High-Energy Hadron Physics at RHIC and EIC

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Nucleon spin physics

• Spin puzzle
  • Origin of the nucleon spin in the quark-gluon picture
    \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L \]
    Orbital angular momentum
    Gluon spin
    Quark spin
  • Quark-spin contribution is only about 30% of the nucleon spin

• Longitudinal-spin (beam axis direction) asymmetry measurement
  • Gluon polarization measurement
  • Anti-quark polarization measurement using W boson

• Transverse-spin asymmetry measurement
  • Understanding of orbital motion inside the nucleon and orbital angular momenta of quarks and gluons from large transverse single-spin asymmetry in the forward kinematic region
Polarized proton acceleration at RHIC

- Keeping and monitoring polarization from the polarized proton source
Polarized proton collision

- $\sqrt{s} = 200$ GeV
  - Average luminosity $6.3 \times 10^{31}$ cm$^{-2}$s$^{-1}$
  - Polarization 55%

- $\sqrt{s} = 510$ GeV
  - Average luminosity $1.6 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - Polarization 52%

First polarized proton collision experiment in 2001
Polarized proton collision experiments

• STAR detector
  • $2\pi$ coverage for jet measurement
  • barrel TPC and EMC
  • endcap EMC

• PHENIX detector
  • limited acceptance
  • high resolution central EMCal
  • high-rate trigger and DAQ
  • forward muon detectors
**Longitudinal polarized proton collision**

- $A_{LL}$ (double-helicity asymmetry) measurement
  - Polarized in the beam axis direction
  \[
  A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}
  \]

- Gluon polarization
  - $A_{LL}$ measurement for gluon+gluon and gluon+quark reactions

Midrapidity jet at STAR

Midrapidity $\pi^0$ at PHENIX
Gluon polarization

• Positive gluon polarization obtained by DSSV and NNPDF groups with the QCD global analysis including polarized proton collision data at RHIC
  • 2014 press releases
  • 200 GeV collision data at RHIC
  • Jet asymmetry from STAR
  • $\pi^0$ asymmetry from PHENIX

\[
Q^2 = 10 \text{ GeV}^2 \quad \int_{0.05}^{0.2} dx \Delta g(x, Q^2)
\]

| NNPDFpol1.1 | $+0.15 \pm 0.06$
| DSSV14       | $0.10^{+0.06}_{-0.07}$

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More measurements

• Di-jets
  • Information about $x_1$ and $x_2$
  • $x$-dependence (shape) of the gluon polarization

• Forward $J/\psi$
  • Gluons from two distinct ranges of $x$
    • $x \sim 0.05$ & $x \sim 0.002$

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PRD95 (2017) 071103(R)

PRD94 (2016) 112008
**Anti-quark polarization**

- Parity-violating $A_L$ measurement with W-boson production

- **Forward rapidity**

  \[
  - \Delta u(x_a) \\
  u(x_a)
  \]

- **Backward rapidity**

  \[
  \frac{\Delta \bar{d}(x_a)}{\bar{d}(x_a)}
  \]

\[
A_L^{W^+} = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)d(x_b) + \bar{d}(x_a)u(x_b)}
\]

- W boson produced in the backward rapidity sensitive to the anti-quark polarization

- W boson data analysis ongoing with sufficient data obtained by 2013
Anti-quark polarization

- $W$ boson data analysis ongoing with sufficient data obtained by 2013
- $\Delta\bar{u} > \Delta\bar{d}$ suggested by the QCD global analysis
  - $\bar{d} > \bar{u}$ in the unpolarized case

PHENIX
$W \rightarrow e$ 2011-13
PRD 93, 051103 (2016)
$W \rightarrow \mu$ 2013 preliminary

STAR
$W \rightarrow e$ 2011-12
PRL 113, 072301 (2014)
$W \rightarrow e$ 2013 preliminary

Transverse polarized proton collision

- $A_N$ (transverse single-spin asymmetry) measurement
  \[ A_N = \frac{d\sigma_{\text{Left}} - d\sigma_{\text{Right}}}{d\sigma_{\text{Left}} + d\sigma_{\text{Right}}} \]
  - Azimuthal angle modulation (or dependence)
  - Large $A_N$ for forward hadron production
    - Similar results in wide $\sqrt{s}$

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3D structure of the nucleon

• Conclusive understanding of the nucleon spin
  • Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons

• TMD (Transverse-Momentum Dependent) distribution function
  • Correlation between the (orbital) motion, spin of partons, and spin of the nucleon

• GPD (Generalized Parton Distribution)
  • Spatial distribution or tomography
Higher-twist effect

- Quantum many-body correlation among quarks and gluons
  - Based on collinear factorization
  - quark-gluon correlation, tri-gluon correlation, twist-3 fragmentation
- Reproducing experimental data with precision calculation of twist-3 fragmentation function

Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).
More measurements

• Heavy flavor production
  • No final state effect from gluon-gluon process
  • Twist-3 tri-gluon correlation

• Multiplicity dependence
  • $A_N$ for different # of photons
  • $A_N$ decreases as the event complexity increases (more jet-like)
  • How much of the large $\pi^0 A_N$ comes from $2 \rightarrow 2$ parton scattering? Or diffreactive events?
**TMD function**

- **Comparison between polarized semi-inclusive DIS and polarized Drell-Yan reaction**
  - Important test to establish TMD (Transverse Momentum Dependent) function
    - Sign change of TMD (Sivers) distribution function
    - Initial- or final-state interaction effect

- **W-boson production**
  - 2011 data at STAR
  - PRL 116 (2016) 132301
  - Higher statistics in 2017

\[
f_{1T}^\perp(x, k_\perp)|_{SIDIS} = -f_{1T}^\perp(x, k_\perp)|_{Drell-Yan}
\]
Quark transversity

- Quark transverse-spin contribution to the transversely polarized nucleon
  - Related to the tensor charge of the nucleon

- $\pi^+\pi^-$ interference fragmentation function
  - Enhancement around the $\rho$-mass region

- Collins fragmentation function
  - Hadron in Jet
  - SIDIS + B-factory based transversity fits
Forward neutral particles

- Forward neutron asymmetry
  - Significant negative $A_N$
  - No $x_F$ dependence within the uncertainties
  - $\sqrt{s}$ or $p_T$ dependence
- RHICf experiment in 2017
  - Collaboration with LHCf group
  - Photon, $\pi^0$, neutron
  - Cross section measurement for input to the phenomenological collision models
  - Asymmetry measurement with wide $p_T$ range ($p_T < 1.2$ GeV/c) and high $p_T$ resolution
Cold nuclear matter effects

- Di-jet suppression at forward rapidities
  - d+Au vs p+p collisions
  - Suppression increasing with increasing $N_{\text{coll}}$
  - Decreasing with increasing $p_T$ (related to increasing $x$)
    - Strong suppression at lowest $x$
    - Gluon saturation at low $x$?

PRL107 (2011) 172301
Polarized p+A collisions

- $\pi^0 A_N$ at forward rapidities
  - Prediction of reduced $A_N$ in polarized p+A collisions due to the gluon saturation
  - No substantial reduction in 2015 STAR data
  - Origin of $A_N$ unclear
- Forward neutron $A_N$
  - Unexpectedly large A dependence and sign change
  - Possible explanation with ultra-peripheral collisions (UPC)
Future of nucleon spin physics at RHIC

- RHIC Cold QCD Plan for 2017–2023
  - arXiv:1602.03922
  - Completion of the RHIC spin program
- A portal to the EIC
  - “providing a comprehensive set of measurements in hadronic collisions that, when combined with data from the EIC, will establish the validity and limits of factorization and universality”
- Transverse-spin asymmetries
  - $A_N$ for charged hadrons and flavor enhanced jets
  - Hadron asymmetries in jet modulations
  - $A_N$ for Drell-Yan / photon
- Nuclear parton distribution and gluon saturation
- Gluon polarization at small Bjorken-$x$
**sPHENIX experiment**

- Large-acceptance jet and upsilon detector around the BaBar superconducting solenoid
  - $|\eta| < 1.1$ and $0 < \phi < 2\pi$
  - EM & hadron calorimeters
  - TPC
  - Silicon detectors (MAPS)

- Construction schedule for 2022-2023 sPHENIX run

- Gluon polarization measurement
  - $> 100$ times of the final statistics of PHENIX at $\sqrt{s} = 200$ GeV polarized $p+p$
  - $\pi^0$, hadron, photon, jet, dijet, ...

