Recent Results on Jet Quenching from STAR

2019 RHIG & AGS Annual User's Meeting – High Pt/Jets Parallel Workshop

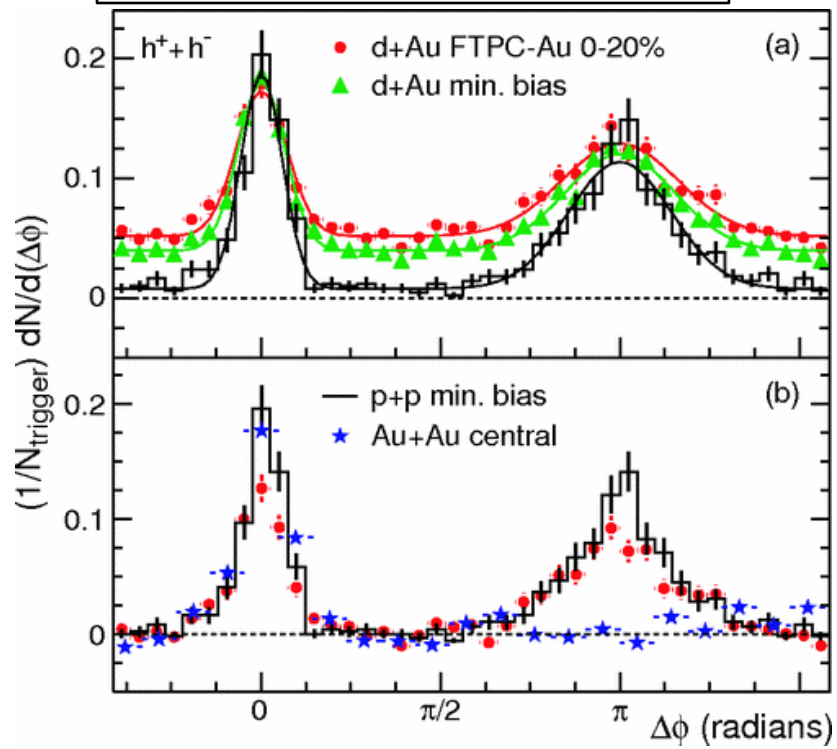
June 4, 2019

Saehanseul Oh for the STAR Collaboration
(Yale University - BNL)

Introduction

- Early experimental evidence of "*jet quenching*" from **STAR**

STAR, Phys. Rev. Lett. **91** (2003) 072304



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- Jets from heavy-ion collisions are *suppressed* and *broadened* compared to those from *pp* collisions

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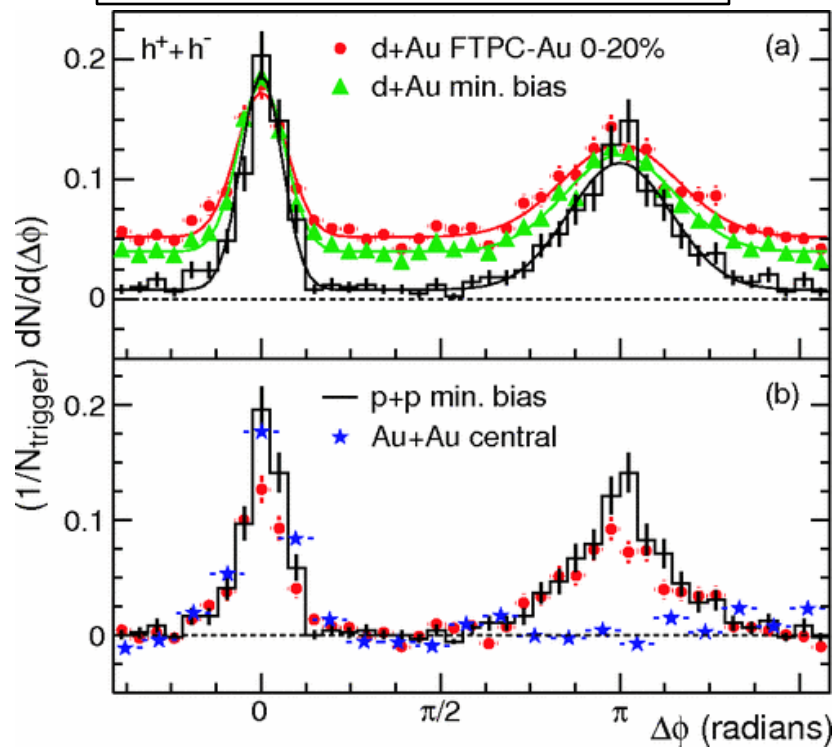

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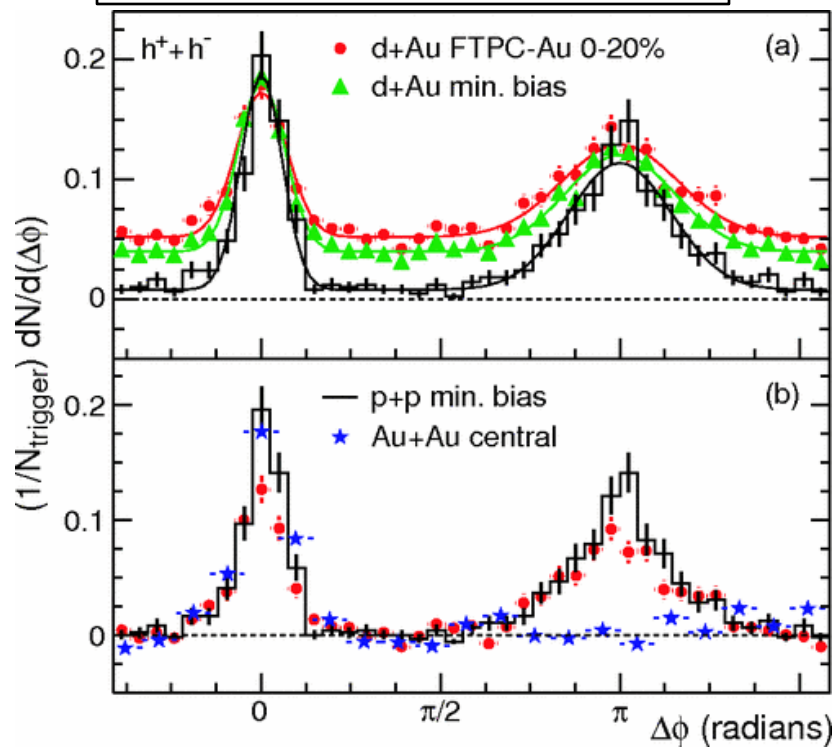


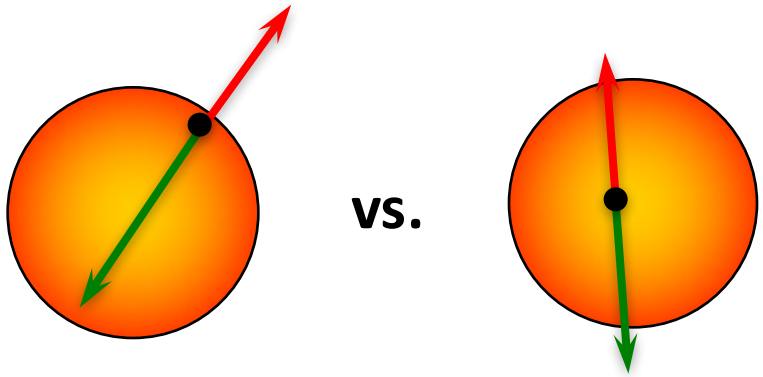
Recent results on jet quenching from STAR

- ✓ Di-jet imbalance
- ✓ Semi-inclusive jet (triggered-jet)
- ✓ Event-plane dependent measurements
- ✓ Jet flavor dependent measurements
- ✓ Jet angular scale dependent measurements

Various measurements can be connected to different aspects of jet properties

Introduction

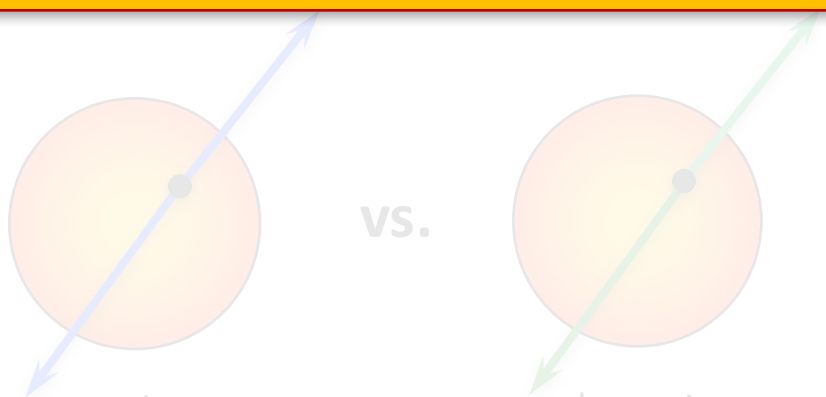
Key questions for more differential jet-quenching measurements



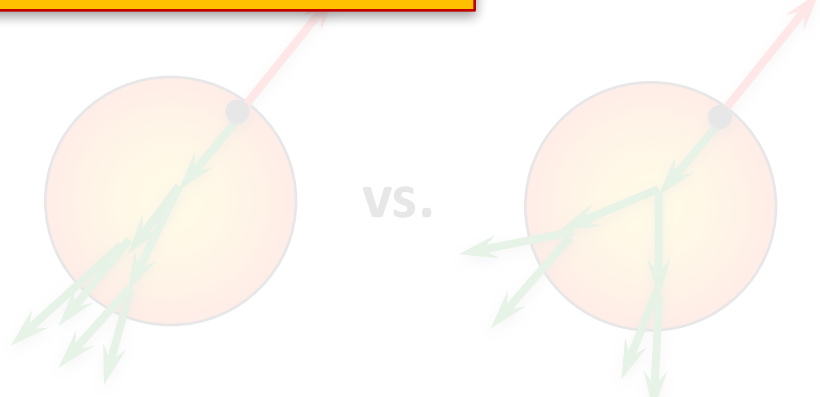
Different jet vertex/direction in the medium

Out-of-plane In-plane

Dependence on where the jet is produced inside of the medium?



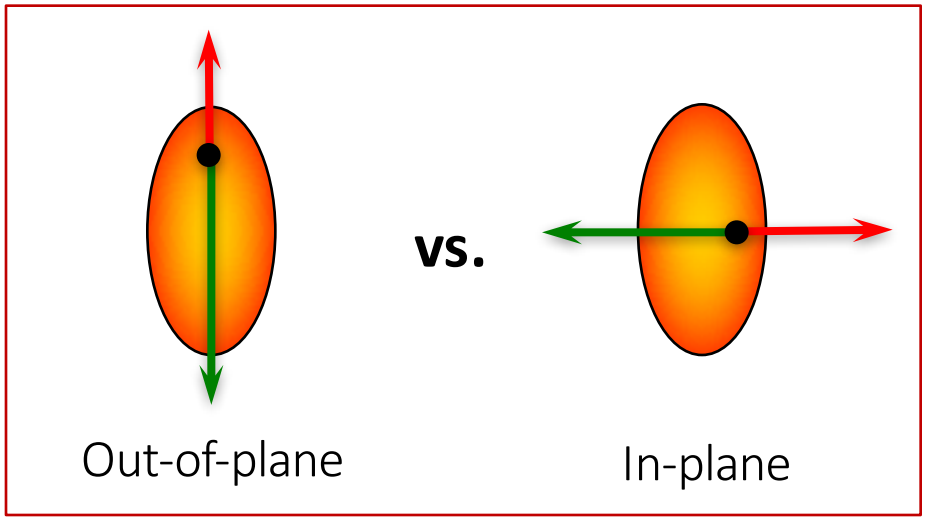
quark-jet gluon-jet



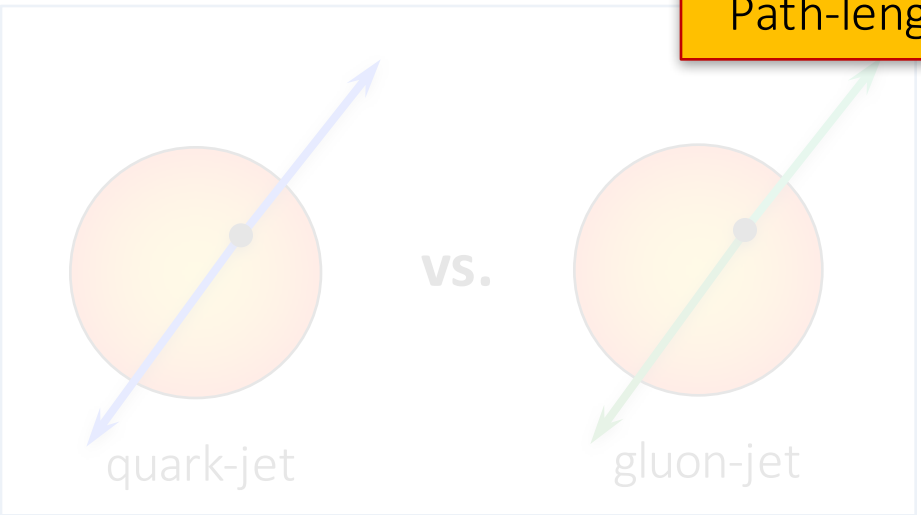
Narrow jet Wide jet

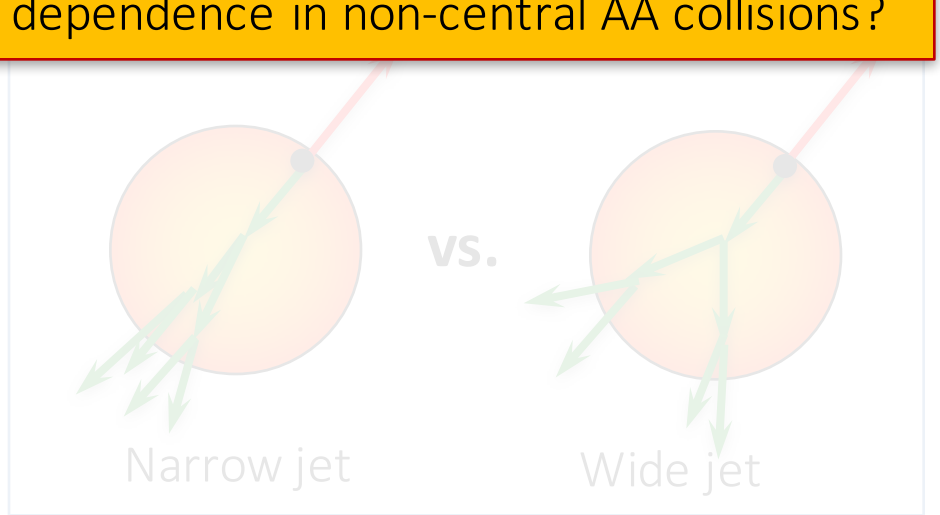
Introduction

Key questions for more differential jet-quenching measurements



Path-length dependence in non-central AA collisions?





Introduction

Key questions for more differential jet-quenching measurements

Different jet vertex/direction in the medium

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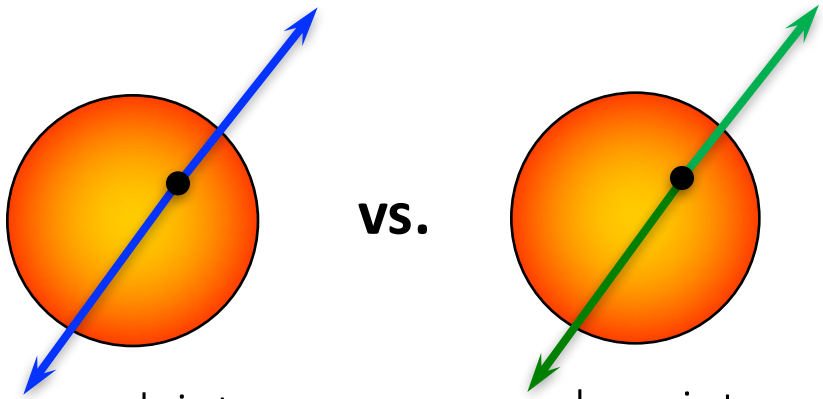

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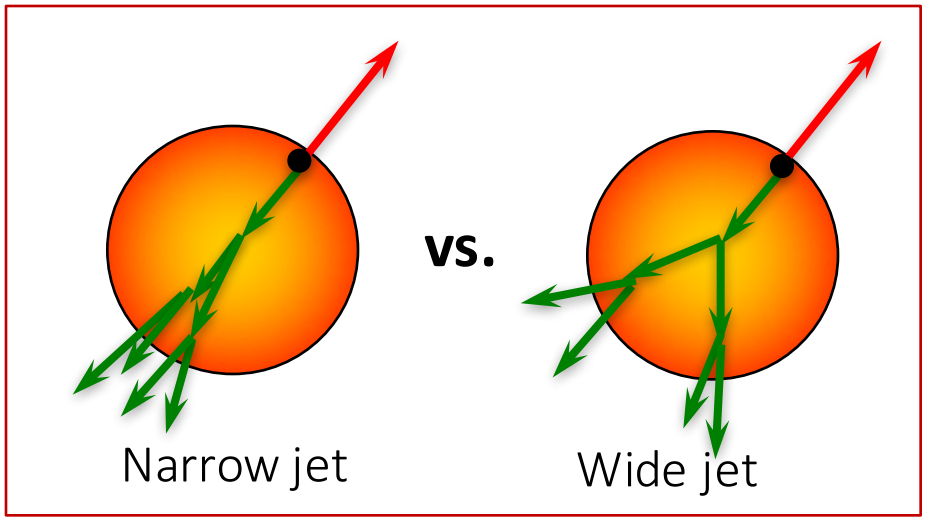
Jet flavor dependence?

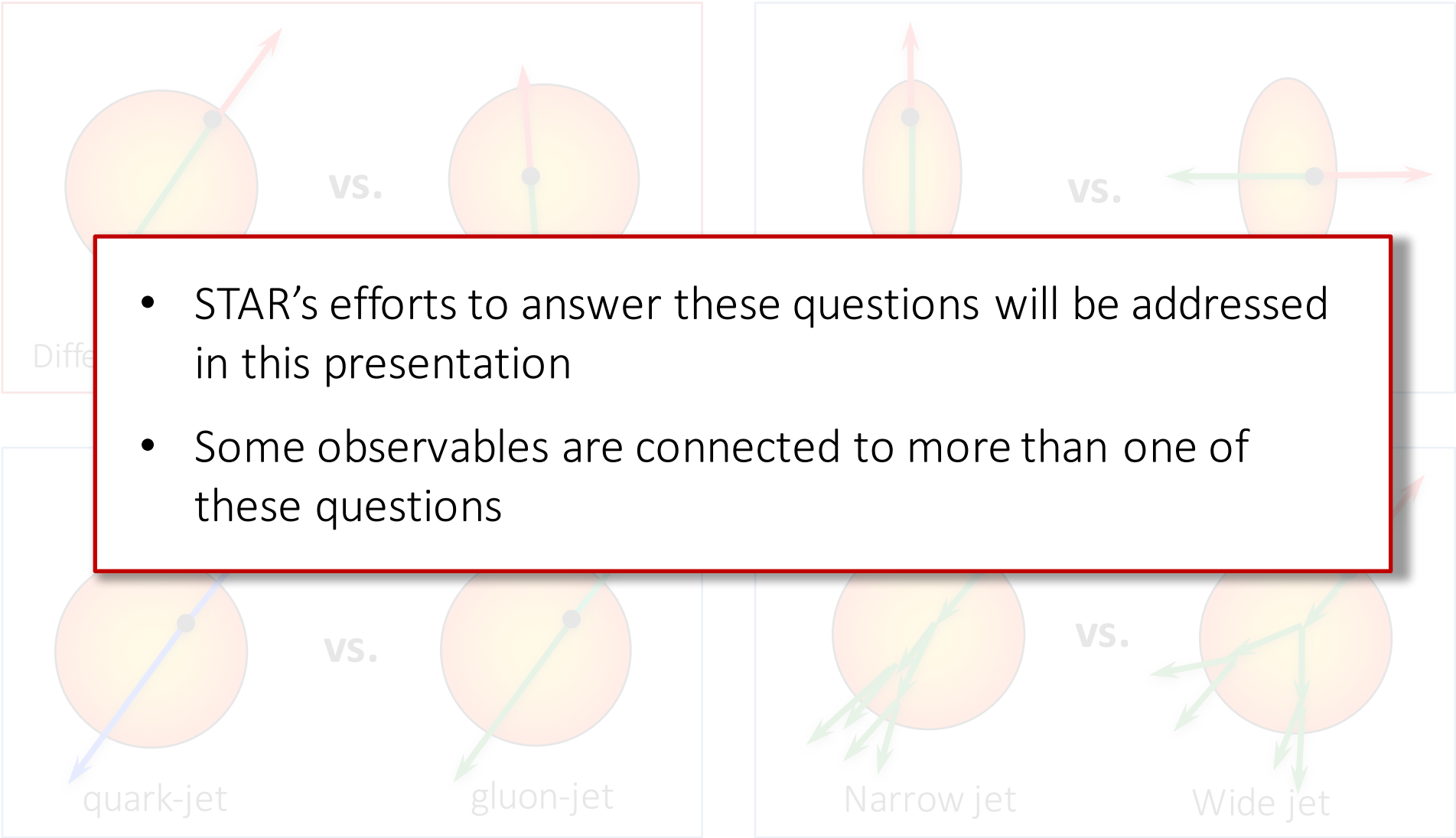
Key questions for more differential jet-quenching measurements



Jet angular scale dependence?

