Physics programs and status of EicC

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On behalf of the EicC Discussion Group

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Wuhan, Hubei, China
Outline

- Introduction
  polarized Electron ion collider in China (EicC)

- Physics Programs in EicC
  PDFs, TMDs, GPDs, Proton Mass,
  pi/K structure function, Hadron Spectroscopy

- Status of EicC

- Summary
• QCD is successful (in general). More than 90% of visible matter in nature governed by strong interaction QCD.

• But not perfect yet. Some fundamental problems to be addressed
  • the origin of the mass and spin.
  • the mechanism for confinement of quarks and gluons.

• Exploring the internal structure of the nucleon is one path.
Introduction

• How to explore the internal structure of the nucleon?
  ➢ spin of nucleon
  ➢ 3D structure
  ➢ mass of nucleon
  ➢ ...

• Electron Ion Collider (EIC), regarded as a “super electron microscope”, can provide the clearest image inside the nucleon.
Facilities Landscape

- RHIC ➔ eRHIC
- FAIR ➔ ENC
- RHIC ➔ LHeC
- CEBAF ➔ JLLEIC
- CERN ➔ HIC
- HIAF ➔ EicC
Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u ($\text{U}^{34+}$)
- CW and pulse modes

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration

Phase I
- Two-plane painting injection scheme
- Fast ramping rate operation

High intensity ion beams for atomic physics, nuclear physics, applied research in biology and material science etc.

Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u ($\text{U}^{34+}$)
- CW and pulse modes
Location of HIAF and EicC
EicC accelerator complex overview

- **pRing**: figure 8
- **2 interaction regions**
- **20GeV p + 3.5 GeV e, √s=16.7GeV**
- **High Lumi.**: $2-4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
Machine Kinematics

- **EicC, \( \sqrt{s} \): 15 ~ 20 GeV**
  - Focus on nuclear physics
  - B-quark hadron production

### Facilities

<table>
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<tr>
<th>Facilities</th>
<th>Main goals</th>
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<td>JLab 12 GeV</td>
<td>Valence quark</td>
</tr>
<tr>
<td>EicC</td>
<td>Valence and Sea</td>
</tr>
<tr>
<td>US and Europe EIC</td>
<td>gluon</td>
</tr>
</tbody>
</table>
Spin of the Proton

Only ~30% of the proton spin from the quark spin, based on experiments.

\[ \frac{1}{2} = S_q + L_q + S_g + L_g \]

\[ S_q(Q^2) = \frac{1}{2} \int_0^1 \Delta \Sigma(x, Q^2) dx = \frac{1}{2} \int_0^1 \left( \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right) (x, Q^2) dx \]

\[ S_q \sim 30\% \ S_p \ [1] \quad L_q < 70\% \ S_p \ [2,3] \]

[8] COMPASS PLB690, 466(2010), 1001.4654
The Longitudinal Spin of the Nucleon

\[ \frac{1}{2} = S_q + L_q + S_g + L_g \]

\[ \frac{1}{2} \left[ \frac{d^2\sigma}{dx\,dQ^2} - \frac{d^2\sigma}{dx\,dQ^2} \right] \approx \frac{4\pi \alpha^2}{Q^4} y (2 - y) g_1(x, Q^2) \]

\[ g_1(x, Q^2) = \frac{1}{2} \sum e_q^2 \left[ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \right] \]

- EicC projection with 50 fb\(^{-1}\) lumi.

- Improving in the low x region

- High luminosity and large acceptance.
The Longitudinal Spin of the Nucleon

EicC SIDS data:
- Pion(+-), Kaon(+-)
- ep: 3.5 GeV X 20 GeV
- eHe-3: 3.5 GeV X 40 GeV
- Pol.: e(80%), p(70%), He-3(70%)
- Lumi: ep 50 fb⁻¹
eHe-3 50 fb⁻¹

Fragmentation function used: DSS

Preliminary

EicC, precise measurements, especially in sea quark region.

Plot Courtesy of Yuxiang Zhao

EicC, Statistic error only

Statistic error only
In Quantum Dynamics, a known particle’s full state is $\psi(\vec{x}, \vec{K}, t)$. In particle physics, the spatial dimension along the energy transfer direction (i.e., Z-axis) is ignored due to the relativistic effect. Also at $t=0$, it is a 5D space.

