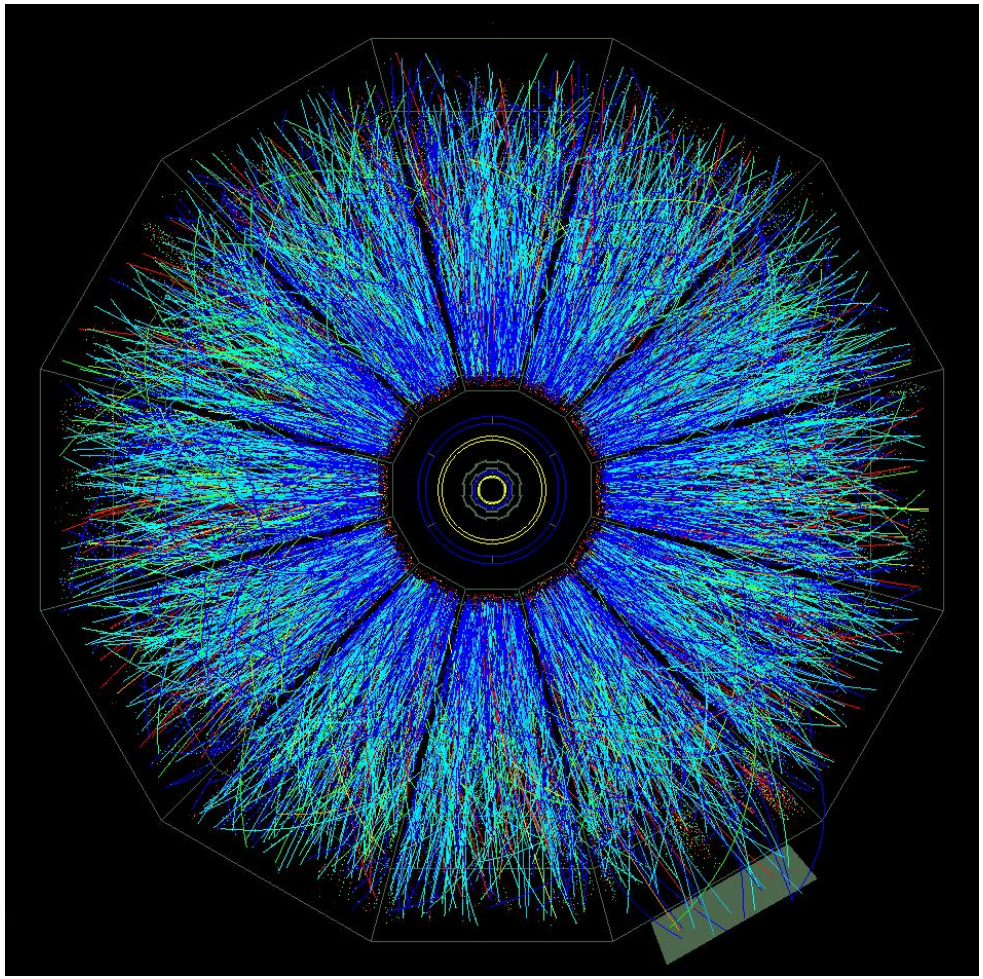
Measurements of Jet v_2 in STAR at RHIC

Alice Ohlson
Yale University
For the STAR Collaboration

17 September 2012

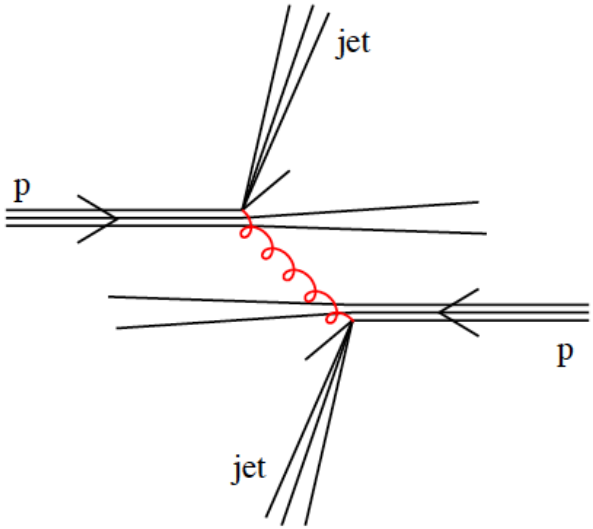
Outline

- What is jet v_2?
- Measuring Jet v_2
- Jets in STAR
- Jet – Event Plane Bias
- Jet v_2 and trigger v_2
- Jet v_2 vs Centrality
- Jet v_2 vs Reconstructed Jet p_T
- Conclusions

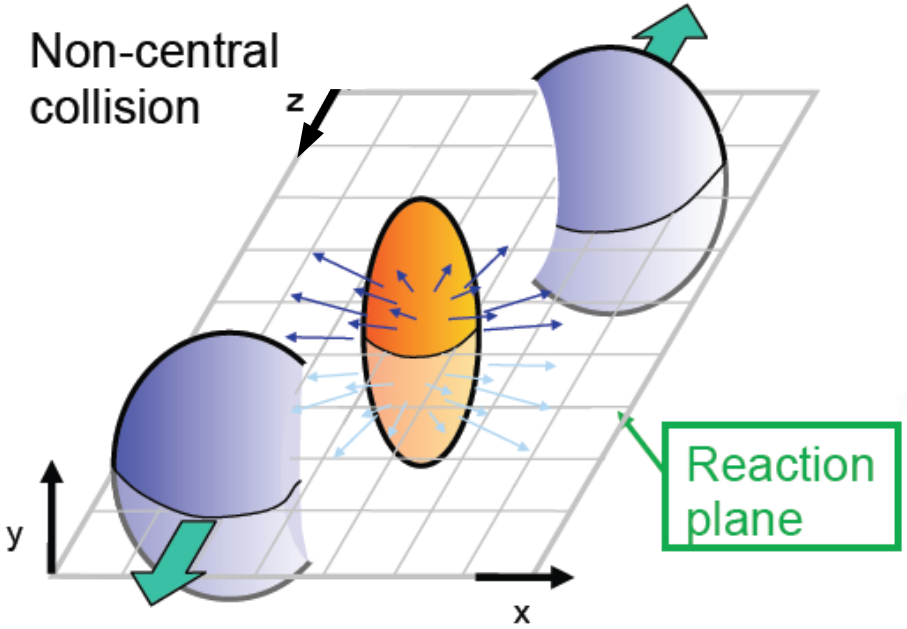


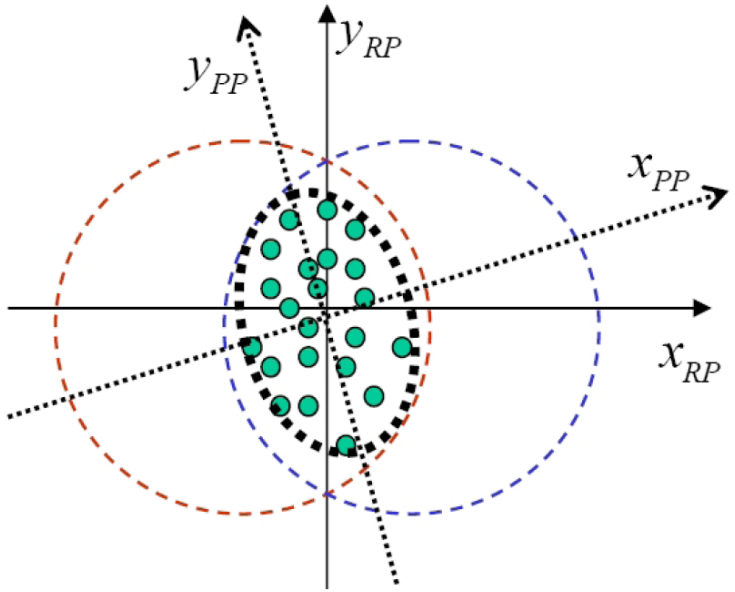
Jets & Azimuthal Anisotropy

- Hard-scattered partons fragment into collimated "jets" of hadrons
- Use jets to probe medium-induced parton energy loss in heavy ion collisions