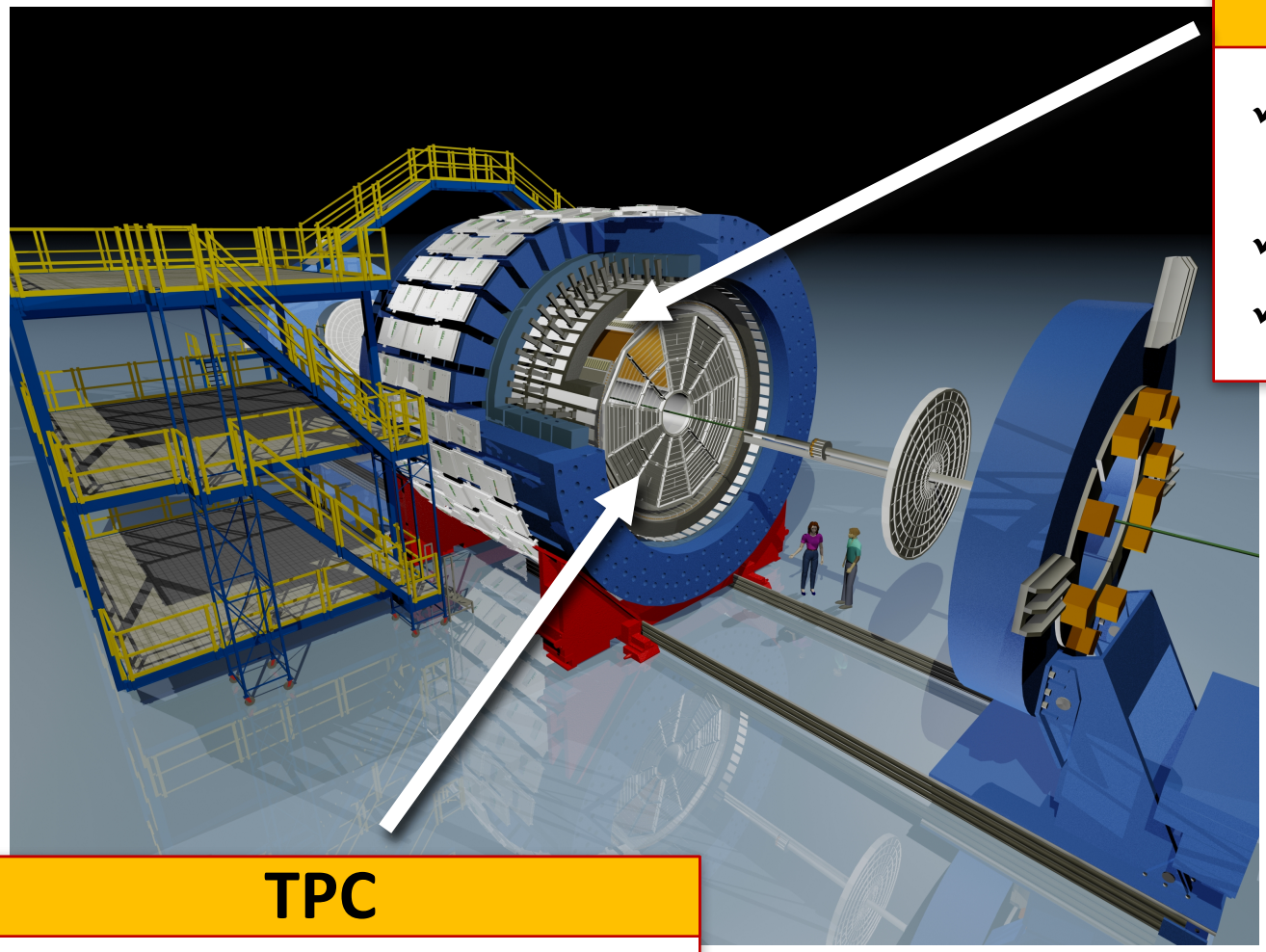
Introduction

Key questions for more differential jet-quenching measurements



- STAR's efforts to answer these questions will be addressed in this presentation
- Some observables are connected to more than one of these questions

The Solenoidal Tracker At RHIC (STAR)



BEMC

- ✓ Barrel Electromagnetic Calorimeter
- ✓ $|\eta| < 1.0, 0 < \varphi < 2\pi$
- ✓ Trigger

TPC

- ✓ Time Projection Chamber
- ✓ $|\eta| < 1.0, 0 < \varphi < 2\pi$
- ✓ Tracking, momentum, dE/dx

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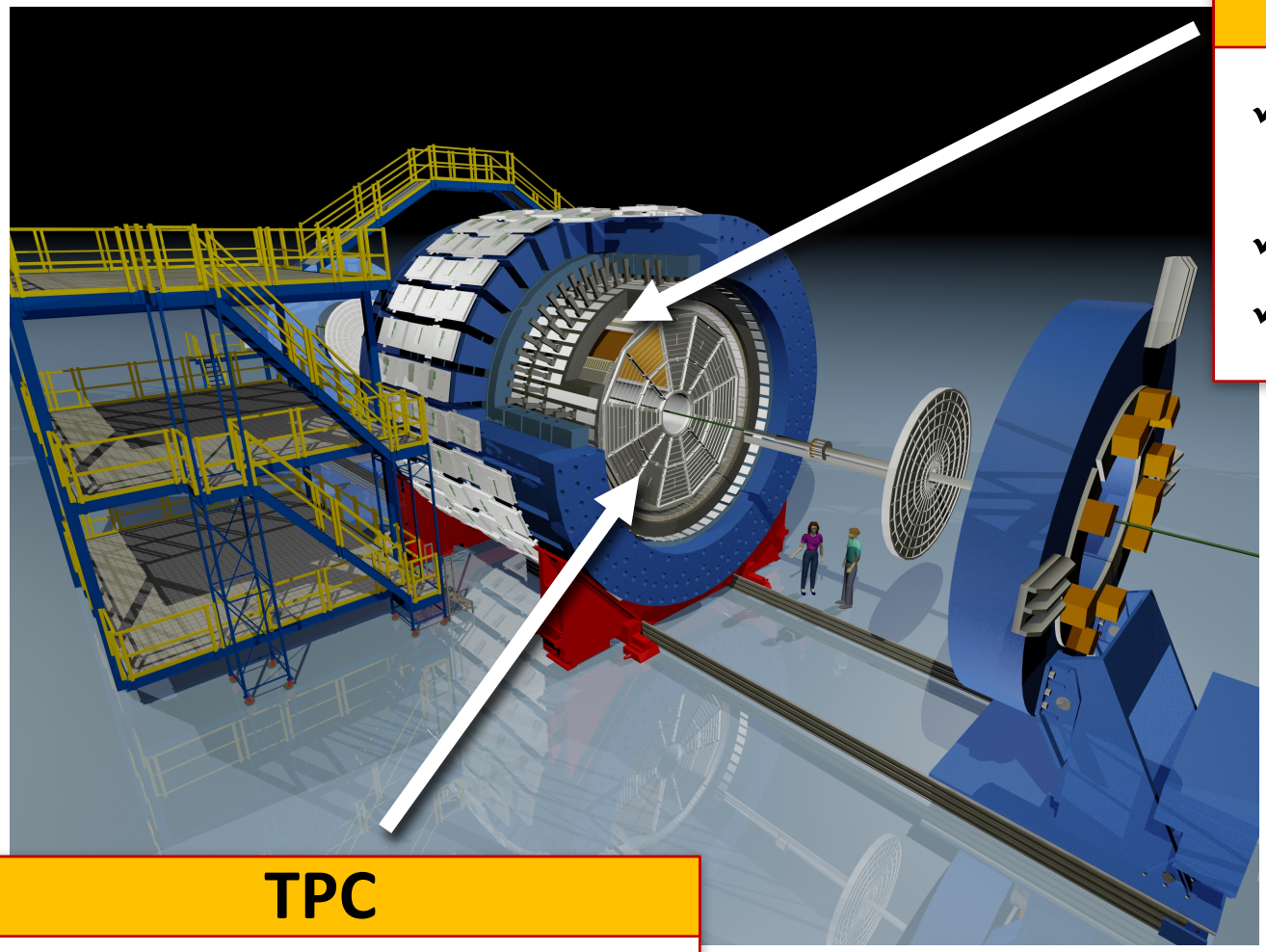

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Neutral constituents

TPC

- ✓ Time Projection Chamber
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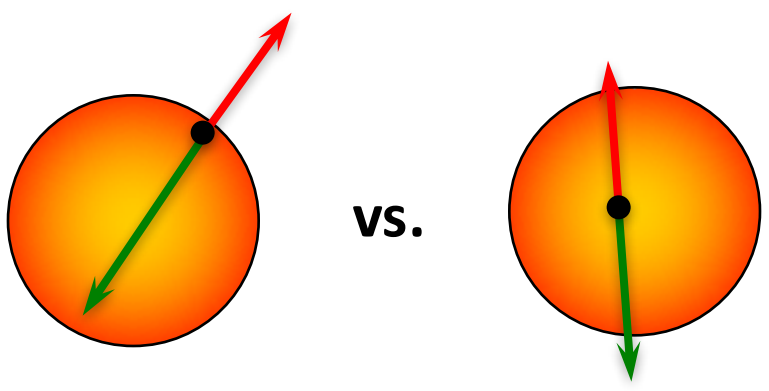
- ✓ Tracking, momentum, dE/dx

Charged constituents

Full Jet

Charged Jet

Di-jet Imbalance



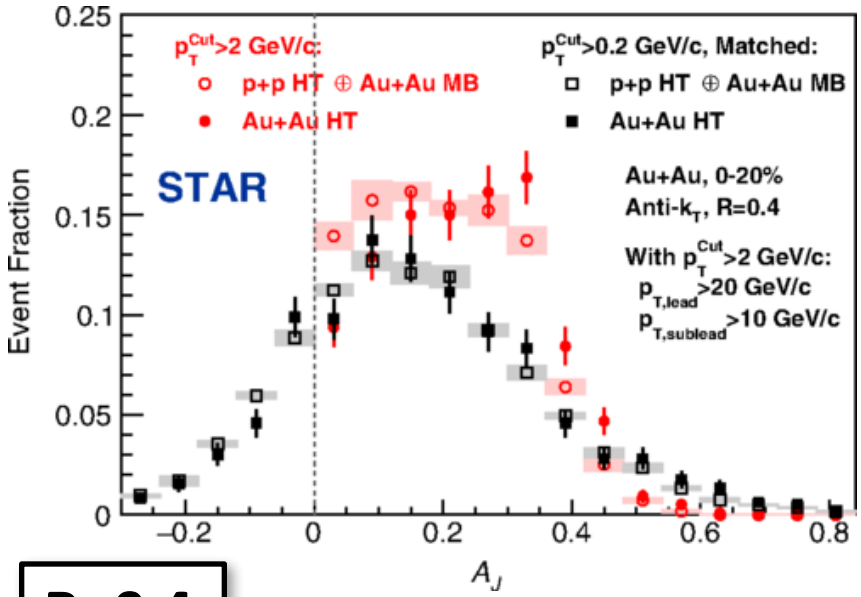
Different jet vertex/direction in the medium

Dependence on where the jet is produced inside of the medium?

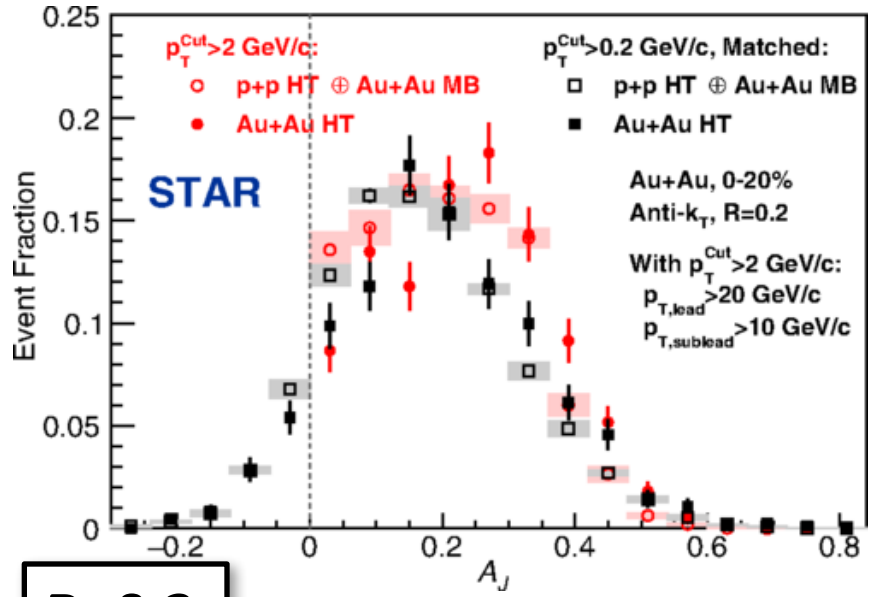
Di-jet Imbalance

- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$
- **Hard-core jet** vs. **Matched jet**

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



R=0.4



R=0.2

- For $R = 0.4$ hard-core jet, more di-jet momentum imbalance compared to p+p
- Balance recovered when soft constituents are included (matched-jet)
- For $R = 0.2$, balance no longer recovered in matched-jet
  - ✓ **Softening** of jet constituents and **Broadening** of the jet structure

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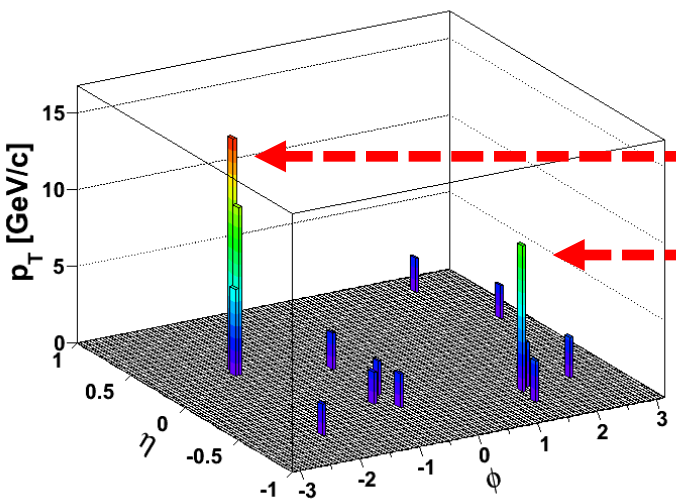
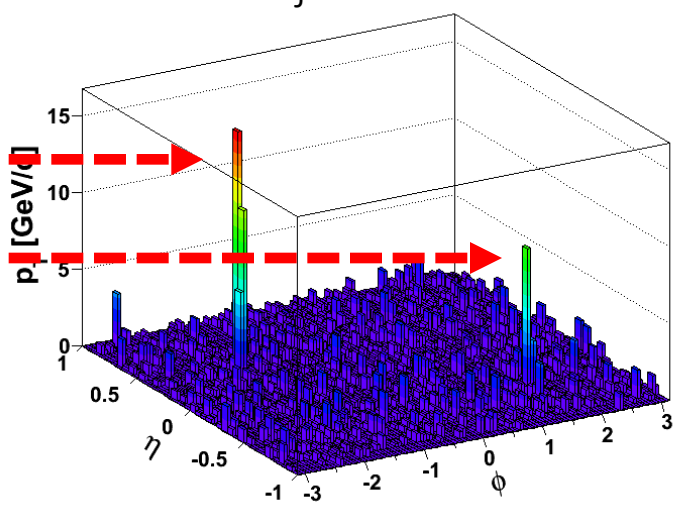
ST Rev. Lett. **119** (2017) 062301

- Constituent p_T^{Cut} = 2 GeV/c
- Reduce BG and combinatorial jets



- Constituent p_T^{Cut} = 0.2 GeV/c
- Geometrically matched to the hard-core jet



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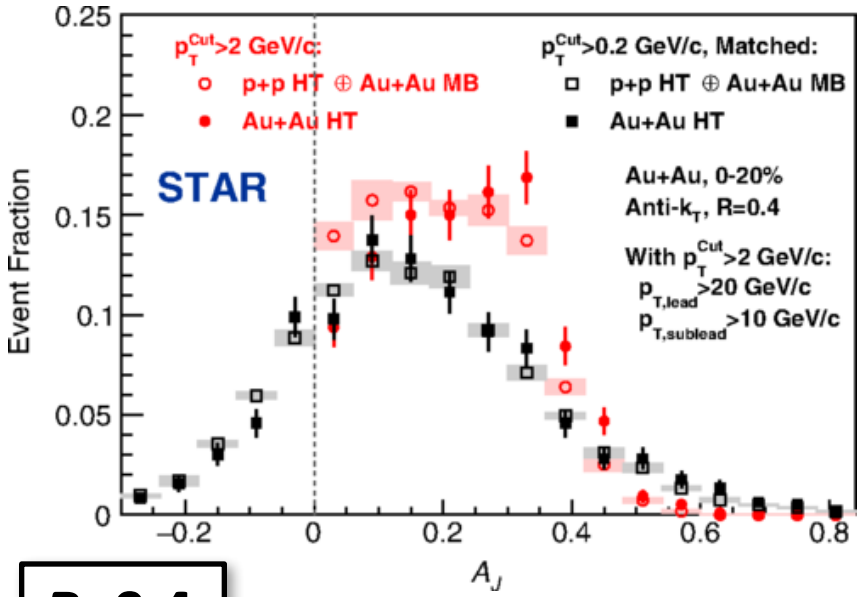
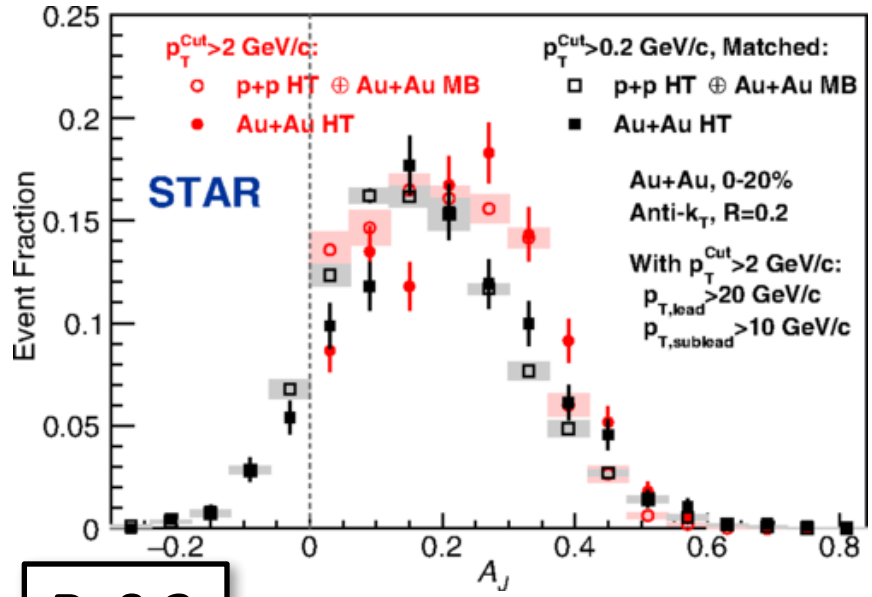


***R*=0.4**



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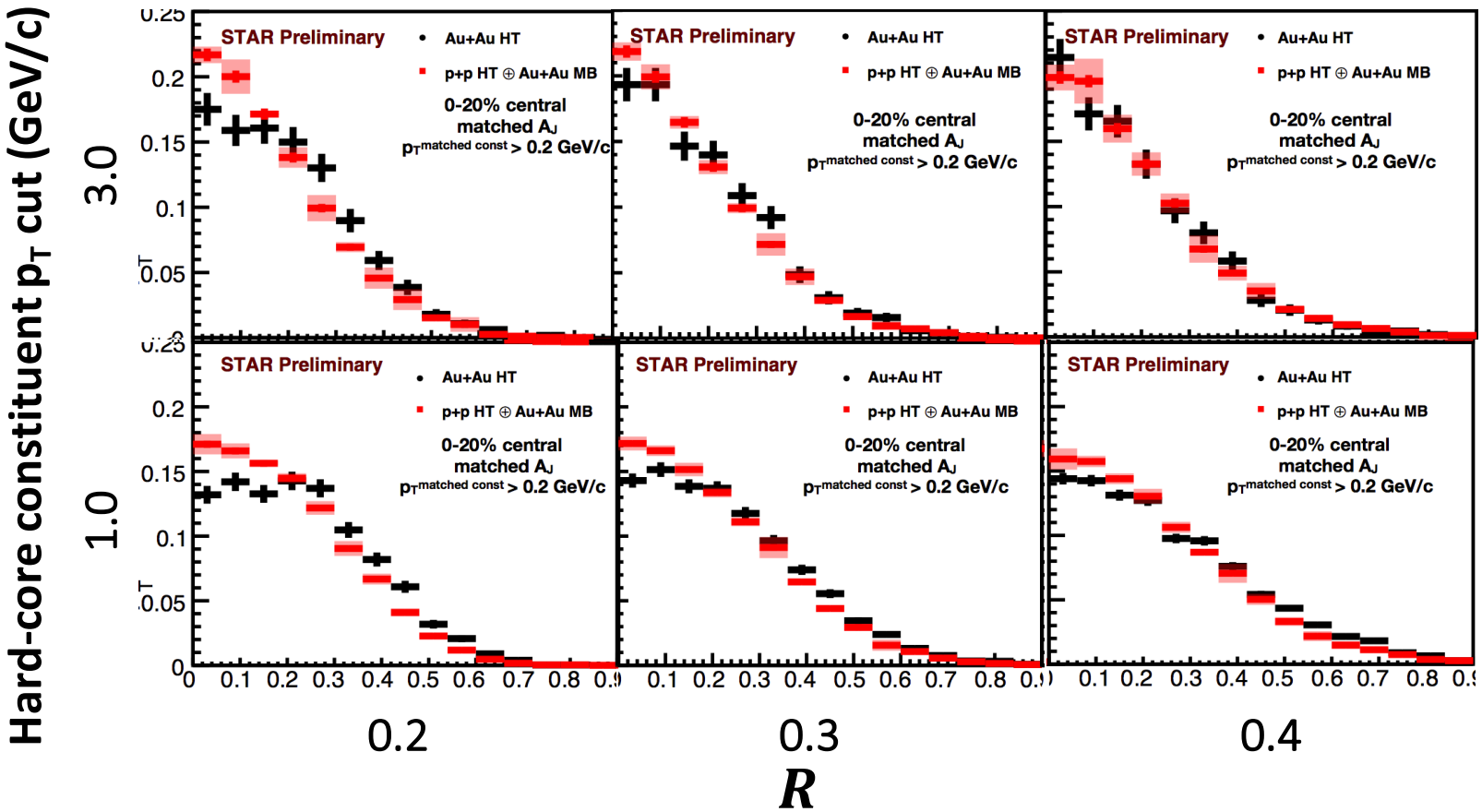
Di-jet Imbalance