**TMD**

$TMD = 1D$ Longitudinally Momentum + $2D$ Transverse Momentum

**GPD**

$GPD = 1D$ Longitudinally Momentum + $2D$ Transverse Position
Transverse Momentum Dependent Functions (TMDs)

Unpolarized Density Function:
\[ f_1(x) = \int d^2 k \perp f_1(x, k \perp) \]

Helicity Function:
\[ g_1(x) = \int d^2 k \perp g_{1L}(x, k \perp) \]

Transversity Function:
\[ h_1(x) = \int d^2 k \perp [h_{1T}(x, k \perp) + \frac{k^2}{2M^2} h_{1T}^{-1}(x, k \perp)] \]

Asymmetries → TMDs
SIDIS Observables

SIDIS: Detect scattered electrons and produced single-hadron in the final state.

Measuring different hadrons, as flavor-tagger to probe the internal quark structure of nucleons.

- perform multidimensional analyses to disentangle all the relevant kinematical dependencies
- provide hadron identification to access the parton flavor
- large and uniform acceptance
- with high luminosity.
EicC projections on Sivers

\[ \text{LO analysis} \]

EicC SIDS data:

- Pion(+/−), Kaon(+/−)
- ep: 3.5 GeV × 20 GeV
- eHe-3: 3.5 GeV × 40 GeV
- Pol.: e(80%), p(70%), He-3(70%)
- Lumi: ep 50 fb⁻¹, eHe-3 50 fb⁻¹

EicC, precise measurements, especially in sea quark region.

Preliminary

Plot Courtesy of Tianbo Liu

EicC, Statistic error only
Generalized Parton Distributions (GPDs)

- GPDs encode information about the spatial distribution of partons inside a hadron, correlated with their distribution in longitudinal momentum.

- GPD is related to quark angular momentum.

Ji’s sum rule $^{[1]}$

$$J^f(Q^2) = \lim_{t \to 0} \int_{-1}^{1} dx ~ x \left[ H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2) \right],$$

- Exclusive reactions, such as DVCS, can get access to GPDs.

Probe GPD via DVCS

- Detect the scattered electron, real photon and nucleon.

- **Absolute Cross Section:**

  \[
  \frac{d\sigma}{dQ^2 dx_B dt d\phi} \propto |\tau_{DVCS}|^2 + I + |\tau_{BH}|^2
  \]

  \[
  \tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x, \xi, t)}{x \pm \xi + i \varepsilon} dx = P \int_{-1}^{+1} \frac{H(x, \xi, t)}{x \pm \xi} dx - i \pi H(\pm \xi, \xi, t),
  \]

- **Asymmetries with polarized target and/or polarized beam:**

  \[
  A = \frac{I}{|\tau_{DVCS}|^2 + I + |\tau_{BH}|^2} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
  \]

  \(\sigma^+/\sigma^-\): Beam or/and Target Polarization.

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Asymmetries</th>
<th>CFFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Beam</td>
<td>(A_L)</td>
<td>(\text{Im}{\mathcal{H}_p, \mathcal{H}_p, \varepsilon_p})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{Im}{\mathcal{H}_n, \mathcal{H}_n, \varepsilon_n})</td>
</tr>
<tr>
<td>Longitudinal Target</td>
<td>(A_L)</td>
<td>(\text{Im}{\mathcal{H}_p, \mathcal{H}_p, \varepsilon_p})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{Im}{\mathcal{H}_n, \mathcal{H}_n, \varepsilon_n})</td>
</tr>
<tr>
<td>Long. Beam + Long. Target</td>
<td>(A_{LL})</td>
<td>(\text{Re}{\mathcal{H}_p, \mathcal{H}_p, \varepsilon_p})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{Re}{\mathcal{H}_n, \mathcal{H}_n, \varepsilon_n})</td>
</tr>
<tr>
<td>Transverse Target</td>
<td>(A_{UT})</td>
<td>(\text{Im}{\mathcal{H}_p, \varepsilon_p})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{Im}{\mathcal{H}_n})</td>
</tr>
<tr>
<td>Long. Beam + Trans. Target</td>
<td>(A_{LT})</td>
<td>(\text{Re}{\mathcal{H}_p, \varepsilon_p})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\text{Re}{\mathcal{H}_n})</td>
</tr>
</tbody>
</table>
EicC can measure GPD related asymmetries:

- In high precision
- In multi-dimensional bins
- On p and n for flavor separations

Plot Courtesy of Qiang Fu and Xu Cao.

