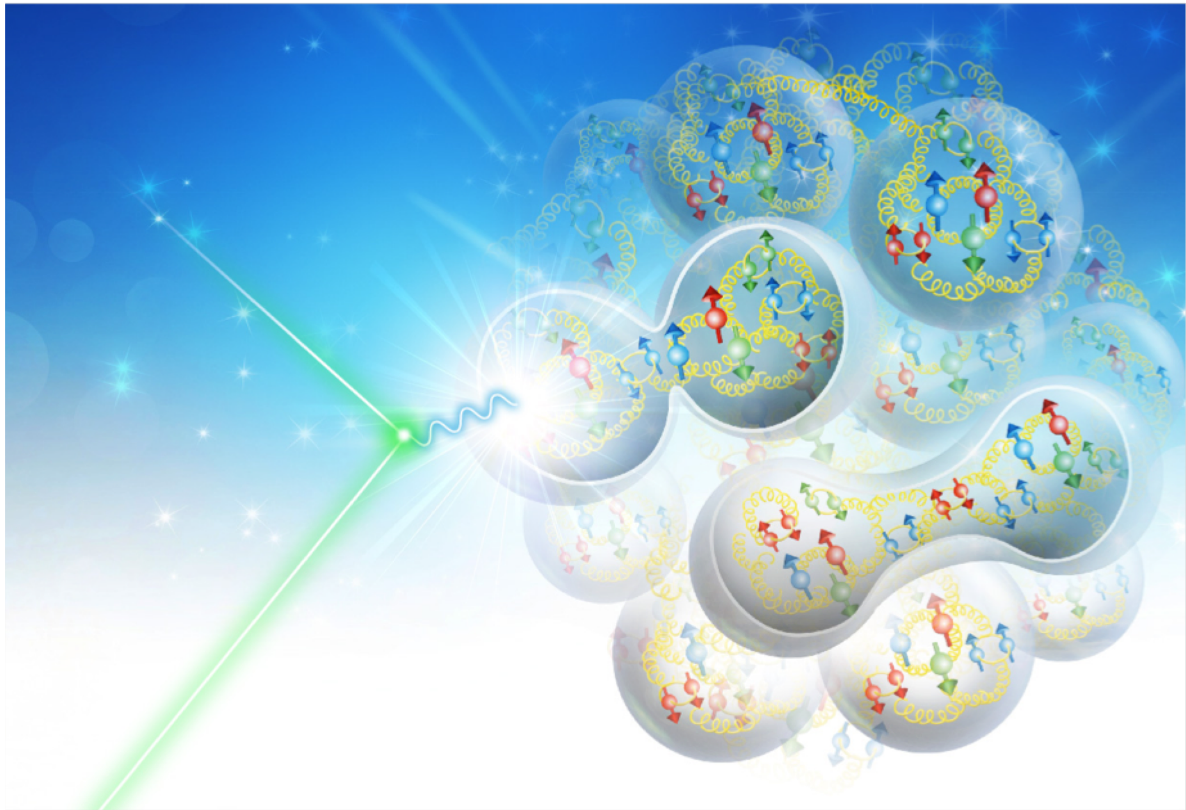
The Foundation of the Next-Generation TMD Studies

Imaging quarks and gluons in nuclear matter

EIC²

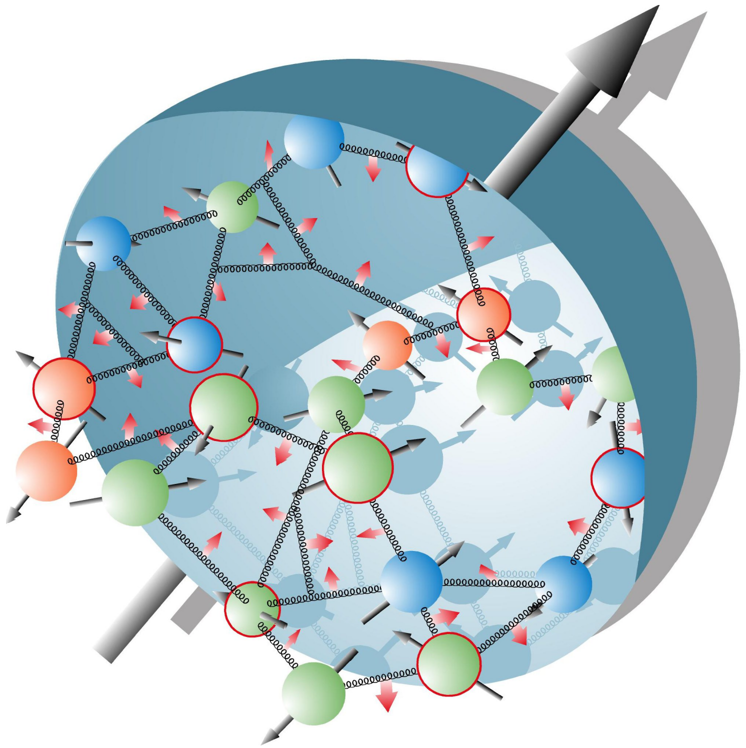
EIC Center at Jefferson Lab

Markus Diefenthaler

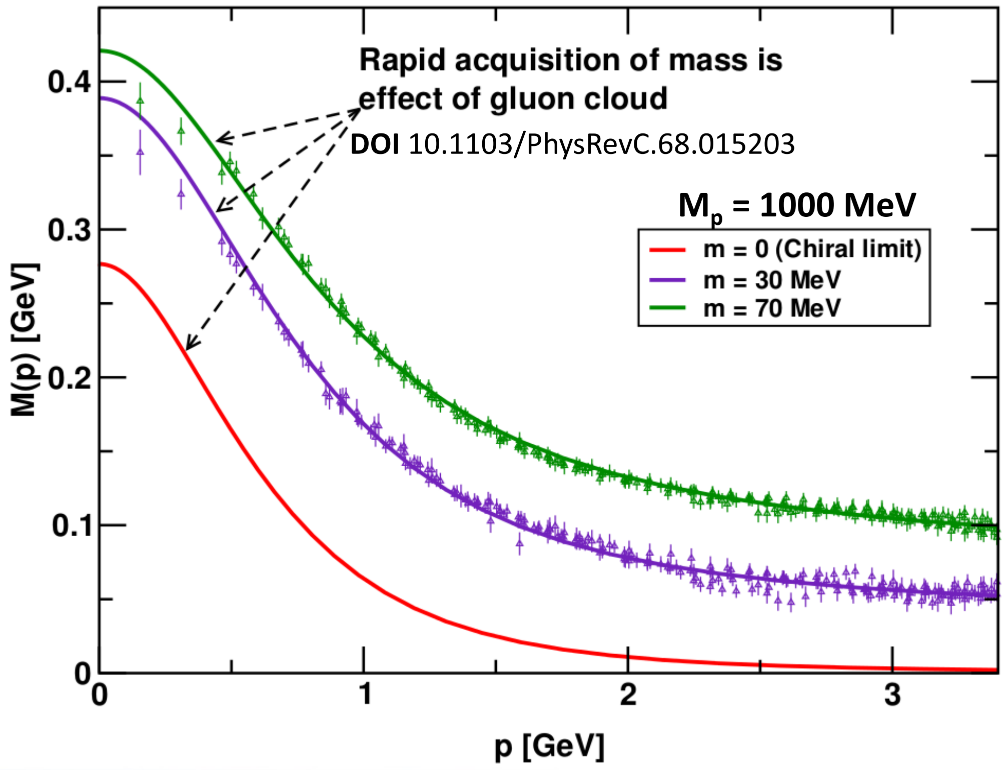


The dynamical nature of nuclear matter

Nuclear Matter Interactions and structures are inextricably mixed up



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



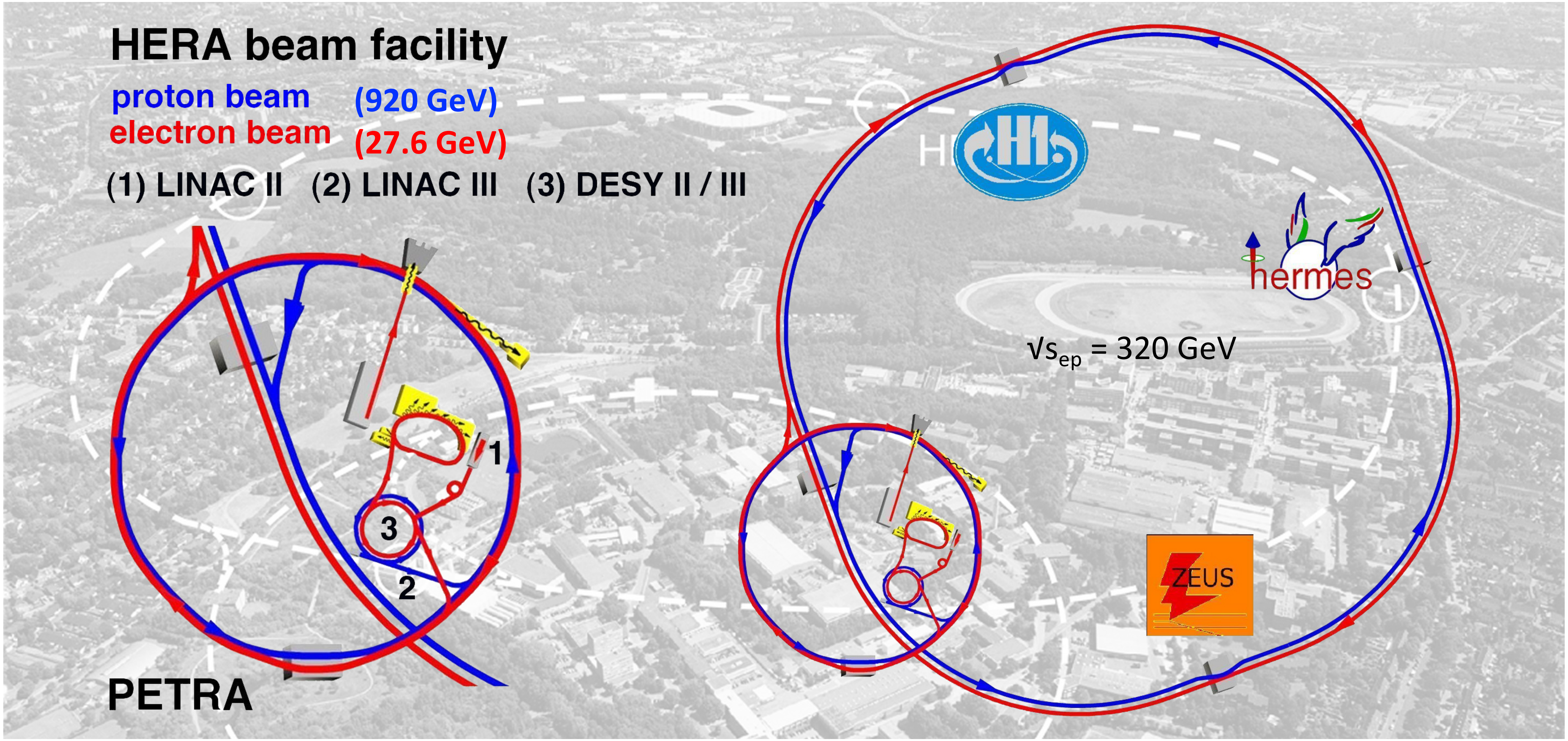
Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

Pioneering measurements

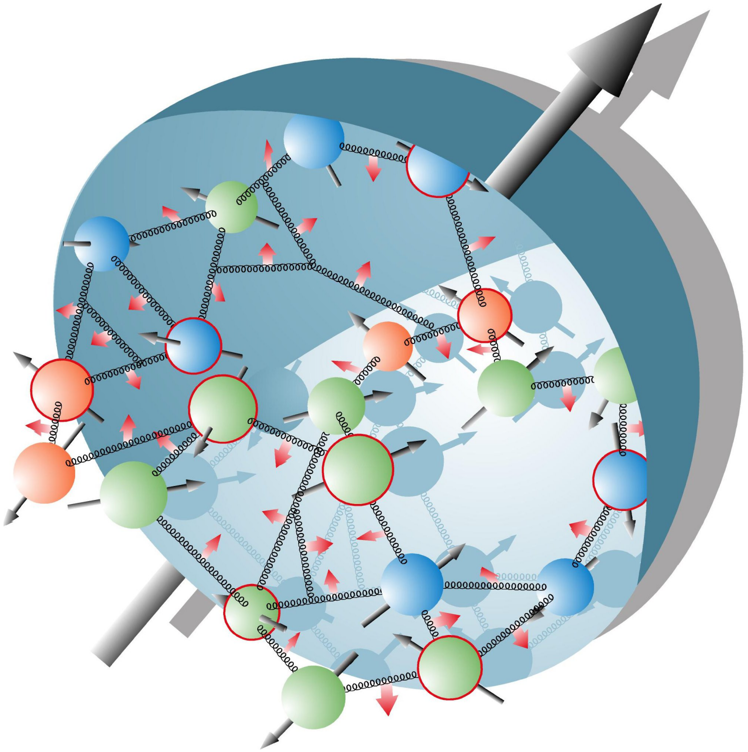
The first Electron-Ion Collider

HERA: The first Electron-Ion Collider

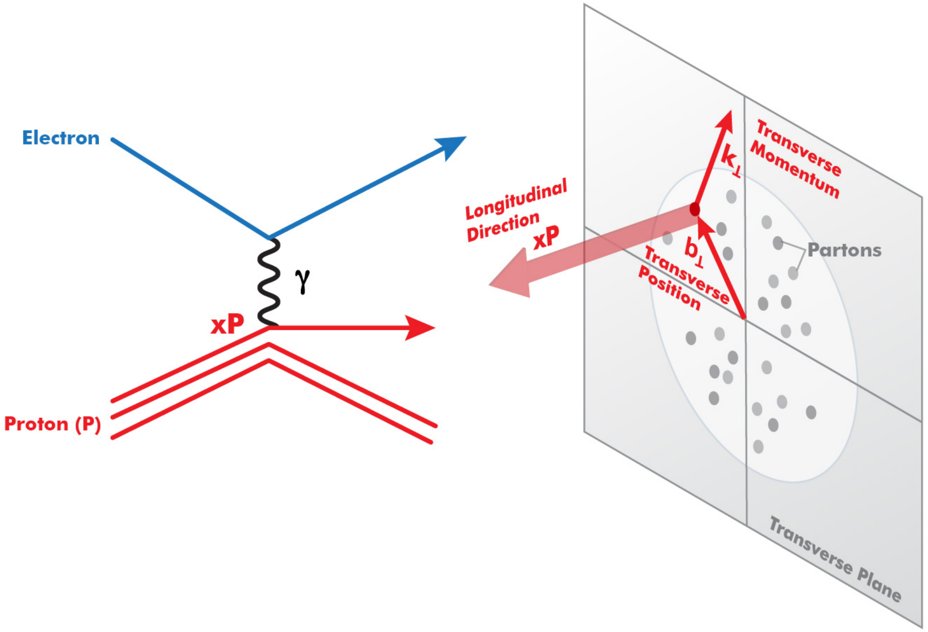


Polarized DIS measurements

hermes Polarization



Novel QCD phenomena



3D imaging in space and momentum

longitudinal structure (PDF)

+ transverse position Information (GPDs)

+ transverse momentum information (TMDs)

order of a few hundred MeV

Transverse-momentum dependent PDFs

Dirac decomposition of the quark-quark correlator

$$\frac{1}{2}\mathrm{Tr}\left[\left(\gamma^{+}+\lambda\gamma^{+}\gamma_5\right)\Phi\left(x,\mathbf{p}_T\right)\right]=\frac{1}{2}\Big[f_1^q\left(x,\mathbf{p}_T^2\right)+S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$$
$$+\lambda\Lambda\, g_1^q\left(x,\mathbf{p}_T^2\right)+\lambda S_T^i p_T^i\frac{1}{M}g_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)\Big],$$

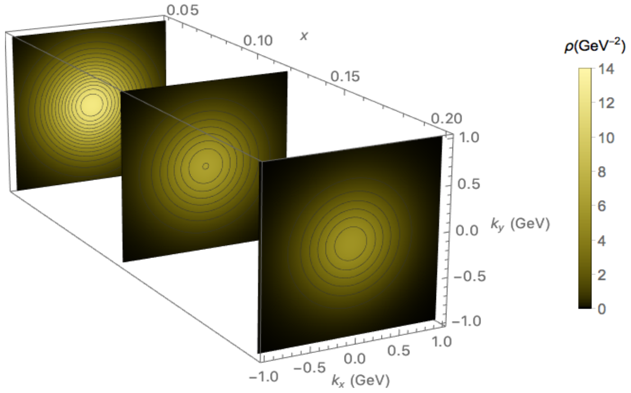
$$\frac{1}{2}\mathrm{Tr}\left[\left(\gamma^{+}-s_T^j i\sigma^{+j}\gamma_5\right)\Phi\left(x,\mathbf{p}_T\right)\right]=\frac{1}{2}\Big[f_1^q\left(x,\mathbf{p}_T^2\right)+S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$$
$$+s_T^i\varepsilon^{ij}p_T^j\frac{1}{M}h_1^{\perp,q}\left(x,\mathbf{p}_T^2\right)+s_T^i S_T^i\,h_1^q\left(x,\mathbf{p}_T^2\right)$$
$$+s_T^i\left(2p_T^ip_T^j-\mathbf{p}_T^2\delta^{ij}\right)S_T^j\frac{1}{2M^2}h_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$$
$$+\Lambda s_T^i p_T^i\frac{1}{M}h_{1L}^{\perp,q}\left(x,\mathbf{p}_T^2\right)\Big].$$

TMD	probabilistic interpretation	chiral properties	naive-T properties
$f_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$	–	chiral-even	naive-T-odd
$h_1^{\perp,q}(x,\mathbf{p}_T^2)$	–	chiral-odd	naive-T-odd
$h_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$	–	chiral-odd	naive-T-even
$h_{1L}^{\perp,q}(x,\mathbf{p}_T^2)$	–	chiral-odd	naive-T-even
$g_{1T}^{\perp,q}(x,\mathbf{p}_T^2)$	–	chiral-even	naive-T-even

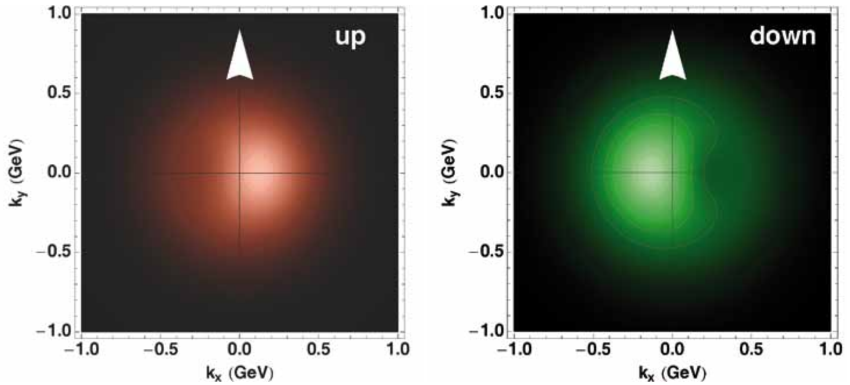
legend
- transverse and longitudinal nucleon polarisation
- transverse and longitudinal quark polarisation