- Jets traverse an anisotropic medium



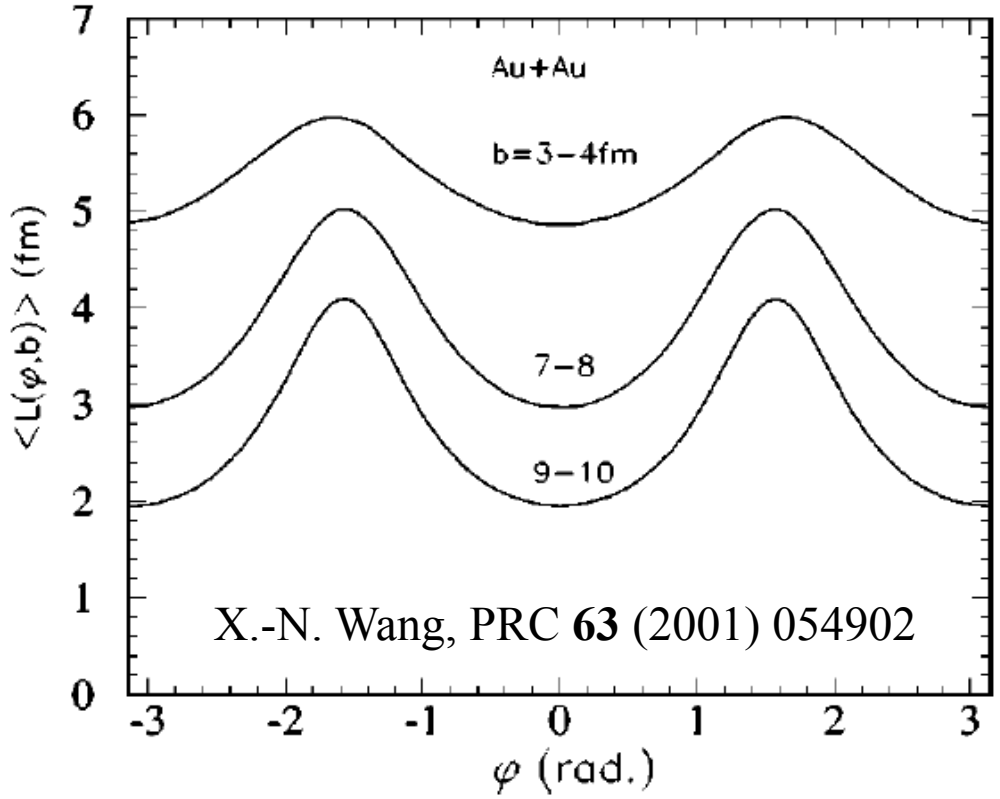


What is Jet v_2?

In-medium pathlength depends on orientation to reaction plane

Pathlength-dependent jet quenching

Energy/number of reconstructed jets may depend on orientation to reaction plane.



- "Jet v_2" → correlation between *reconstructed* jets and the reaction plane (or 2nd -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:

$$v_2^{\text{jet}} = \frac{\left\langle \cos\left(2(\phi_{\text{jet}} - \Psi_{\text{EP}})\right)\right\rangle}{Res}$$

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:

1) Angle of reconstructed jet axis

$$v_2^{\text{jet}} = \frac{\left\langle \cos\left(2(\phi_{\text{jet}} - \Psi_{\text{EP}})\right)\right\rangle}{Res}$$

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:

$$v_2^{\text{jet}} = \frac{\left\langle \cos\left(2(\phi_{\text{jet}} - \Psi_{\text{EP}})\right)\right\rangle}{Res}$$

1) Angle of reconstructed jet axis
2) Azimuthal angle of event plane

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

Measuring Jet v_2

- 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:

$$v_2^{\text{jet}} = \frac{\left\langle \cos\left(2(\phi_{\text{jet}} - \Psi_{\text{EP}})\right)\right\rangle}{Res}$$