Need far-forward detection of scattered proton.

Preliminary

EicC can measure GPD related asymmetries:

- In high precision
- In multi-dimensional bins
- On p and n for flavor separations

Integrated Lumi. 50 fb⁻¹

Statistic error only

Plot Courtesy of Qiang Fu and Xu Cao.
Proton Mass decomposition[1]:

\[
\begin{align*}
\tilde{M}_q &= \frac{\langle P|H_q|P\rangle}{\langle P|P\rangle} = \frac{3}{4} \left( a - \frac{b}{1 + \gamma_m} \right) M, \\
\tilde{M}_g &= \frac{\langle P|H_g|P\rangle}{\langle P|P\rangle} = \frac{3(1 - a)}{4} M, \\
\tilde{M}_m &= \frac{\langle P|H_m|P\rangle}{\langle P|P\rangle} = \frac{b}{4} \frac{4 + \gamma_m}{1 + \gamma_m} M, \\
\tilde{M}_a &= \frac{\langle P|H_a|P\rangle}{\langle P|P\rangle} = \frac{1 - b}{4} M.
\end{align*}
\]

- \(a\): related to PDFs, well constrained
- \(b\): related to quarkonium-proton scattering amplitude \(M_{\psi p}\) near-threshold

Other interesting topics

- Pion/Kaon structure
- Hadronization
- Hadron Spectroscopy
- And more...
Very first design; detector options are open.
EicC Status

4 pre-Collaboration meetings up to now.

Discussions on:
physics programs,
simulations
accelerator, detector.

EicC white paper
1. Chinese Version by the end of 2019,
EicC and Lattice QCD

- Complementary.

- Start from quantities both can do: (Un)polarized PDFs

Good agreement between extracted moments of helicity distributions and lattice calculation.

- Lattice calculation of proton mass, spin, ...[1,2,3,4]

- Lattice calculation of TMD parton distributions possible[5,6].

And more, ... ...

Southern Nuclear Science Computing center (SNSC)

- A specialized computing center for contemporary nuclear physics problems: Experimental and Theoretical activities
- Computing power: 5~10 Petaflops (GPUs dominate + some CPUs)
- Scientific interests:
  - Lattice QCD
  - Lattice EFT
  - Machine learning
  - Heavy-ion physics
  - Light-front quantization
  - Data analysis (CEE, HIAF, EicC...)
  - ……
- Expected to start running in 2021.
Electron Ion Collider in China

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Summary

- EicC has been proposed based on the HIAF facility.
  - polarized electron beam (3.5 GeV)
  - polarized proton beam (20 GeV)/ion beam (20 GeV/u)

- High precision measurements for 1D (helicity), 3D (TMDs/GPDs) nucleon structure study with flavor separation in the valence and sea quark dominated region.

- Other interesting physics topics will be delivered as well, not mentioned here in details.

- Input from Lattice Community will be helpful.

Welcome to join us!

EicC@impcas.ac.cn
Thank You
EicC detector requirements

SIDIS: very general requirement.

DVCS: detection of proton at forward direction.

Pion/Kaon structure: detection of neutron at forward direction.
High Intensity heavy-ion Accelerator Facility

**Superconducting Ion Linac:**
- Length: 180 m
- Energy: 17 MeV/u ($^{34+}$U)
- CW and pulse modes

**Booster Ring:**
- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration

**Spectrometer Ring:**
- Circumference: 270.5 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler
- Deacceleration

**Phase I**
- Two-plane painting injection scheme
- Fast ramping rate operation

**Superconducting Ion Linac:**
- Length: 180 m
- Energy: 17 MeV/u ($^{34+}$U)
- CW and pulse modes
Transverse Momentum Dependent Parton Distributions

$f_1^q(x, k_T)$, unpolarized, probability of finding a quark carrying $x$, and a transverse momentum $k_T$.

$g_{1L}^q(x, k_T)$, longitudinal polarized.

