8 helicity flip trans. GPDs

whitepaper accepted by EPJ-A: https://arxiv.org/abs/2405.15386

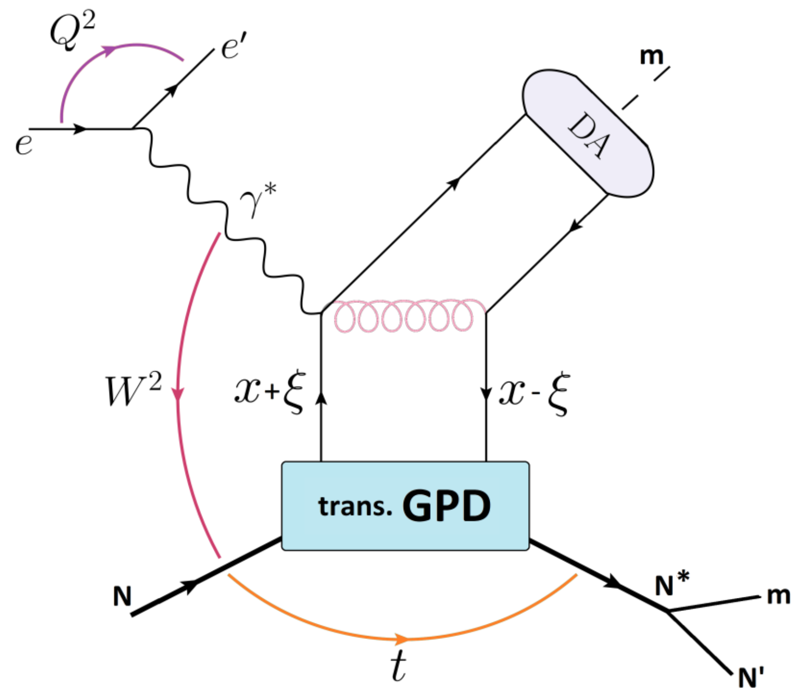
Experimental Access to Transition GPDs

N→N* DVCS



Access to the helicity non-flip transition GPDs

N→N* DVMP



+ Access to the helicity flip transition GPDs

W > 2 GeV

Factorisation expected for: $-t / Q^2 \ll 1$, x_B fixed and $Q^2 > M^2_{N^*}$

Example: The N → Δ^{++} DVMP Process @ CLAS

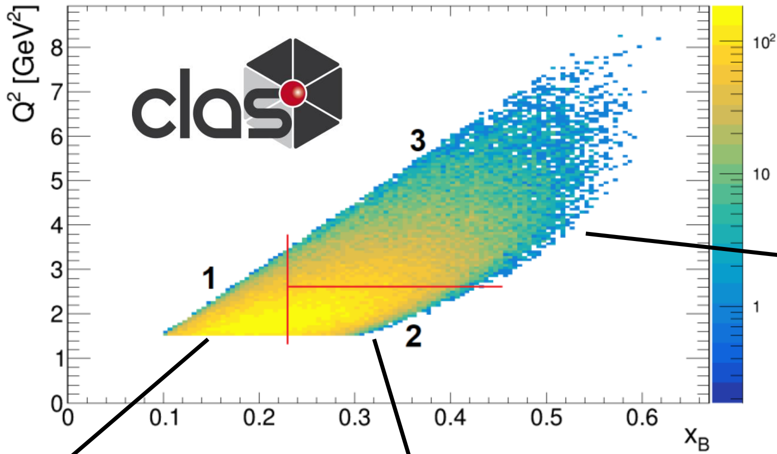
$$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$$