Unpolarized nucleon

JHEP 1706 (2017) 081



Transversely polarized nucleon



Single-spin asymmetries (SSA) at high energies

E704 at Fermilab

$$p^{\Uparrow} p \rightarrow hX$$

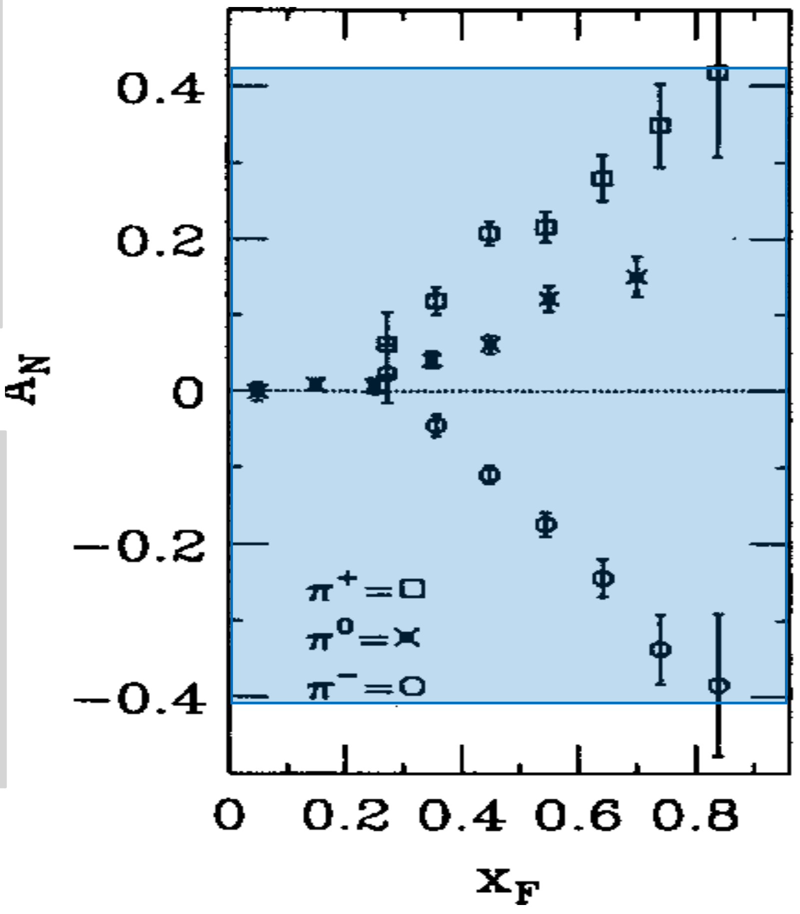
$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

QCD prediction

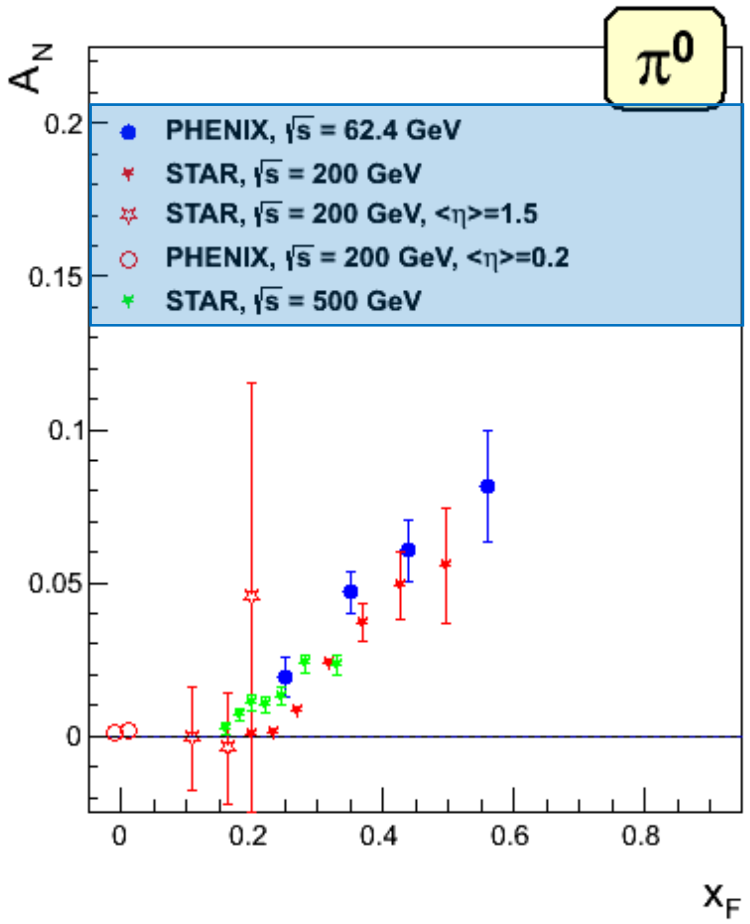
$$A_N \propto \alpha_s m_q / P_T \rightarrow 0$$

Kane, Pumplin, Repko [KPR78]

E704 SSA at √s ≈ 20 GeV



Confirmed at √s up to 500 GeV



SSA at HERMES

SSA in QCD

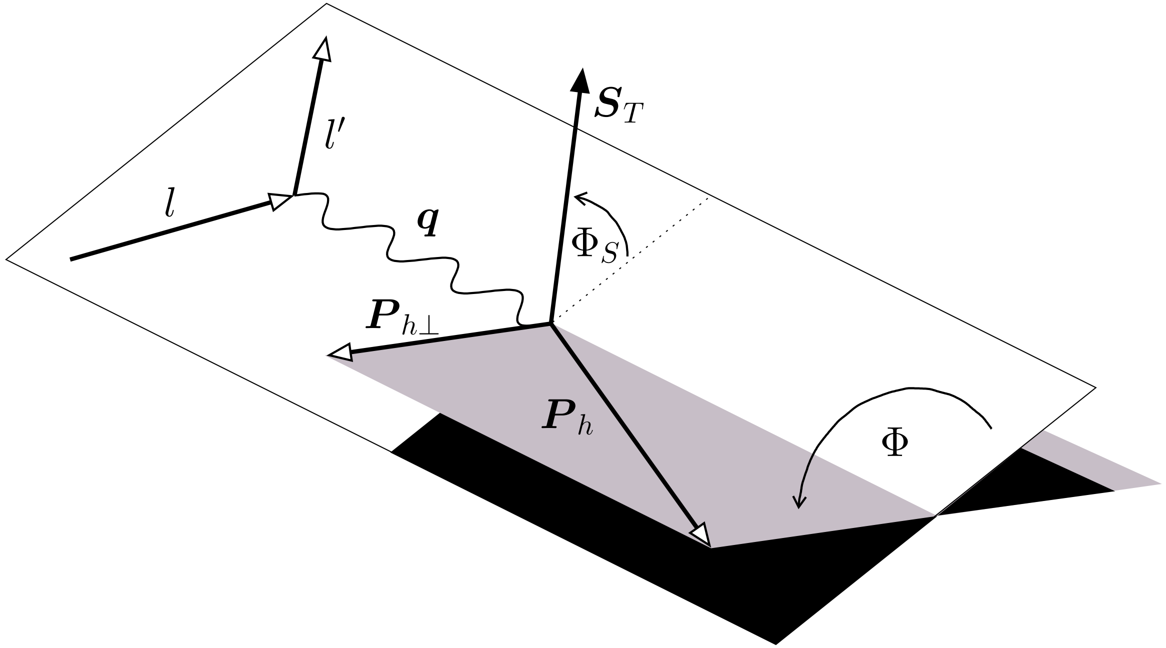
- spin-orbit correlations

$$\mathbf{S} \cdot (\mathbf{p}_1 \times \mathbf{p}_2) \qquad \textbf{E704} \quad \vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$$

- **Brodsky, Hwang, Schmidt [BHS02]** caused by the interference of scattering amplitudes with different complex phases coupling to the same final state
- **Transverse SSA** related to the interference of scattering amplitudes with different hadron helicities:
  - **[KPR78]** suppressed in hard scattering processes
  - **[BHS02]** caused by initial- or final-state interactions
- **naive-*T*-odd** function with the property to induce SSA

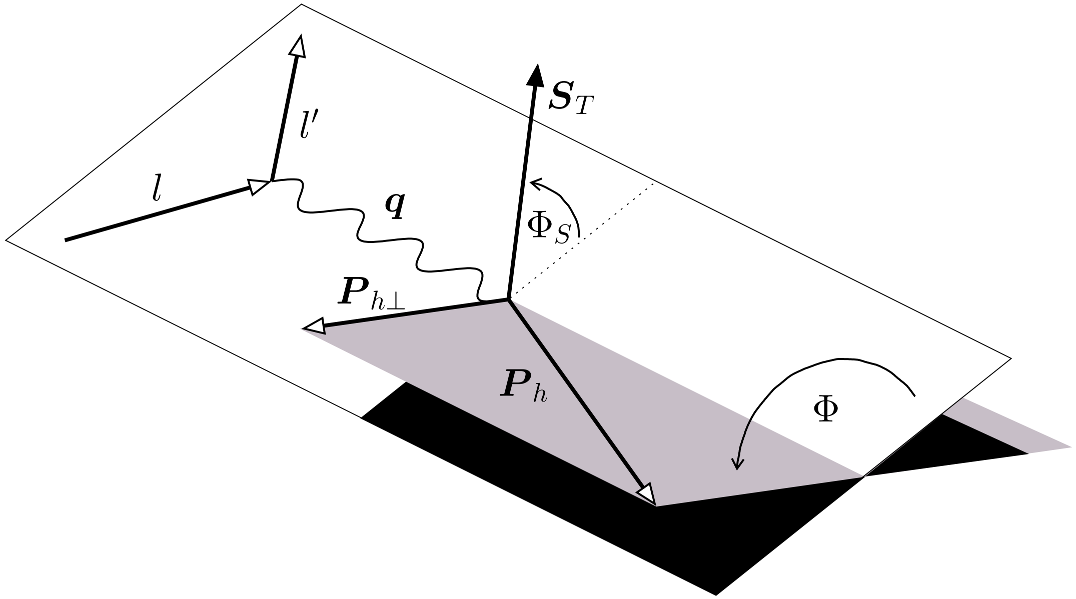
TSSA at HERMES

- two naive-*T*-odd functions at leading twist:
  - Sivers TMD: **Sivers effect** $\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{P}_h)$
  - Collins FF: **Collins effect** $\mathbf{s}_q \cdot (\mathbf{p}_q \times \mathbf{P}_h)$



Jefferson Lab

Semi-inclusive deep-inelastic scattering (SIDIS)



SIDIS

Hadron h is detected
in **coincidence** with the scattered lepton l'

Observable

SIDIS cross section

Factorization theorem (perturbative QCD)

Distribution functions (PDF, TMD PDF) empirical description of non-perturbative structure (confinement)

Perturbative part Cross section for elementary photon-quark interaction
Calculable (asymptotic freedom)

Fragmentation functions (FF, TMD FF) empirical description of non-perturbative structure (hadronization)

Signals for TMD PDFs and TMD FFs

Differential cross section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} =$$

Cross section decomposition in terms of structure functions

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \left[F_{UU,T}+\varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right]$$

Sivers effect

$$+ \quad S_T \left[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)\right.$$

Collins effect

$$+\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)}$$

$$\left.+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\right]$$

Factorized results in terms of TMD PDFs and TMD FFs

at tree-level and twist-2 and twist-3 accuracy

Assuming one-photon exchange, current fragmentation only, TMD factorization hold, small transverse momenta, Gaussian Ansatz valid

Sivers TMD and spin-independent FF

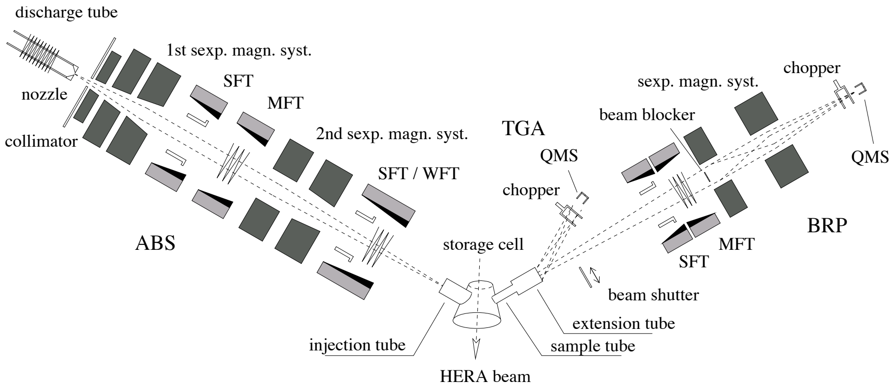
$$F_{UT,T}^{\sin(\phi-\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

Transversity PDF and Collins FF

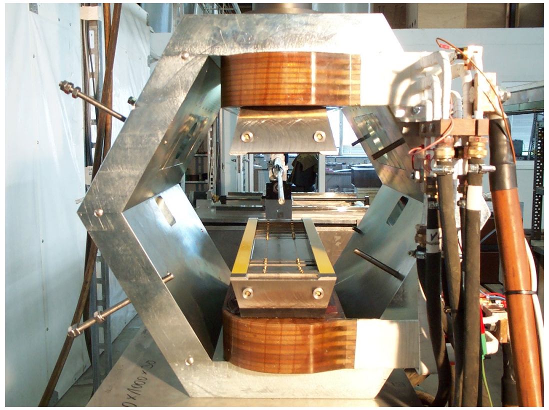
$$F_{UT}^{\sin(\phi+\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

HERMES experiment

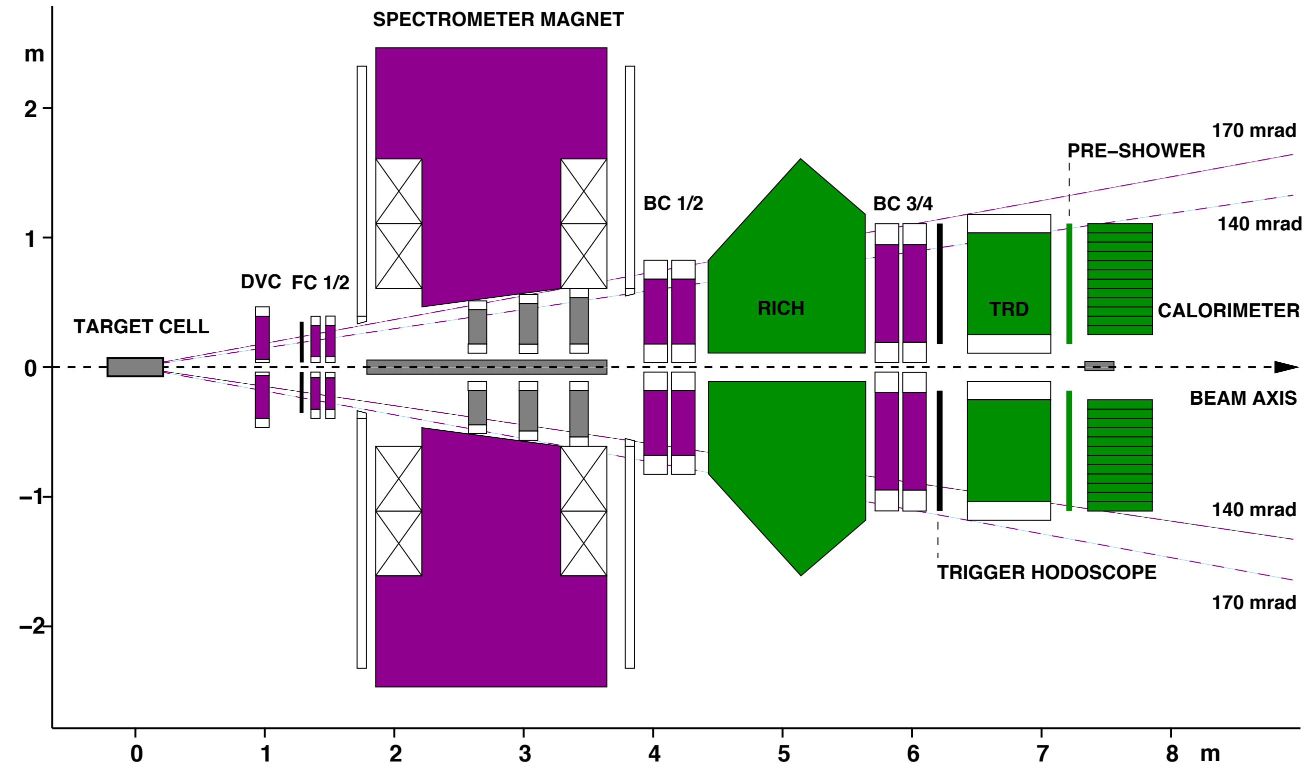
Internal gas target



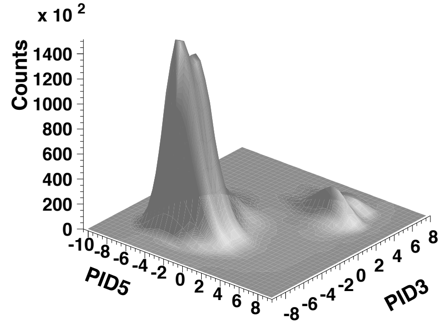
Transverse target magnet

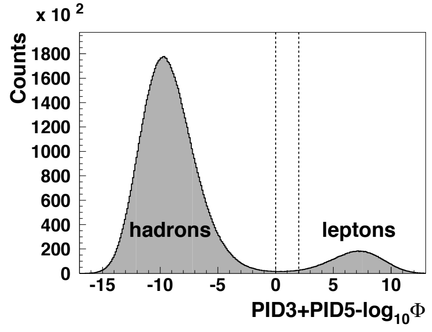


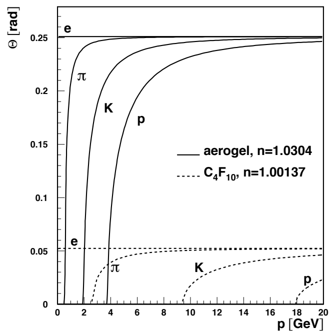
Spectrometer



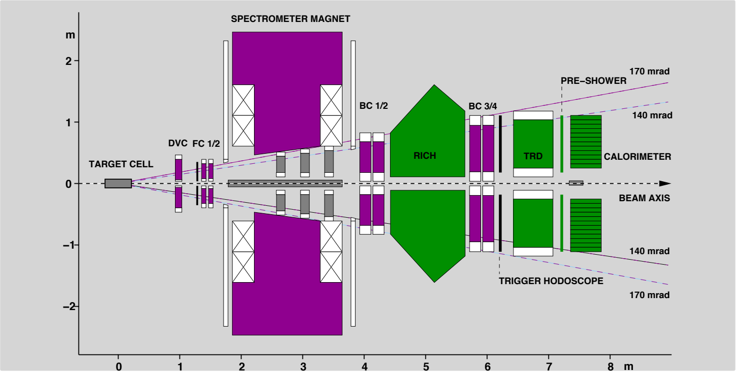
PID

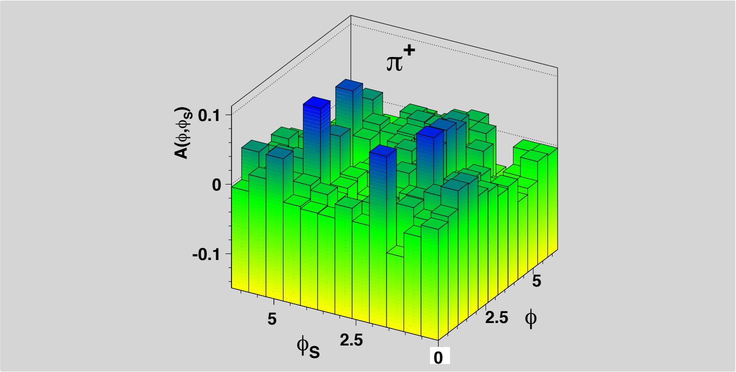






Hermes measurement of TSSA





$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \varepsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+\ S_T\ \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \varepsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \varepsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

Measurement of SIDIS

- **transversely polarized proton target**
- detect π-mesons and charged K-mesons in coincidence with scattered lepton in:

$$0.023 < x < 0.4, \quad 0.2 < z < 0.7, \quad 0.0\,\mathtt{GeV} < |\mathbf{P}_{h\perp}| < 2.0\,\mathtt{GeV}$$