$h_1^q(x, k_T)$, transversely polarized.

\[
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2}\right)
\times \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \ldots \right\}
\]

### Fragmentation Functions (FF):

- **$D_1 \rightarrow$ Unpolarized FF, $H_1^\perp \rightarrow$ Collins FF**
  - Describe the process of the struck quark fragmenting into a hadron
  - Can be obtained from $(e + e^- \rightarrow h^\pm + X)$ data (e.g., BELLE)

### 3D Structure of Nucleons

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<tr>
<th>Leading Twist TMDs</th>
<th>Quark Polarization</th>
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<tr>
<td><strong>Unpolarized</strong> (U)</td>
<td>$f_1(x, k_T^2)$</td>
</tr>
<tr>
<td><strong>Longitudinally Polarized</strong> (L)</td>
<td>$g_1(x, k_T^2)$</td>
</tr>
<tr>
<td><strong>Transversely Polarized</strong> (T)</td>
<td>$h_1^T(x, k_T^2)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>probes TMD using SIDIS</th>
<th>Quark Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unpolarized</strong> (U)</td>
<td>$F_{UU}$</td>
</tr>
<tr>
<td><strong>Longitudinally Polarized</strong> (L)</td>
<td>$A_{LL}$</td>
</tr>
<tr>
<td><strong>Transversely Polarized</strong> (T)</td>
<td>$A_{UT}$</td>
</tr>
</tbody>
</table>

- $f_1^U \propto h_1^U \otimes D_1$
- $g_1^U \propto g_1 \otimes D_1$
- $h_1^T \propto h_1^T \otimes D_1$

<table>
<thead>
<tr>
<th>TMDs via SIDIS</th>
<th>Unpolarized (U)</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unpolarized</strong> (U)</td>
<td>$f_{UU}$</td>
<td>$A_{UU}$</td>
<td>$A_{UT}$</td>
</tr>
<tr>
<td><strong>Longitudinally Polarized</strong> (L)</td>
<td>$A_{LL}$</td>
<td>$A_{UL}$</td>
<td>$A_{LT}$</td>
</tr>
<tr>
<td><strong>Transversely Polarized</strong> (T)</td>
<td>$A_{UT}$</td>
<td>$A_{UT}$</td>
<td>$A_{TT}$</td>
</tr>
</tbody>
</table>

**Additional notation:**
- $e^- e^+ \rightarrow h^\pm + X$
- $\bar{q} q \rightarrow h^\pm + X$
- $\gamma^* \rightarrow q \bar{q}$
- $\pi^0$ and $\rho^0$ production
Present status of TMDs extraction

Sivers

Transversity

Pretzelosity

Collins fragmentation function
Transverse Momentum Dependent Parton Distributions


Extract TMDs from asymmetries
With recent progresses in [5, 6] it is possible to calculate the TMD parton distributions with Lattice QCD.
Transverse Momentum Dependent Parton Distributions

Experimental observables
Generalized Parton Distributions (GPDs)

Eight GPDs for quarks or gluons

- $x \rightarrow$ Longitudinal quark momentum fraction (not experimental accessible)
- $\xi \rightarrow$ Longitudinal momentum transfer. In Bjorken limit: $\xi = x_B/(2-x_B)$
- $t \rightarrow$ Total squared momentum transfer to the nucleon: $t = (P-P')^2$

$$J^q = \frac{1}{2} \int dxf(x, \xi = 0 + E^q(x, \xi, t = 0))$$

HIAF Timetable

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<th>Construction and Installation</th>
<th>Commissioning</th>
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<td>Approval 21</td>
<td>Construction</td>
<td>Commissioning</td>
</tr>
<tr>
<td>Approval 15</td>
<td>Key technology R&amp;D</td>
<td>Facility commissioning</td>
<td>Operation 24</td>
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<tr>
<td>Preliminary design</td>
<td>Conceptual design</td>
<td>Sub-system commissioning</td>
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<tr>
<td>Approval</td>
<td>Detailed design &amp; prototype</td>
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<td></td>
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<tr>
<td>Civil construction</td>
<td>Fabrication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
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</tbody>
</table>

- **Design**
  - Preliminary design
  - Conceptual design
  - Approval
  - Detailed design & prototype

- **Construction and Installation**
  - Civil construction
  - Fabrication
  - Installation

- **Commissioning**
  - Sub-system commissioning
  - Facility commissioning
  - Operation
EicC 总体规划