- Varying the jet definition (R, constituent p_T cut, …) effectively controls the path length and vertex of jets in the medium (Jet Geometry Engineering)



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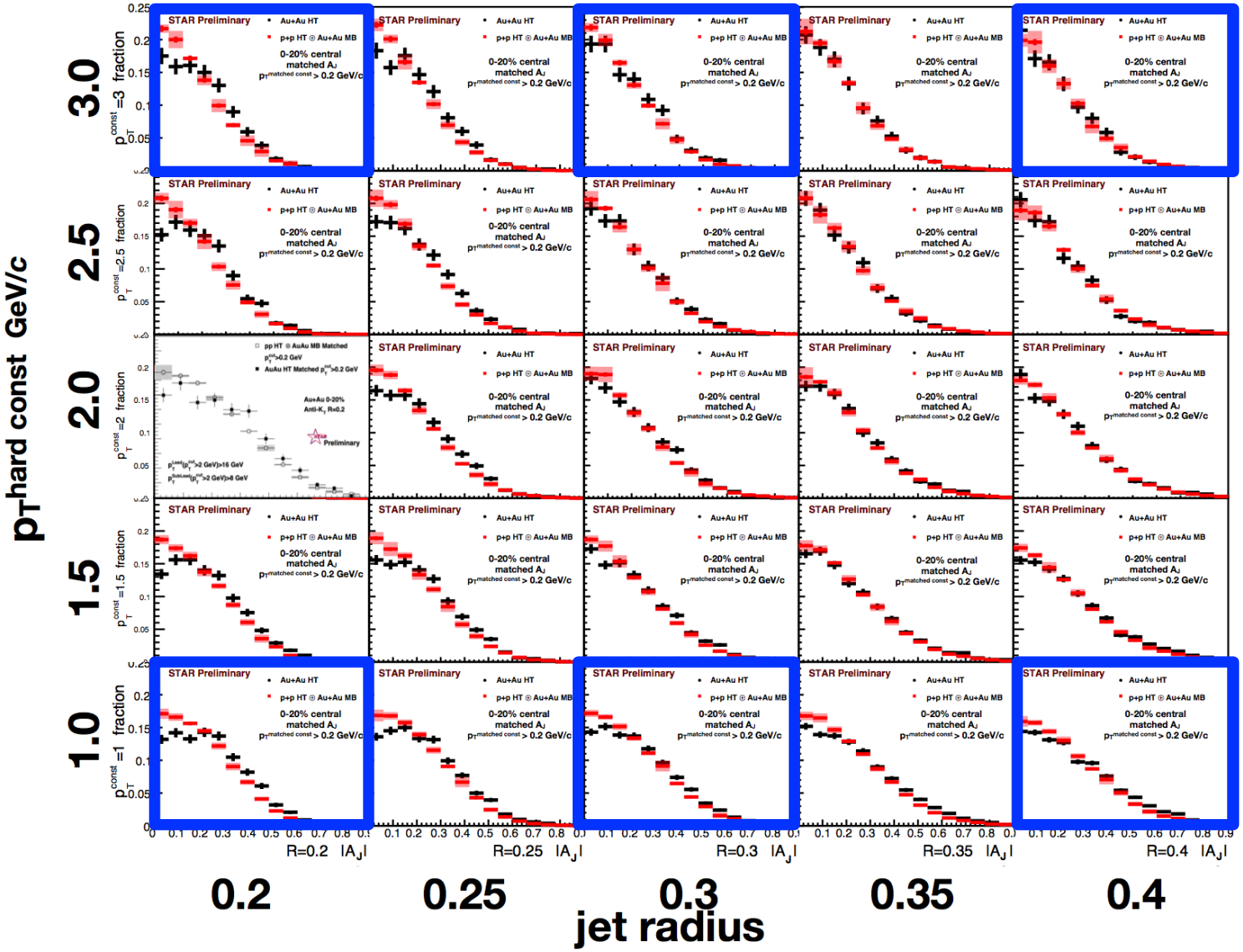

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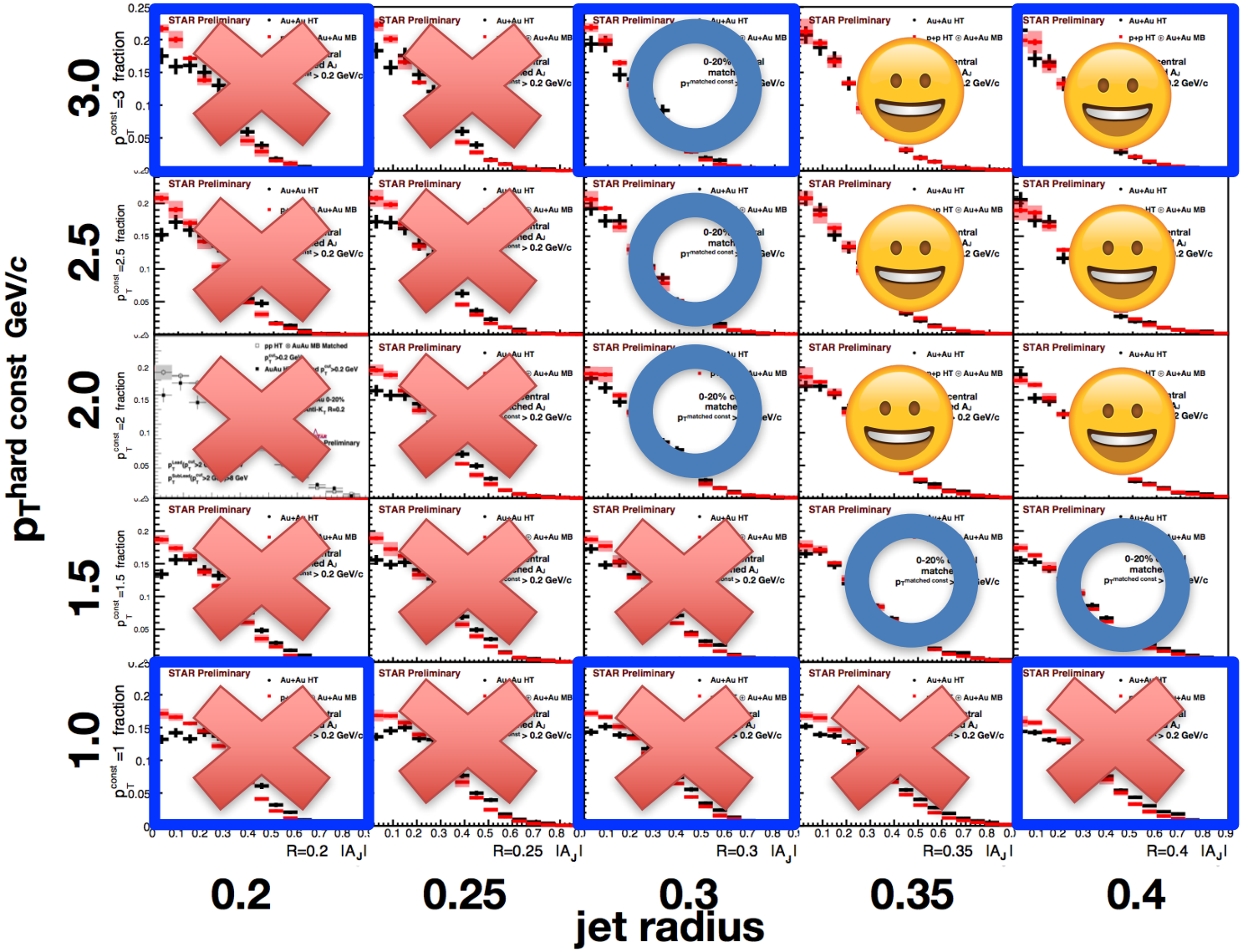

With Kolmogorov-Smirnov two-sample test

Imbalanced Semi-balanced balanced

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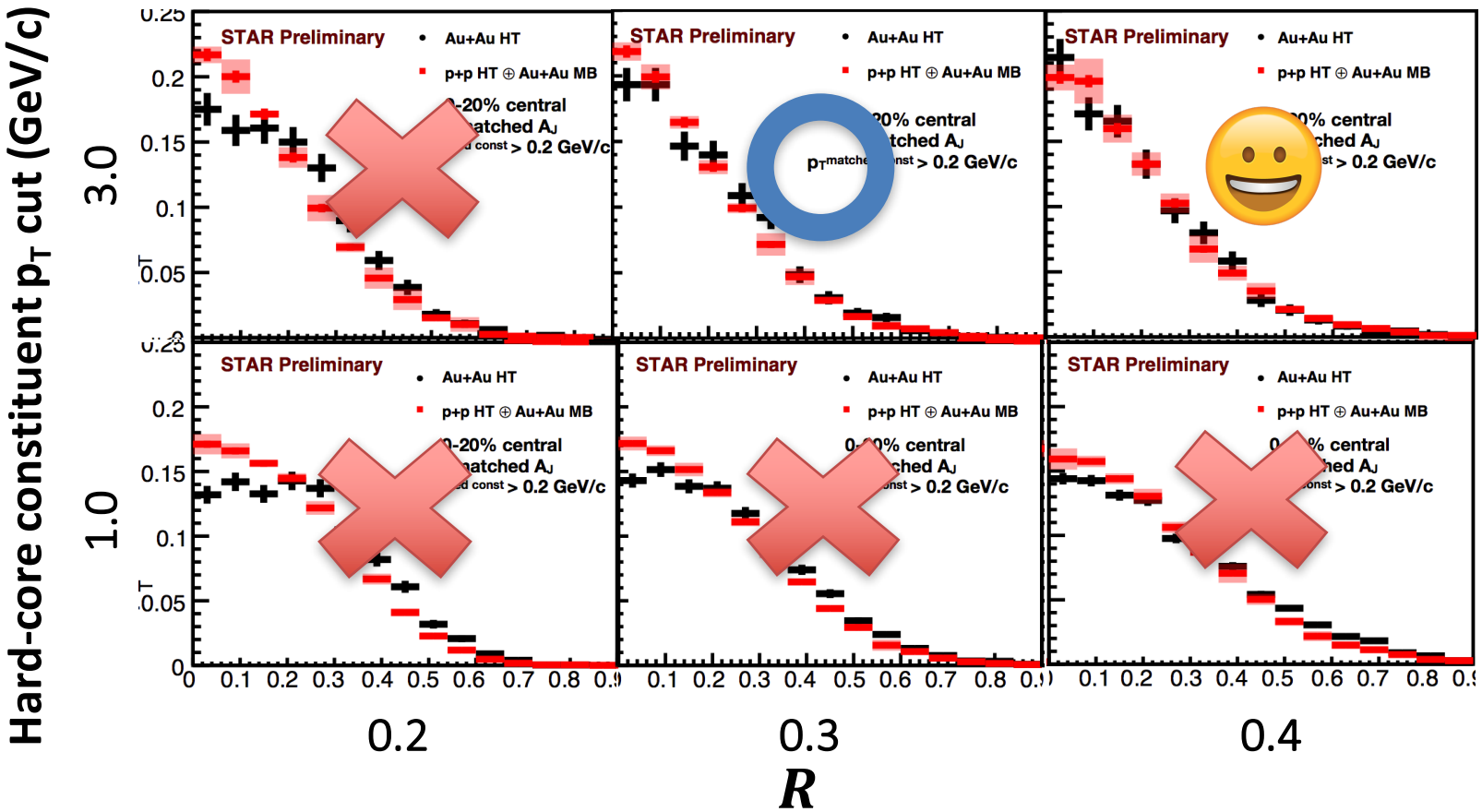

- Matched jet with various hard-core constituent p_T cut and R
  - ✓ Imbalance at small R
  - ✓ Balance ONLY restored with increased R (~0.35) when soft particles are included

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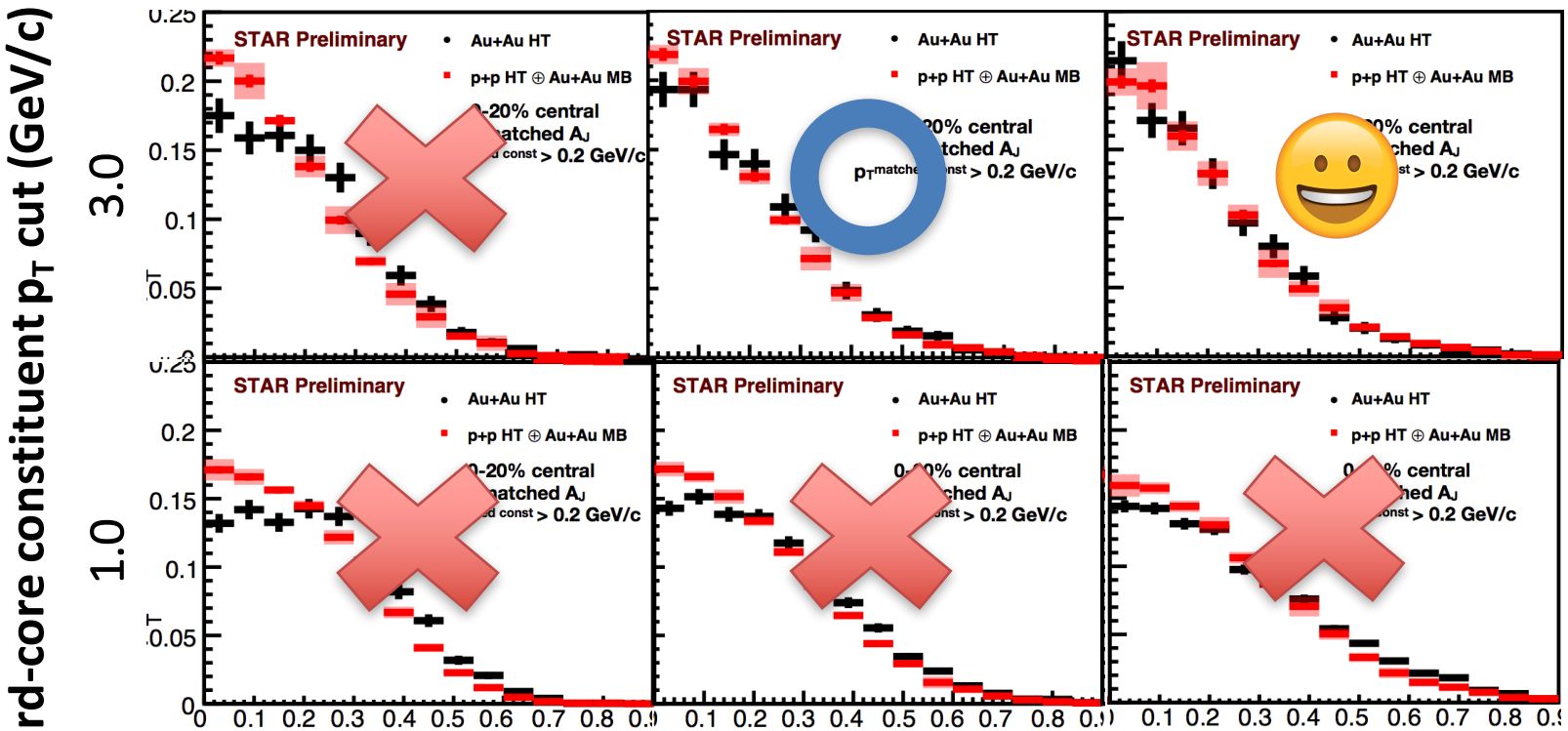
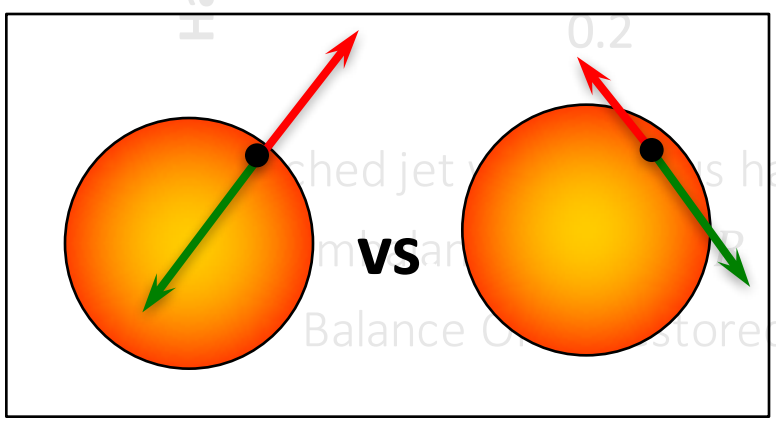
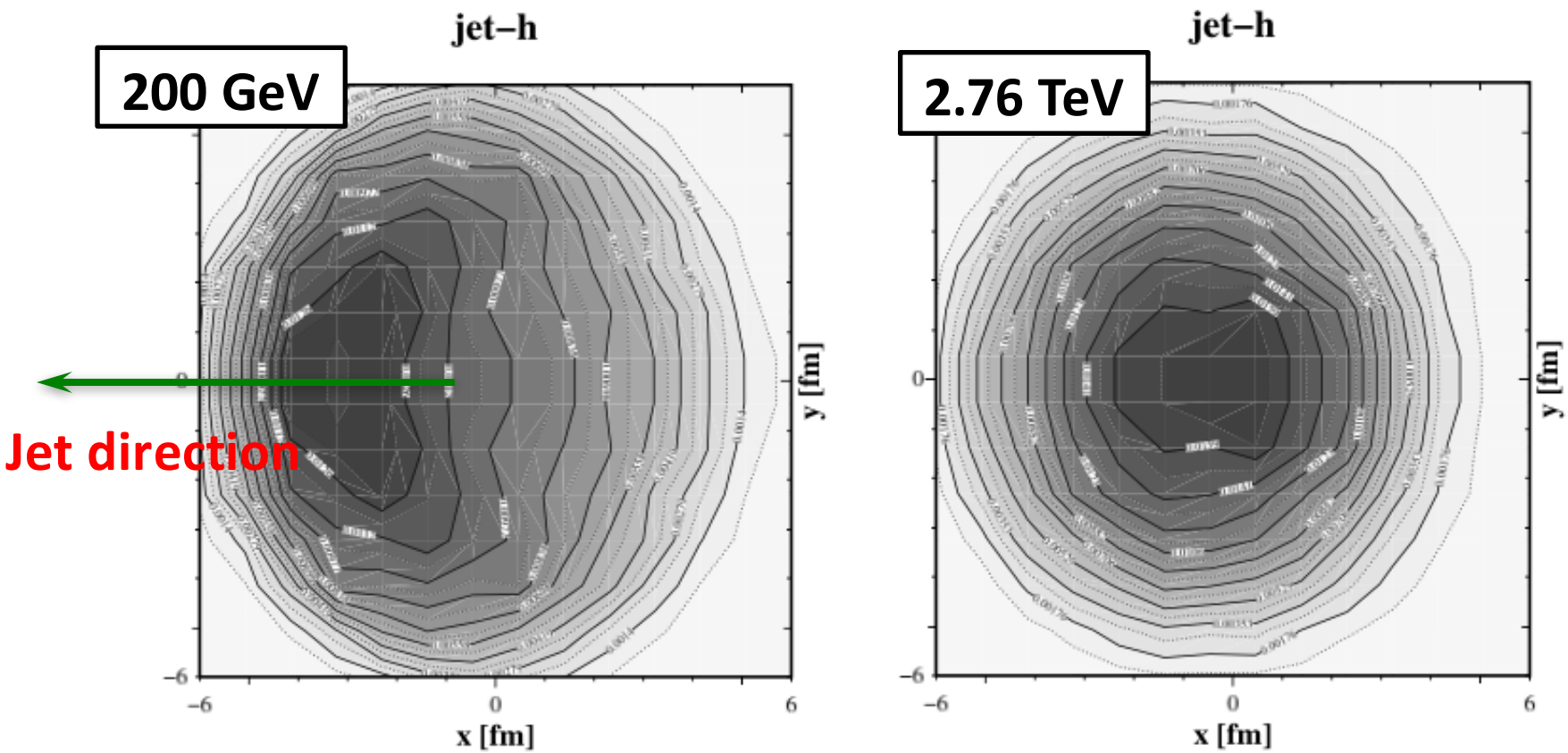




Jet Geometry Engineering Works!

