INFN PAVIA
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SIDIS studies at ePIC

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on behalf of the ePIC Collaboration

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3D Nucleon Tomography

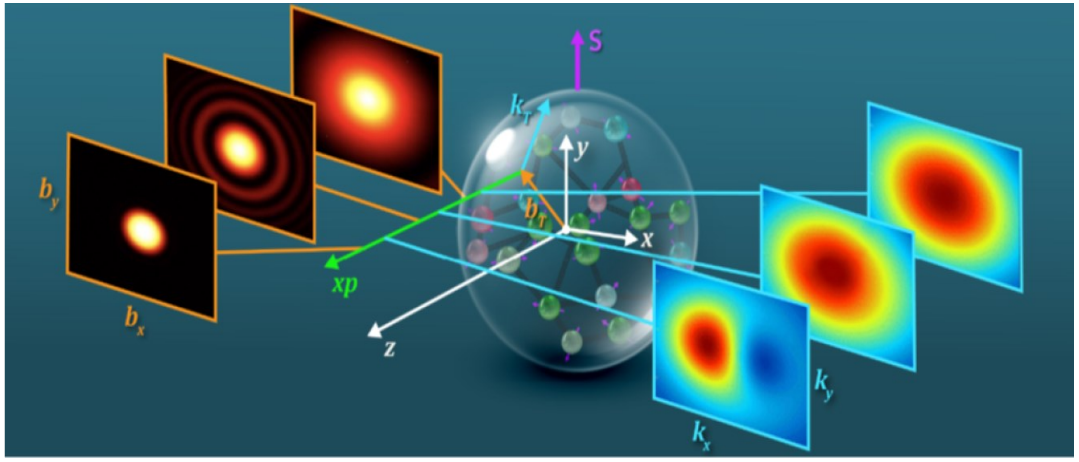
Beyond 1D Structure:

While standard parton distributions (PDFs) address the longitudinal momentum of partons, they do not expose details of their transverse motion (k_T) and spatial position (b_T). To understand the origin of nucleon spin and mass, such **3D maps** are needed.

Mapping the Phase Space:

need of a complete **tomographic scan of the nucleon**, bridging two complementary views not directly connected by a Fourier Transform.

Impact Parameter (b_T): Spatial tomography accessed via exclusive processes.



Transverse Momentum (k_T): Momentum tomography accessed via semi-inclusive processes.

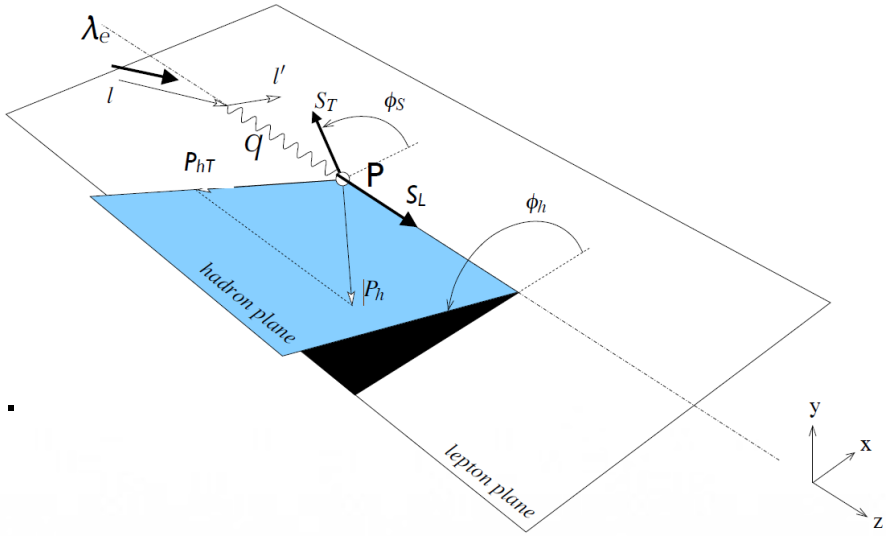
The golden channel

Semi-Inclusive Deep Inelastic Scattering (SIDIS)

Semi-inclusive measurements allow us to **unlock momentum space**, revealing the confined motion of quarks and fundamental **spin-momentum correlations** in the nucleon.

The Process:

$$e(k) + p(P) \rightarrow e'(k') + h(P_h) + X$$



Key Variables:

- x, Q^2 : Probe resolution and parton momentum fraction.
- z : Energy fraction carried by the detected hadron.
- P_{hT} : Transverse momentum of the detected hadron.

Access Strategy:

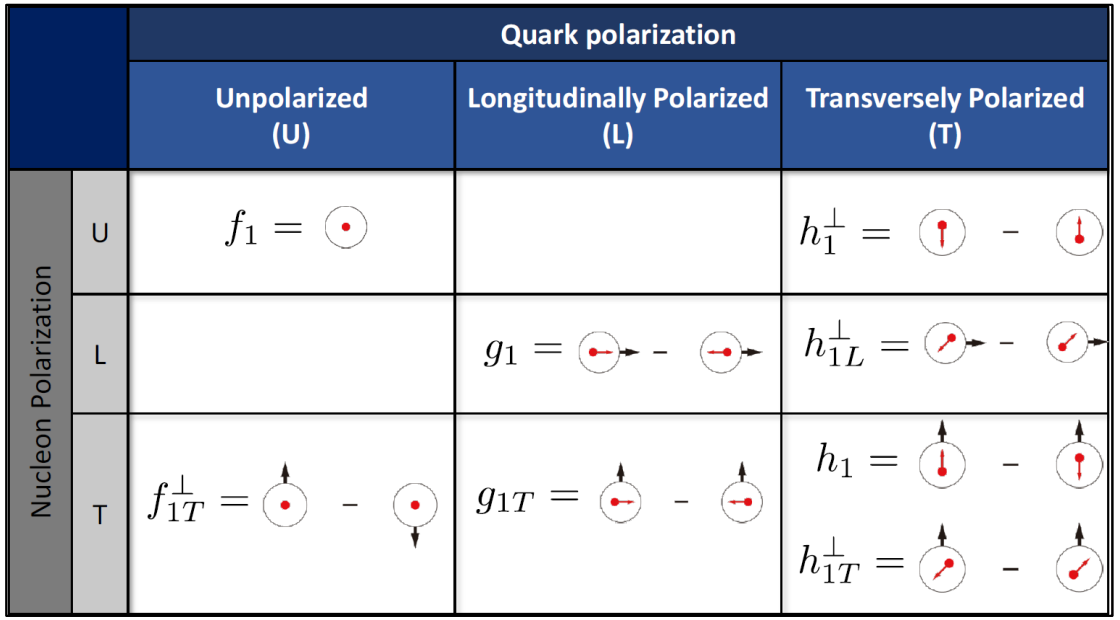
P_{hT} is the key scale to access **Transverse-Momentum Dependent Parton Distribution Functions (TMD-PDFs or TMDs)**.

The TMD landscape

Mapping the Nucleon in 3D

Theoretical framework: At leading twist, **eight TMDs** describe the nucleon structure, encoding correlations between the quark k_T and the quark and nucleon spins.

The "zoo": the distributions are classified according to the polarization state of the parent nucleon (rows: Unpolarized, Longitudinal, Transverse) and the quark (columns: U, L, T).



EIC Potential: The **Electron Ion Collider**, with its **high luminosity and wide kinematic coverage**, will allow the simultaneous extraction also of naive time-reversal odd effects $(f_{1T}^\perp,\ h_1^\perp)$ with **unprecedented precision**.