EicC 总体方案布局

高功率重离子压缩环
高能量密度研究
7.6 GeV/u(U^{34+})
5.0×10^{12}ppp, 50-100ns

电子对撞环
5.0 GeV
C: 1.5-2.0 km

高能电子对撞环
HeRing
5-10 GeV
C: 1.5-2.0 km

高能离子对撞环
HpRing
60-100 GeV
C: 1.5-2.0 km

电子注入器:
SRF Linac-ring, 3.5-10 GeV

离子对撞环 - pRing
20 GeV, C: 1347 m Polarized proton

HIAF-I

EicC-I

EicC-II

HFRS
SRing
MRing

BRing

电子对撞环
eRing
5.0 GeV
A Ring-Ring (polarized) Lepton-Proton collider with 320 GeV CM energy

1981 Proposal
1984 Start construction
1991 Commissioning, first Collisions
1992 Start Operations for H1 and ZEUS, 1st exciting results with low luminosity
1994 Install East Spin Rotators
   Longitudinal polarized leptons for HERMES
1996 Install 4th Interaction region for HERA-B
1999 High Luminosity Run with electrons
2000 High efficient luminosity production: 100 /pb/y
2001 Install luminosity upgrade,
   Spin Rotators for H1 and ZEUS
2003 Longitudinal polarization in high energy collisions
2007 End of a highly successful program

Final luminosity (1.5 to 5)x10^{31} cm^{-2}s^{-1}

Tunnel: 5.2 m diameter
电子环方案: ERL，NS-FFAG

质心能量: $255\text{GeV/p} + 15.9\text{GeV/e}$

设计亮度: $4.4 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ – 无冷却

$1.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ - 冷却

工程计划: 2022-2025之间开建
美国-JLab: JLEIC

CEBAF

11 GeV max energy

12 GeV max energy
**Present baseline: Ring-Ring**

- **Energy:** 3-12 GeV e on 20-100 GeV p
  or up to 40 GeV/u ion
- **Polarized light ions (p, d, $^3$He), unpolarized ions up to A=200 (Au, Pb)
- **New ion complex & two collider rings**
- **Up to 3 interaction points**
- **High polarization for both beams**
- **Conventional electron cooling**
- **Upgradable to 20 GeV electron, 250 GeV proton or 100 GeV/u ion**
CERN: LHeC

电子环方案：ERL circulator Ring

质心能量: 7 TeV p + 60 GeV e

设计亮度: $1.6 \times 10^{34}$ cm$^{-2}$s$^{-1}$

工程计划：2025-2035 方案设计

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<thead>
<tr>
<th>10$^{34}$ cm$^{-2}$s$^{-1}$ Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>GeV</td>
<td>7000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>10$^{33}$cm$^{-2}$s$^{-1}$</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance $g_{xy}$</td>
<td>mm</td>
<td>2.5</td>
</tr>
<tr>
<td>Beta Funtion $b_{xy}$</td>
<td>m</td>
<td>0.05</td>
</tr>
<tr>
<td>rms Beam size $s_{xy}$</td>
<td>mm</td>
<td>4</td>
</tr>
<tr>
<td>Beam Current</td>
<td>mA</td>
<td>1112</td>
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<tr>
<td>Bunch Spacing</td>
<td>ns</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>10$^9$</td>
<td>2.2$\times$10$^{11}$</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>nC</td>
<td>35</td>
</tr>
</tbody>
</table>
国际EIC研究目标

**EicC**
- 20(p)+5 (e) GeV
- 100(p)+10 (e) GeV
- 质心能: 20/45 GeV

**JLEIC**
- 100(p)+5 (e)GeV
- 100(p)+10 (e)GeV
- 质心能: 45/63 GeV

**eRHIC**
- 255(p)+15.9(e)GeV
- 质心能: 126 GeV

**LHeC**
- 7TeV+60GeV
- 非极化
- 质心能: 1296 GeV
The Longitudinal Spin of the Nucleon

\[ \frac{1}{2} = S_q + L_q + S_g + L_g \]

\[ \Delta f(x, Q^2) = f^+(x, Q^2) - f^-(x, Q^2) \quad f = u, d, s, \bar{u}, \bar{d}, \bar{s}, g \]

\[ S_q(Q^2) = \frac{1}{2} \int_0^1 \Delta \Sigma(x, Q^2) dx \equiv \frac{1}{2} \int_0^1 (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) (x, Q^2) dx \]

\[ \frac{1}{2} \left[ \frac{d^2 \sigma}{dx dQ^2} \right] \simeq \frac{4\pi \alpha^2}{Q^2 y(2-y)} g_1(x, Q^2) \]

\[ g_1(x, Q^2) = \frac{1}{2} \sum c_q^2 \left[ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \right] \]