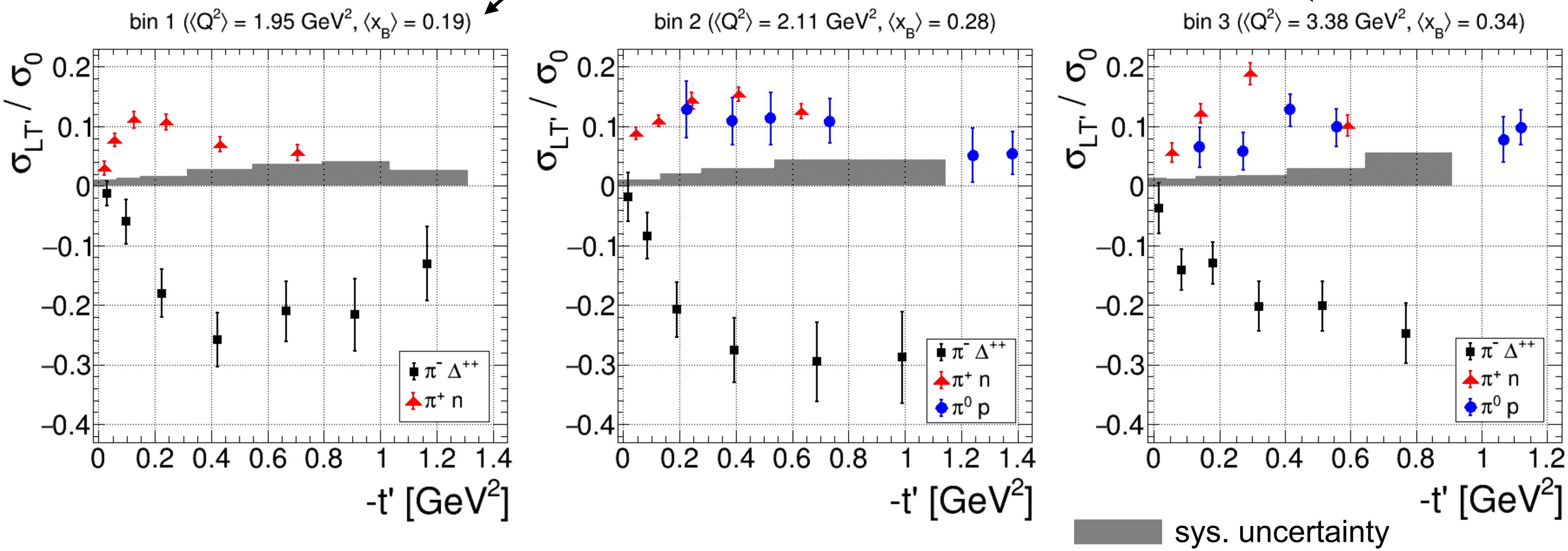
proton (uud)

$\to$ neutron (udd) π^+ $(|u\bar{d}\rangle)$

$\to \Delta^{++}$ (uuu) π^- $(|d\bar{u}\rangle)$

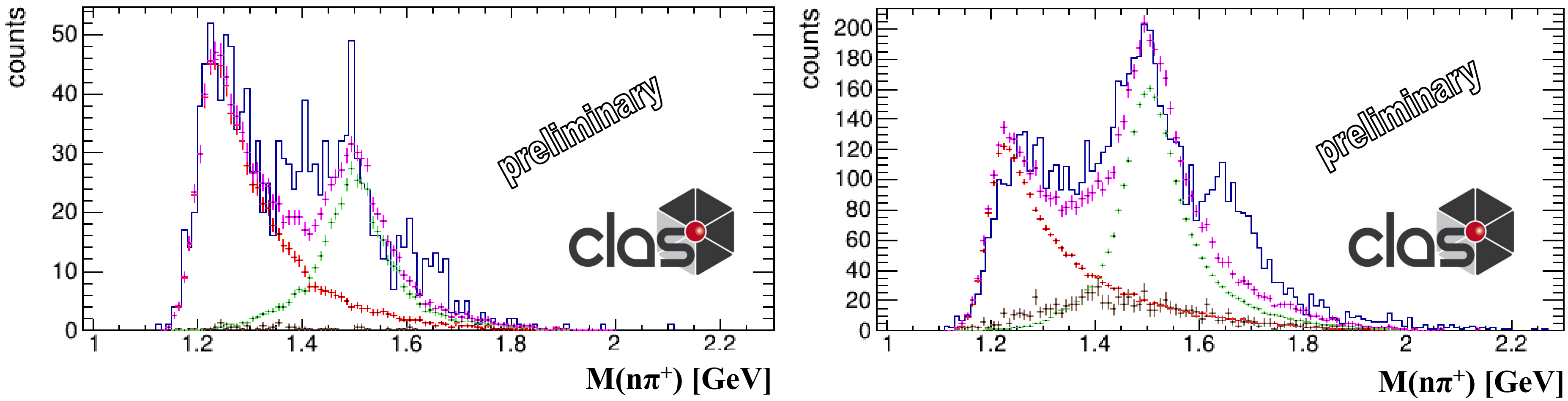
S. Diehl et al. (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023).
https://doi.org/10.1103/PhysRevLett.131.021901





