Medium Effects on Hadrons and Jets in $\sqrt{s_{NN}} = 200$ GeV Isobar Collisions at STAR

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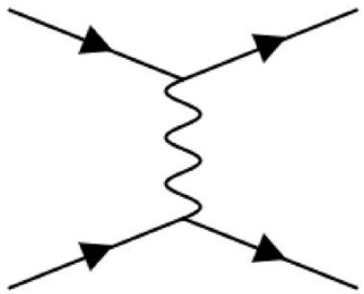
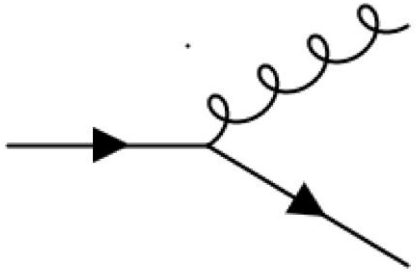
Jet Modification in Heavy-Ion Collisions

- Jet formation and fragmentation in pp is well understood
  - Use as probe of Quark-Gluon Plasma
- Jet formation time is early in the collision
  - Experience full evolution of medium
- High momentum objects passing through a QGP lose energy through collisional and radiative processes
- Understanding the contribution of each process can help distinguish between models

- Collisional Processes
  - $E_{\text{loss}} \propto L$

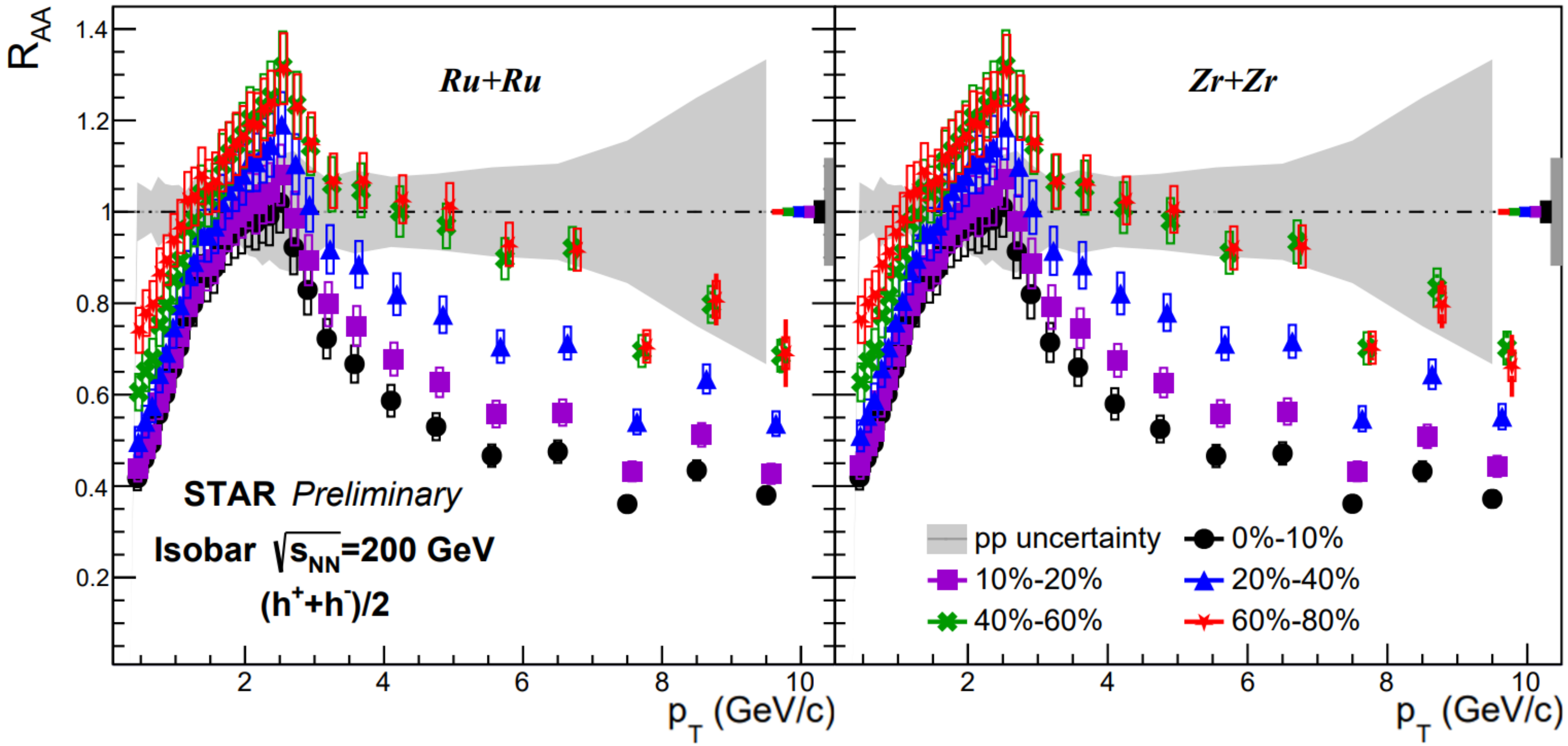


- Radiative Processes
  - $E_{\text{loss}} \propto L^2$



J.D. Bjorken, FERMILAB-PUB-82-059-THY
Baier, Dokshitzer, Mueller, Peigne, Schiff, Nucl.Phys.B483:291-320,1997

High p_T Hadron Modification in Heavy-Ion Collisions



$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{ev}}^{\mathrm{AA}}} \frac{d^2N^{\mathrm{AA}}/d\eta dp_{\mathrm{T}}}{T_{\mathrm{AA}} d^2\sigma^{\mathrm{NN}}/d\eta dp_{\mathrm{T}}}$$

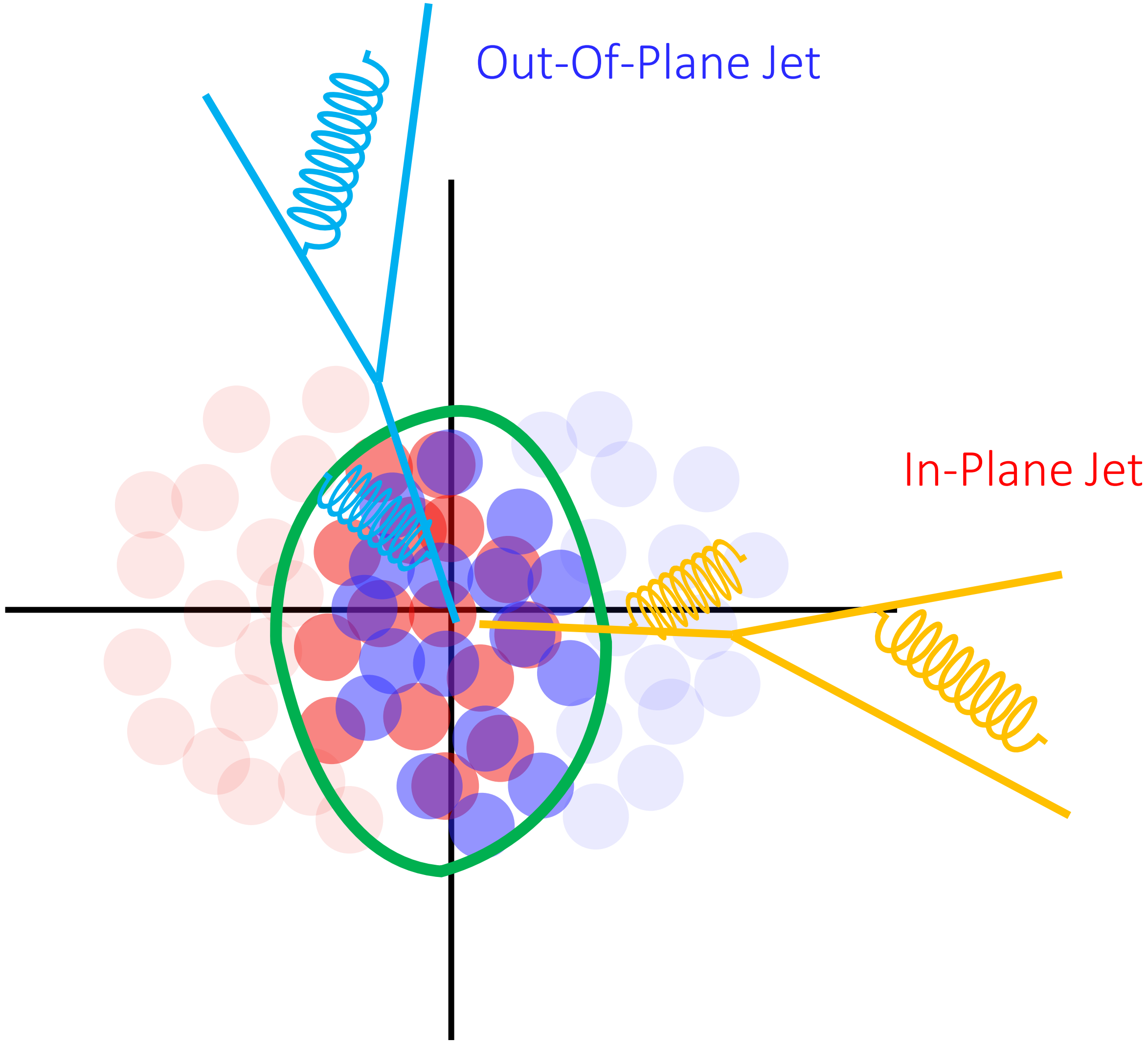
$$T_{\mathrm{AA}} = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

- STAR recorded Ru+Ru and Zr+Zr collisions in 2018, a medium-sized system
  - Ru/Zr: A=96
  - Au: A=197
- Central collisions show significant hadron suppression at high momentum
- Strong centrality dependence hints at path-length dependent effects
- We can use the collision geometry to select the path length to better understand the dependence

See poster by Isaac Mooney for more details!