Measurement of SSA

- HERMES was designed to measure cross section asymmetries not absolute cross sections

$$A_{\mathrm{U}\perp}^h(\phi,\phi_S) = \frac{1}{|S_\perp|}\frac{L_\Downarrow N_\Uparrow^h(\phi,\phi_S) - L_\Uparrow N_\Downarrow^h(\phi,\phi_S)}{L_\Downarrow N_\Uparrow^h(\phi,\phi_S) + L_\Uparrow N_\Downarrow^h(\phi,\phi_S)}$$

Fourier decomposition of SSA

$$\mathscr{L}(2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{U}\perp}^h) = \prod_{n=1}^{N^h} P(x_n, Q_n^2, z_n, P_{h\perp,n}, \phi_n, \phi_{S,n}; 2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{U}\perp}^h)$$

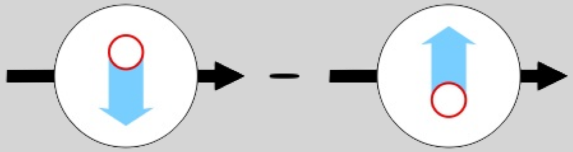
HERMES results on Sivers effect

PRL103 (2009) 152002

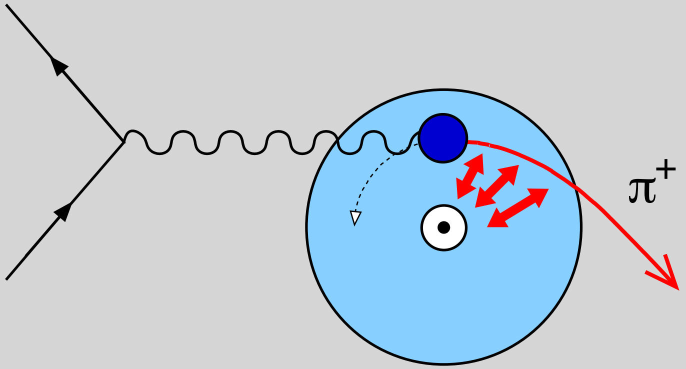
SSA amplitude

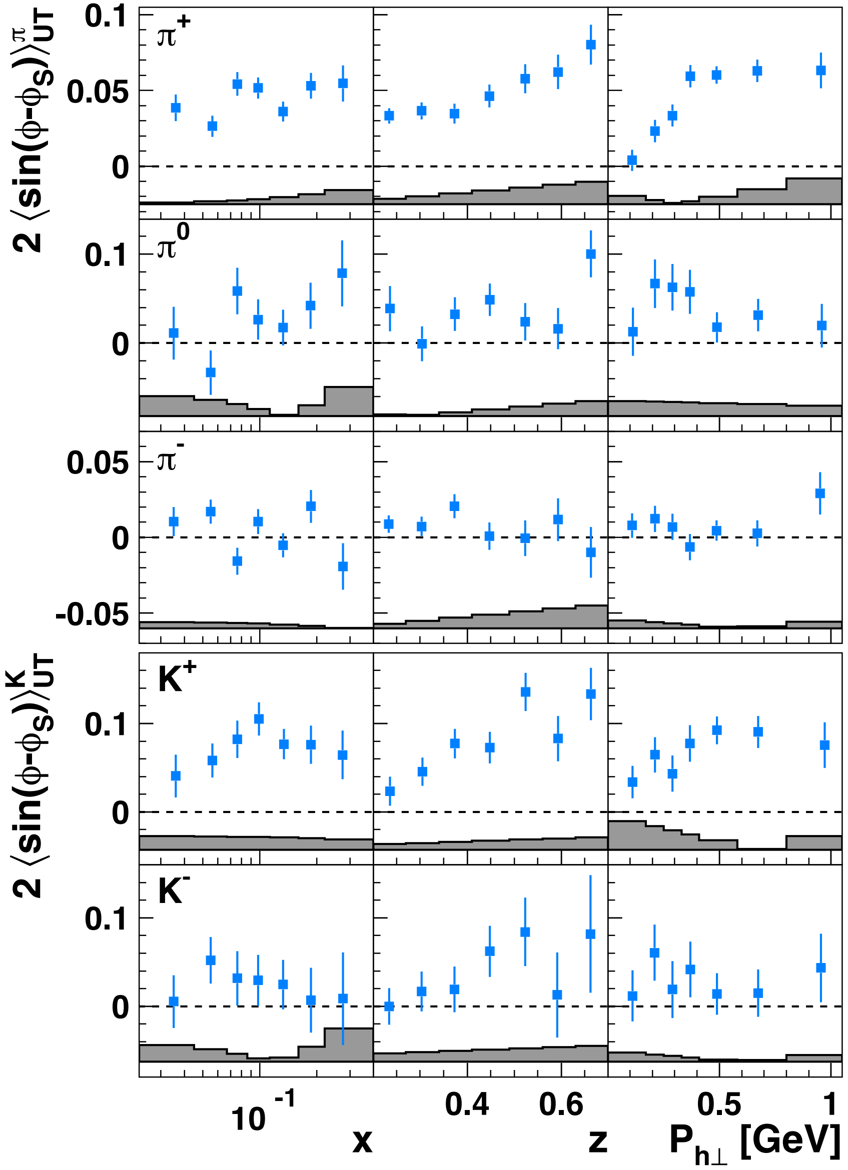
$$2\left\langle \sin\left(\phi-\phi_S\right)\right\rangle_{\mathrm{UT}}^{h} = -\frac{\mathscr{C}\left[\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_{1\mathrm{T}}^{\perp,q}\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}{\mathscr{C}\left[f_1^q\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}$$

Sivers TMD



Semi-classical picture



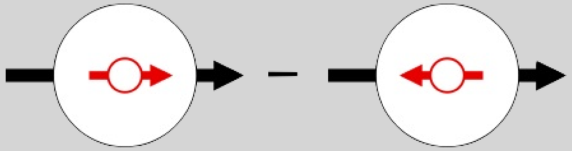


JHEP 0806 (2008) 017

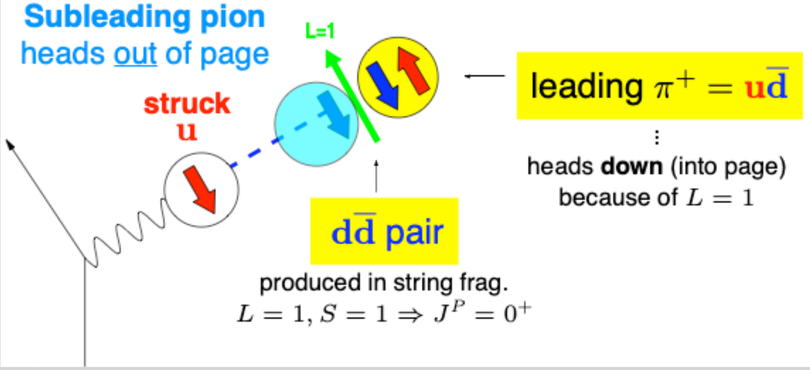
SSA amplitude

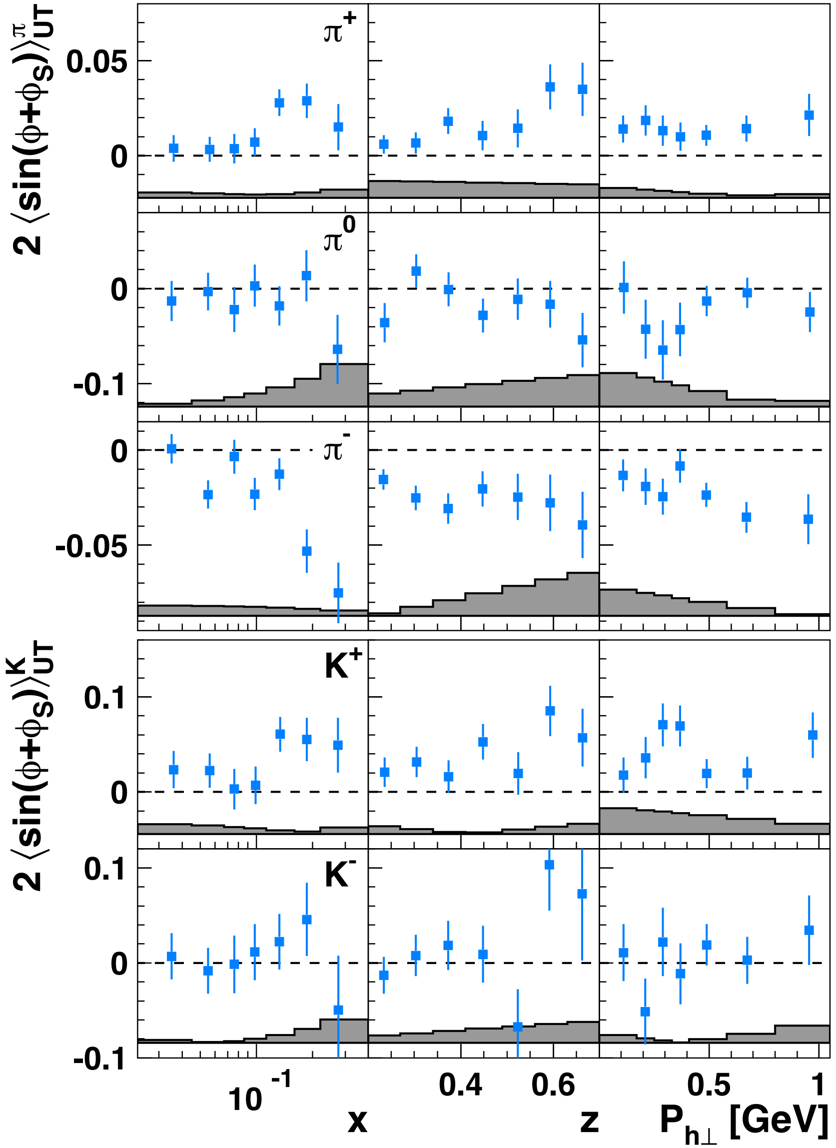
$$2\langle\sin(\phi+\phi_S)\rangle_{UT}^{h} = \frac{\mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h} h_1^q\left(x,\mathbf{p}_T^2\right) H_1^{\perp,q}\left(z,z^2\mathbf{k}_T^2\right)\right]}{\mathscr{C}\left[f_1^q\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}$$

Transversity PDF

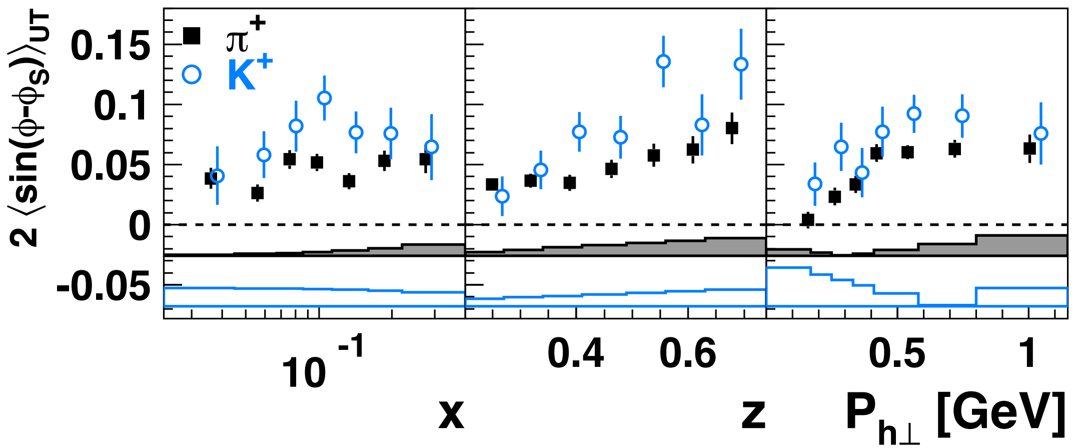


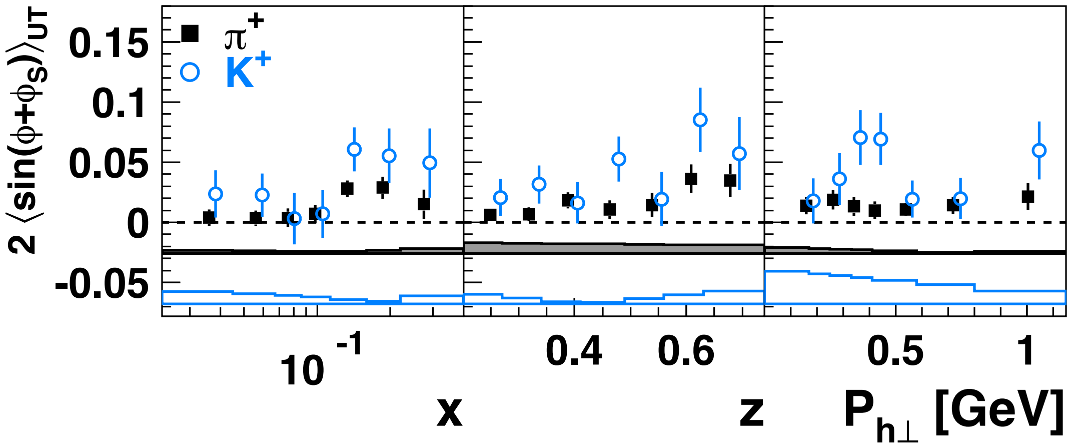
Lund model and $^3P_0$ hypothesis

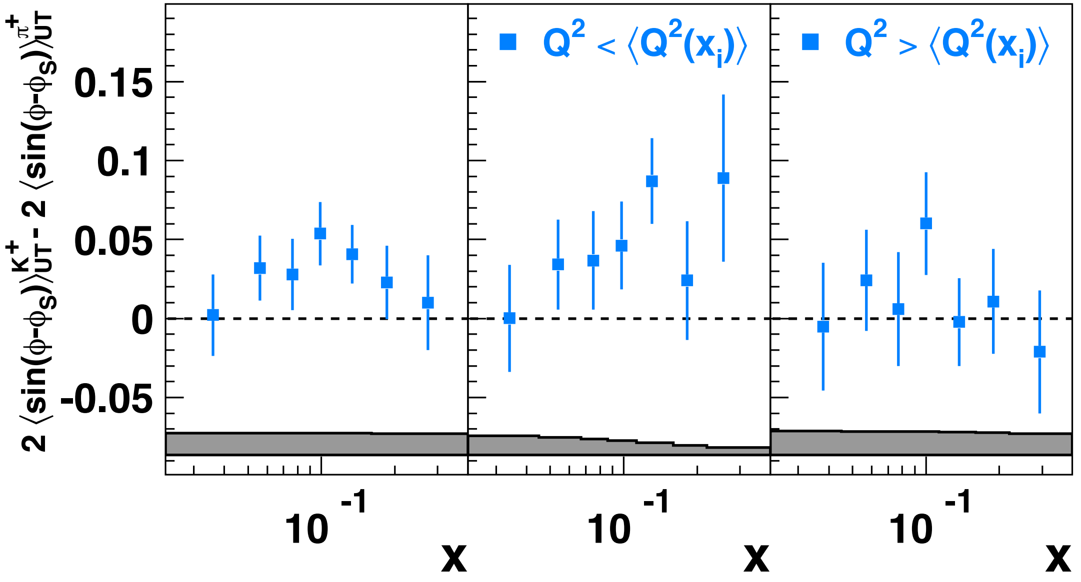


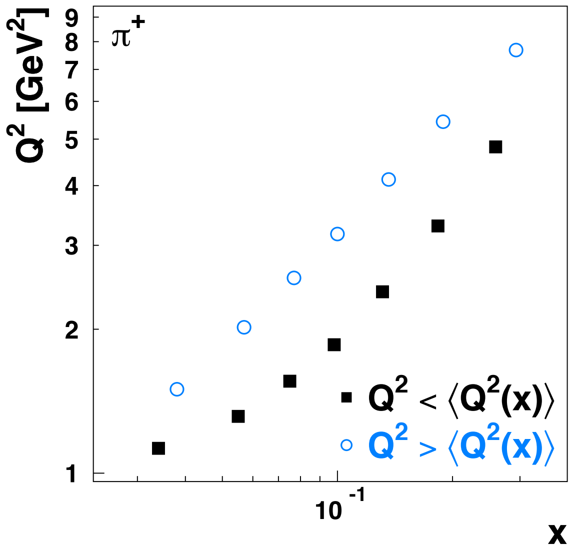


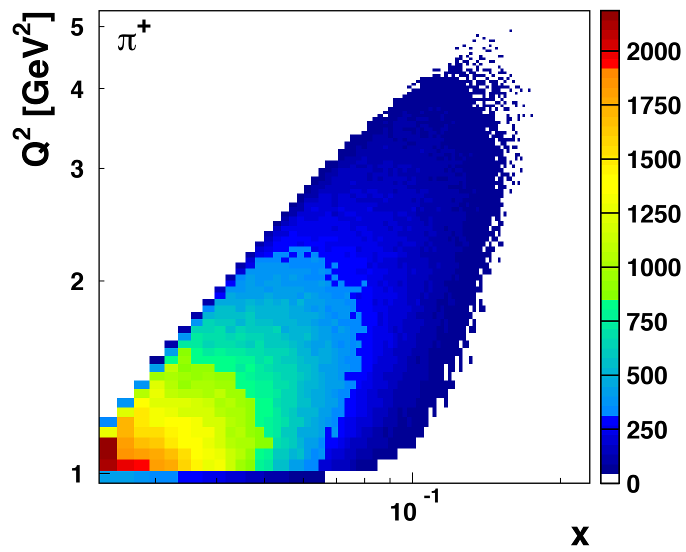
The picture of u-quark dominance and the role of higher twist



