

Jet Geometry Engineering and systematic di-jet imbalance measurements at STAR

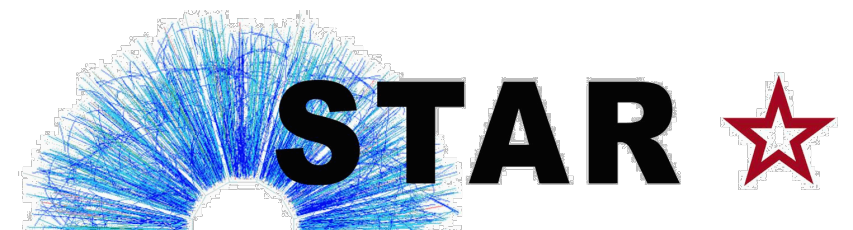
Nick Elsey for the STAR Collaboration
Wayne State University

13th International Workshop on High- p_T Physics in the RHIC/LHC era
Knoxville TN, March 2019



U.S. DEPARTMENT OF
ENERGY

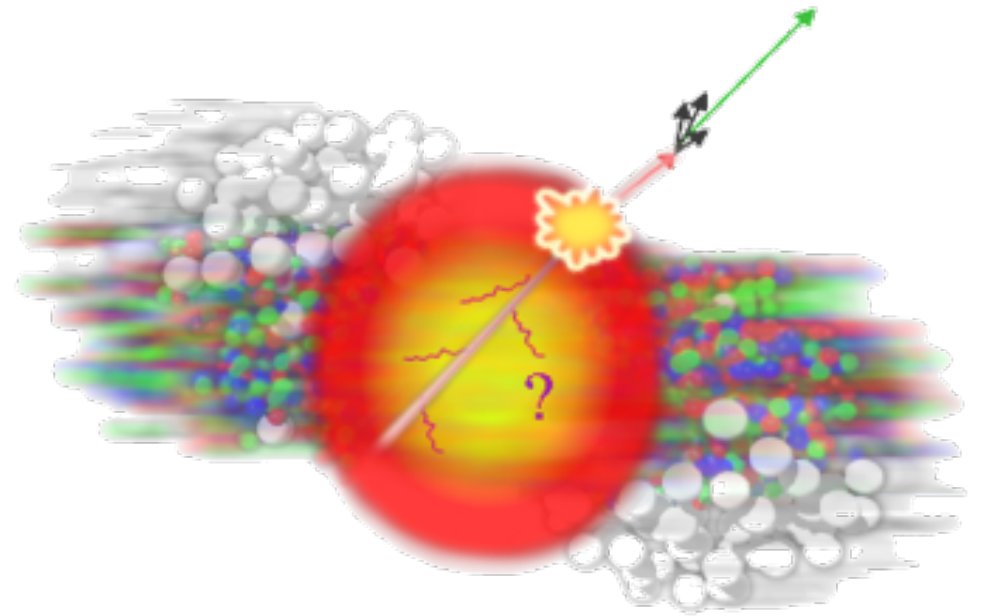
Office of
Science



Jet quenching in a nutshell

partonic energy loss

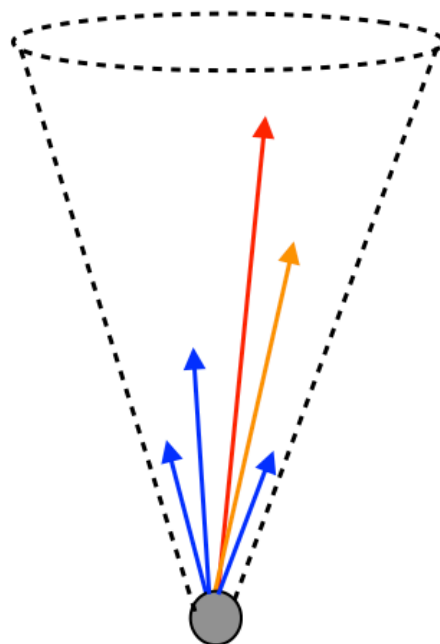
- gluon radiation (**primary**)
- collisional energy loss (small)



→ broadening and softening

Jet in vacuum

$$E_{\text{Vacuum}}^{\text{Jet}}$$

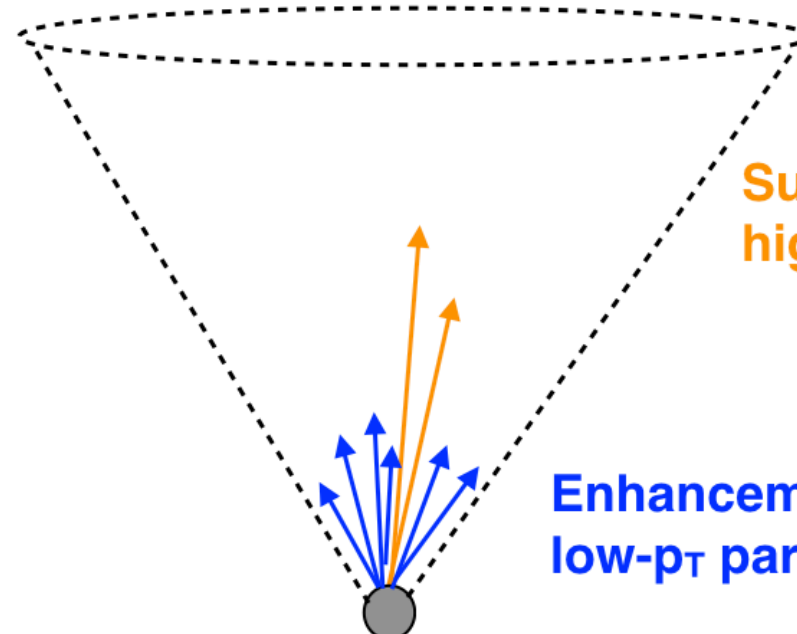


Jet quenching/
gluon radiation

Jet in medium

$$E_{\text{Medium}}^{\text{Jet}} = E_{\text{Vacuum}}^{\text{Jet}}$$

Jet broadening



Suppression of
high- p_T particles

Enhancement of
low- p_T particles

Jet production at RHIC & LHC

orders of magnitude difference
in jet production cross section

trigger: high- p_T hadron,
jet w/ constituent cut, etc

models (Renk, Zapp,...)

