Measurements of Jet Anisotropy in Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR

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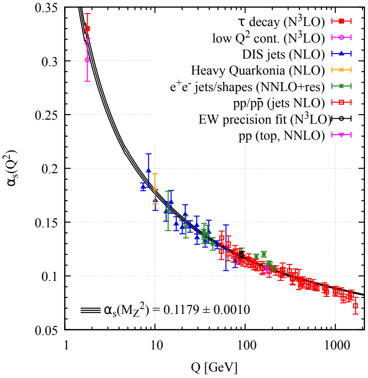
Probing the QGP

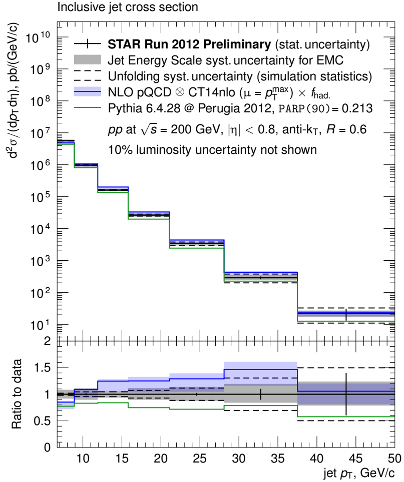
- How can we study the properties of a strongly coupled QGP?
- To study the medium, which exists in the nonperturbative, low Q^2 (momentum exchanged in the interaction) regime, it is helpful to have a probe with a short length scale
- As length scale is inversely proportional with exchanged momentum, such a probe can be described with perturbative QCD



P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

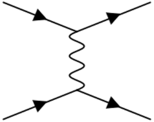
Jets in the Vacuum

- Hard partonic scatterings produce jets
- The cross section of hard scattered partons is perturbatively calculable
- The hard parton fragments in a way well described by Dokshitzer-Griboc-Lipatov-Altarelli-Parisi (DGLAP) type equations
- A jet finding algorithm clusters final state particles such that
    - The jet does not depend on the details of fragmentation or hadronization
    - We have a direct connection between jet and parton kinematics
- There is good agreement between theory and experiment for jet cross section over a wide range of kinematics in $p+p$ collisions

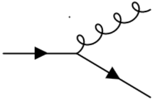


Jets in the QGP

- Jets are produced early in heavy-ion collisions
    - Formation time $\propto 1/Q^2$, so before QGP formation
- Jets traverse the QGP and interact with it
    - Jet quenching
    - Partons lose energy via both collisional and radiative processes
    - Collisional and radiative processes may have different path-length dependence
- We are interested in understanding the path-length dependence of jet quenching
- The path-length dependence could help to distinguish between different models of jet-medium interactions



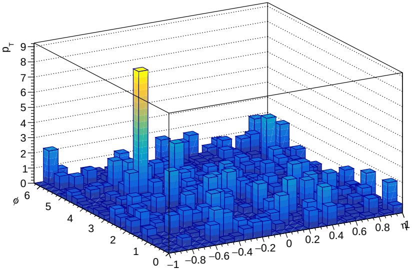
Collisional energy loss



Radiative energy loss

Understanding the Underlying Event

- Jets are far from the only process in heavy-ion collisions
- Soft processes produce a fluctuating background
  - Estimated by calculating the average momentum per unit area, ρ
  - Two leading jets, found by the k_T algorithm, are excluded
- Background assumed to be product of ρ and the jet area A.
  - $p_T = p_T^{\text{measured}} - \rho * A$
- Combinatorial jets are made of particles solely from the soft background



Charged particle momentum distribution in Ru+Ru collision

- A jet finder can not distinguish between real and combinatorial jets
- How can we identify "real" jets?