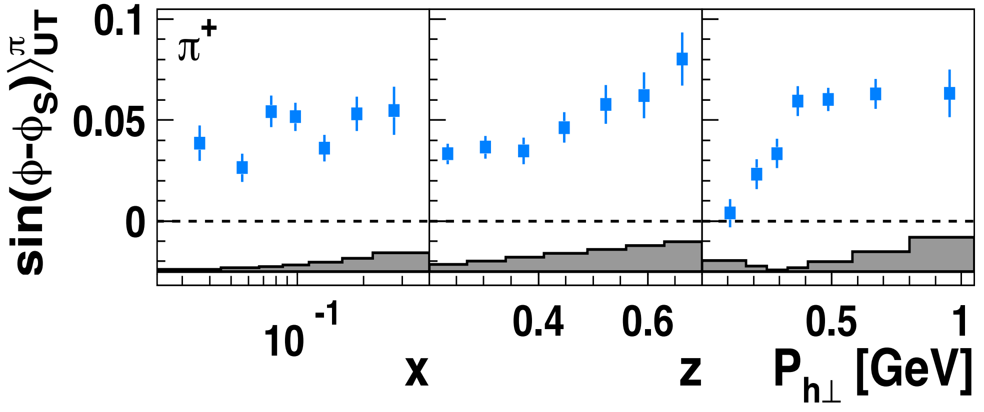


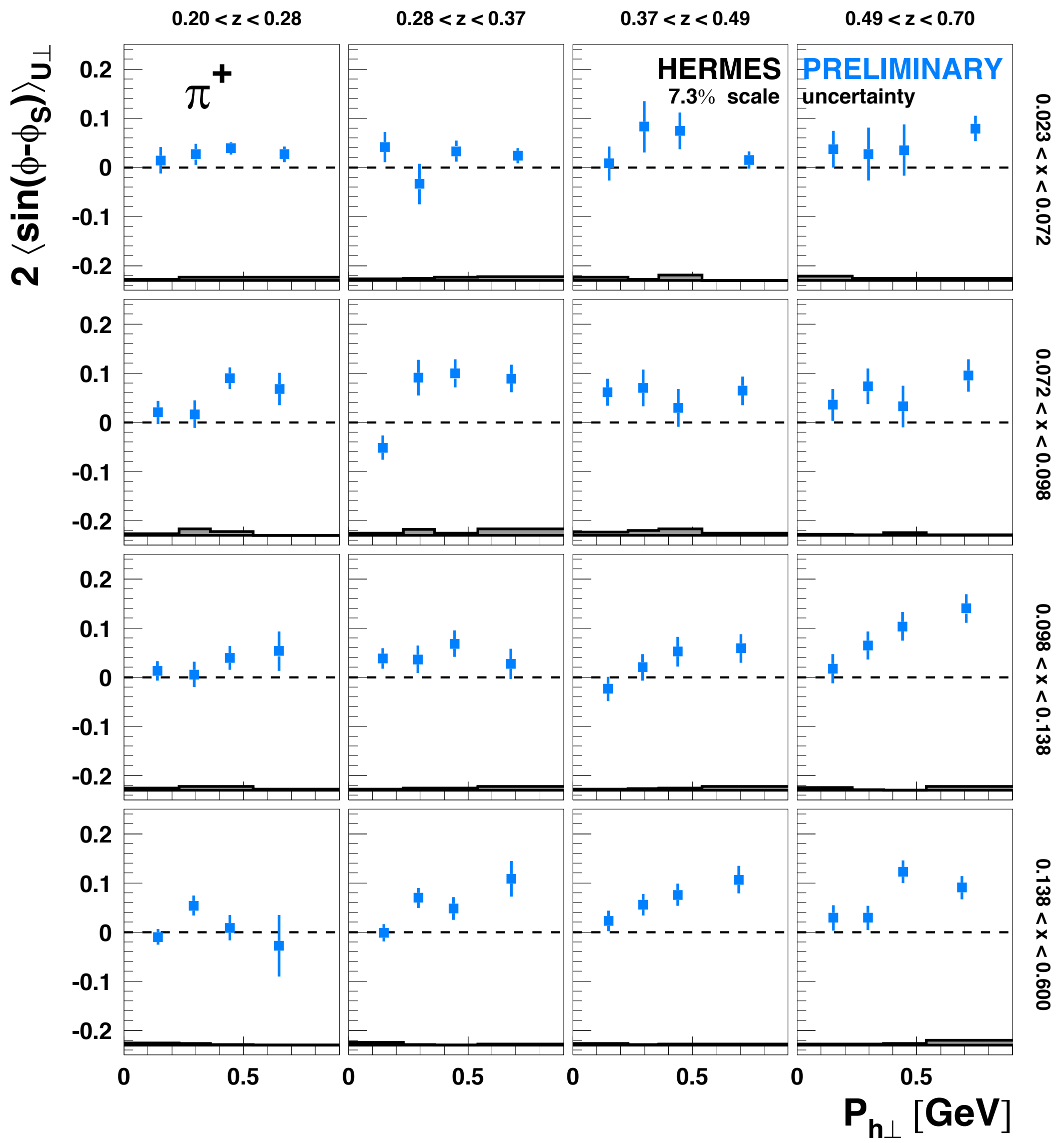






Multi-dimensional analysis



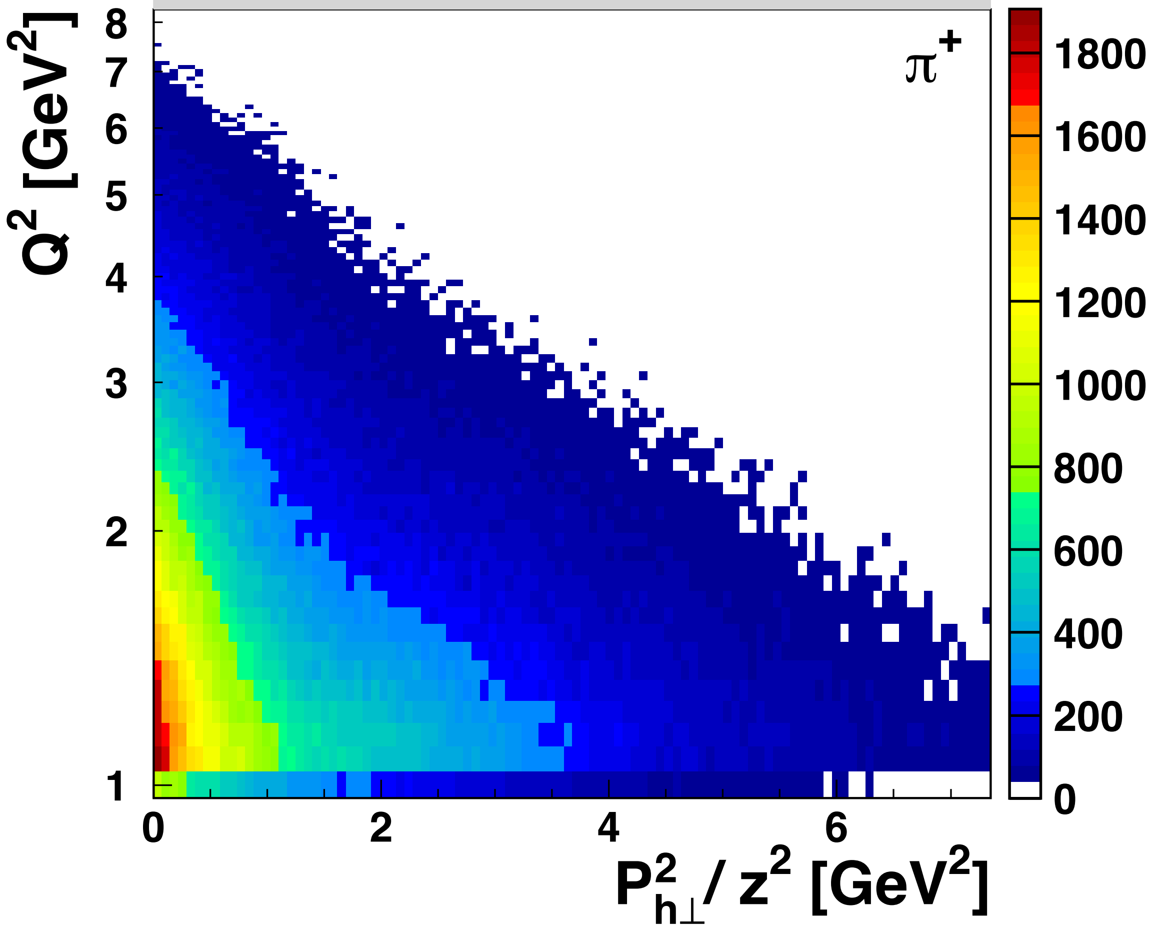


Goal: Fully differential approach with small bin-sizes (similar to this analysis):

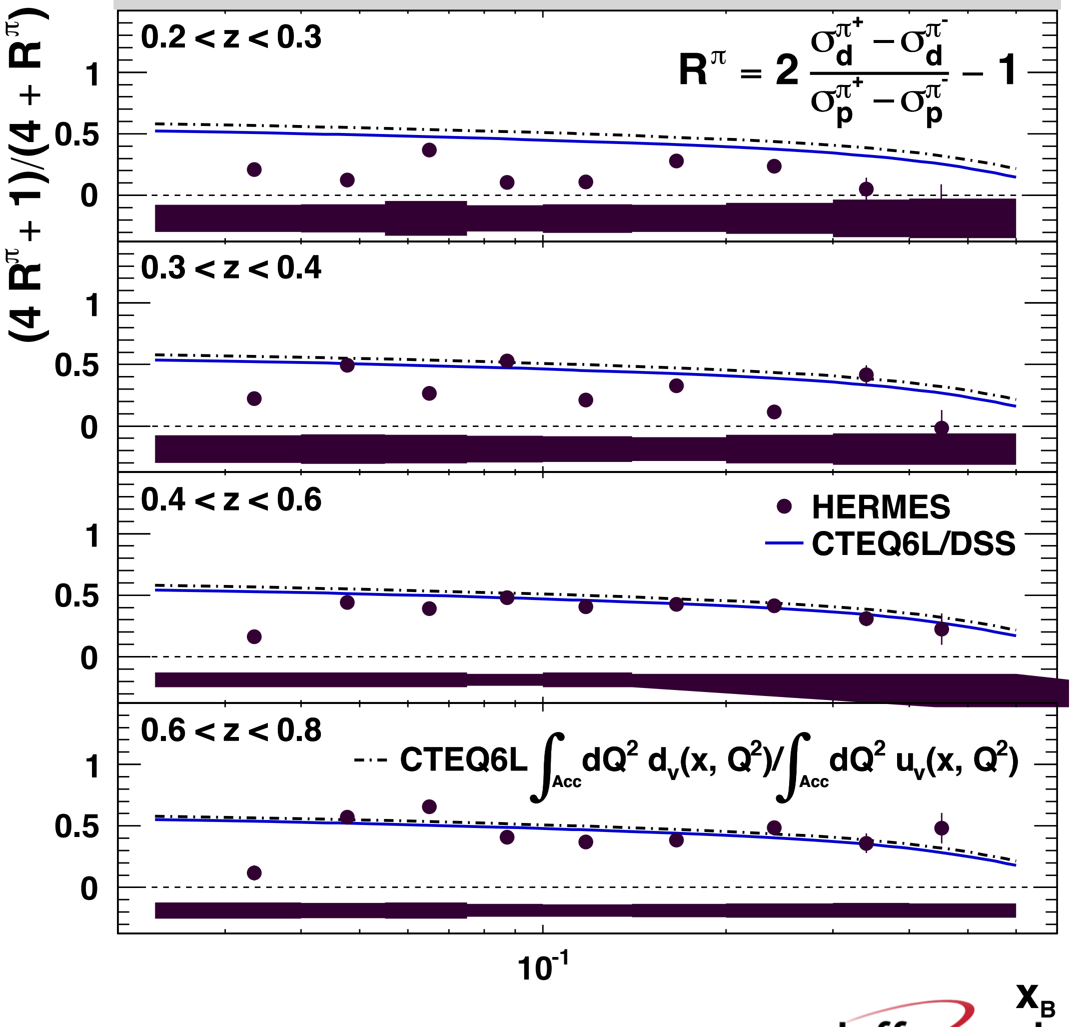
- minimizes the dominant contributions to the systematic uncertainty, and therefore maximizes the attainable experimental precision
- maximize information for QCD analysis

Factorization scales and breaking

TMD factorization partonic scale << hard-scattering scale

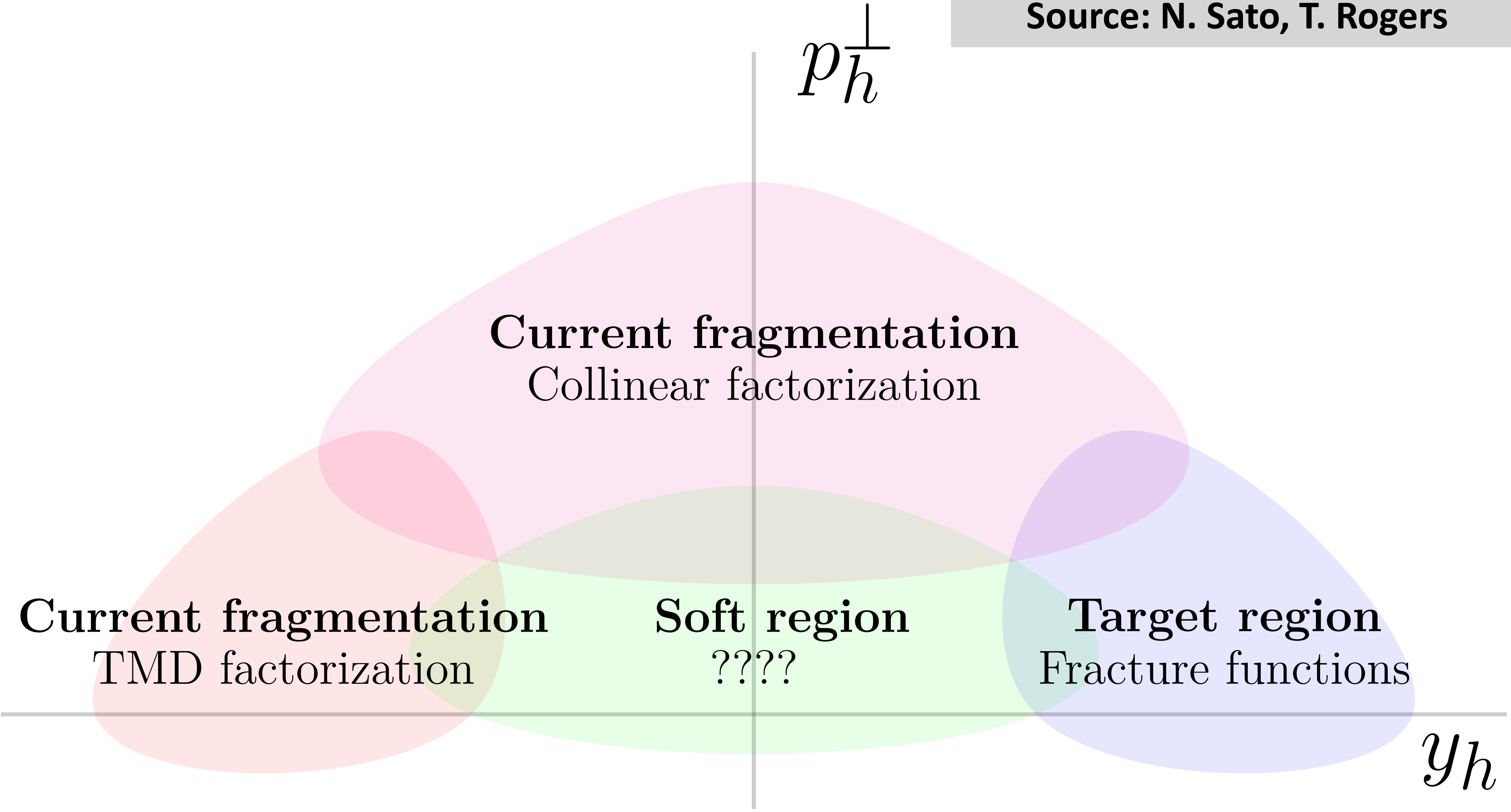


HERMES multiplicities from unpolarized SIDIS sample



Exploring SIDIS regions

Source: N. Sato, T. Rogers



Exploring the nature of matter

The 12 GeV Science Program at Jefferson Lab

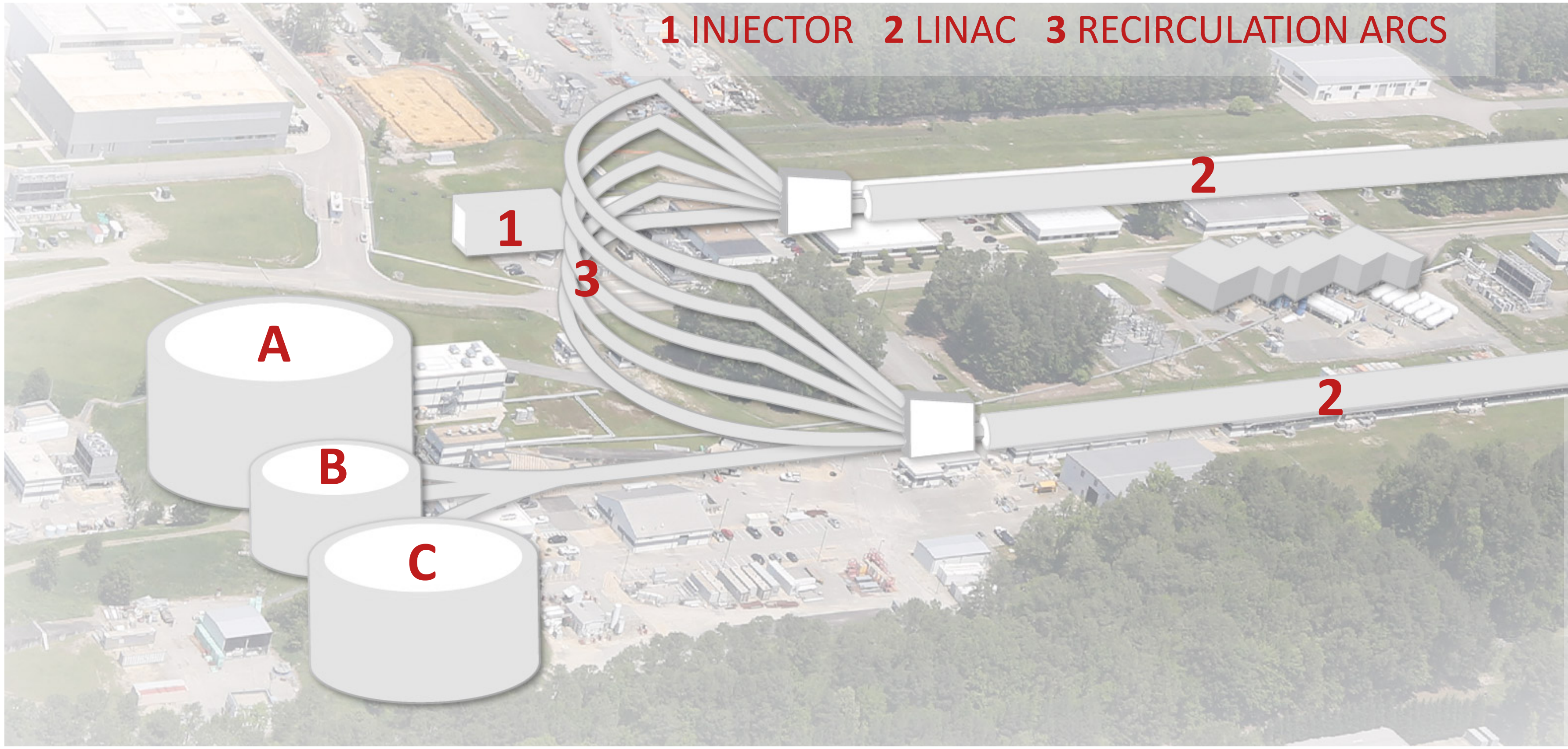
Exploring the nature of matter

Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

Jefferson Lab's unique and exciting mission is to expand humankind's knowledge of the universe by **studying the fundamental building blocks of matter** within the nucleus: subatomic particles known as **quarks and gluons**.

More than 1,500 nuclear physicists worldwide come to Jefferson Lab to conduct and collaborate on research.