predict that with the

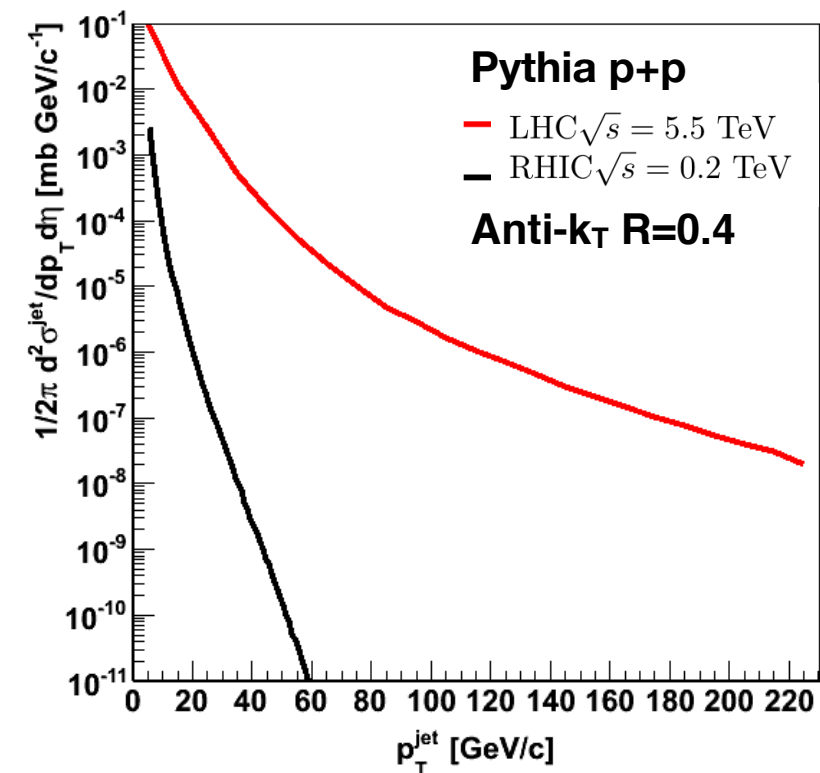
softer **RHIC** spectrum

trigger → surface bias

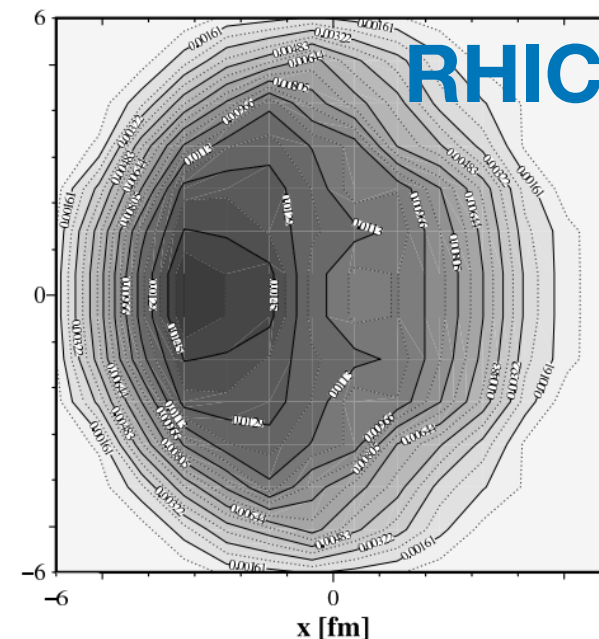
however, at the higher

LHC energies,

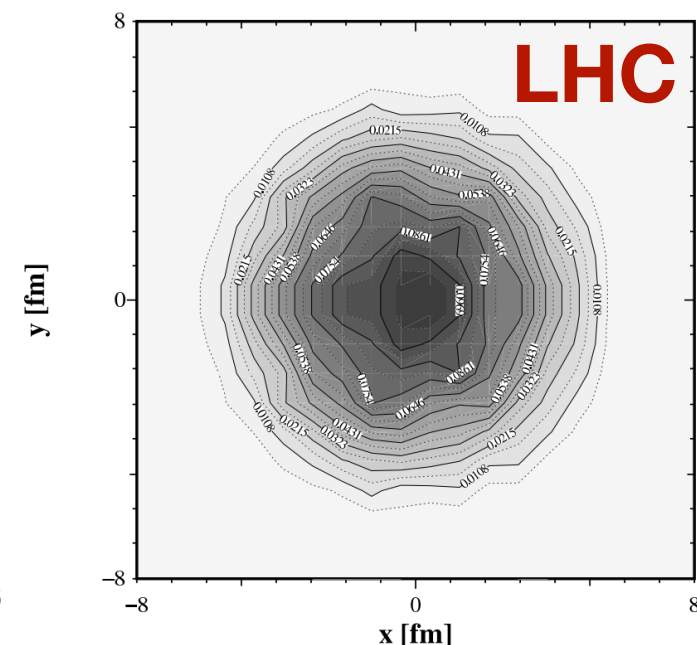
trigger → no surface bias



high p_T hadron trigger



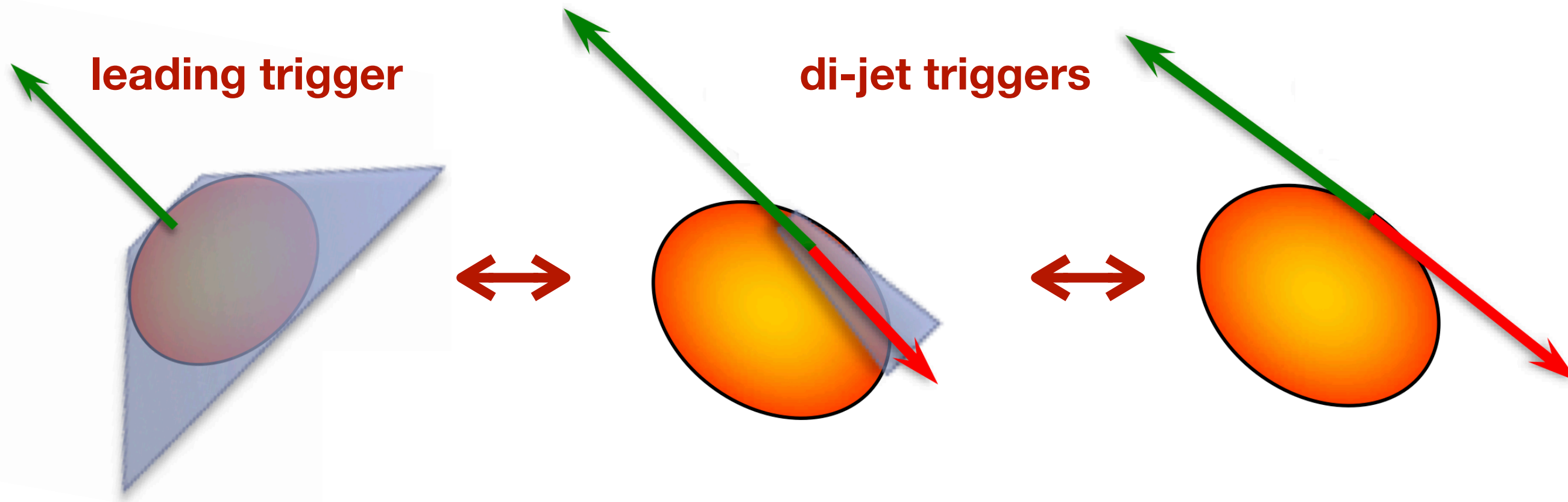
Renk, Phys.Rev. C 87, 024905 (2013)



Renk, Phys. Rev. C 85, 064908 (2012)

Jet trigger bias

this bias can be helpful - opportunity to use jet definition (R , p_T^{const}) to select jet production vertex and di-jet orientation -
jet geometry engineering



**jet+hadron correlations,
hadron+jet spectra**

STAR, PRL 112, 122301 (2014)

STAR, PRC 96, 024905 (2017)

**di-jet imbalance,
di-jet hadron correlations**

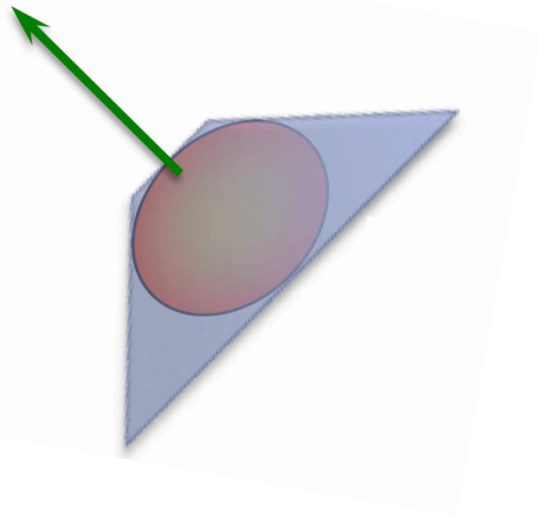
STAR, Phys. Rev. Lett. 119, 062301 (2017)

2+1 correlations

STAR, PRC 83 061901 (2011)

STAR, PRC 87 44903 (2013)

