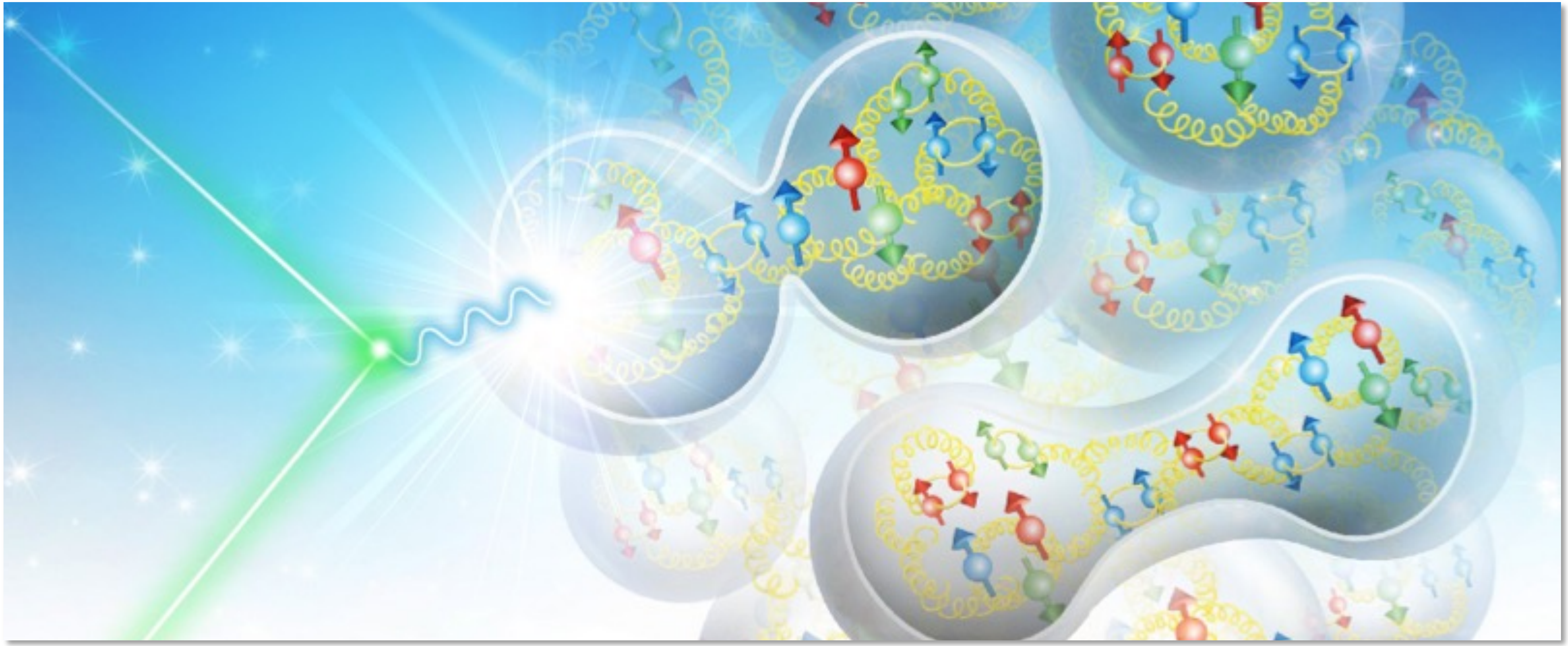
TMD Studies at the Upcoming Electron-Ion Collider