CEBAF at Jefferson Lab



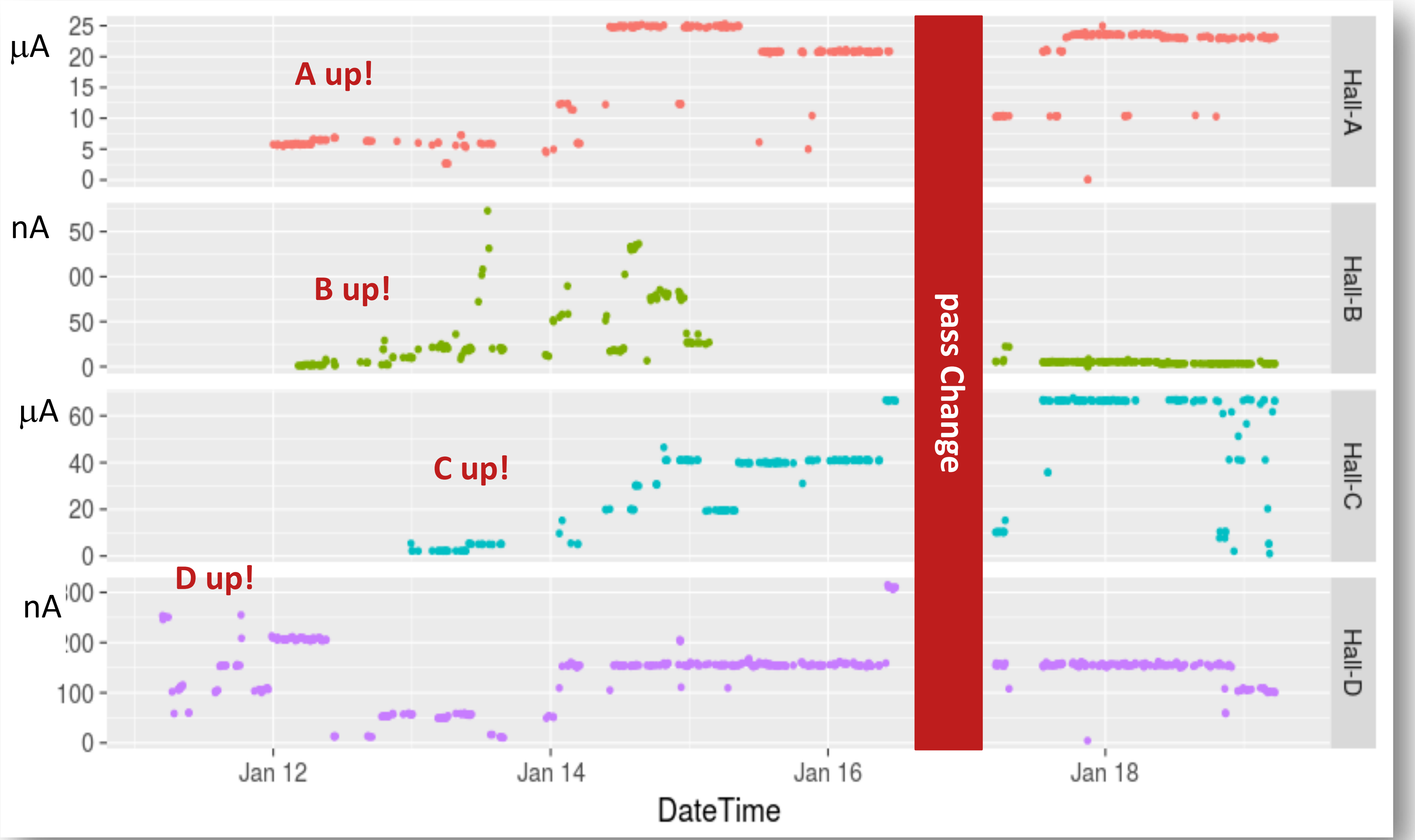
CEBAF upgrade

- completed in 09/2017
- CW electron beam
- E_{max} = 12 GeV
- I_{max} = 90 mA
- Pol_{max} = 90%

CEBAF

- ultra-high luminosities: up to 10^{39} electrons-nucleons /cm^2/ s
- world-record polarized electron beams
- highest intensity tagged photon beam at 9 GeV
- versatile: deliver range of beam energies and currents to multiple halls simultaneously

Simultaneous Hall operation



Approved experiments of the 12 GeV Science Program

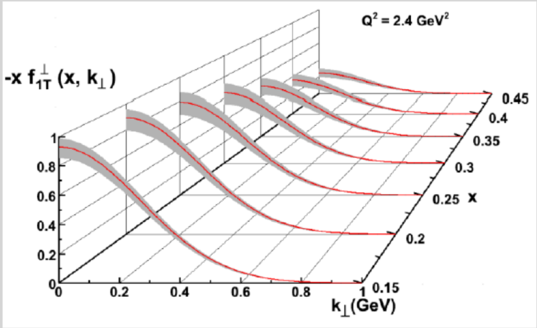
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	2	1	3	0	**6**
The transverse structure of the hadrons	**6**	**3**	**3**	**1**	**0**	**13**
The longitudinal structure of the hadrons	**2**	**3**	**6**	**0**	**0**	**11**
The 3D structure of the hadrons	**5**	**9**	**6**	**0**	**0**	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**23**	**5**	**3**	**78**

TMD studies at the 12 GeV Science Program

Goal

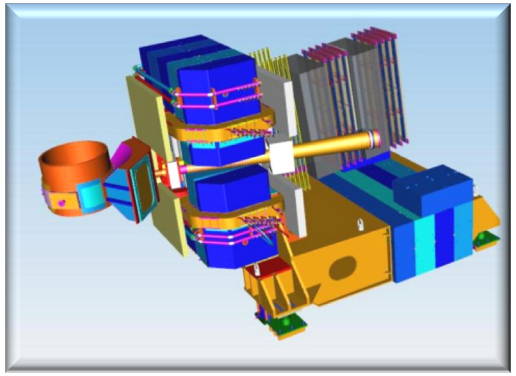
- Precision in 3D imaging in (space and) momentum for x > 0.1 (valence quark region)

Sivers TMD for d quarks



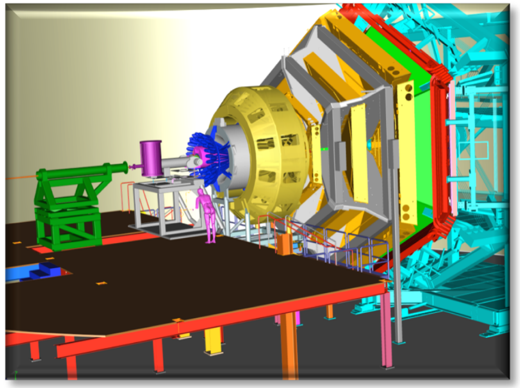
Experimental techniques enabling TMD experiments

- high luminosity
- polarized beams
- polarized targets
- large acceptance experiments with good PID capabilities



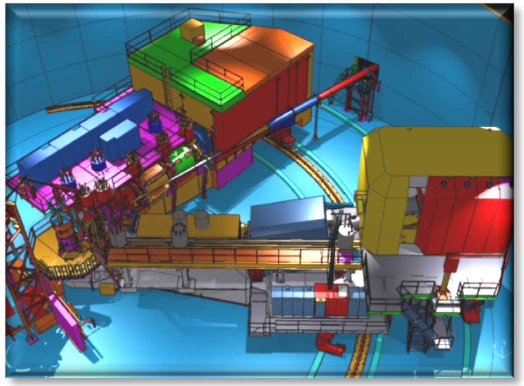
Hall A

Super Bigbite Spectrometer (SBS): dedicated large-*x* TMD study with medium acceptance and high luminosity



Hall B

CEBAF Large Acceptance Spectrometer (CLAS12): general survey experiments, large acceptance and medium luminosity



Hall C

HMS, SHMS, and Neutral-Particle Spectrometer (NPS): precision cross sections for L-T studies and ratios, small acceptance and high luminosity

Hall C SIDIS Program (HMS+SHMS)

Accurate cross section measurements for

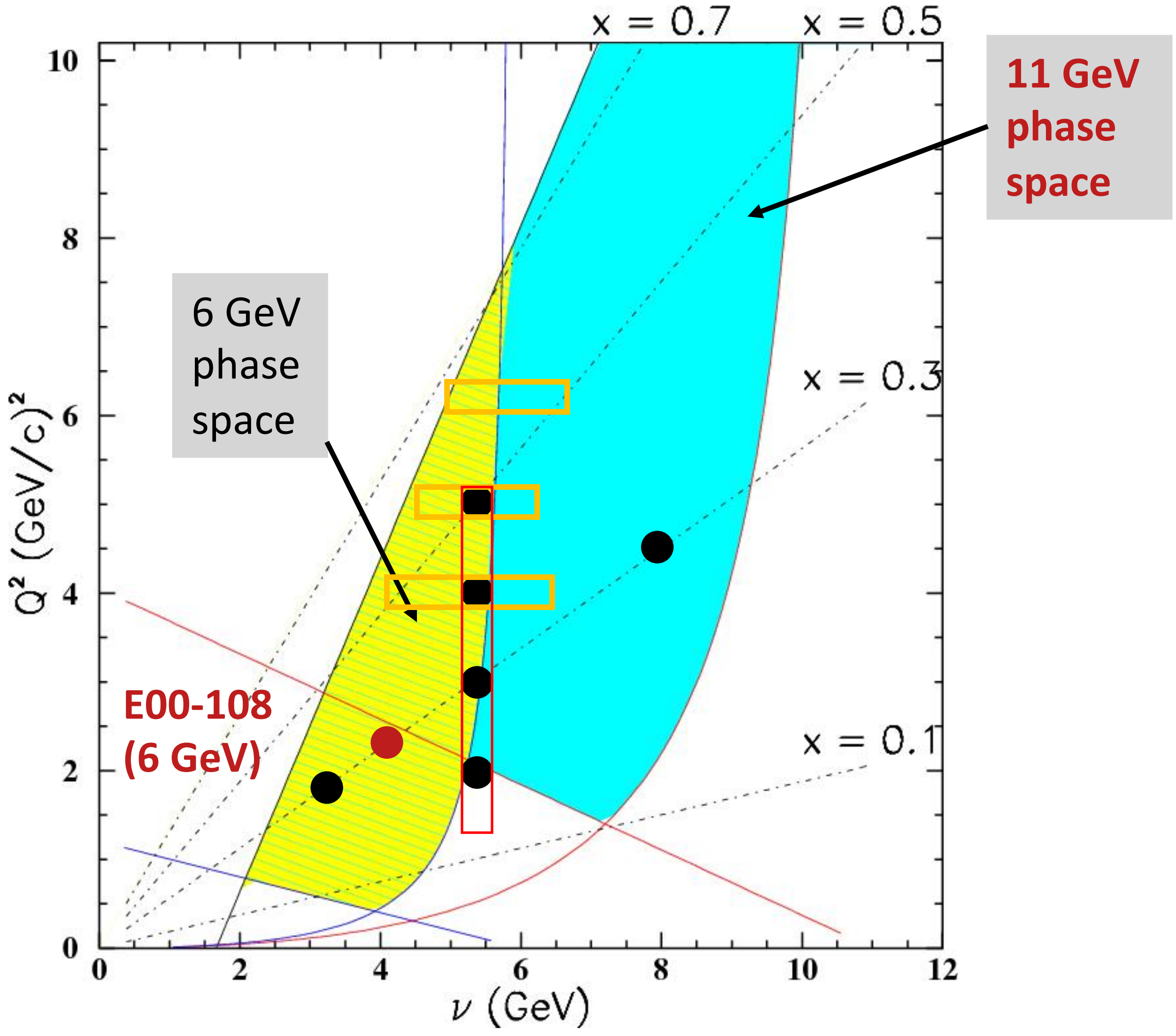
- validation of SIDIS factorization framework
- L/T separations

Experiments Spring / Fall 2018

● E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2
at fixed x

▭ E12-09-002
+ scans in z

▯ E12-06-104
L/T scan in (z,P_T)



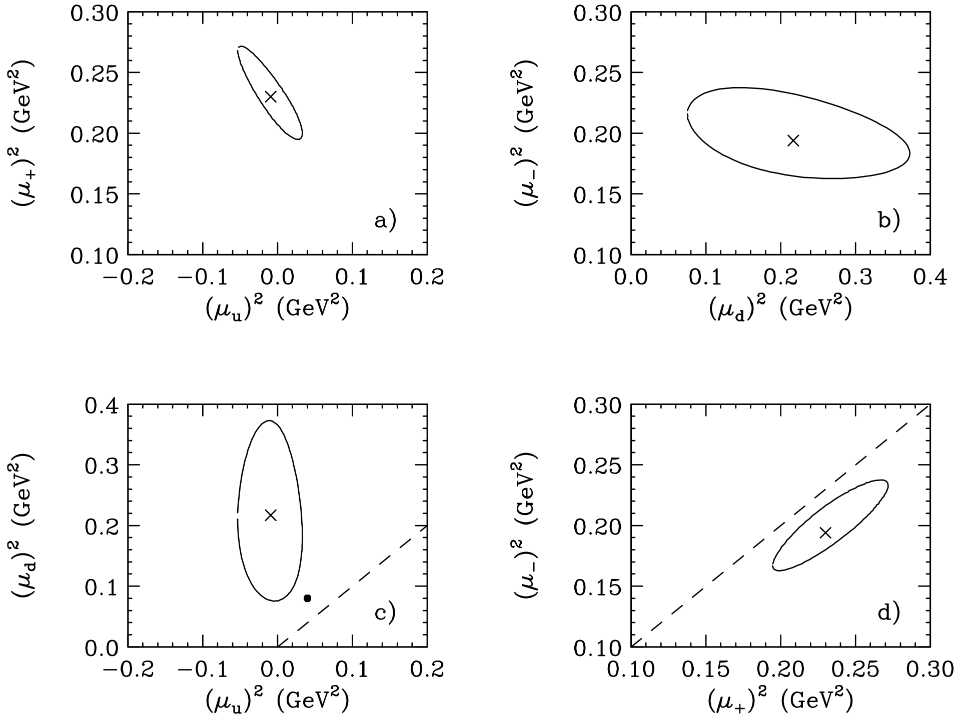
E12-09-017: Transverse Momentum Dependence of Semi-Inclusive Pion Production

Experiment goal Extract information about transverse distribution of quarks by measuring π^+/π^- cross sections and ratios from LH2 and LD2
→ Need to make measurements over a range of transverse momentum at fixed x and Q^2

- Ran for about 28 days in Spring 2018
- Ran for another 2 weeks in Fall 2018 to complete experiment

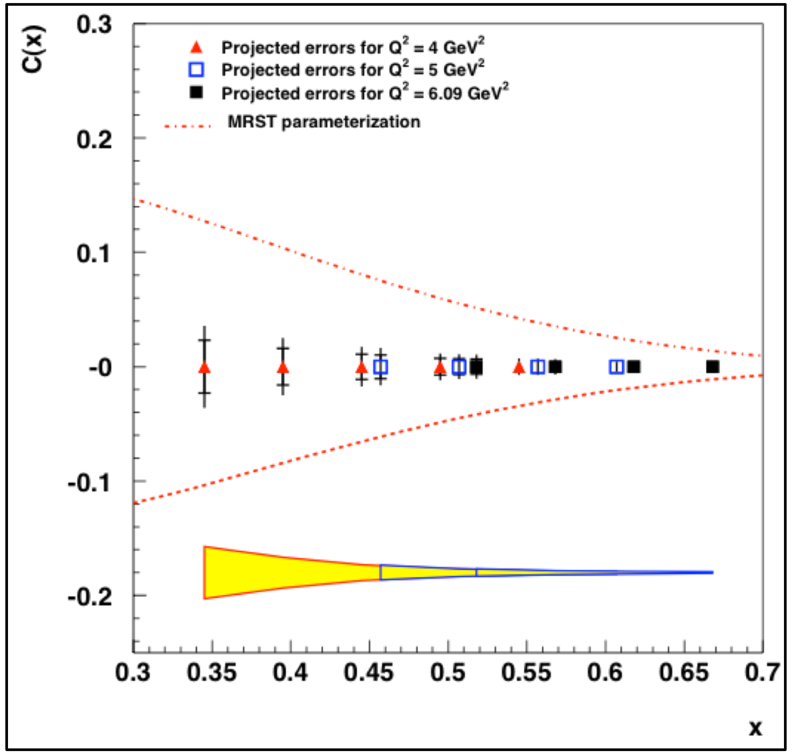
Kinematics:

1. $x=0.31$, $Q^2=3.1$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$
2. $x=0.3$, $Q^2=4.1$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$
3. $x=0.45$, $Q^2=4.5$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$



Results from Hall C 6 GeV data

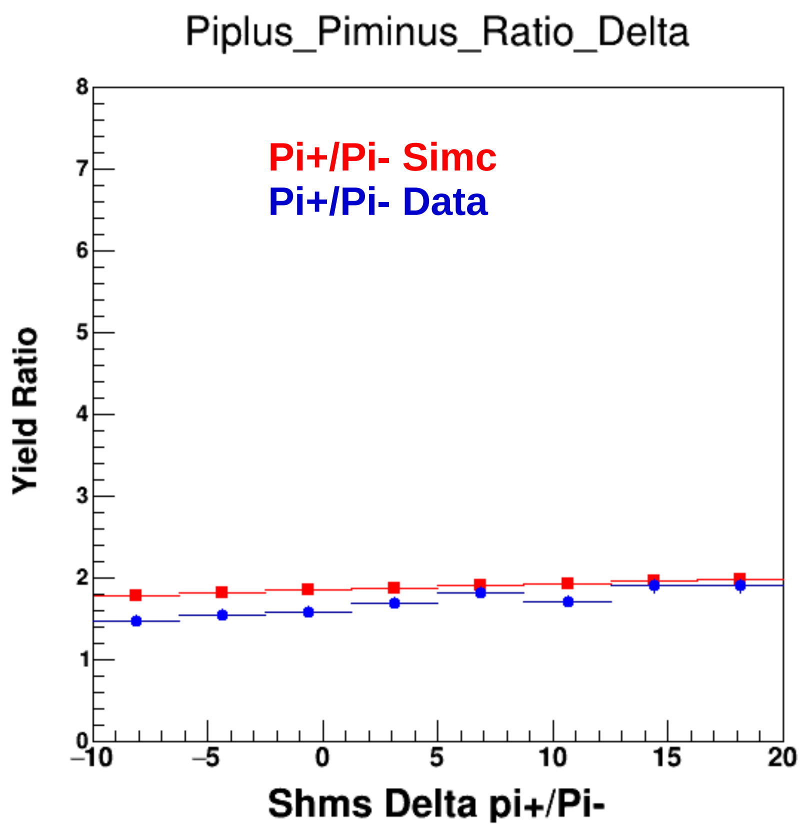
E12-09-002: Charge Symmetry Violating Quark Distributions via π^+/π^- in SIDIS



Experiment goal: place constraints on charge symmetry violation in quark distributions using by making precise measurements of π^+/π^- ratios from LD2

Fall 2018 Ran for 19 days, finished measurements at 2 lowest Q^2 values

Spring 2019: Will run for another 15 days to finish largest Q^2



Kinematics: $P_T \sim 0$ ***z=0.4, 0.5, 0.6, and 0.7***

$Q^2 = 4.0$ GeV^2 x=0.35, 0.40, 0.45, 0.50

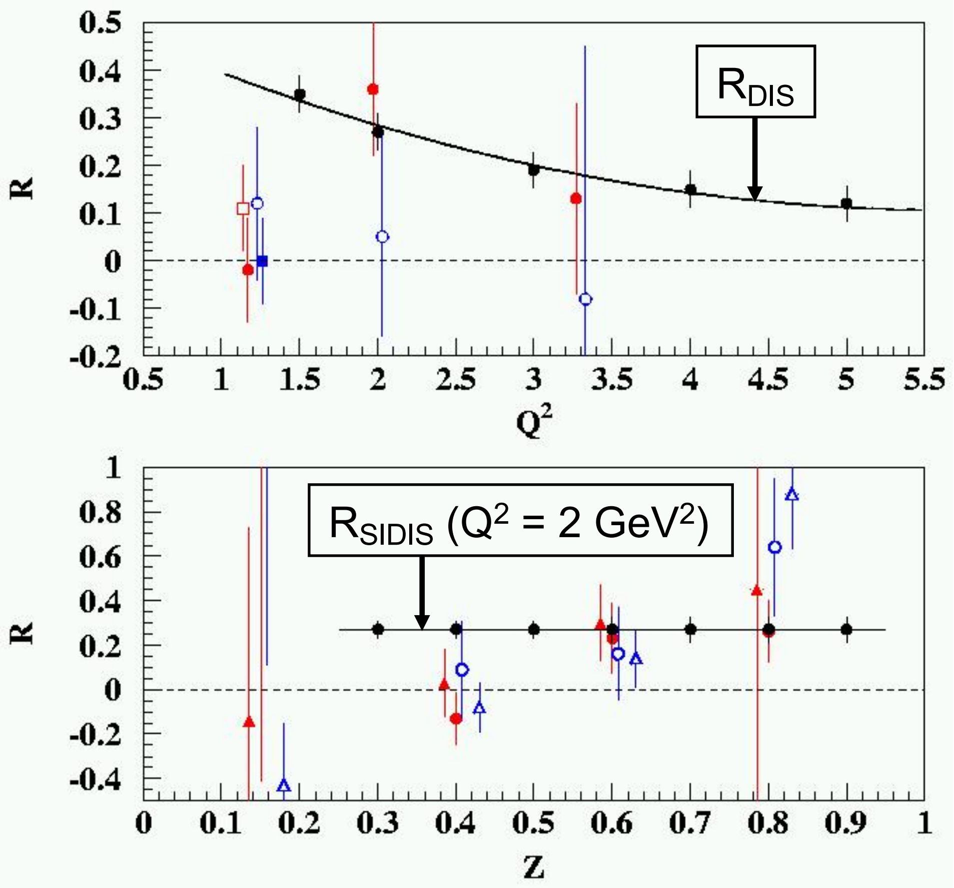
$Q^2 = 4.75$ GeV^2 x=0.45, 0.50, 0.55, 0.60