Outline

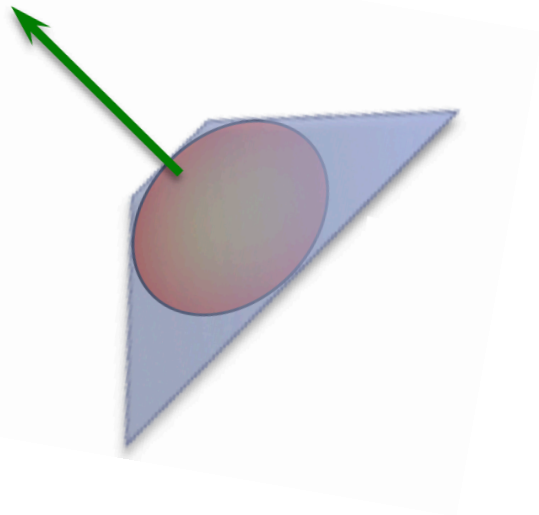


jet-like triggers

jet-hadron correlations

hadron-jet spectra

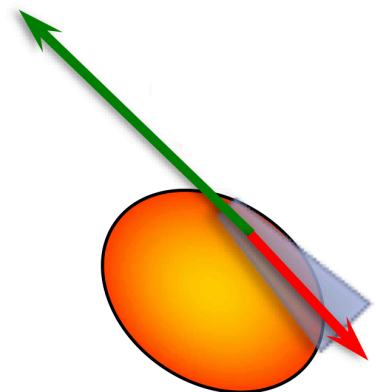
Outline



jet-like triggers

jet-hadron correlations

hadron-jet spectra

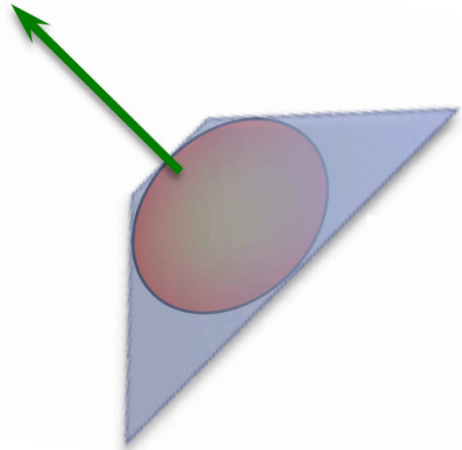


di-jet triggers

di-jet imbalance

di-jet hadron correlations

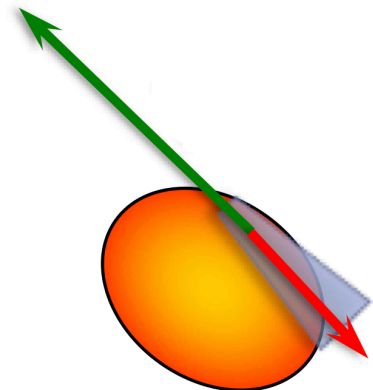
Outline



jet-like triggers

jet-hadron correlations

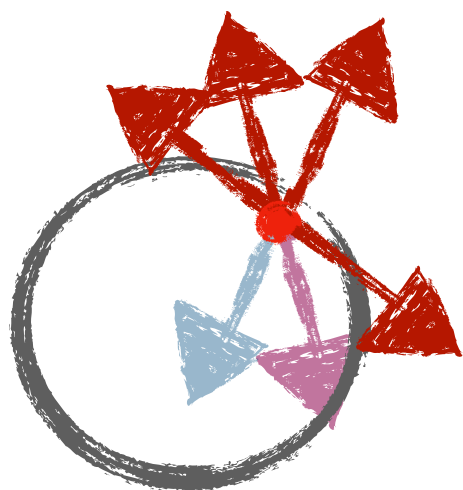
hadron-jet spectra



di-jet triggers

di-jet imbalance

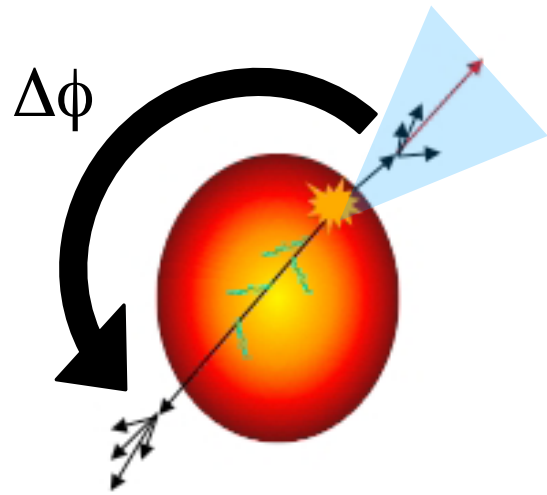
di-jet hadron correlations



jet geometry engineering

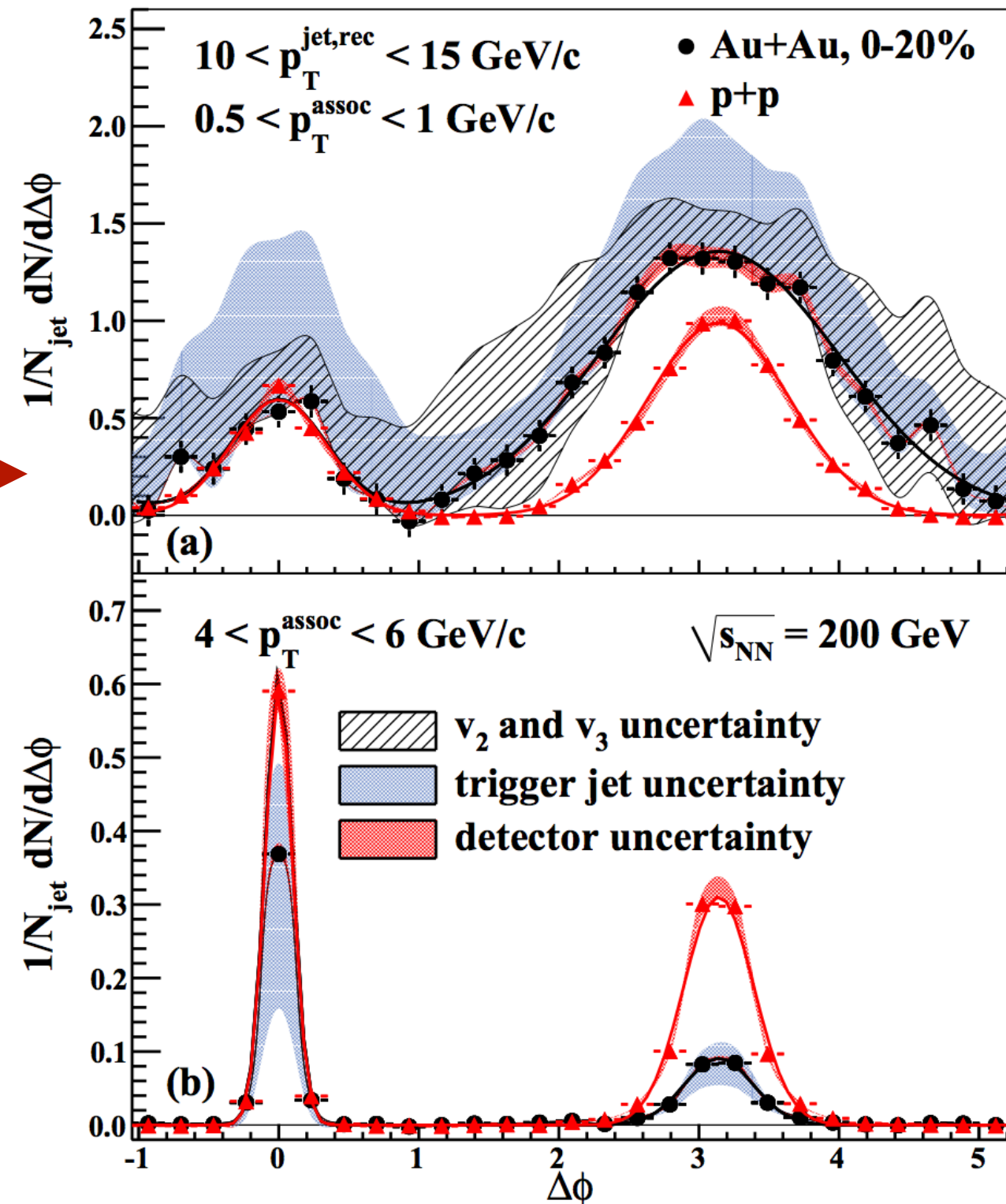
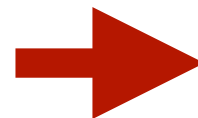
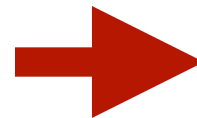
differential di-jet imbalance

Jet+hadron correlations



enhancement of recoil jet
low- p_T constituents,
broadening

suppression of recoil jet
high- p_T constituents



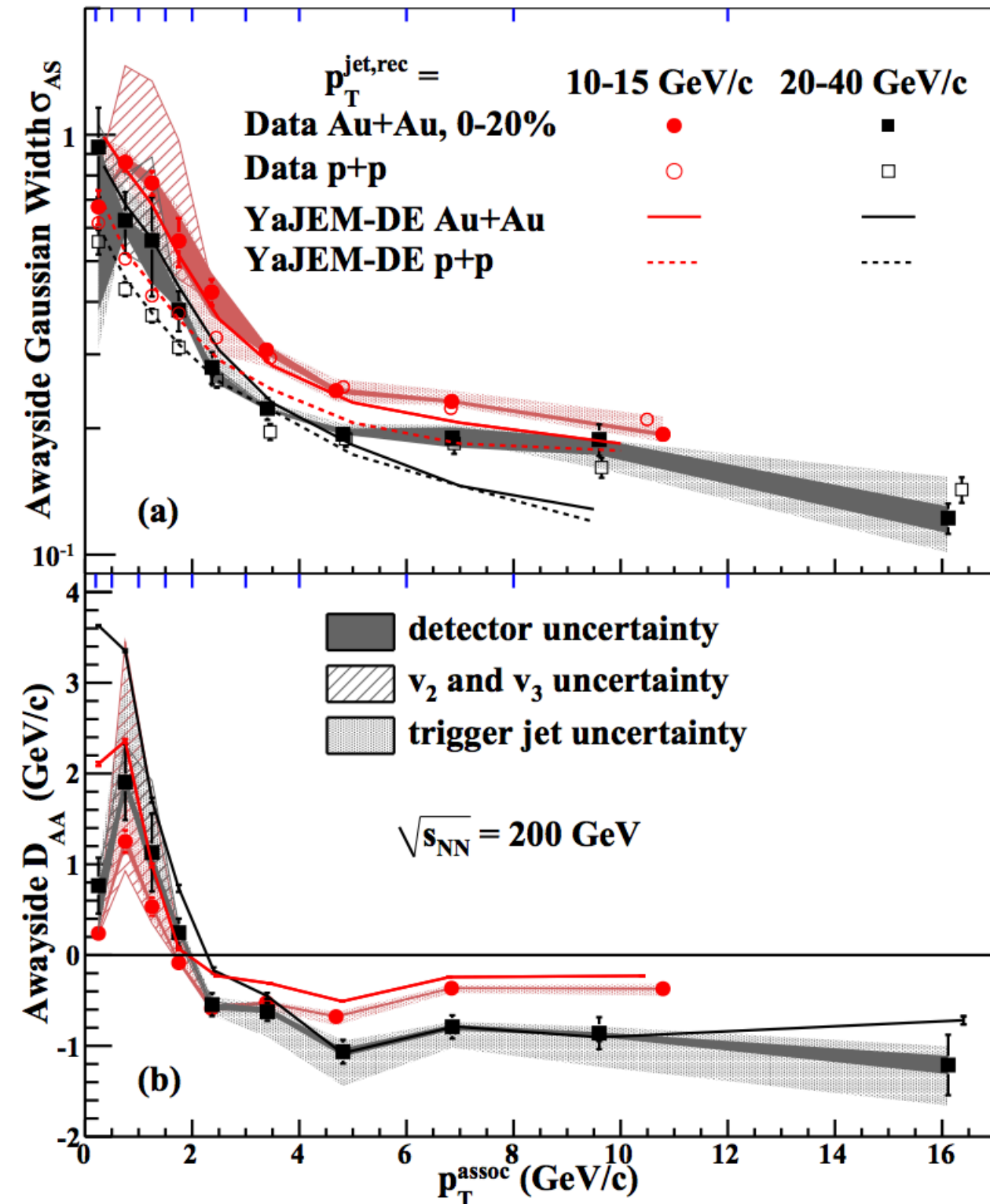
STAR, PRL 112, 122301 (2014)

Jet+hadron correlations

➔ clear signal of **softening** and **broadening** in recoil jet

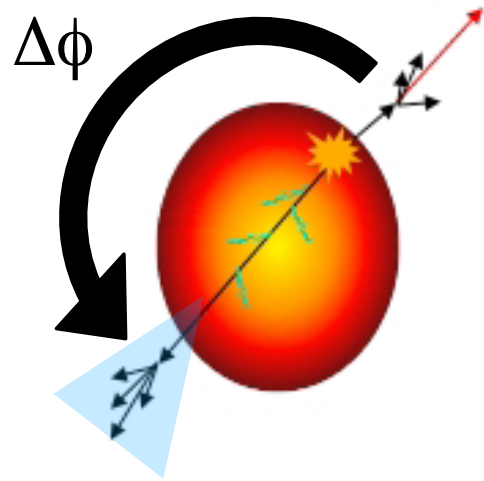
➔ “energy loss” in high- p_T region balanced by low- p_T excess

$$D_{AA}(p_T^{\text{assoc}}) = Y_{AA}(p_T^{\text{assoc}}) \cdot p_{T,AA}^{\text{assoc}} - Y_{PP}(p_T^{\text{assoc}}) \cdot p_{T,PP}^{\text{assoc}}$$