Constraining the Path Length

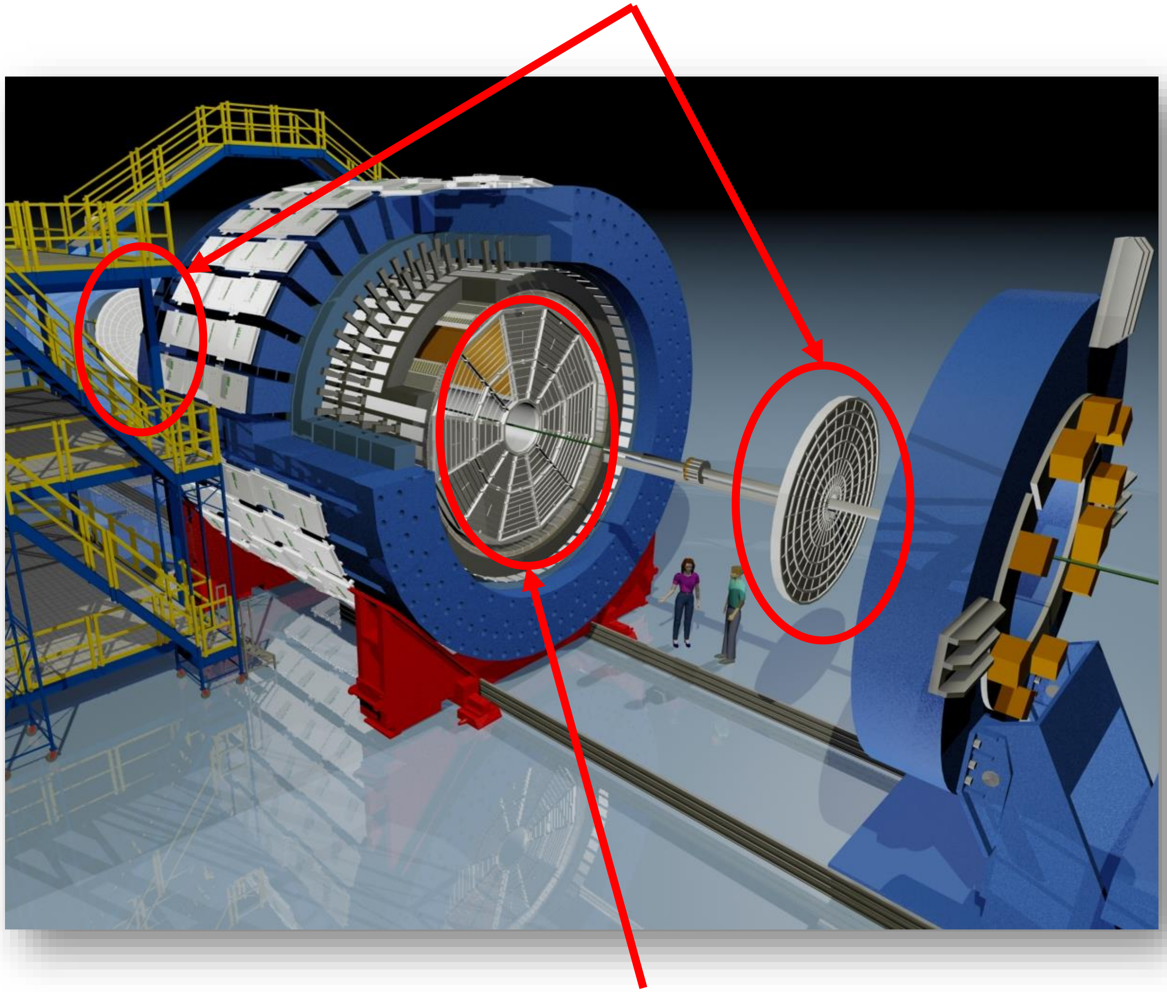
- Semi-central collisions produce an approximately elliptical QGP
- Jets which travel in-plane will experience a shorter path length through the medium than those which travel out-of-plane
- Thus, the expected in-plane yield should be greater than the out-of-plane yield
- The anisotropy is reported with the second order Fourier coefficient, v_2
  - Though the language is the same, high p_{T} v_2 (quenching) is driven by different effects than low p_{T} v_2 (flow)



$$\frac{dN}{d\Delta\phi} \propto 1 + 2\, v_2 \cos(2(\phi - \Psi_2))$$

The STAR Detector

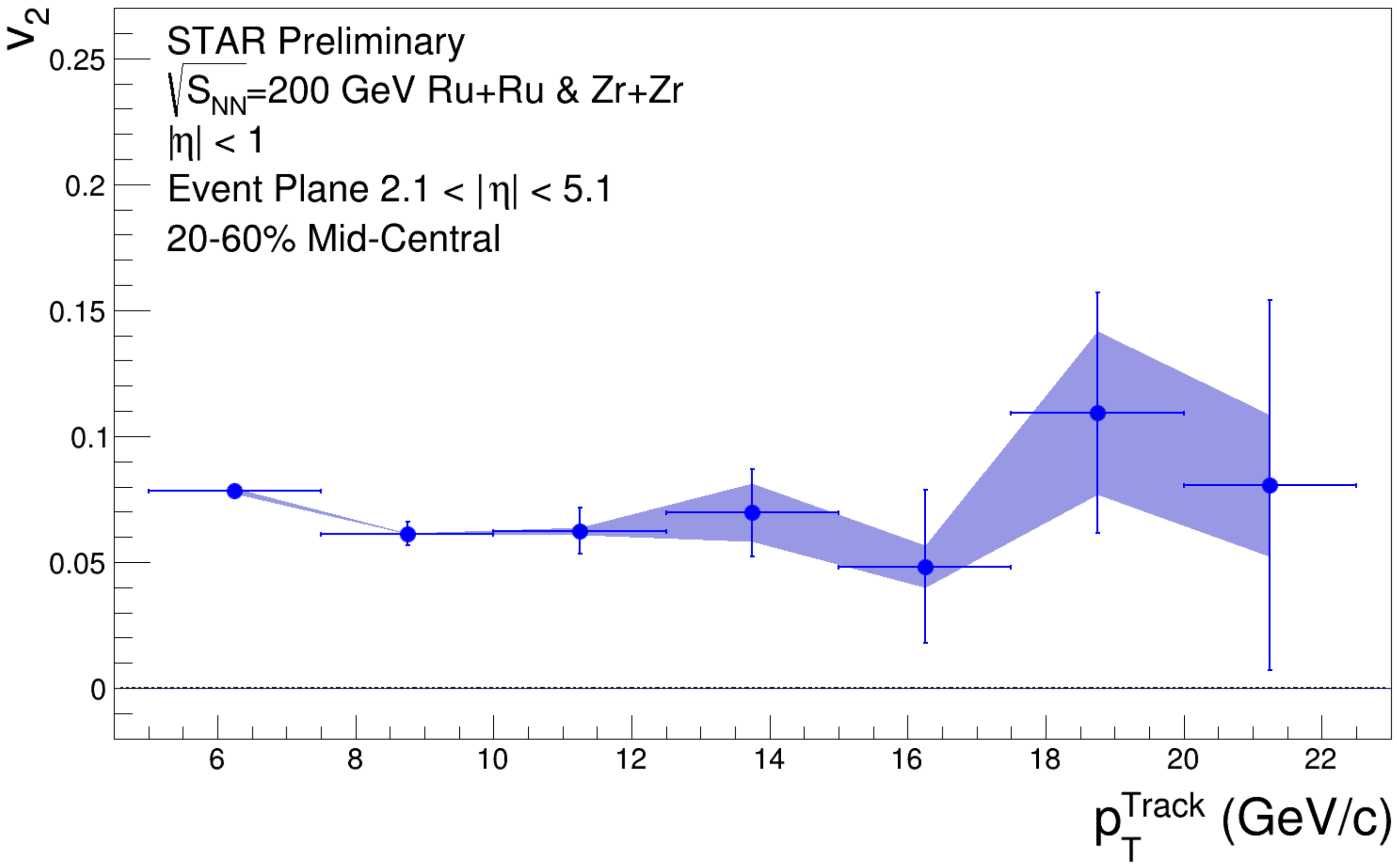
- Event Plane Detector upgrade at STAR allows for determination of the event plane at large rapidity
  - Installed in 2018
  - Scintillating hit detector
  - 16 η divisions, 24 ϕ divisions
- Rapidity gap between jet finding and event plane determination avoids autocorrelation
  - Event plane measured in $2.1 < |\eta| < 5.1$
- Charged jets measured in Time Projection Chamber
  - $|\eta| < 1$, full azimuthal coverage
- Analyze electromagnetic calorimeter triggered events
  - $|\eta| < 1$, full azimuthal coverage, $E_T > 3.4$ GeV



High p_T Charged Particle v_2

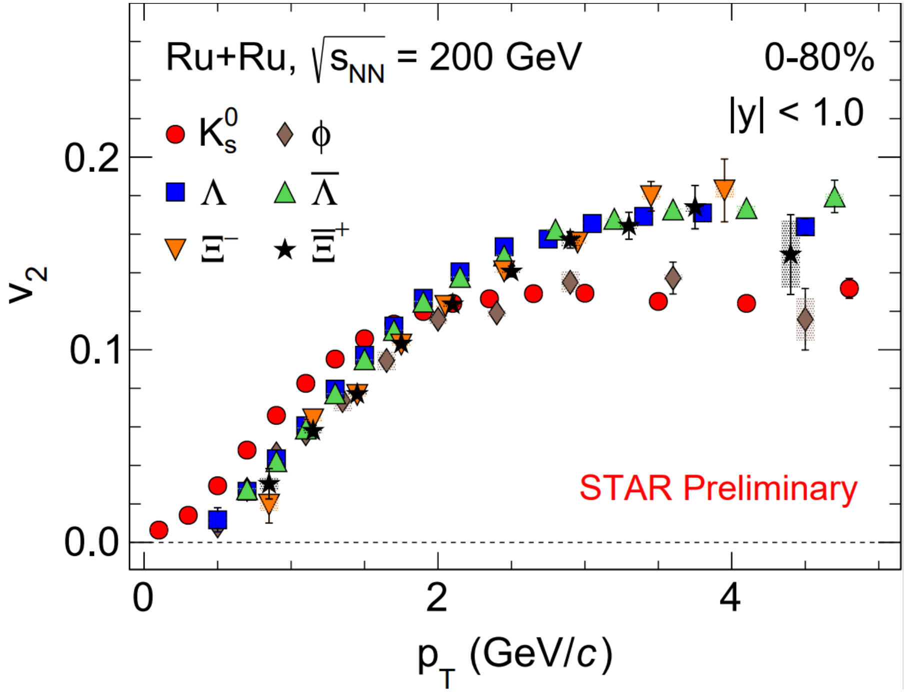
$$\frac{dN}{d\Delta\phi} \propto 1 + 2\, v_2 \cos(2(\phi - \Psi_2))$$