$Q^2 = 5.5$ GeV^2 x=0.50, 0.55, 0.60, 0.65

Raw, barely offline ratios

- 1 out 8 settings taken in Fall 2018
- roughly consistent with MC expectation

$R = \sigma_L/\sigma_T$ in SIDIS



R_{DIS}

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:

$$R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$$

- $R_{DIS} \to 0$ at $Q^2 \to \infty$ is a consequence of scattering from free spin-½ constituents

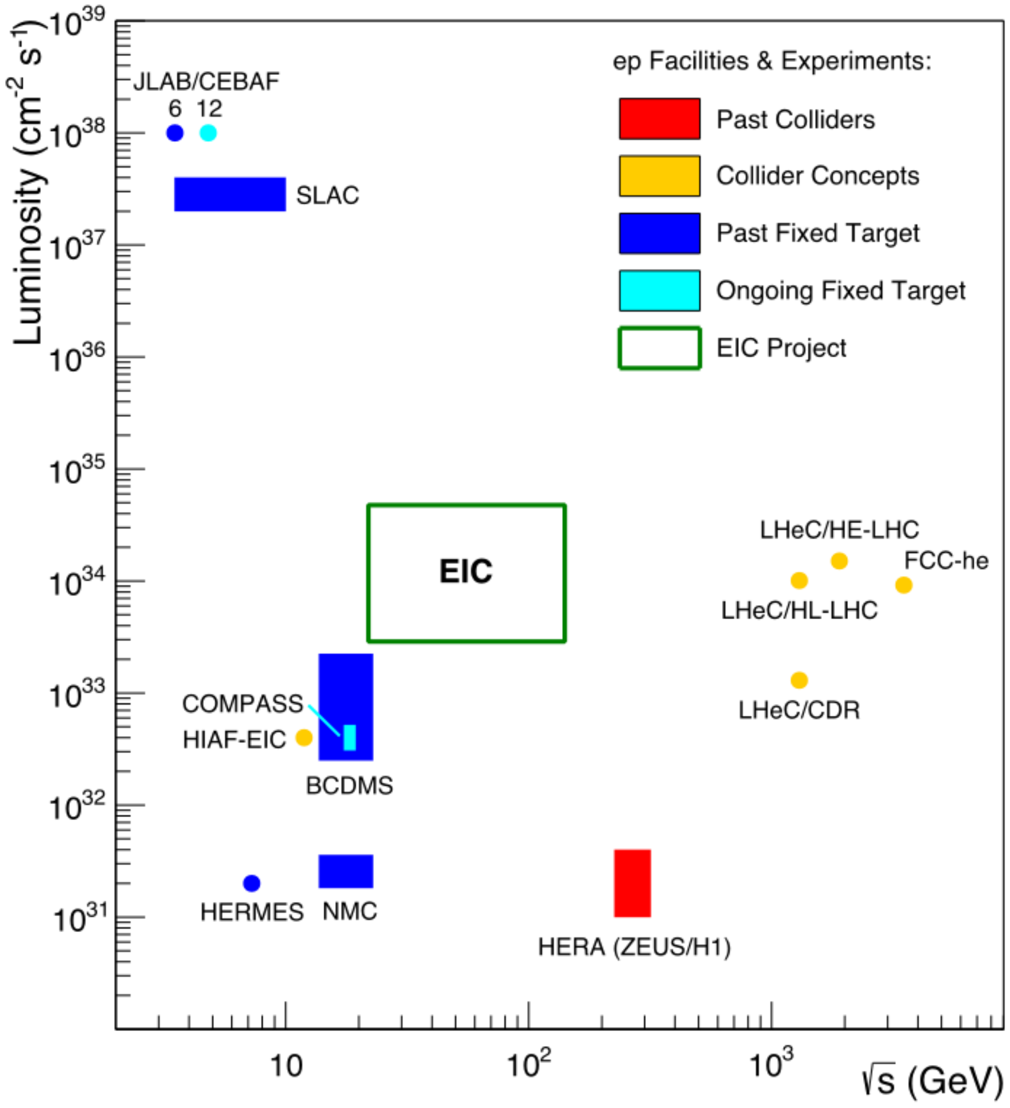
R_{SIDIS}

- knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may vary with *z* and with p_T
- knowledge on R_{SIDIS} needed for any TMD-related measurement, requirement for TMD program at EIC

A new frontier in Nuclear Physics

The Electron-Ion Collider Project

The Electron-Ion Collider (EIC)



Frontier accelerator facility in the U.S.

World's first collider of

- polarized electrons and polarized protons/light ions (d, ^{3}He)
- electrons and nuclei

Versatile range of

- beam energies: $\sqrt{s_{ep}}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- beam polarizations for electrons, protons and light ions (longitudinal, transverse, tensor), at least ~70% polarization
- ion beam species: D to heaviest stable nuclei

High luminosity

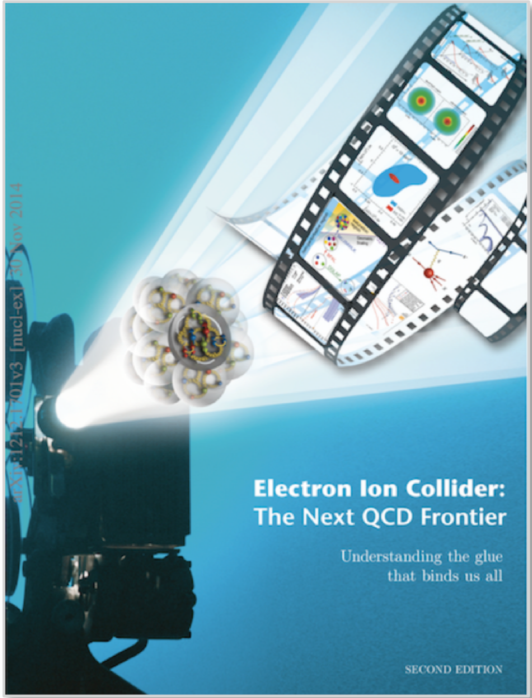
- 100 to 1000 times HERA luminosity

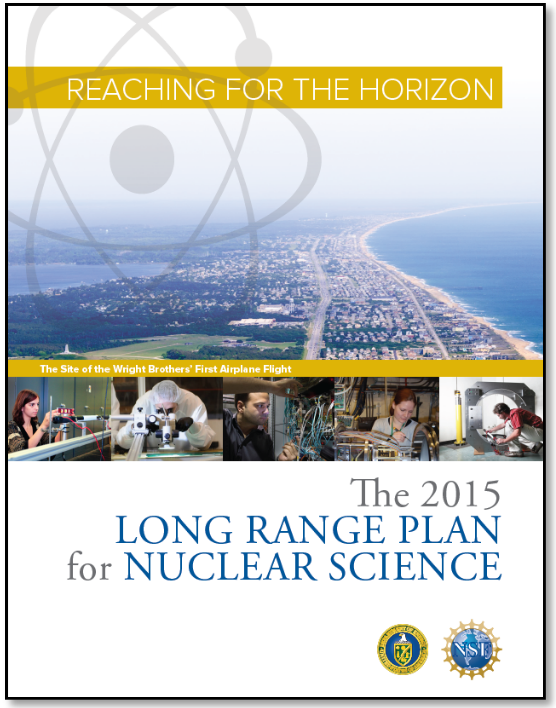
Why an Electron-Ion Collider?

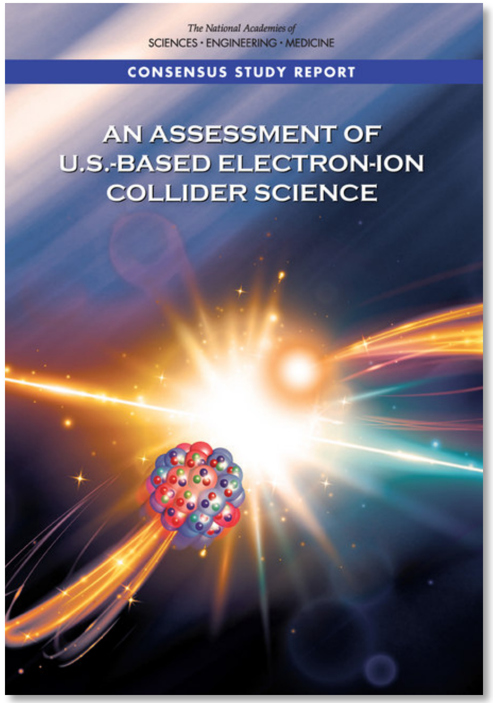
Right tool:

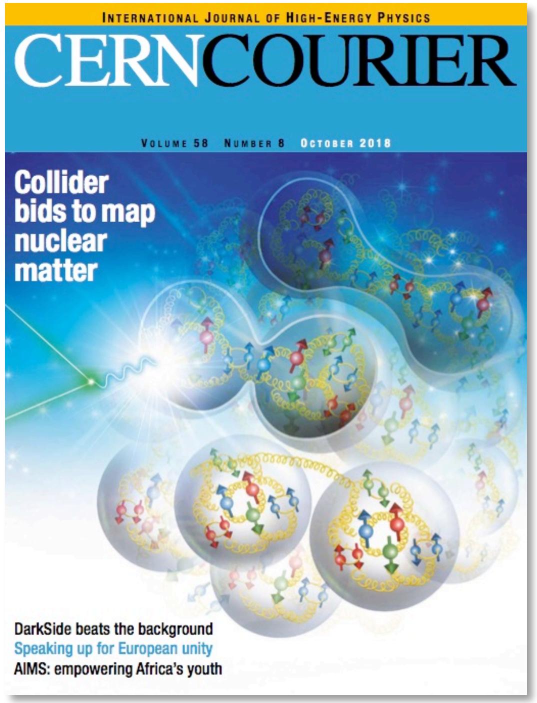
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

Understanding of nuclear matter is **transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

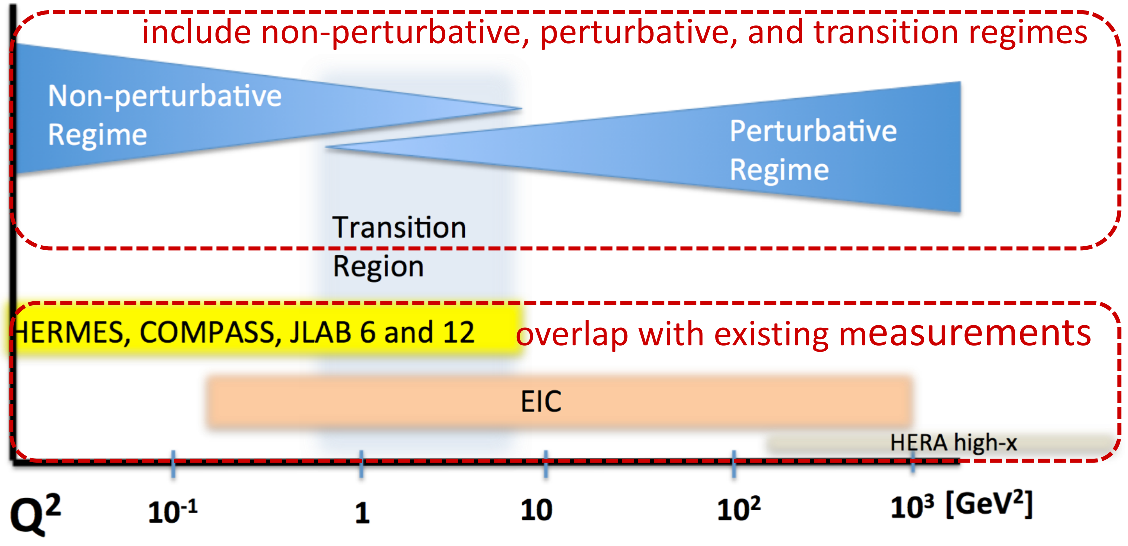


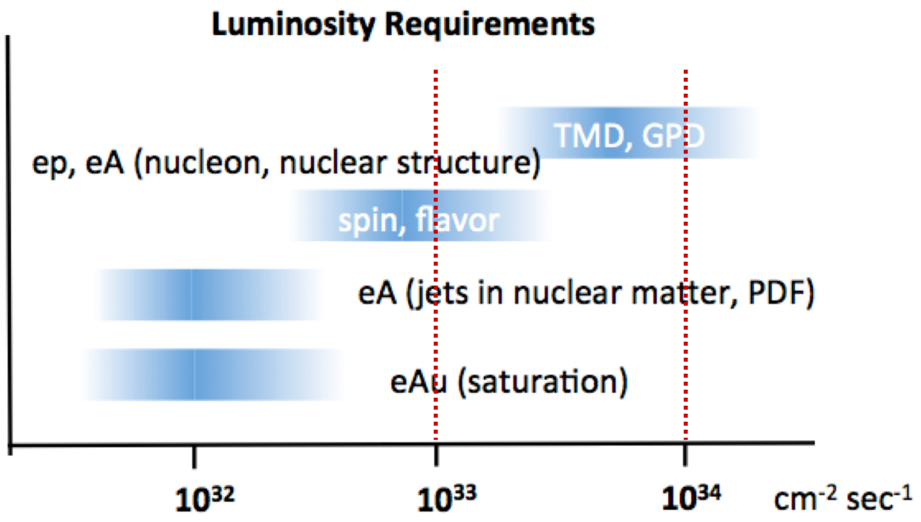






EIC: Ideal facility for studying QCD





Various beam energy

broad Q^2 range for

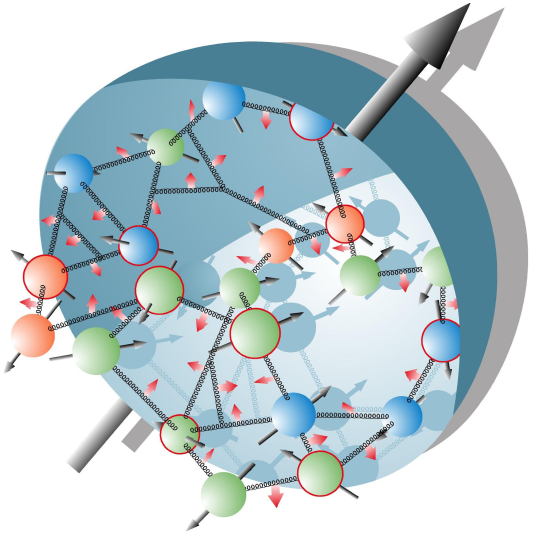
- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

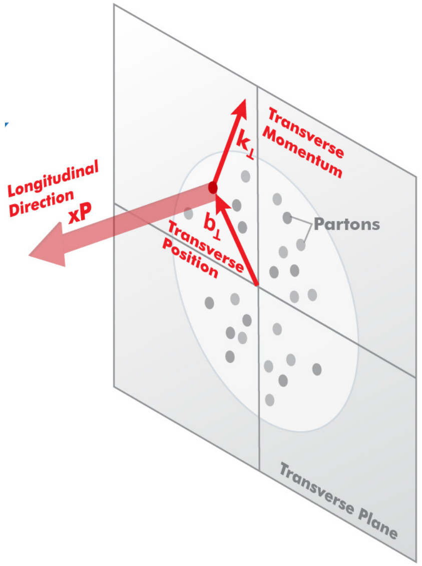
High luminosity

high precision

- for various measurements, e.g., multi-dimensional SIDIS analysis in five or more kinematic dimensions and multiple particles
- in various configurations

EIC: ideal facility for studying QCD





Polarization

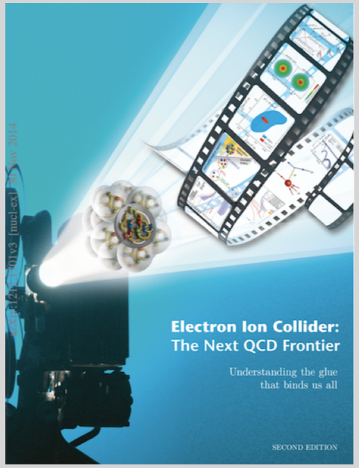
Understanding hadron structure cannot be done without understanding spin:

- polarized **electrons** and
- polarized **protons/light ions (d, ^{3}He)** including tensor polarization for d

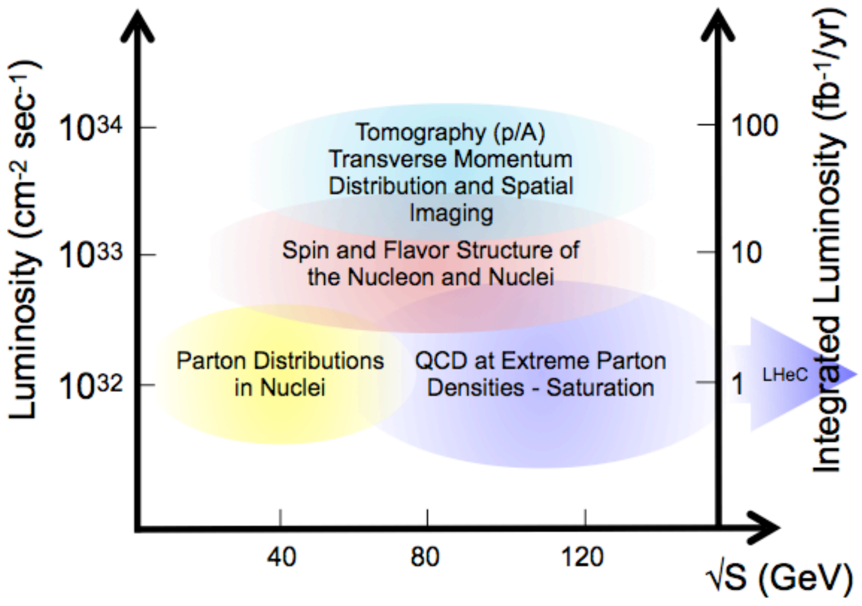
Longitudinal and transverse and polarization of light ions (d, ^{3}He)

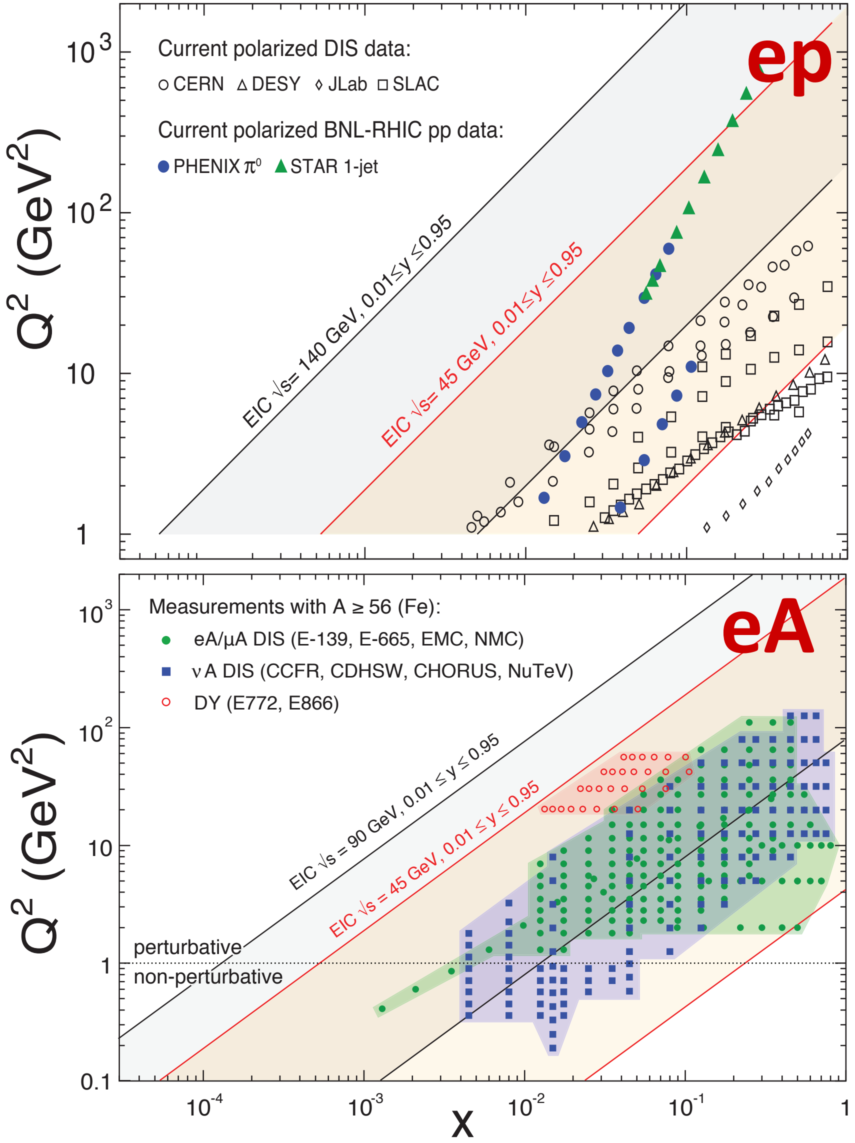
- 3D imaging in space and momentum
- spin-orbit correlations