Jet Geometry Engineering at RHIC

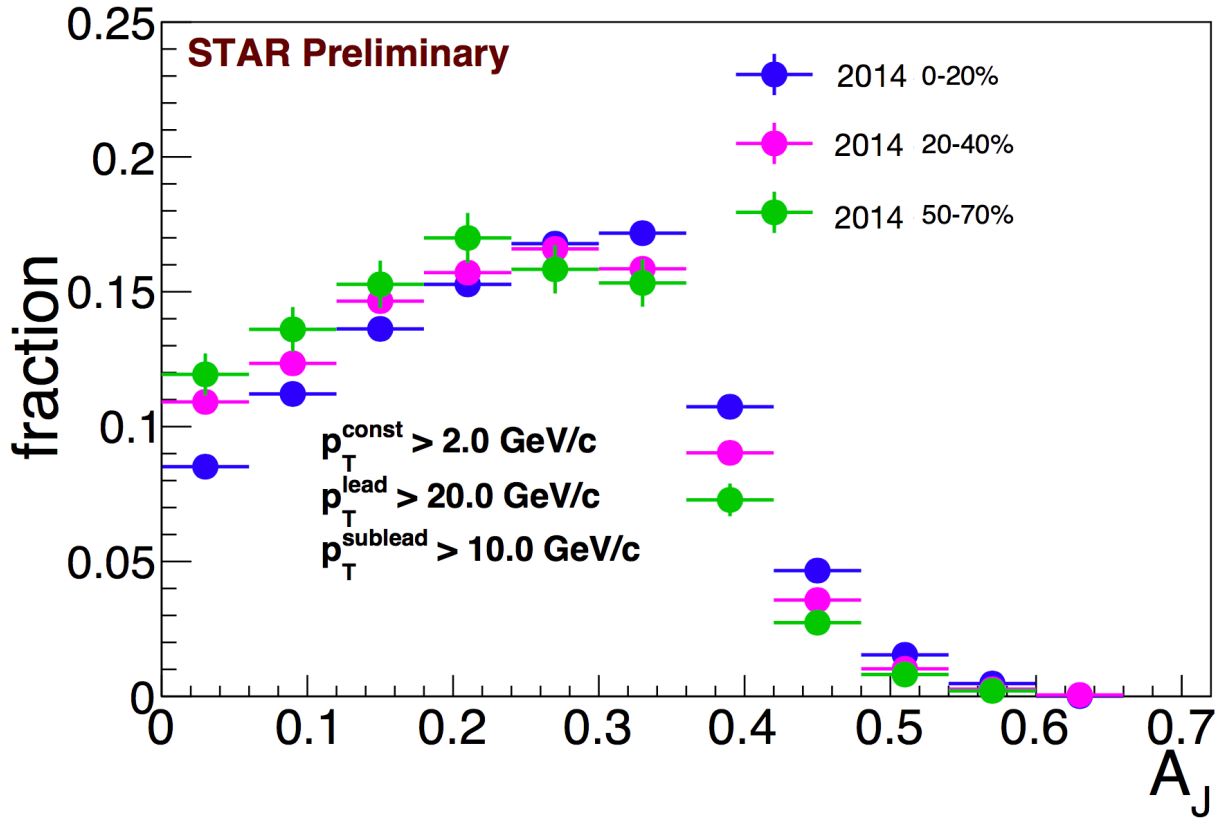
- At RHIC energies, we can better utilize the jet vertex bias via different jet definitions for more differential measurements



T. Renk, Phys. Rev. C 88 (2013) 054902

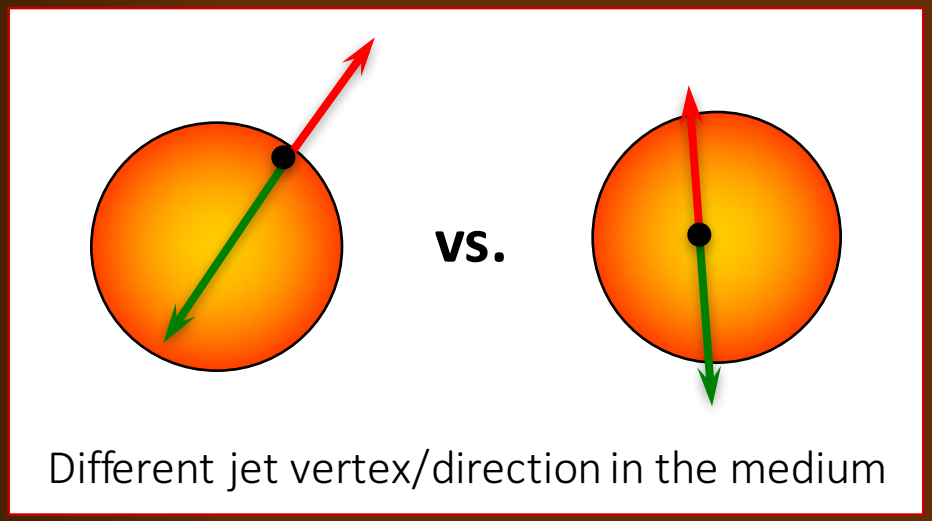
Jet reconstruction with constituent hadrons $p_T > 2.0$ GeV/c

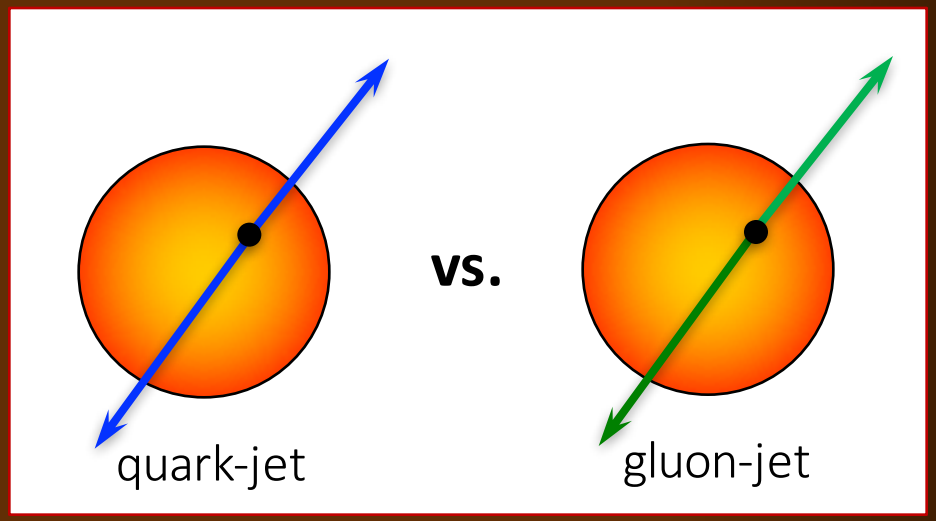
Di-jet Imbalance



- More differential measurements with the help of increase in statistics with recent RHIC runs
- Centrality dependence of A_J – More balanced in peripheral Au+Au collisions

Semi-inclusive Spectra



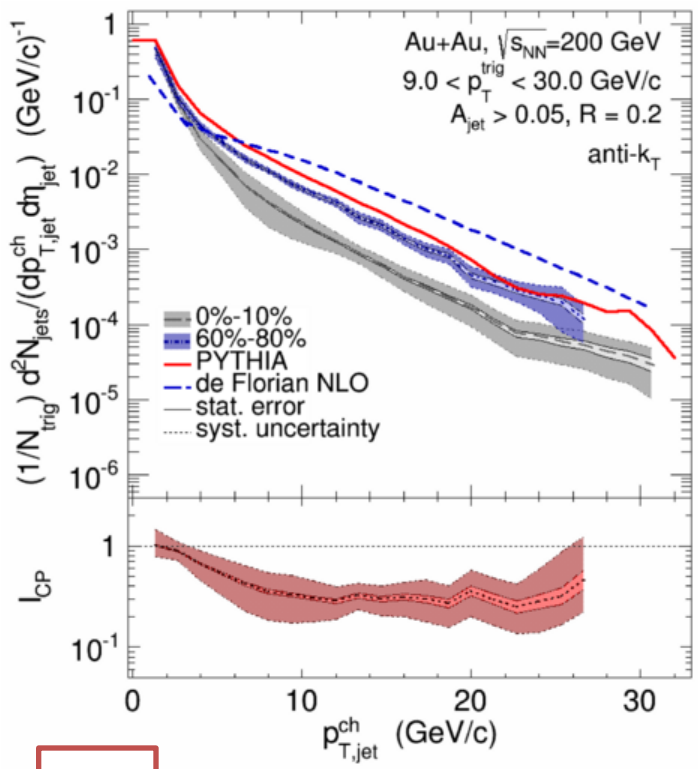


Jet vertex dependence?

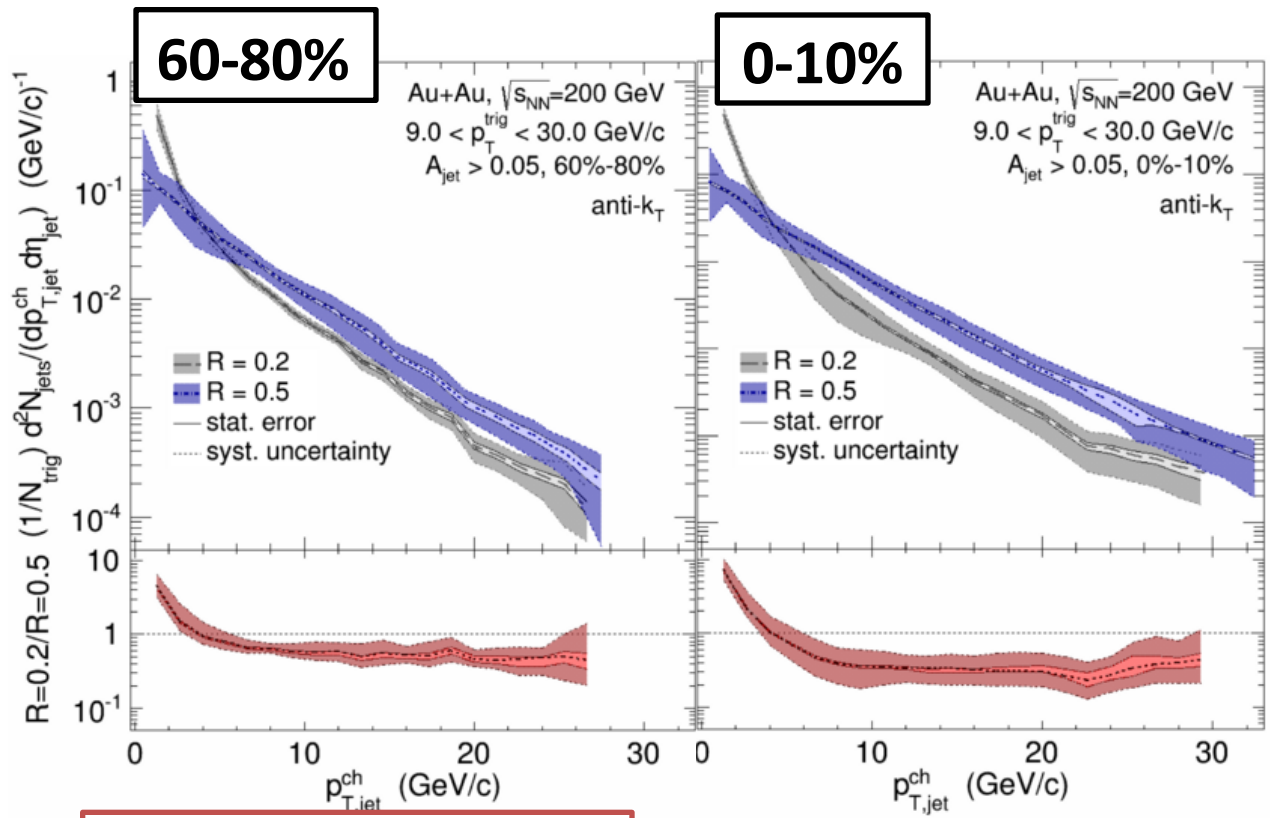
Jet flavor dependence?

h-Triggered Recoil Jets

STAR, Phys. Rev. C **96** (2017) 24905



I_{CP}



***R*=0.2 vs. *R*=0.5**

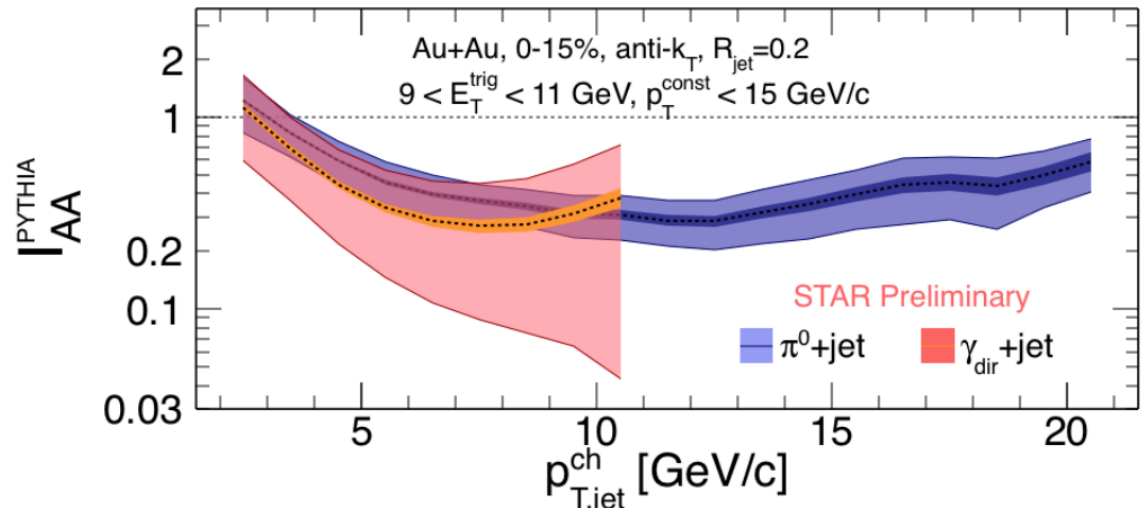
Charged Jet

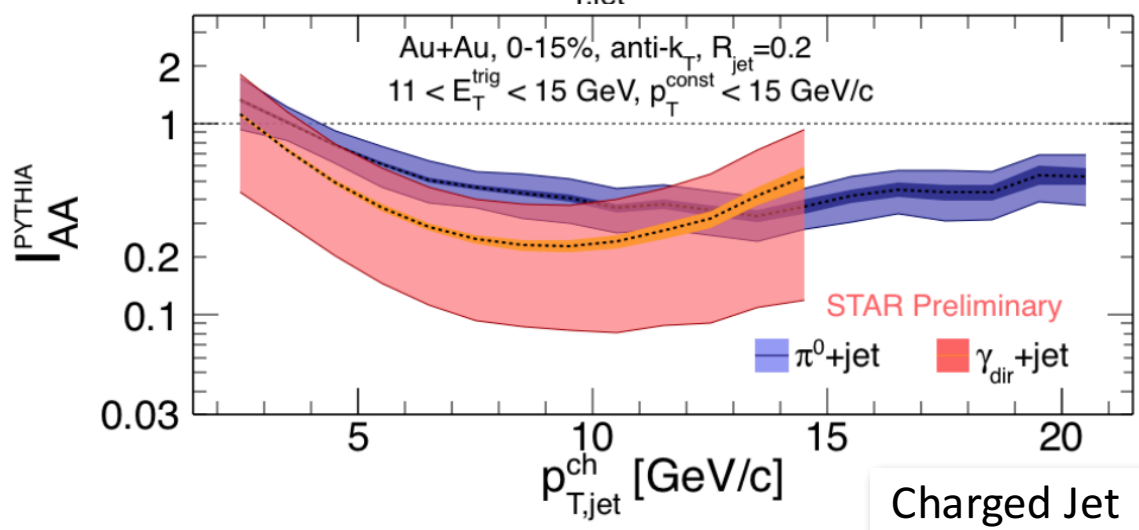
- Fully corrected $h^{\pm}$-triggered charged recoil jet
  - ✓ Strong suppression via I_{CP}
  - ✓ Medium-induced broadening ⇦ Comparison between $R = 0.2$ and $R = 0.5$

γ-Triggered Recoil Jets

- γ_{dir}+jet and π^0+jet
  - ✓ Path length
  - ✓ Color factor (toward *q*-jet)
  - ✓ Parton energy

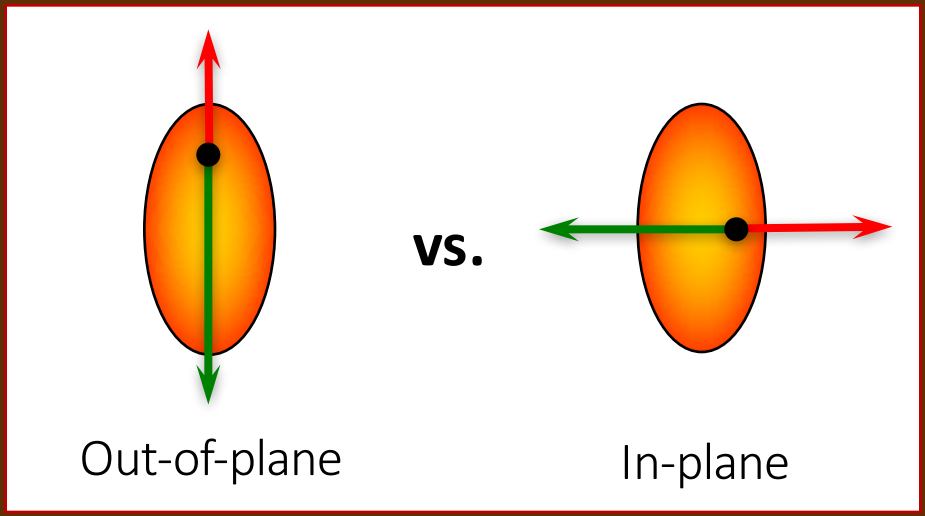
- Similar level of suppression observed





Charged Jet

Event-plane Dependent Measurements

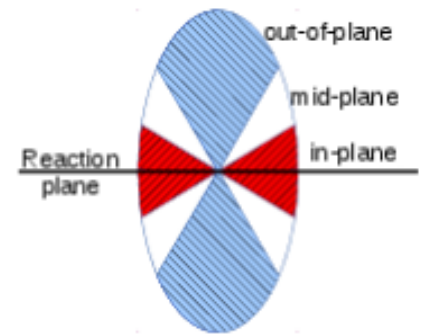


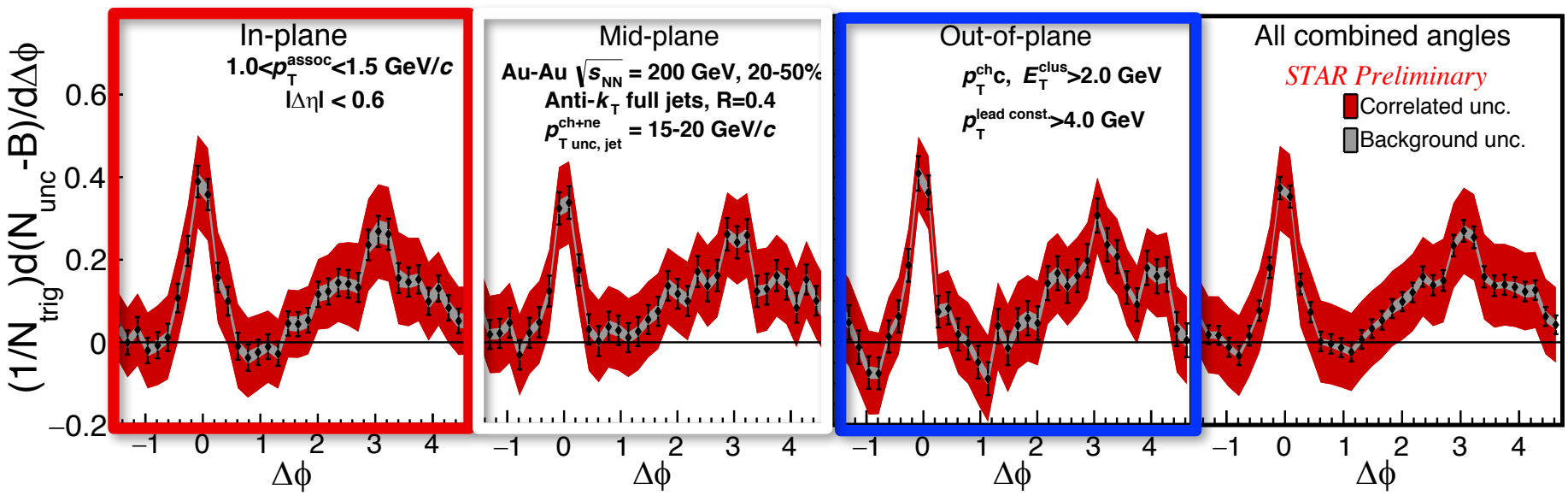
Path-length dependence in non-central AA collisions?

