Forward+near-forward azimuthal correlations in p+p and d+Au collisions at $\sqrt{s_{NN}} = 200\text{GeV}$ at STAR

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Outline

• Motivation
  – How sharp is the transition from dilute parton gas to saturated parton density: eg. Color Glass Condensate (CGC)?

• Forward+near-forward correlations at STAR
  – Near-forward jet-like cluster reconstruction
  – Forward $\pi^0$ + near-forward jet-like cluster azimuthal correlations
  – Correlations in p+Au approach comparison with d +Au results

• Summary & Outlook
How to probe low x gluons

- Forward particle production.

  - The factorization mechanism is taken as universal and applied in nucleon (nucleus) + nucleon (nucleus) collisions.

\[ x_q = \frac{p_q}{p_N}, \quad x_g = \frac{p_g}{p_N}, \]

\[ \eta_\pi = -\ln(\tan(\theta_\pi/2)) \]

\[ p_T \approx E_\pi \sin(\theta_\pi) \]

- Large rapidity ($\eta_\pi \sim 4$) inclusive $\pi$ production and correlations probe asymmetric partonic collisions.

- Mostly high-$x_q$ valence quark ($x > 0.2$) + low-$x_g$ gluon ($x < 0.01$).

- Forward back-to-back correlations can probe low x gluon.
STAR Detector setup

- The schematics of STAR in RHIC run8.

**Forward Meson Spectrometer (FMS) with 2.5<\(\eta<4.0\)**

**Endcap electro-magnetic calorimeter (EEMC) with 1.08<\(\eta<2.0\)**

**Barrel electro-magnetic calorimeter (BEMC) with -1<\(\eta<1\)**

- We use the data of run8 \(p+p\) and \(d+Au\) collision at \(\sqrt{s} = 200\text{GeV}\).
The soft gluon $x$ is related to associated particle in correlations

- The pseudo-rapidity of the associated particle is strongly correlated with soft gluon $x$ in the asymmetric parton scattering.

$\ln\left(\frac{1}{x}\right)$ $x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$

$Q_s^2(x) \sim A^{1/3} e^{\lambda y}$

$y =$ rapidity, $\lambda = 0.3$

PYTHIA simulation

FMS-FMS Correlation

FMS-EEMC Correlation

FMS-BEMC Correlation

Iancu and Venugopalan, hep-ph/0303204

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Existing STAR forward di-hadron measurements
— forward-forward, forward-mid correlations

- **Forward-forward:** significant broadening from p+p to d+Au in back-to-back peak. Suppression in central d+Au.

- **Forward-mid:** No significant broadening from p+p to d+Au.


**Central dAu**

\[ \text{pp} \rightarrow \pi^0 \pi^0 + X, \sqrt{s} = 200 \text{ GeV} \]
\[ p_T > 2 \text{ GeV/c}, 1 \text{ GeV/c} < p_T < 3 \text{ GeV/c} \]
\[ \langle \eta \rangle = 3.2, \langle \eta_T \rangle = 3.1 \]

\[ \text{dAu} \rightarrow \pi^0 \pi^0 + X, \sqrt{s} = 200 \text{ GeV} \]
\[ p_T > 2 \text{ GeV/c}, 1 \text{ GeV/c} < p_T < 3 \text{ GeV/c} \]
\[ \langle \eta \rangle = 3.2, \langle \eta_T \rangle = 3.2 \]

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**ArXiv:1102.0931**

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\(\pi^0\) reconstruction in the FMS

- Leading forward \(\pi^0\) is reconstructed in the most forward detector — FMS with HT trigger.

- There are clear \(\pi^0\) peaks in the FMS during p+p and d+Au collisions.
Jet-like cluster reconstruction in the EEMC

- The jet-like cluster are reconstructed based on cone algorithm.

One event of the energy deposition in the EEMC with FMS π⁰ trigger($p_t$>2.0GeV/c) in p+p collision at $\sqrt{s} = 200$GeV.

The EEMC energy deposition is jetty.

- Energy $E_{\text{jet}}$: $E_{\text{jet}} = \Sigma E_{T_i}$, $E_{T_i}$ is the energy of tower i.

