d+Au dihadron correlations from STAR

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Outline

• Physics motivations
• Analysis details
• Results (extensive systematics)
  – 2D correlations and $\Delta \phi$ and $\Delta \eta$ projections
  – Concentrate on $1<p_T^{\text{trig}}, p_T^{\text{assoc}}<3$ GeV/c bin, but have $p_T$ dependence
  – Fourier Coefficients

• Summary
Motivations: pp, p+Pb ridge@LHC; d+Au@RHIC?

- Ridge in small systems
- Double-ridge from central – peripheral technique
Motivations: to kill or learn from models

- Ridge in high-mult. pp and p-Pb at LHC. Very large $\Delta \eta$.
- PHENIX claims ridge in d+Au at $0.5<|\Delta \eta|<0.7$ by central – peripheral.
- Hydro models (curves in the left plot) reproduce data.
- CGC (middle & right plot) reproduces LHC data. RHIC unclear.
• STAR d+Au data taken in 2003
• **Three centrality definitions**: TPC, FTPC-E, ZDC-E
• Vertex z matching in mixed-events
• Discrete multiplicity match in mixed-events with TPC and FTPC centrality definitions; For ZDC centrality, ZDC-E-sum 10-size bins
• Correlation functions: various trigger and assoc. pT bins; normalize per trigger; efficiency corrected for assoc. particle
  – Both trigger and assoc. in TPC
  – **TPC**(trag)**-FTPC**(assoc)** correlations
Centrality definitions

- Three different centrality definitions
- Correlations are broad
2D TPC-TPC correlation functions

\[ 1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c} \]

Centrality def.

TPC mult. \(|\eta| < 1\)

FTPC-E (Au-side) -3.8<\eta<-2.8

ZDC-E (Au-side)
Δφ projections vs Δη (TPC as centrality)

$1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

- ZYAM syst. error from different sizes of Δφ region for ZYAM.
- Efficiency corrected: 85 ± 5% .

Multiplicity biases jets
Δφ projections vs Δη (FTPC as centrality)

1 < p_T^{trig}, p_T^{assoc} < 3 GeV/c

- ZYAM syst. error from different sizes of Δφ region for ZYAM.
- Efficiency corrected: 85 ± 5% .

- Multiplicity biases jets.
- Remaining back-to-back structure at large Δη.
ZYAM-ed $\Delta \eta$ correlations, ZYAM'ed

$1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

Shaded: PHENIX acceptance

- ZYAM syst. error from different sizes of $\Delta \phi$ region for ZYAM.
- Efficiency corrected: $85 \pm 5\%$.
TPC-FTPC correlations

40-100%, $1 < p_T^{(l)} < 3 \text{ GeV/c}, 0.15 < p_T^{(a)} < 3 \text{ GeV/c}$

0-20%, $1 < p_T^{(l)} < 3 \text{ GeV/c}, 0.15 < p_T^{(a)} < 3 \text{ GeV/c}$

\(\Delta \eta\) triangle acceptance
Raw and ZYAM’ed $\Delta \eta$ Correlations

ZDC centrality, $1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

Discontinuity because it’s $\Delta \eta$ not $\eta$ distribution.
At $\Delta \eta = 2$, TPC-TPC and TPC-FTPC pairs come form different $\eta$’s.
ZYAM’ed yield vs multiplicity

- Jets are biased by multiplicity
- Small ridge yield after ZYAM at large $\Delta \eta$; 2-3$\sigma$ effect
Fourier coefficients