Event-plane Dependent Jet-hadron Correlations

- Previous jet-hadron correlations by STAR (Phys. Rev. Lett. 112 (2014) 122301)
  - ✓ Suppression of high-p_T associated particle yield is balanced by low p_T associated particle enhancement

- More differential measurement using the trigger jet angle with respect to the event plane
  - ✓ In-plane, mid-plane, and out-of-plane





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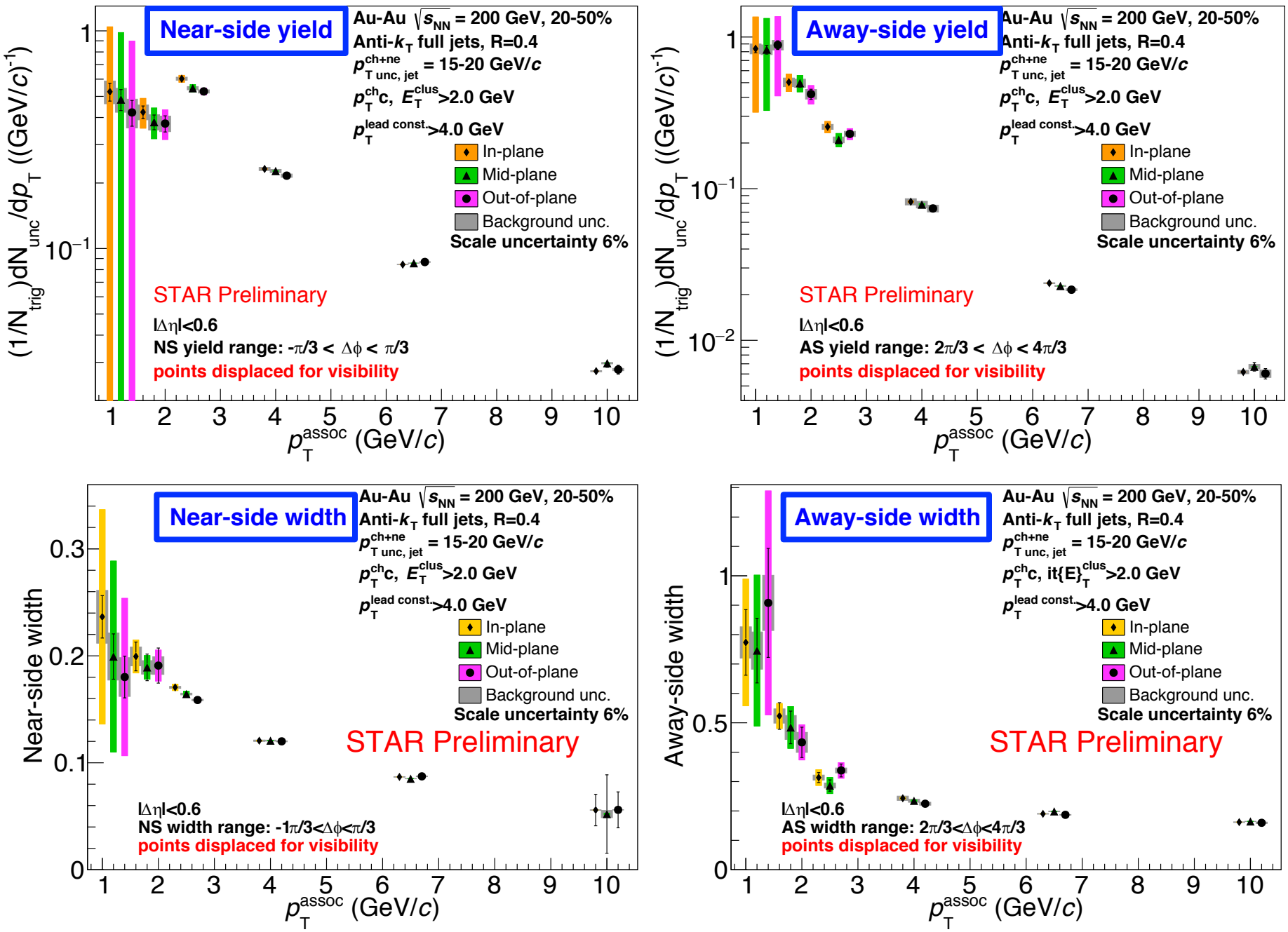
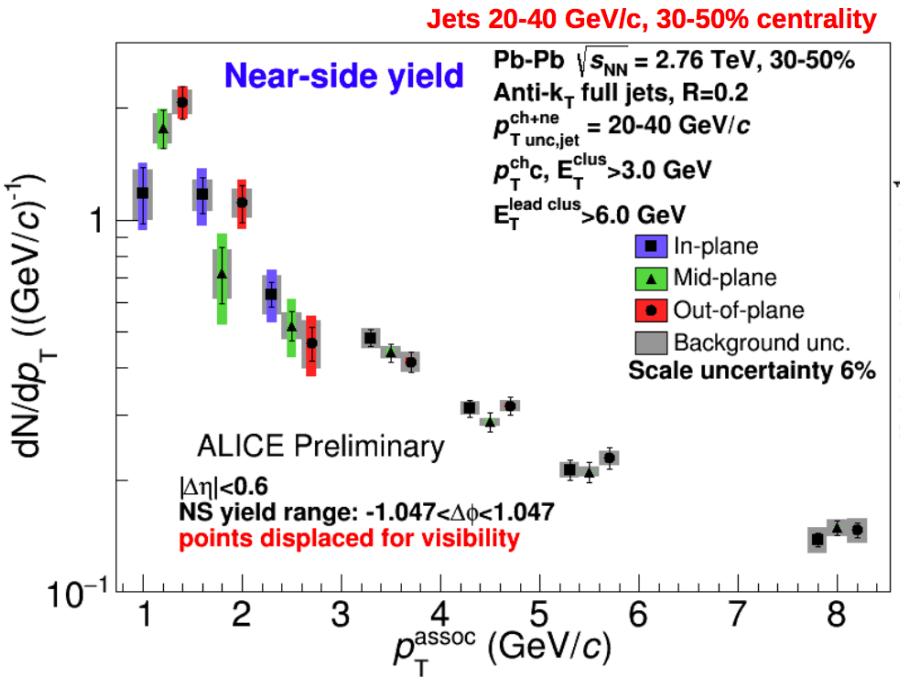
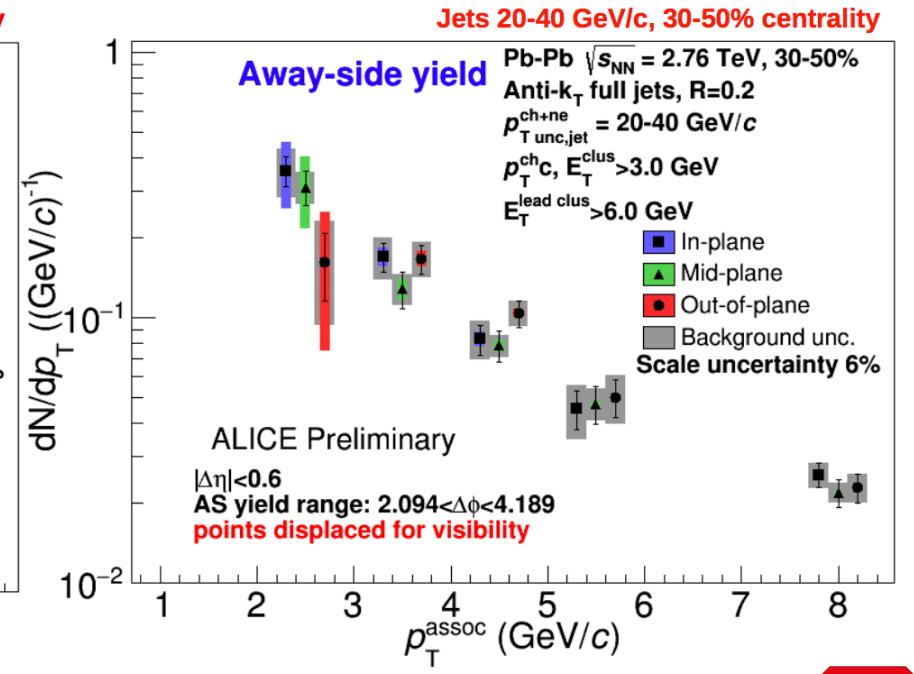


Event-plane Dependent Jet-hadron Correlations

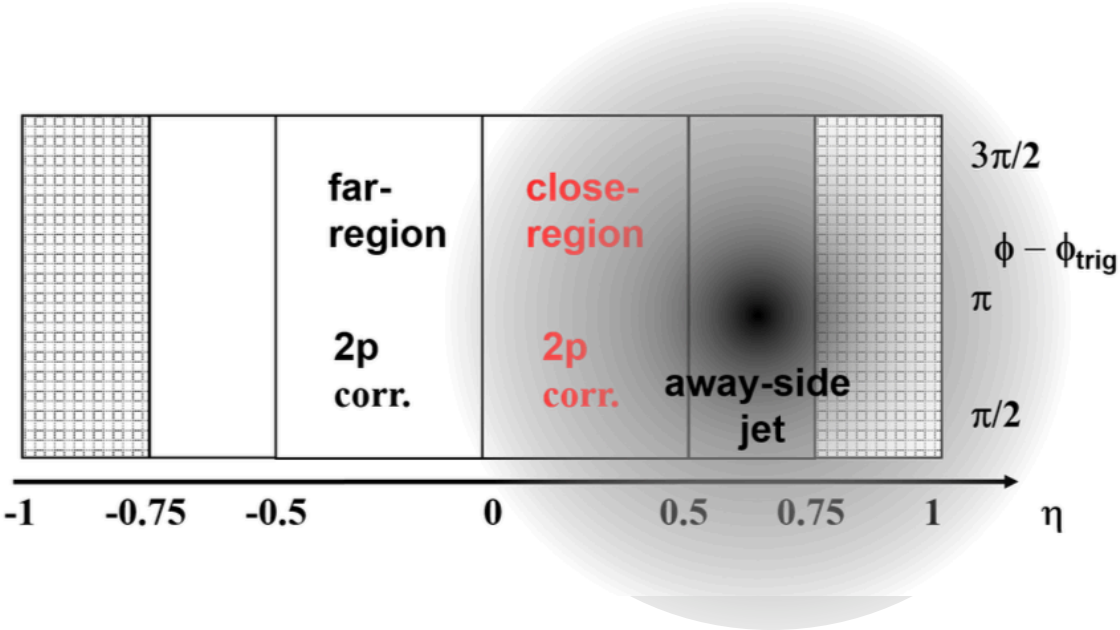
No significant event plane dependence is observed within uncertainties

Consistent with LHC results





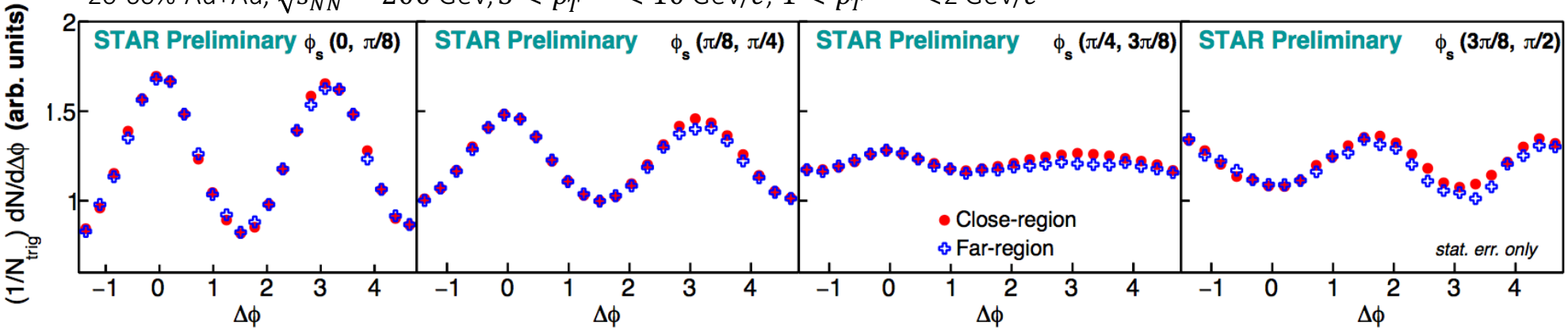
Event-plane Dependent Di-hadron Correlations – Recoil Width



- After selecting events with high recoil momentum within $0.5 < \eta < 1.0$, two-particle correlation functions in **close-region** and **far-region**

- Under the assumption that the flow contribution is equal in two regions, the difference between **close-region** and **far-region** correlation functions provides information on **away-side width** of jet-like correlations without the flow contribution

20-60% Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $3 < p_T^{trig} < 10$ GeV/c, $1 < p_T^{assoc} < 2$ GeV/c



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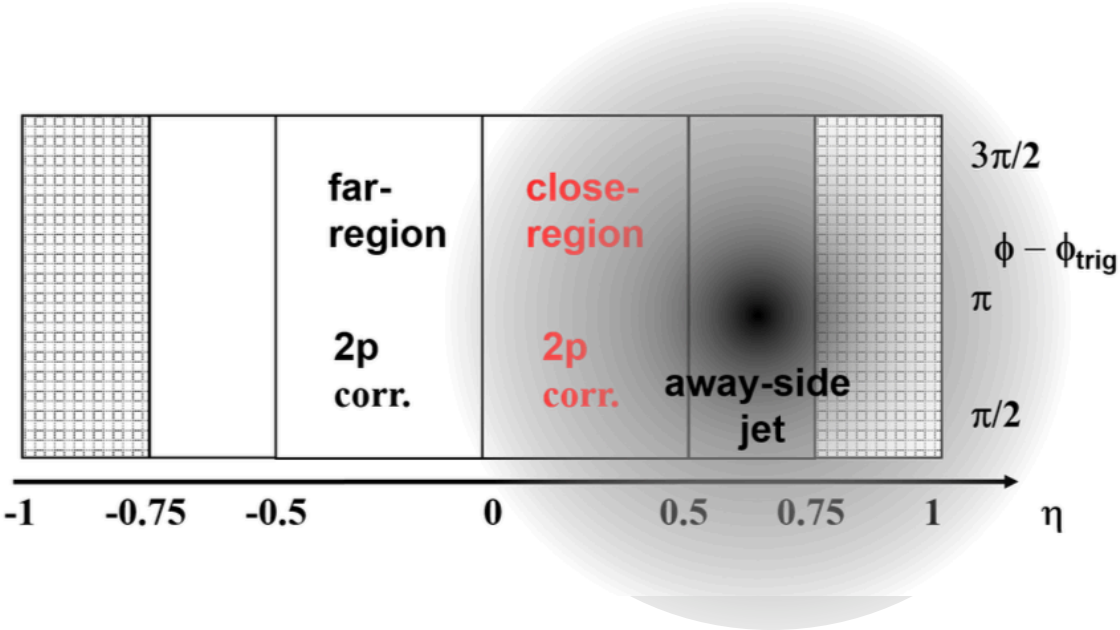

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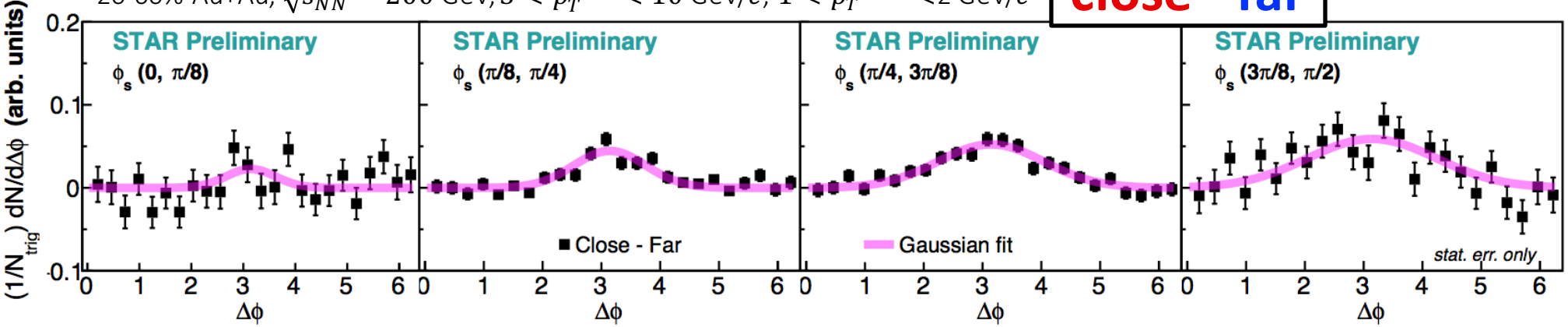
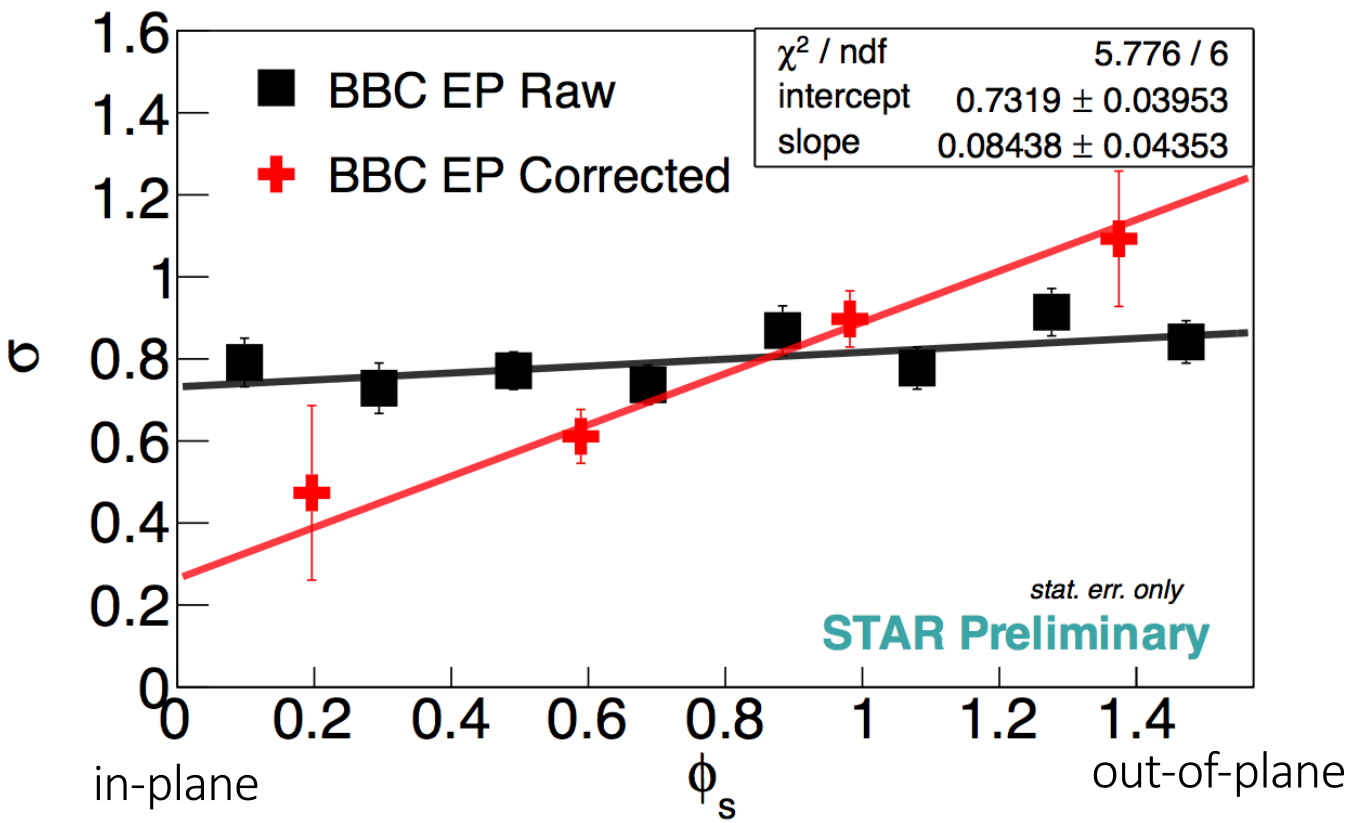
close - far



Event-plane Dependent Di-hadron Correlations – Recoil Width

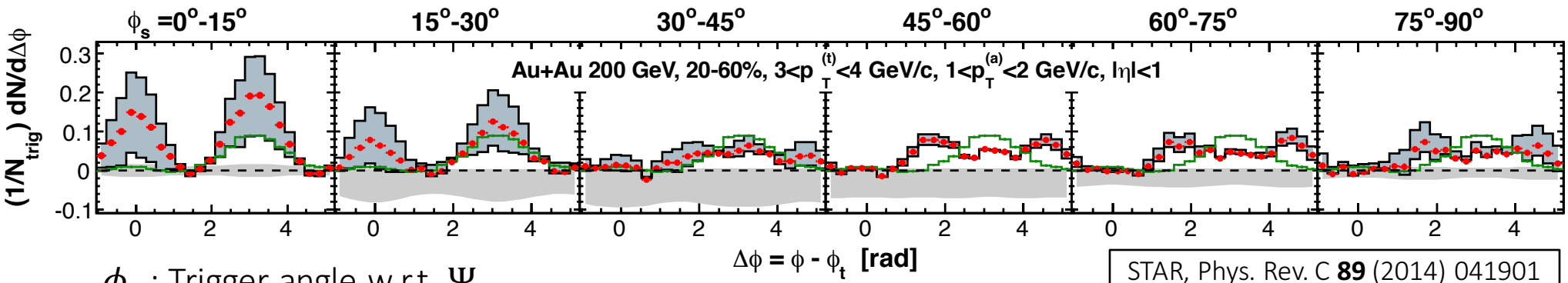


- Depending on the trigger particle angle with respect to the event plane ($= \phi_s$), the difference of two-particle correlation functions shows different away-side widths ($= \sigma$) after correcting for the EP resolution
- Larger width for out-of-plane triggers – Hint of jet-medium interactions