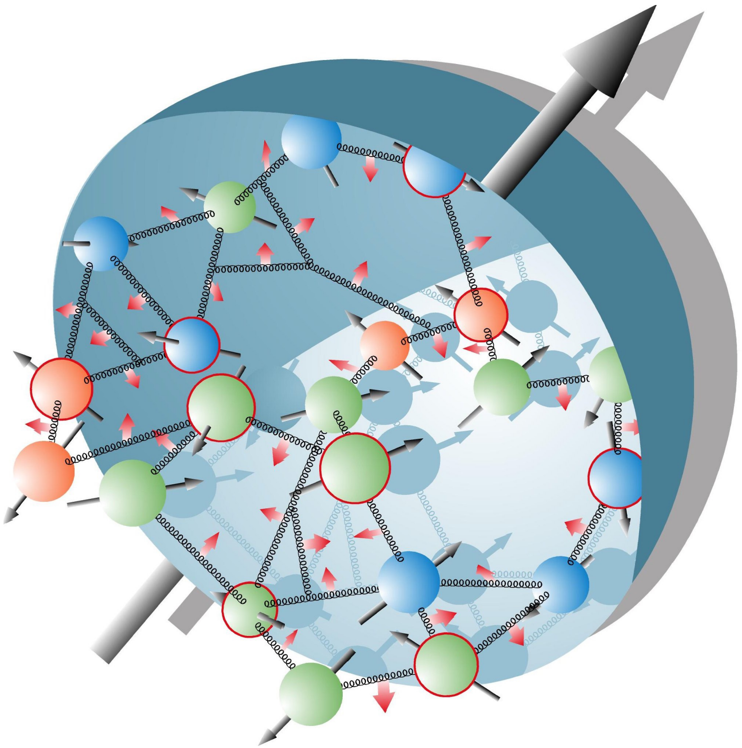


Markus Diefenthaler

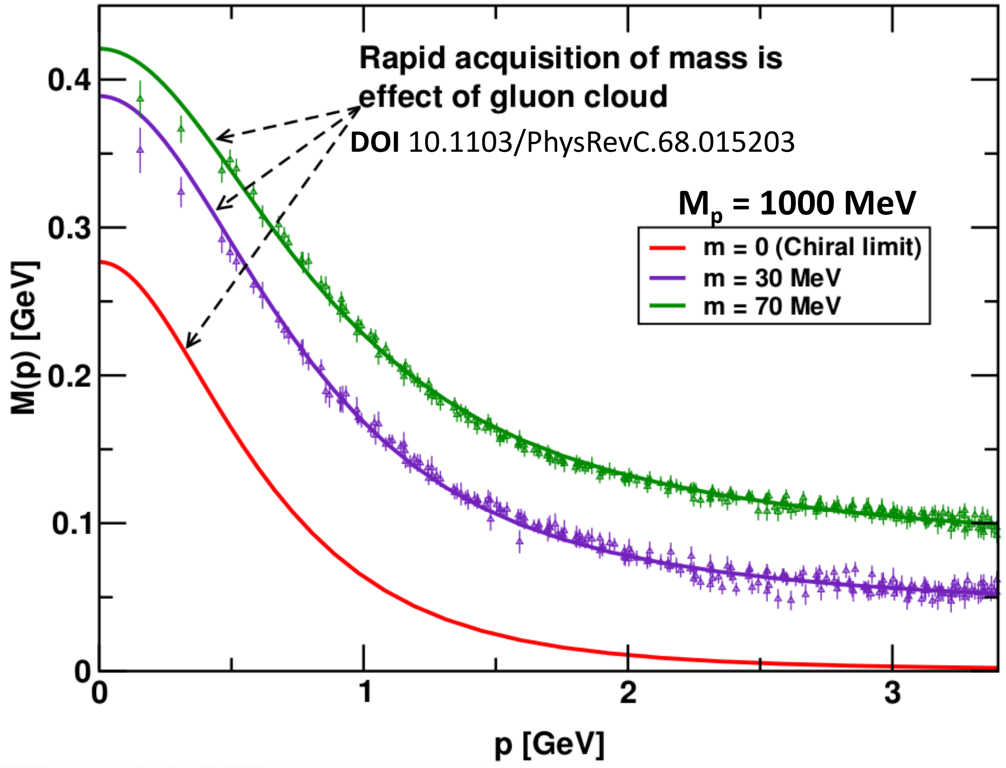
Jefferson Lab

Deepening our Understanding of Nuclear Matter

Nuclear Matter Interactions and structures are inextricably mixed up



Observed properties such as mass and spin emerge out of the complex system



Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

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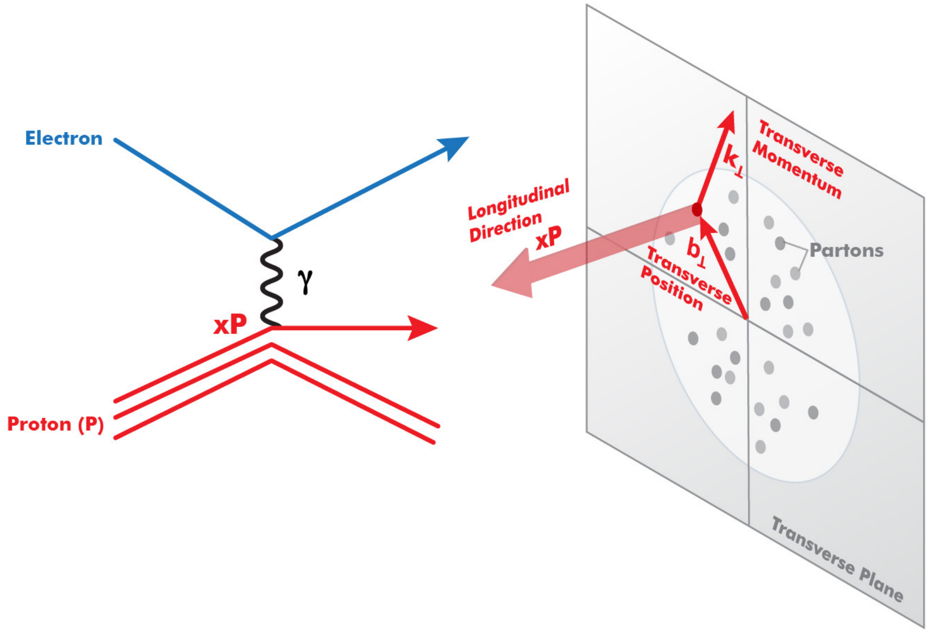
Imaging Quarks and Gluons

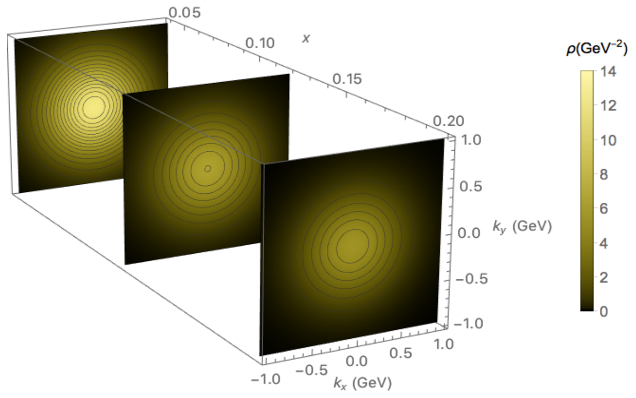
Advances in pQCD



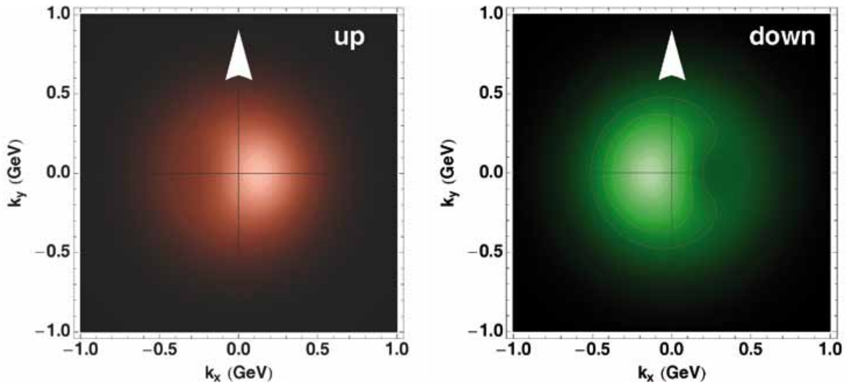
longitudinal structure (PDF)
+ transverse position information (GPDs)
+ transverse momentum information (TMDs)