Identifying Real Jets

- Combinatorial jets are made of soft particles, so we attempt to select jets with hard fragments

Hard Core Matching

- Find jets with constituents $p_T > 2$ GeV/c
  - Hard cores
- Match hard core with $p_T > 10$ GeV/c to highest p_T jet within the jet resolution in $\eta - \phi$
- Used in other STAR analyses
  - Phys. Rev. Lett. 119, 062301 (2017)
  - Phys. Rev. C 105, 044906 (2022)

Leading Track p_T Cut

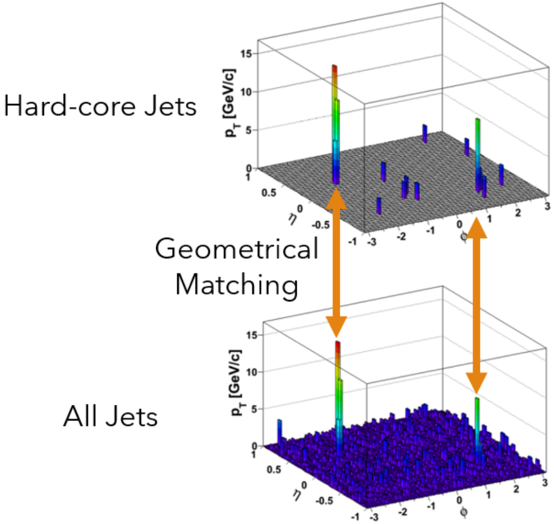
- Require jets to include a constituent with $p_T > 3$ GeV/c
- Used in ALICE $v_2^{ch\ jet}$ measurement
  - Phys. Lett B 753 (2016) 511

Hard Core Matching

- This analysis uses hard core matching
- Geometrically match hard cores to largest p_T jet within the jet resolution

$$dR = \sqrt{(\eta_{hc} - \eta_{jet})^2 + (\phi_{hc} - \phi_{jet})^2} < R_{resolution}$$

- Soft processes do not produce high p_T particles
- May bias jet selection towards surface



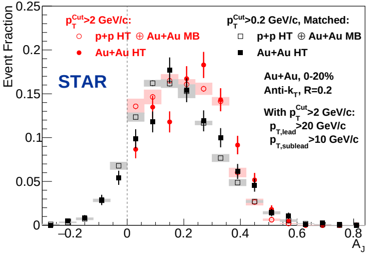
Hard-core Jets

Geometrical Matching

All Jets

Dijet Imbalance

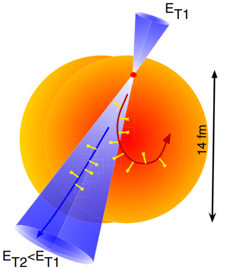
- Jet modification can be studied through dijet pairs
- 2-jet events with back-to-back jets



Au+Au, *STAR Phys. Rev. Lett. 119, 062301 (2017)*

$$A_j = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

- A_j quantifies their difference in transverse momentum
- Difference in p+p and Au+Au shows that jets are modified in the QGP
- We see the difference in A_J between p+p and Au+Au still exists in the matched jets for R=0.2
  - The lost energy is not recovered for R=0.2 hard core matched jets

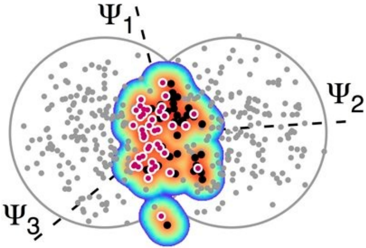


Casalderrey-Solana, Milhano, Wiedemann, Phys. G: Nucl. Part. Phys. 38 124086

What's Missing?

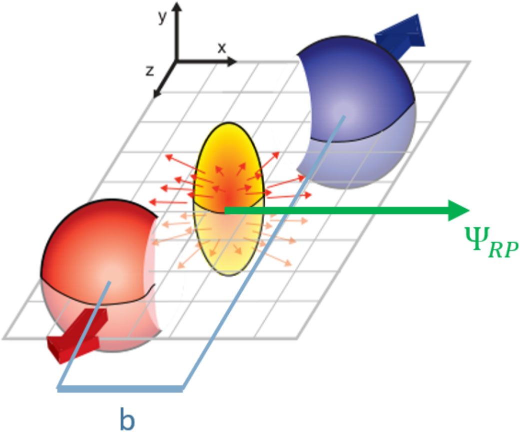
- Dijet imbalance is an ambiguous measurement
  - Each jet loses energy to the medium
  - We do not know how much of the QGP each jet interacted with