**EicC:**

- e p: 3.5 GeV 20 GeV 50fb-1
- e 80% pol. p 70% pol.
- e He-3: 3.5GeV 40/3 GeV/u
- 50fb-1 e 80% pol. He-3 70% pol.
\[ T^{\mu\nu} = \frac{1}{2} \bar{\psi} \gamma^\mu \mathcal{D}_\nu \psi + \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F_{\alpha}, \]

First of all, let me decompose the \( T^{\mu\nu} \) into traceless and trace parts,

\[ T^{\mu\nu} = \bar{T}^{\mu\nu} + \hat{T}^{\mu\nu}, \quad (7) \]

where \( \bar{T}^{\mu\nu} \) is traceless. According to Eq. (4), I have,

\[ \langle P | \bar{T}^{\mu\nu} | P \rangle = \left( P^\mu P^\nu - \frac{1}{4} M^2 g^{\mu\nu} \right) / M, \quad (8) \]

\[ \langle P | \hat{T}^{\mu\nu} | P \rangle = \frac{1}{4} g^{\mu\nu} M. \quad (9) \]

Combining Eq. (6) with the above three equations, I get,

\[ \langle \bar{T}^{00} \rangle = \frac{3}{4} M, \quad (10) \]

\[ \langle \hat{T}^{00} \rangle = \frac{1}{4} M. \quad (11) \]

Thus 3/4 of the nucleon mass comes from the traceless part of the energy-momentum tensor and 1/4 from the trace part. The magic number 4 is just the space-time dimension. This
The traceless part of the energy-momentum tensor can be decomposed into the contribution from the quark and gluon parts.

\[ \overline{T}^{\mu\nu} = \overline{T}_q^{\mu\nu} + \overline{T}_g^{\mu\nu}, \]  

\[ \langle \overline{T}^{00}_q \rangle = \frac{3}{4} a(\mu^2)M, \]

\[ \langle \overline{T}^{00}_g \rangle = \frac{3}{4} (1 - a(\mu^2))M. \]

Finally, I turn to the trace part of the energy-momentum tensor \( \hat{T}^{\mu\nu} \). According to Eq. (5), I decompose it into \( \hat{T}^{\mu\nu}_m \) and \( \hat{T}^{\mu\nu}_a \), the mass term and trace anomaly term, respectively. Both operators are finite and scale independent. If I define,

\[ b = 4 \langle \hat{T}^{00}_m \rangle / M, \]  

then according to Eq. (11), the anomaly part contributes,

\[ \langle \hat{T}^{00}_a \rangle = \frac{1}{4} (1 - b)M. \]

Thus, the energy-momentum tensor \( T^{\mu\nu} \) can be separated into four gauge-invariant parts, \( \hat{T}^{\mu\nu}_q, \hat{T}^{\mu\nu}_g, \hat{T}^{\mu\nu}_m, \) and \( \hat{T}^{\mu\nu}_a \). They contribute, respectively, \( 3a/4, 3(1 - a)/4, b/4, \) and \( (1 - b)/4 \) fractions of the nucleon mass. The corresponding breakdown for the hamiltonian is, \( H_{QCD} = H'_q + H_g + H'_m + H_a \), with
\[ H'_q = \int d^3 \vec{x} \left[ \bar{\psi} (-i \mathbf{D} \cdot \mathbf{\alpha}) \psi + \frac{3}{4} \bar{\psi} m \psi \right], \]
\[ H_g = \int d^3 \vec{x} \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2), \]
\[ H'_m = \int d^3 \vec{x} \frac{1}{4} \bar{\psi} m \psi, \]
\[ H_a = \int d^3 \vec{x} \frac{9 \alpha_s}{16 \pi} (\mathbf{E}^2 - \mathbf{B}^2). \]

\[ H_q = \int d^3 \vec{x} \bar{\psi} (-i \mathbf{D} \cdot \mathbf{\alpha}) \psi, \]
\[ H_m = \int d^3 \vec{x} \bar{\psi} m \psi, \]

then the QCD hamiltonian becomes,

\[ H_{\text{QCD}} = H_q + H_m + H_g + H_a. \]