TMDs of unpolarized nucleon

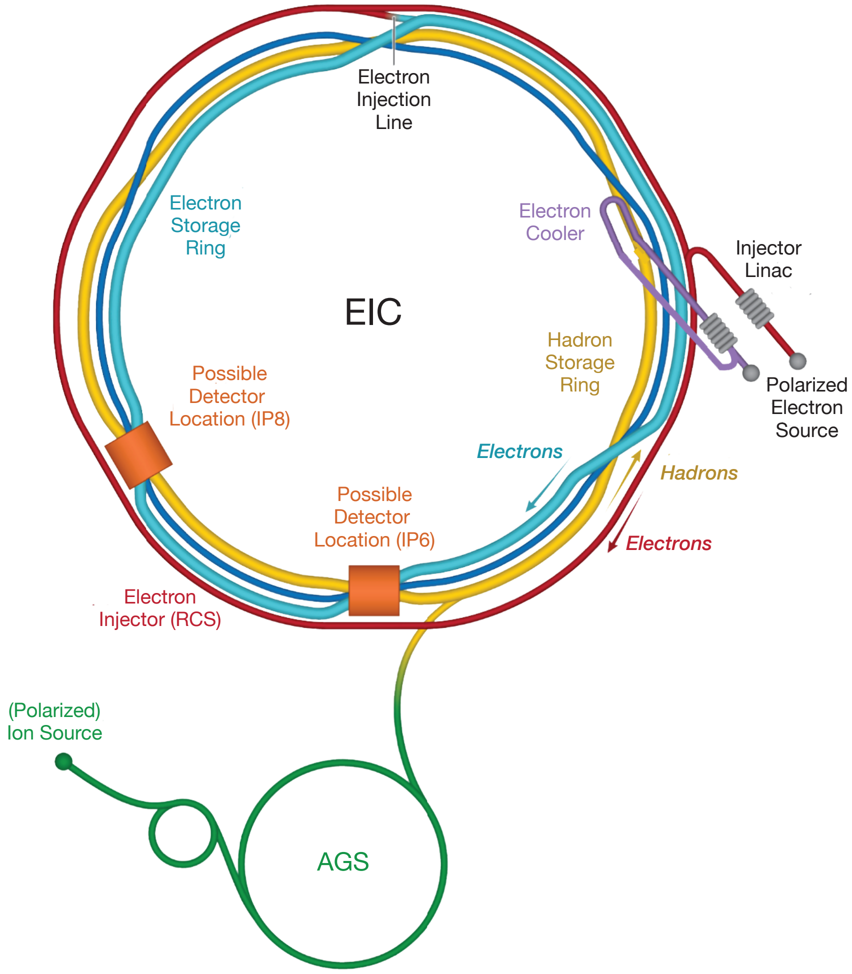
JHEP 1706 (2017) 081



TMDs of transversely polarized nucleon



The Electron-Ion Collider: Ultimate Tool for Imaging of Quarks and Gluons

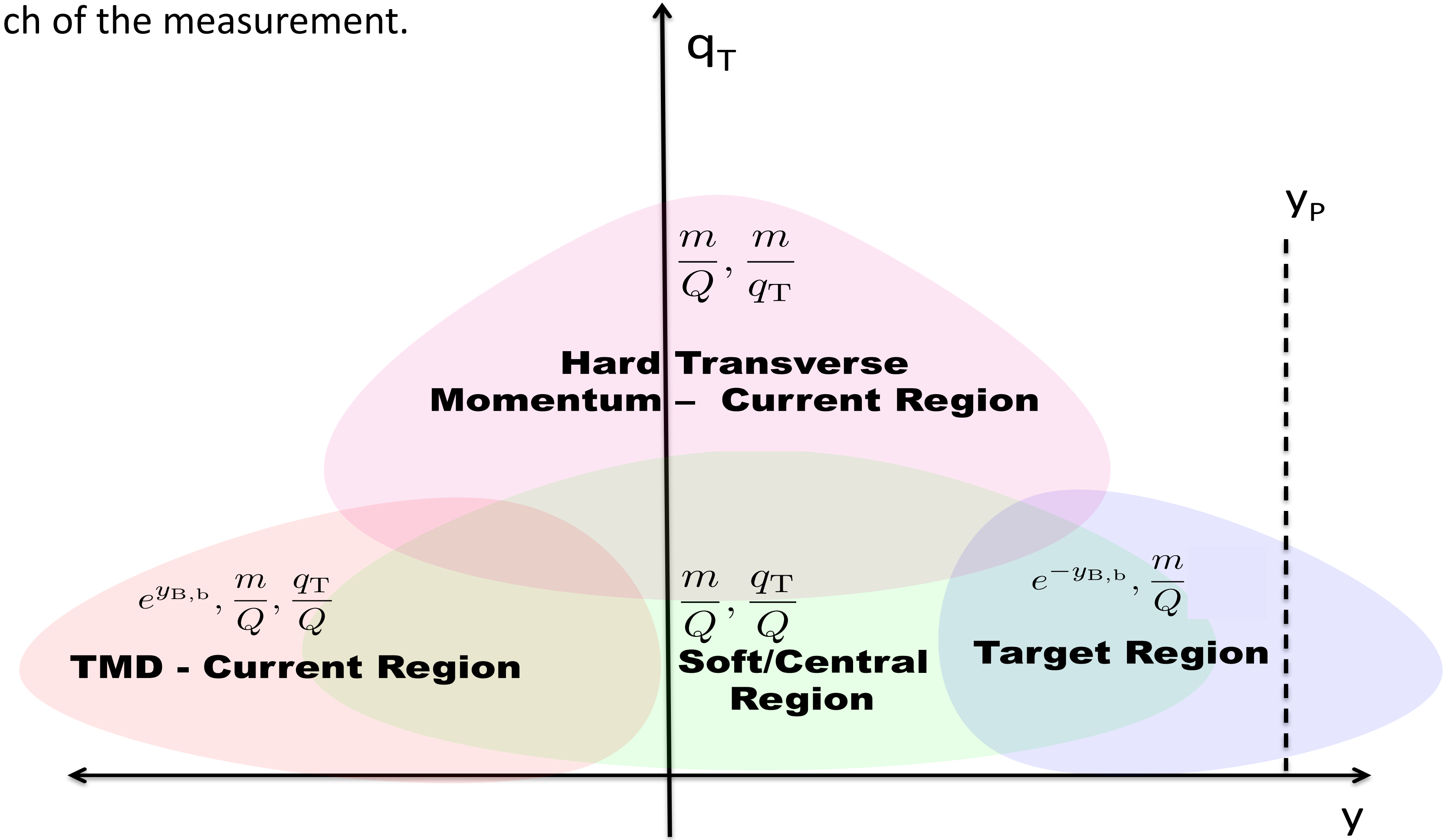


Frontier accelerator facility in the U.S.

- **World's first collider of**:
  - Polarized electrons and polarized protons,
  - Polarized electrons and light ions (d, ^{3}He),
  - Electrons and heavy ions (up to Uranium).
- The EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that is relevant.
- Jefferson Lab and BNL will be host laboratories for the EIC Experimental Program. Leadership roles in the EIC project are shared.
- **For more information on the EIC**: The EIC Yellow Report describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the EIC.