1) Angle of reconstructed jet axis
2) Azimuthal angle of event plane

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

3) Event plane resolution

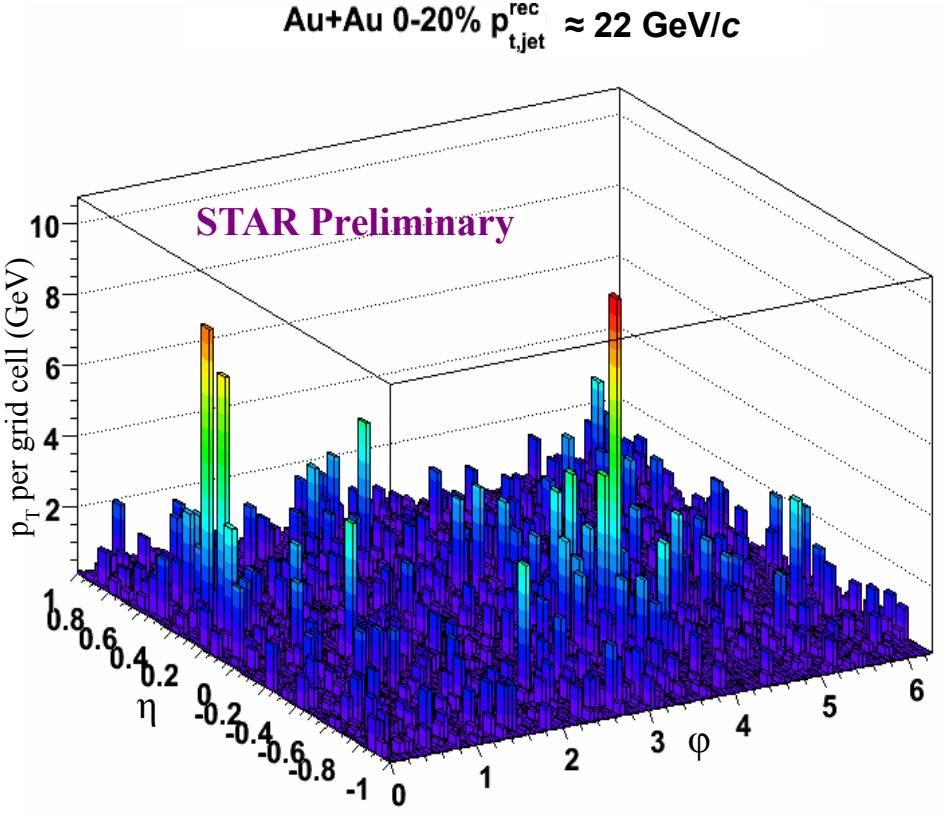
Jets at STAR

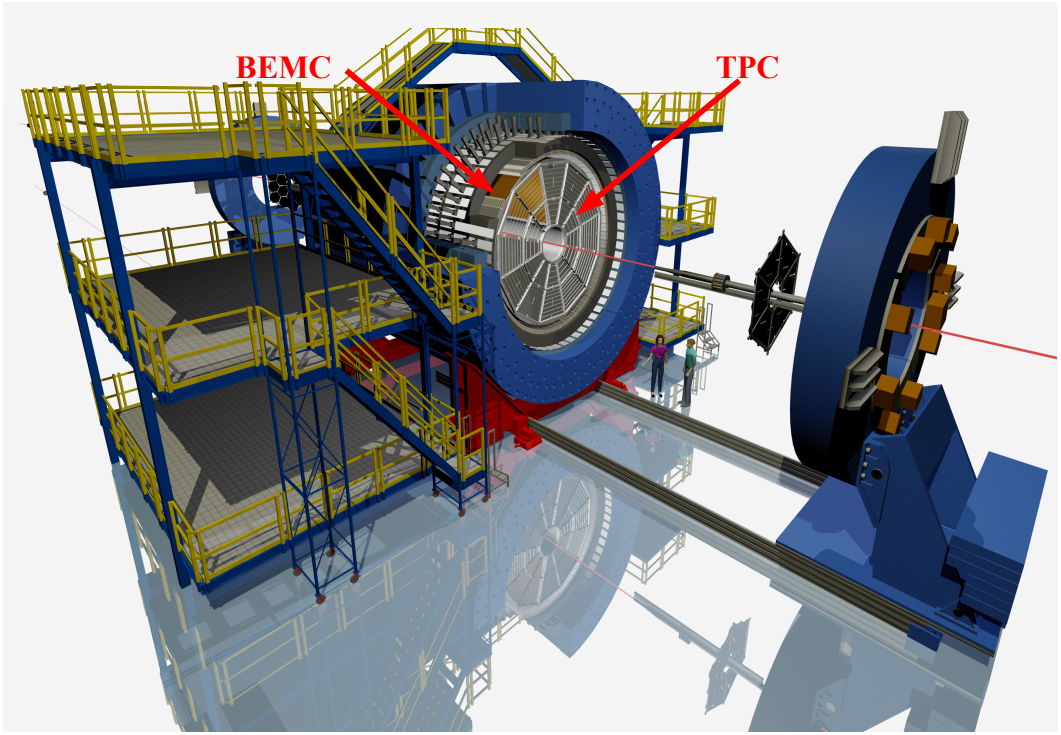
Run 7 Au+Au $\sqrt{s_{NN}}$ = 200 GeV

High Tower (HT) Trigger → Online Trigger
E_T > 5.4 GeV in one tower
$\Delta\varphi \times \Delta\eta = 0.05 \times 0.05$
Offline cut: E_T > 5.5 GeV

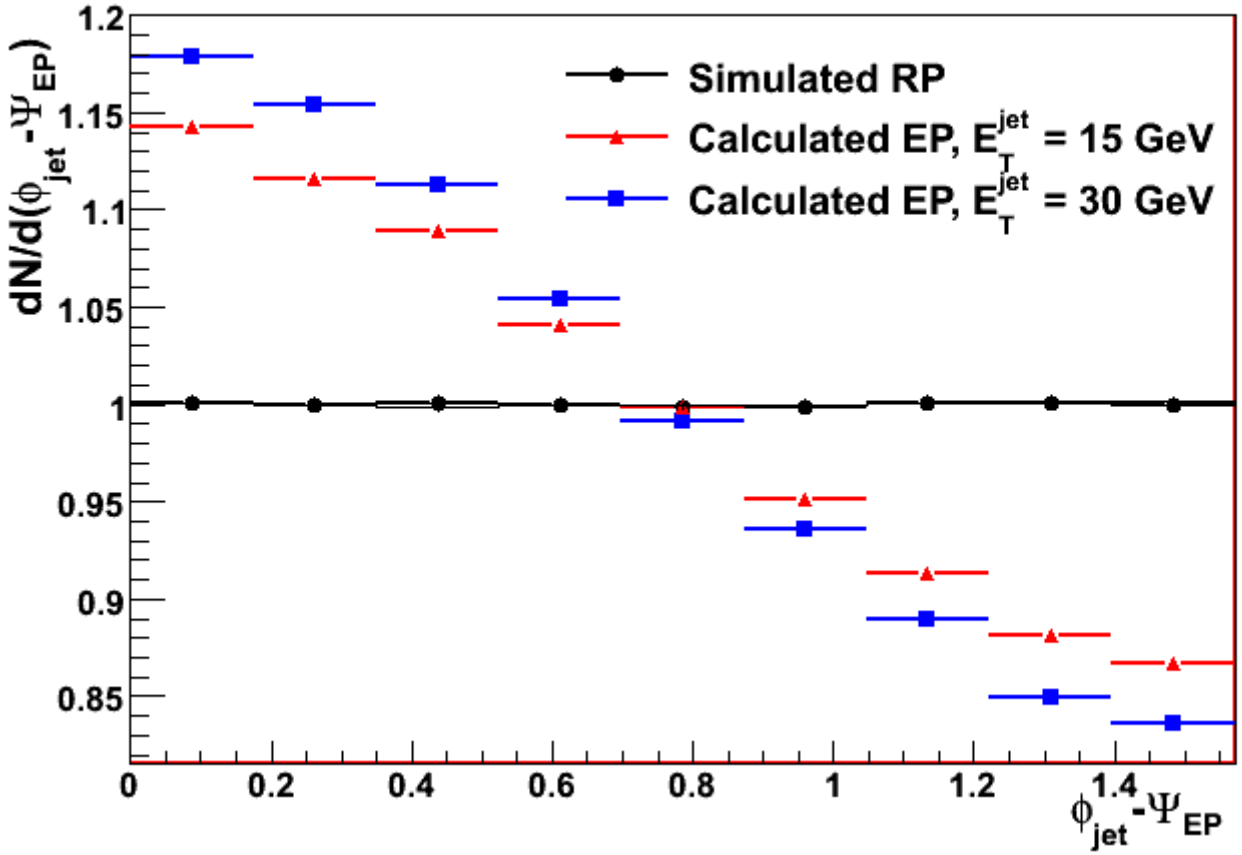
Trigger Jets found with Anti-k_T algorithm [1]
($R = 0.4$, $p_T^{track,tower} > 2$ GeV/c).

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





Jet – Event Plane Bias

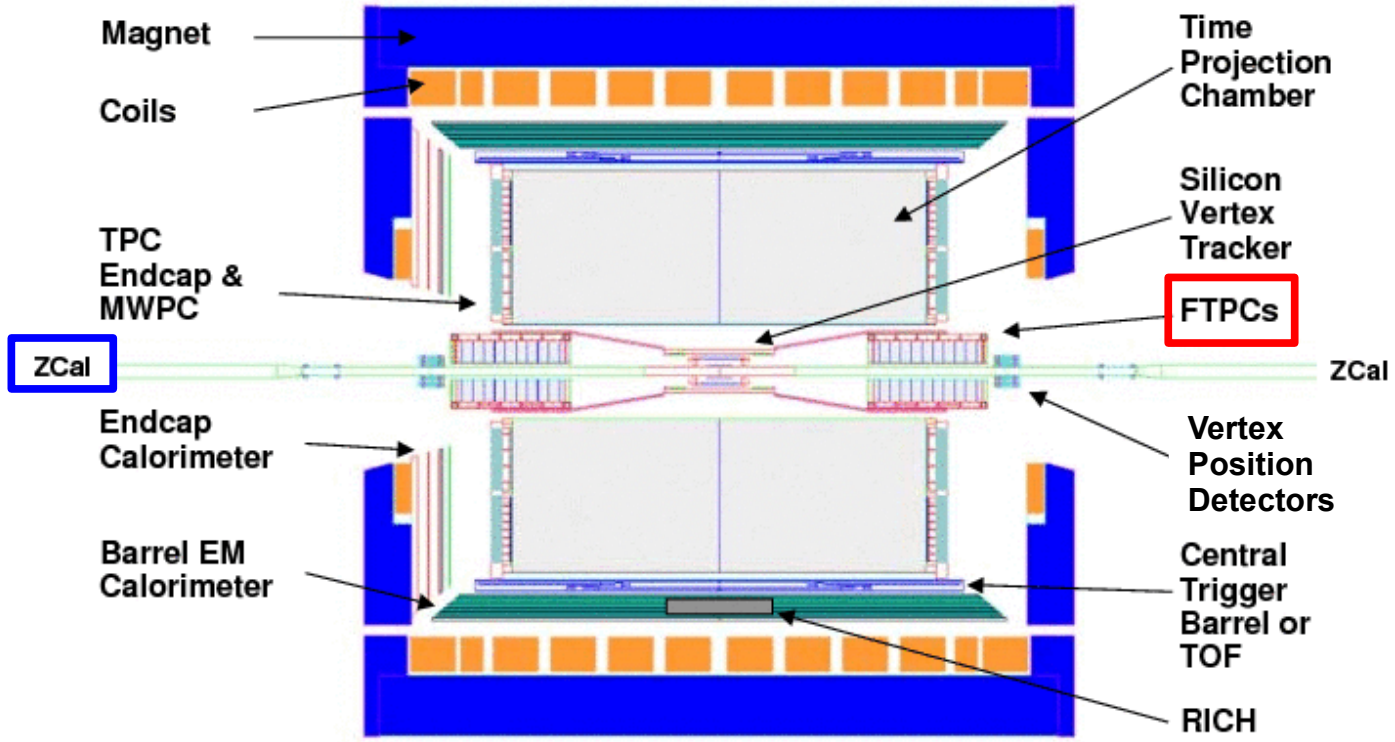


Simulation:
PYTHIA jets embedded
in thermal background

- 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...

