Measurements of the Correlation between Reconstructed Jets and the Reaction Plane in STAR at RHIC

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Outline

- What is jet $v_2$?
- Measuring Jet $v_2$
- Jets in STAR
- Artificial Sources of Anisotropy
  → Background Fluctuations
  → Biased Event Plane
- Jet $v_2$ and trigger $v_2$
- Jet $v_2$ vs Centrality
- Jet $v_2$ vs Reconstructed Jet $p_T$
- Conclusions
What is Jet $v_2$?

- "Jet $v_2$" → correlation between reconstructed jets and the reaction plane (or 2\textsuperscript{nd} -order participant plane)
- "Jet $v_2$" ≠ "Jet flow"
Measuring Jet $v_2$

- Why measure Jet $v_2$?
  - Information about pathlength-dependent parton energy loss
  - Information about jet-finding techniques and biases
  - Necessary for background subtraction in jet-hadron correlations

- How to measure jet $v_2$:

\[
\frac{v_2}{v_2^{\text{jet}}} = \frac{\langle \cos \left(2(\phi_{\text{jet}} - \Psi_{\text{EP}})\right) \rangle}{\text{Res}}
\]
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- How to measure jet $v_2$:
  1) Angle of reconstructed jet axis

$$v_2^\text{jet} = \frac{\langle \cos \left( 2(\phi_{\text{jet}} - \Psi_{\text{EP}}) \right) \rangle}{R_{\text{es}}}$$
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- How to measure jet $v_2$:
  1) Angle of reconstructed jet axis
  2) Azimuthal angle of event plane

\[
\nu^2 = \frac{\left \langle \cos \left( 2(\phi_{\text{jet}} - \Psi_{\text{EP}}) \right) \right \rangle}{Res}
\]

\[
\Psi_{\text{EP}} = \frac{1}{2} \tan^{-1} \left( \frac{\sum_i w_i \sin (2\phi_i)}{\sum_i w_i \cos (2\phi_i)} \right)
\]
Measuring Jet $v_2$

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  → Information about pathlength-dependent parton energy loss
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- How to measure jet $v_2$:

  \[ v_2 = \left\langle \cos \left( 2\left( \phi_{jet} - \Psi_{EP} \right) \right) \right\rangle \]

  1) Angle of reconstructed jet axis
  2) Azimuthal angle of event plane
  \[ \Psi_{EP} = \frac{1}{2} \tan^{-1} \left( \frac{\sum_i w_i \sin (2\phi_i)}{\sum_i w_i \cos (2\phi_i)} \right) \]
  3) Event plane resolution
Jets at STAR

Run 7 Au+Au $\sqrt{s_{NN}} = 200$ GeV

High Tower (HT) Trigger

Trigger Jets found with Anti-$k_T$ algorithm [1]

$(R = 0.4, p_T^{\text{track,tower}} > 2 \text{ GeV}/c)$.

[1] M. Cacciari and G. Salam, Phys. Lett. B 641, 57 (2006)

Online Trigger

$E_T > 5.4$ GeV in one tower

$\Delta \phi \times \Delta \eta = 0.05 \times 0.05$

Offline cut: $E_T > 5.5$ GeV

Au+Au 0-20% $p_{t,jet}^{\text{rec}} \approx 22$ GeV/c

STAR Preliminary
Artificial Sources of Anisotropy

• **Background Fluctuations and the Jet Energy Scale**
  Background particles (with $p_T > 2$ GeV/c) with significant $v_2$ are more likely to be clustered into the jet cone in-plane versus out-of-plane
  → more low-$p_T$ jets reconstructed with a higher $p_T$
  → increased number of in-plane jets in a fixed reconstructed jet $p_T$ range

• **Biased Event Plane**
  Jet fragments included in event plane calculation
  → event plane pulled towards jet
Background Fluctuations

- Embed p+p HT jets isotropically into Au+Au minimum bias events
- Reconstruct $p_T$ of p+p jet before and after embedding
- Correlate reconstructed jet axis with event plane of Au+Au event
- Calculate jet $v_2$ for a given range in jet $p_T$

Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

Jet $p_T$ calculated before embedding

STAR Preliminary statistical errors only

10 < $p_T^{jet}$ < 40 GeV/c
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Jet $p_T$ calculated after embedding
Background Fluctuations

- Embed $p+p$ HT jets isotropically into Au+Au minimum bias events
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Artificial jet $v_2$ caused by background fluctuations is $\sim 4\%$

Subtract from measured jet $v_2$ values.
Calculating the event plane at mid-rapidity leads to significant jet – event plane bias!