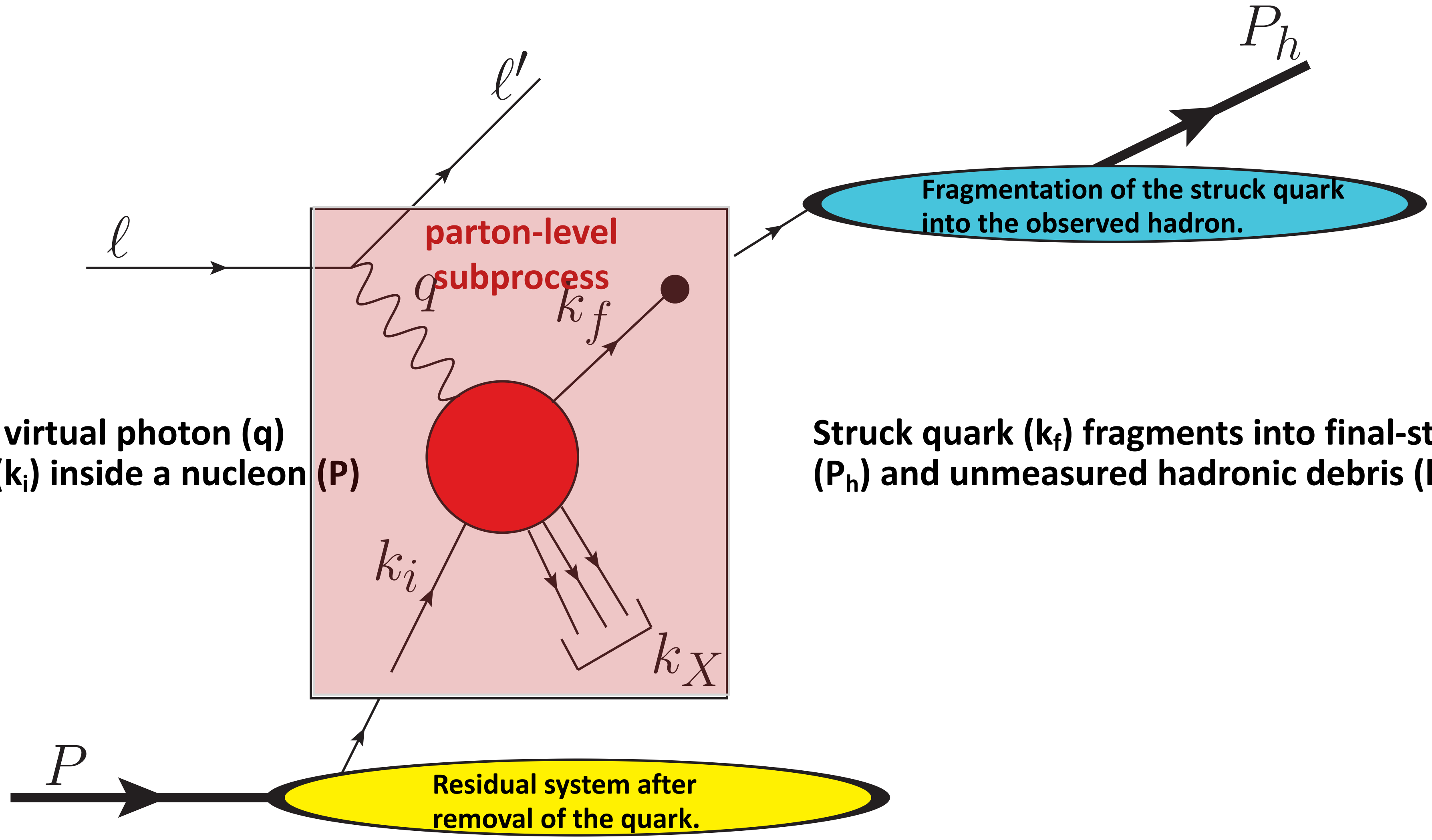
Measurement of TMDs: Semi-Inclusive DIS: $lP \rightarrow l'P_hX$

Interpreting these measurements in terms of QCD requires factorization theorems that are valid for the process and the kinematic reach of the measurement.



More details: New tool for kinematic regime estimation in SIDIS, *JHEP* 04 (2022) 084

Measurement of TMDs: SIDIS Process: $lP \to l'P_hX$



Exchange of a virtual photon (q) from a quark (k_i) inside a nucleon (P)

Struck quark (k_f) fragments into final-state hadron (P_h) and unmeasured hadronic debris (k_X)

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Kinematic Regions in SIDIS and Region Indicators R_i

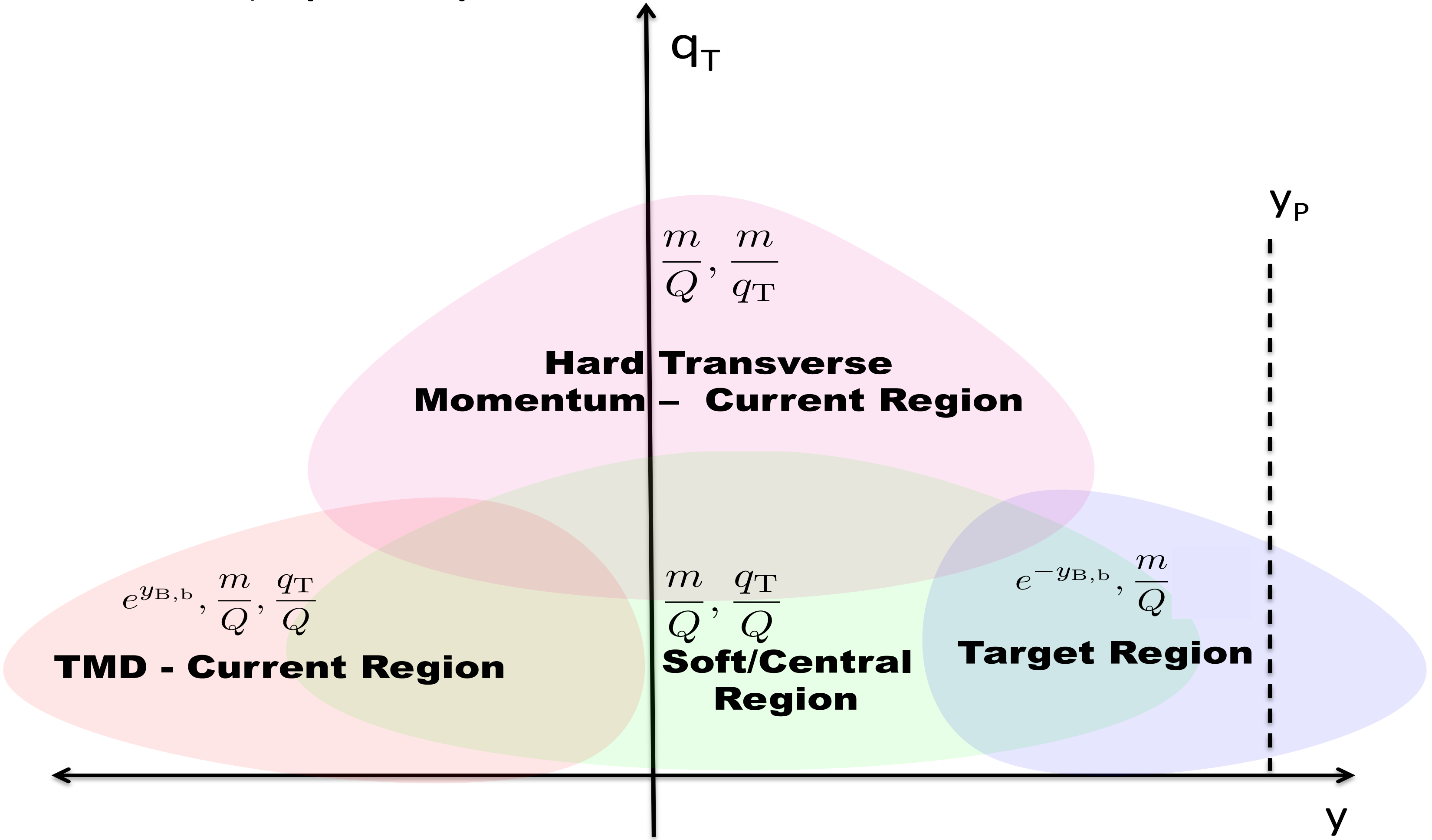
Ratio		Definition	
R_0	general hardness	$\max\left(\left\vert\frac{k_i^2}{Q^2}\right\vert, \left\vert\frac{k_f^2}{Q^2}\right\vert, \left\vert\frac{\delta k_T^2}{Q^2}\right\vert\right)$	Partonic description requires $R_0 << 1$.
R_1	collinearity	$\frac{P_h \cdot k_f}{P_h \cdot k_i}$	Small for current region, large for central and target region.
R_1'	target proximity	$\frac{P_h \cdot P}{Q^2}$	Small for target region.
R_2	transverse hardness	$\frac{\vert k^2\vert}{Q^2}$	Small for 2 → 1 process $\gamma^* q \to q'$
R_3	spectator virtuality	$\frac{\vert k_X^2\vert}{Q^2}$	Small for low order pQCD to be applicable. Large for high order pQCD to be applicable.
R_4	large transverse momentum	$\max\left(\left\vert\frac{k_i^2}{k^2}\right\vert, \left\vert\frac{k_f^2}{k^2}\right\vert, \left\vert\frac{\delta k_T^2}{k^2}\right\vert, \left\vert\frac{k_{iT}^2}{k^2}\right\vert\right)$	Small for collinear region.