- Can we learn more by utilizing the initial collision geometry?
  - Heavy-ion collisions produce a QGP with an eccentricity related to the impact parameter
  - The minor axis of the eccentricity lies within the participant plane



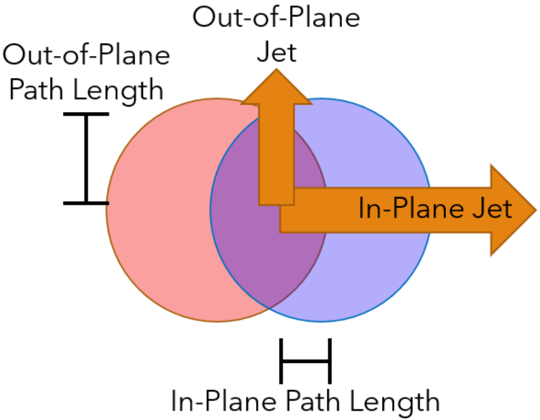
Event Geometry

- A heavy-ion collision can be characterized by its
  - Impact parameter, $\vec{b}$
  - Reaction plane, Ψ_{RP}
- Cannot measure these directly
  - $\vec{b} \rightarrow$ centrallity
  - $\Psi_{RP} \rightarrow \Psi_{EP}$



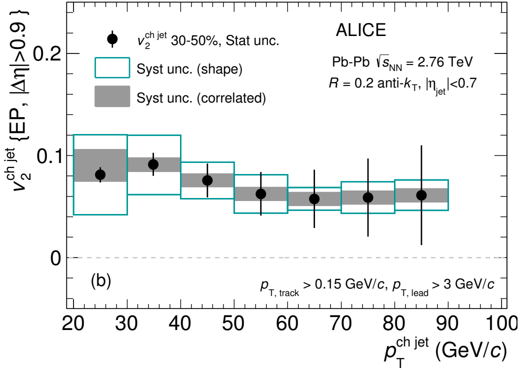
Path Length Dependent Energy Loss

- In semi-central events, the QGP has a significant eccentricity
- A jet interacts with less medium in-plane than out-of-plane
- Since jet production has no preferred orientation, differences in yields with respect to the event plane are expected as a result of path-length dependent energy loss
- Quantified with Fourier decomposition
  - $\frac{dN}{d\Delta\phi} \propto 1 + 2v_2^{jet}\cos(2(\Psi_2 - \phi_{jet}))$
- High p_T v_2 is not a result of the pressure gradient like flow