STAR Forward Capabilities



Zero Degree Calorimeter – Shower Maximum Detectors

→ Spectator neutrons

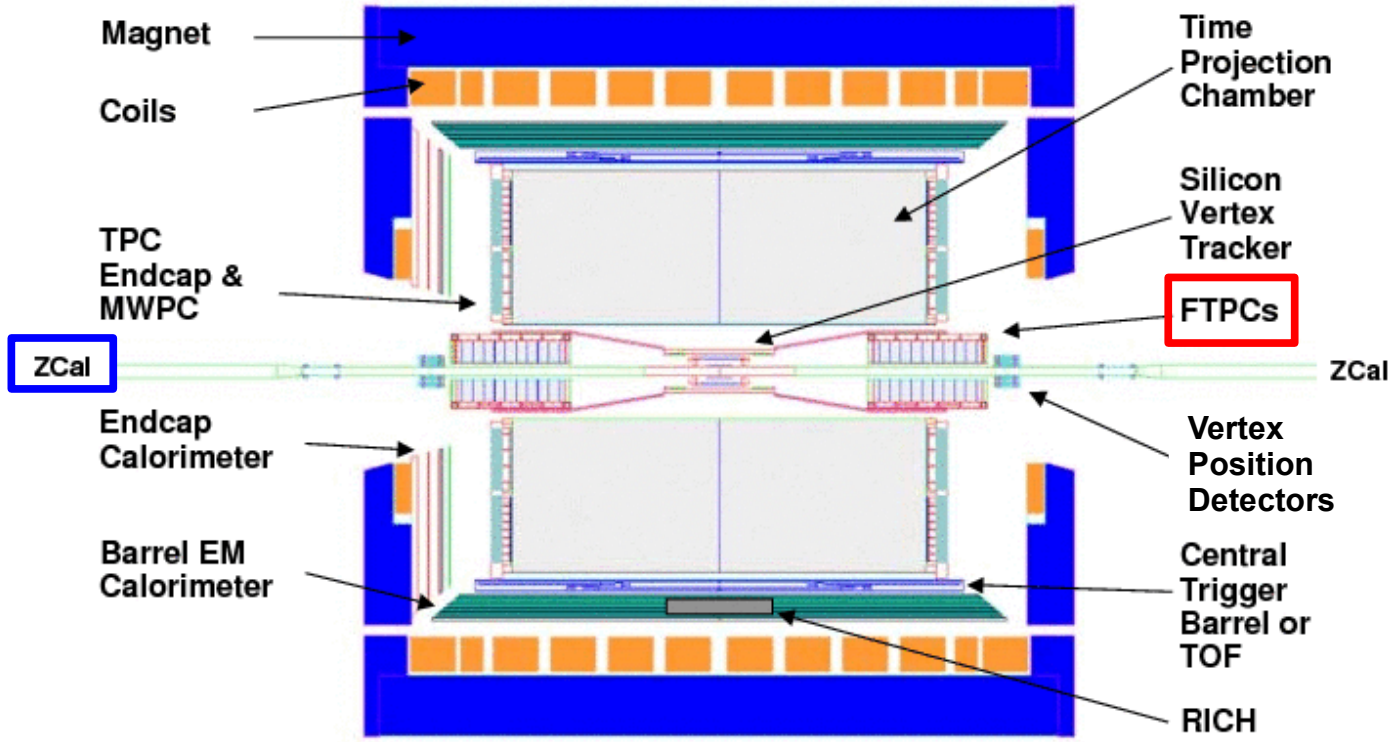
$|\eta| > 6.3$

Forward Time Projection Chambers

→ Charged particle tracks

$2.8 < |\eta| < 3.7$

STAR Forward Capabilities



Zero Degree Calorimeter – Shower Maximum Detectors

→ Spectator neutrons

$|\eta| > 6.3$

Forward Time Projection Chambers

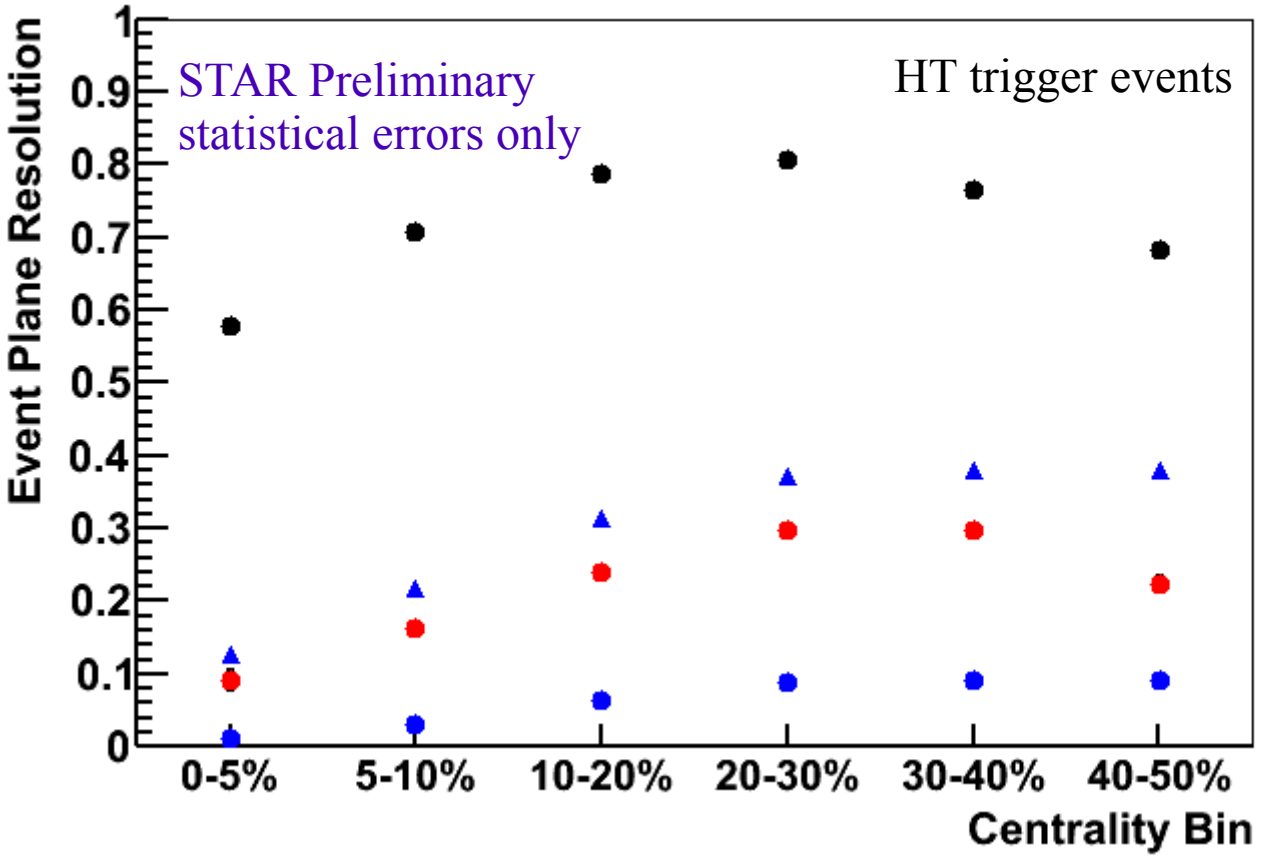
→ Charged particle tracks

$2.8 < |\eta| < 3.7$

$|\Delta\eta| > 5.7$ $\quad |\eta_{jet}| < 0.6$ $\quad |\Delta\eta| > 2.2$

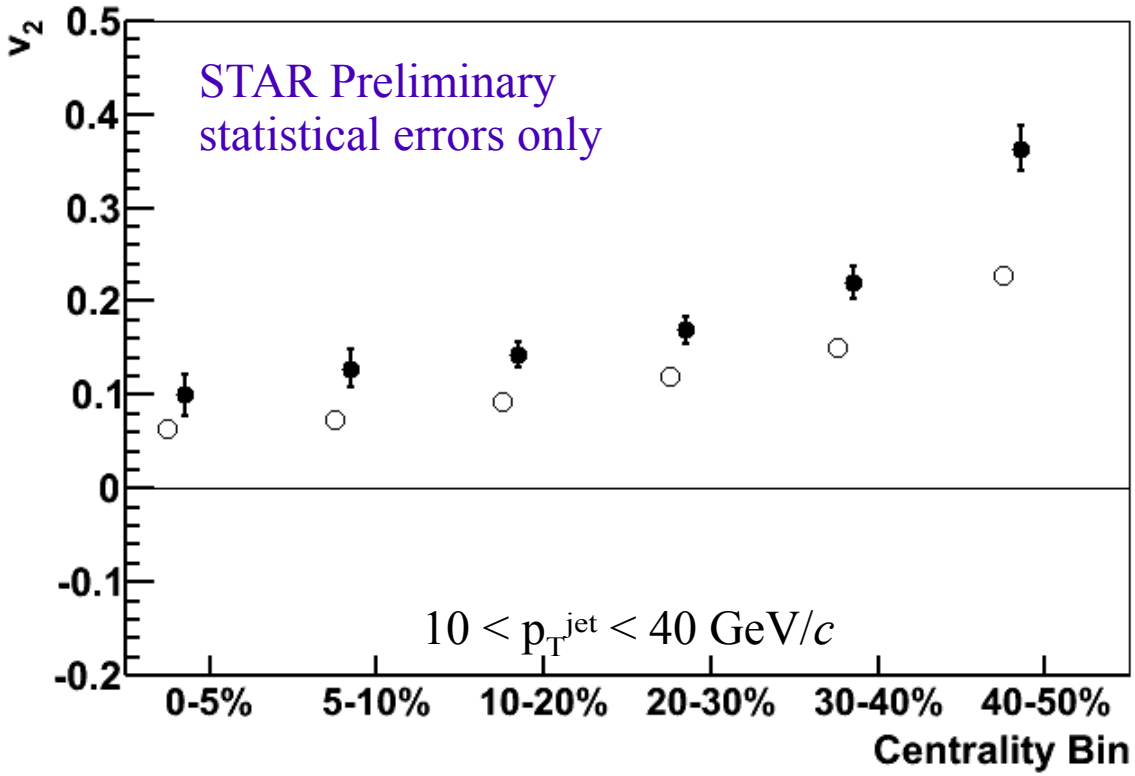
Event Plane Resolution