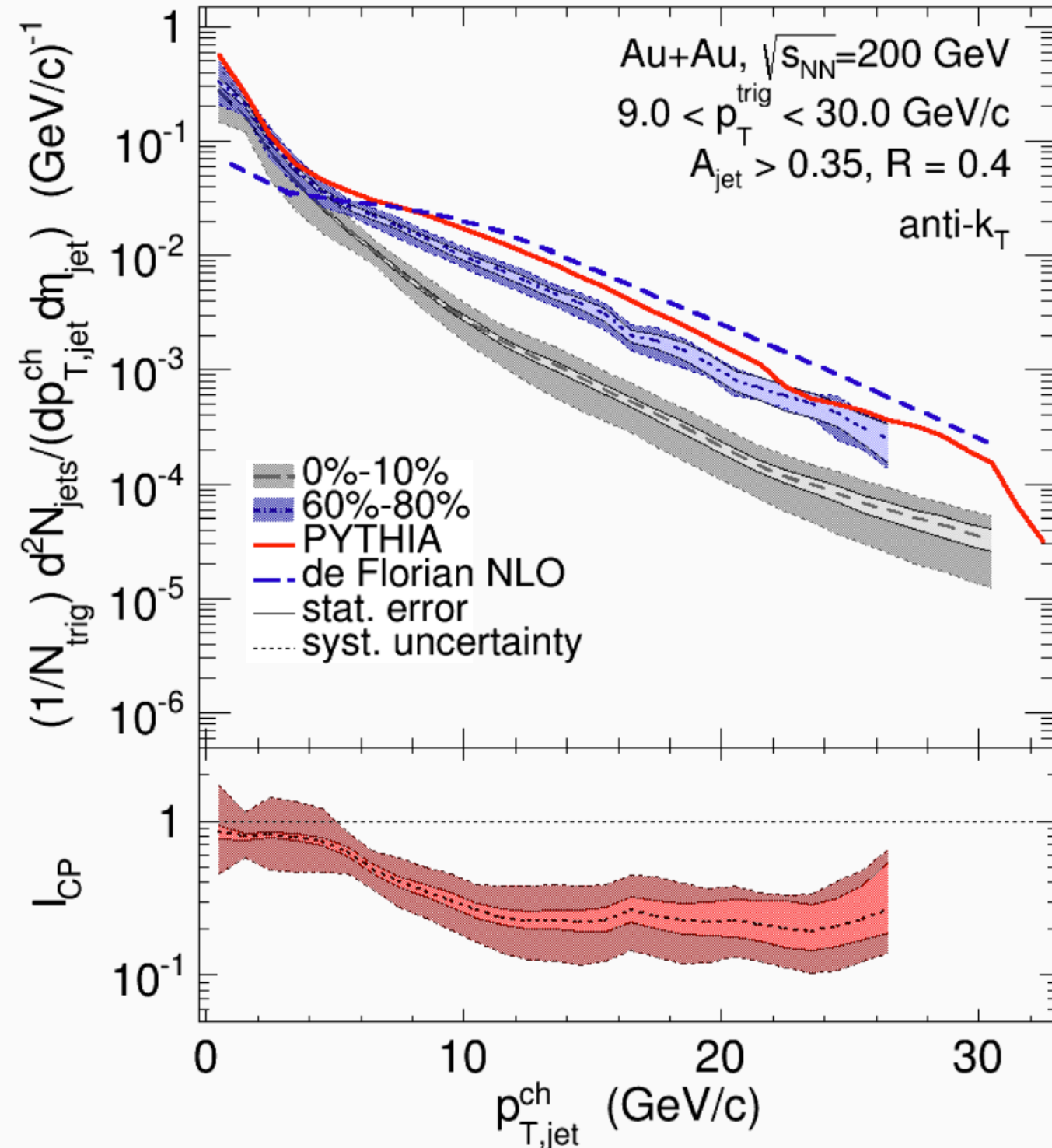
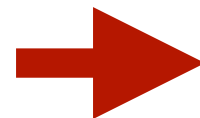
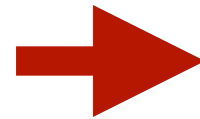
STAR, PRL 112, 122301 (2014)

Hadron+jet spectra



yield of jets recoiling from
high p_T hadron

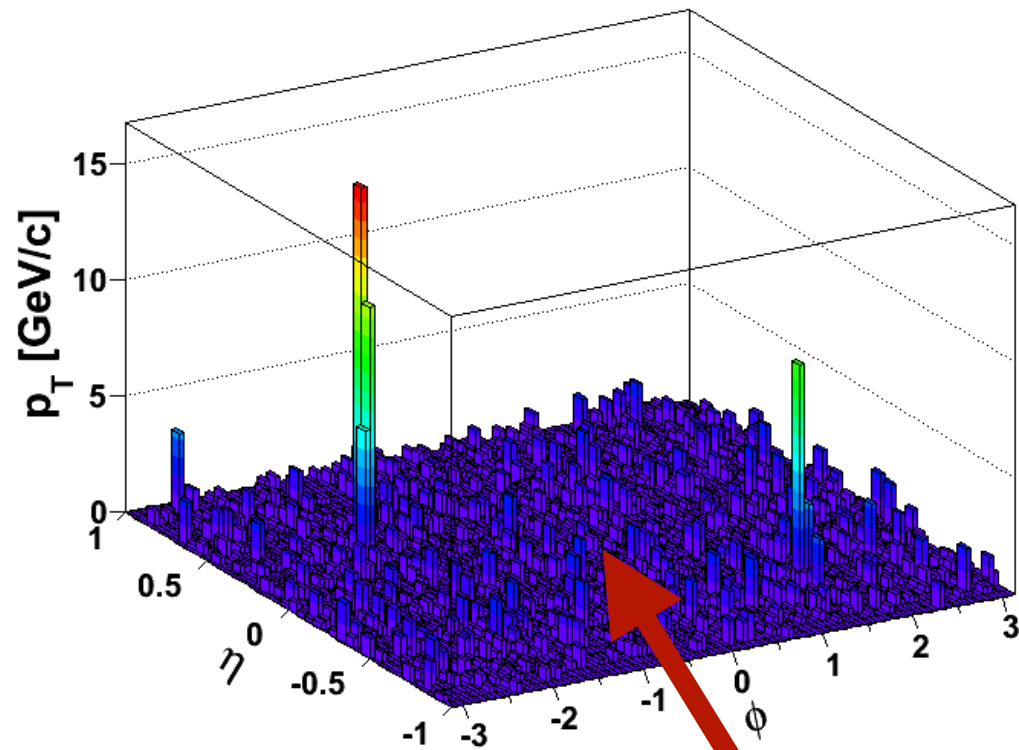
suppression of recoil jet
in central collisions
compared to peripheral



STAR, Phys.Rev. C96, 024905 (2017)