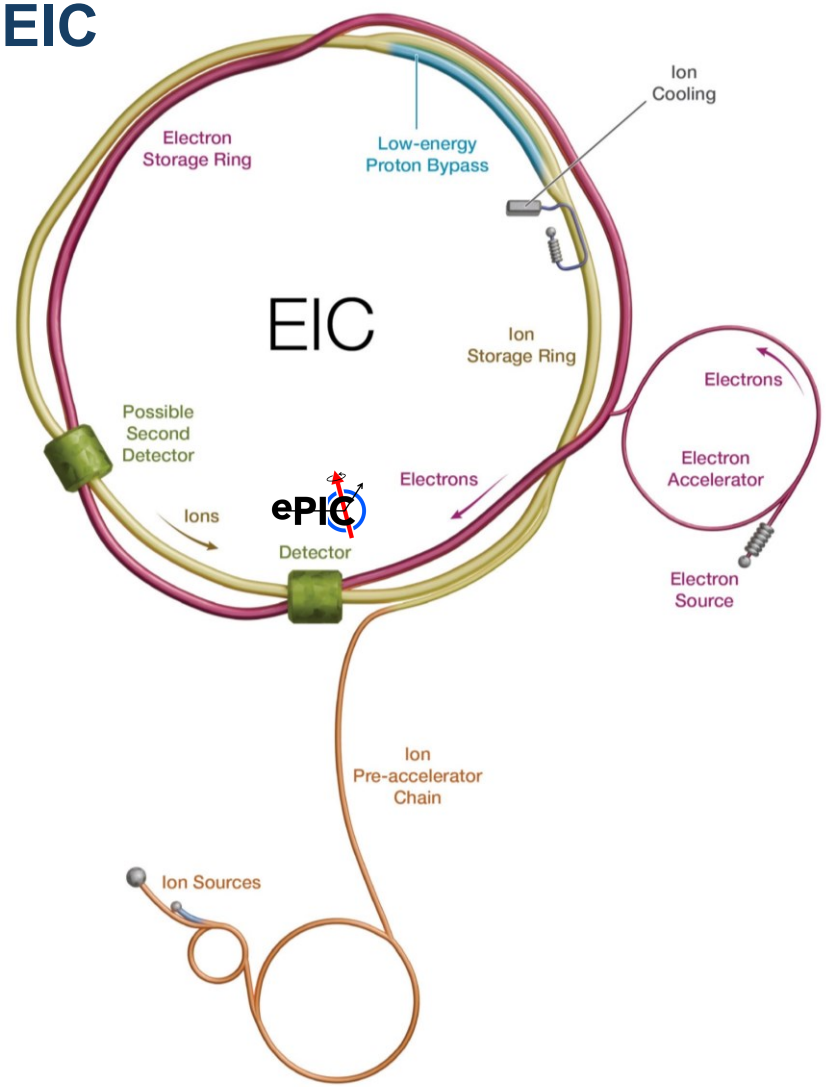
The Electron Ion Collider

The Facility: from RHIC to EIC

World's First: located at **Brookhaven National Lab (BNL)**, the **Electron Ion Collider (EIC)** transforms the **RHIC** complex into the only collider of **polarized electrons** and **polarized ions**, capable of exploring the sea quark frontier.

Extreme Luminosity: Reaching $\mathcal{L} \approx 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, it delivers the massive statistics required for the **multi-dimensional binning** $(x,\ Q^2,\ z,\ P_{hT})$ essential to TMD extraction.

Wide Reach: Variable CM energy ($\sqrt{s} \approx 28 - 140\ \mathrm{GeV}$) and high beam polarization ($\sim 70\%$) provide **unique access to the nucleon's spin structure**.



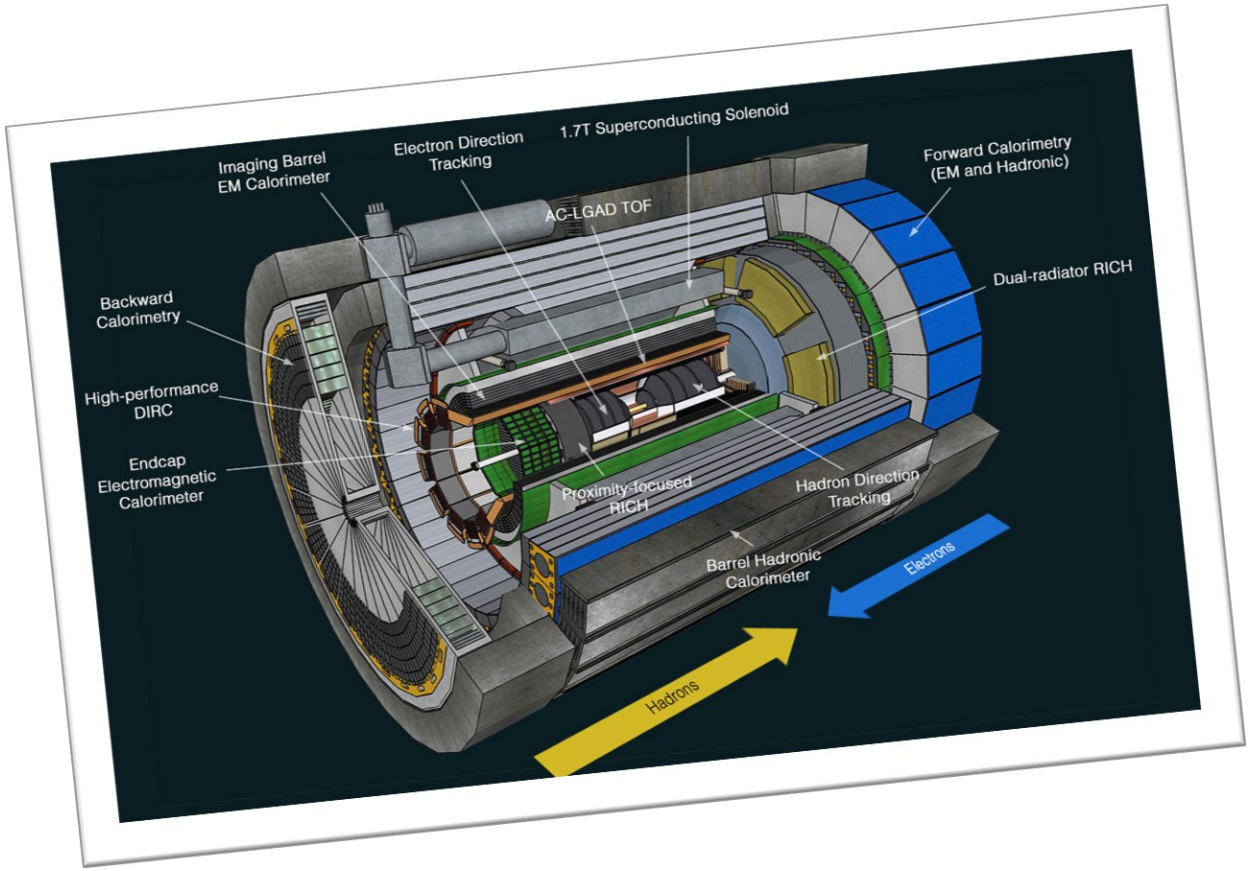
The ePIC detector

A 4π general purpose detector

Full Acceptance: A **hermetic design** ensures detection of the scattered electron and the full hadronic final state.

Precision Tracking:
High-resolution vertexing captures the delicate transverse momentum (P_{hT}) kicks, essential for TMD extraction.

Flavour Hunter: A Multi-Technology approach with state-of-the-art PID detectors (RICH + ToF) distinguishes $\pi/K/p$ over a wide range, unlocking **Quark Flavour Separation**.