- Resolution determined from sub-event plane method
- Mixed harmonics: measure $v_2\{\text{ZDC-SMD}\}$ with respect to Ψ_1



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

Jet v_2 and Trigger v_2

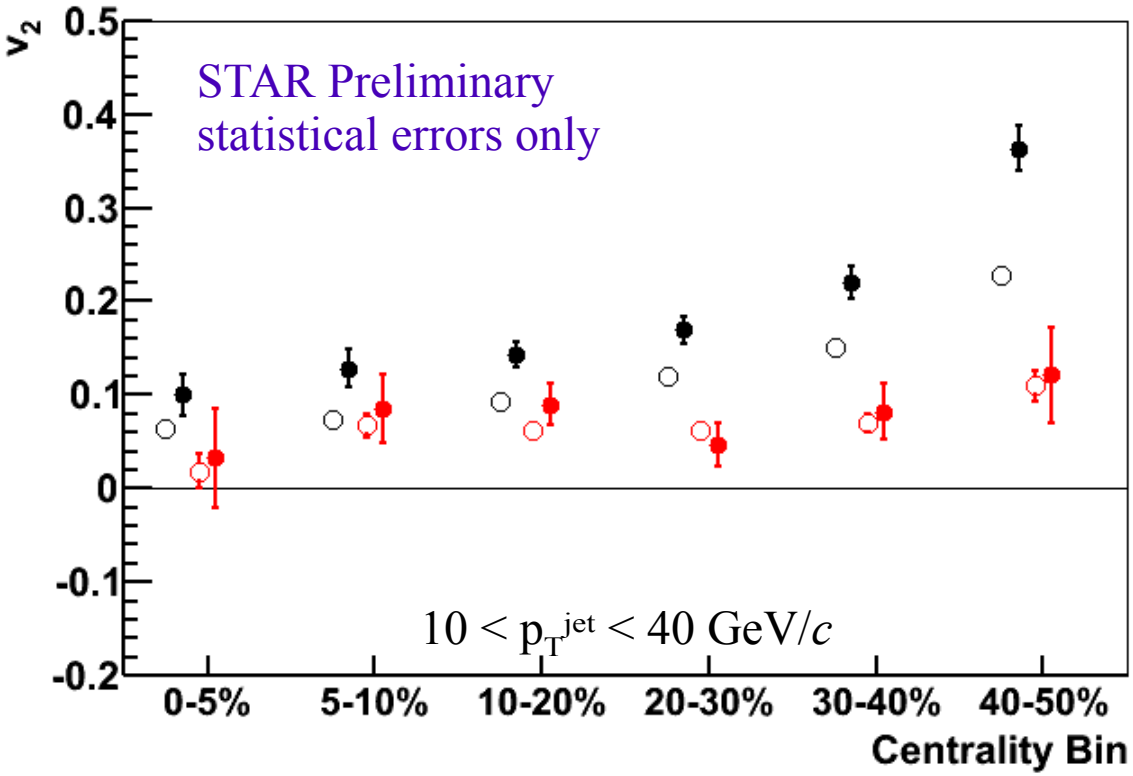


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- ● Jet v_2 {TPC EP}
- ○ HT trigger v_2 {TPC EP}

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

Jet v_2 and Trigger v_2

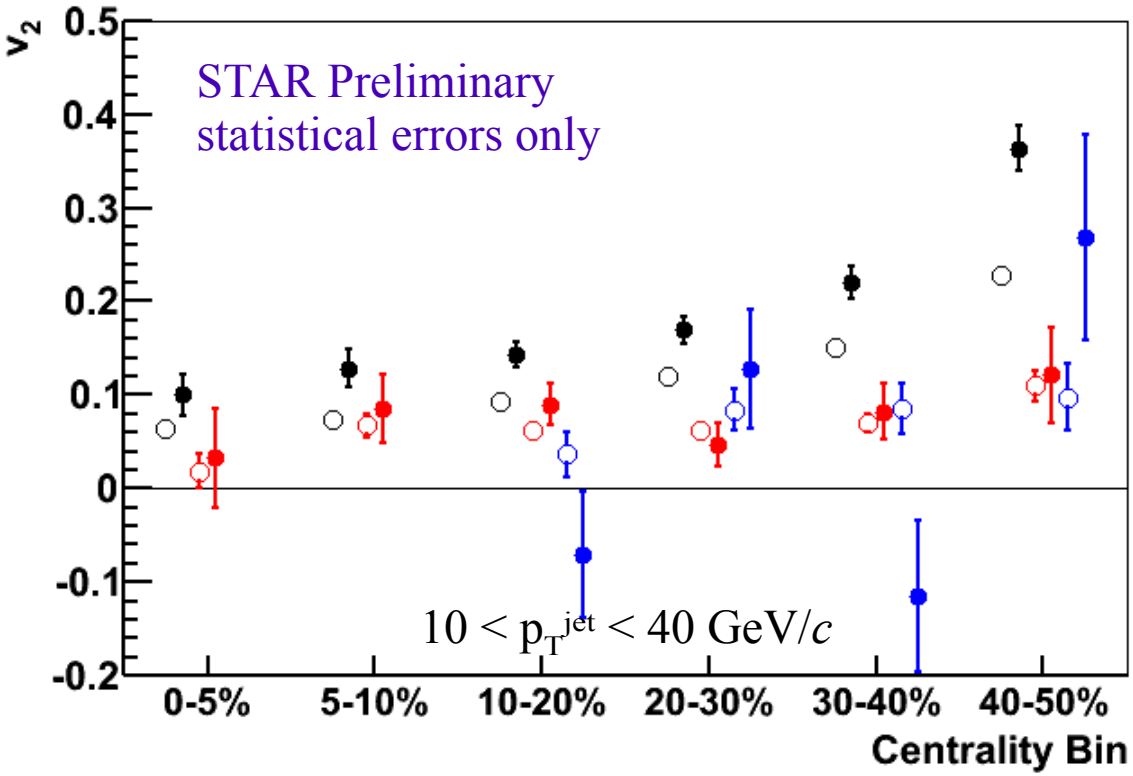


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- Jet v_2{TPC EP}
- Jet v_2{FTPC EP}
- HT trigger v_2{TPC EP}
- HT trigger v_2{FTPC EP}