Hard core jets at STAR

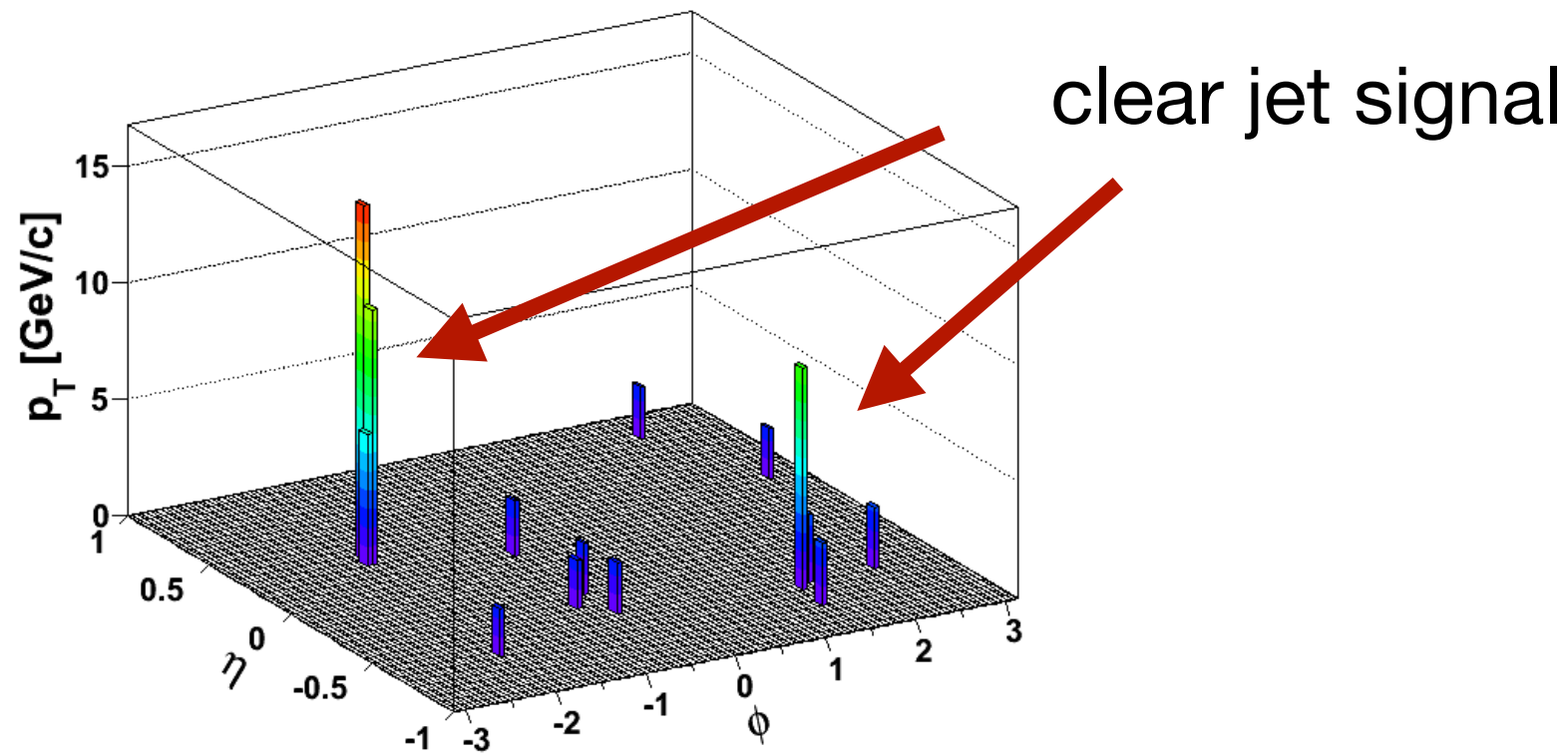
in a heavy-ion collision



large background energy density

Hard core jets at STAR

in a heavy-ion collision

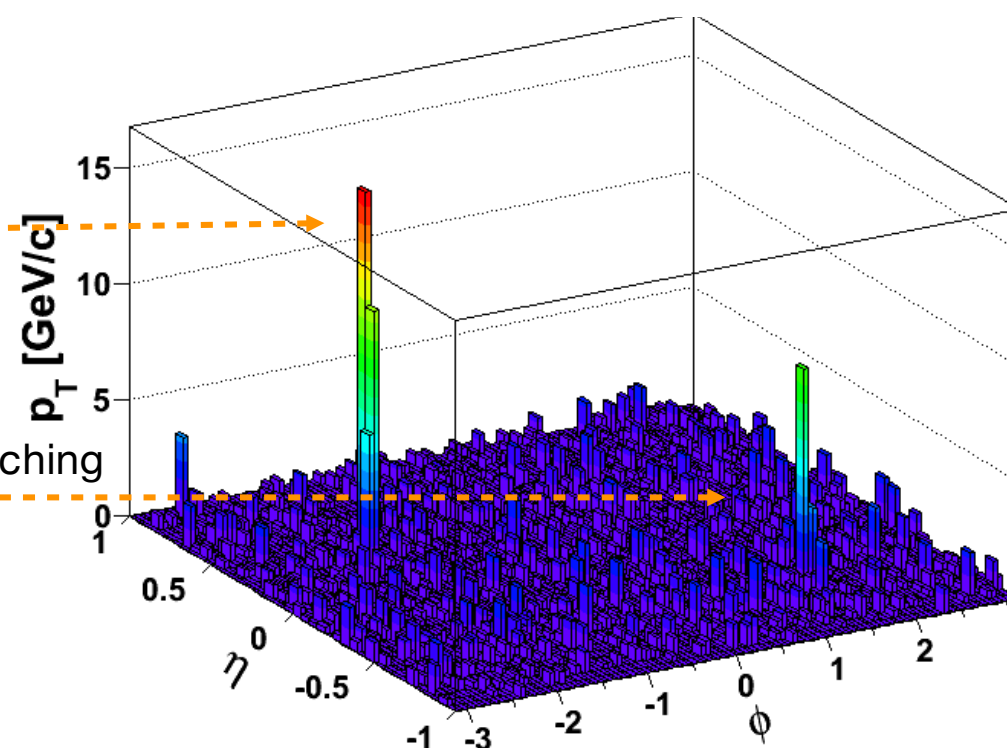
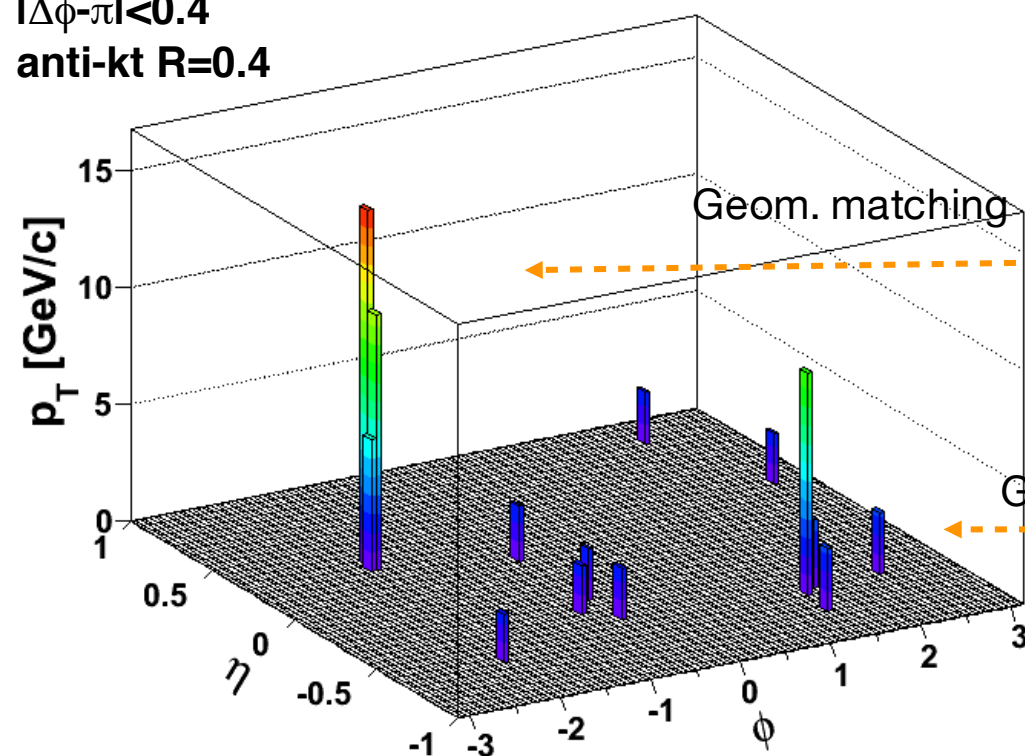


$p_T^{\text{hard const}} > 2 \text{ GeV/c}$ cut $\longrightarrow$ removes almost all background

Hard core jets at STAR

in a heavy-ion collision

$p_{T}^{\text{hard const}} > 2 \text{ GeV}/c$
 $p_{T}^{\text{lead}} > 20 \text{ GeV}/c$
 $p_{T}^{\text{subLead}} > 10 \text{ GeV}/c$
 $|\Delta\phi - \pi| < 0.4$
anti-kt $R=0.4$



$p_{T}^{\text{hard const}} > 2 \text{ GeV}/c$ cut $\longrightarrow$

removes almost all background

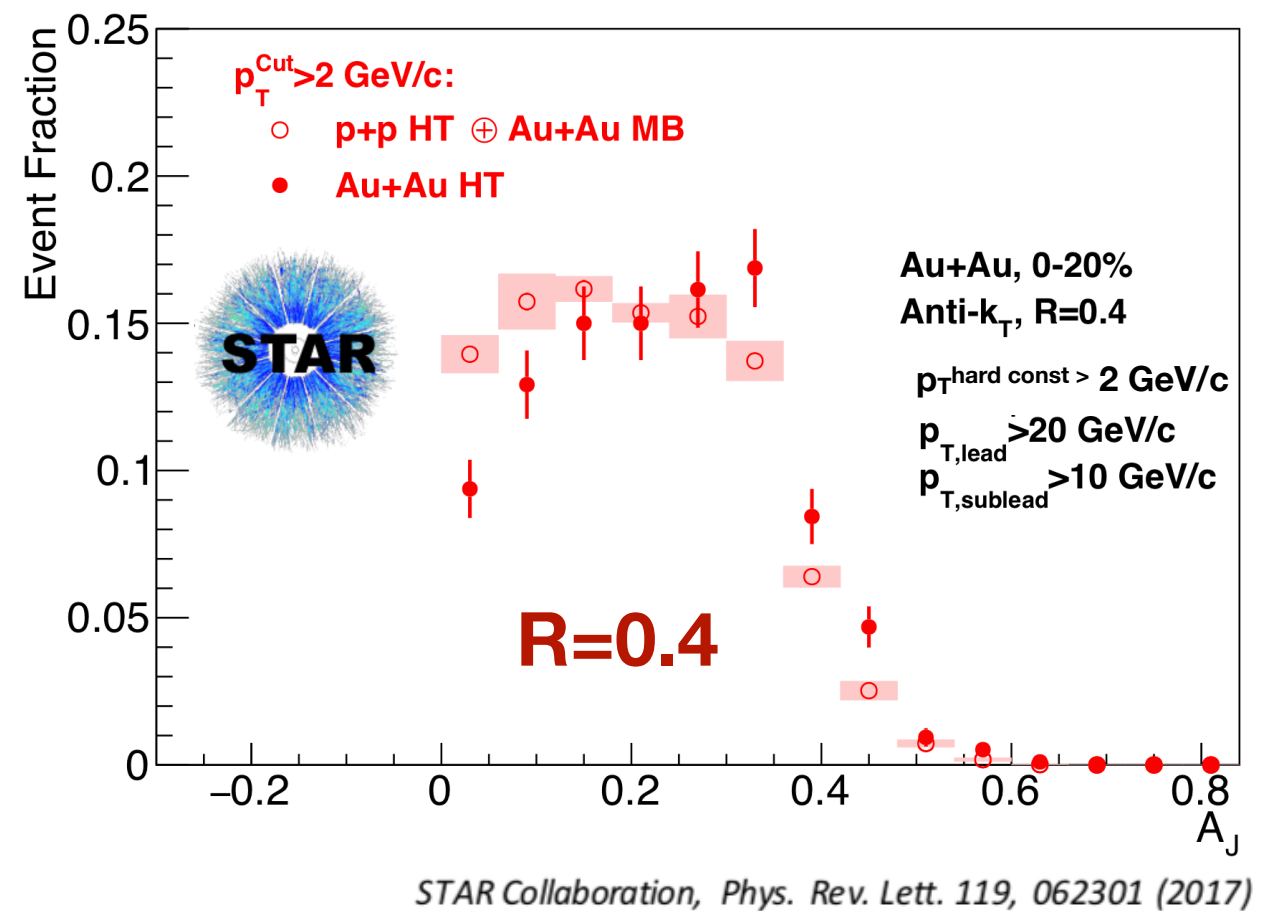
geometric matching
 $p_{T}^{\text{match const}} > 0.2 \text{ GeV}/c$ $\longrightarrow$