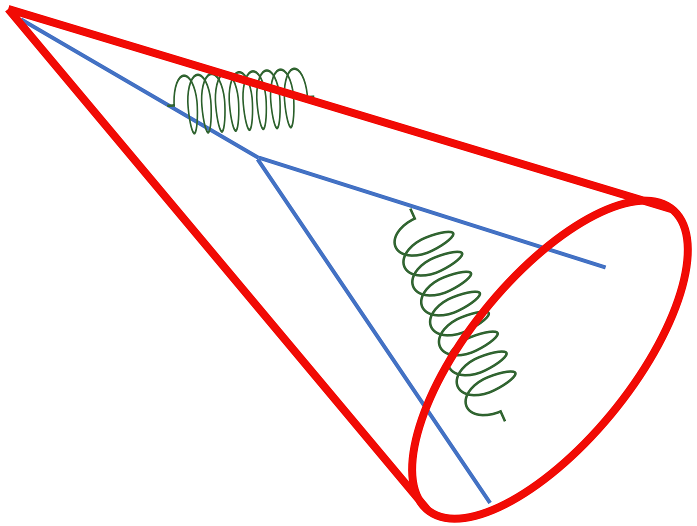
- High transverse momentum charged particle v_2 is non-zero
- No strong transverse momentum dependence of v_2 at high p_T
- Systematic uncertainty dominated by tracking



From Hadrons to Jets

- Measuring high p_{T} charged hadron v_2 allows the same observable to study flow and quenching effects
- But, hard partons may fragment and emit softer radiation
- Clustering into jets reduces measurement sensitivity to fragmentation and hadronization
- Jet v_2 was measured for anti-k_{T} jets with resolutions (R) of 0.2, 0.4, and 0.6
- The effects of the background needs to be carefully considered
    - Combinatorial jets
    - Modulated underlying event

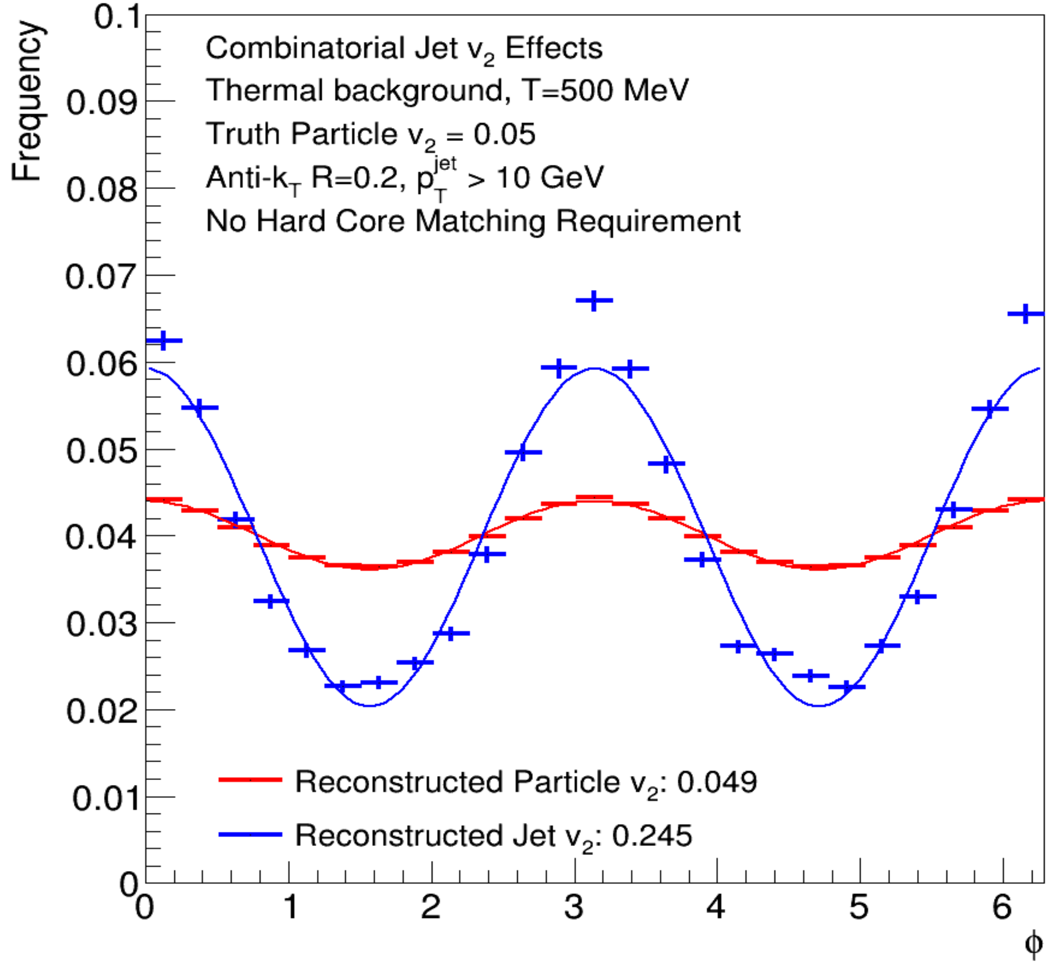




Combinatorial Jets

- Hotspots in the underlying event can be clustered into combinatorial jets
- This combined with an underlying flow driven v_2 can enhance the observed jet v_2 if not properly corrected
- Demonstrated with toy model with purely thermal background – no hard processes!
- Need to select jets from hard partonic scattering

Enhanced Jet v_2 in Toy Model

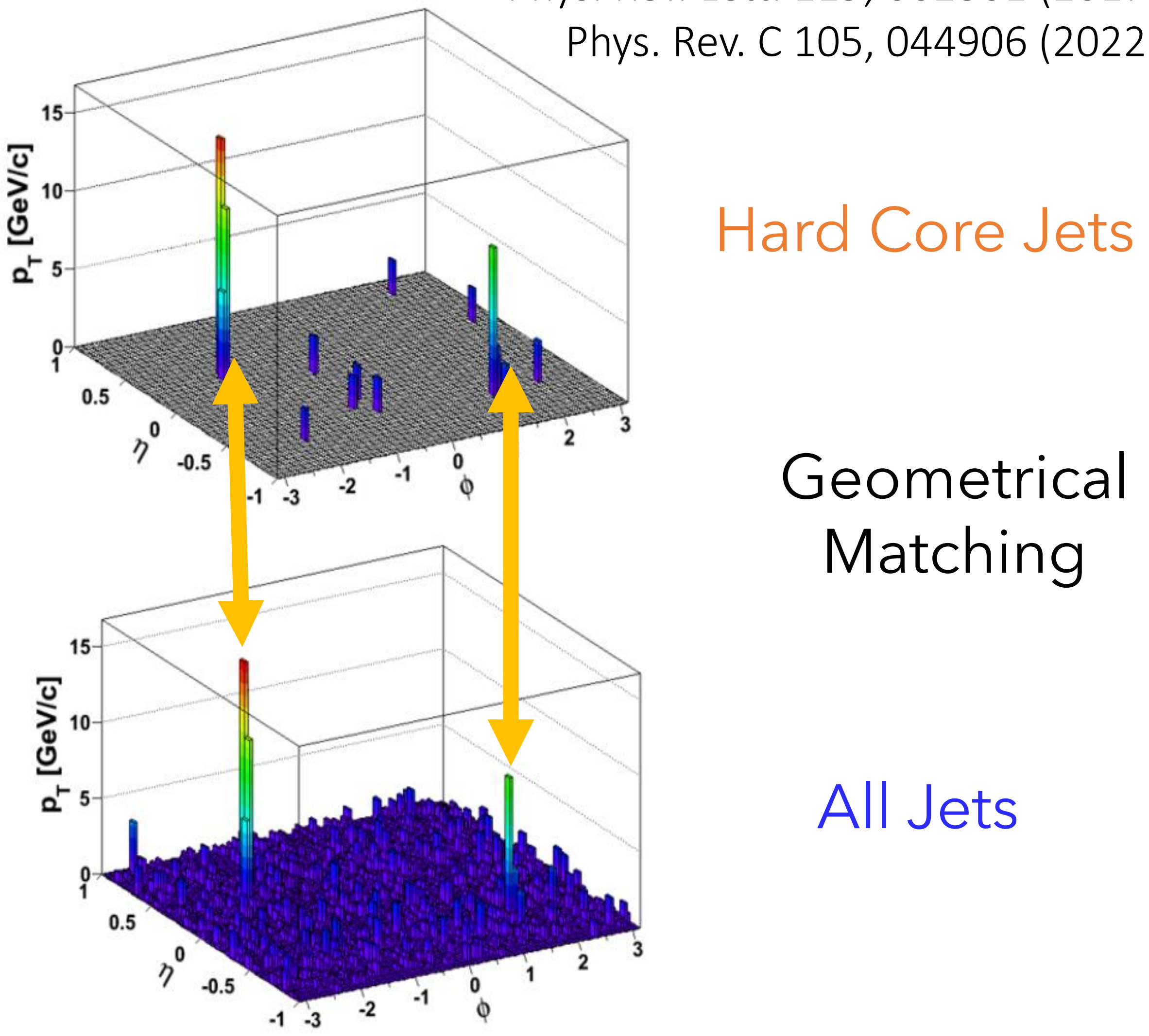


Thermal background only – No jet proxy!

Previously used in
Phys. Rev. Lett. 119, 062301 (2017)
Phys. Rev. C 105, 044906 (2022)

Rejecting Combinatorial Jets

- Tracks with $p_{\mathrm{T}} > 2$ GeV/c are selected and clustered with anti-k_{T} algorithm into hard core jets
  - Idea: Cluster only tracks from hard scattering
- Hard core jets with $p_T > 10$ GeV/c are geometrically matched to jets with constituent $p_T > 0.2$ GeV/c if $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < R$
- Only jets matched with a hard core jet are analyzed
- Jet energy scale corrected by area-based subtraction
  - $p_{\mathrm{T}}(\phi) = p_{\mathrm{T}}^{\mathrm{measured}} - \rho(\phi)A$
  - ρ modulated with assumed underlying event flow of 4% (varied as source of uncertainty)