EIC science program

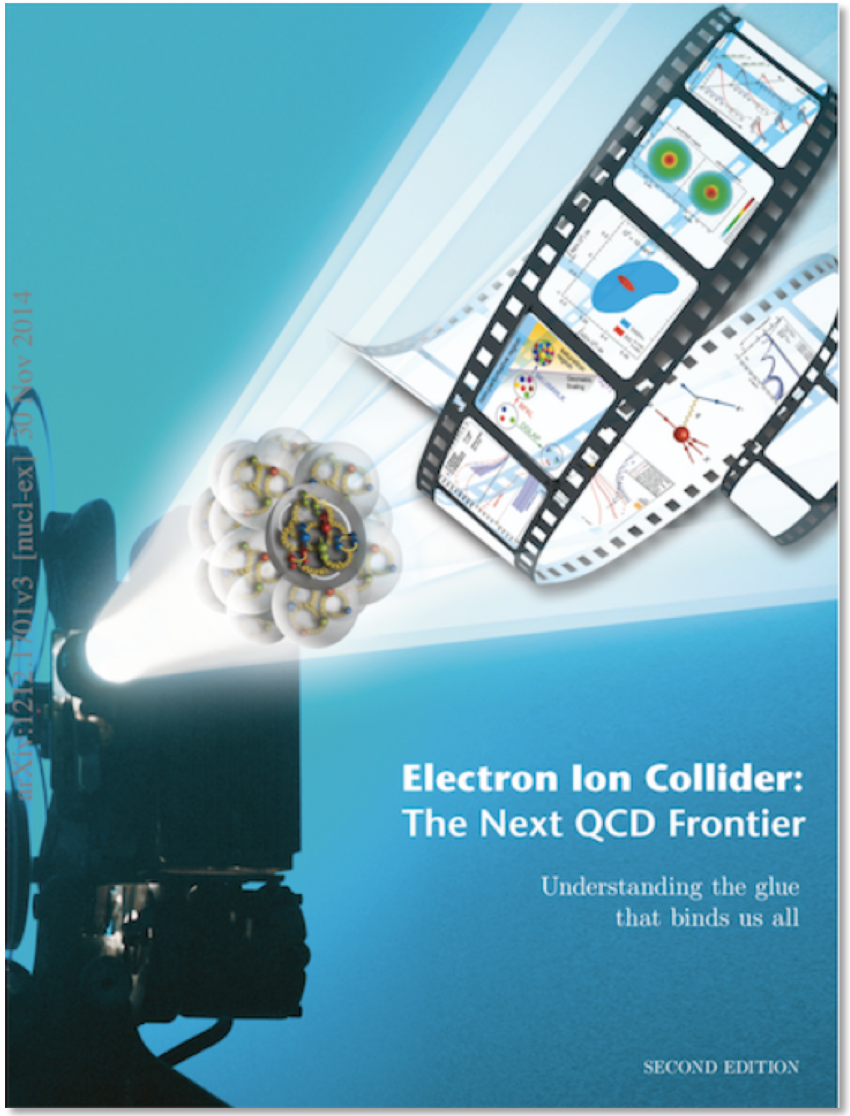


Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.





TMD program in EIC White Paper



Ultimate measurement of TMDs for quarks

- **high luminosity**
  - high-precision measurement
  - multi-dimensional analysis (x, Q^2, $\phi_{S,}$ z, P_t, ϕ_h)
- **broad *x* coverage** $0.01 < x < 0.9$
- **broad Q^2 range** disentangling non-perturbative / perturbative regimes

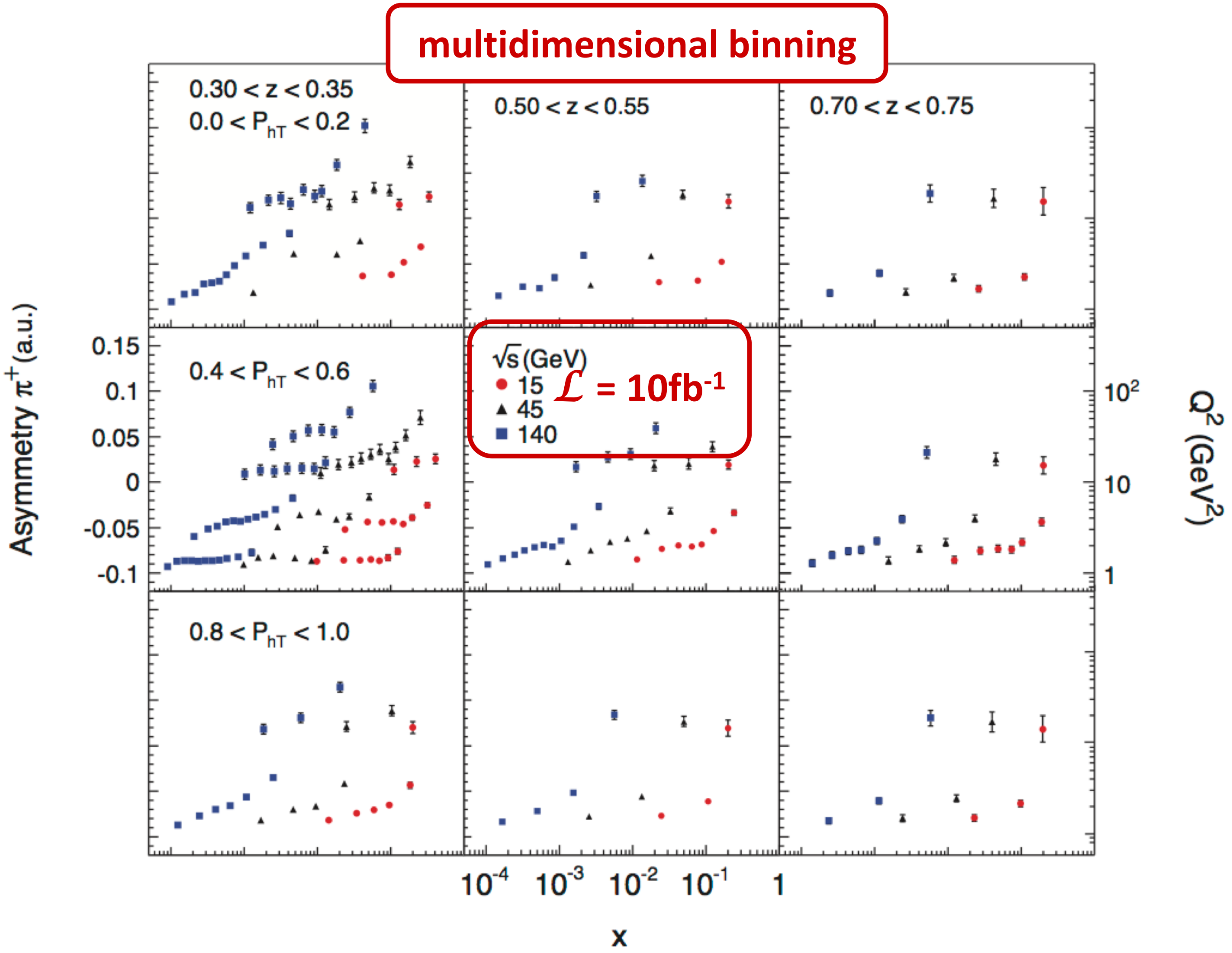
First (?) measurement of TMDs for sea quarks

First (?) measurement of TMDs for gluons

Nuclear dependence of TMDs

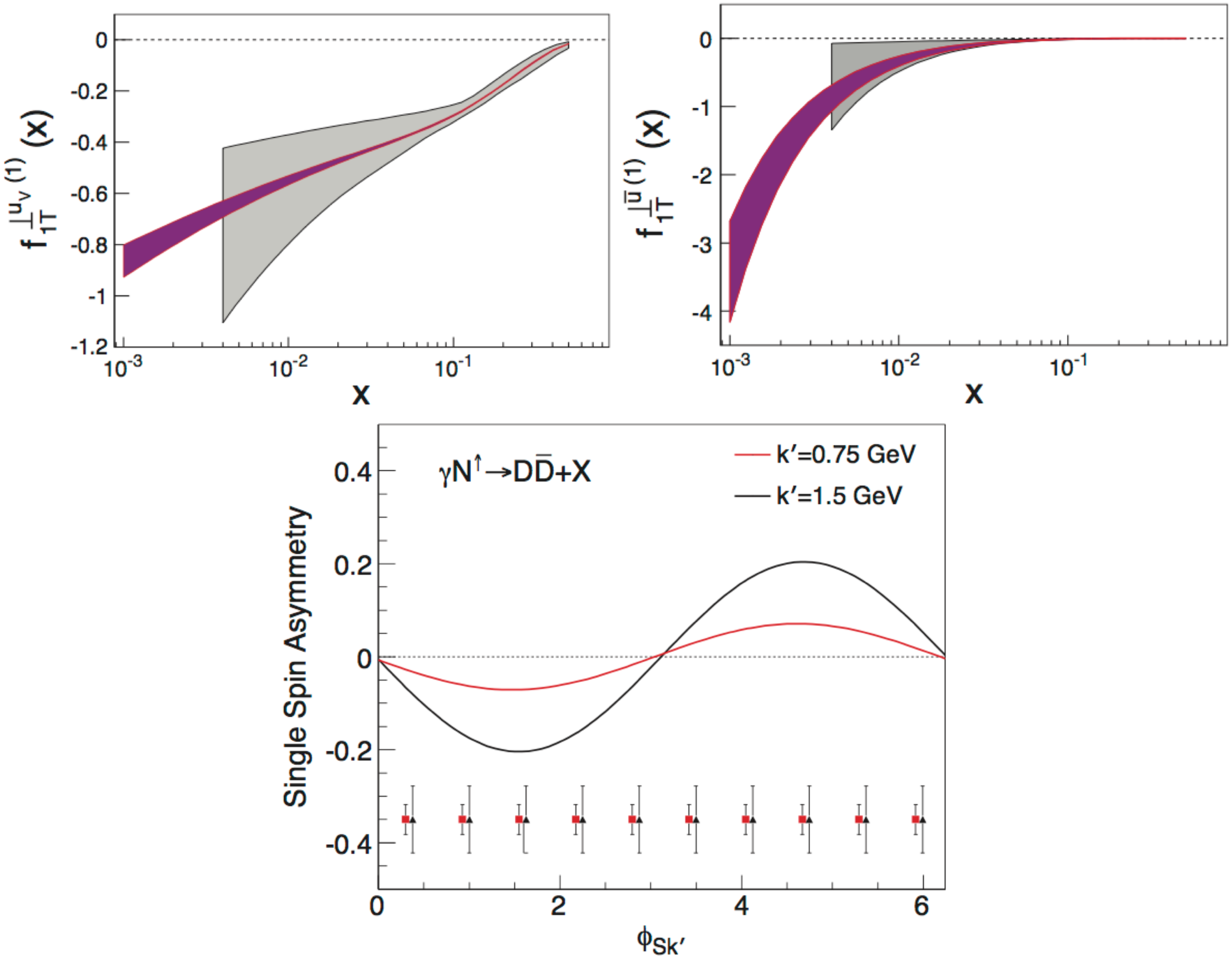
Systematic factorization studies

Ultimate measurement for TMDs



Jefferson Lab

TMDs for sea quarks and gluons



Jefferson Lab

Requirements for TMD measurements

Discussion

- What are our goals for the TMD program at the EIC?
- How do we accomplish our goals?
- What can we do now and what do we need to do now?
- **E.g.**: We need to know R_{SIDIS} and we plan to measure it at Jefferson Lab.

- **Theory**
  - If we have precise measurements of TMDs what do we learn about big questions, e.g., chiral symmetry breaking, confinement, spin of the nucleon etc.? What will be our next steps?
  - Extraction of TMDs from SIDIS measurements requires comprehensive understanding of TMD hadronization
  - **Interplay Theory and Experiment** "*It will be **joint progress of theory and experiment** that moves us forward, not in one side alone*" Donald Geesaman (ANL, former NSAC Chair)

- **Accelerator** Building the right probe: High luminosity, sensitivity to intrinsic transverse momenta

- **Detector** Total acceptance detector and particle identification over a broad momentum range,

- **Analysis** Multi-dimensional analysis on event level, high-precision MCEG

Software and the next-generation of TMD studies

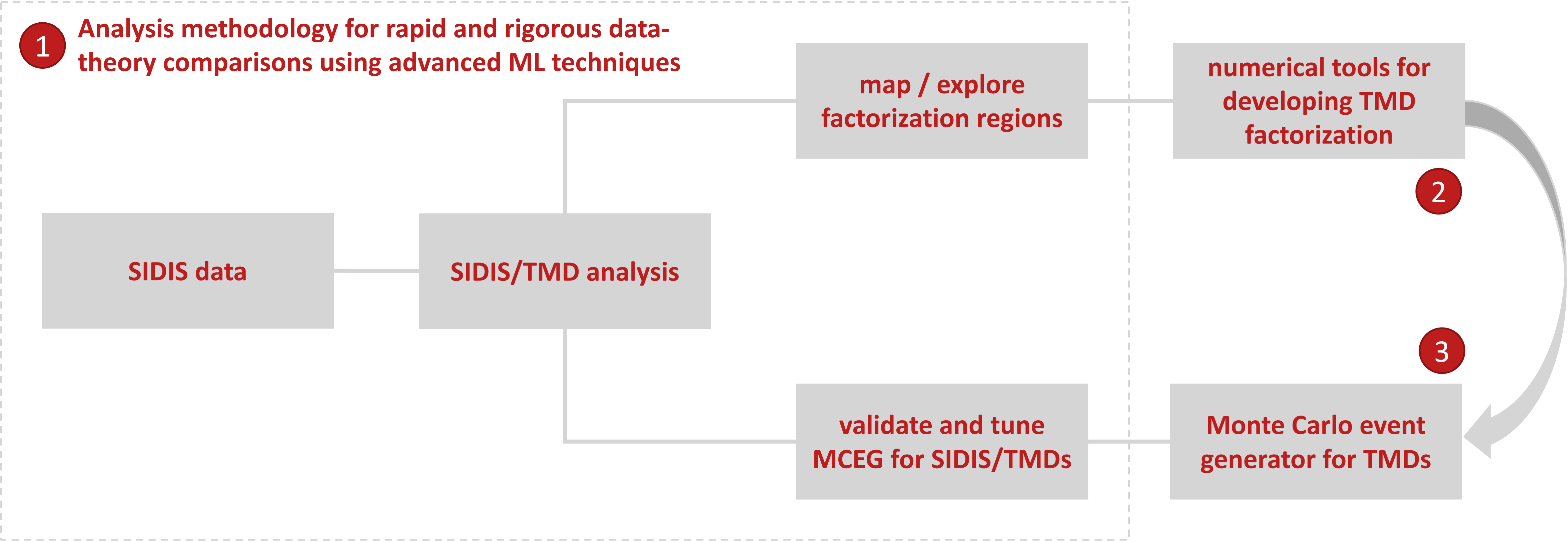
“The purpose of computing is insight, not numbers.”

Richard Hamming (1962)

The Foundation of the Next-Generation TMD Studies

Lay foundation of the next-generation of TMD studies

Advances in theory, experiment, computer and data science
12 GeV Data becoming available and increased EIC activities



Advance TMD physics

Rigorous and systematic tests of TMD factorization, detailed mapping of factorization regions in SIDIS
Improve our understanding of hadronization by connecting LUND string model with polarized TMD phenomenology