Identifying Kinematic Regions in SIDIS

Region	R_0	R_1	R_1'	R_2	R_3	R_4
TMD	small	small	$\times$	small	$\times$	$\times$
matching	small	small	$\times$	small	$\times$	$\times$
collinear	small	small	$\times$	large	small (LO pQCD) large (HO pQCD)	small
target	small	large	small	$\times$	$\times$	$\times$
central	small	not small	not small	small	$\times$	$\times$

Identifying Kinematic Regions in SIDIS

Region indicators R_i depend on parton kinematics that we do not know and cannot measure.



How can we apply them to a phenomenological or experimental analysis?

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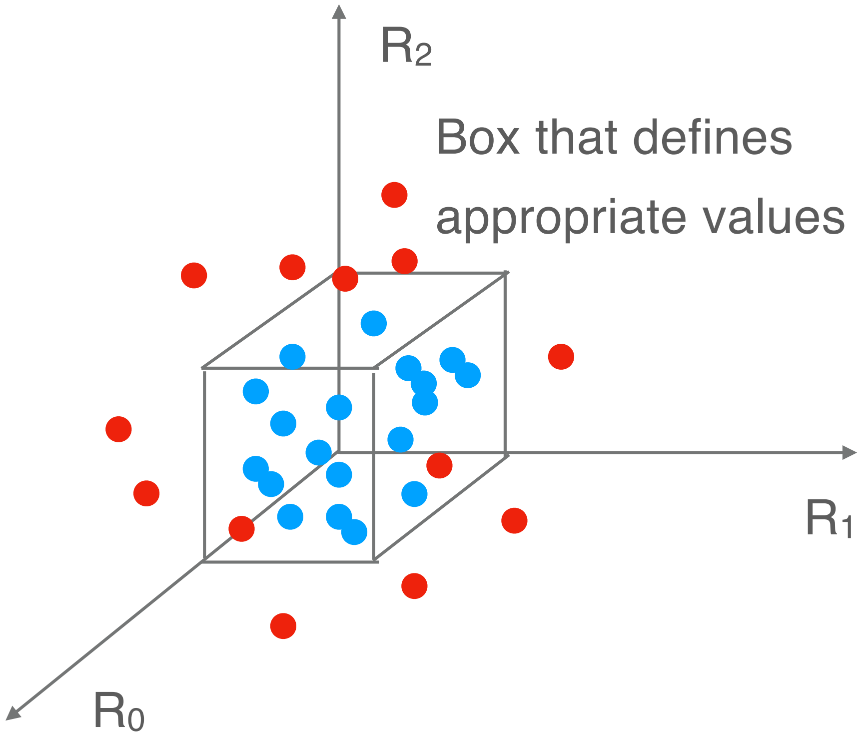
Affinity Tool

Sample kinematics bins for ratios based on Monte Carlo method



Box size Estimated, using existing TMD phenomenology for guidance.

Affinity = **# times in** / **(#times in** + **#times out**)

Affinity ranges from 0% to 100% and indicates affinity of a bin of a measurement to a particular kinematic region.

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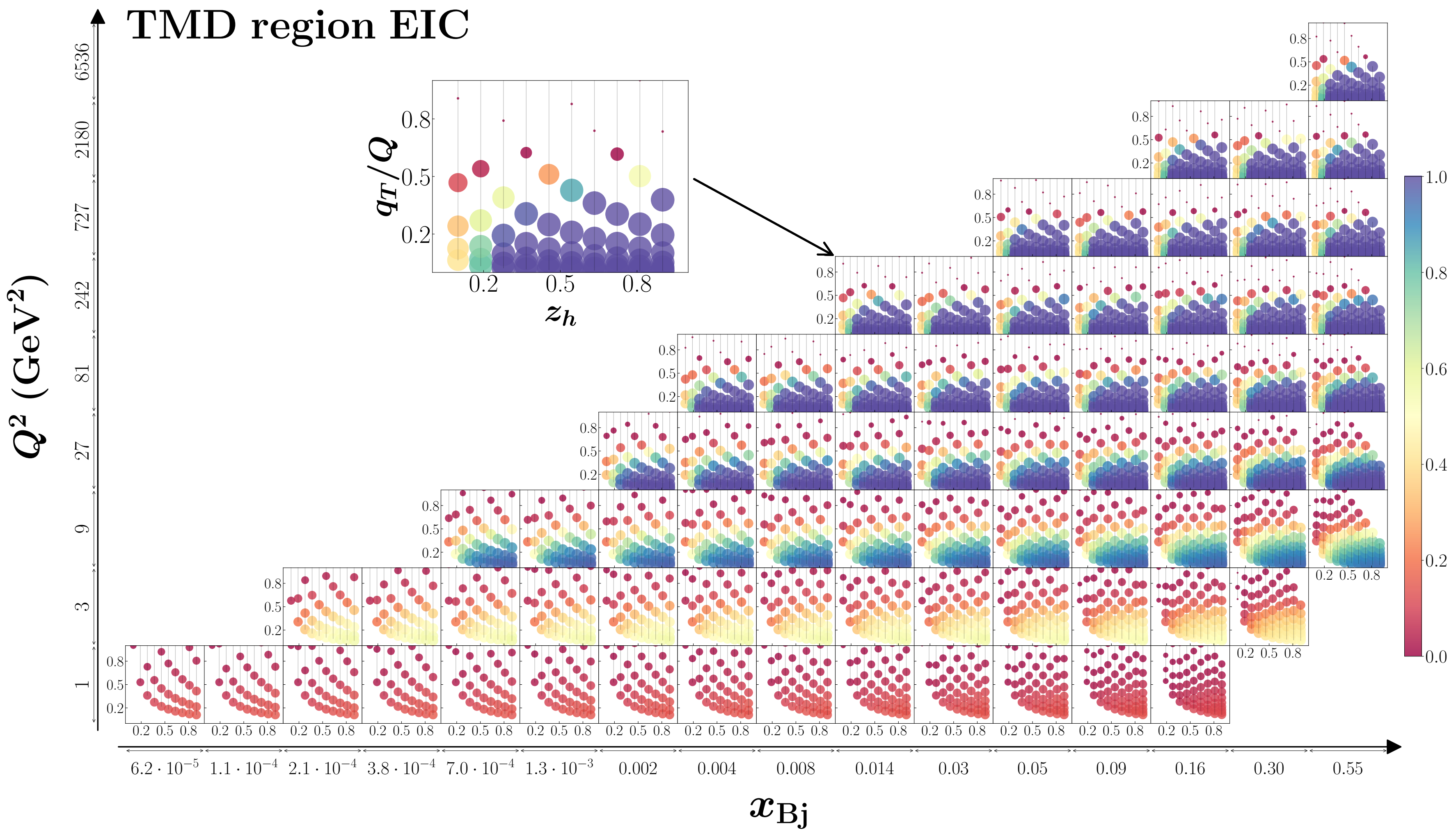
TMD region at EIC Kinematics