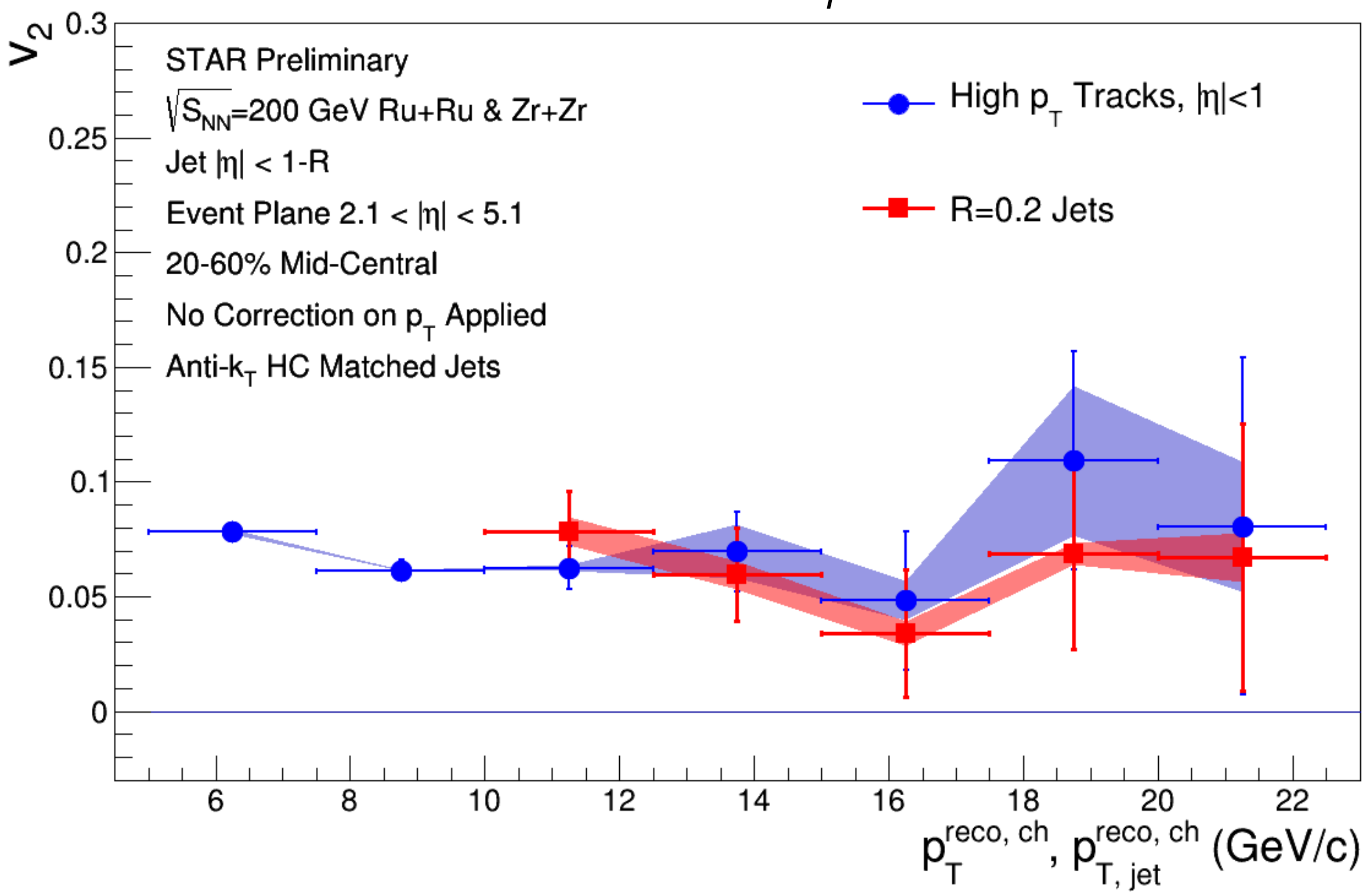


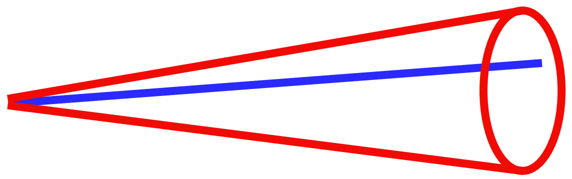
R: Jet resolution parameter
ρ: Average transverse momentum density
A: Jet area

Jet v_2 in the Isobar Collisions

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\,v_2\cos(2(\phi - \Psi_2))$$

- Non-zero jet v_2 is observed for R=0.2 hard core matched jets in isobar collisions
- Like inclusive charged particle v_2, no strong p_T dependence
- No p_T correction applied





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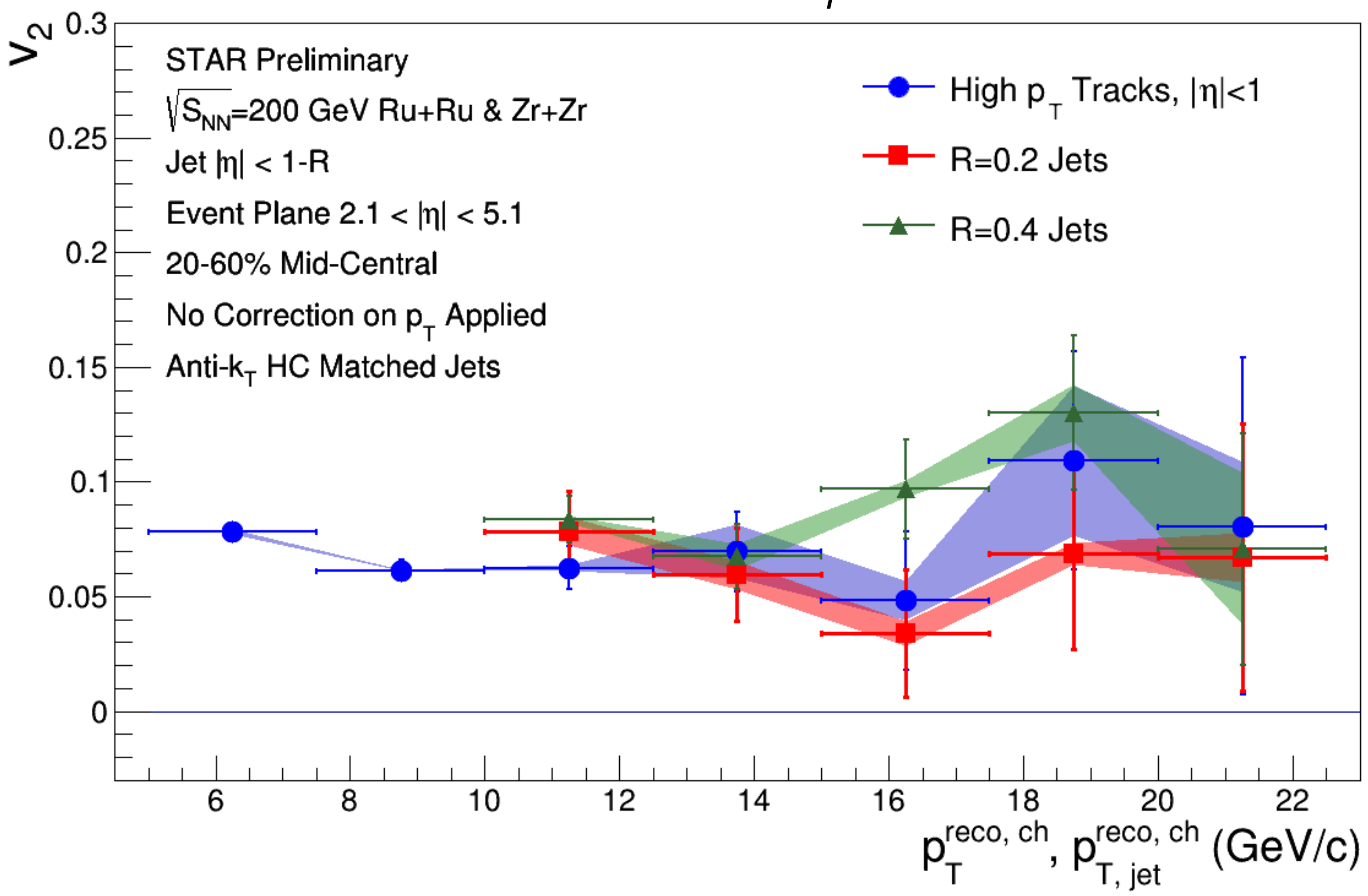
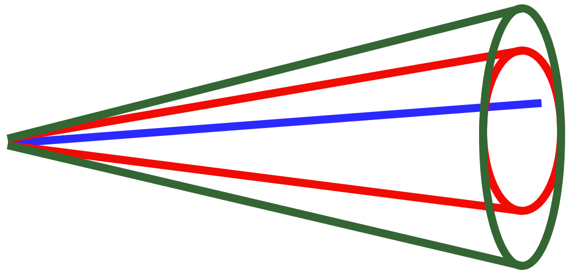
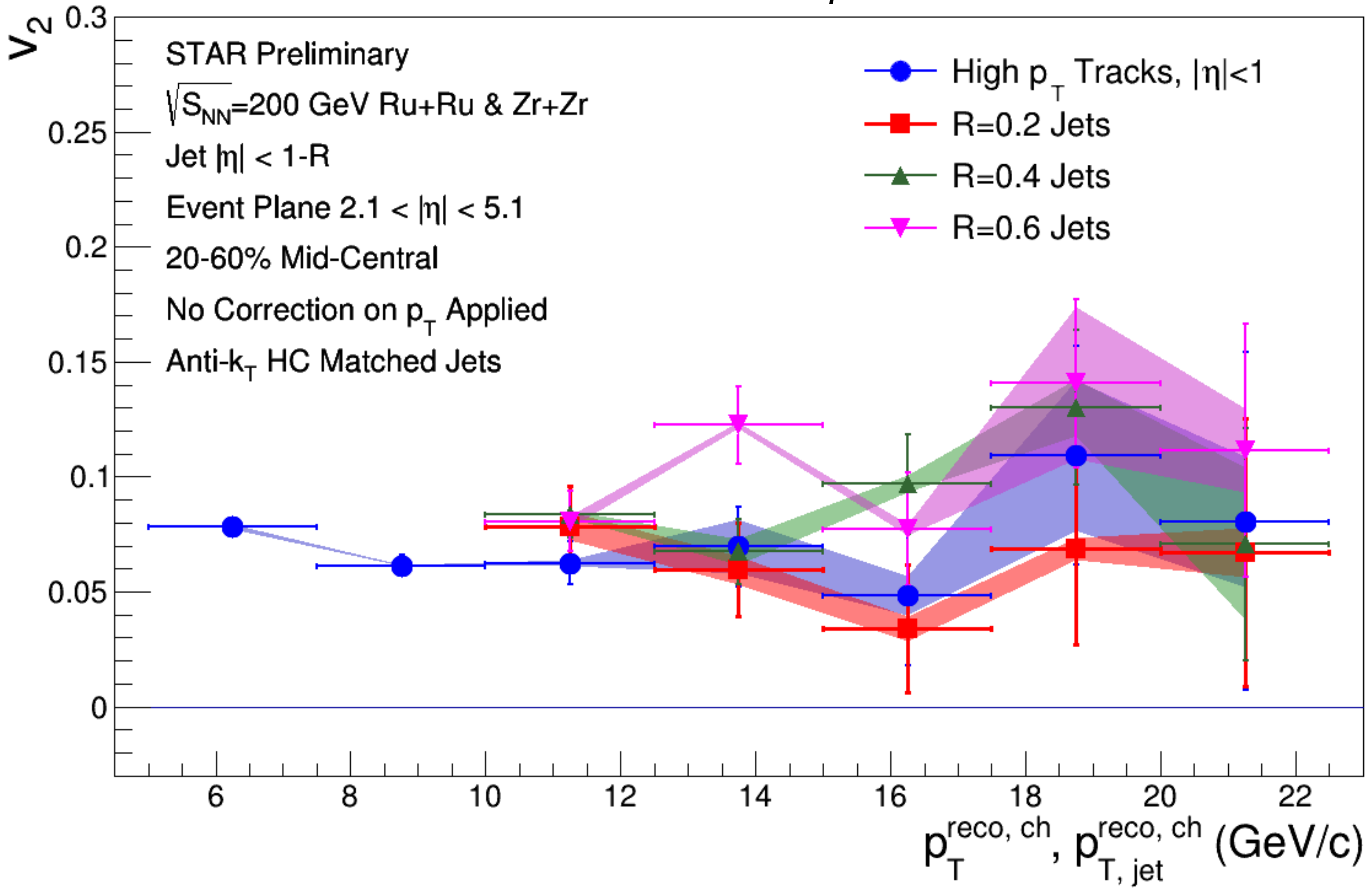