Here \( H_q \) (Eq. (26)) represents the quark and antiquark kinetic and potential energies and contributes \( 3(a - b)/4 \) fraction of the nucleon mass. \( H_m \) (Eq. (27)) is the quark mass term and contributes \( b \) fraction of the mass. \( H_g \) (Eq. (23)) is the normal part of the gluon energy and contributes \( 3(1 - a)/4 \) fraction of the mass. Finally, \( H_a \) (Eq. (25)) is the gluon energy from the trace anomaly. It contributes \( (1 - b)/4 \) fraction of the mass.
\[ \frac{d\sigma}{dx
dy
dz
d\phi_h
dP^2_{h\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2} \right) \times \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2}\varepsilon(1+\varepsilon) \cos \phi_h F^\cos_{UU} + \varepsilon \cos(2\phi_h) F^\cos_{UU} \right. \\
+ \lambda_e \sqrt{2}\varepsilon(1-\varepsilon) \sin \phi_h F^\sin_{LU} + S_{\parallel} \left[ \sqrt{2}\varepsilon(1+\varepsilon) \sin \phi_h F^\sin_{UL} + \varepsilon \sin(2\phi_h) F^\sin_{UL} \right] \\
+ S_{\parallel} \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2}\varepsilon(1-\varepsilon) \cos \phi_h F^\cos_{LL} \right] \\
+ |S_-| \left[ \sin(\phi_h - \phi_s) \left( F^\sin_{UT,T} + \varepsilon F^\sin_{UT,L} \right) + \varepsilon \sin(\phi_h + \phi_s) F^\sin_{UT} \right] \\
+ \varepsilon \sin(3\phi_h - \phi_s) F^\sin_{UT} + \sqrt{2}\varepsilon(1+\varepsilon) \sin \phi_s F^\sin_{UT} \\
+ \sqrt{2}\varepsilon(1+\varepsilon) \sin(2\phi_h - \phi_s) F^\sin_{UT} \\
+ |S_-| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_s) F^\cos_{LT} + \sqrt{2}\varepsilon(1-\varepsilon) \cos \phi_s F^\cos_{LT} \right] \\
+ \sqrt{2}\varepsilon(1+\varepsilon) \cos(2\phi_h - \phi_s) F^\cos_{LT} \right\} \} ,
One particular example is the quark Sivers function \( f_{1T}^{LQ} \) which describes the transverse momentum distribution correlated with the transverse polarization vector of the nucleon. As a result, the quark distribution will be azimuthally asymmetric in the transverse momentum space in a transversely polarized nucleon. Figure 2.13 demonstrates the deformations of the up and down quark distributions. There is strong evidence of the Sivers effect in the DIS experiments observed by the HERMES, COMPASS, and JLab Hall A collaborations [71, 72, 73]. An important aspect of the Sivers functions that has been revealed theoretically in last few years is the process dependence and the color gauge invariance [74, 75, 76, 77]. Together with the Boer-Mulders function, they are denoted as naive time-reversal odd (T-odd) functions. In SIDIS, where a leading hadron is detected in coincidence with the scattered lepton, the quark Sivers function arises due to the exchange of (infinitely many) gluons between the active struck quark and the remnants of the target, which is referred to as final state interaction effects in DIS. On the other hand, for the Drell-Yan lepton pair production process, it is due to the initial state interaction effects. As a consequence, the quark Sivers and Boer-Mulders functions differ by a sign in these two processes. This non-universality is a fundamental prediction from the gauge invariance of QCD [75]. The experimental check of this sign change is currently one of the outstanding topics in hadronic physics, and Sivers functions from the Drell-Yan process can be measured at RHIC.
The Longitudinal Spin of the Nucleon

\[\frac{1}{2} = S_q + L_q + S_g + L_g\]

\[\Delta f(x, Q^2) \equiv f^+(x, Q^2) - f^-(x, Q^2) \quad f = u, d, s, \bar{u}, \bar{d}, \bar{s}, g\]

\[S_q(Q^2) = \frac{1}{2} \int_0^1 \Delta \Sigma(x, Q^2) dx \equiv \frac{1}{2} \int_0^1 (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) (x, Q^2) dx\]

\[\frac{1}{2} \left[ \frac{d^2 \sigma^{+\rightarrow}}{dx \, dQ^2} - \frac{d^2 \sigma^{-\rightarrow}}{dx \, dQ^2} \right] \approx \frac{4\pi \alpha^2}{Q^4} y(2 - y) g_1(x, Q^2)\]

\[g_1(x, Q^2) = \frac{1}{2} \sum e_q^2 \left[ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \right]\]