Event-plane Dependent Di-hadron Correlations with ESE

- Previous event-plane (EP) dependent di-hadron correlations
  - ✓ Implication of path-length dependence of energy loss in the medium (**shorter** path-length for in-plane trigger and **longer** path-length for out-of-plane trigger)

in-plane ⟷ out-of-plane



ϕ_s : Trigger angle w.r.t. Ψ_{EP}

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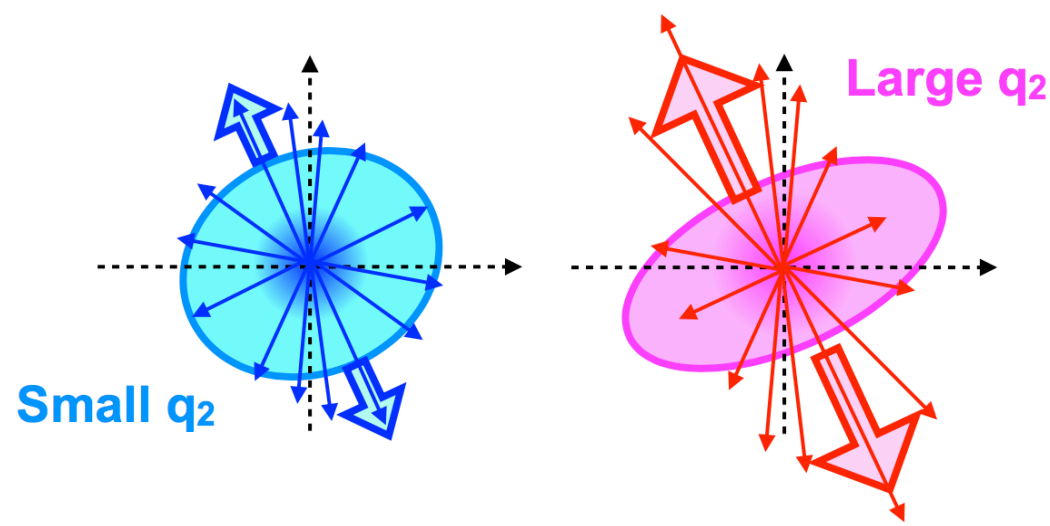
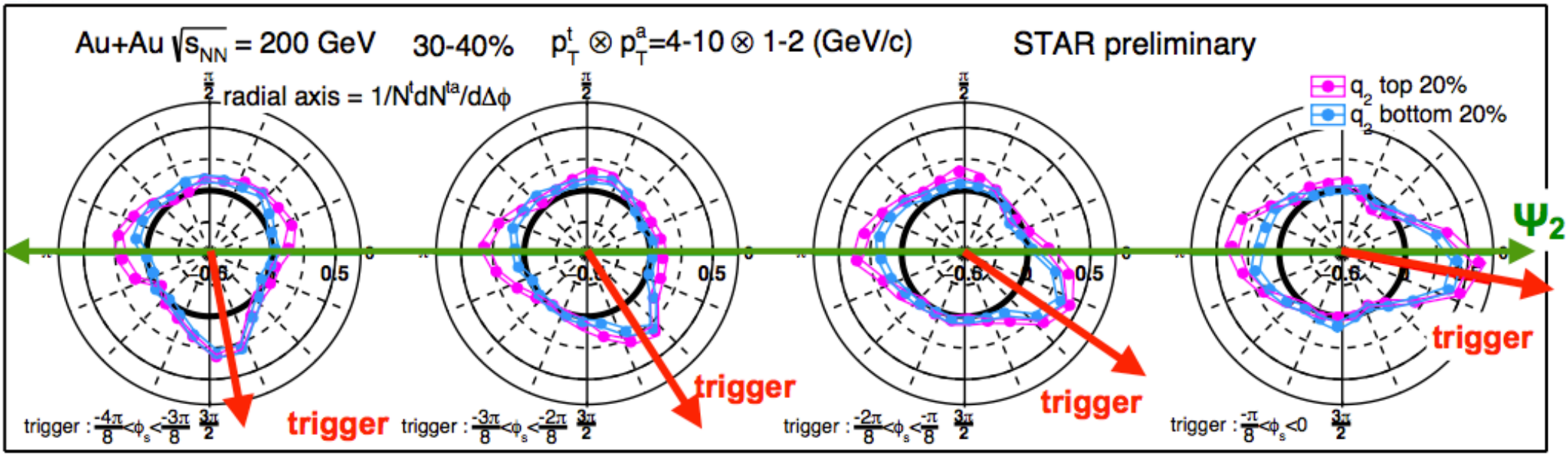
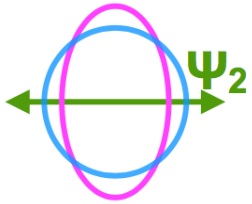
- Event shape engineering (**ESE**) can further control the initial geometry with the fixed average energy density – Measurements in small-q_2 and large-q_2 events separately



Event-plane Dependent Di-hadron Correlations with ESE



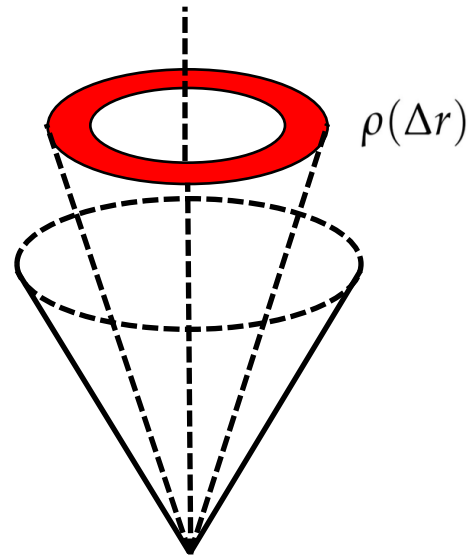
- Polar representation of two-particle angular correlations
- **Near-side** – Higher peak in large-q_2 events with **in-plane** trigger
- **Away-side**
  - ✓ Larger associated particle yields toward in-plane direction
  - ✓ Higher peak in large-q_2 events with **in-plane** trigger
    - ➪ Consistent with path-length dependent picture?



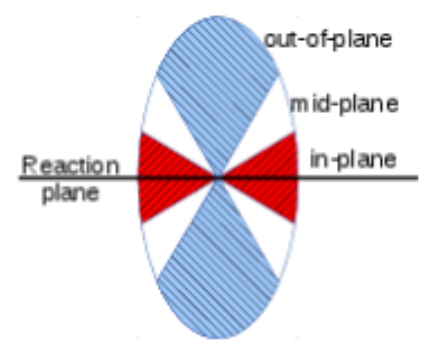
Event-plane Dependent Jet Shape

- Jet shapes represent the average distribution of jet energy as a function of distance from the jet axis

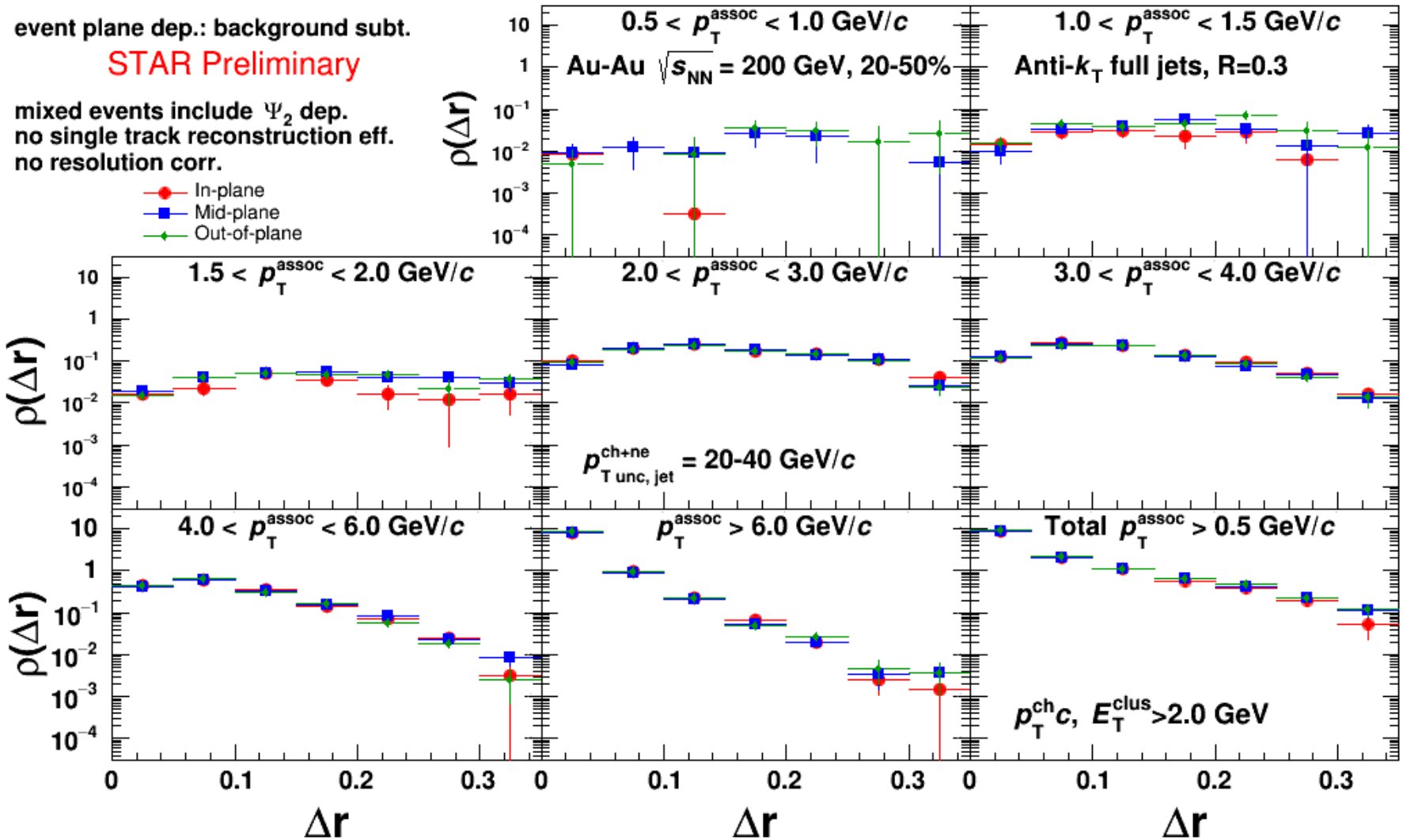
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}p_{\text{T}}^{\text{trk}}}{p_{\text{T}}^{\text{jets}}}$$



- In 20-50% centrality Au+Au collisions, jet shapes of Anti-k_T jets with $20 < p_T < 40$ GeV/c from different trigger jet angle with respect to the event plane
  - ✓ In-plane, mid-plane, and out-of-plane

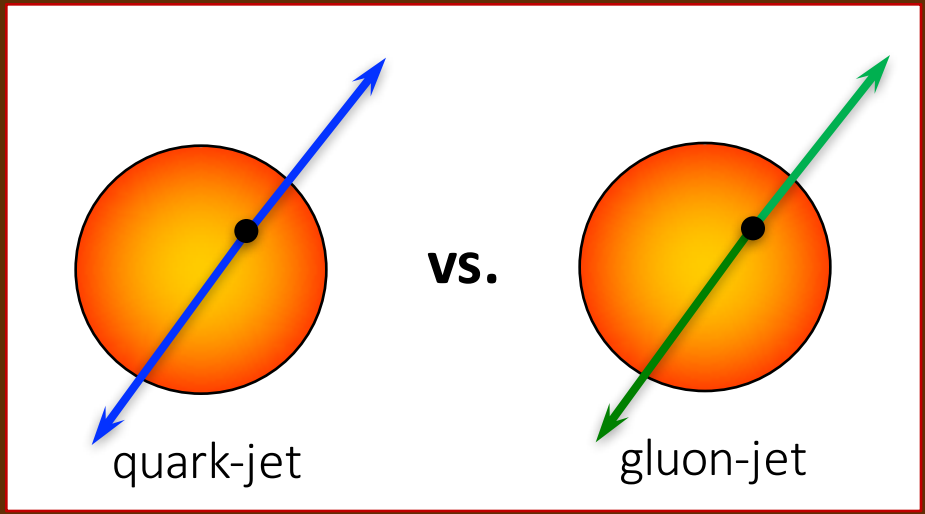


Event-plane Dependent Jet Shape



- Hint of event plane ordering at low p_T?
- Correction for the event-plane resolution effects not applied

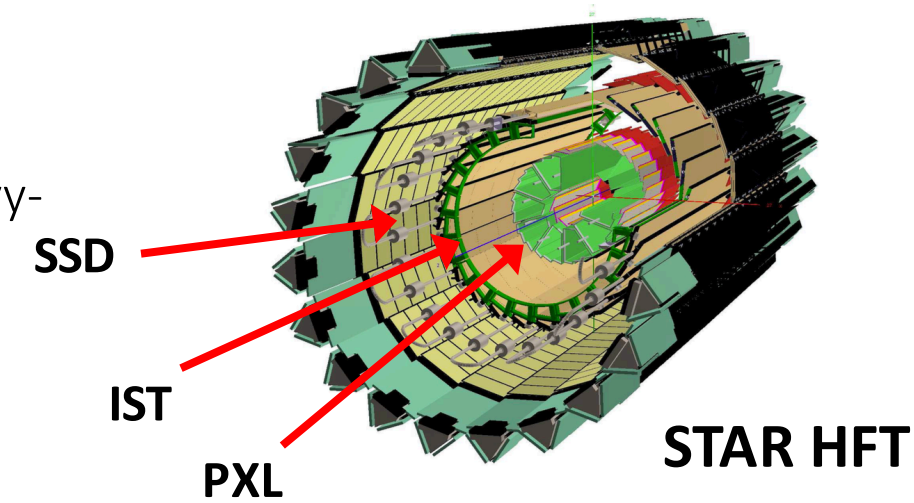
Jet Flavor Dependent Measurements



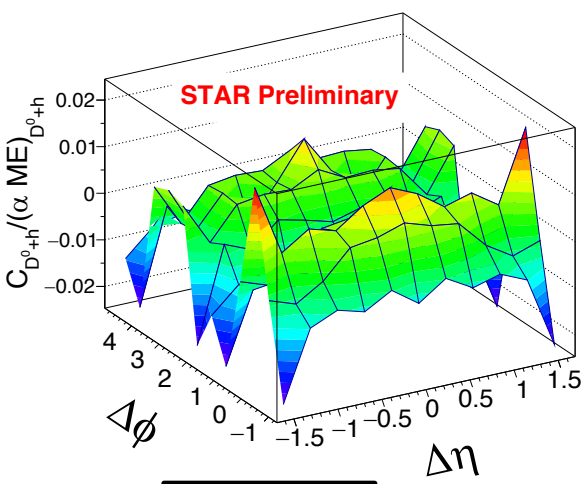
Jet flavor dependence?

D^0-hadron Correlations

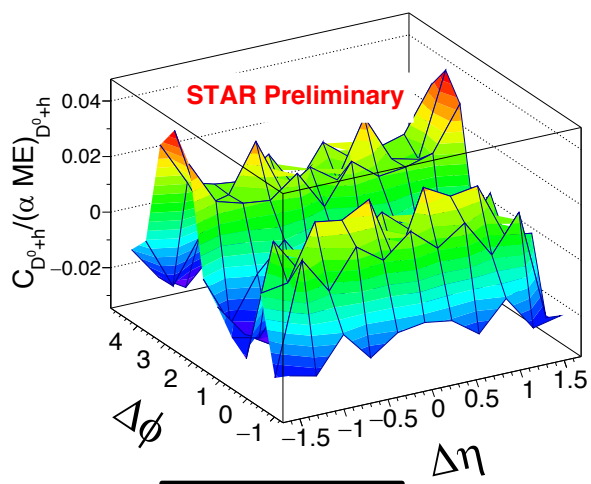
- Heavy Flavor Tracker (HFT) provides significantly better identification of heavy-flavor particles
- D^0-hadron two-particle angular correlations with $D^0 \rightarrow \pi^{\pm}K^{\mp}$ channel



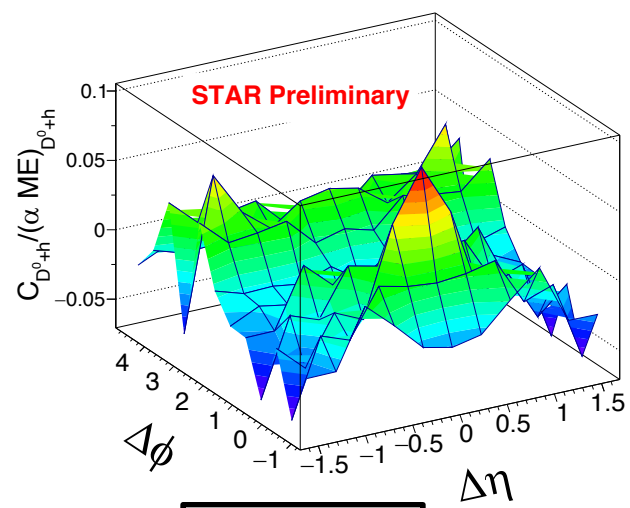
Au+Au, $\sqrt{s_{NN}} = 200$ GeV, D^0 $p_T = 2$–10 GeV/c, $h^{\pm}$ $p_T > 0.15$ GeV/c



0-20%

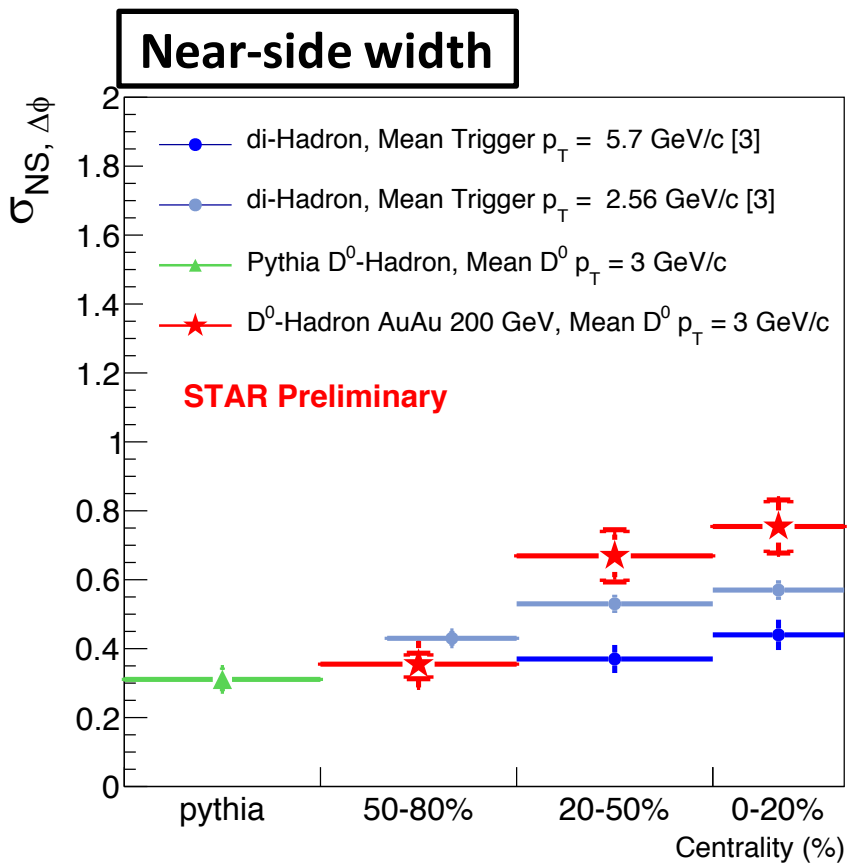


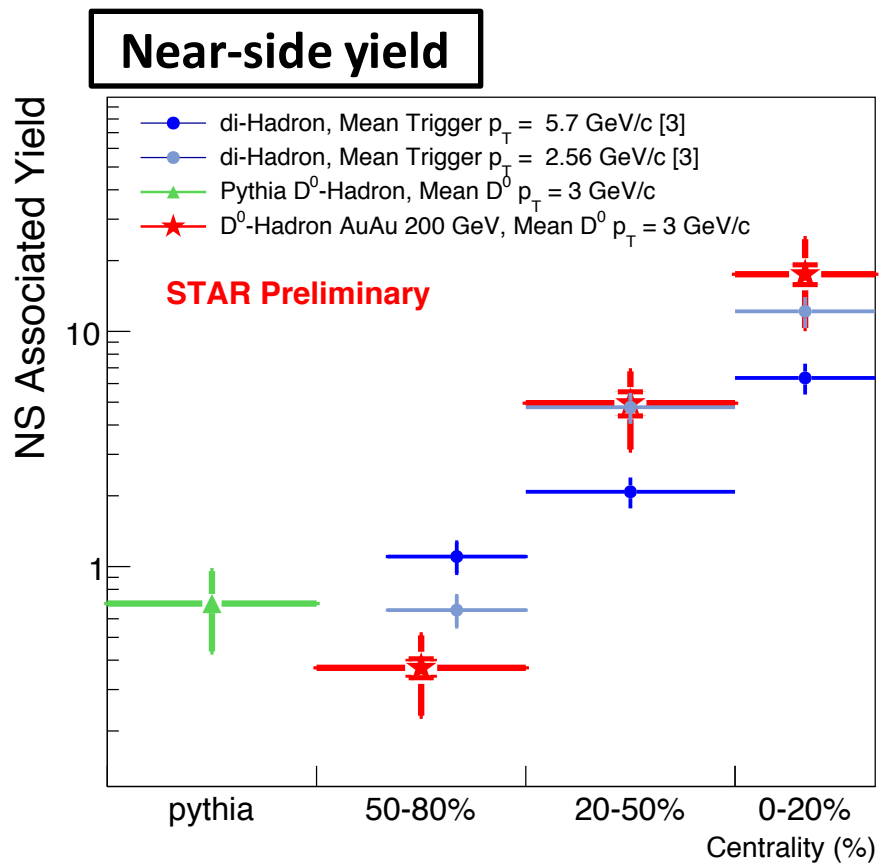
20-50%



50-80%

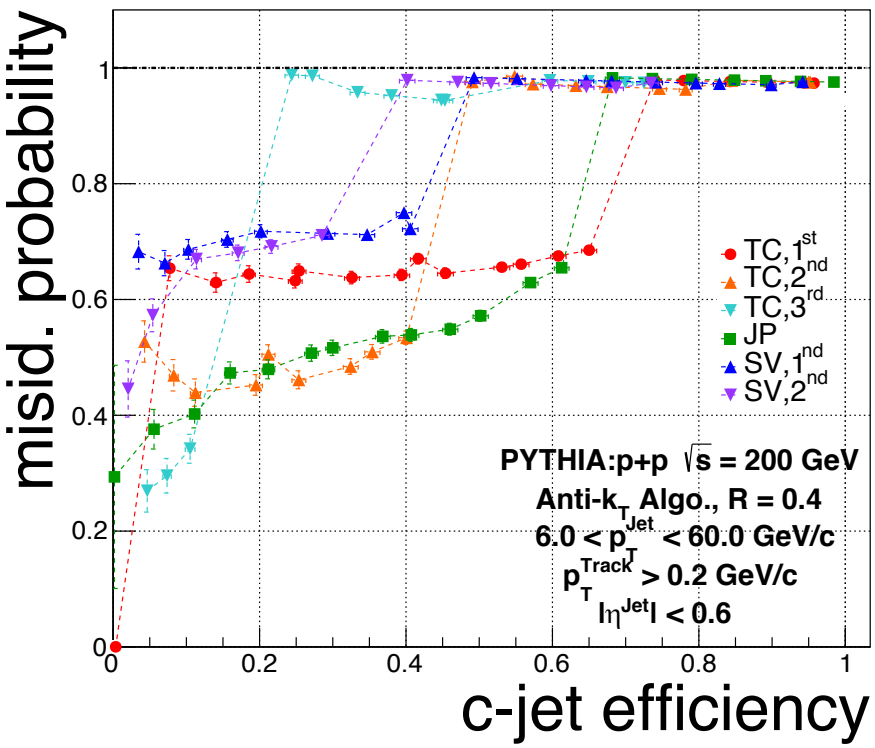
D^0-hadron Correlations

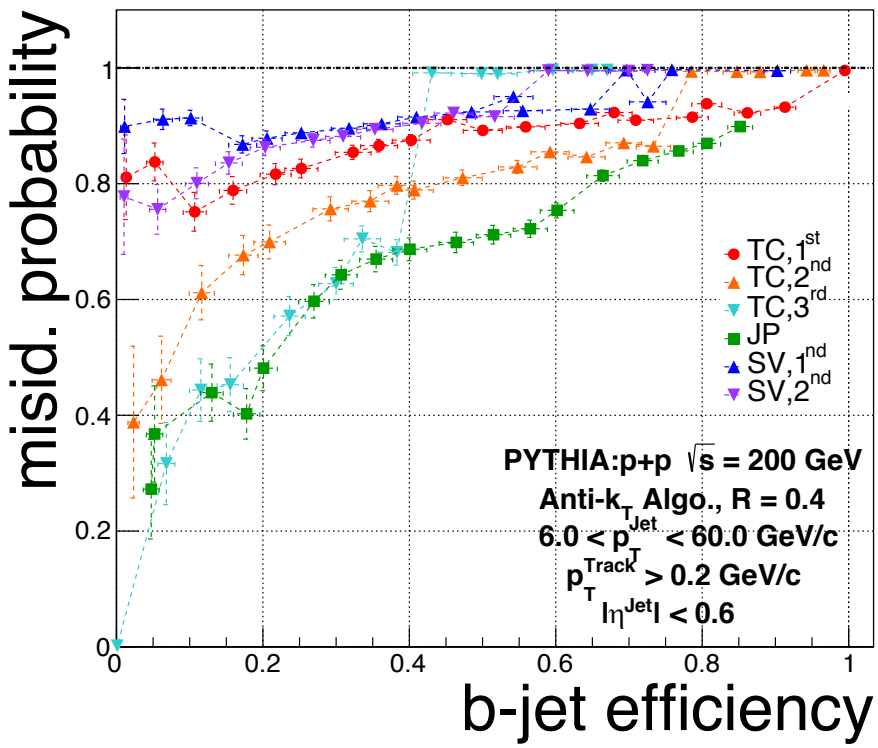




- Similar width and yield results to light-flavor correlations – Indication of similar behavior of correlations between light-flavor and charm-quarks