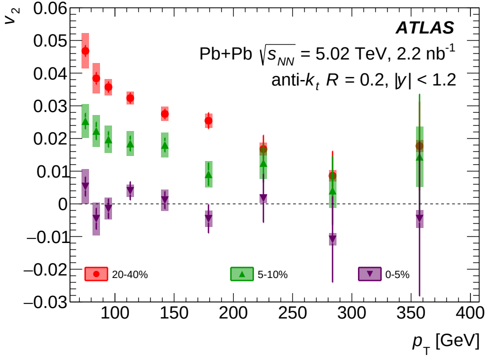


LHC Results

- Jet v_2 has previously been measured at the LHC



ALICE *Phys. Lett B 753 (2016) 511*



ATLAS *Phys. Rev. C 105 (2022) 064903*

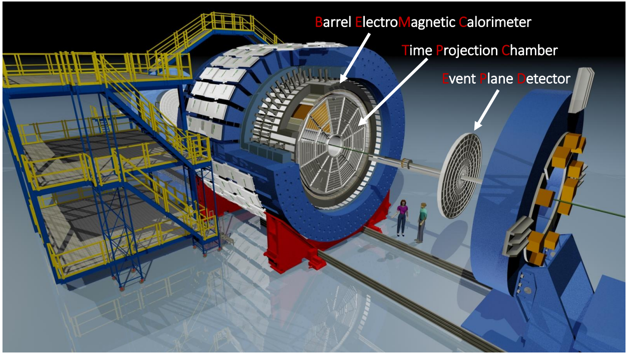
Complementarity of STAR Measurements

- RHIC produces a cooler QGP than the LHC
- STAR can measure jets at lower p_T
  - Down to 10GeV/c
- STAR recorded $\sqrt{s_{NN}} = 200$ GeV Ru+Ru and Zr+Zr collisions
  - 4 billion good minimum bias events
  - Isobars with 96 nucleons
  - Zr: 40 protons, 56 neutrons
  - Ru: 44 protons, 52 neutrons
  - A smaller system than Au+Au (197 nucleons) or Pb+Pb (208 nucleons)

The STAR Detector

This analysis makes use of STAR's

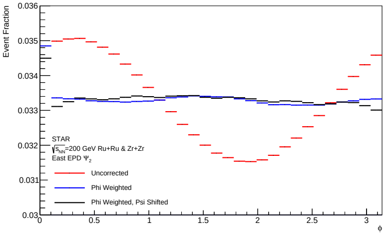
- Time Projection Chamber
  - Reconstructs charged particle tracks
  - $0 < \phi < 2\pi$, $-1 < \eta < 1$
- Barrel Electromagnetic Calorimeter
  - 3.4 GeV E_T trigger
  - $0 < \phi < 2\pi$, $-1 < \eta < 1$
- Event Plane Detector
  - Measures charged particle multiplicity
  - Event plane reconstruction
  - $0 < \phi < 2\pi$, $2.1 < |\eta| < 5.1$

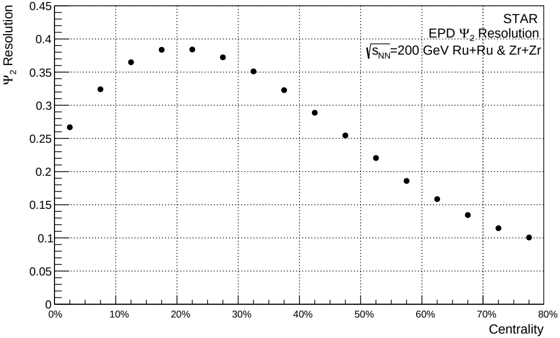


Measuring the Event Plane

- STAR was upgraded in 2018 with an Event Plane Detector
- Measures charged particle multiplicity in forward region
  - 2π in ϕ, $2.1 < |\eta| < 5.1$
- Event plane $\Psi_{n,\,EP}$ calculated using

$$\Psi_{n,\,EP} = \frac{1}{n}\tan^{-1}\left(\frac{\sum_i w_i \sin(n\Delta\phi)}{\sum_i w_i \cos(n\Delta\phi)}\right)$$

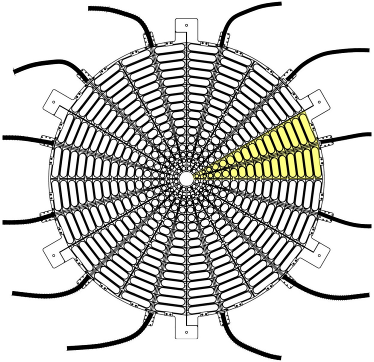




- Event plane distribution is flattened to be isotroptic in ϕ
- Phi-weighting assumes same flux for each tile in a ring
- Psi-shifting determines event-by-event shift to get flat distribution

The Need for a Forward Detector

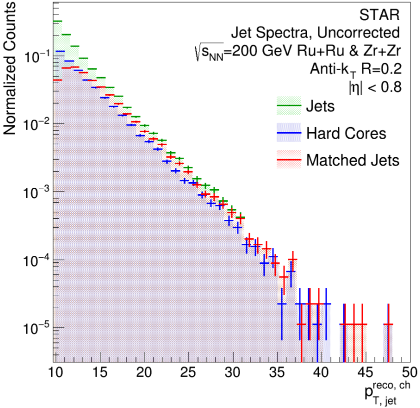
- A jet v_2 measurement was difficult at STAR before the EPD was installed
- Jets bias the determination of the event plane at mid-rapidity
    - Leads to overestimation of v_2
    - *Phys.Rev.C 87 (2013) 3, 034909*
- Pseudorapidity gap of 1.1 units decouples event plane finding and jet finding