- Jet v_2{TPC} > HT v_2{TPC} → Jet – event plane bias is more significant when jets have additional high-p_T fragments
- Jet v_2{FTPC} ~ HT v_2{FTPC} → Surface bias / bias towards unmodified jets is largely driven by high-p_T trigger requirement

Jet v_2 and Trigger v_2

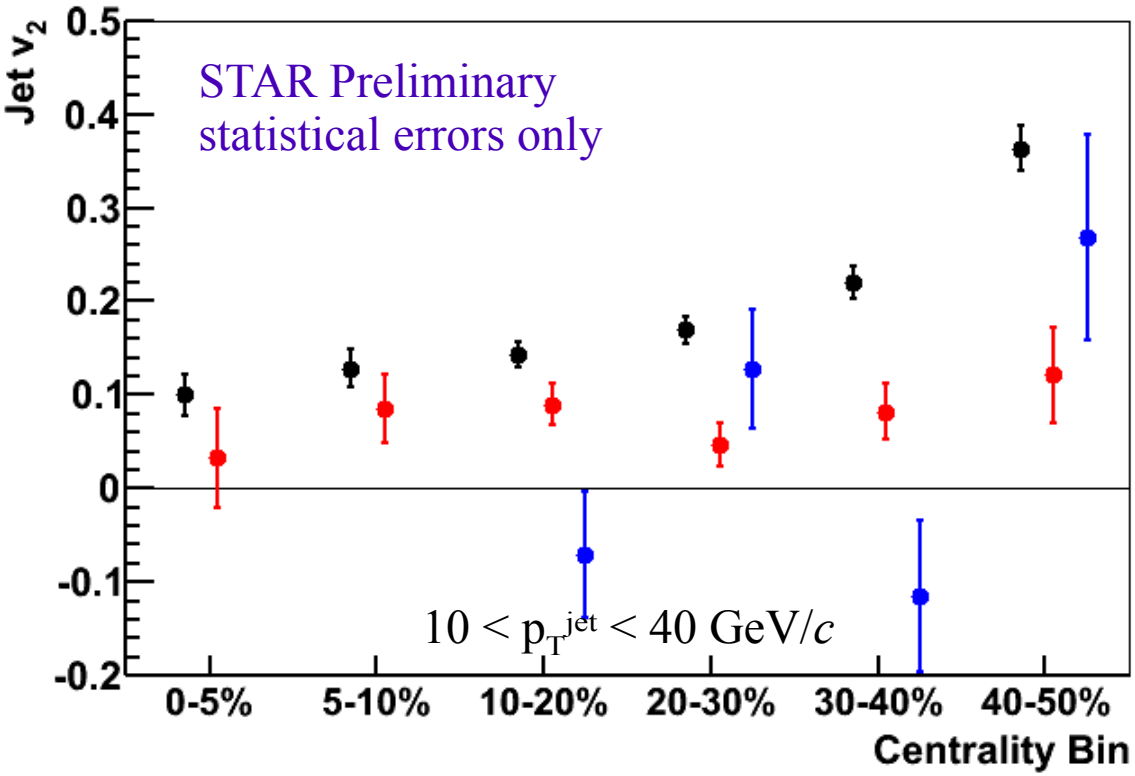


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- Jet v_2{TPC EP}
- Jet v_2{FTPC EP}
- Jet v_2{ZDC-SMD EP}
- HT trigger v_2{TPC EP}
- HT trigger v_2{FTPC EP}
- HT trigger v_2{ZDC-SMD EP}

- Jet v_2{TPC} > HT v_2{TPC} → Jet – event plane bias is more significant when jets have additional high-p_T fragments
- Jet v_2{FTPC} ~ HT v_2{FTPC} → Surface bias / bias towards unmodified jets is largely driven by high-p_T trigger requirement
- HT v_2{ZDC-SMD EP} > 0

Jet v_2 vs Centrality



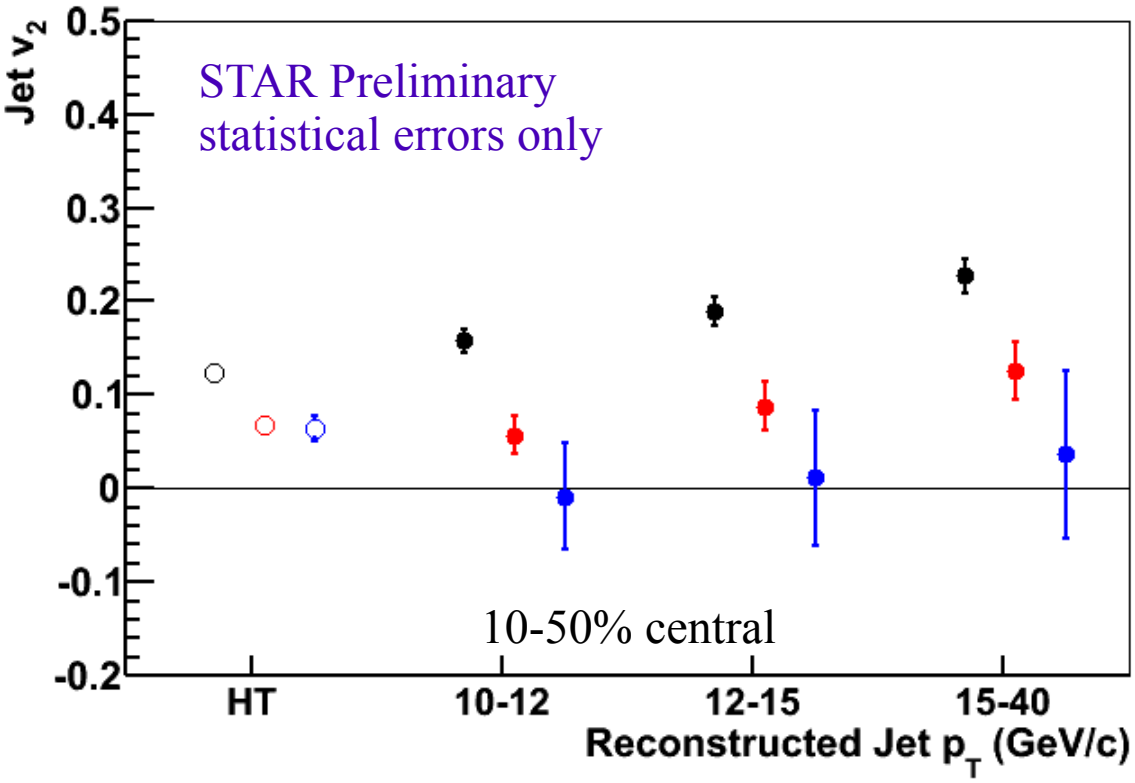
Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

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

- Jet v_2 {FTPC} is non-zero.