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Forward sPHENIX (fsPHENIX)

- LoI for fsPHENIX
  - $1.2 < \eta < 4$
  - EM calorimeter
  - Hadron calorimeter
  - Trackers
    - GEM / sTGC
    - Silicon detector
  - Magnetic field shaper
  - Within 4.5 m eRHIC IR constraint

- Physics at fsPHENIX
  - Transverse-spin asymmetries
    - Jet + hadron
  - Gluon polarization at small-$x$
Spin physics at fsPHENIX

- Jet asymmetries tagging positive/negative hadrons
  - Flavor dependence of the twist-3 ETQS distribution
  - Evolution of the twist-3 ETQS distribution function
- EM + Hadron calorimeters & tracker are necessary
  - For jet + hadron measurement & triggering

Figure 2-11: Left: up quark (red points), down quark (blue points) and all jet (black points) single spin asymmetries as a function of $x_F$ as calculated by the ETQS based on the SIDIS Sivers functions. Right: Expected experimental sensitivities for jet asymmetries tagging in addition a positive hadron with $z$ above 0.5 (red points), a negative hadron with $z$ above 0.5 (blue points) or all jets (black) as a function of $x_F$. Note: these figures are currently for 200 GeV center-of-mass energy proton collisions – the 500 GeV results are expected to be qualitatively similar but with reduced uncertainties due to the larger luminosities expected.
**Spin physics at fsPHENIX**

- Hadron angular distribution in jets
- Transversity & Collins function

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**Figure 2-14:** Expected $h^-$ Collins asymmetry uncertainties (black points) compared to positive (red) and negative (blue) pion asymmetries based on the Torino extraction [45] (full lines) and the Soffer bound [83] (dashed lines) as a function of fractional energy $z$ for various bins in jet rapidity and transverse momentum.

**Expected $h^-$ Collins asymmetry uncertainties**
**EIC (Electron Ion Collider) project**

- World’s first polarized electron + proton / light-ion / heavy-ion collider
  - Wide \((Q^2, x)\) region
- Electron + proton / light-ion collision
  - Polarized beam
    - \(e, p, d/\text{He}\)
  - High luminosity
    - \(L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}\)
    - 100-1000 times HERA
- Collision energy
  - \(\sqrt{s} = 20 – 100 (140) \text{ GeV}\)
- Electron + heavy-ion collision
  - Wide range in nuclei
Gluon physics

• 3D structure of nucleon and nuclei
  • TMD / GPD measurements
  • Gluon distribution (radius...)
• Nucleon spin
  • Small Broken-$x$ region and evolution
  • GPD and orbital angular momentum
• Gluon saturation (discovery)
  • Collective gluon field
  • Initial state of Quark-Gluon Plasma
• Hadronization and jet production in nuclei
3D structure of the nucleon

• How are quarks and gluons confined in the nucleon?
  • Bug model
    • gluon radius > charged radius
  • Constituent quark model
    • gluon radius ~ charged radius
  • Lattice gauge theory
    • gluon radius < charged radius

• Need measurement of transverse images of the quarks and gluons in the nucleon
  • Combined understanding of nucleon (or hadron) property at low energy and quark-gluon picture at high energy?

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GPD (Generalized Parton Distribution)

- Tomography of the nucleon / nucleus
  - DVCS (Deeply Virtual Compton Scattering)
  - Meson production
- Spatial imaging of gluons and sea quarks
  - 2D (spatial) + 1D (longitudinal moment) coordinate space image
- Gluon GPDs from $J/\psi$ production at EIC

DVCS (Deeply Virtual Compton Scattering)

Meson Production

$J/\psi$, $\phi$, $\rho$, etc.
Gluon GPDs at HERA

VM production and DVCS: t-dependence, $b(Q^2 + M^2_{VM})$

- $d\sigma/dt \sim e^{-b|t|}$
- Data show $b$ decreasing vs $Q^2 + M^2_{VM}$ up to an asymptotic value
- In optical model approach, via Fourier transform, $b$ is related to the size of the interaction region:
  \[ b \sim \frac{(R_p^2 + R_{VM}^2)}{4} \]
- For $b \sim 4.5$ GeV$^{-2}$ → radius of interaction $\sim 0.6$ fm, smaller than the radius of proton tested in EM interactions to be 0.8 fm

Size of interacting gluons within the protons is smaller than the size of the quarks in the proton and is getting smaller with $Q^2 + M^2_{VM}$
Gluon saturation

- Gluon density saturated where gluon emission and recombination comparable
  - Color glass condensate (CGC)
  - First observation of a collective gluonic system

\[
\text{gluon emission} = \text{gluon recombination at } Q_s^2
\]