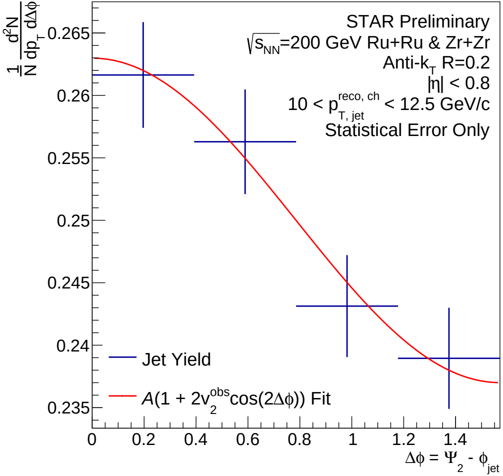
The STAR Event Plane Detector

Jet Finding

- Studying anti-k_T jets with a resolution of 0.2
- Using hard core matched, charged only jets from high tower triggered data
- Requiring hard core constituents $p_T > 2$ GeV/c
- Requiring hard core $p_{T\ jet}^{reco} > 10$ GeV/c
- Modulating background ρ with charged particle v_2



Jet Yield Relative to Event Plane



- Jet yield is measured for jets which are matched to a hard core
- Binned as a function of the angle between the jet axis and the event plane
- The yield is fit with a Fourier expansion to extract charged jet $v_2^{ch\ jet}$

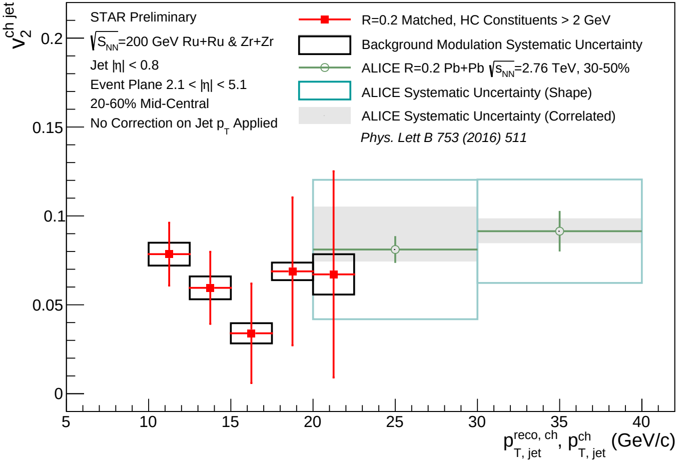
$$\frac{d^N}{d\Delta\phi d\eta} = A(1 + 2v_{2\ obs}^{ch\ jet}\cos(2\Delta\phi))$$

- The observed $v_{2\ obs}^{ch\ jet}$ needs to be corrected for the event plane resolution, $\mathcal{R}(\Psi_{2,EP})$

$$v_2^{ch\ jet} = \frac{v_{2\ obs}^{ch\ obs}}{\mathcal{R}(\Psi_{2,EP})}$$

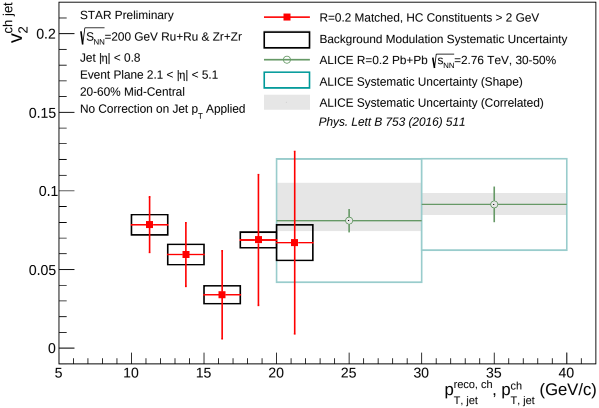
Jet v_2^{ch}

- Evidence of a non-zero $v_2^{ch\ jet}$ in a medium sized system!
    - 3.5 σ from zero
- Systematic uncertainty from varying background modulation by $\pm 2\%$
- In general agreement with ALICE Pb+Pb $v_2^{ch\ jet}$
    - ALICE results unfolded

