RHICf Analysis Update

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June 10th, 2019
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for the RHICf Collaboration
RHICf collaboration


RHICf is partially supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics, and performed by strong collaboration with the STAR collaboration
RHICf experiment

- EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment
  - Cross section and asymmetry measurement of neutral particle production (neutron, photon, $\pi^0$) with $\sqrt{s} = 510$ GeV polarized proton collisions
  - Wide $p_T$ region covered by changing the position of the RHICf detector vertically (up to 1.2 GeV/c)
  - Much higher position resolution than ZDC+SMD so that enable us higher resolution of $p_T$ measurement
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

- Large $A_N$ for forward hadron production
  
  • $1 < \eta < 4$, similar results in wide $\sqrt{s}$

- TMD (Transverse Momentum Dependent) function and higher-twist function in pQCD regime
  
  • Initial-state effect or “Sivers” effect
  • Final-state effect or “Collins” effect

- Hard scattering and/or non-perturbative effect?
New question

• $A_N$ DY jet asymmetry
  • Small $A_N$ of forward jet production comparing with that of forward hadron production
  • Mixture (cancellation) of u-quark jet and d-quark jet, or other non-perturbative effects?

• STAR multiplicity dependence
  • $A_N$ for different number of photons
  • $A_N$ decreases as the event complexity increases (more jet-like)
  • How much of the large $\pi^0 A_N$ comes from hard scattering?

• $\pi^0$ asymmetry at RHICf
  • $p_T < 1$ GeV/$c$, $\eta > 6$
  • Limited by the shadow of the beam pipe
  • Non-perturbative regime

2017 operation

• June 24 – 27 physics data acquisition
  • $\beta^* = 8\text{m}$, radial polarization
  • 27.7 hours, $\sim 110\text{M events}$, $\sim 700\text{ nb}^{-1}$

• 3 detector positions: TL center / TS center / Top position
**π⁰ reconstruction**

- π⁰ peak with ~10 MeV/c² width
  - 3σ region selected as π⁰ candidates

Type-I

Type-II

(same as single high-E photon)

π⁰ kinematics: $p_T < 1.0$ GeV/c  
$0.2 < x_F < 1.0$
$A_N$ of very forward $\pi^0$

- $p_T$ dependence
  - Large asymmetry (up to 0.1) even at low $p_T$ ($p_T < 0.6 \text{ GeV/c}$)
  - Becoming larger (more than 0.1) at high $p_T$ ($0.6 \text{ GeV/c} < p_T$)

Data analysis has been performed by Minho Kim (Korea Univ.)

Background asymmetry (measured, zero consistent) subtracted

Bar: statistical error
Box: systematic uncertainties including beam center correction, acceptance correction, polarization, and background asymmetry subtraction
$A_N$ of very forward $\pi^0$

- $x_F$ dependence
  - $A_N \sim 0$ at $p_T < 0.09$ GeV/$c$
  - $A_N > 0$ at $0.09$ GeV/$c < p_T$ and rising with $x_F$
To do

• Event type categorization

• Diffraction + resonance tagging with STAR + RHICf combined data analysis
  • Resonance with STAR Roman Pot
  • Diffraction with STAR forward detectors (FMS, BBC, VPD)
  • Or no activity

• Event type, multiplicity (FMS) dependence of cross section & asymmetry to be obtained
  • For more information to study production mechanism
Summary & plan

• Preliminary $A_N$ result of very forward $\pi^0$ obtained
  • $p_T$ & $x_F$ dependences
  • Large asymmetry in non-perturbative regime
  • Matching to pQCD regime?

• STAR + RHICf combined analysis to be performed
  • For production mechanism, soft & hard components
  • Event type definition with STAR forward detectors and Roman Pot
  • Neutron analysis with RHICf + STAR ZDC
  • Asymmetry of STAR forward and midrapidity detectors with neutron/$\pi^0$ tag at RHICf

• Possible future plan
  • STAR at $\sqrt{s} = 510$ GeV in 2022
    • Possible RHICf proposal of p+p (& p+A ?)
  • sPHENIX at $\sqrt{s} = 200$ GeV
    • Baseline 2023-2025: p+p & p+A in 2024
  • Detector development in collaboration with people having common interest in position-sensitive calorimeter
Backup Slides
**RHICf detector**

- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber (44 $X_0$, 1.6 $\lambda_{\text{int}}$)
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)
Physics at RHICf