- Fourier decomposition of correlation functions
- No ZYAM
- No central – peripheral
TPC-TPC correlations Fourier decomposition

\[ 1 < p_T^{\text{trig}} , p_T^{\text{assoc}} < 3 \text{ GeV/c} \]

\[ \Delta \phi \]

\[ \frac{1}{N_{\text{trig}}} \frac{d^2N}{d\Delta\eta d\Delta\phi} \]

\[ \Delta \text{TPC cent. 50-80\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.101 \pm 0.001 \]
\[ V_1 = -0.088 \pm 0.008 \]
\[ V_2 = 0.009 \pm 0.004 \]
\[ \chi^2/\text{ndf} = 19/29 \]

\[ \Delta \text{FTPC cent. 40-100\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.180 \pm 0.001 \]
\[ V_1 = -0.062 \pm 0.003 \]
\[ V_2 = 0.021 \pm 0.003 \]
\[ \chi^2/\text{ndf} = 46/29 \]

\[ \Delta \text{ZDC cent. 40-100\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.169 \pm 0.001 \]
\[ V_1 = -0.061 \pm 0.005 \]
\[ V_2 = 0.011 \pm 0.006 \]
\[ \chi^2/\text{ndf} = 19/29 \]

\[ \Delta \text{TPC cent. 0-10\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.495 \pm 0.002 \]
\[ V_1 = -0.028 \pm 0.002 \]
\[ V_2 = 0.014 \pm 0.002 \]
\[ \chi^2/\text{ndf} = 20/29 \]

\[ \Delta \text{FTPC cent. 0-20\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.383 \pm 0.001 \]
\[ V_1 = -0.033 \pm 0.002 \]
\[ V_2 = 0.015 \pm 0.002 \]
\[ \chi^2/\text{ndf} = 9/29 \]

\[ \Delta \text{ZDC cent. 0-20\%, } 1 < p_T < 3 \text{ GeV/c, } 1.4 < |\Delta\eta| < 2 \]

\[ B = 0.334 \pm 0.002 \]
\[ V_1 = -0.038 \pm 0.003 \]
\[ V_2 = 0.016 \pm 0.004 \]
\[ \chi^2/\text{ndf} = 36/29 \]

TPC-FTPC correlations Fourier decomposition

$1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

$\Delta \phi$, TPC cent. 50-80%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.062 \pm 0.000$
$V_1 = -0.027 \pm 0.002$
$V_2 = 0.005 \pm 0.002$
$\chi^2/\text{ndf} = 21/29$

$\Delta \phi$, FTPC cent. 40-100%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.057 \pm 0.000$
$V_1 = -0.023 \pm 0.001$
$V_2 = 0.004 \pm 0.001$
$\chi^2/\text{ndf} = 22/29$

$\Delta \phi$, ZDC cent. 40-100%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.070 \pm 0.000$
$V_1 = -0.022 \pm 0.001$
$V_2 = 0.006 \pm 0.001$
$\chi^2/\text{ndf} = 42/29$

$\Delta \phi$, FTPC cent. 0-10%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.210 \pm 0.000$
$V_1 = -0.011 \pm 0.001$
$V_2 = 0.006 \pm 0.001$
$\chi^2/\text{ndf} = 29/29$

$\Delta \phi$, FTPC cent. 0-20%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.241 \pm 0.000$
$V_1 = -0.010 \pm 0.001$
$V_2 = 0.005 \pm 0.001$
$\chi^2/\text{ndf} = 41/29$

$\Delta \phi$, ZDC cent. 0-20%, $1 < p_T < 3 \text{ GeV/c}, -4.5<\Delta\eta<2$

$B = 0.180 \pm 0.000$
$V_1 = -0.011 \pm 0.001$
$V_2 = 0.005 \pm 0.001$
$\chi^2/\text{ndf} = 30/29$
Calculated Fourier coefficients vs $\Delta \eta$

$$V_n = \langle \cos(n\Delta \phi) \rangle$$

1 $< p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

0.5 $< p_T^{\text{trig}}, p_T^{\text{assoc}} < 2 \text{ GeV/c}$
Calculated Fourier coefficients vs $\Delta \eta$

$$V_n = \left\langle \cos(n\Delta \phi) \right\rangle$$

$1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}$

$0.5 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 2 \text{ GeV/c}$
Calc. Fourier coefficients vs $p_T$