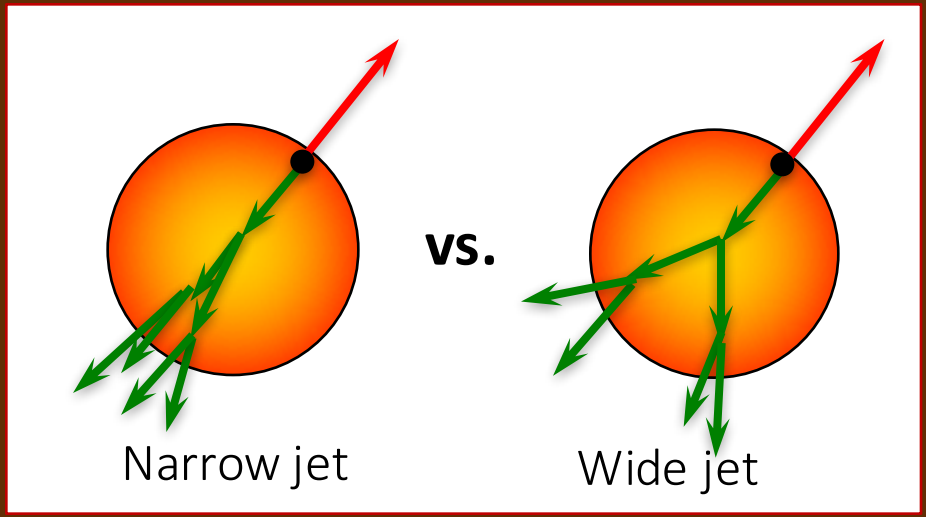
Heavy-flavor Jet Tagging in *pp*





- Heavy-flavor jet tagging performance in pp with low-level tagging algorithms
- Possibility of future heavy-flavor tagged jet analysis in STAR with HFT

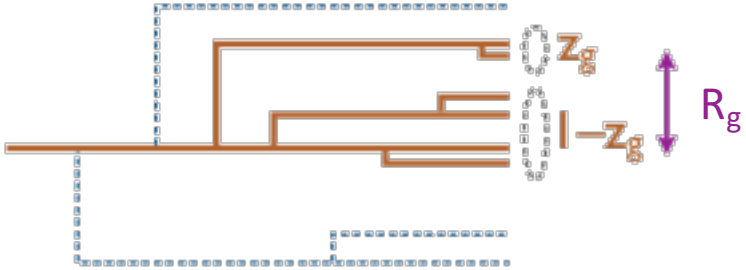
Jet Angular Scale Dependent Measurements + Jet Substructure



Jet angular scale dependence?

Jet Substructure in *pp*

- Experimental observables related to quantities in jet evolution
  - With SoftDrop algorithm Phys. Rev. D 91, 111501 (2015)
    - ✓ Momentum scale, z_g
    - ✓ Angular scale, R_g
  - Invariant jet mass, M

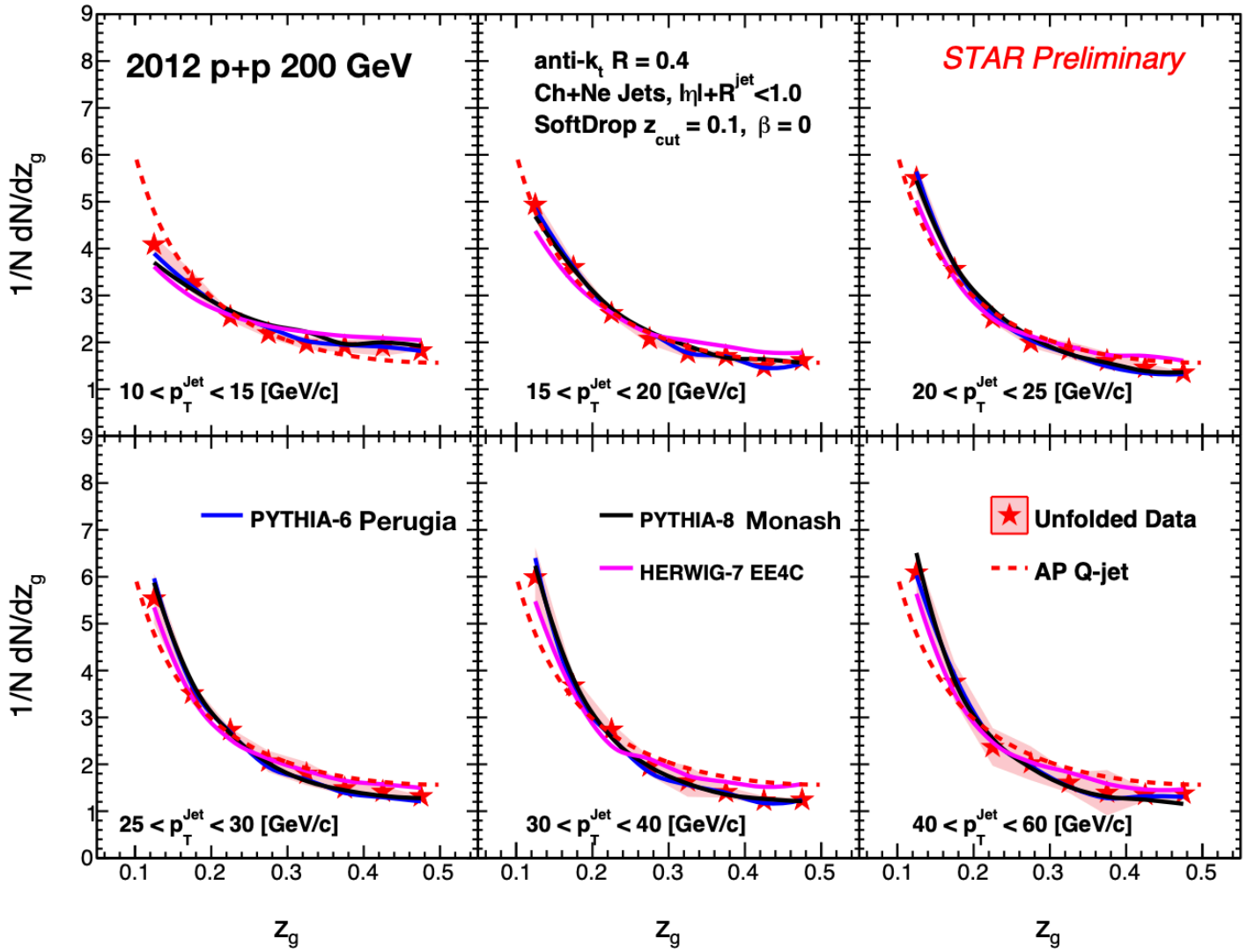


Based on declustering an angular-ordered tree

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

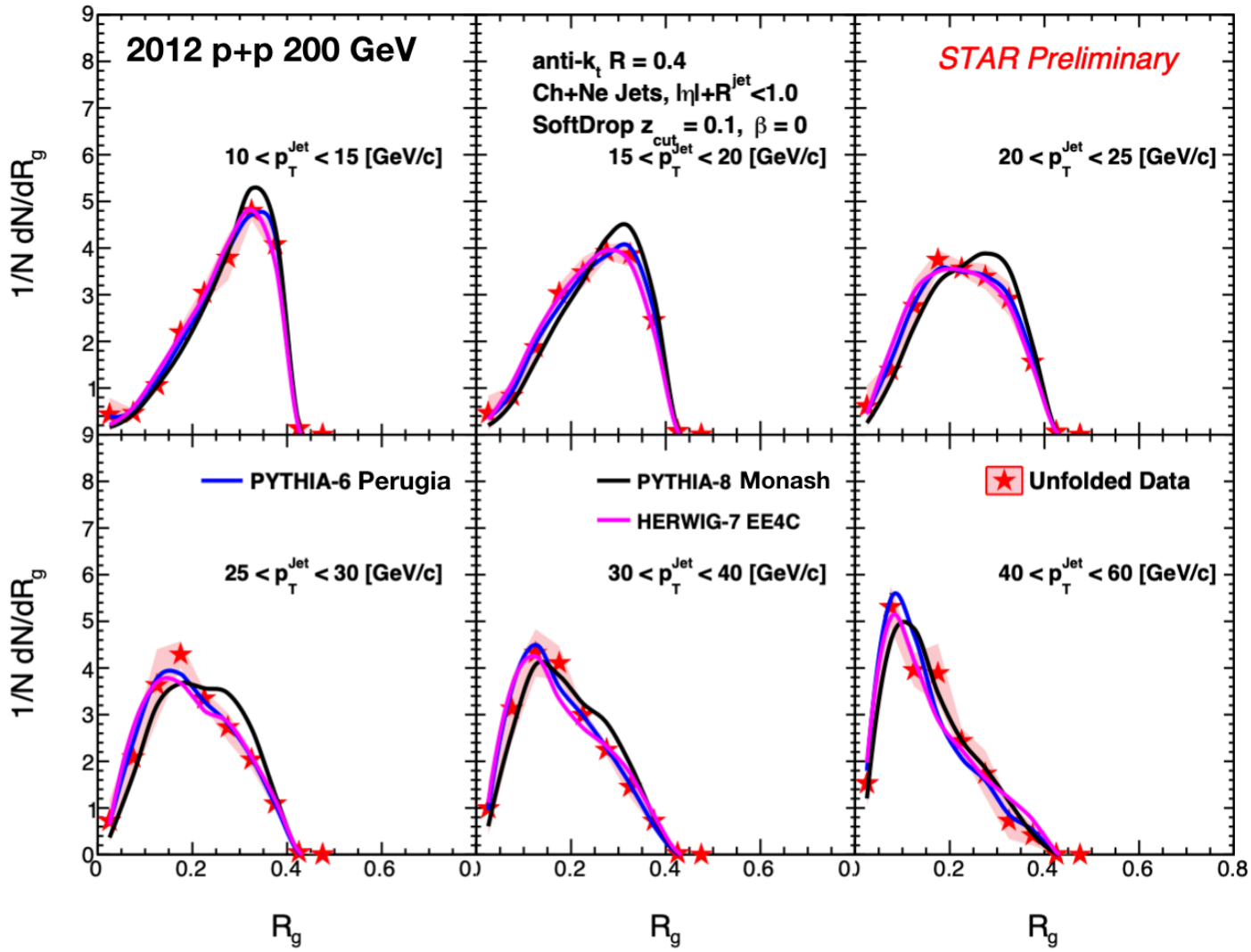
- Measurements of these observables in *pp* set a vacuum baseline

Jet Substructure in *pp* - z_g



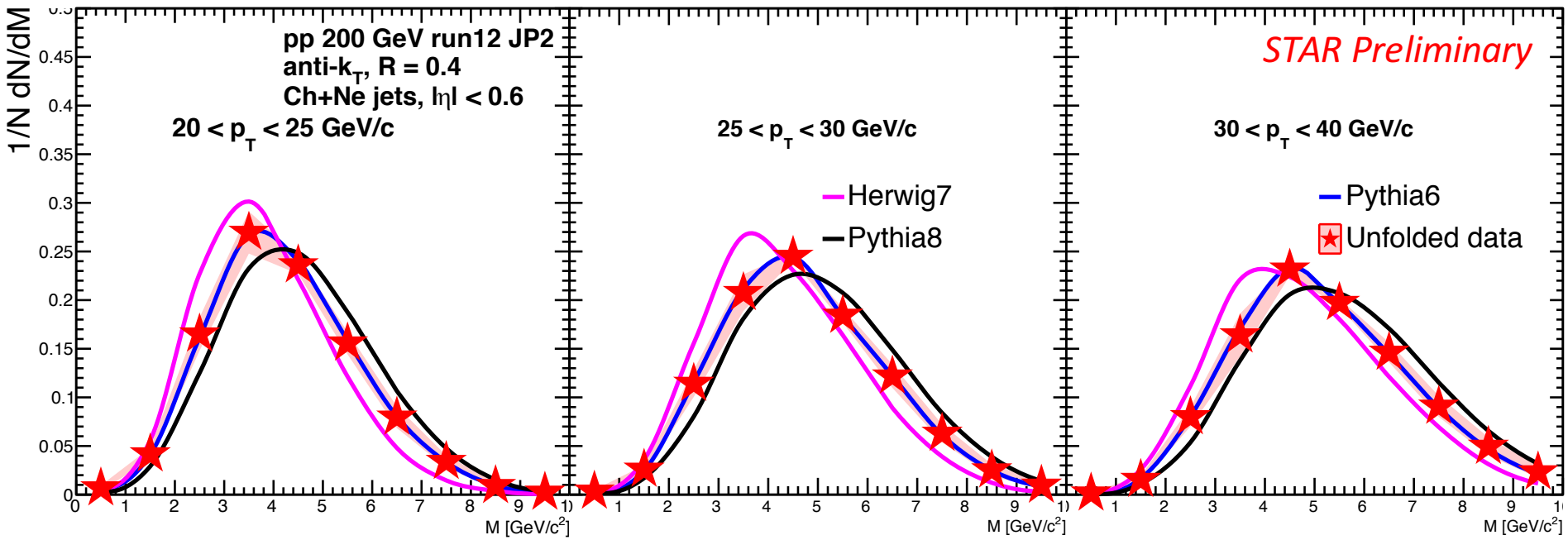
- *1/z* behavior recovered for jet p_T > 20 GeV/*c*
- z_g in *pp* described by leading order MC generators

Jet Substructure in *pp* - R_g



- Momentum dependent narrowing of jet angular structure
- R_g overall shape in *pp* described by leading order MC generators

Jet Substructure in *pp* - *M*



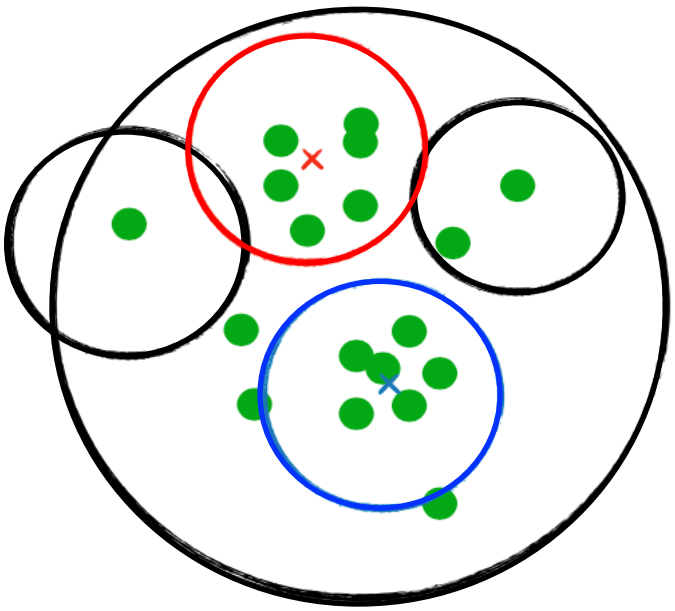
- Jet mass increases with increasing jet p_T
- PYTHIA-8 generally over-predicts jet mass and HERWIG-7 under-predicts jet mass

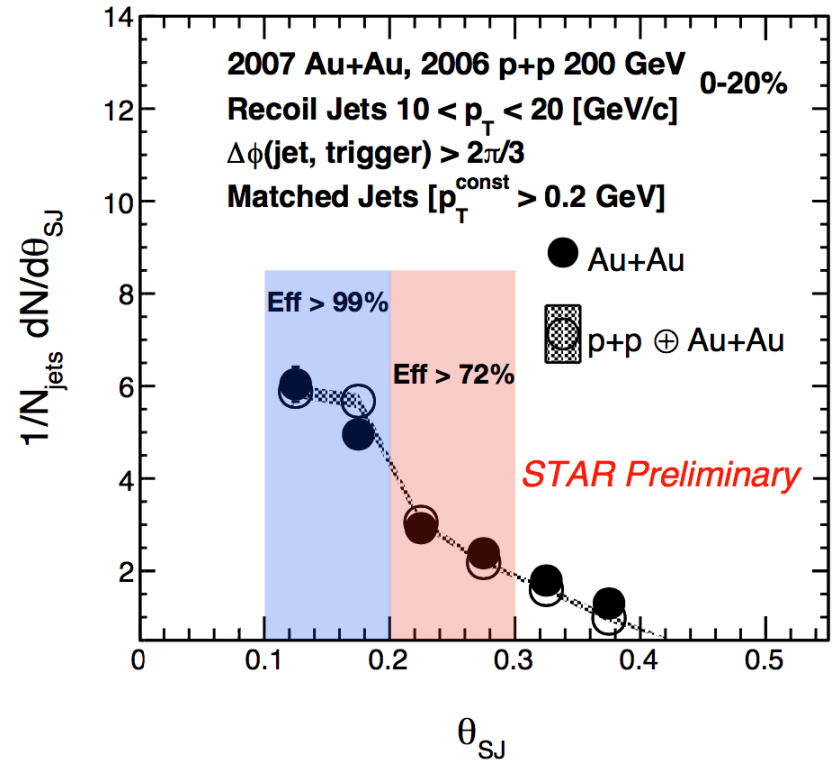
Opportunity to further tune MC generators at RHIC kinematics

Jet Angular Scale Dependent A_J

- Interaction of the jet with medium could depend on the jet's angular scale

  Majumder, A and Putschke, J Phys Rev C 93 054909
  Mehtar Tani, Y and Tywoniuk, K arXiv:1707.07361





- Clustering all constituents into smaller radius jets ($R = 0.1$) → leading and subleading subjets
- θ_{SJ} = ΔR(LeadingSJ axis, SubleadingSJ axis)
- More robust to the heavy ion background than SoftDrop R_g

Jet classification based on θ_{SJ}

Jet Angular Scale Dependent A_J

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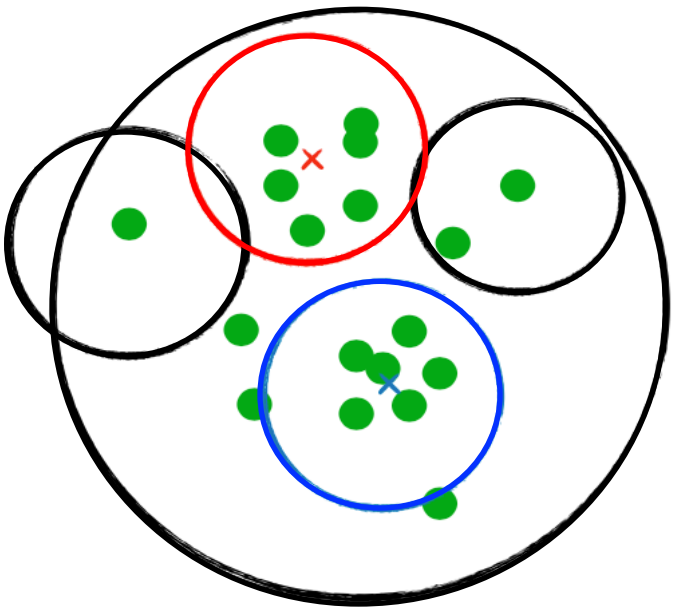