PID synergy

dRICH: Forward Region (η > 1.5)

- Dual-radiator RICH (Aerogel + C_2F_6 gas)
- The only system capable of π/K separation at high momenta (up to 50 GeV/c)

hpDIRC: Barrel Region (| η | < 1.0)

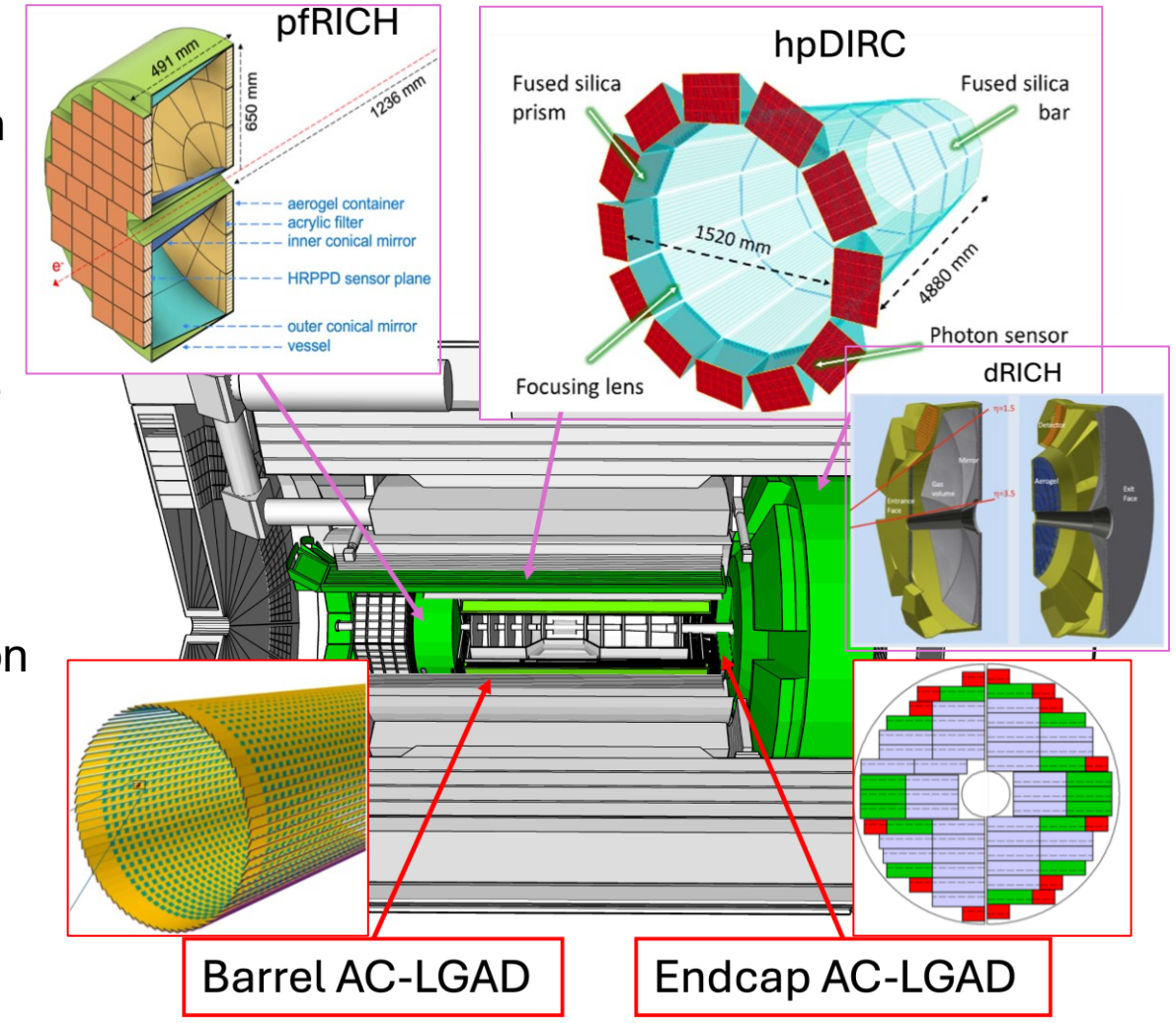
- High-Performance DIRC with fused silica bars
- Highly compact design, excellent separation in the central region up to 6 GeV/c

pfRICH: Backward Region (η < -1.5)

- Proximity Focusing RICH (Aerogel)
- Compact configuration for e/h and π/K identification up to 7 GeV/c

TOF System: Barrel and Forward Region

- AC-LGAD sensors providing < 30 ps timing resolution.
- Bridges the low-momentum gaps (p < 2 GeV/c) where Cherenkov detectors are below threshold.



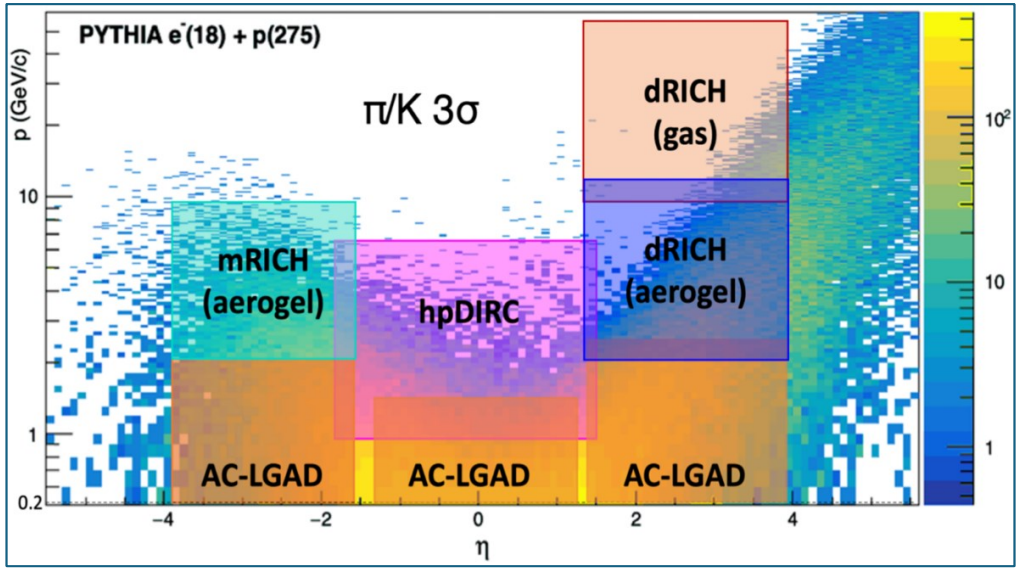
The PID challenge in SIDIS

Flavour Tagging: To correctly map the strange sea (via kaons) and the valence quarks (via pions), unambiguous $\pi/K/p$ separation is needed.

The Kinematic Reality: Pions dominate the final state. Even a small misidentification rate of pions into kaons leads to severe background contamination, washing out the spin asymmetries.

Why Multiple Technologies? No single detector can cover the entire phase space

- **TOF:** Crucial for low-momentum tracks (p < 2 GeV/c) below Cherenkov thresholds.
- **hpDIRC & pfRICH:** Provide robust separation in central and backward regions
- **dRICH:** The gas radiator allows the identification reach up to 50 GeV/c in the forward direction

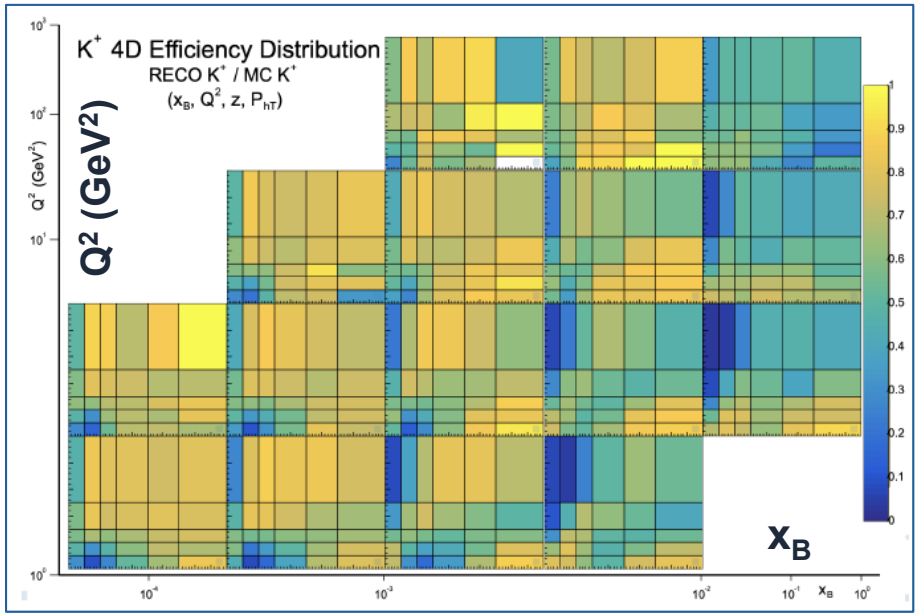


The ePIC Goal: Achieving continuous, >3σ separation over the full 4π acceptance to ensure the high purity required for precision SIDIS measurements.