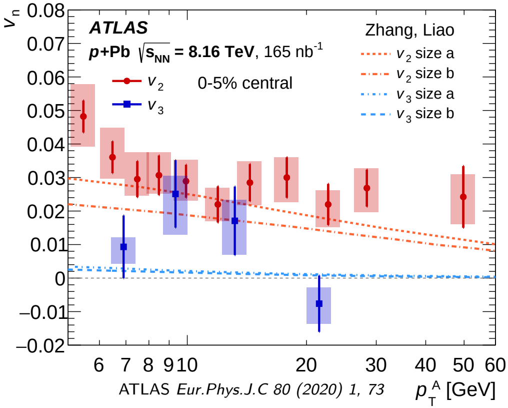


Jet v_2 in Smaller Systems

- ATLAS has measured non-zero v_2 in jet triggered p+Pb collisions
- Theory can be tweaked to match this, but then $R_{p\mathrm{Pb}} < 1$ is predicted and not observed
- So the jet-quenching model for v_2 in small systems is not complete. Studies in medium size systems will be useful



Phys. Lett B 753 (2016) 511



ATLAS *Eur.Phys.J.C 80 (2020) 1, 73*

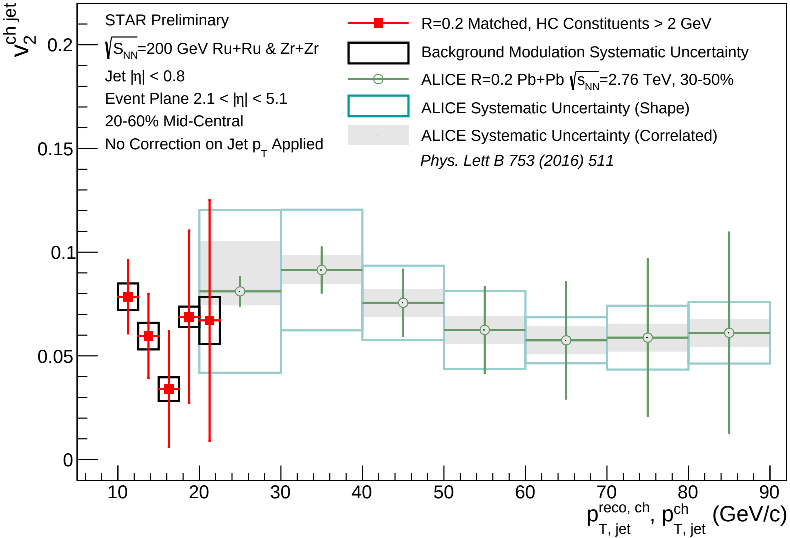
Conclusions

- Evidence for a non-zero $v_2^{ch\ jet}$ is observed in a medium sized system
- Finite $v_2^{ch\ jet}$ and high p_T charged particle suppression are consistent with the naive expectation of path length dependent energy loss
    - Need full systematics before drawing strong conclusions
    - What (if any) role does the surface biasing from the hard core selection play?
    - What (if any) role does the fluctuating background play?
    - v_2 of high p_T particles in small systems indicates it can partially come from a different source
    - See Tong Liu's talk for high p_T charged hadron R_{AA} in isobar collisions