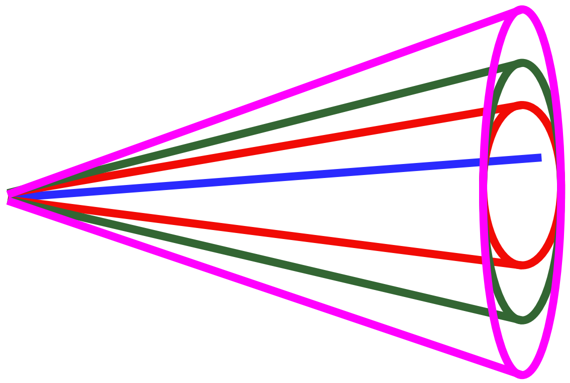
Jet v_2 in the Isobar Collisions

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\,v_2\cos(2(\phi - \Psi_2))$$

- Non-zero jet v_2 is observed for R=0.2, R=0.4, and R=0.6 hard core matched jets in isobar collisions
- Like inclusive charged particle v_2, no strong p_T dependence
- No p_T correction applied

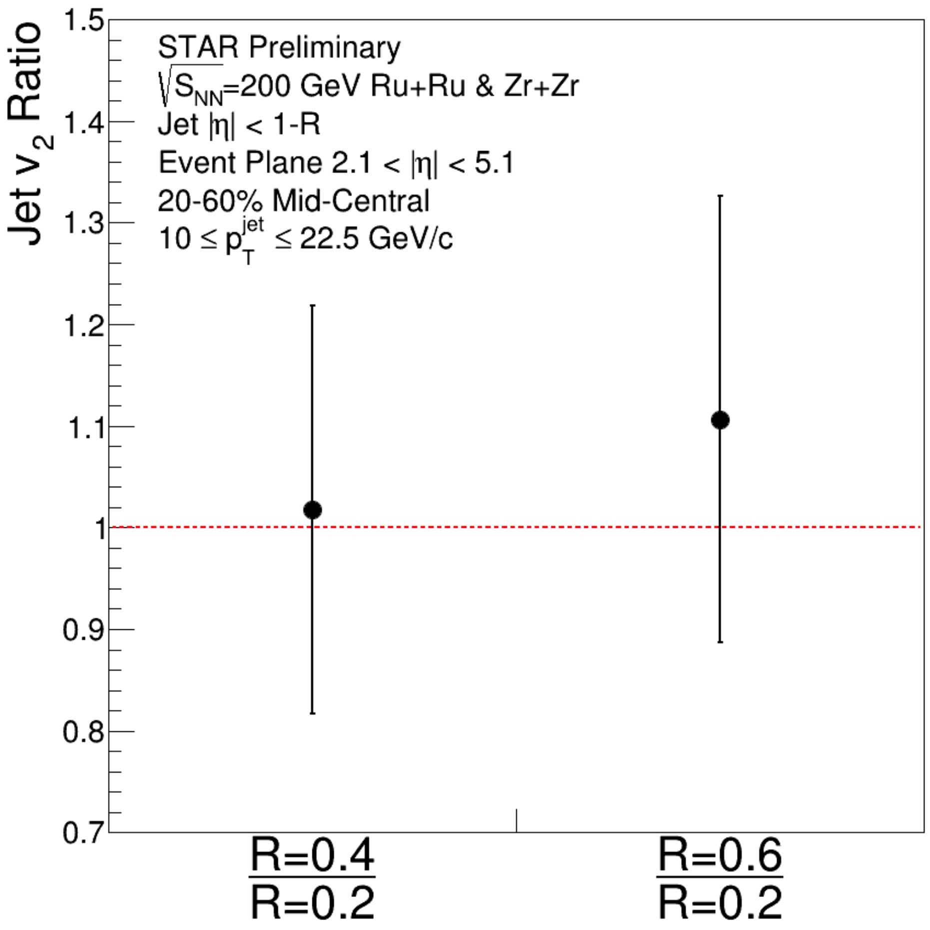


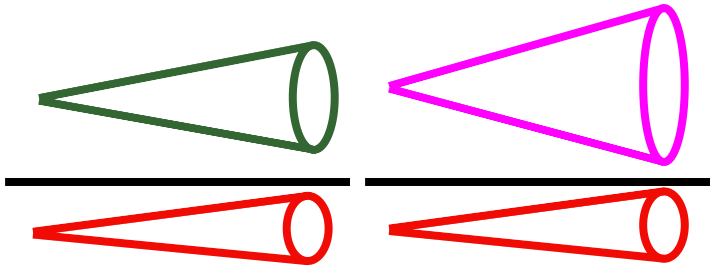
No obvious R dependence!



R Dependence of Jet v_2

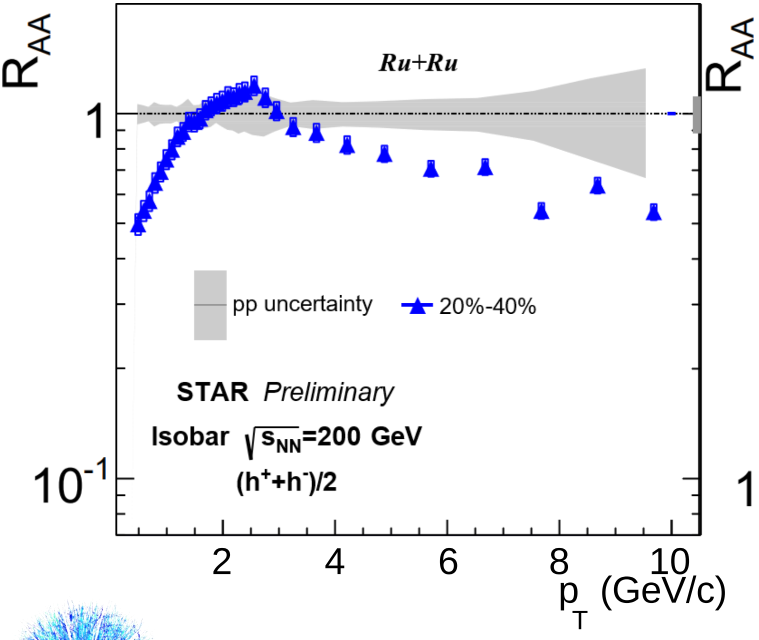
- Under naïve expectation that larger cones capture more radiated energy, we might expect jet v_2 to decrease with increasing R
- To remove correlations in the statistical uncertainties, the dataset was divided in half such that jets of different radii were measured using statistically independent samples.
- No evidence for R dependence of jet v_2 for hard core selected jets
- Hard core selection imposes a fragmentation bias and influences where in the collisional geometry jets are found