- Mass $M_{\text{jet}}$: (1) Assuming tower hits are zero mass. Projecting $T_i$ energy to its center to get the momentum vector of the tower $p_{T_i}$. (2) The jet-like momentum vector $p_{\text{jet}} = \Sigma p_{T_i}$. (3) $M_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - P_{\text{jet}}^2}$.
What is the underlying events

• Underlying event can shift physical jet to observed jet.
• Underlying events: Initial and final state interactions (“color and spectator baggage”) [ISMD05, Rick Field].

In back to back correlation (away side jet must remain \([5\pi/6,7\pi/6]\)), define jet #1 direction is \(\phi = 0\), then the regions \([\pi/3,2\pi/3]\) and \([4\pi/3,5\pi/3]\) are the underlying event study areas (transverse region).
The mass spectrum of the back-to-back jet-like cluster and the underlying events in the EEMC

- Data and simulation comparison under the condition: FMS $\pi^0$ ($p_t^{FMS}>2.0\text{GeV}/c$), the back-to-back EEMC jet-like cluster ($1.0\text{GeV}/c<p_t^{\text{EEMC}}<p_t^{FMS}, M>0.2\text{GeV}/c^2$) and the underlying events (no M cut and no $p_t$ cut).

500MeV tower threshold
FMS ($\pi^0$)-EEMC (jet-like cluster) correlations

(Low $p_t$)

$P_T(\text{FMS}) > 2.0 \text{ GeV/c} ; \ 1.0 \text{ GeV/c} < P_T(\text{EEMC}) < P_T(\text{FMS})$

- $\sigma_{pp} = 0.80 \pm 0.01, \sigma_{dAu} = 0.89 \pm 0.02$
- $A_{1pp} = 0.005, A_{1dAu} = 0.016$
- $b_{pp} = 0.0008$ and $b_{dAu} = 0.0097$

- To suppress underlying event contribution, we use 600MeV tower threshold for the EEMC and 0.4GeV/$c^2$ as the lower mass limit for the reconstructed jet-like cluster.

- $\sigma_{dAu} - \sigma_{pp} = 0.10 \pm 0.02^{+0.04}_{-0.02}$ Significant broadening from p+p to d+Au.

Fit function: $G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{1}{2} \left(\frac{x - A_2}{\sigma}\right)^2\right)$

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The correlation results on the tower threshold dependence

- The EEMC tower thresholds are selected from 250MeV, 400MeV, 500MeV to 600MeV. Results are after mixed event corrections. Fit function is \( G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma} \exp\left(\frac{1}{2}\left(\frac{x - A_2}{\sigma}\right)^2\right) \), \( \sigma \) is defined as width.

\[
R_{\text{threshold}} = \frac{\int_{0.2\text{GeV}/c^2}^{\infty} dN/dM_{\text{underly}}}{\int_{0.2\text{GeV}/c^2}^{\infty} dN/dM_{\text{jet}}} 
\]

- The different tower thresholds do not impact on the width differences between pp and dAu much.
FMS ($\pi^0$)-EEMC (jet-like cluster) correlations

(High $p_t$)

$P_T(FMS) > 2.5$ GeV/c ; $1.5$ GeV/c < $P_T(EEMC) < P_T(FMS)$

High $p_t$ cuts, p+p → $\pi^0$ + jet-like + X, $\sqrt{s}=200$GeV

High $p_t$ cuts, d+Au → $\pi^0$ + jet-like + X, $\sqrt{s}=200$GeV

Fit function: $G(x) = b + \frac{A_1}{\sqrt{2\pi}A} \exp\left(\frac{1}{2} \left( \frac{x - A_2}{A} \right)^2 \right)$

- $\sigma_{pp} = 0.71 \pm 0.01$, $\sigma_{dAu} = 0.84 \pm 0.02$
- $A_{1pp} = 0.006$, $A_{1dAu} = 0.018$
- $b_{pp} = 0.0007$, $b_{dAu} = 0.0094$

• To suppress underlying event contribution, we use 600MeV tower threshold for the EEMC and 0.4GeV/c$^2$ as the lower mass limit for the reconstructed jet-like cluster.

• $\sigma_{dAu} - \sigma_{pp} = 0.13 \pm 0.02$ $^{+0.03}_{-0.02}$ Significant broadening from p+p to d+Au.

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Summary on the correlation peak

- Compare the width differences from $p+p$ to $d+Au$ collisions for different di-hadron correlations.