One particle $p_T$ is fixed 0.5-2 GeV/c

- For TPC cent. 50-80 $1.4<|\Delta\eta|<2$
- For TPC cent. 0-20 $1.4<|\Delta\eta|<2$

- For FTPC cent. 40-100 $1.4<|\Delta\eta|<2$
- For FTPC cent. 0-20 $1.4<|\Delta\eta|<2$

$V_1$ and $V_2$ are shown.
Calc. Fourier coefficients vs multiplicity

1 < \( p_T^{\text{trig}} \), \( p_T^{\text{assoc}} < 3 \text{ GeV/c} \)

- Correlations have \( V_1 \) and \( V_2 \) components
- \( V_1 \) appears \( \sim 1/N \). \( V_2 \) \( \sim \) constant over multiplicity
- Even at very forward d-side, \( V_2 \) component is large (maybe even larger than Au-side).
LHC $v_2\{2\}$ is also relatively insensitive to multiplicity.
LHC $v_2\{4\}$ is independent of multiplicity except peripheral. Nonflow or flow?

**Hydrodynamic flow**: In peripheral? No increase with multiplicity?

**CGC**: No increase with multiplicity?
Simple math, general remarks

\[ 1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV/c}; \ 1.4 < |\Delta \eta| < 1.8 \]

\[
\text{Peripheral} = N_{\text{peri}} \left( 1 - 2V_1^{\text{peri}} \cos \Delta \phi + 2V_2 \cos 2\Delta \phi \right)
\]

\[
\text{Central} = N_{\text{cent}} \left( 1 - 2V_1^{\text{cent}} \cos \Delta \phi + 2V_2 \cos 2\Delta \phi \right)
\]

\[
\text{Central} - \text{Peripheral} = \left( N_{\text{cent}} - N_{\text{peri}} \right) \left( 1 + 2V_2 \cos 2\Delta \phi \right)
\]

- ZYAM may give distorted information.
- Central=peripheral jets and anisotropic triggers do not go hand-in-hand naturally.
Summary

• Near-side Gaussian peak in $\Delta \eta$. Away-side approximately flat.
• Central – peripheral excess resembles near- and away-side jet shapes and charge ordering.
  – STAR large acceptance allows detailed investigation.
• $d+Au$ data mainly consistent with jet phenomenology.
  – Large multiplicity events $\rightarrow$ larger-energy jets?

• Near-side large-$\Delta \eta$ yield is small, 2-3$\sigma$ at 1-3 GeV/c.
• There seems a similar $v2$ component in dihadron correlation function in peripheral and central, including deuteron-going forward rapidity.
• Not ready to rule out models.
Compare to PHENIX results

PHENIX not normalized by bin size?
Factor would be: $0.22 \times 2 \times 0.314 = 0.13$
Then good consistency for the two high-$p_T$ bins.
Not so for the two low-$p_T$ bins.

Note: not exact $p_T$ matching
Sanity check

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All charged hadrons

\[ 3 \times \frac{4 \Delta \eta \times 2\pi}{2(\text{acc.}) \times 2\eta} \approx 20 \]

\[ 2 \times \frac{3 \Delta \eta \times 2\pi}{2(\text{acc.}) \times 1\eta} \approx 20 \]

\[ 0.5 \times \frac{3 \Delta \eta \times 2\pi}{2(\text{acc.}) \times 1\eta} \approx 5 \]
One particle $p_T$ is fixed 0.5-2 GeV/c

- $V_1$ quite different between peripheral and central.
- $V_2$ similar.
LHC $v_2$ vs multiplicity

- LHC $v_2\{2\}$, i.e. Fourier $v_2$ of two-particle correlation, is also relatively insensitive to multiplicity.
- LHC $v_2\{4\}$ is independent of multiplicity except peripheral. Nonflow or flow?
- Hydrodynamic flow: In peripheral? No increase with multiplicity?
- CGC: No increase with multiplicity?