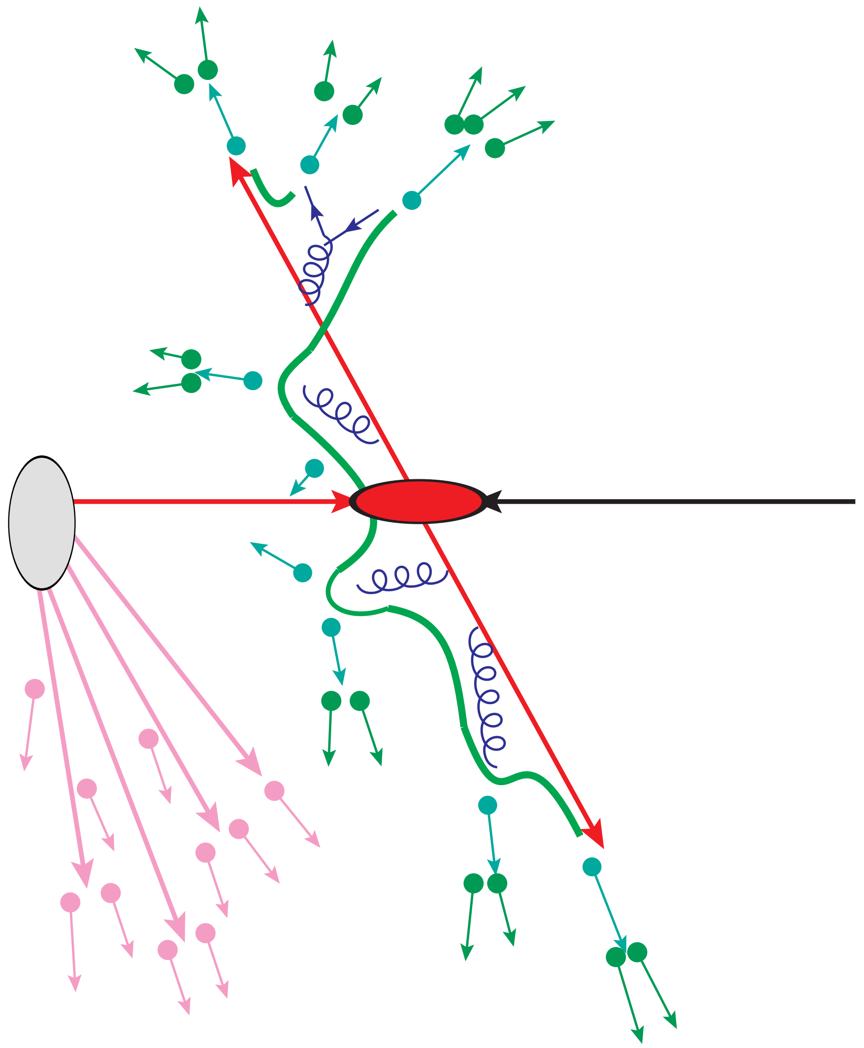
Monte Carlo Event Generator

MCEG

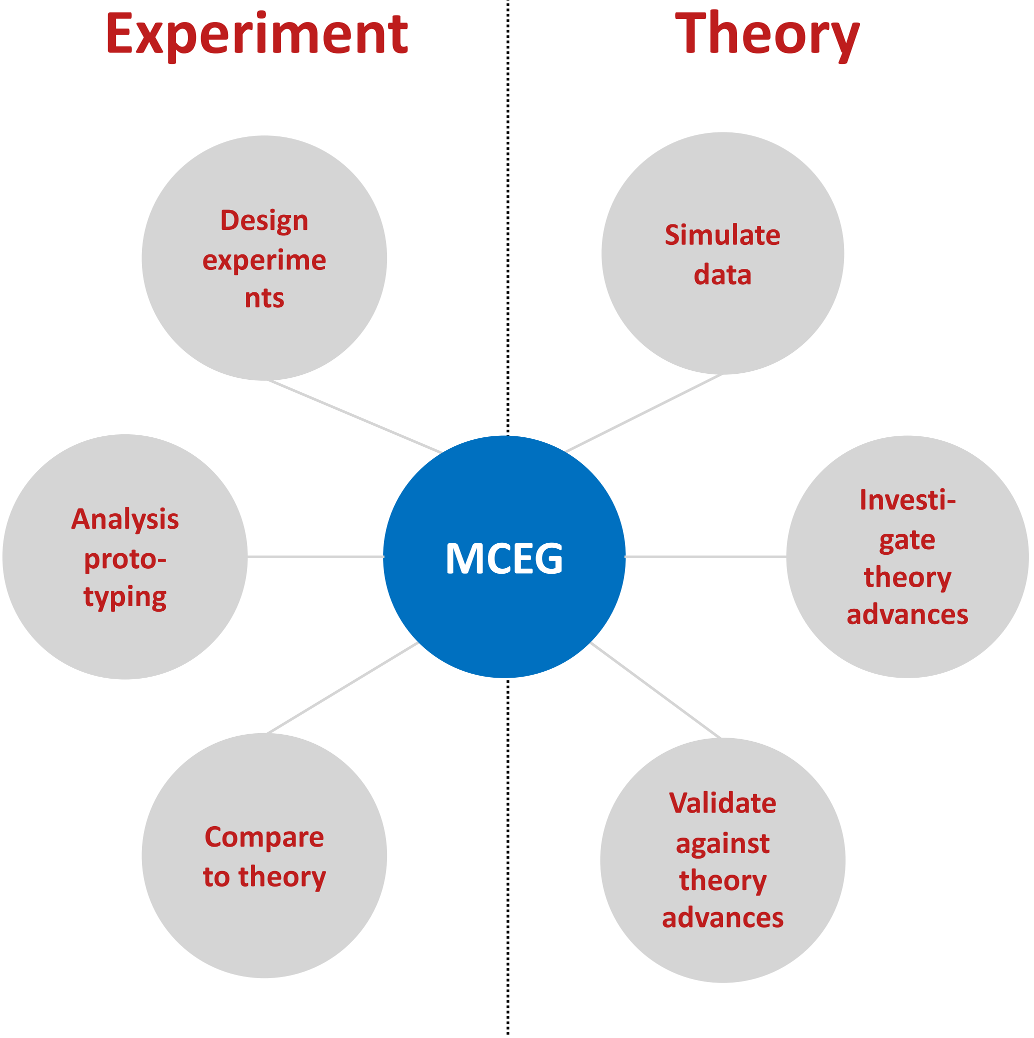
- faithful representation of QCD dynamics
- based on QCD factorization and evolution equations

MCEG algorithm

1. Generate kinematics according to fixed-order matrix elements and a PDF.
2. QCD Evolution via parton shower model (resummation of soft gluons and parton-parton scatterings).
3. Hadronize all outgoing partons including the remnants according to a model.
4. Decay unstable hadrons.



MCEG in Experiment and Theory



Lesson from HEP high-precision QCD measurements require high-precision MCEGs

Workshops: MCEGs for future ep and eA facilities

MCEG2018 19–23 March 2018

- Started as satellite workshop during POETIC-8

POETIC 8
8th International Conference on Physics Opportunities at an ElecTron-Ion-Collider
19-23 March 2018, University of Regensburg

- Collaboration EICUG-MCnet

Goal of workshop series

- Requirements for MCEGs for ep and eA
- R&D for MCEGs for ep and eA

MCEG2019 20–22 February 2019

- Status of ep and eA in general-purpose MCEG
- Status of NLO simulations for ep
- TMDs and GPDs and MCEGs
- Merging QED and QCD effects

Vibrant community

MCEG Workshop
DESY, February 2019

F Hautmann

First all flavor. all Q^2, all x and all k_t TMD at NLO determined.

- Introduction
- The Parton Branching (PB) method
- New results and applications

F Hautmann: MCEG Workshop, DESY - February 2019 1

TMD and parton shower: CASCADE-3

Hannes Jung (DESY)

with contributions from
A. van Hameren, K. Kutak, A. Kusina,
A. Bermudez Martinez, P. Connor F. Hautmann, O. Lelek, R. Zlebcik

- From inclusive to exclusive distributions
  - Parton Branching method for TMDs

First TMD parton shower using higher order splitting function.

H. Jung, TMD and Parton Shower CASCADE3 , MCEG for future ep facilities, Hamburg, Feb 2019 1

NCN

nTMD using PB method

Krzysztof Kutak

Instytut Fizyki Jądrowej
im. Henryka Niewodniczańskiego
Polskiej Akademii Nauk

First all Q^2, all x, all k_t TMD at NLO for nuclei. Comparison with DY data (pp, pPb, CMS)

Updates for KaTie

Andreas van Hameren
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków

presented at the
MCEGs for future ep and eA facilities
21-02-2019, DESY, Hamburg

Lively discussion: Factorization Theorem and MCEG approaches
To what extent are TMDs a result of a coherent branching evolution as, e.g., implemented in Herwig

Next: Comparison to TMD theory
Extract TMD from the different MCs and compare to analytic results.

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

INFN
Istituto Nazionale di Fisica Nucleare

21st February 2019,
DESY,
Hamburg

Revisited version of a recursive model for the fragmentation of polarized quarks

Albi Kerbizi
University of Trieste, Trieste INFN Section

Lund string + 3P0; good description of Collins and di-hadron asymmetries; Boer-Mulders, jet handedness can be simulated.

Gluon TMDs from precision DIS data using CCFM evolution

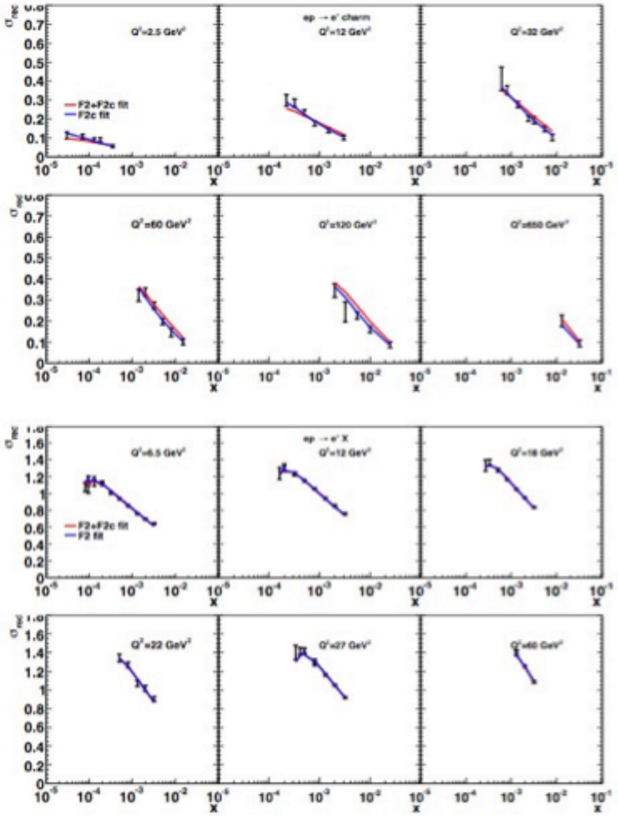
Slide prepared by F. Hautmann (University of Oxford)

CCFM evolulution

- BFKL variant including large x
- √s >> M

Parton Branching

- evolution equation, connected in a controllable way with DGLAP evolution of collinear PDF
- applicable over broad kinematic range from low to high k_T



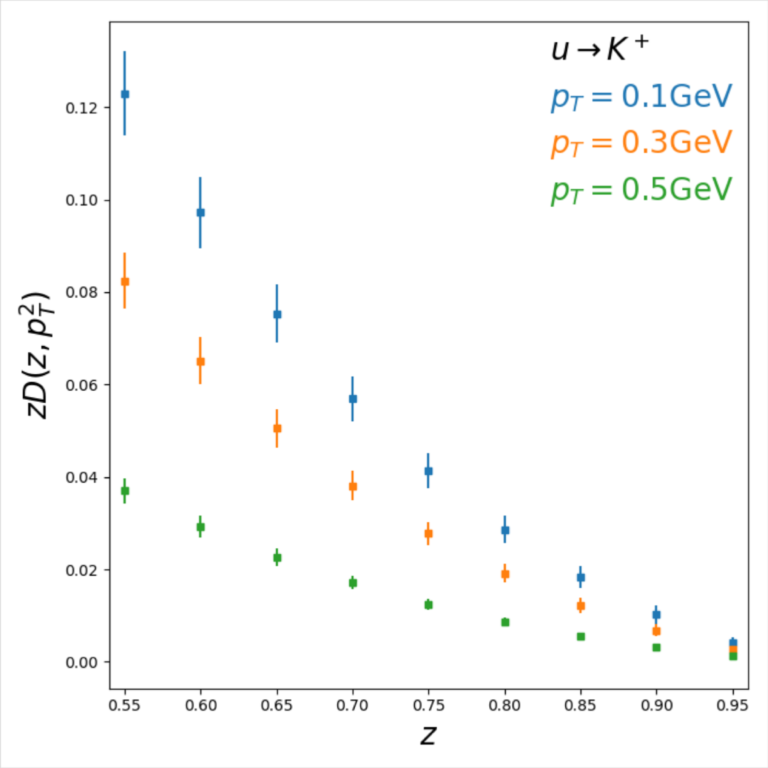
[Hautmann and Jung, Nucl. Phys. B 883 (2014) 1]

- Good description of inclusive DIS data with TMD gluon
- Sea quark yet to be included at TMD level
- Uses uPDFevolv evolution code arXiv:1407.5935 [hep-ph]
- Fit performed with xFitter arXiv:1410.4412 [hep-ph]

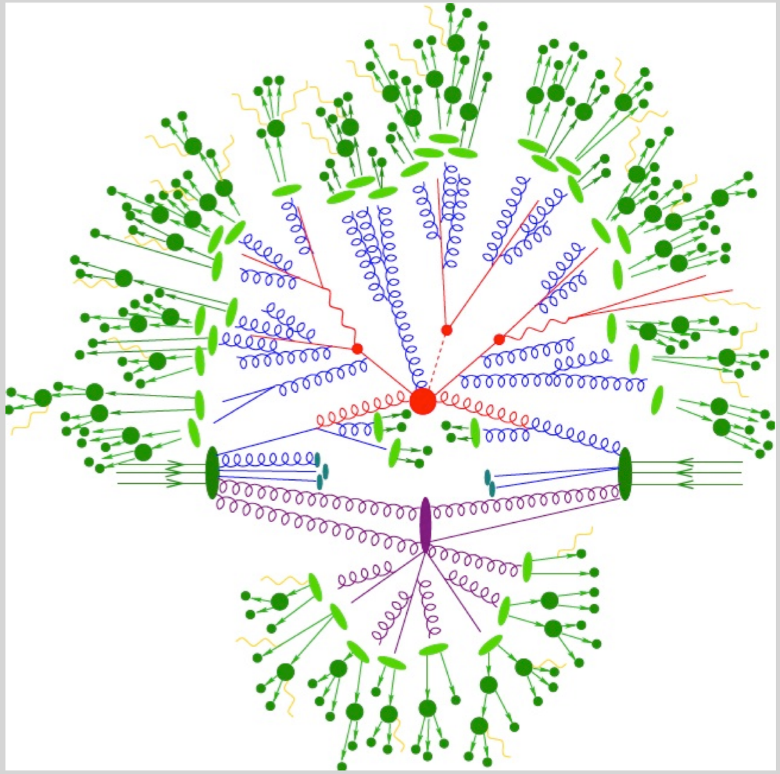
	$\chi^2/ndf\,(F_2^{(charm)})$	$\chi^2/ndf\,(F_2)$	$\chi^2/ndf\,\left(F_2 \text{ and } F_2^{(charm)}\right)$
3-parameter	0.63	1.18	1.43
5-parameter	0.65	1.16	1.41

Studying hadronization in two complementary approaches

Purely phenomenological description with empirical fragmentation functions using factorization theorems in pQCD



Hadronization models folded with many parameters to describe experimental observations as applied in Monte Carlo Event Generators.

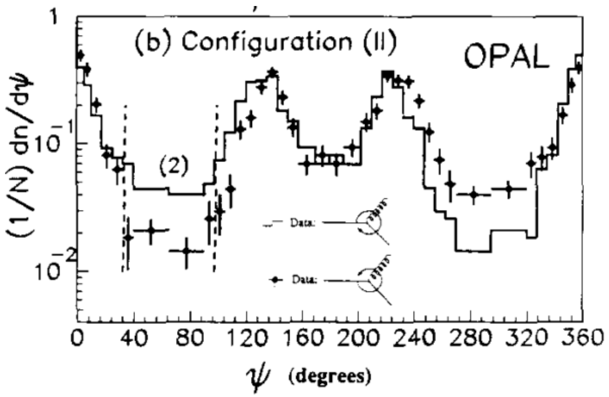


Jefferson Lab

Understanding the hadronization process

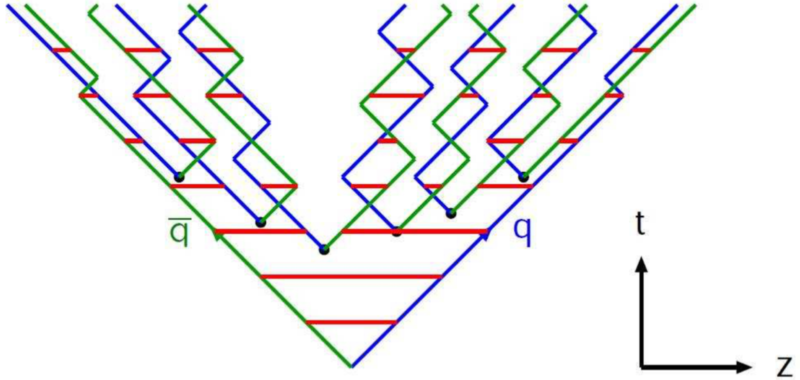
LUND String Model for hadronization (1977 – *now*)

- simple but powerful phenomenological model
- no (promising) new hadronization models in last 40 years
- **LDRD project at Jefferson Lab**
  - review
  - connect with modern QCD, including TMD and spin effects

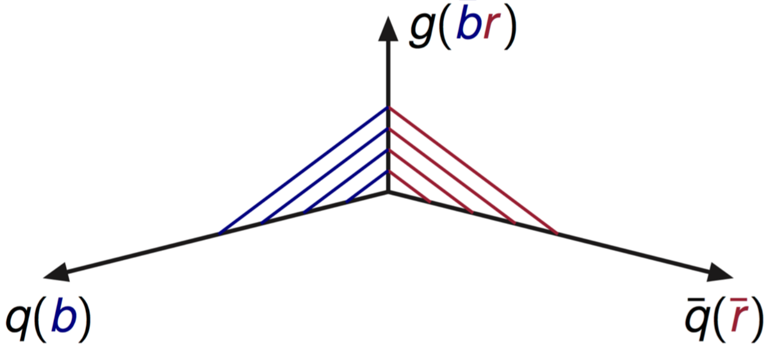


evidence of string effects
particle flow asymmetry at OPAL

String breakup



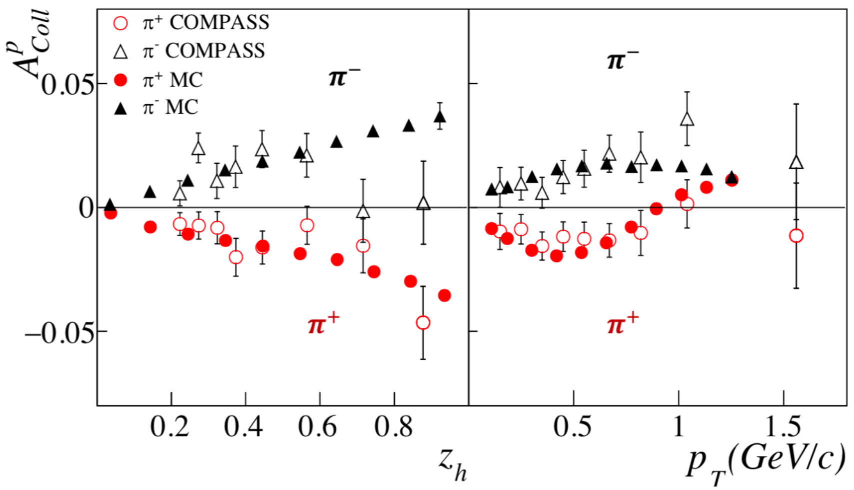
String drawing



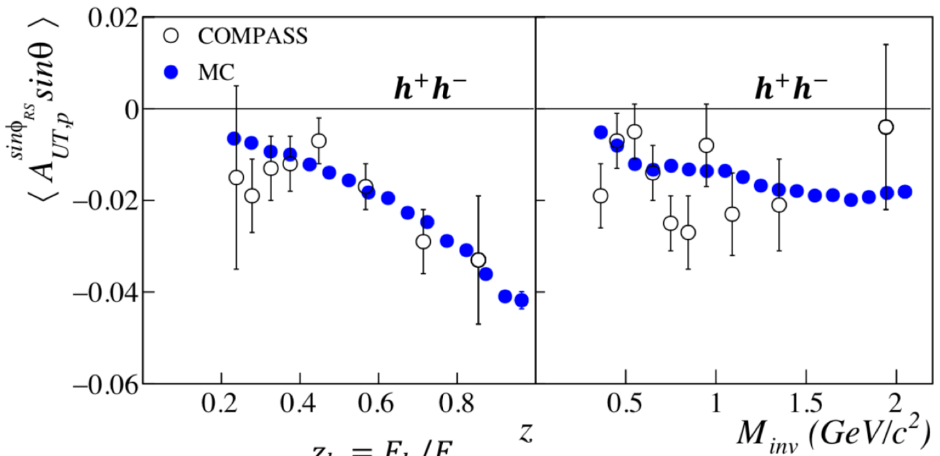
Recursive model for the fragmentation of polarized quarks

Albi Kerbizi (Trieste)

COMPASS Collins SSA



COMPASS di-hadron asymmetry



$z_h = E_h/E_{q_A}$

$z = z_{h^+} + z_{h^-}$

- The string + $^3P_0$ model for pseudo-scalar meson emission has been implemented in a stand alone MC code
- The comparison with experimental data on Collins and di-hadron asymmetries is very promising
- Other effects like Boer-Mulders or jet-handedness can be simulated

- The same results can be obtained with different choices for the $\check{g}$ function acting on the spin-independent correlations between quark transverse momenta
- The choice $\check{g} = 1/\sqrt{N_a(\varepsilon_h^2)}$ guarantees again LR symmetry and allows to simplify
  - the formalism and the analytical calculations
  - **the improvement of the simulations (i.e. adding vector mesons) → ongoing**
  - **the interface with external event generators and in particular with PYTHIA → ongoing**

Markus Diefenthaler

mdiefent@jlab.org

TMDs Imaging quarks and gluons

- **HERMES** Pioneering TMD measurements at the first Electron-Ion Collider
- **Precision TMD studies** The 12 GeV Science Program at Jefferson Lab
- **EIC** A new frontier in Nuclear Physics
- **The Foundation of the Next-Generation TMD Studies** in light of the ongoing 12 GeV Science Program and the upcoming EIC