no combinatoric jets,
recover all constituents

Di-jet asymmetry at STAR

hard core di-jets more
imbalanced with
respect to p+p

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$

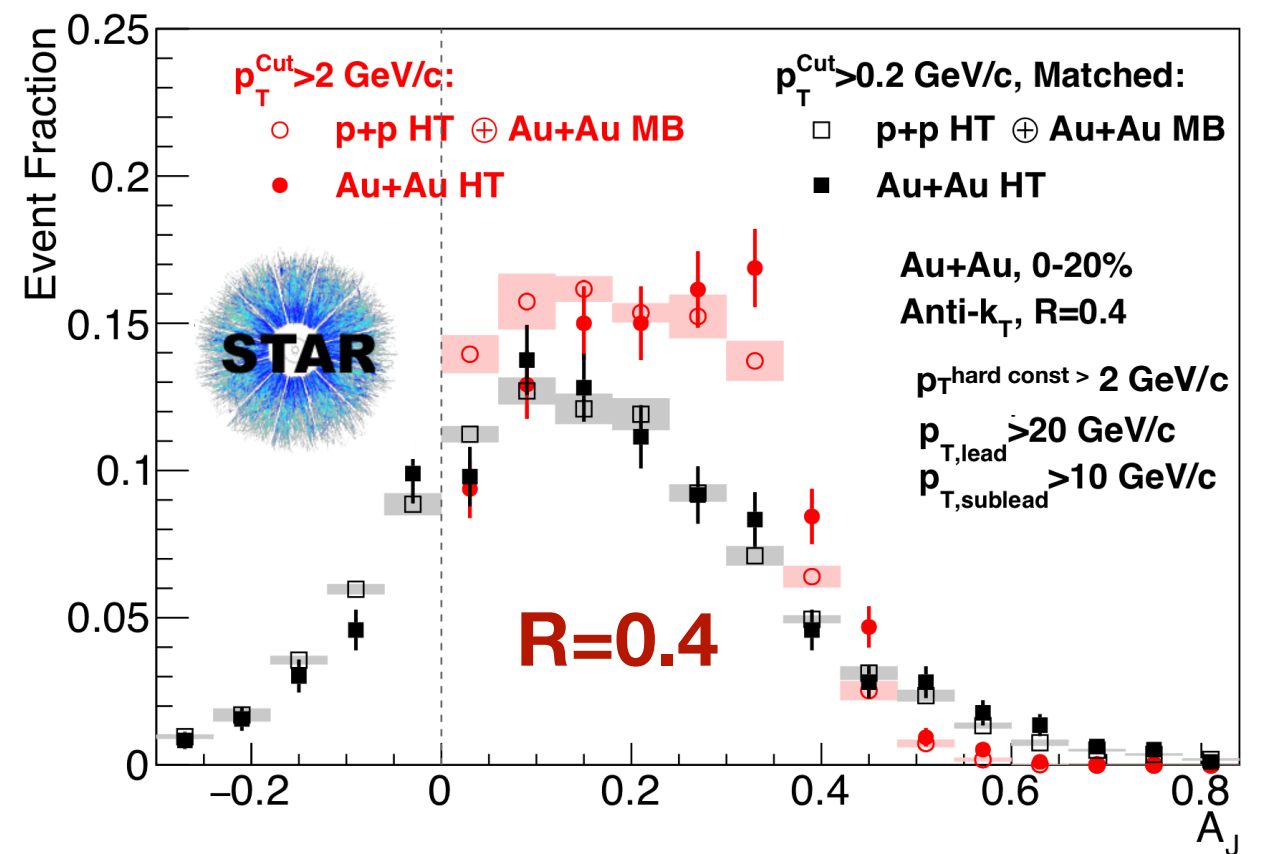


Di-jet asymmetry at STAR

hard core di-jets more
imbalanced with
respect to p+p

when soft constituents
are included:
balance **recovered** to level
of p+p reference with $R=0.4$

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$



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

Di-jet asymmetry at STAR

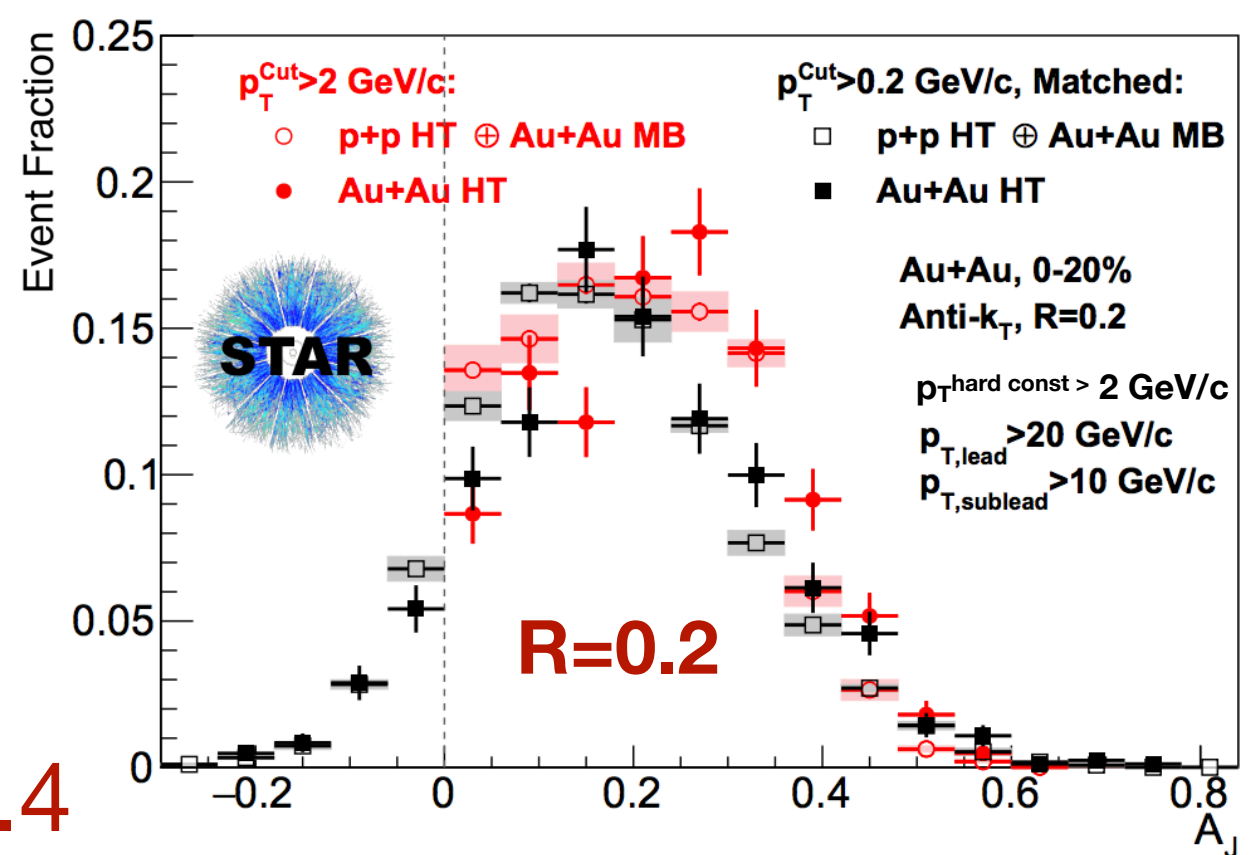
hard core di-jets more imbalanced with respect to p+p

when soft constituents are included:

balance **no longer restored** to the level of p+p in $R=0.2$

broadening of jet from 0.2 to 0.4
softening of jet constituents

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$



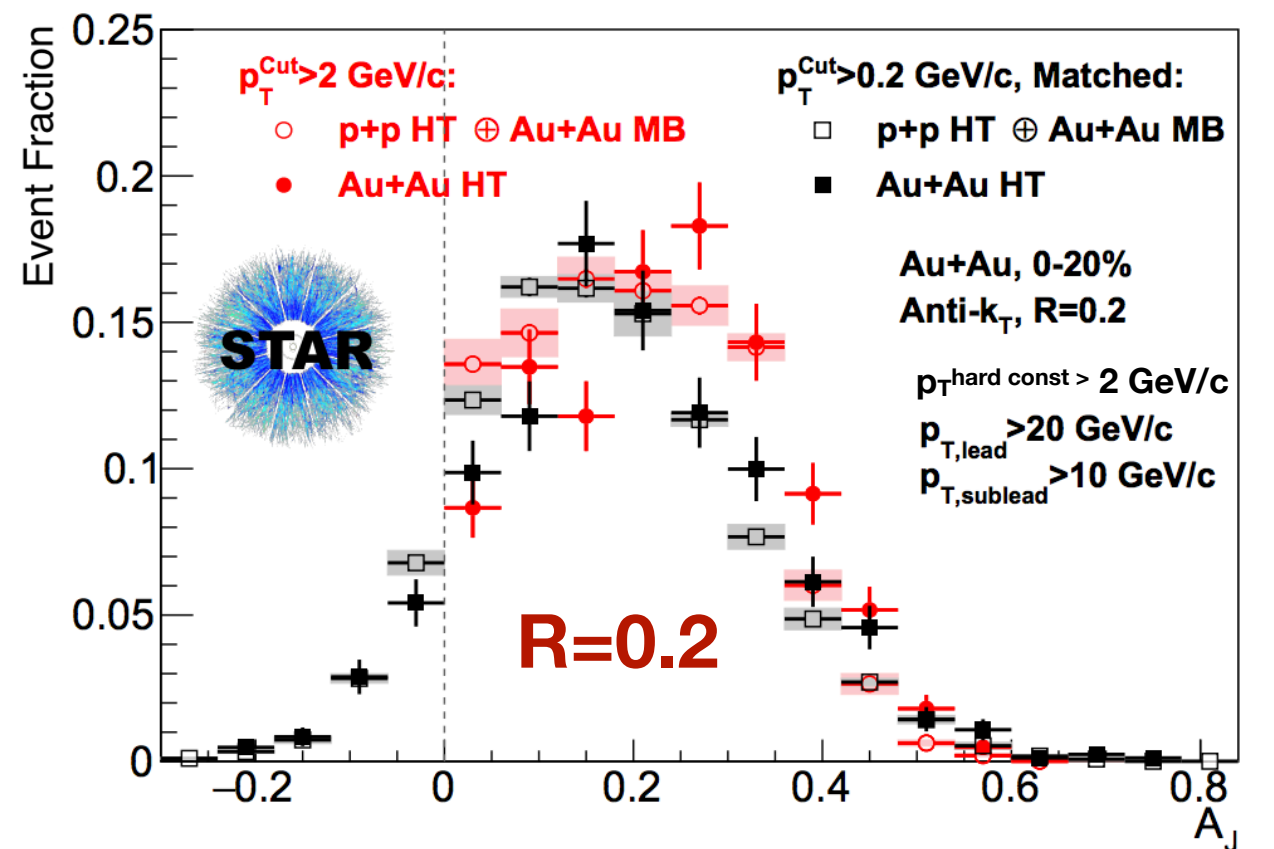
STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Di-jet asymmetry at STAR