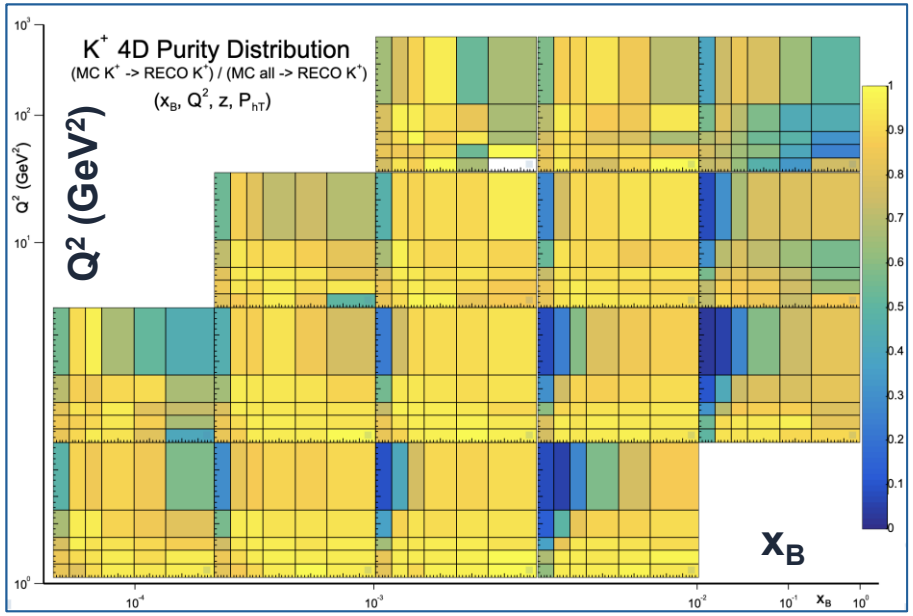
PID purity and efficiency

Validation via full simulation

- **High Purity:** Mandatory to suppress pion background and isolate the strange quark.



Work from L. Polizzi (Univ. Ferrara), *ePIC preTDR*, 2025



- **High Efficiency**: Values > 90% ensure maximal statistics for the fit.

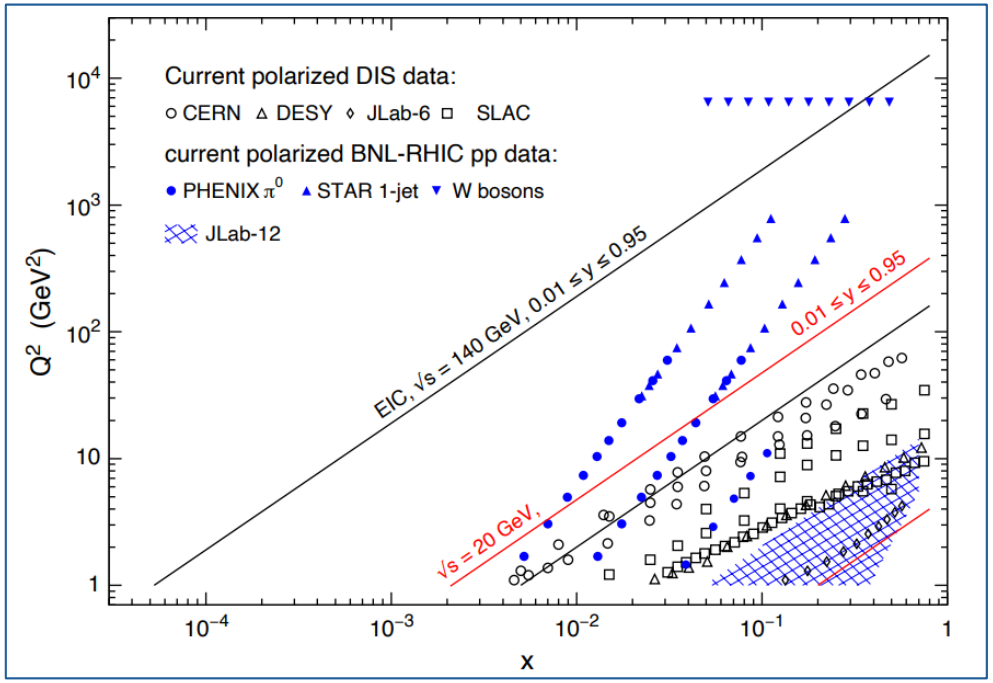
Impact on Physics: **High purity and efficiency** are mandatory for precise multi-dimensional binning, allowing to disentangle the flavour-dependent 3D nucleon structure.

The ePIC Early Science program

A New Kinematic Frontier: The EIC will immediately extend SIDIS measurements into an unexplored $x - Q^2$ regime.

Unpolarised Physics:

- **Unpolarised Baseline:** Precise mapping of Fragmentation Functions (FFs) and nuclear FFs.
- **Unpolarised TMDs:** Extraction of P_{hT} distributions to access the intrinsic quark k_T.



Spin Asymmetries:

- **Sivers effect:** multi-D mapping of transverse spin-orbit correlations.
- **Collins effect:** extraction of tensor charges and link to BSM physics.
- **SIDIS helicity measurements:** pin down strange quark helicities via kaon A_1 asymmetries.

Detector Validation: Using "Day-1" physics to stress-test ePIC's tracking and integrated PID capabilities.

Hadron multiplicities

Hadron multiplicity is the fundamental unpolarized observable, providing access to fragmentation dynamics:

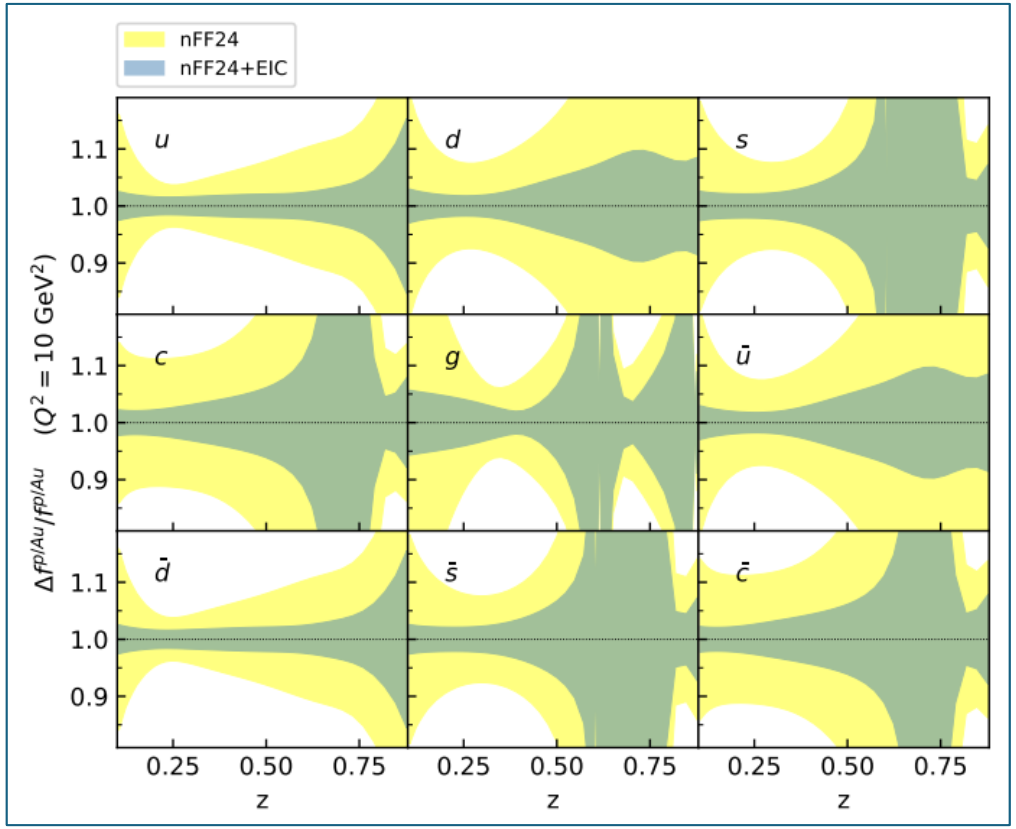
$$M_h(z, Q^2) = \frac{1}{N_{DIS}} \frac{\mathrm{d}N_h}{\mathrm{d}z}$$

Fragmentation Functions: Accessing $D_1(z)$ to describe quark-to-hadron transition.

Nuclear Medium Effects: Probing e+Au collisions to extract nuclear FFs (nFFs).

PID requirement: High purity is vital to avoid π/K contamination in cross-sections.

Early-Science Impact: ePIC's wide coverage will drastically reduce nFF uncertainties.



Work from P. Zurita (Complutense Univ. Madrid) & C. Van Hulse (UAH), in preparation for the *ePIC Early Science Report,* July 2026

Flavour-Dependent 3D Tomography

Separating u, d, s contributions

Physics Goal:

Investigating the non-perturbative QCD dynamics through the extraction of unpolarized TMDs. The objective is to determine the **flavour dependence of the k_T -distributions** of valence and sea quarks.

Nucleon Mapping:

The unpolarized TMD $f_1^q(x, k_T; Q)$ provides a **3D representation of the nucleon** in momentum space. Disentangling the k_T-widths for each quark species q is a crucial step towards a complete understanding of the internal nucleon structure.

Multi-flavour Baseline:

While current world data are limited by significant uncertainties, high-precision EIC data will enable the **first definitive, flavour-separated map of the k_T landscape** across a broad kinematic range.

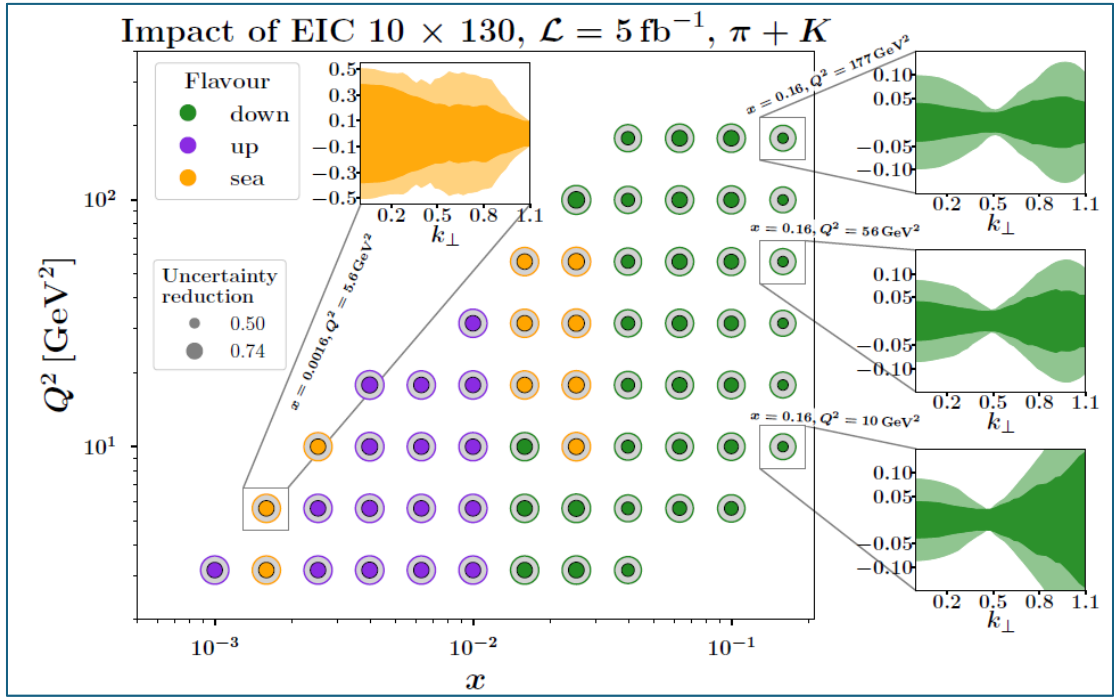
Impact on TMD precision

Impact of ePIC Early Science data on the extraction of TMD PDFs for selected *x* - Q^2 bins

Representative cases for the flavour-dependent analysis

Impact on the **unpolarized down-quark TMD** ($f_1^d(x, k_T; Q)$) and on the **unpolarized sea-quark TMDs** using pions and kaons.

- **Light bands:** current uncertainty from the MAPTMD24 global fit.
- **Dark bands:** projected precision achievable with the ePIC detector.



Work from M. Radici (INFN-Pavia) & L. Rossi (Univ. Milano), in preparation for the *ePIC Early Science Report,* July 2026 (original version from *ATHENA detector proposal*, 2022 JINST 17 P10019)

The path to precision

Impact quantification:

In order to quantify the ePIC sensitivity, the relative uncertainty on the TMD distribution is evaluated:

$$\frac{f_1(x, k_T; Q) - \langle f_1(x, k_T; Q) \rangle}{\langle f_1(x, k_T; Q) \rangle}$$

Experimental Requirements:

The dramatic reduction in the uncertainty bands is a direct consequence of ePIC's high-luminosity and advanced **Hadron Identification** (PID). High purity in $\pi/K/p$ separation is mandatory to perform a clean flavour decomposition.

Outlook:

The EIC will enable the transition from a qualitative to a **high-precision quantitative era in 3D imaging**, providing the definitive test for flavour-dependent non-perturbative QCD effects.

Azimuthal modulations

The Sivers asymmetry

Definition: Describes the correlation between the nucleon's transverse spin and the quark's transverse momentum k_T.

Physics Impact: 3D imaging: it provides a "tomographic" view of the parton distribution in momentum space, revealing the underlying spin-orbit correlations.

Orbital Motion: Often associated with the internal "swirl" of quarks. The formal connection to **Orbital Angular Momentum (OAM)** is model-dependent and not a direct measurement.

Experimental signature: Extracted from the $\sin(\phi_h - \phi_S)$ azimuthal modulation.

The Collins asymmetry

Definition: Describes the fragmentation of a transversely polarized quark into an unpolarized hadron.

Physics Impact: It acts as a "microscopic polarimeter" to access the **Transversity PDF (h_1)**, the last poorly known leading-twist distribution.

Link to BSM Physics: Crucial for a precise extraction of the nucleon's **tensor charge**, a fundamental property that provides a sensitive probe for **BSM physics** (e.g. new CP-violating interactions)

Experimental signature: Extracted from the $\sin(\phi_h + \phi_S)$ azimuthal modulation.

