Istituto Nazionale di Fisica Nucleare

SIDIS measurements at the EIC: probing TMDs with the ePIC detector

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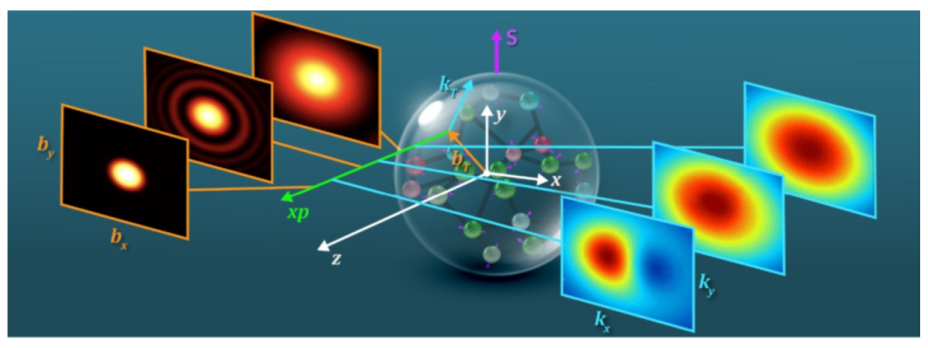
Main Goal

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:** The **Electron Ion Collider** (EIC) provides 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.

- **Unlocking Momentum Space:** Semi-inclusive measurements allow us to reconstruct the **right panel** scenarios, revealing the confined motion of quarks and their crucial link to **Orbital Angular Momentum**.

Method

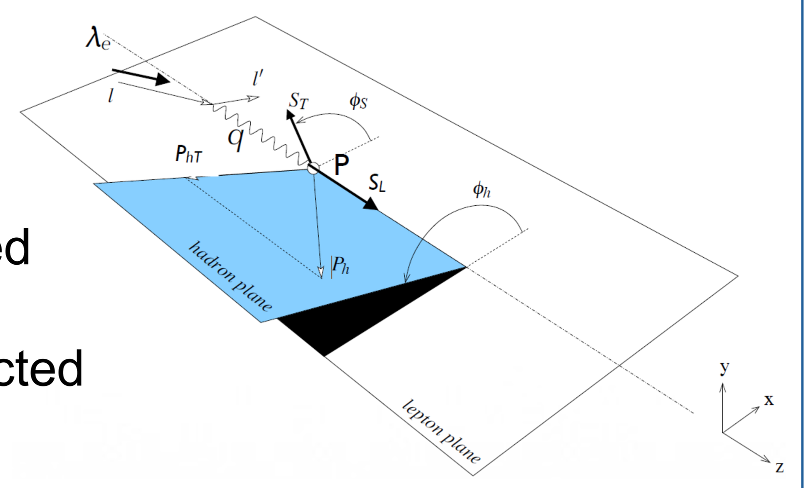
The Golden Channel: Semi-Inclusive Deep Inelastic Scattering (SIDIS)

- **The Process:**

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

Unlike inclusive Deep Inelastic Scattering (DIS), detecting a final-state hadron h connects the experimental observable P_{hT} to the intrinsic quark motion k_T.

- **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

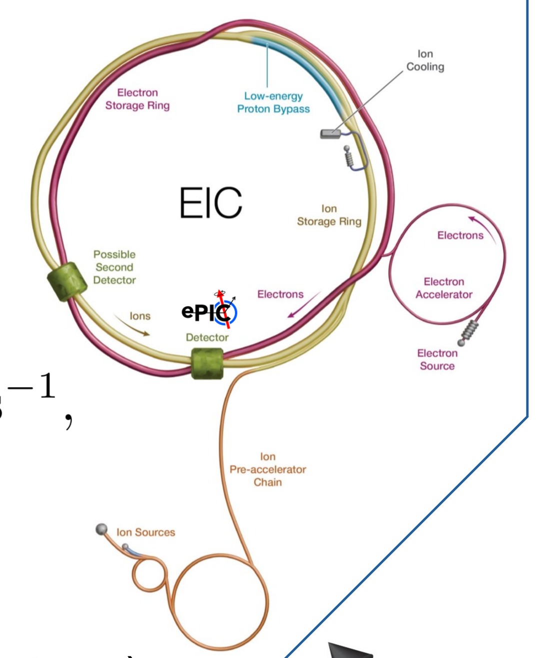


- **Access Strategy:** P_{hT} is the key scale to access **Transverse-Momentum dependent parton Distributions (TMDs)**.

The EIC

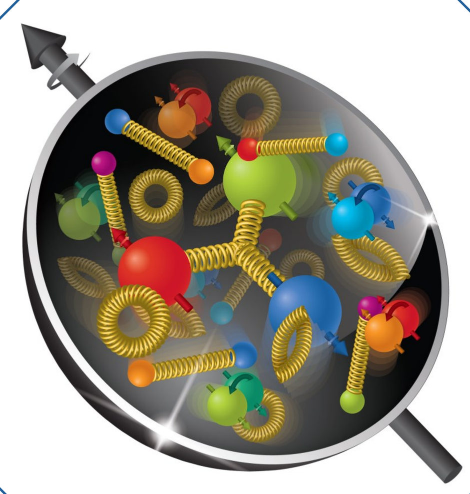
The Facility: from RHIC to EIC

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 $(\sqrt{s} \approx 20 - 140\ \mathrm{GeV})$ and high beam polarization $(\sim 70\%)$ provide **unique access to the nucleon's spin structure**.