**Low $p_t$**

$\pi^0+\pi^0$ (stat. error only) [ArXiv:1102.0931]

$\pi^0$+jet-like cluster

Systematical error

**High $p_t$**

$\pi^0+\pi^0$ (stat. error only) [ArXiv:1102.0931]

$\pi^0$+jet-like cluster

Systematical error
Summary on the correlation peak

\[ x \sim \frac{2p_T}{\sqrt{s}} e^{-y} \]

\( y = \text{rapidity}, \lambda = 0.3 \)

\[ Q_s^2(x) \sim A^{1/3} e^{\lambda y} \]

For+for Correlation
For+near-for Correlation
For+mid Correlation

*Not only \( x \) dependence but also \( Q^2 \) dependence.*

- Evolution of results in assoc particle \( \eta \) is consistent with a smooth transition from dilute parton system to Color Glass Condensate state (or saturation).
Tagging Spectator Neutrons from Deuteron Beam as p+Au approach

Independent double parton scattering only contributes to the correlation pedestal.

Deuteron-facing (West) ZDC Response

- Clear neutron peak in deuteron-facing ZDC in d+Au collisions.
• Multi-parton interactions appear to contribute to the pedestal in d+Au collisions but less significantly to p+Au collisions.
Summary

• Significant broadening from p+p to d+Au collisions for the FMS $\pi^0$ – EEMC jet-like cluster correlation peak width.

• Comparisons of p+Au to d+Au suggest independent double parton scattering is present in d+Au, affecting only the azimuthal correlation pedestal.

• The rapidity dependences of the correlations suggest a smooth transition process from dilute parton gas to dense CGC state.
Outlook of nucleus gluon saturation study

The final state $\pi^0$s or jet-like clusters are complex objects that can include not only color interactions from initial states but also from final states.

- A Electron Ion Collider (EIC)?

- Go to lower $x$ than fixed target experiment.
- DIS process is much cleaner than the hadron-hadron interaction.
Backup
What does the nucleon parton distribution look like?

- The nucleon quark distribution is well known.

Can’t increase indefinitely. Saturation?

Arxiv: hep-ph/0201195

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How about a larger nucleus?

• Fixed target experiments derived the nuclear gluon density only at $0.02 < x < 0.3$.

Nuclear (mass number $A$) gluon density $\approx A^{1/3} \times$ nucleon gluon density at a given $x$, leading to the expectation $Q_s^2 \approx A^{1/3} x^\beta$. [hep-ph/0304189]

For example, for Au nucleus, the saturation is expected at $x \approx 0.001$. 

Need go to lower $x$
Why do forward $\pi^0$ production in a hadron collider?

- Large rapidity $\pi$ production ($\eta_\pi \sim 4$) probes asymmetric partonic collisions

- Mostly high-$x$ valence quark + low-$x$ gluon
  - $0.3 < x_q < 0.7$
  - $0.001 < x_g < 0.1$
- $<z>$ nearly constant and high $0.7 \sim 0.8$

- Large-$x$ quark polarization is known to be large from DIS
- Directly couple to gluons $\Rightarrow$ probe of low $x$ gluons

\[ Q^2 \sim p_T^2 \]
\[ \sqrt{s} = 2E_N \]
\[ \eta = -\ln(\tan(\theta/2)) \]
\[ x_q \approx x_F / \langle z \rangle \]
\[ x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta_z} \]

(collinear approx.)

\[ p + p \rightarrow \pi^0, \eta_\pi = 3.8, \sqrt{s} = 200\text{GeV} \]

\[ <z> \quad \text{NLO pQCD} \quad \text{Jaeger, Stratmann, Vogelsang, Kretzer} \]

\[ <x_q> \quad <x_g> \]

\[ E_\pi (\text{GeV}) \]

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Tagging Spectator Neutrons from Deuteron Beam

- It may also be useful to distinguish between p+Au and d+Au collisions by looking for events where the neutron in the deuteron remains intact.

Deuteron-facing (West) ZDC Response

Gold-facing (East) BBC Charge Sum

- Minimum Bias Run 8 d+Au Data
- Tag spectator neutrons using deuteron-facing (West) ZDC
- Clear single-neutron peak
- Cutting on single-neutron peak biases towards peripheral collisions

From Chris’ DIS talk

ArXiv:1109.0649
ZDC west neutron tag in deuteron beam

• dAu FMS $\pi^0$ and EEMC jet-like coincidence.