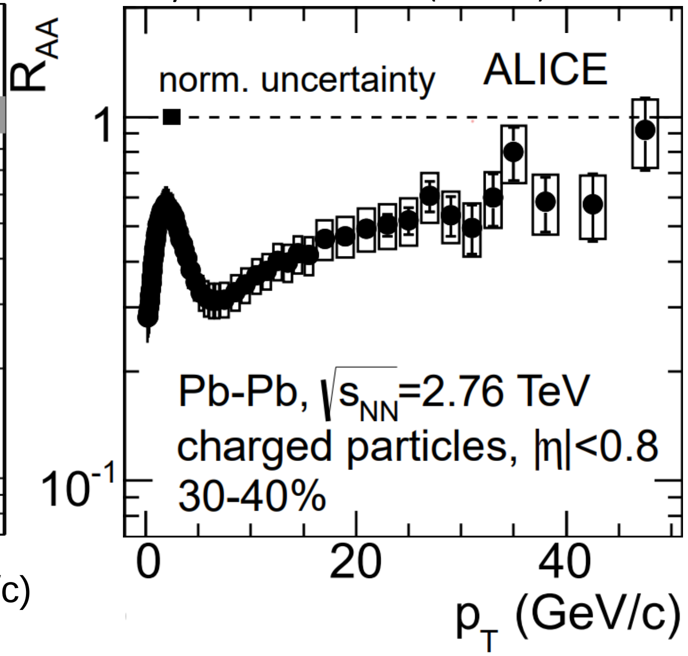


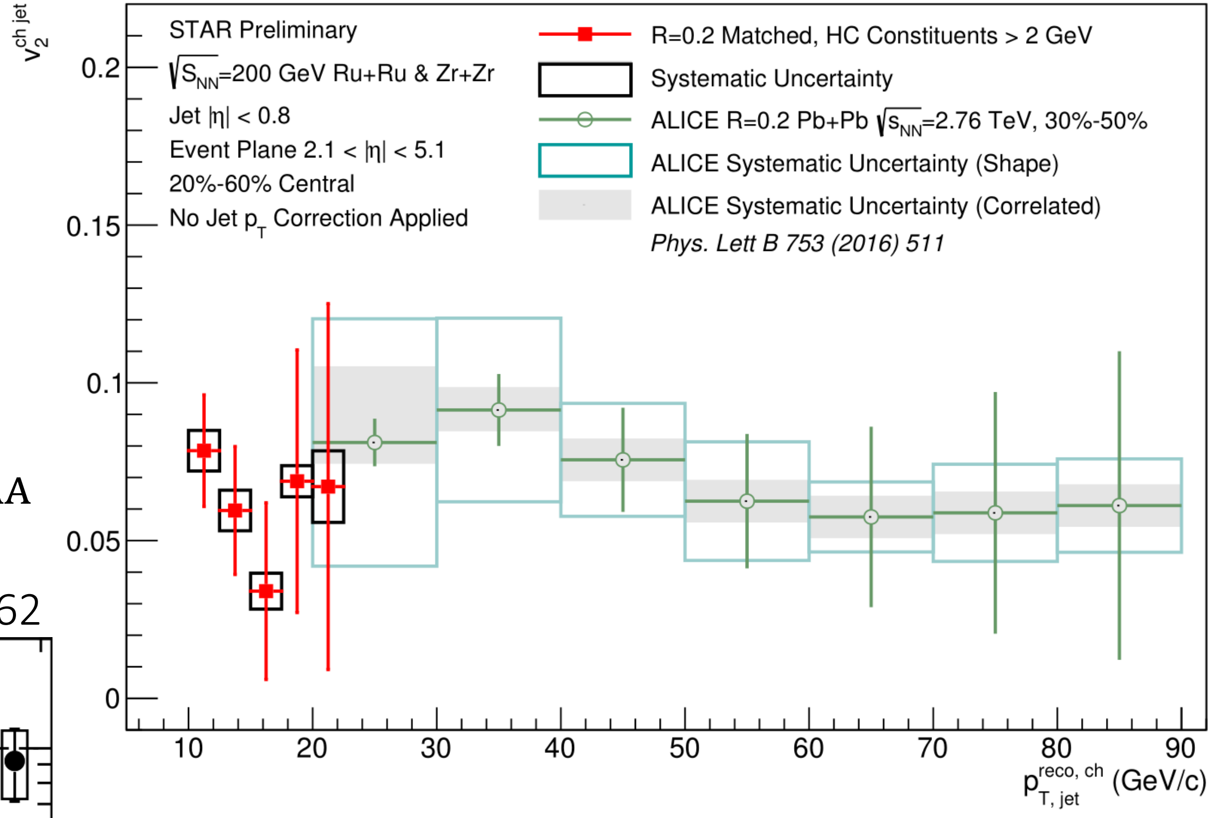
Comparison to Larger Systems

- Jet v_2 consistent in overlapping p_T region between $\sqrt{s_{NN}} = 200$ GeV Ru+Ru & Zr+Zr (A=96) and $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb (A=208) collisions
- Different energy, system size, and charged particle R_{AA}



Phys.Lett. B720 (2013) 52-62





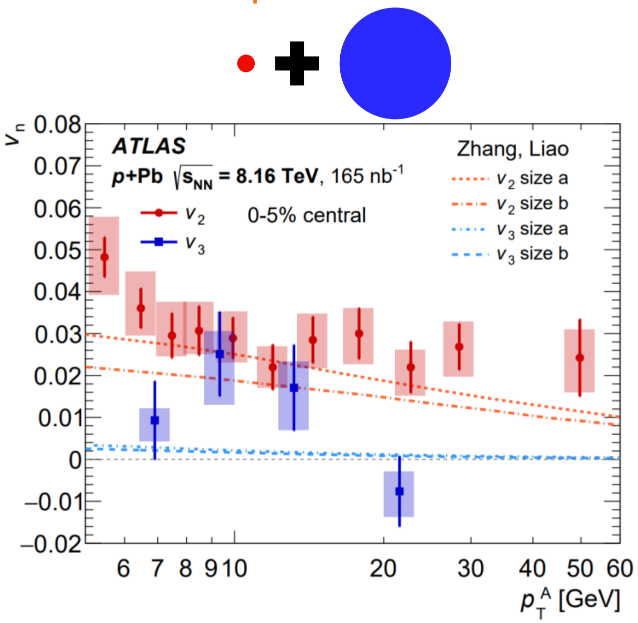
Why might jet v_2 similar at RHIC and LHC?

- v_2 driven by relative, not absolute suppression
- Different quark/gluon ratios at RHIC/LHC
- Probing different depths into the medium?
- Are we seeing a geometry, fragmentation, or survivorship bias?
- Do the different spectral shapes come into play?

System Size Dependence

- Measuring jet v_2 at different system sizes and collision energies can disentangle competing effects
- In the limiting case of jet quenching picture, if $R_{AA} \rightarrow 1$ a path-length dependent v_2 should go to 0
- But, non-zero v_2 in pA has been observed! (not jet quenching!)

p+Pb



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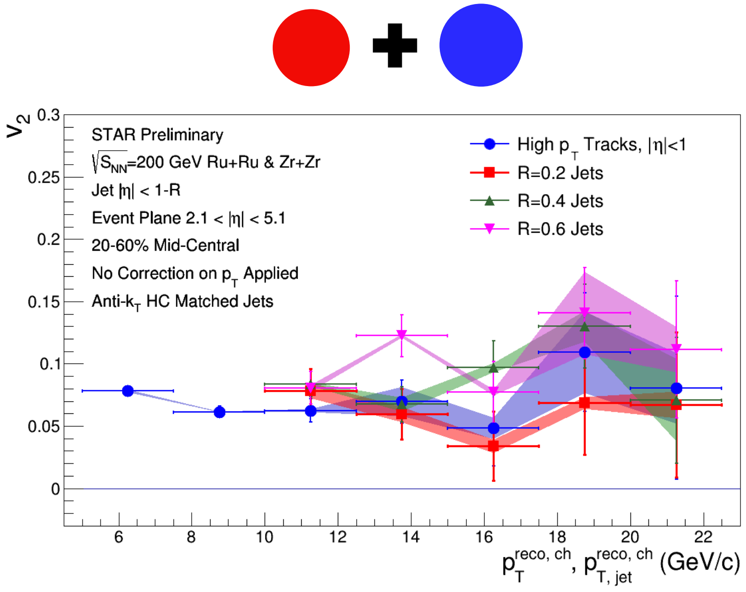
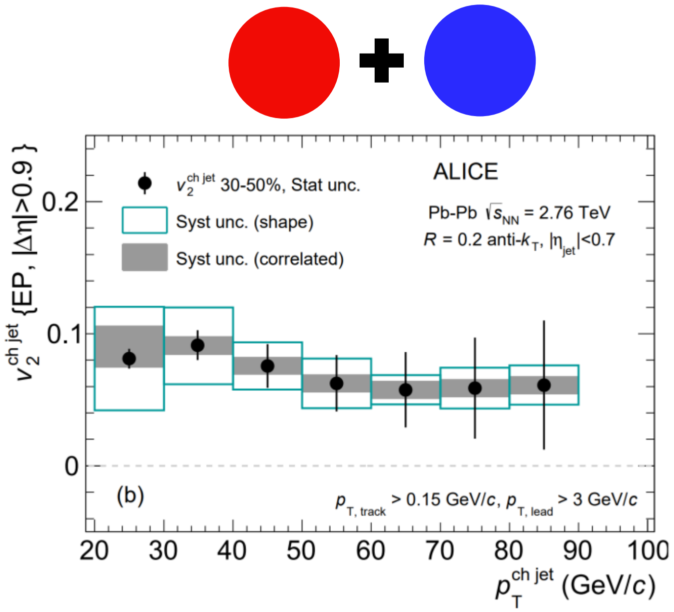
Ru+Ru & Zr+Zr



Pb+Pb



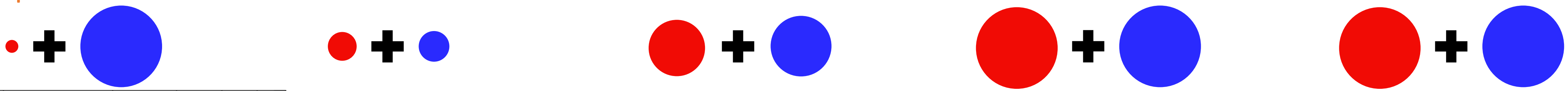
Phys.Lett. B 753 (2016) 511-525

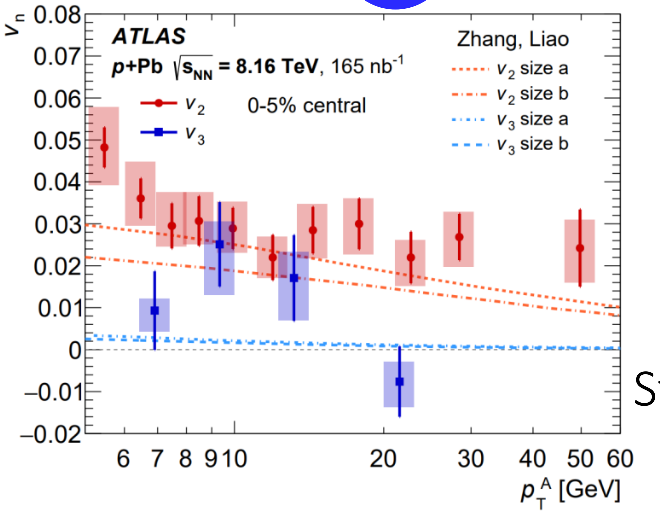
System Size Dependence

- Measuring jet v_2 at different system sizes and collision energies can disentangle competing effects
- In the limiting case of jet quenching picture, if $R_{AA} \to 1$ a path-length dependent v_2 should go to 0
- But, non-zero v_2 in pA has been observed! (not jet quenching!)

- O+O collisions offer an opportunity to explore jet v_2 in smaller, less dense systems
  - RHIC 2021, Planned at LHC – Comparison of same small system at different energies!
- Upcoming Au+Au data will offer high precision at top RHIC energy

p+Pb | O+O | Ru+Ru & Zr+Zr | Au+Au | Pb+Pb





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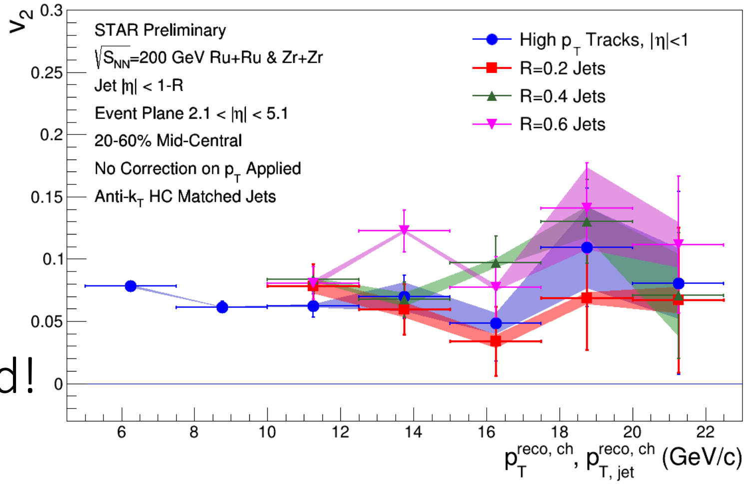
Stay tuned!