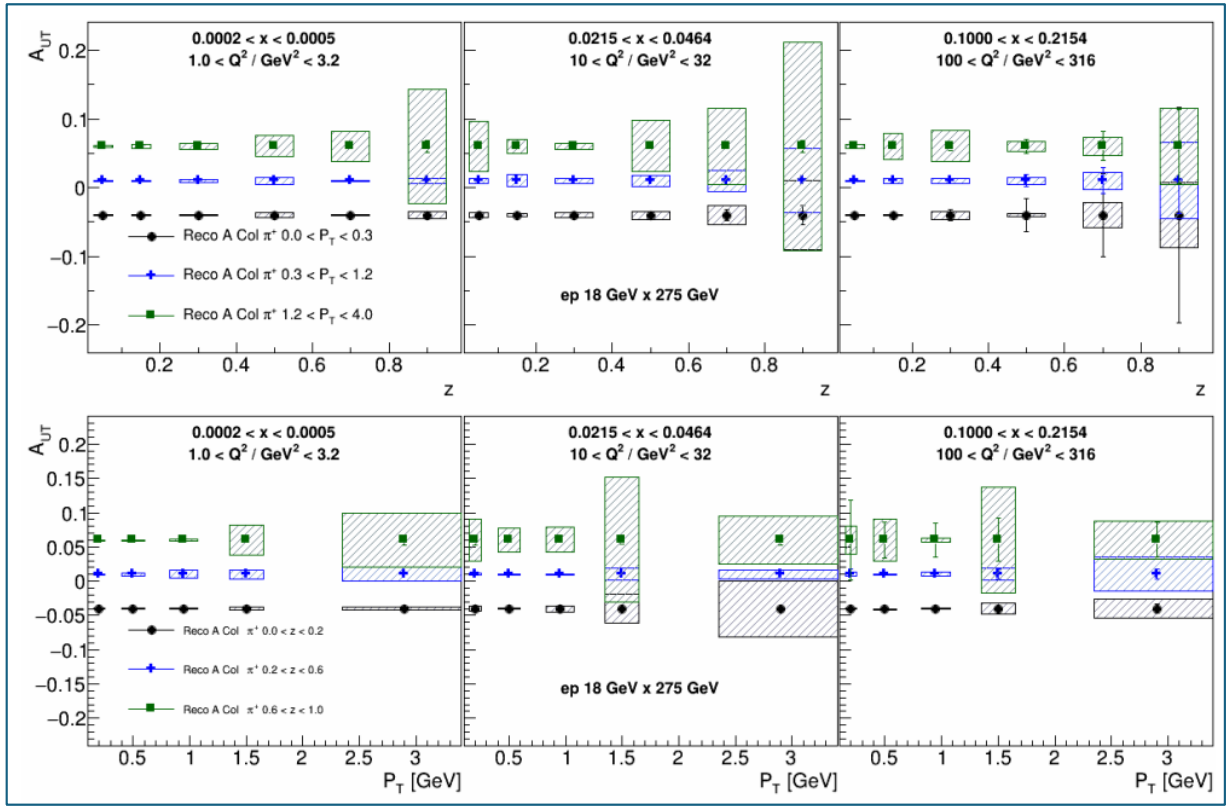
Azimuthal modulations

Early Science projections at ePIC

Expected uncertainties in three example *x*-Q^2 bins for the **Collins asymmetries for positive pions**, assuming a luminosity of 10 fb^{-1} for the 18 GeV x 275 GeV energy option.

Precision: Even with initial luminosity, ePIC's high-resolution tracking and nearly 4π acceptance allow for a clean separation of these overlapping modulations.

Flavour Separation: Excellent PID allows us to measure these asymmetry specifically for identified kaons to probe the strange sea.



R. Seidl, *ECCE sensitivity studies for single hadron transverse single spin asymmetry measurements*, NIM A 1049 (2023) 168017

Outlook

Comprehensive SIDIS Program

High-precision flavour separation enabled by 4π hermeticity and the synergy of integrated PID systems (dRICH, hpDIRC, pfRICH, TOF).

Unlocking 3D Nucleon Structure

Accessing the origin of spin and mass through multi-dimensional mapping of TMD distributions.

Early Science Impact

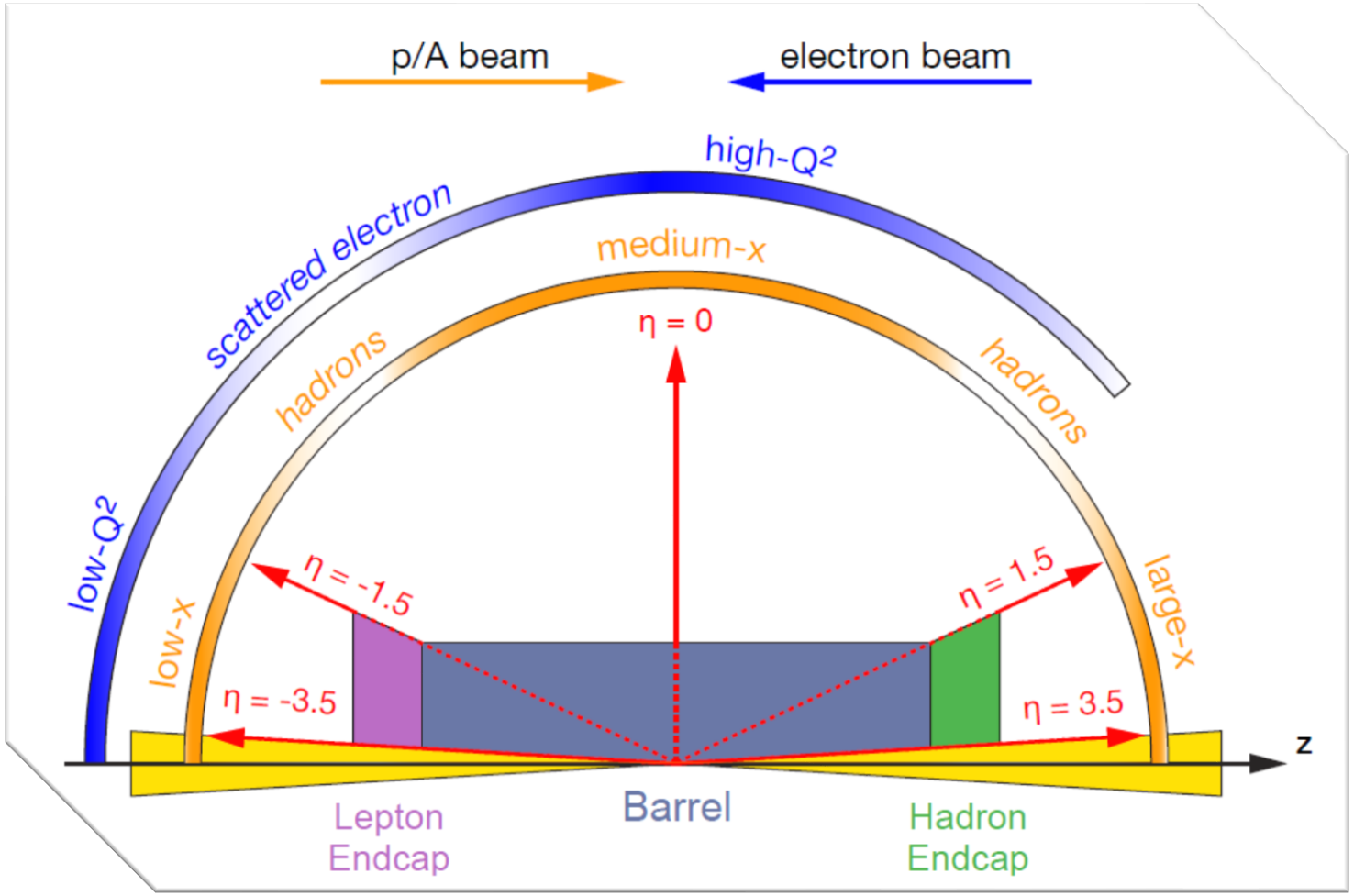
Transformative results with initial integrated luminosity (~10 fb^{-1})

- New constraints on (nuclear) Fragmentation Functions via hadron multiplicities.
- First maping of Sivers and Collins asymmetries in a new $x - Q^2$ regime.