• In 200k dAu simulation with shadowing setup, using HIJING neutron and apply ZDC acceptance. With FMS $\pi^0 p_t>2.0\text{GeV/c}$ trigger.

The ZDC neutron bump has photon background, but the ZDC neutron tag events are dominated by pAu collisions.
ZDC west neutron tag in deuteron beam

- dAu FMS $\pi^0$ and EEMC jet-like coincidence.

The ZDC west charge sum in forward $\pi^0$ triggered dAu looks similar like forward-forward data.
Mixed events studies

• Algorithm. The studies initially use MB data for EEMC jet-like cluster B.

FMS stream data

FMS triggered data with at least 2 good photons in the FMS

Reconstruct FMS $\pi^0$ A and EEMC jet-like cluster C in the same event.

Physical correlation AC

MB trigger + east FPD trigger + FMS LED trigger

Only reconstruct EEMC jet-like cluster B

Mixed events AB
The correlation results on the lower limit of the mass cut for the EEMC jet-like clusters

- The EEMC jet-like cluster lower limit of the mass cut $a=0.2\text{GeV/c}^2$, $0.3\text{GeV/c}^2$ and $0.4\text{GeV/c}^2$. Results are after mixed event corrections. Fit function is $G(x) = b + \frac{A_1}{\sqrt{2\pi}\sigma} \exp\left(\frac{1}{2}\left(\frac{x - A_2}{\sigma}\right)^2\right)$ and $\sigma$ is width.

$$R_{\text{mass}} = \frac{\int a dN/dM_{\text{underly}}}{\int a dN/dM_{\text{jet}}}$$

- The different mass lower limit cuts do not impact on the width differences between pp and dAu much.
Different form

- Different EEMC tower threshold.

- Different low mass cut for EEMC jet-like cluster.
The mass spectrum of the back-to-back jet-like cluster and the underlying events in the EEMC

- Data and simulation comparison under the condition: FMS $\pi^0$ ($p_t^{\text{FMS}} > 2.0\text{GeV/c}$), the back-to-back EEMC jet-like cluster ($1.0\text{GeV/c} < p_t^{\text{EEMC}} < p_t^{\text{FMS}}, M > 0.2\text{GeV/c}^2$) and the underlying events (no $M$ cut and no $p_t$ cut).

600MeV tower threshold
Systematic uncertainties on the width differences

• Systematic uncertainty sources:
  – (I) Cone radius R
  – (II) EEMC tower energy threshold
  – (III) Pseudo-rapidity cuts for the EEMC jet-like cluster
  – (IV) Mass cut lower limit for the EEMC jet-like cluster

• We change only one cut and fix the other cuts to see the systematic uncertainties.
  – Standard cuts: R=0.6, EEMC tower threshold 600MeV, jet-like cluster with 1.1<\eta<1.9, and jet-like cluster mass lower limit 0.4GeV/c^2.
Systematic uncertainties

• Consider the four sources on previous slide.

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<th>Width differences $\Delta \sigma$ (low $p_t$)</th>
<th>Width differences $\Delta \sigma$ (high $p_t$)</th>
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</table>

• Based on the systematic studies shown above, the correlation width differences between p+p collisions and d+Au collisions for the coincidence probability of FMS $\pi^0$ and EEMC jet-like cluster are,

• $0.0957 \pm 0.0200^{+0.0351}_{-0.0187}$ with low $p_t$ cuts,

• $0.1295 \pm 0.0229^{+0.0329}_{-0.0188}$ with high $p_t$ cuts.
Reduce underlying event contribution impact on
the fit constant value most

- For FMS $\pi^0$-EEMC jet-like cluster correlations.
FMS $\pi^0$ background contribution

- In p+p full simulation, inclusive FMS $\pi^0$ mass.
Ongoing corrections on the forward+forward correlations

- Corrections are:
  - $\Delta\phi$ dependent background subtraction.
  - $\Delta\phi$ dependent efficiency correction.

- Test corrections in PYTHIA/GEANT for $p+p \rightarrow \pi^0+\pi^0$.
- Good agreement with PYTHIA (no detector) information.