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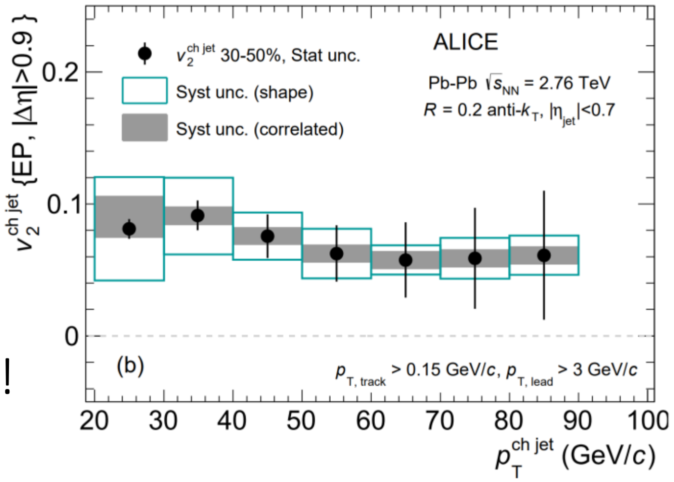
Stay tuned!



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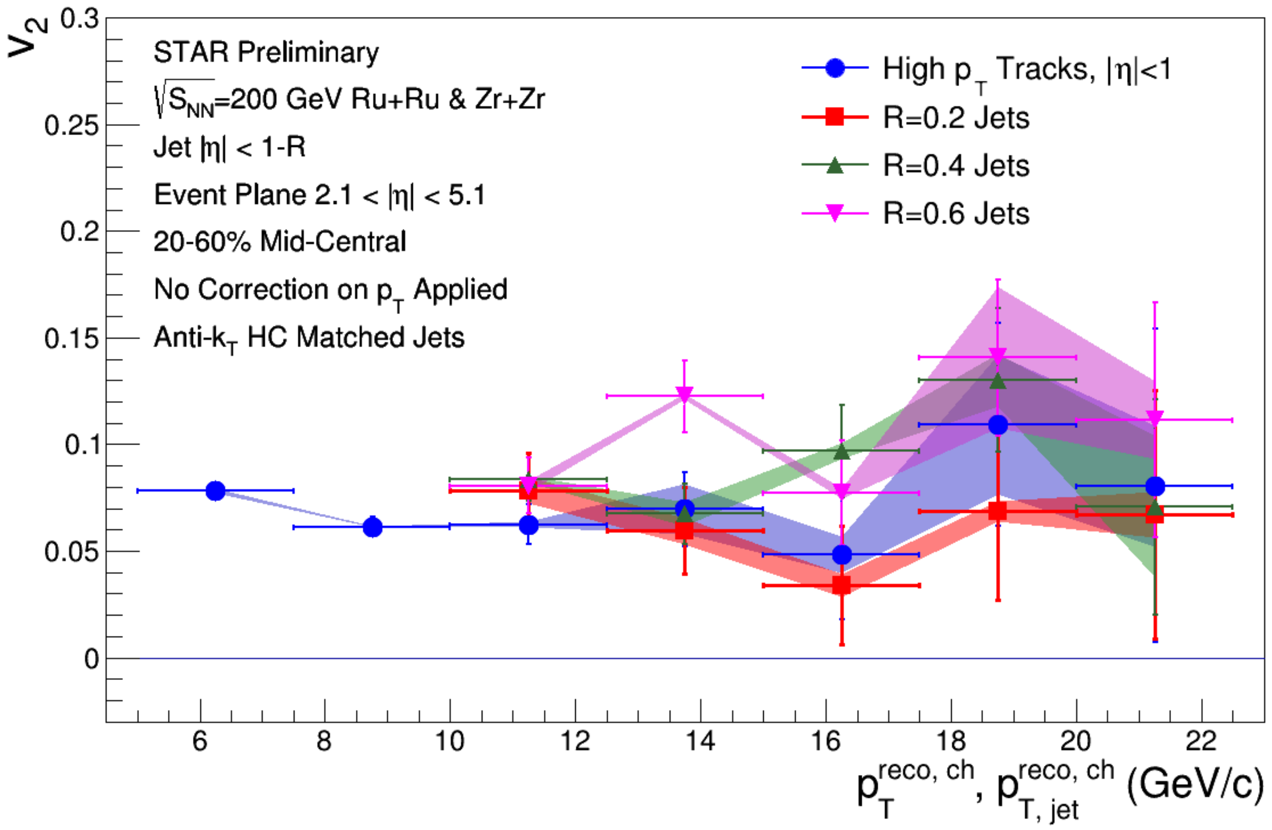
Phys.Lett. B 753 (2016) 511-525

Conclusions

- The centrality dependence of high p_T R_{AA} hints at path-length dependent quenching
- The path length can be controlled using event geometry information
  - Centrality class, event plane angle
- In semi-central isobar collisions, a non-zero v_2 is observed for high p_T objects
  - Measured for inclusive charged particles, R=0.2, R=0.4, and R=0.6 anti-k_T jets
- Jet v_2 exhibits no strong jet resolution parameter dependence for hard core selected jets
- Various biases, e.g. geometry, fragmentation, etc. need to be understood for proper interpretation of jet v_2
  - Need input from theory on which biases are significant! Lots of data coming soon

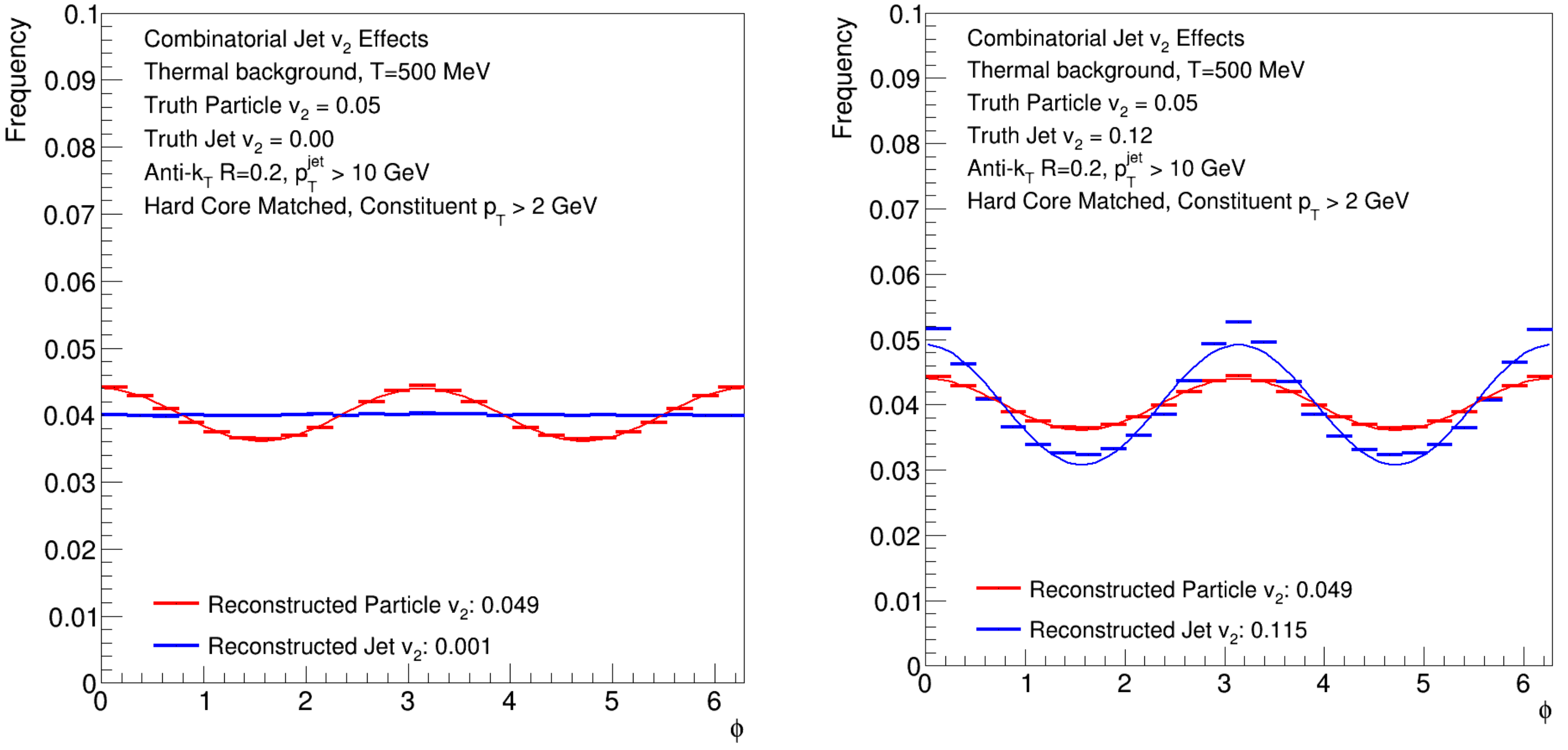


Backup

Combinatorial Jets

- High p_{T} tracks are added to the thermal background with and without a v_2.
- Analyzing only hard core matched jets, the correct v_2 is recovered
- This methodology allows the true jet v_2 to be determined and is not affected by the modulated underlying event