Try it out yourself: Interactive Affinity Tool



More details: New tool for kinematic regime estimation in SIDIS, *JHEP* 04 (2022) 084

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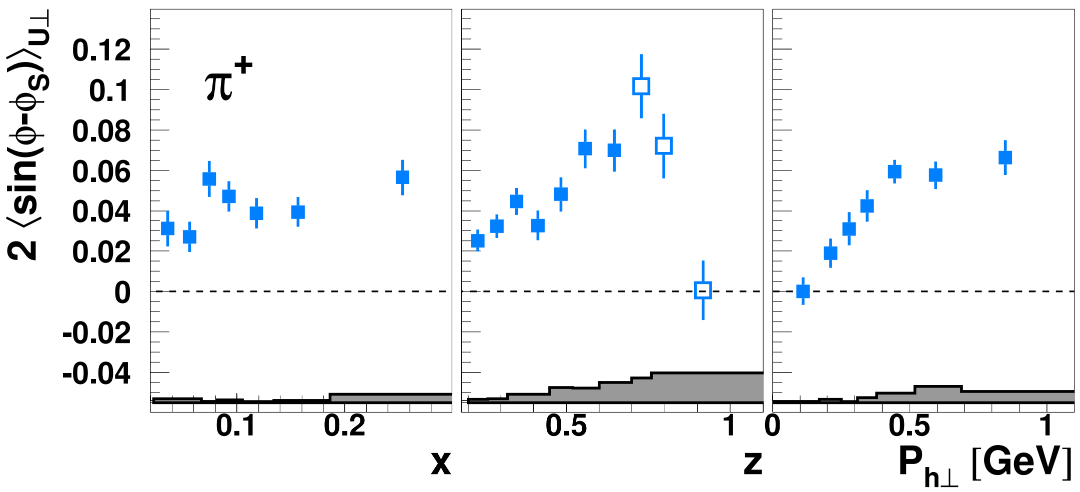
Tackling Some of the Most Challenging Scientific Problems

What are the challenges in extracting TMDs…

… and how can we address them?

Experimentalists measure signals for TMDs



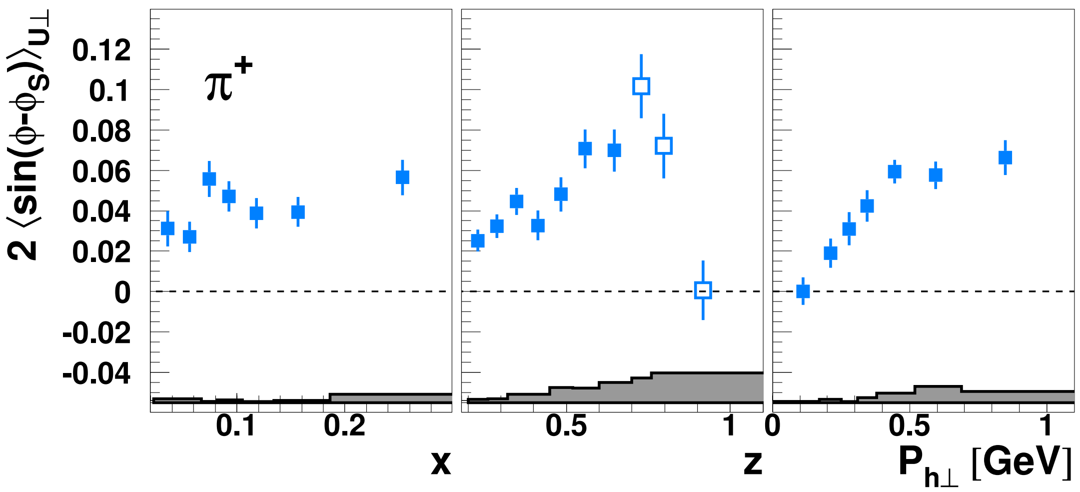
Experimentalists measure signals for TMDs
One Example: Pioneering TMD studies by HERMES

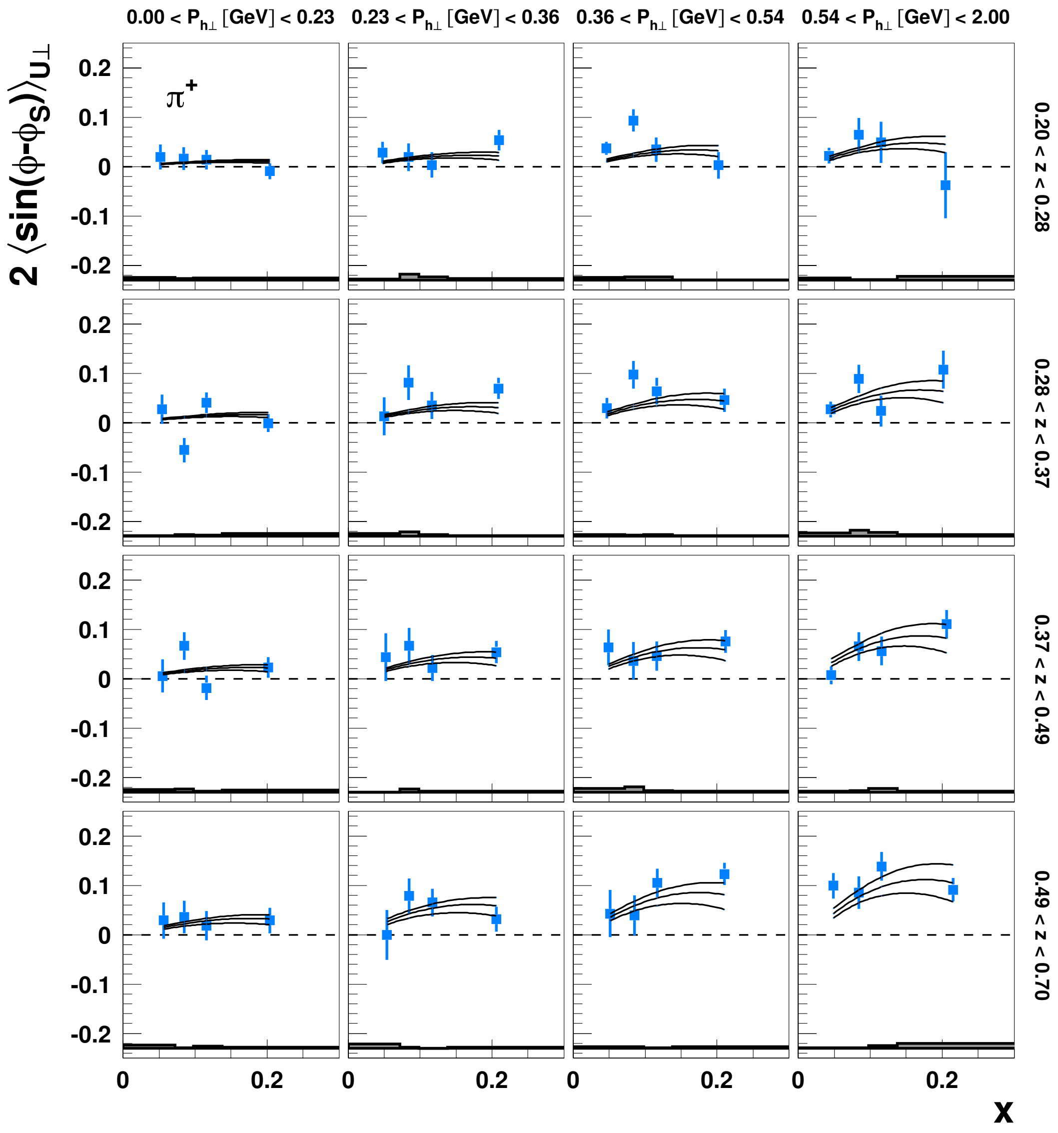
- SIDIS measurement of π^+
- Plot shows structure function related to Sivers effect
  - Allows extraction of Sivers TMD
- Information about 755k π^+ compressed in 24 data points