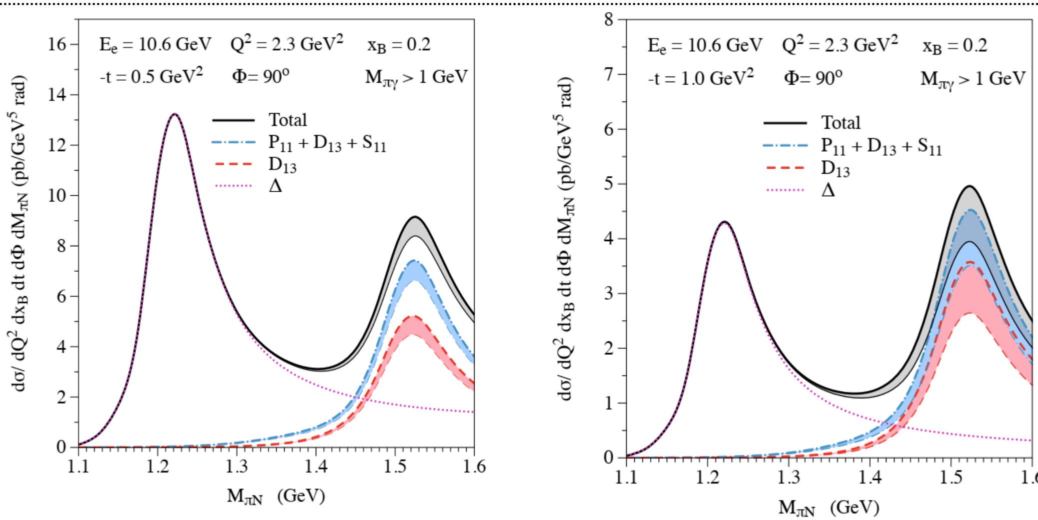
The N → N* DVCS Process: ep → e'Δ⁺γ → enπ⁺γ

W > 2 GeV, Q² > 1.5 GeV²



exp. data — sim. Δ(1232) / 2nd res. region — sim. full DIS — sim. sum

Experiment: S. Diehl (JLU Gießen + UConn)



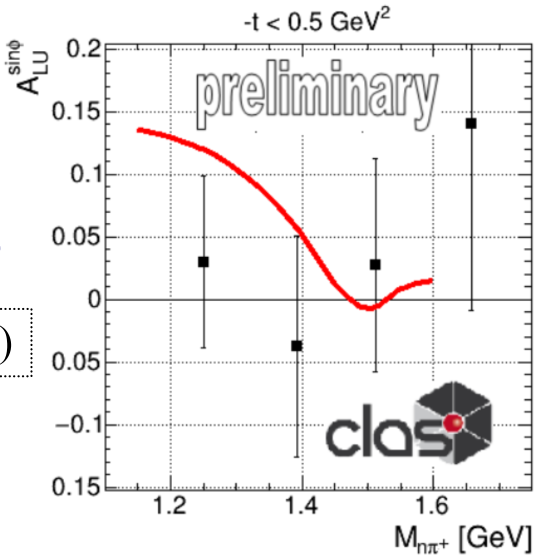
Theroy:
K. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D 108, 034021 (2023)