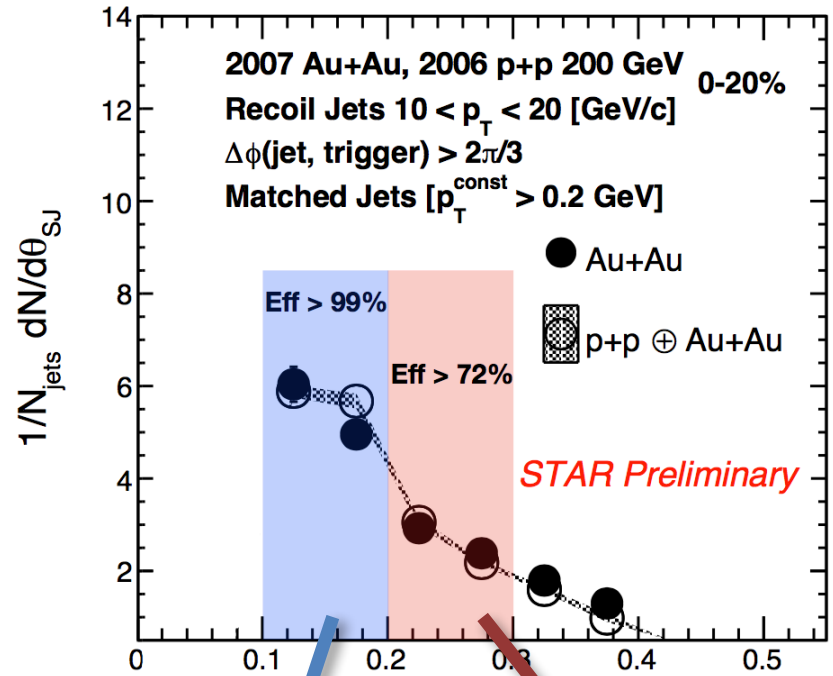

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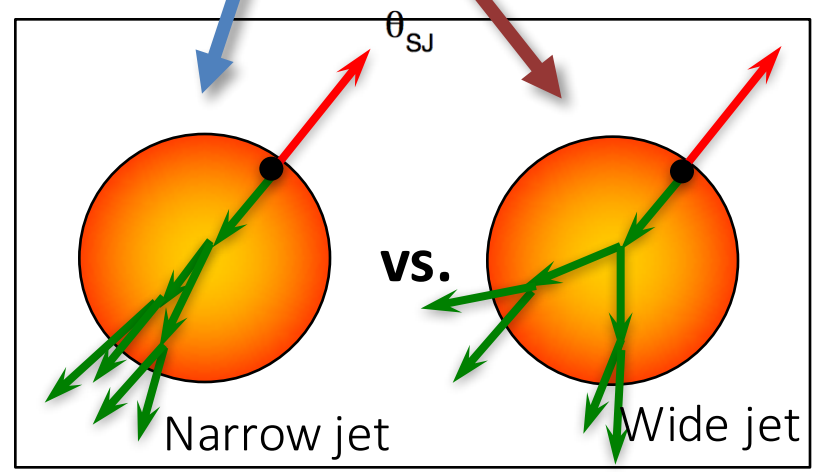
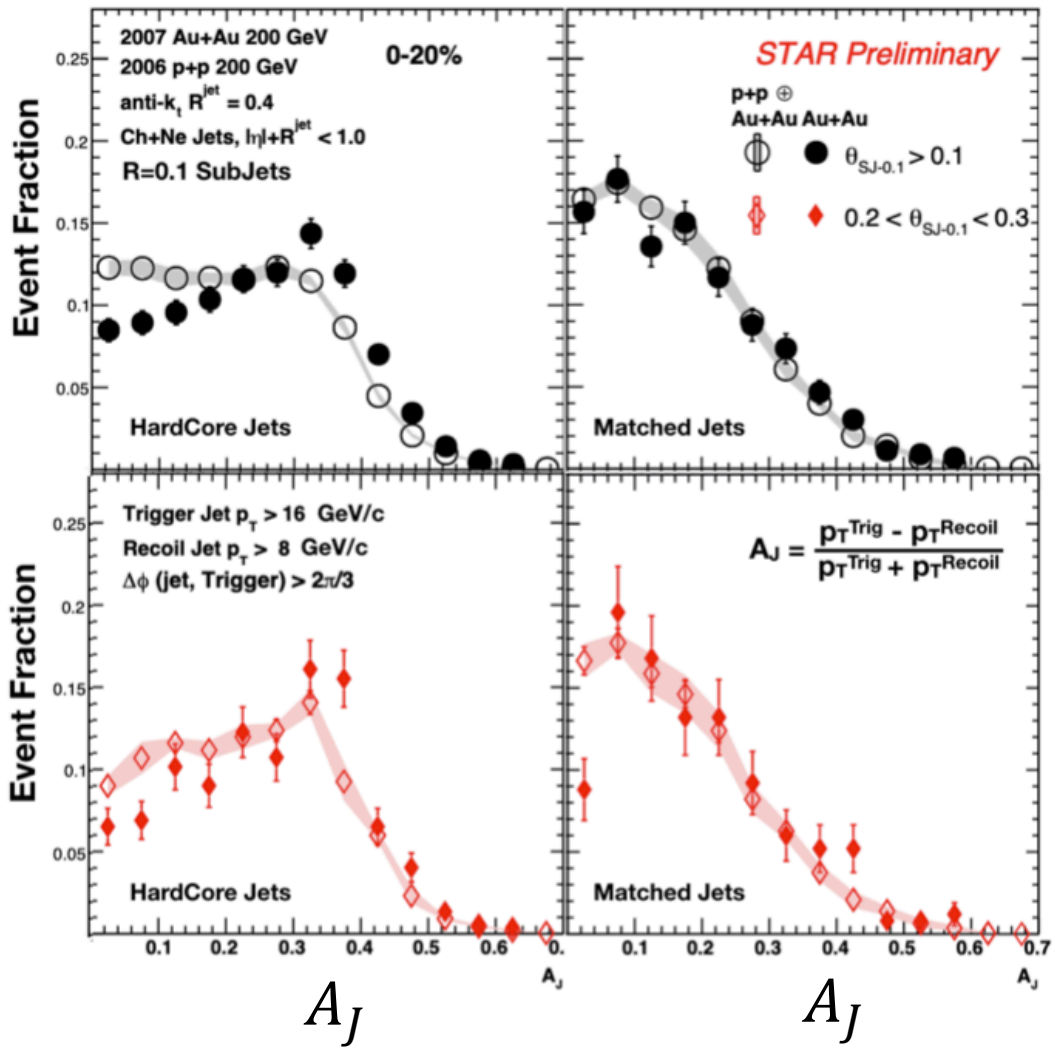


Jet Angular Scale Dependent A_J

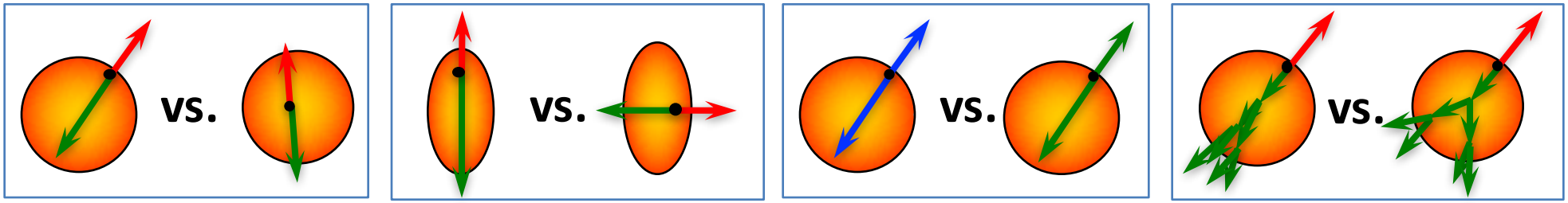
$\theta_{SJ} = \Delta R$(LeadingSJ axis, SubleadingSJ axis)



- A_J measurements for hard-core and matched jets with different θ_{SJ} selections
- No significant difference between different θ_{SJ} selections

Summary

- Various jet measurements are on-going in STAR

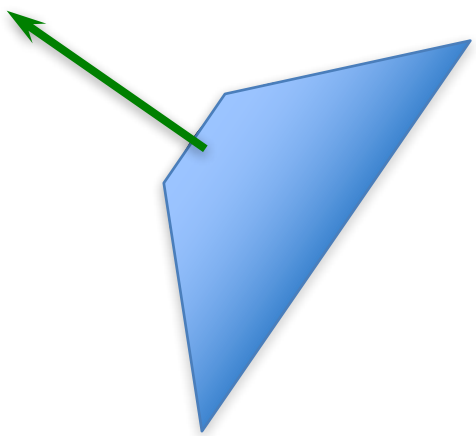


- Di-jet imbalance for hard-core di-jets
  - ✓ Balance recovered with soft particles within $\mathrm{R} = 0.4$
  - ✓ More differential measurements (Centrality, jet reconstruction parameter)
- Event-plane dependent measurements
  - ✓ Indication of jet-medium interaction + path-length dependence
  - ✓ On-going efforts for comprehensive understanding
- Semi-inclusive measurements (h+jet, γ+jet) and D^0-hadron measurements
  - ✓ Model comparisons needed
- Jet angular scale dependent A_J - No significant dependence

Backup

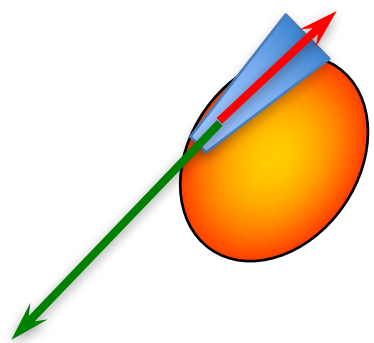
Jet Geometry Egineering at RHIC

- Steeply falling p_T spectrum at RHIC – good correlation between jet and parton energies

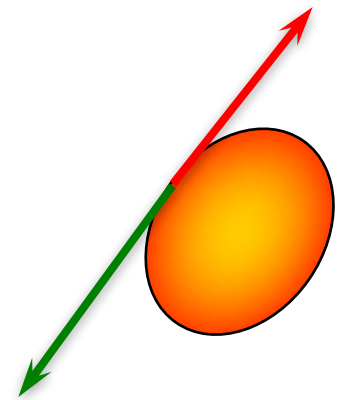


Leading trigger

- ✓ Jet+hadron correlation
- ✓ h+jet spectra



Di-jet imbalance



2+1 correlations

- Surface bias from trigger selection, particuarly at RHIC energies, enables to use jet definition (R, constituent p_T cut, …) to select jet production vertex and di-jet origentation

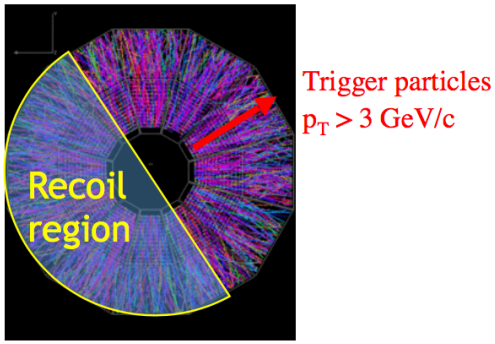
Event-plane Dependent Di-hadron Correlations – Recoil Width

- Event selection with high recoil momentum within $0.5 < \eta < 1.0$

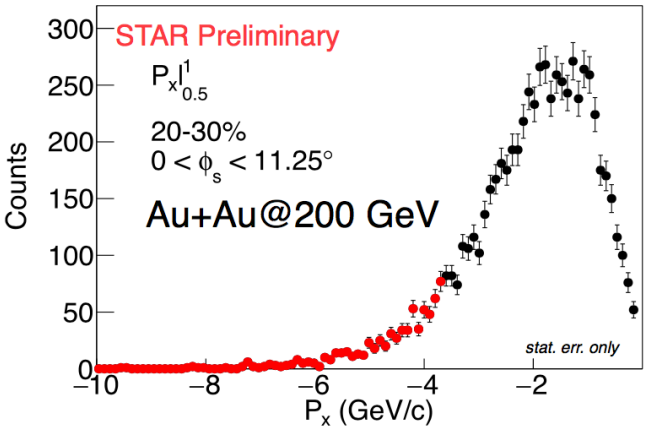
P_x : projection of away-side p_T onto trigger axis

$$P_x|_{\eta_1}^{\eta_2} = \sum_{\eta_1<\eta_a<\eta_2, |\phi_a-\phi_{trig}|>\frac{\pi}{2}} p_T^a \cos(\phi_a - \phi_{trig}) \frac{1}{\epsilon}$$

ϵ:single-particle acceptance efficiency



For each centrality,
cut on 10% left tail of P_x distribution to enhance away-side jet population in (η_1, η_2) acceptance

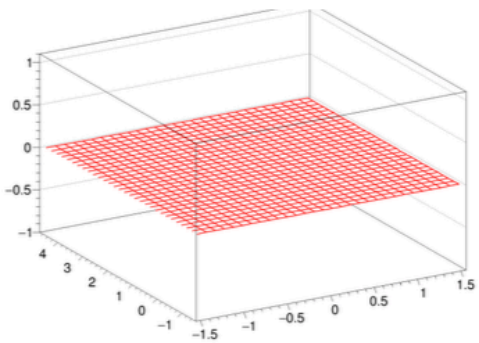


D^0-hadron Correlations

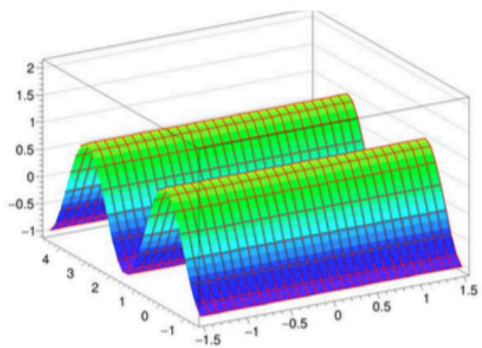
- Two-particle correlation functions are fitted with a model with 8 parameters

- $A_0 + 2A_Q\{2D\}Cos(2\Delta\varphi) + A_{NS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{NS,\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{NS,\Delta\varphi}}} + A_{AS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{AS,\Delta\eta}}} * e^{-\frac{1}{2}\frac{(\Delta\varphi-\pi)^2}{\sigma^2_{AS,\Delta\varphi}}} + periodicity\ for\ \Delta\varphi\ Gaussian$

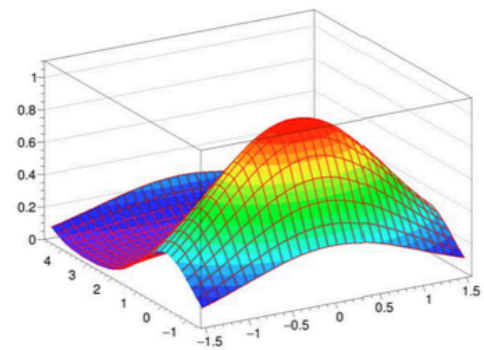
Constant-offset



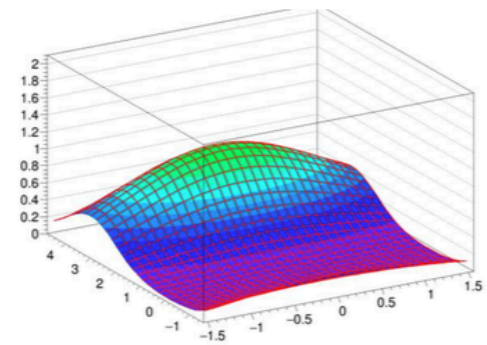
Quadrupole



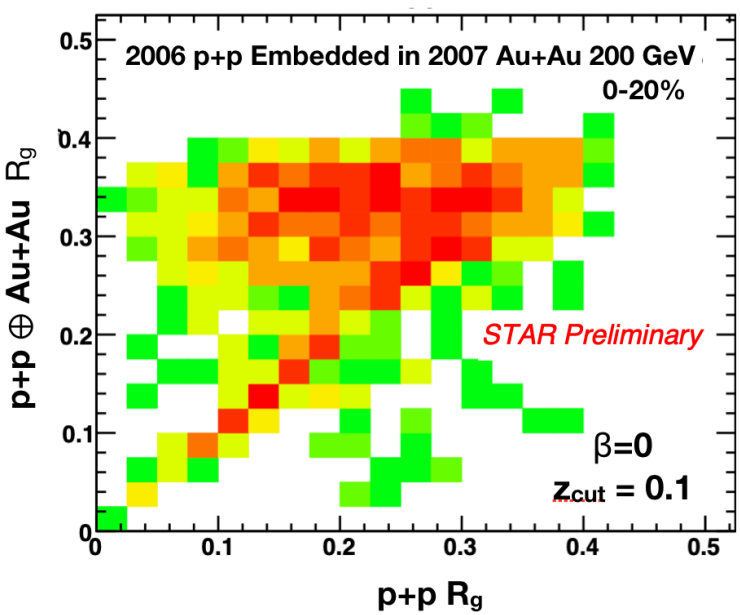
Near-Side 2D Gaussian



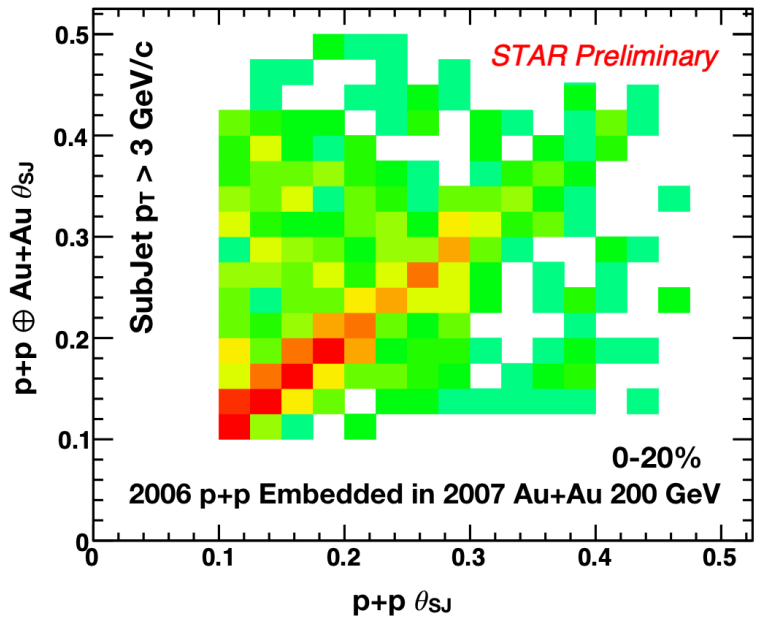
Away-Side 2D Gaussian



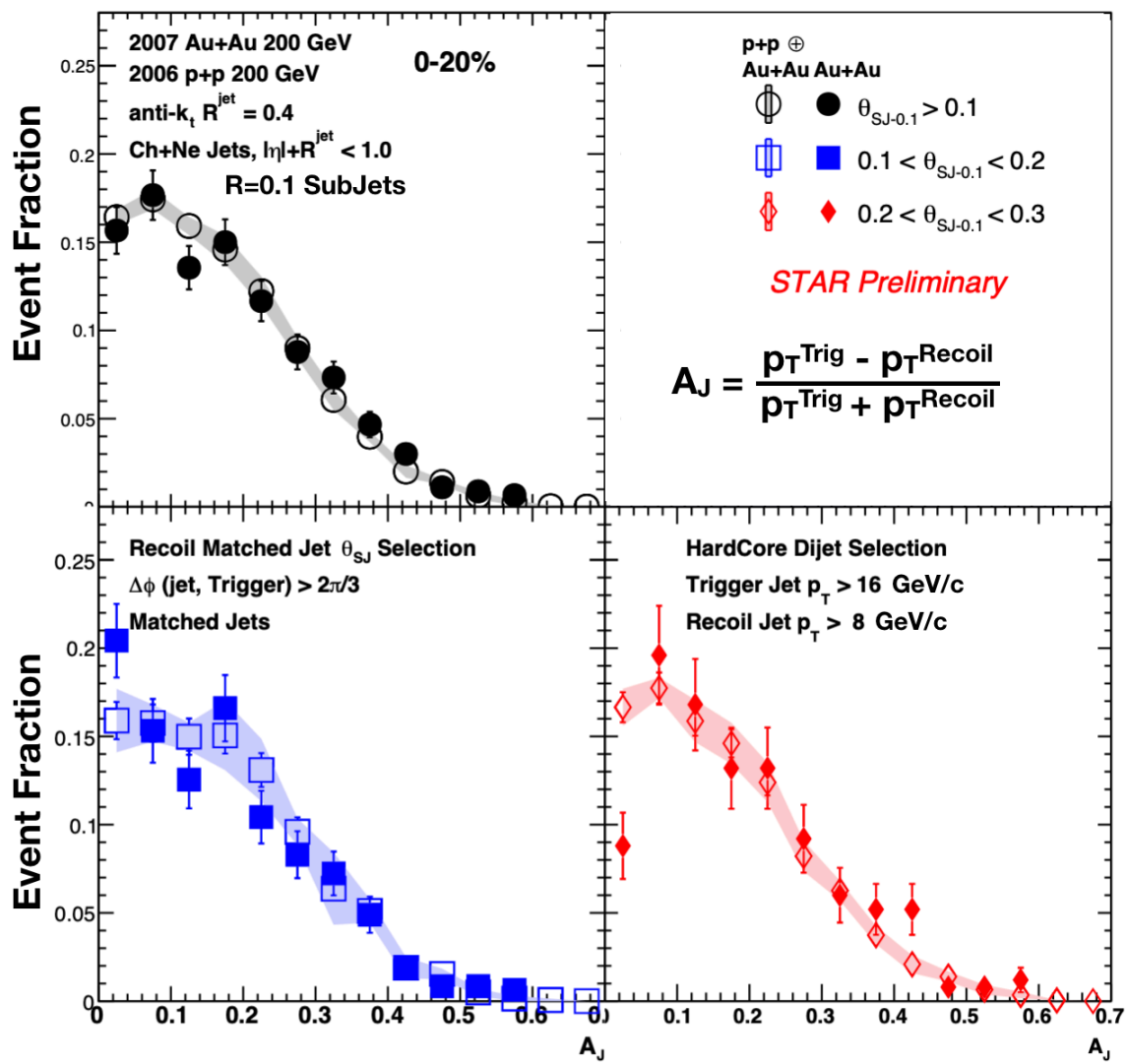
SoftDrop R_g vs. θ_{SJ}



SoftDrop R_g



θ_{SJ}

- SoftDrop R_g is more sensitive to background fluctuations

Jet Angular Scale Dependence