- Majority of energy flow from hadronic collisions concentrated in the very forward region, but reaction mechanism insufficiently understood there.
- How to apply for understanding air-shower from ultra-high energy cosmic rays
  - Phenomenological approach
- How to understand non-perturbative aspect in QCD
  - Asymmetry measurement in addition to cross section
**Cross section measurement**

- Majority of energy flow from hadronic collisions concentrated in the very forward region, but reaction mechanism insufficiently understood there
  - Uncertainty to understand air-shower from ultra-high energy cosmic rays
  - Improvement of high-energy collision models based on measurement essential

- Feynman scaling
  - Energy-independent $x_F$ & $p_T$ distribution of the cross section of very forward particle production
  - Wider $p_T$ coverage at RHIC energy (limited at LHC low energy collision)

LHCf results of $\pi^0$ production cross section at $\sqrt{s}=7$TeV and 2.76TeV

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
  - $1 < \eta < 4$, similar results in wide $\sqrt{s}$

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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
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).
\( \pi^0 \) asymmetry at RHICf

- \( p_T < 1 \text{ GeV/c}, \eta > 6 \)
- Non-perturbative regime
  - How much \( \pi^0 \) asymmetry?
  - Matching to pQCD regime?

\[ \chi^2/\text{ndf} = 11.12/9 \]
\[ p0 = -0.0019 \pm 0.0025 \]
\[ p1 = -0.1484 \pm 0.0000 \]

PHENIX & STAR \( \sqrt{s} = 200 \text{ GeV} \)

PHYS. REV. D90 (2014) 012006.

RHIC-IP12 \( \sqrt{s} = 200 \text{ GeV} \) \( p_T < 0.1 \text{ GeV/c} \)
Very forward \( \pi^0 \) raw asymmetry

Table 1
Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of \((1.0^{+0.47}_{-0.24})\).

<table>
<thead>
<tr>
<th></th>
<th>Forward</th>
<th>Backward</th>
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<tbody>
<tr>
<td>Neutron</td>
<td>(-0.090 \pm 0.006 \pm 0.009)</td>
<td>(0.003 \pm 0.004 \pm 0.003)</td>
</tr>
<tr>
<td>Photon</td>
<td>(-0.009 \pm 0.015 \pm 0.007)</td>
<td>(-0.019 \pm 0.010 \pm 0.003)</td>
</tr>
<tr>
<td>(\pi^0)</td>
<td>(-0.022 \pm 0.030 \pm 0.002)</td>
<td>(0.007 \pm 0.021 \pm 0.001)</td>
</tr>
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</table>
$\pi^0$ asymmetry at RHICf

- $\pi^0 A_N$ measurement using TL at $+y=16.6\text{mm}$, $\langle \eta \rangle = 6.4$, $\sqrt{s} = 510$ GeV
  - $3 \times 10^5 \pi^0$ detected in 4-hour measurement
  - Comparison of existing $\eta$ region (3–4) and RHICf high-$\eta$ region (> 6)

- Higher-twist effect calculation by Pitonyak
- pQCD calculation does not apply for the very low $p_T$ values
- At $p_T > 0.75$ GeV/c, this mechanism cannot generate $A_N$ since phase space vanishes

See Minho's presentation of first result from RHICf
Forward neutron production

PHENIX, PRD, 88, 032006 (2013)

\( p_T < 0.11 \times_F \) GeV/c
\( \sqrt{s} = 30-60 \) GeV @ISR
\( \sqrt{s} = 200 \) GeV @RHIC

• PHENIX explains the result by 1 pion exchange
• More complicated exchanges at >TeV?

LHCf
\( p_T < 0.11 \times_F \) GeV/c
\( \sqrt{s} = 7000 \) GeV @LHC
Forward neutron production

- Cross section measurement at HERA(e+p)/NA49(p+p)
  - High resolution $p_T$ distribution
  - $\sigma \propto a(x_F) \cdot \exp(-b(x_F) \cdot p_T^2)$, $b \sim 8$ GeV$^{-2}$ for $0.3 < x_F < 0.85$
  - $x_F$ distribution
    - Suppression of the forward peak at high $\sqrt{s}$?

- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input

Wide $\eta$ & $p_T$ coverage

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Commissioning

- $\sqrt{s} = 510$ GeV
- Large $\beta^* = 8$ m
  - Requirement of parallel beam for angle and $p_T$ precision
  - Luminosity $\sim 10^{31}$ cm$^{-2}$s$^{-1}$
- Vertical → Radial polarization
  - For asymmetry measurement at large angle (or large $p_T$)
  - Change of polarization direction with Spin Rotator magnet
2017 operation

- June 23 commissioning of polarized proton collisions, detector installation at the final position, detector commissioning
  - $\beta^* = 8m$, radial polarization
- June 24 – 27 physics data acquisition
  - 27.7 hours, $\sim$110M events, $\sim$700 nb$^{-1}$
- 3 detector positions
  - TL center / TS center / Top position
Data accumulation & statistics

• \( \sim 700 \text{ nb}^{-1} \) integrated luminosity, \( \sim 110 \text{ M events recorded} \)
• Common data taken by RHICf DAQ and STAR DAQ
  • separated data streams and records
• RHICf triggers
  • Shower (baseline)
    • Hits in 3 consecutive layers on TS or TL
    • Large prescale
  • 2 photons (for \( \pi^0 \))
    • Hits in 3 consecutive layers in upstream 7 layers of both TS and TL
    • No prescale
  • High-energy photon (for \( \gamma \) and \( \pi^0 \))
    • Large energy deposit in the 4th layer of TS or TL
    • Small prescale (\( \sim 2 \))
• STAR trigger
  • With or without TPC data
  • Roman Pot + TPC data
    • for diffraction event selection

All data \( \sim 110 \text{M} \)
RHICf+STAR Shower
High-energy photon
2 photon

2 photon
\( \sim 700 \text{ nb}^{-1} \)
High-energy photon
Shower

Sampling
Position
Absorber

June 10, 2019
Quick performance evaluation

- Beam center position
  - Checked with > 200 GeV hadron shower incident position
- $\pi^0 \rightarrow \gamma \gamma$
  - Invariant mass distribution of photon-pair event
  - To be improved by energy calibration and shower leakage correction
**RHICf & STAR correlation**

- Correlation of RHICf calorimeter and STAR ZDC
  - (Anti)correlation with deep-penetrating hadronic shower in the RHICf calorimeter and shower leakage measured in the ZDC
  - Correlation only with the West ZDC as expected
  - Event correspondence of RHICf DAQ and STAR DAQ correctly confirmed
Neutron asymmetry

- Very large left-right asymmetry ($A_N$) of very forward neutron discovered at RHIC
  - $A_N(62 \text{ GeV}) < A_N(200 \text{ GeV}) < A_N(500 \text{ GeV})$
  - $\sqrt{s}$ dependence or $p_T$ dependence?
- Interference of pion exchange and other Reggeon exchange?
  - Kopeliovich, Potashnikova, Schmidt, Soffer: PRD84, 114012 (2011)
- Improved $p_T$ precision and wider $p_T$ coverage ($p_T < 1.2 \text{ GeV}/c$) at $\sqrt{s} = 510 \text{ GeV}$ in the RHICf experiment

Inclusive neutron

Neutron with charged particles
**π⁰ reconstruction**

- Positions of decay photons measured by 1 mm dimension GSO bars
- Energy corrections
  - Position dependence
  - Energy scale
  - Performance confirmed with test beams
$\pi^0$ reconstruction

- $\pi^0$ peak with $\sim 10$ MeV/c$^2$ width
- 3$\sigma$ region selected as $\pi^0$ candidates
\( \pi^0 \) reconstruction

- Relative peak position of reconstructed \( \pi^0 \) mass in each run

- \( \pi^0 \) kinematics
  - \( p_T < 1.0 \text{ GeV/c} \)
  - \( 0.2 < x_F < 1.0 \)
$\pi^0$ kinematics

- $\pi^0$ peak with $\sim 10$ MeV/$c^2$ width
  - $3\sigma$ region selected as $\pi^0$ candidates
- $p_T < 1.0$ GeV/$c$
- $0.2 < x_F < 1.0$

Type-I

Type-II

(same as single high-E photon)
Future plan

• RHIC schedule
  • STAR p+p √s = 510 GeV in 2021 (?)
    • Possible RHICf proposal of p+p & p+A
  • sPHENIX p+p √s = 200 GeV & p+A
    • Baseline 2023-2025: p+p & p+A in 2024
    • Extension 2026-2027 (before EIC)

• Detector development
  • Collaboration with people having common interest in position-sensitive calorimeter
  • Possible proposal for EIC R&D program for very forward measurements
    • “Generic Detector R&D for an Electron Ion Collider” operated by BNL
    • Radiation tolerance / position-sensitive calorimeter / EIC IR design (ZDC + spectrometer)