Need to determine event plane at forward rapidities to measure jet $v_2$ at mid-rapidity...

Simulation: PYTHIA jets embedded in thermal background
Zero Degree Calorimeter – Shower Maximum Detectors
→ Spectator neutrons $|\eta| > 6.3$

Forward Time Projection Chambers
→ Charged particle tracks
$2.8 < |\eta| < 3.7$
STAR Forward Capabilities

Zero Degree Calorimeter – Shower Maximum Detectors
→ Spectator neutrons
  \(|\eta| > 6.3\)
  \(|\Delta\eta| > 5.7\)

Forward Time Projection Chambers
→ Charged particle tracks
  \(2.8 < |\eta| < 3.7\)
  \(|\eta_{\text{jet}}| < 0.6\)
  \(|\Delta\eta| > 2.2\)
Event Plane Resolution

- Resolution determined from sub-event plane method
- Mixed harmonics: measure $v_2\{\text{ZDC-SMD}\}$ with respect to $\Psi_1$

![Graph showing event plane resolution with different symbols representing different measurements.]

- $R_{22}\{\text{TPC}\}$
- $R_{22}\{\text{FTPC}\}$
- $R_{11}\{\text{ZDC-SMD}\}$
- $R_{12}\{\text{ZDC-SMD}\} = (2/\pi)R_{11}^2$

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Jet $v_2$ and Trigger $v_2$

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statistical errors only

Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- $v_2$ {TPC EP}
- $v_2$ {FTPC EP}
- $v_2$ {ZDC-SMD EP}

$10 < p_T^{jet} < 40$ GeV/c

Centrality Bin

- Jet $v_2$ {TPC} > HT $v_2$ {TPC} $\rightarrow$ Jet – event plane bias is more significant when jets have additional high-$p_T$ fragments
Jet $v_2$ and Trigger $v_2$

- Jet $v_2 \{\text{TPC}\} > HT v_2 \{\text{TPC}\} \rightarrow$ Jet – event plane bias is more significant when jets have additional high-$p_T$ fragments

- Jet $v_2 \{\text{FTPC}\} \sim HT v_2 \{\text{FTPC}\} \rightarrow$ Surface bias / bias towards unmodified jets is largely driven by high-$p_T$ trigger requirement

Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T$ cut $= 2$ GeV/$c$

10 < $p_T^{\text{jet}}$ < 40 GeV/$c$

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Jet $v_2$ in STAR – A. Ohlson
Jet $\nu_2$ and Trigger $\nu_2$

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Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{\text{cut}} = 2$ GeV/$c$

- Jet $\nu_2 \{\text{TPC EP}\}$
- Jet $\nu_2 \{\text{FTPC EP}\}$
- Jet $\nu_2 \{\text{ZDC-SMD EP}\}$
- HT trigger $\nu_2 \{\text{TPC EP}\}$
- HT trigger $\nu_2 \{\text{FTPC EP}\}$
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- Jet $\nu_2 \{\text{TPC}\} > \text{HT } \nu_2 \{\text{TPC}\} \rightarrow$ Jet – event plane bias is more significant when jets have additional high-$p_T$ fragments

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- HT $\nu_2 \{\text{ZDC-SMD EP}\} > 0$

**Centrality Bin**

$10 < p_T^{\text{jet}} < 40$ GeV/$c$
Jet $v_2$ vs Centrality

Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/$c$

- $Jet v_2 \{TPC \text{ EP} \}$
- $Jet v_2 \{FTPC \text{ EP} \}$
- $Jet v_2 \{ZDC-SMD \text{ EP} \}$

- Jet $v_2 \{FTPC\}$ is non-zero.
  $\rightarrow$ Pathlength-dependent parton energy loss

- No clear centrality dependence outside statistical uncertainties.