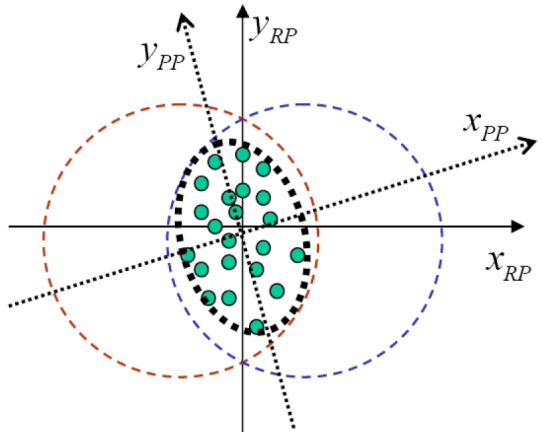
  → Pathlength-dependent parton energy loss
- v_2 {FTPC} shows no clear centrality dependence outside statistical uncertainties.
- Caveat: Reconstructed jet energy has slight dependence on centrality

Jet v_2 vs Reconstructed Jet p_T



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

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



- 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?

Conclusions

- The correlation between reconstructed jets and the reaction plane / 2nd-order participant plane has been measured.

Conclusions

- The correlation between reconstructed jets and the reaction plane / 2nd-order participant plane has been measured.
- Jet – event plane bias is reduced by using detectors at forward rapidities for event plane determination.

Conclusions

- The correlation between reconstructed jets and the reaction plane / 2nd-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.

Conclusions

- The correlation between reconstructed jets and the reaction plane / 2nd-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.

Conclusions

- The correlation between reconstructed jets and the reaction plane / 2nd-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: $0.2 < p_T^{track} < 2.0$, p_T-weighting

  Corrections: φ-weighting

- FTPC: $0.2 < p_T^{track} < 2.0$, p_T-weighting

  Corrections: recentering, shifting

- ZDC-SMD

  Corrections: recentering, shifting

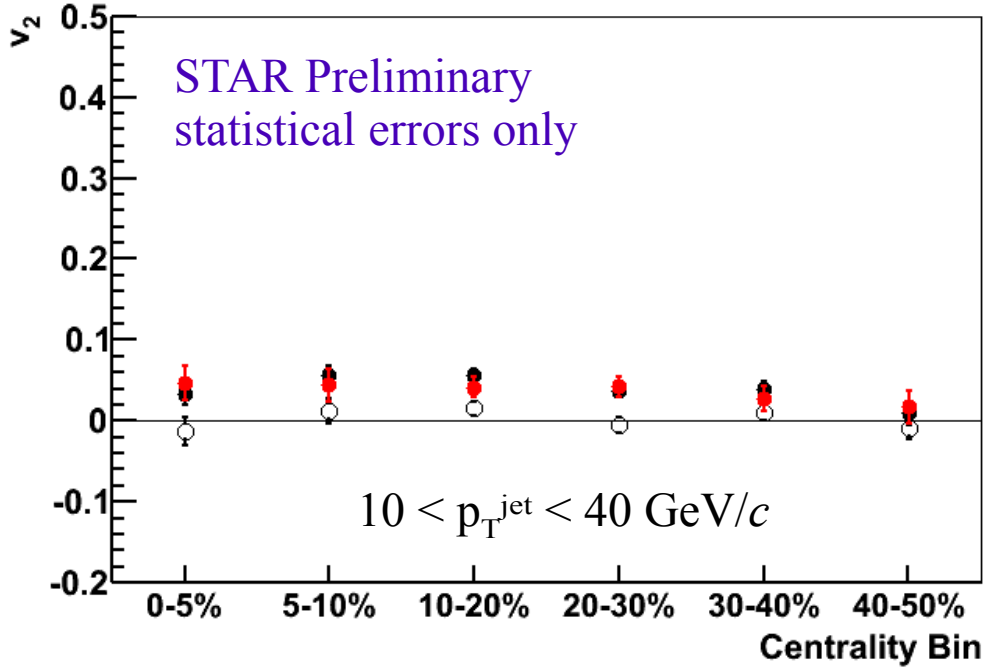
Artificial Sources of Anisotropy

- **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

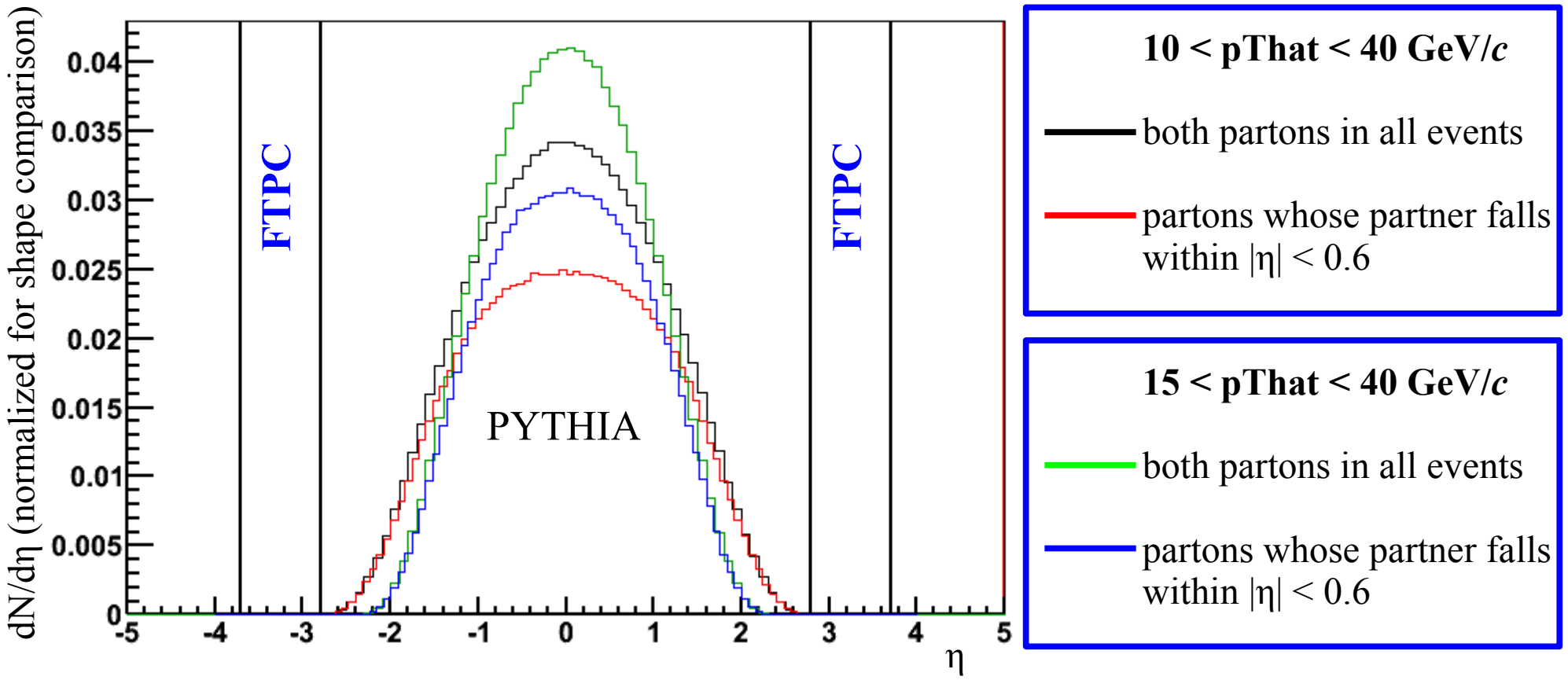


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- ○ jet p_T calculated before embedding
- ● jet p_T calculated after embedding
- ● difference

- Artificial jet v_2 caused by background fluctuations is ~ 4%
- Subtract from measured jet v_2 values.

Does the recoil jet hit the FTPC?