Theoreticians extract TMDs from these data points

- And many other data points in a global analysis
- They wait years for the data points to become available.
- HERMES example:
  - Data taking in 2002–2005
  - Publications in 2005
    - *Phys.Rev.Lett.* 94 (2005) 012002, 755 citations, only 2002 data
    - *Phys.Rev.Lett.* 103 (2009) 152002, 378 citations
    - *Phys.Lett.B* 693 (2010) 11-16, 240 citations
    - *JHEP* 12 (2020) 010, 24 citations

Multi-Dimensional Data Challenge





Fully differential approach with small bin-sizes

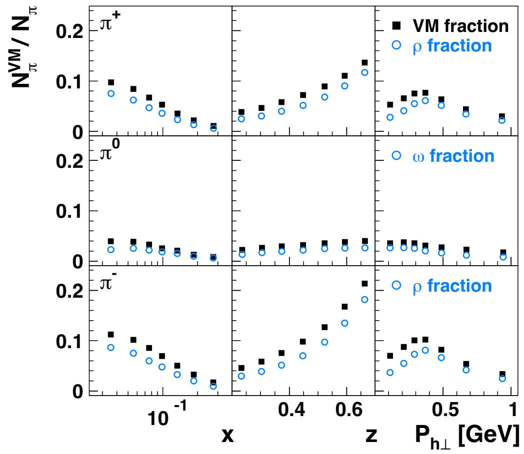
- minimizes the dominant contributions to the systematic uncertainty, and therefore maximizes the attainable experimental precision
- maximize information for QCD analysis

To advance this even further

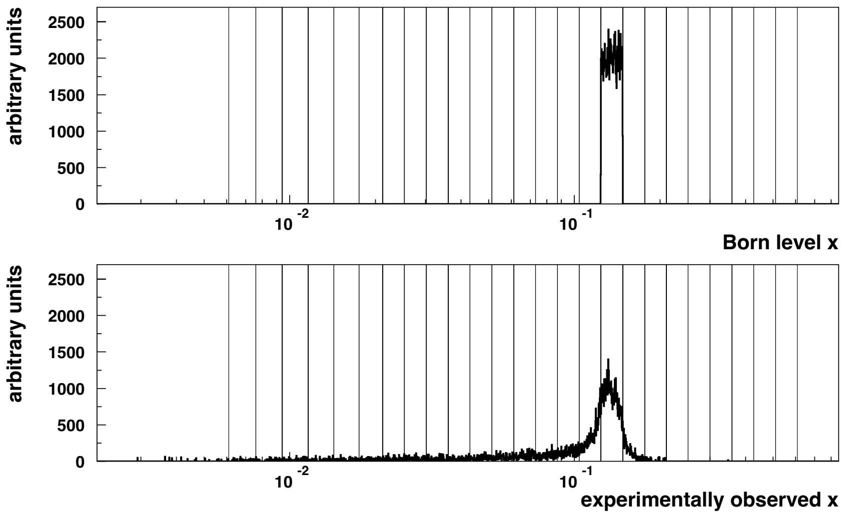
- Analysis on **event level**

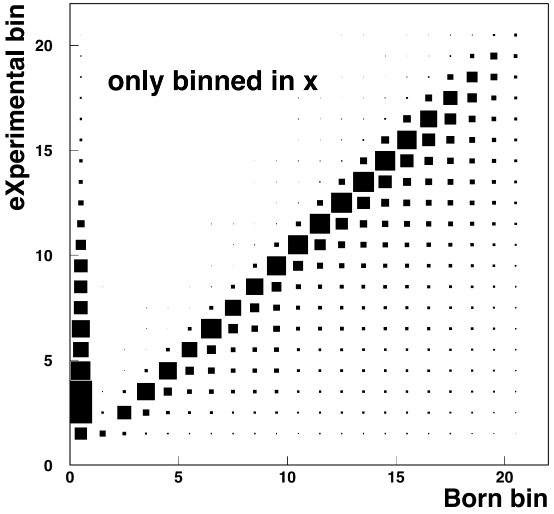
Joint Experimental-Theoretical Analysis

- Avoid mismatches between experimental-theoretical analysis
  - E.g.:
    - Some experimental analyses remove final-state hadrons originating from decay of diffractively produced vector-mesons.
    - However, these final-state hadrons are not removed in factorization proofs. Removing them in the experimental analysis would result in a mismatch between the experimental-theoretical analyses.



- Treat theoretical calculations and assumptions consistently
  - E.g.:
    - Treatment of QED radiative effects and detector smearing





- Correction via unfolding approach requires theoretical model for QED radiative effects.
- Irreversible. Limits re-use and re-interpretability of experimental analysis.
- **Solution**: Consistent treatment of QED effects in joint experimental-theoretical analysis.