- Enhancement with nucleus
  - Saturation at significantly lower energy in e+A collisions at EIC
Diffractive process

- Gluon saturation
  - Diffraction is the most sensitive way
  - More diffraction if saturation/CGC at EIC e+A
Diffractive process

- 3D structure of nucleus
Hadronization

• Response of nuclear matter to fast moving color charge passing through it
EIC project

- Recommendation for new facility construction in NSAC 2015 Long Range Plan
- Review by NAS (National Academy of Science) Committee underway
- eRHIC detector
  - LoI of upgrade from sPHENIX to ePHENIX
  - ePHENIX hadron arm from fsPHENIX + new electron arm
- Operation in 2025 or later
Summary

• RHIC spin program
  • Origin of the nucleon spin 1/2 (spin puzzle)
    • Positive gluon spin contribution to the nucleon spin (gluon polarization) measured similar to the quark spin contribution
    • $\Delta \bar{u} > \Delta \bar{d}$ suggested for the anti-quark polarization
  • Understanding of the transverse polarization phenomena with higher-twist and TMD (Transverse Momentum Dependent) functions
    • Measurement of the 3D structure of the nucleon and orbital motion inside the nucleon

• Cold QCD plan to complete the RHIC spin program
  • Construction of the sPHENIX detector and proposal of the forward sPHENIX detector

• EIC (Electron Ion Collider) project
  • eRHIC at BNL or JLEIC at JLab
  • Review process underway, formation of the EIC User Group
  • Proposal of upgrade from sPHENIX to ePHENIX
Backup Slides
RHICスピン計画

• 理研BNL国際協力
• 1995: RHICでのスピン物理のための理研BNL間のMoU
  • RHIC偏極陽子加速のためのスネーク磁石、偏極度計
  • PHENIX実験ミューオンアーム磁石、検出器
• 1997: 理研BNL研究センター
(Unpolarized) cross section measurements

- Applicability of (NLO) perturbative QCD
- Basis for polarized measurements

Midrapidity jet at STAR

Midrapidity $\pi^0$ at PHENIX
Extention of Bjorken-x region

- Bjorken-x: energy fraction of parton in the proton
- Large-x
  - $A_{LL}$ measurement at $\sqrt{s} = 62.4$ GeV
- Small-x
  - $A_{LL}$ measurement at $\sqrt{s} = 510$ GeV
  - Forward measurement
    - Reaction of 2 partons with separated Bjorken-x
    - Muon arms & MPC at PHENIX
    - Endcap calorimeter and FMS at STAR

\[ x_T = \frac{2p_T}{\sqrt{s}} \]

\[ p_T \text{ (GeV)} \]

PHENIX MPC projection

\[ A_{LL} \]

\[ A_{LL}^\pi^0 \]

Physics Rev. D79 (2009) 012003

Physics Rev. D 93 (2016) 011501
**Bjorken-x 領域の拡張**

- **Bjorken-x**: 陽子中のパートークの持つエネルギー比
- **Large-x**
  - $\sqrt{s} = 62.4$ GeV での $A_{LL}$ 測定
- **Small-x**
  - 最高衝突エネルギー $\sqrt{s} = 510$ GeV での $A_{LL}$ 測定
  - 前方測定


π⁰ 非対称度 ($A_{LL}$)

- 衝突エネルギー 510 GeV での測定（2012-2013）
  - 衝突エネルギー 200 GeV での測定よりも
    - 小さな $x$ 領域のグルーオンの測定
    - 大きな非対称度となる（摂動QCD計算）
    - 高ルミノシティーによる高統計測定

- 正のπ⁰非対称度が測定された
  - $x$~0.01 までの領域の測定

Transverse polarization phenomena

- TMD (Transverse Momentum Dependent) function and higher-twist function
- "Sivers" effect
  - Initial-state effect
  - TMD (Sivers) distribution function
    - Need 2 scales ($p_T$ and $Q^2$)
    - Drell-Yan, W/Z boson production
  - Higher-twist distribution function
    - Need 1 scale ($p_T$)
    - Hadron, photon, jet production
- "Collins" effect
  - Transversity + final-state effect
  - TMD (Collins) fragmentation function
  - Higher-twist fragmentation function
sPHENIX experiment

- Large-acceptance jet and upsilon detector around the BaBar superconducting solenoid
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$\pi^0 A_{LL}$ at $\sqrt{s} = 200$ GeV