A New Era of QCD

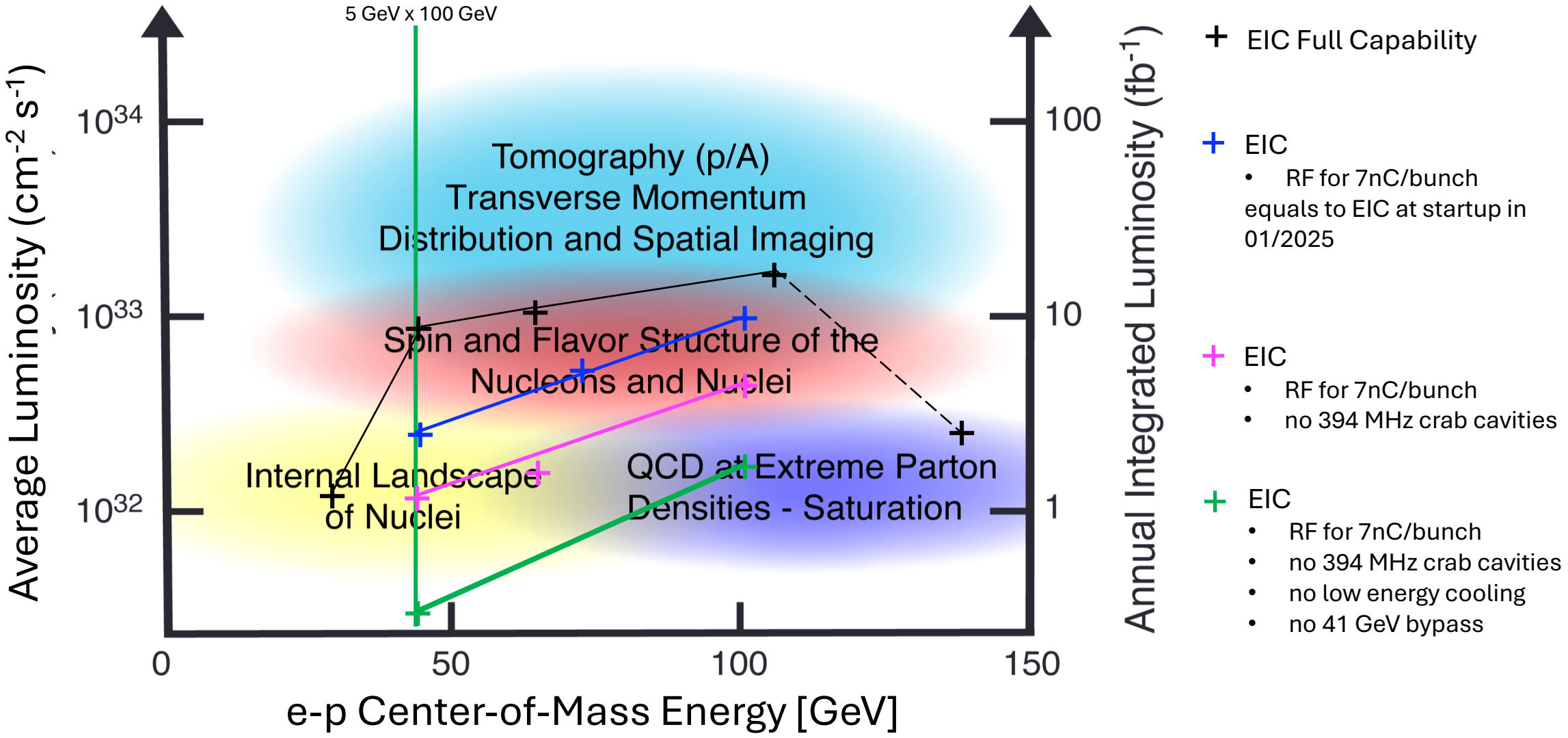
ePIC is poised to deliver the definitive 3D map of the nucleon, realizing the full scientific potential of the Electron-Ion Collider.

Distribution of scattered *e* and *h*

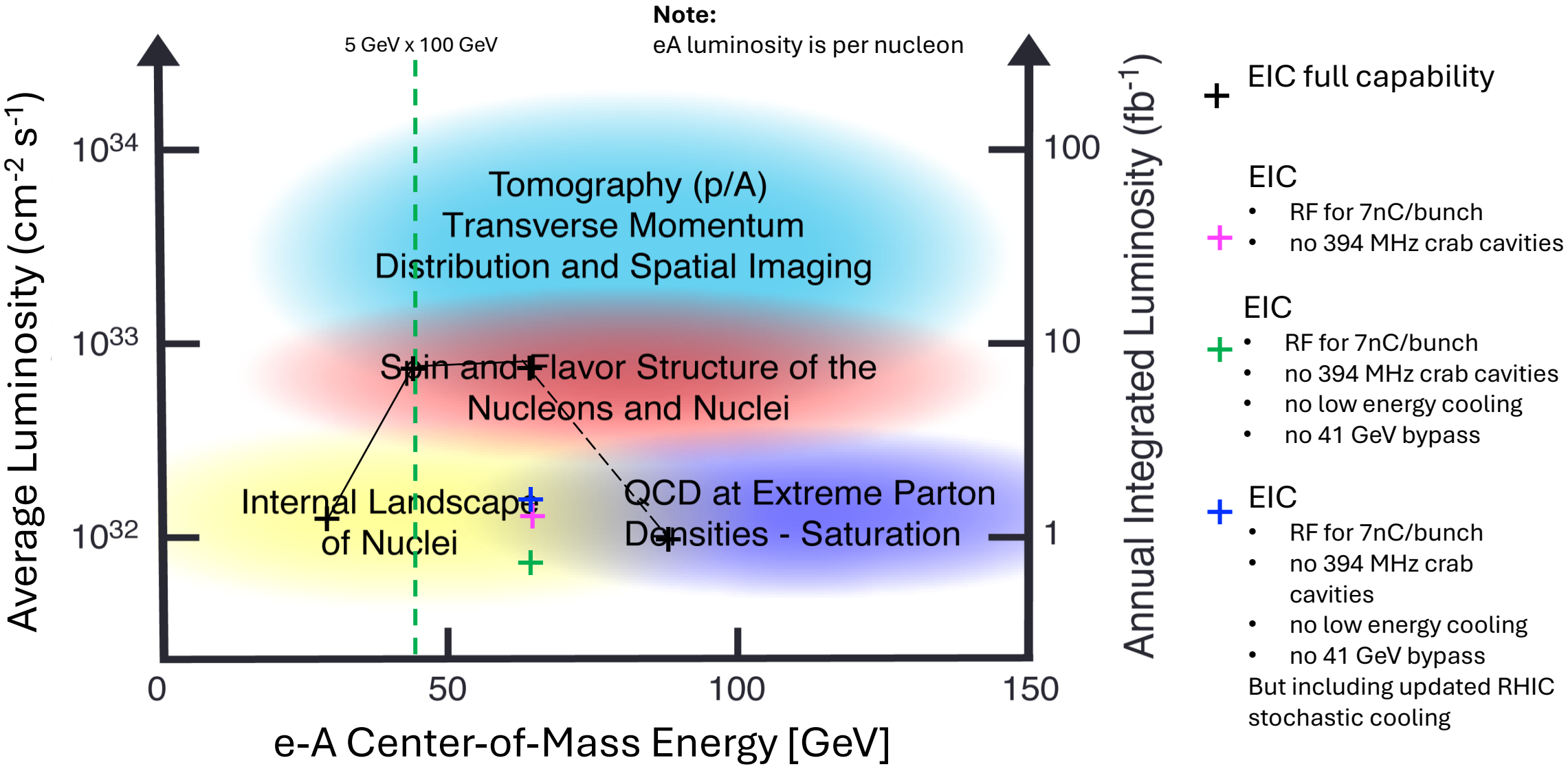


A schematic showing how the scattered electron for different x - Q^2 and hadrons are distributed over the detector rapidity coverage.