A_J is insensitive to the details of which jet is modified

➔ di-jet hadron correlations

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$



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

Di-jet hadron correlations

di-jet definition

$$p_{T}^{\text{hard const}} > 2 \text{ GeV}/c$$

$$p_{T}^{\text{Lead}} > 20 \text{ GeV}/c$$

$$p_{T}^{\text{SubLead}} > 10 \text{ GeV}/c$$

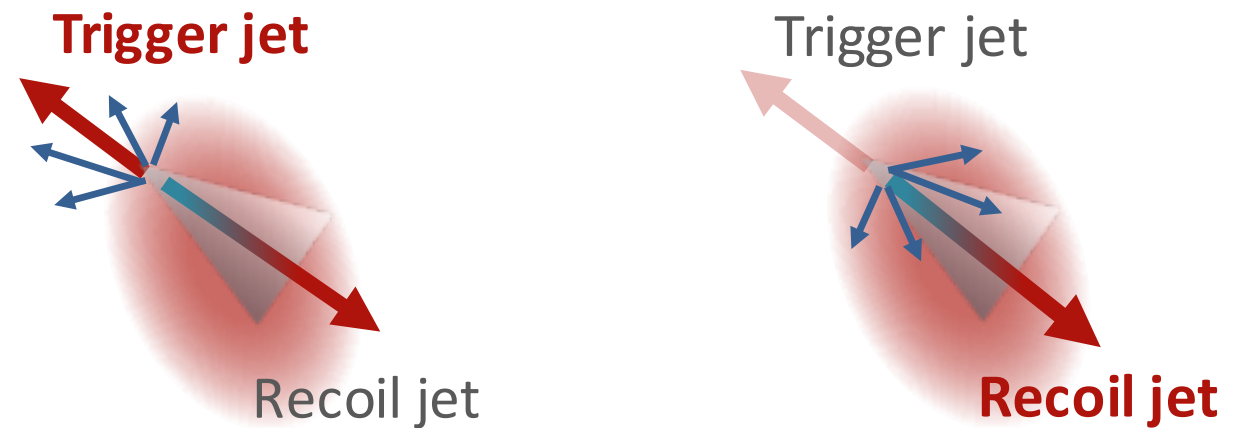
$$|\Delta\phi - \pi| < 0.4$$

$$\text{anti-}k_T \text{ } R = 0.4$$

correlations

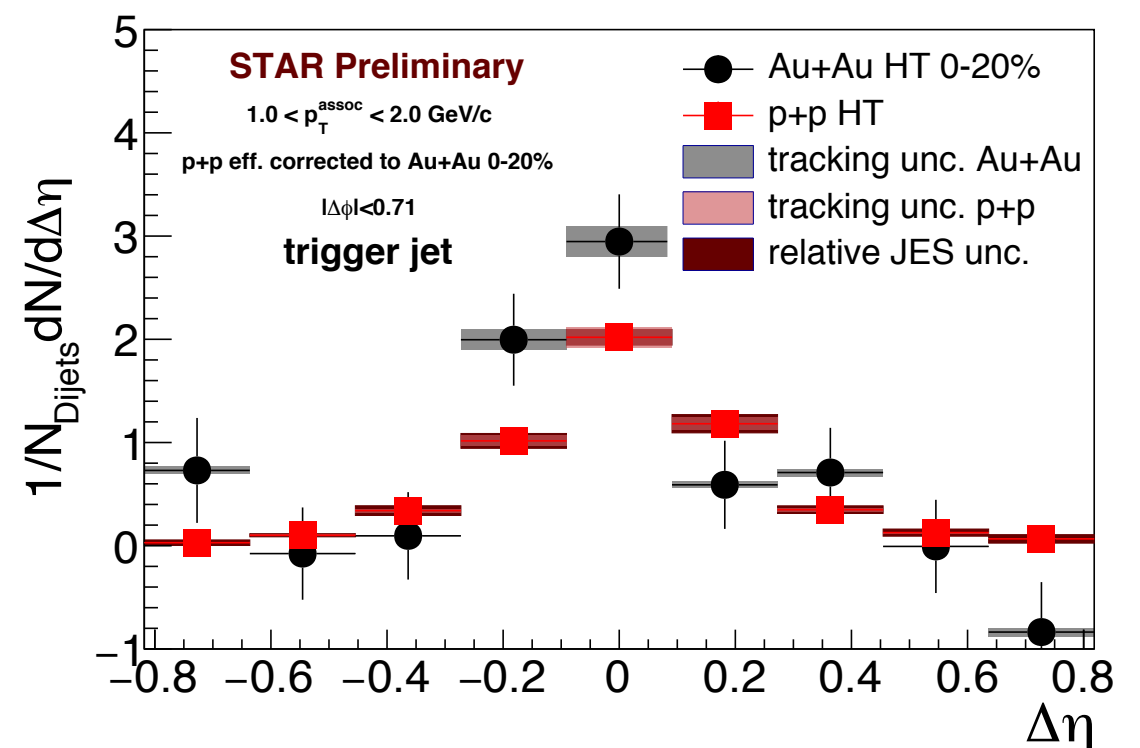
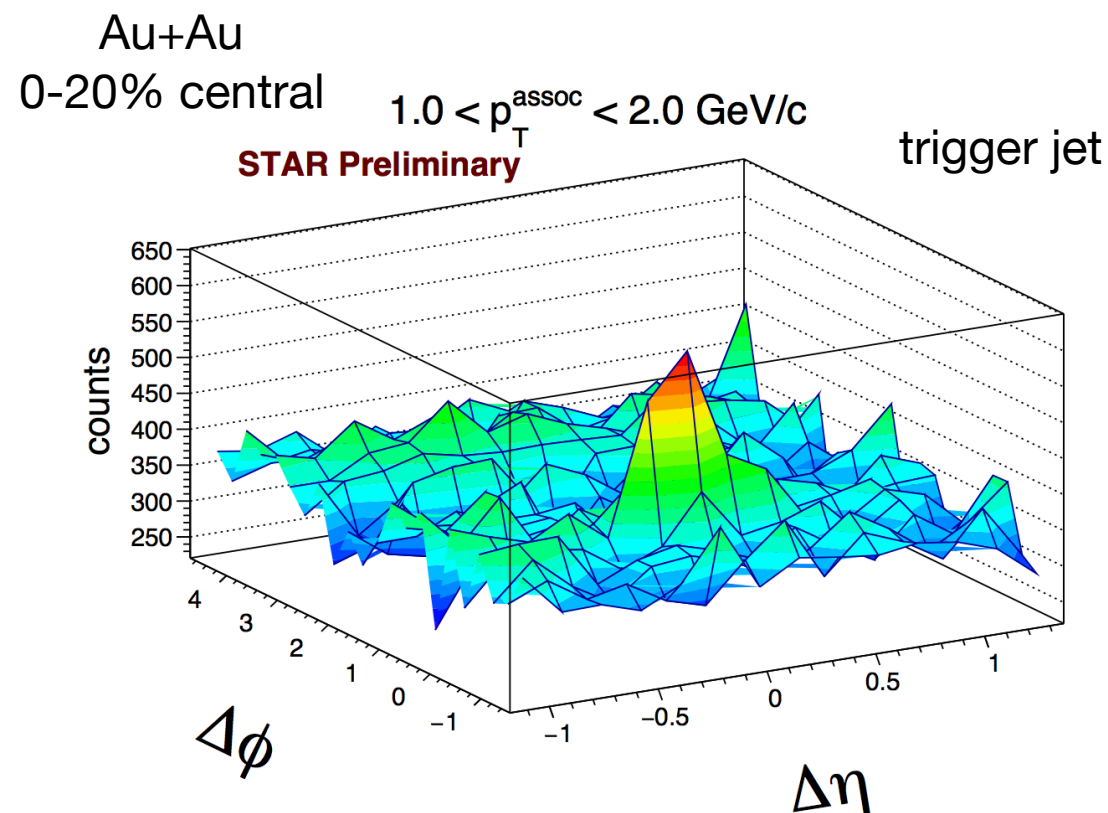
$$\Delta\eta = \eta^{\text{jet}} - \eta^{\text{track}}$$