Corrected Jet v_2 In Toy Model



Thermal background with high p_T tracks inserted

Comparison with Smaller Systems

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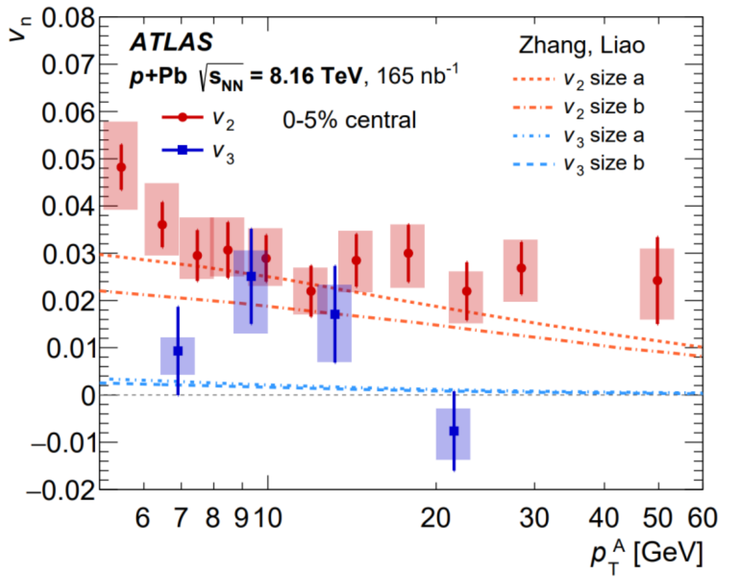
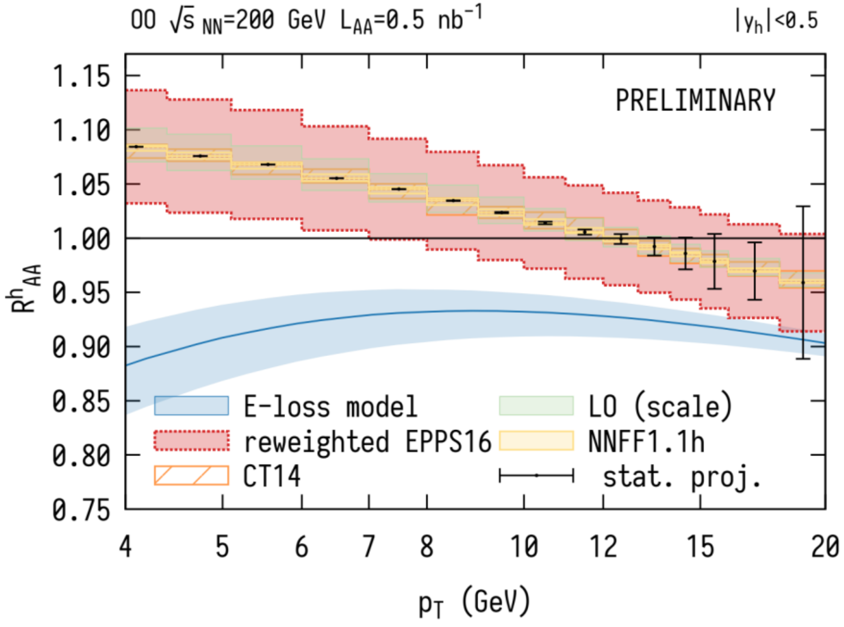
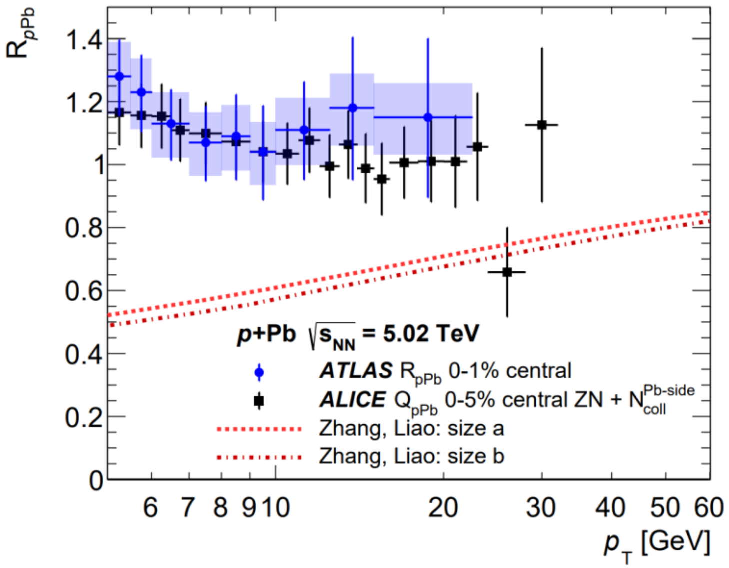


- In pA systems, the measured high-p_{T} R_{pA} is consistent with unity, suggesting no nuclear suppression
- However, a non-zero jet v_2 is observed
- STAR can help fill in the gap with small system data

- Oxygen-Oxygen (A=16) collisions recorded at STAR in run 21
- Measurements of R_{AA} and jet v_2 and help fill gap in system size

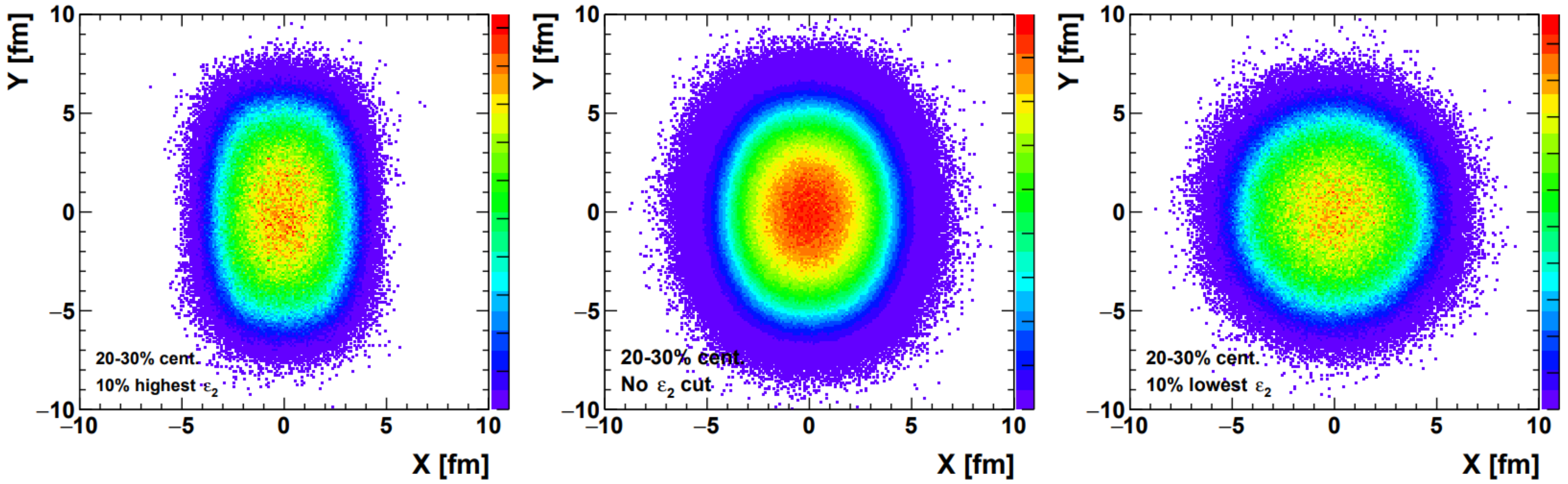




Further Constraining the Path Length

- Within a given centrality class, many different event shapes exist
- To better constrain the path length we want to select on the eccentricity ϵ_2
- Use q_2 as a proxy for ϵ_2, found in the Event Plane Detector to avoid autocorrelation

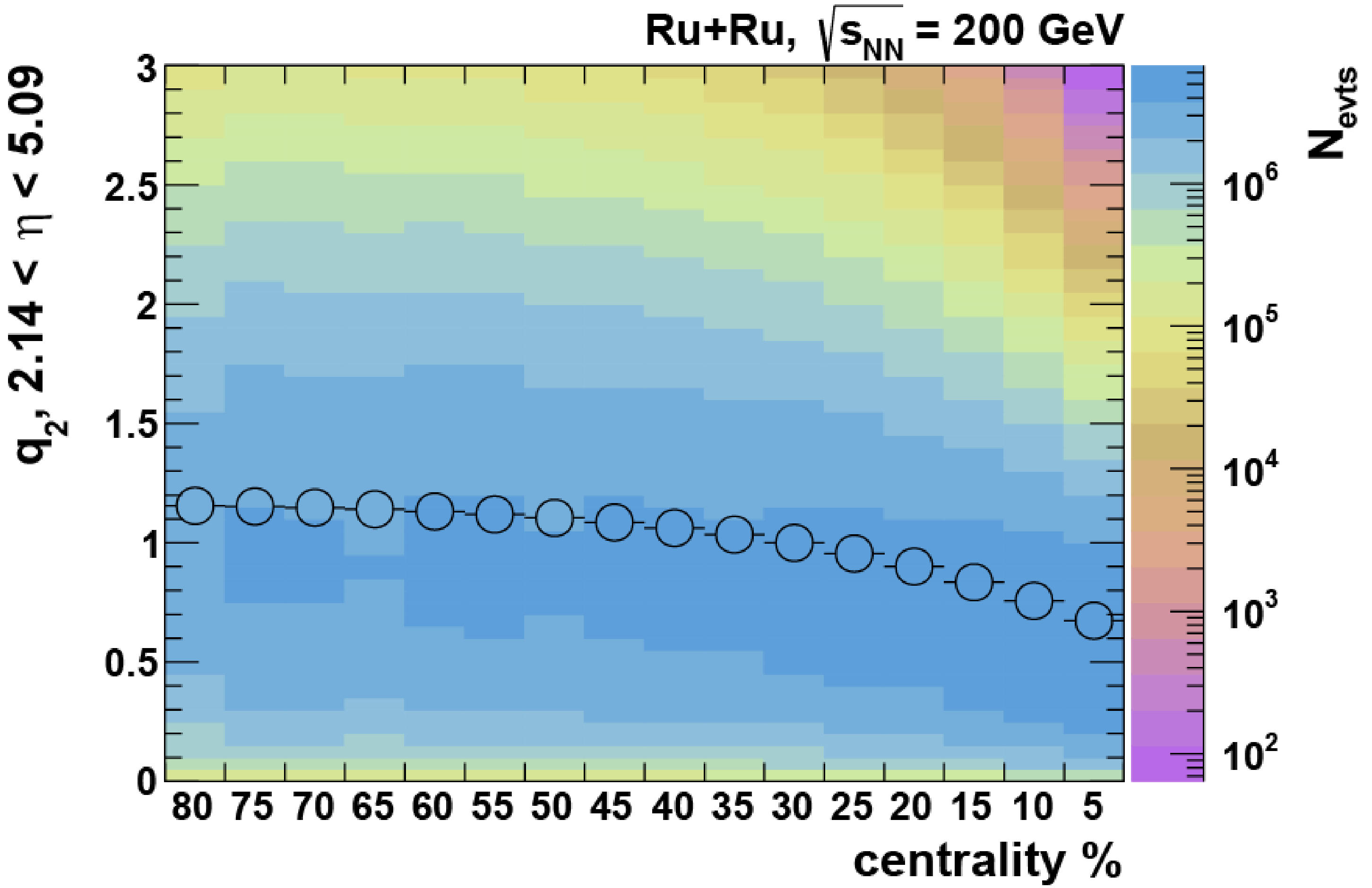
Christiansen 2016 J. Phys.: Conf. Ser. 736 012023



Simulation at LHC energy

Event Shape vs Centrality

- High statistics in isobar data set will allow fine selection on event shape
- Measuring jet v_2 for different q_2 classes controls the in-plane to out-of-plane path length
- Event plane detectors are located symmetrically on both sides of interaction point
  - Allows independent determination of event plane and event shape



$$Q_{2,x} = \Sigma w_i \cos(2\phi_i)$$
$$Q_{2,y} = \Sigma w_i \sin(2\phi_i)$$

$$q_2 = \frac{|Q_2|}{\sqrt{M}}$$