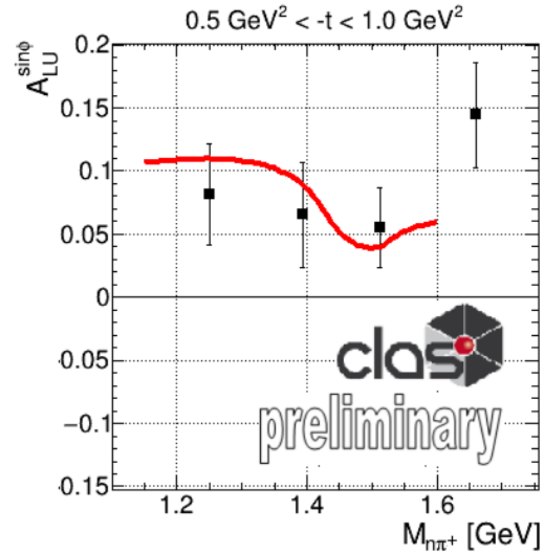
➔Talk by Kirill on Thursday

Results for N → N* DVCS ($\langle Q^2 \rangle$ = 2.47 GeV², $\langle x_B \rangle$ = 0.25)

S. Diehl
(JLU Gießen + UConn)

$$BSA \sim A_{LU}^{\sin(\phi)} \cdot \sin(\phi)$$

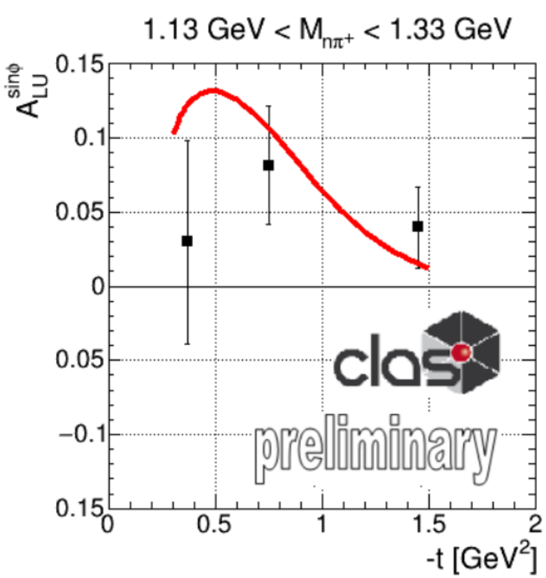


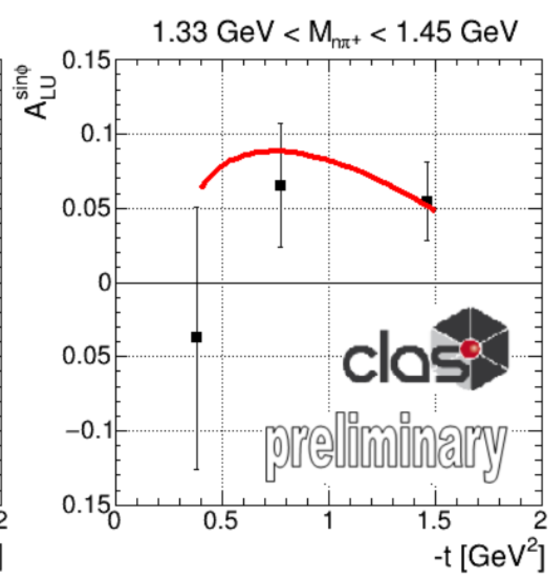


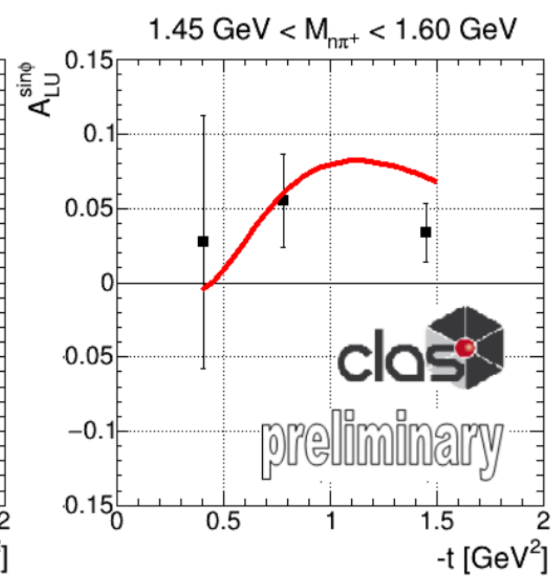
<u>Transition GPD based theory curves in CLAS12 kinematics from</u>:

K. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D **108**, 034021 (2023)

<u>Data:</u>
No π^0 background subtraction so far!







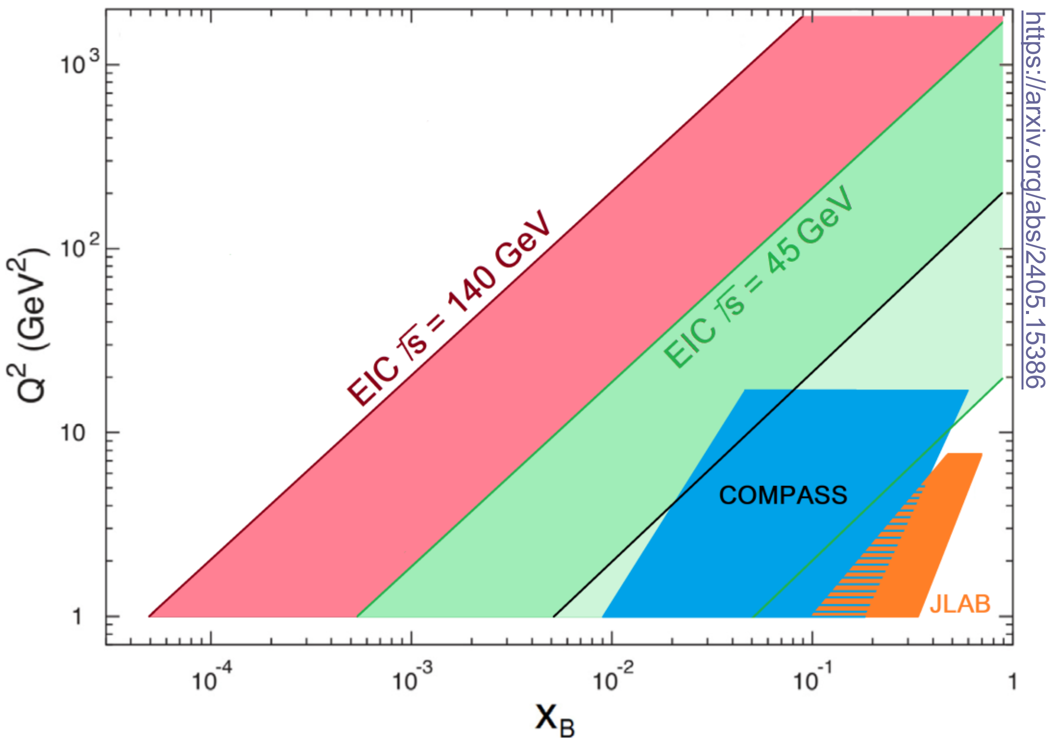
Tranistion GPDs at the EIC

EIC: Extension of the kinematic regime to the sea-quark and gluonic sector

➔ Low x_B and higher Q^2 values

➔ Potential for unique insights into the contributions of sea quarks and gluons to the excitation process and to the characteristics of baryon resonances

➔ Detailled EIC theory predictions and ePIC simulation studies are needed



Summary

- **EIC science program** will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all
- **Exclusive processes** will help us to map the spatial distributions of quarks and gluons in the nucleon and potentially also in baryon resonances
- The **EIC** provides polarized electron and hadron beams and unpolarized nuclear beams with high luminosities and cm enegies up to 241 GeV
- **ePIC** provides access to EIC physics through large kinematic coverage, good resolutions and excellent PID
- A **second cemplementary EIC detector** is under investigation
- **First science in 2032+**

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