- For pThat > 10 GeV/*c*, in 2M events, < 10 partons point towards the η region covered by the FTPC
- For pThat > 15 GeV/*c*, in 2M events, 0 partons point towards the η region covered by the FTPC

Participant vs. Reaction Plane

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

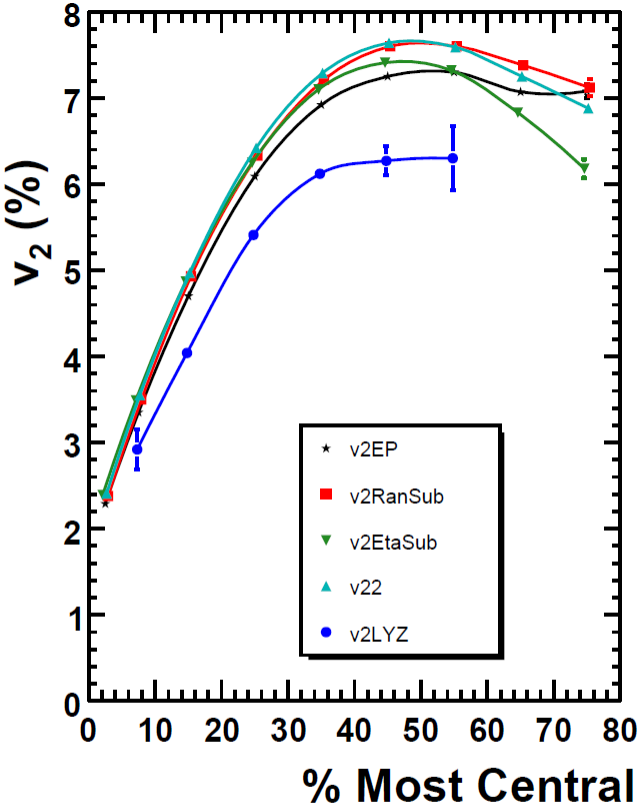


FIG. 6: (Color online) The values of v_2 from various analysis methods vs centrality. Both the upper lines [3] and the lower line [25] are STAR data.

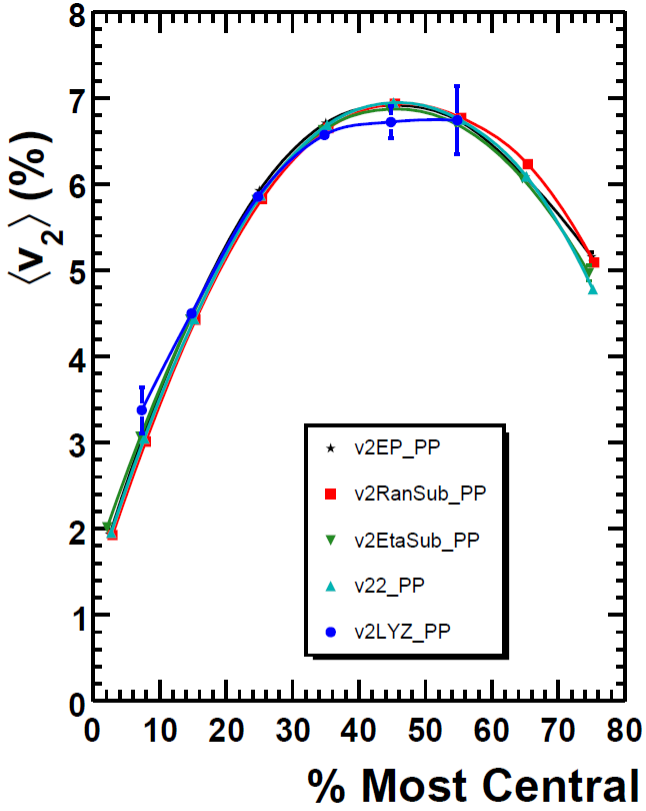
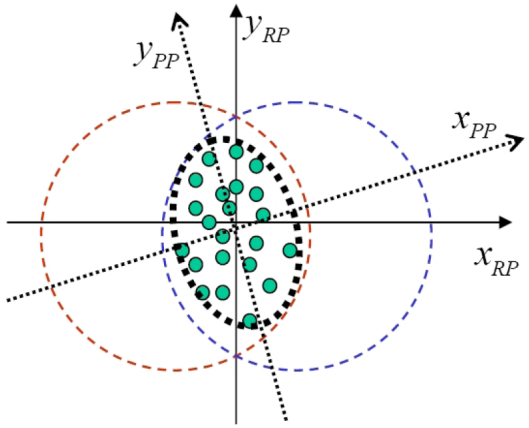


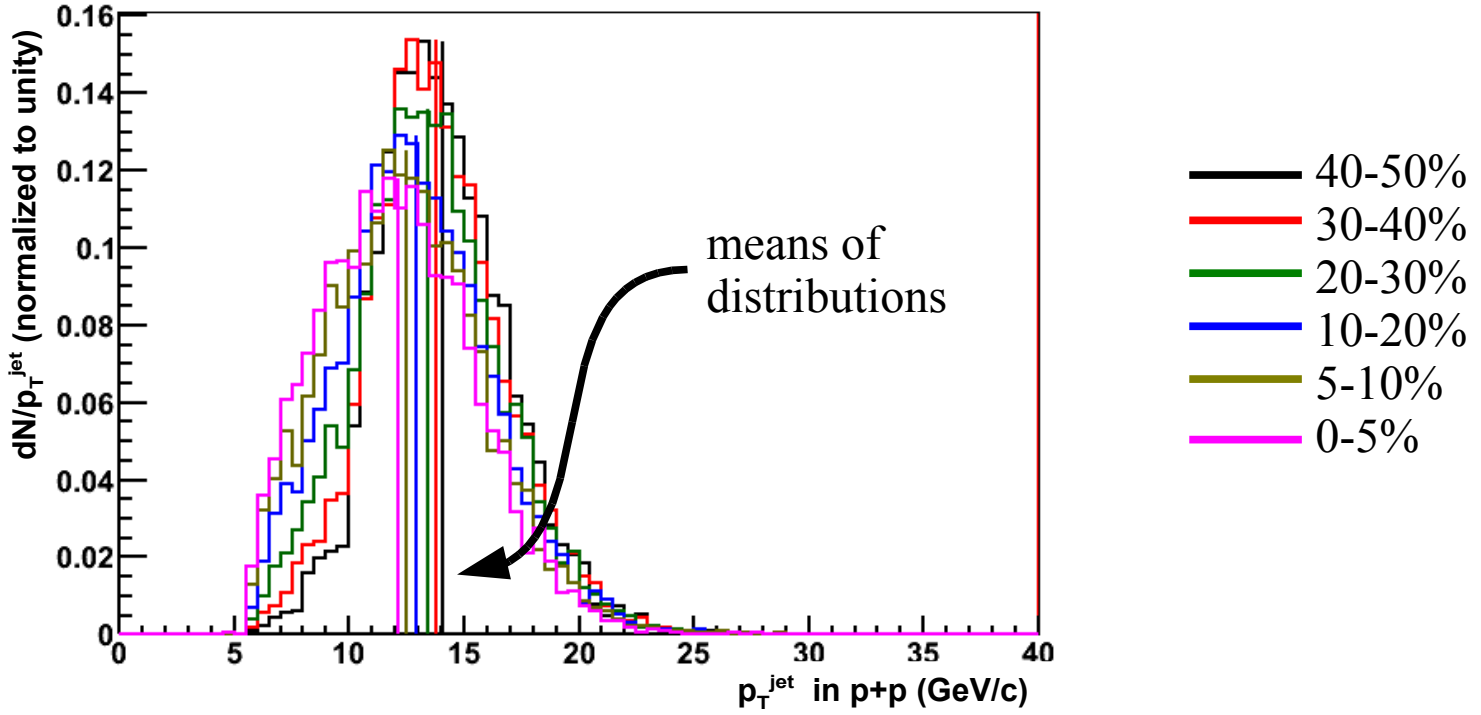
FIG. 7: (Color online) The data from Fig. 6 corrected to $\langle v_2 \rangle$ in the participant plane.

J.-Y. Ollitrault, A. M. Poskanzer, and S. A. Voloshin, PRC **80** (2009) 014904



Reco. Jet p_T vs. Centrality

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



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