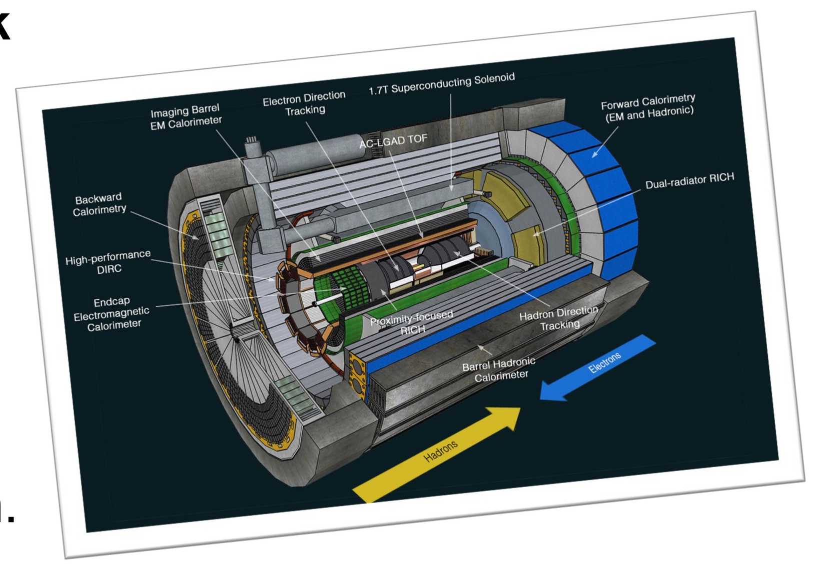
The ePIC detector

The Tool: ePIC detector

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

Flavour Hunter: State-of-the-art PID (RICH + ToF) distinguishes $\pi,\ K,\ p$ over a wide range, unlocking **Quark Flavour Separation**.

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



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).

Nucleon Polarization	Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 =$		$h_1^\perp =$ -
L		$g_1 =$ -	$h_{1L}^\perp =$ -
T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

EIC Potential: **High luminosity and wide kinematic coverage** allow the simultaneous extraction also of exotic time-reversal odd effects $(f_{1T}^\perp,\ h_1^\perp)$ with **unprecedented precision**.

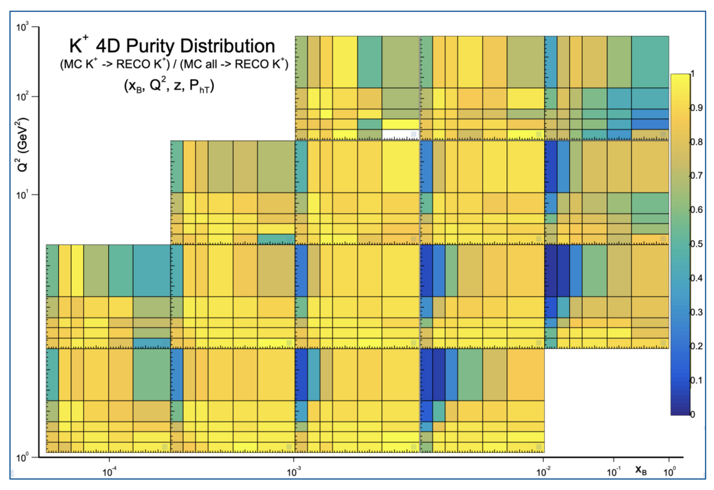
PID Performance

Flavour Tagging

Detector systems: **Full PID coverage** (0.5 - 50 GeV/c) is provided by **hpDIRC**, **pfRICH**, **dRICH** and **TOF.**

Performance

- **High Purity** (Fig.): Mandatory to suppress pion background and isolate the strange quark.
- **High Efficiency**: Values > 90% (not shown) ensure maximal statistics for the fit.



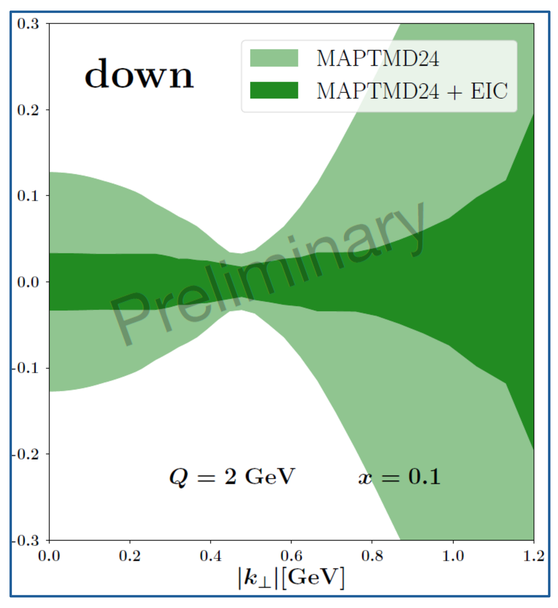
Impact on Physics: **High purity and efficiency** are mandatory for precise multi-dimensional binning, allowing to disentangle the flavour-dependent 3D nucleon structure.

Towards Precision Tomography of Hadrons

Flavour-Dependent 3D Tomography

- **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 of ePIC projections on **unpolarized down-quark TMD** $(f_1^d(x, k_T; Q))$ as a representative case for the flavour-dependent analysis.



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

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.

References

MAPTMD24: A. Bacchetta et al. (MAP Coll.), JHEP08 (2024) 232, arXiv:2405.13833
EIC Yellow Report: R. Abdul Khalek et al., *Nucl. Phys. A* **1026**, 122447 (2022)
EIC White Paper: A. Accardi et al., Eur. Phys. J. A, 52(9):268, 2016, doi:10.1140/epja/i2016-16268-9

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