EIC Science Reach for ep



EIC Science Reach for eA



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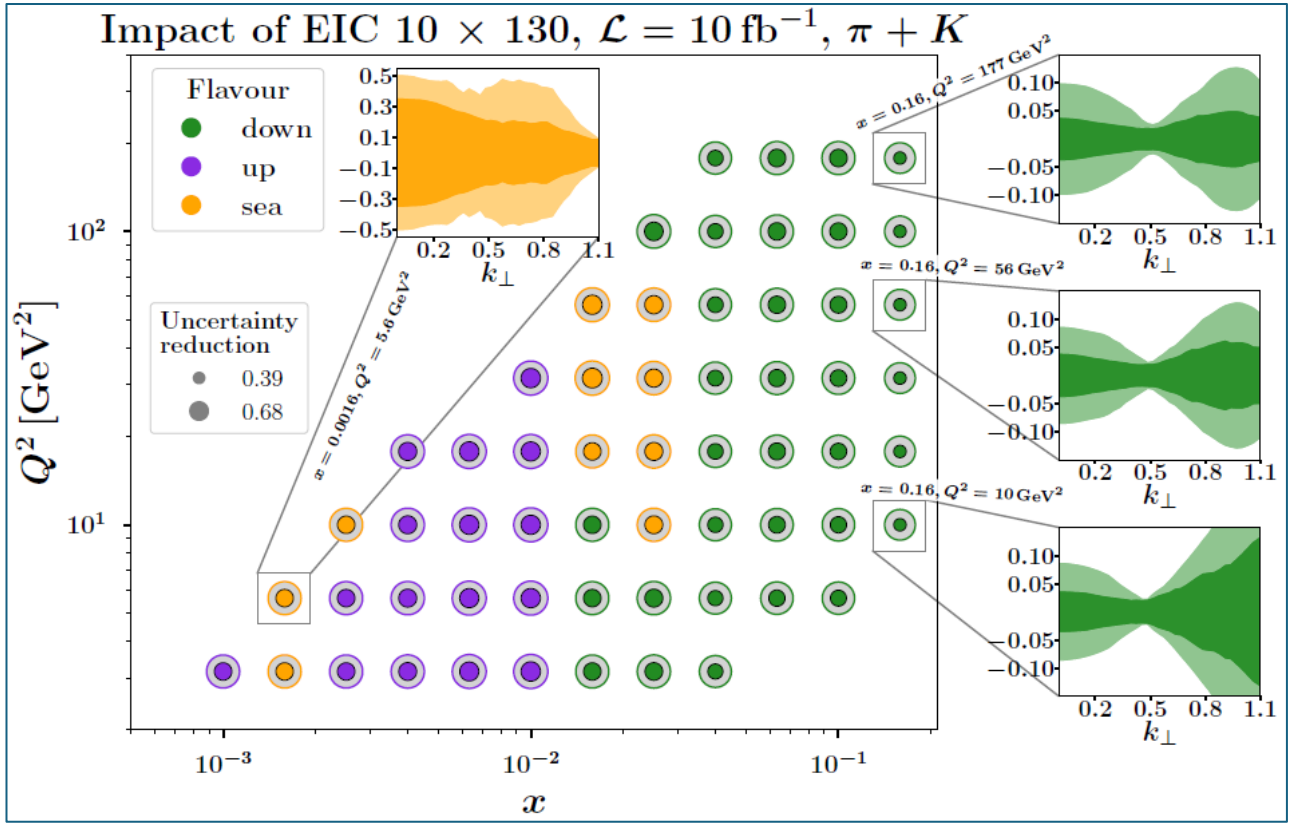

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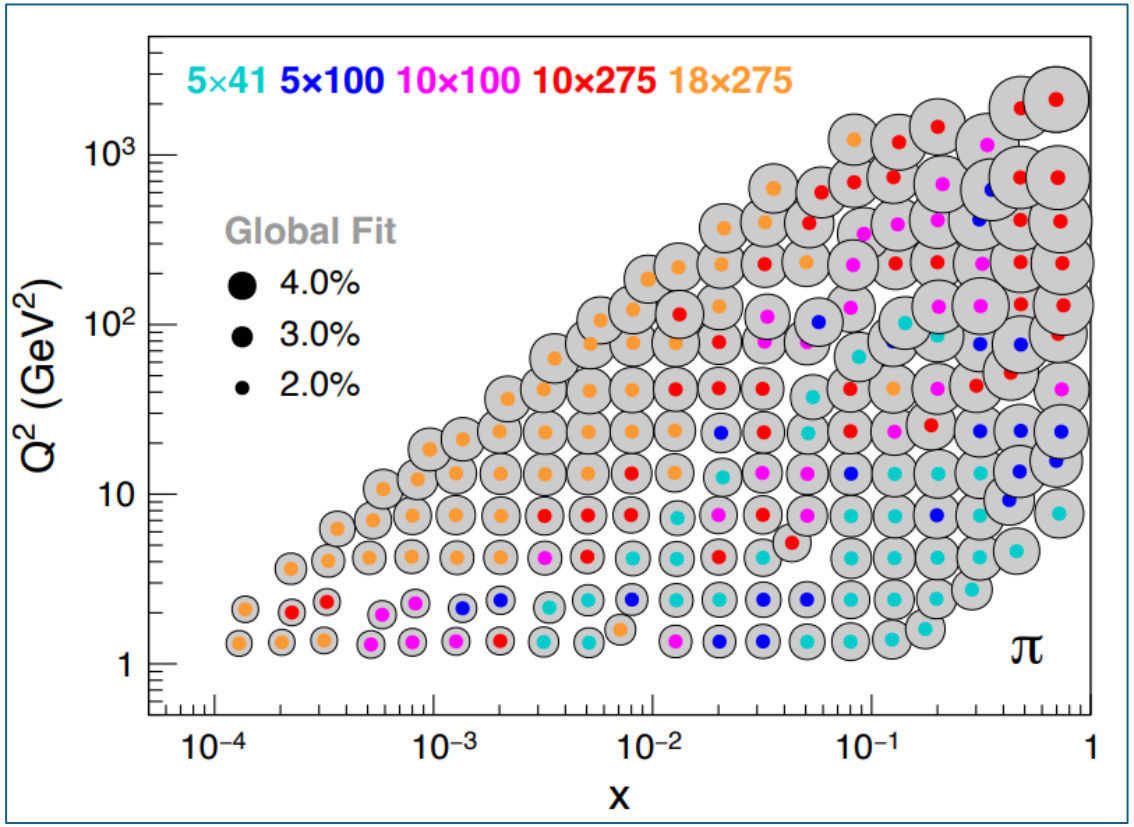
Impact on TMD precision

Impact of ePIC Early Science data on the extraction of TMD PDFs for selected x - Q^2 bins

Projected uncertainties for the unpolarized cross sections with ATHENA

- **Grey dots:** uncertainties of the PV17 TMD PDF extraction
- **Different colours:** different energy
- **Markers size:** uncertainties of the corresponding datasets. At each point the data and theory relative uncertainties are shown where the data has the relative highest impact



ATHENA detector proposal, 2022 JINST 17 P10019