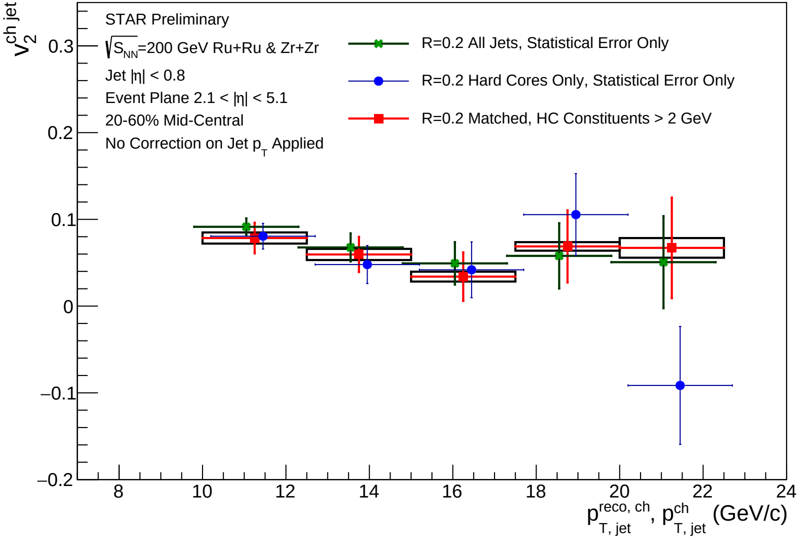
- Up next: exploration of hard process selection
    - Varying hard core constituent requirement - change the surface bias
    - Try ALICE leading constituent high-p_T criteria
- $v_2^{ch\ jet}$ for larger jet resolution
    - Does capturing more of the jet's energy change the observed anisotropy?

Backup

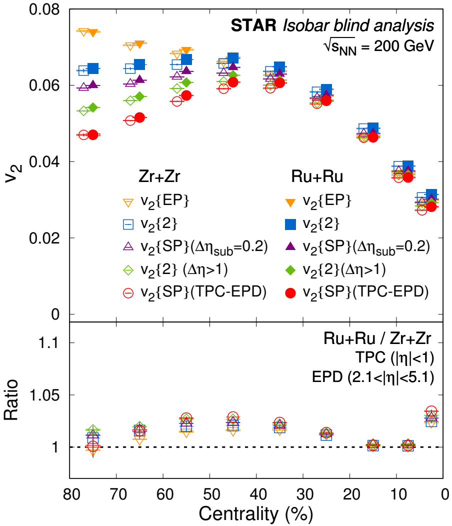
Jet v_2^{ch}


STAR Preliminary
$\sqrt{s_{NN}}$=200 GeV Ru+Ru & Zr+Zr
Jet |η| < 0.8
Event Plane 2.1 < |η| < 5.1
20-60% Mid-Central
No Correction on Jet p_T Applied
R=0.2 Matched, HC Constituents > 2 GeV
Background Modulation Systematic Uncertainty
ALICE R=0.2 Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, 30-50%
ALICE Systematic Uncertainty (Shape)
ALICE Systematic Uncertainty (Correlated)
Phys. Lett B 753 (2016) 511
$v_2^{ch\ jet}$
0
0.05
0.1
0.15
0.2
10
20
30
40
50
60
70
80
90
$p_{T,\ jet}^{reco,\ ch}$, $p_{T,\ jet}^{ch}$ (GeV/c)

Jet v_2^{ch}


STAR Preliminary
$\sqrt{S_{NN}}$=200 GeV Ru+Ru & Zr+Zr
Jet |η| < 0.8
Event Plane 2.1 < |η| < 5.1
20-60% Mid-Central
No Correction on Jet p_T Applied
R=0.2 All Jets, Statistical Error Only
R=0.2 Hard Cores Only, Statistical Error Only
R=0.2 Matched, HC Constituents > 2 GeV
$v_2^{ch\ jet}$
0.3
0.2
0.1
0
−0.1
−0.2
8
10
12
14
16
18
20
22
24
$p_{T,\ jet}^{reco,\ ch}$, $p_{T,\ jet}^{ch}$ (GeV/c)

Charged Particle v_2 in Isobars



Phys.Rev.C 105 (2022) 1, 014901