- Caveat: Reconstructed jet energy has slight dependence on centrality

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$10 < p_T^{jet} < 40$ GeV/$c$
Jet $v_2$ versus Reconstructed Jet $p_T$

- Jet $v_2$\{FTPC\} increases slightly with jet $p_T$

- Jet $v_2$\{FTPC\} $>$ Jet $v_2$\{ZDC-SMD\}
  
  → In single-particle $v_2$ measurements, this difference is attributed to flow in participant plane vs. reaction plane, $v_2$(PP) $>$ $v_2$(RP)

→ Jet energy loss sensitive to geometry in participant frame?

Jet Definition:
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constituent $p_T^{cut} = 2$ GeV/c

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- Jet $v_2$\{FTPC EP\}
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Conclusions

- The correlation between reconstructed jets and the reaction plane / $2^{nd}$-order participant plane has been measured.
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- Non-zero reconstructed jet $v_2\{\text{FTPC}\}$ is observed.
  → Indicative of pathlength-dependent parton energy loss.
Conclusions

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  \[\rightarrow\text{Indicative of pathlength-dependent parton energy loss.}\]
- Measurements of jet $v_2$ with respect to the event plane measured at forward rapidities show...
  \[\rightarrow\text{The bias towards unmodified jets is largely due to the trigger requirement.}\]
  \[\rightarrow\text{Within the kinematic regions studied, jet } v_2 \text{ increases with } p_T \text{ and is roughly independent of centrality.}\]
Conclusions

- The correlation between reconstructed jets and the reaction plane / 2\textsuperscript{nd}-order participant plane has been measured.
- Jet – event plane bias is reduced by using detectors at forward rapidities for event plane determination.
- Non-zero reconstructed jet $v_2\{\text{FTPC}\}$ is observed. → Indicative of pathlength-dependent parton energy loss.
- Measurements of jet $v_2$ with respect to the event plane measured at forward rapidities show...
  → The bias towards unmodified jets is largely due to the trigger requirement.
  → Within the kinematic regions studied, jet $v_2$ increases with $p_T$ and is roughly independent of centrality.
- Can be used to further constrain theories of pathlength-dependent parton energy loss and parton-medium interactions.
Backup
Event Plane Calculations

- TPC: \(0.2 < p_T^{\text{track}} < 2.0\), \(p_T\)-weighting
  Corrections: \(\phi\)-weighting

- FTPC: \(0.2 < p_T^{\text{track}} < 2.0\), \(p_T\)-weighting
  Corrections: recentering, shifting

- ZDC-SMD
  Corrections: recentering, shifting
Does the recoil jet hit the FTPC?

- For $p_{T\text{lab}} > 10$ GeV/$c$, in 2M events, < 10 partons point towards the $\eta$ region covered by the FTPC.
- For $p_{T\text{lab}} > 15$ GeV/$c$, in 2M events, 0 partons point towards the $\eta$ region covered by the FTPC.

10 < $p_{T\text{lab}}$ < 40 GeV/$c$
- Black line: both partons in all events
- Red line: partons whose partner falls within $|\eta| < 0.6$

15 < $p_{T\text{lab}}$ < 40 GeV/$c$
- Green line: both partons in all events
- Blue line: partons whose partner falls within $|\eta| < 0.6$
Participant vs. Reaction Plane

- $v_2\{PP\} > v_2\{RP\}$

**Fig. 6:** (Color online) The values of $v_2$ from various analysis methods vs centrality. Both the upper lines [3] and the lower line [25] are STAR data.

**Fig. 7:** (Color online) The data from Fig. 6 corrected to $\langle v_2 \rangle$ in the participant plane.
Reco. Jet $p_T$ vs. Centrality

- Embed $p+p$ HT trigger jets into Au+Au minimum bias events
- Reconstructed jet energy of embedded jets: $10 < p_T^{\text{jet}} < 15$ GeV/c
- Distribution of $p+p$ jet energies (reconstructed before embedding, with $p_T^{\text{cut}} = 0.2$ GeV/c):

- Reconstructing jets in Au+Au samples slightly higher parton energies in peripheral events than in central (by $\sim 2-5$ GeV)