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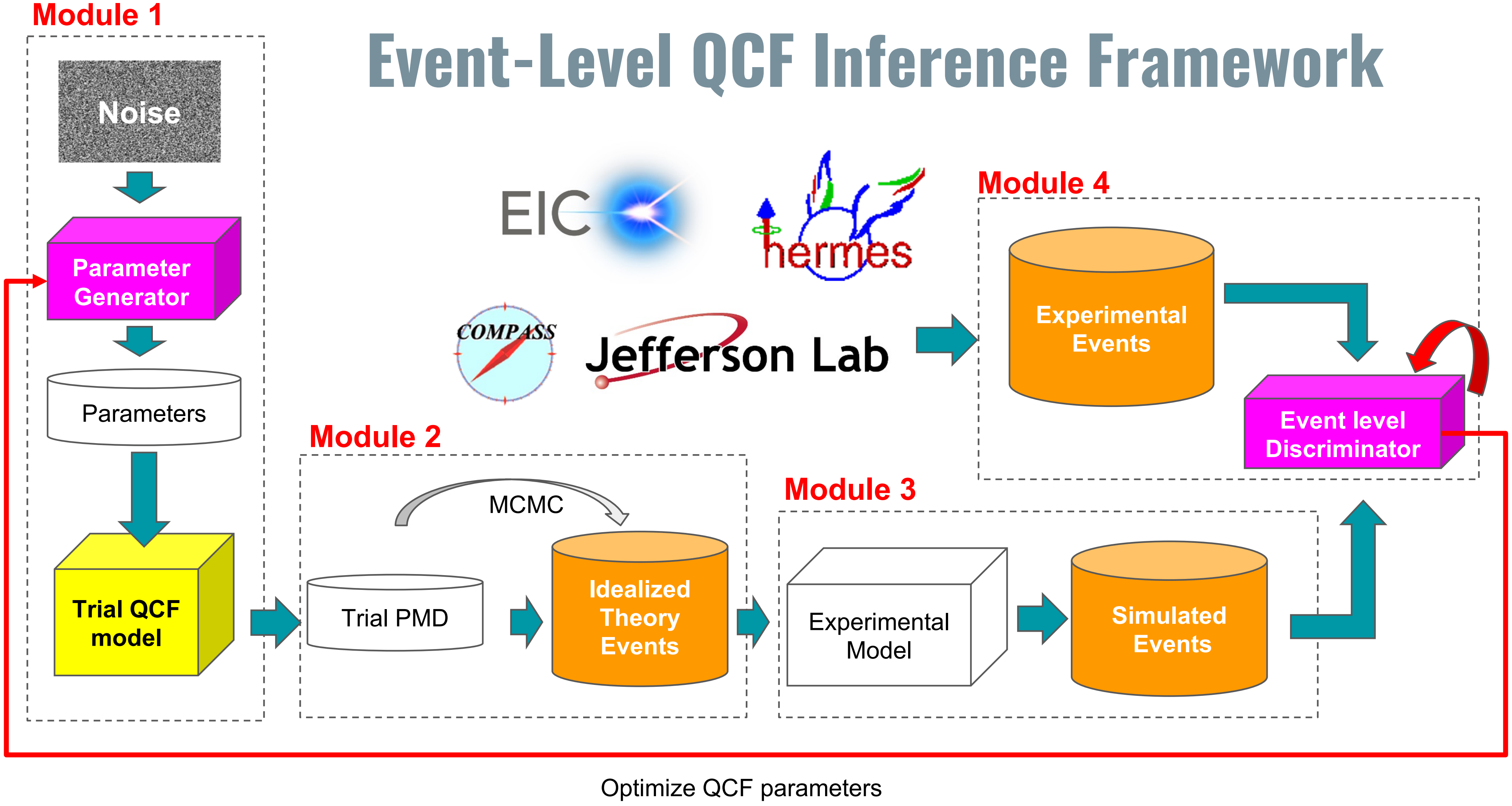
QuantOm: Femtoscale Imaging of Nuclei using Exascale Platforms

Funded via SciDAC (Scientific Discovery Through Advanced Computing)



How We Advance the Experimental-Theoretical Workflow

- **Developing a workflow on the event level**:
  - The extraction of PDFs, TMDs, and GPDs is a multidimensional data challenge. We analyze high statistics data sets with strong correlations in five or more kinematics and with various final-state particles. Access to the data on event level allows theoreticians to studying these correlations directly.

- **Developing a joint experimental-theoretical workflow**:
  - Extracting PDFs, TMDs, or GPDs directly from the experiment allows experimentalists and theoreticians to work closely together. This not only removes the delay in providing the experimental measurement but truly enables joint experimental-theoretical wok.

- **Developing a HPC workflow**:
  - The extremely parallelized architecture allows to study the strong correlations in the data in an unprecedented manner, while maximizing the experimental precision at the same time.
  - The accelerated hardware of the new HPC systems is ideal for AI/ML, allowing us to do the parallelized workflow at the event level in near real-time.
    - EIC will produce analysis-ready data in near real-time using streaming readout and AI/ML.

Event Generators for the EIC

arXiv:2203.11110

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Event Generators for High-Energy Physics Experiments

We provide an overview of the status of Monte-Carlo event generators for high-energy particle physics. Guided by the experimental needs and requirements, we highlight areas of active development, and opportunities for future improvements. Particular emphasis is given to physics models and algorithms that are employed across a variety of experiments. These common themes in event generator development lead to a more comprehensive understanding of physics at the highest energies and intensities, and allow models to be tested against a wealth of data that have been accumulated over the past decades. A cohesive approach to event generator development will allow these models to be further improved and systematic uncertainties to be reduced, directly contributing to future experimental success. Event generators are part of a much larger ecosystem of computational tools. They typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models. Making both these data, and the analyses with which they have been obtained accessible to future users is an essential aspect of open science and data preservation. It ensures the consistency of physics models across a variety of experiments.

CP3-22-12 DESY-22-042 FERMILAB-PUB-22-116-SCD-T IPPP/21/51
JLAB-PHY-22-3576 KA-TP-04-2022 LA-UR-22-22126 LU-TP-22-12
MCNET-22-04 OUTP-22-03P P3H-22-024 PITT-PACC 2207 UCI-TR-2022-02

arXiv:2203.11110v1 [hep-ph] 21 Mar 2022

Monte Carlo Simulation of

- electron-proton (ep) collisions,
- electron-ion (eA) collisions, both light and heavy ions,
- including higher order QED and QCD effects,
- including a plethora of spin-dependent effects.

Common challenges, e.g. with HL-LHC: **High-precision QCD measurements require high-precision simulations**.

Unique challenges MCEGs for electron-**ion** collisions and **spin-dependent** measurements, including novel QCD phenomena (e.g., GPDs or TMDs).
Will result in deeper understanding of QCD factorization and evolution, QED radiative corrections, hadronization models etc.

MC4EIC 2022

A lot of relevant information about MCEGs for EIC at Resummation, Evolution, Factorization 2022

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The EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that is relevant.

TMDs Imaging quarks and gluons within nucleons and nuclei

- **Electron-Ion Collider** Precision TMD studies for sea quarks and gluons.

The Foundation of the Next-Generation TMD Studies in light of the upcoming EIC:

- **New affinity tool** for kinematic regime estimation in SIDIS.
- **QuantOm**: Joint Experimental-Theoretical Analysis of TMDs.
- **The 12 GeV Science Program at Jefferson Lab**: Precision TMD studies for valence quarks.