$$\Delta\phi = \phi^{\text{jet}} - \phi^{\text{track}}$$



trigger jet: require EMCal hit w/ $E_T > 5.4 \text{ GeV}$

recoil jet: back-to-back with trigger jet

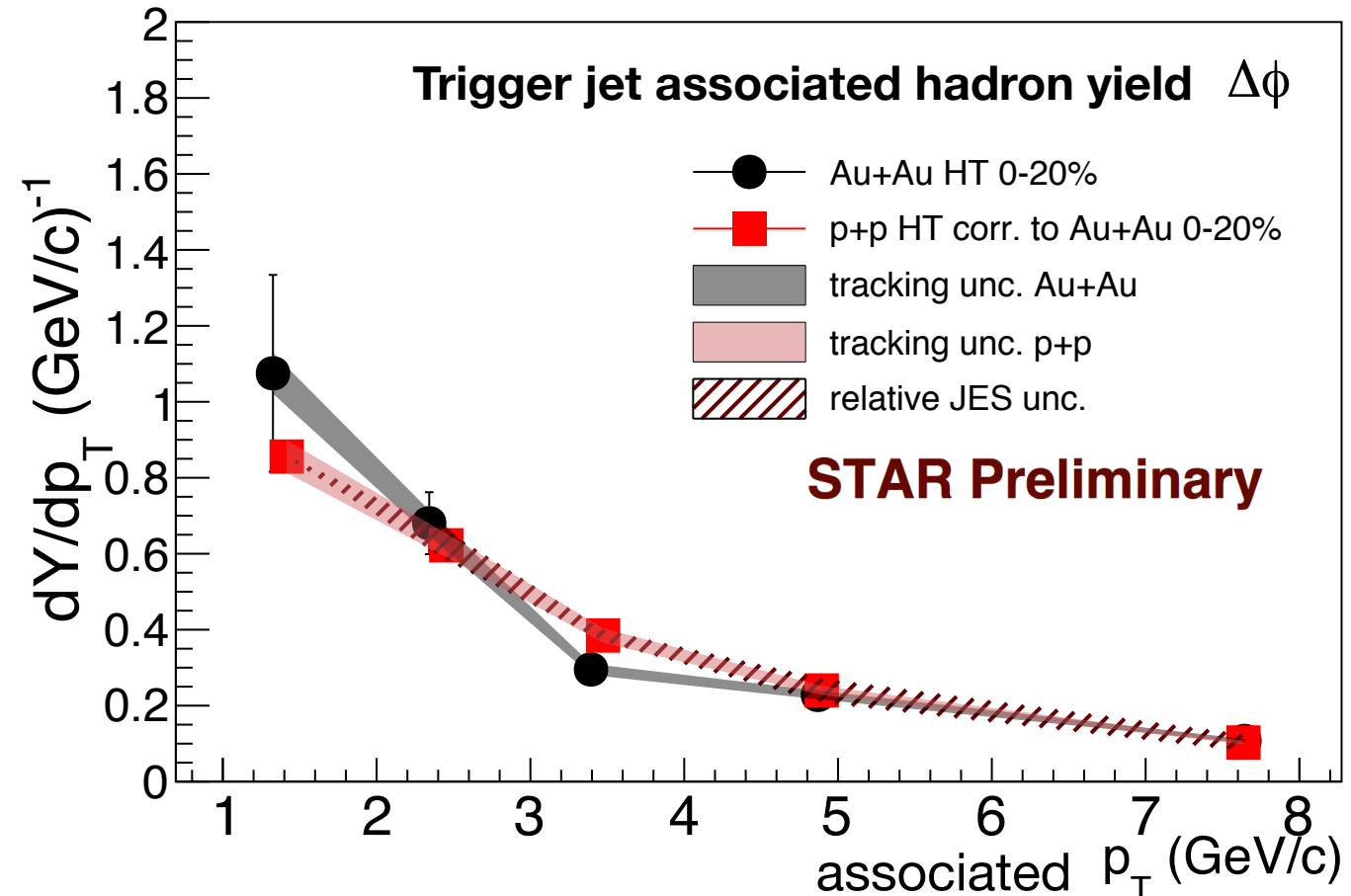
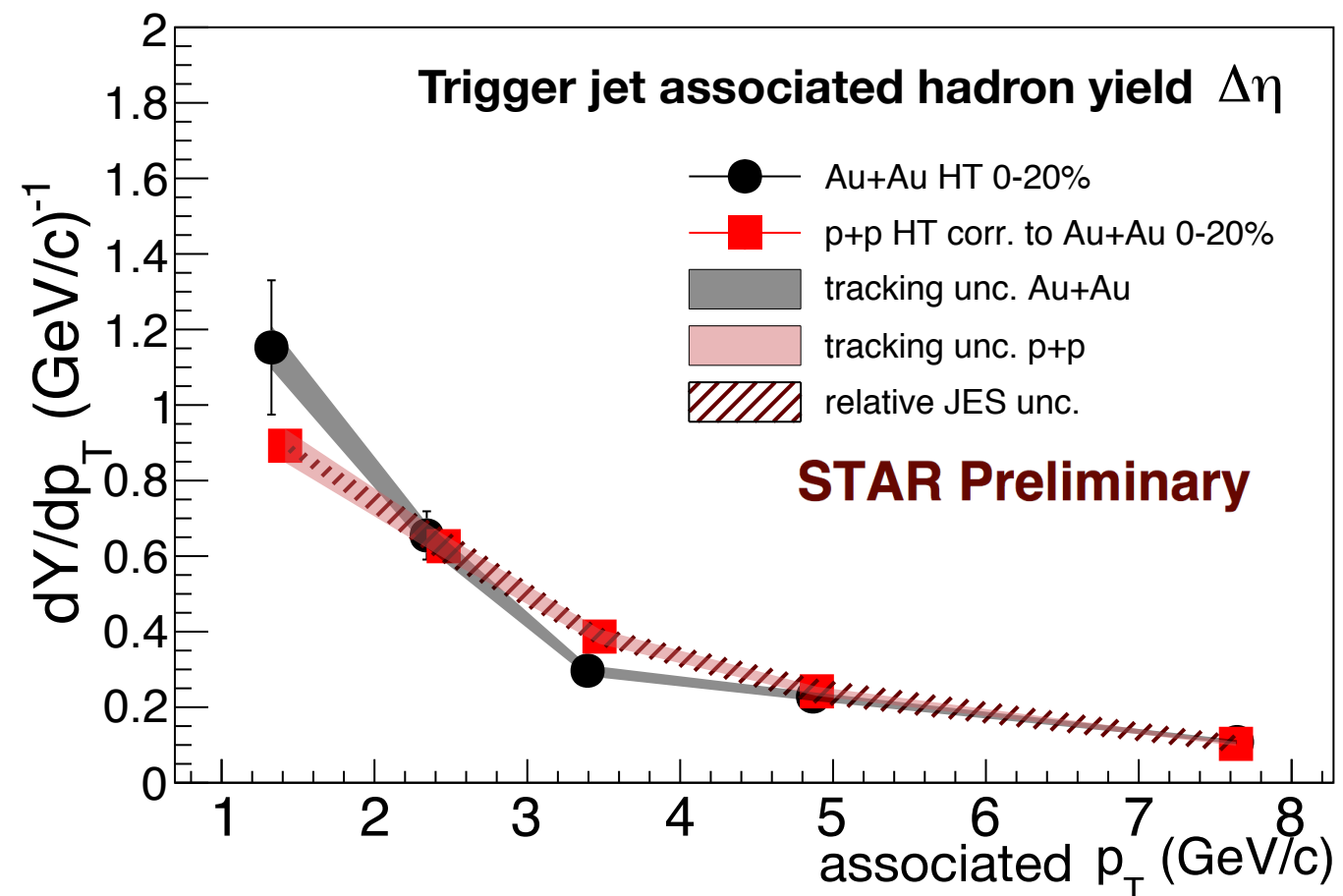


Correlated jet yield

yields consistent between
 $\Delta\phi$ & $\Delta\eta$

→ yield contained within $R=0.4$
for all p_T , consistent with A_J

→ trigger jet: p+p like
"surface bias"



Correlated jet yield

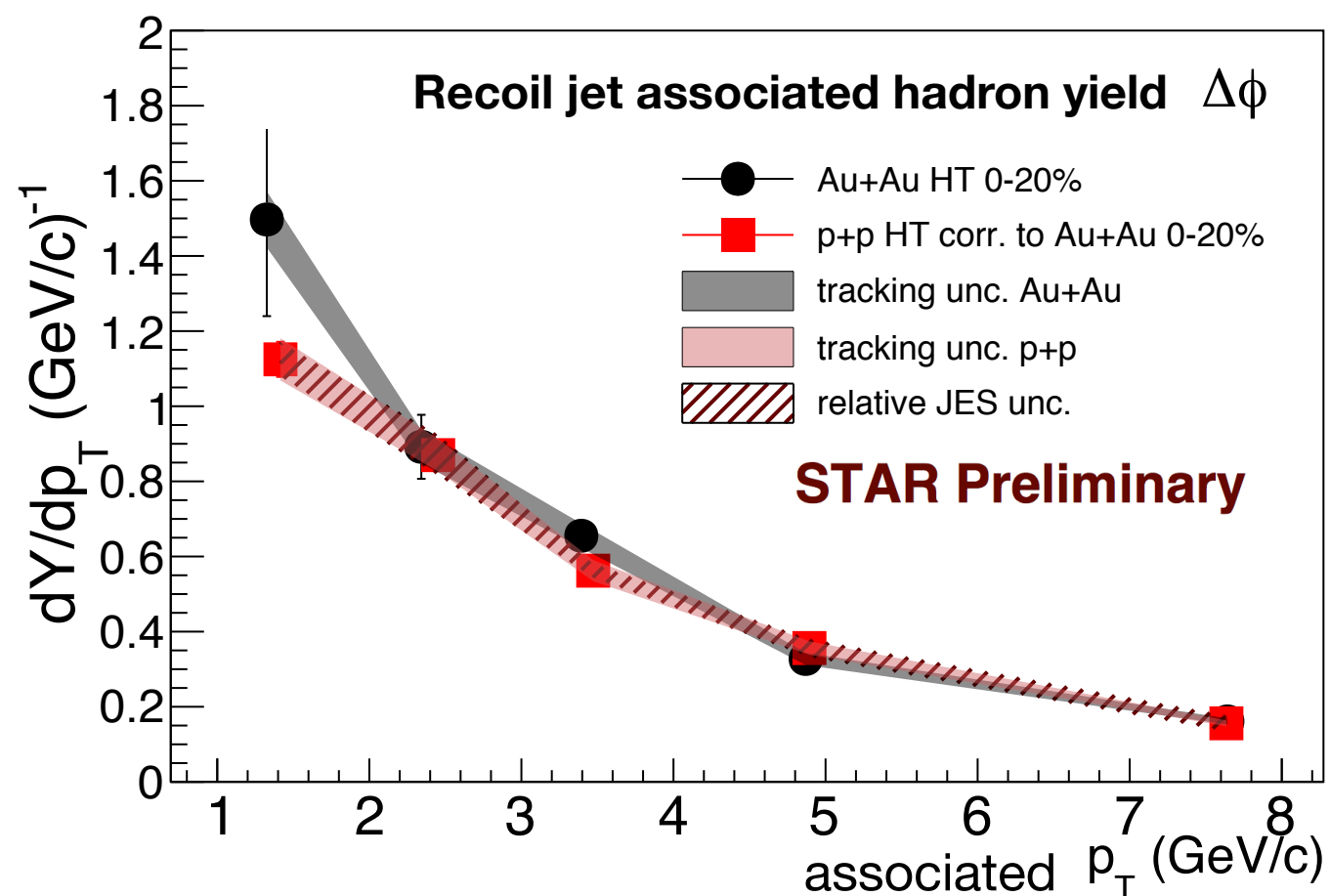
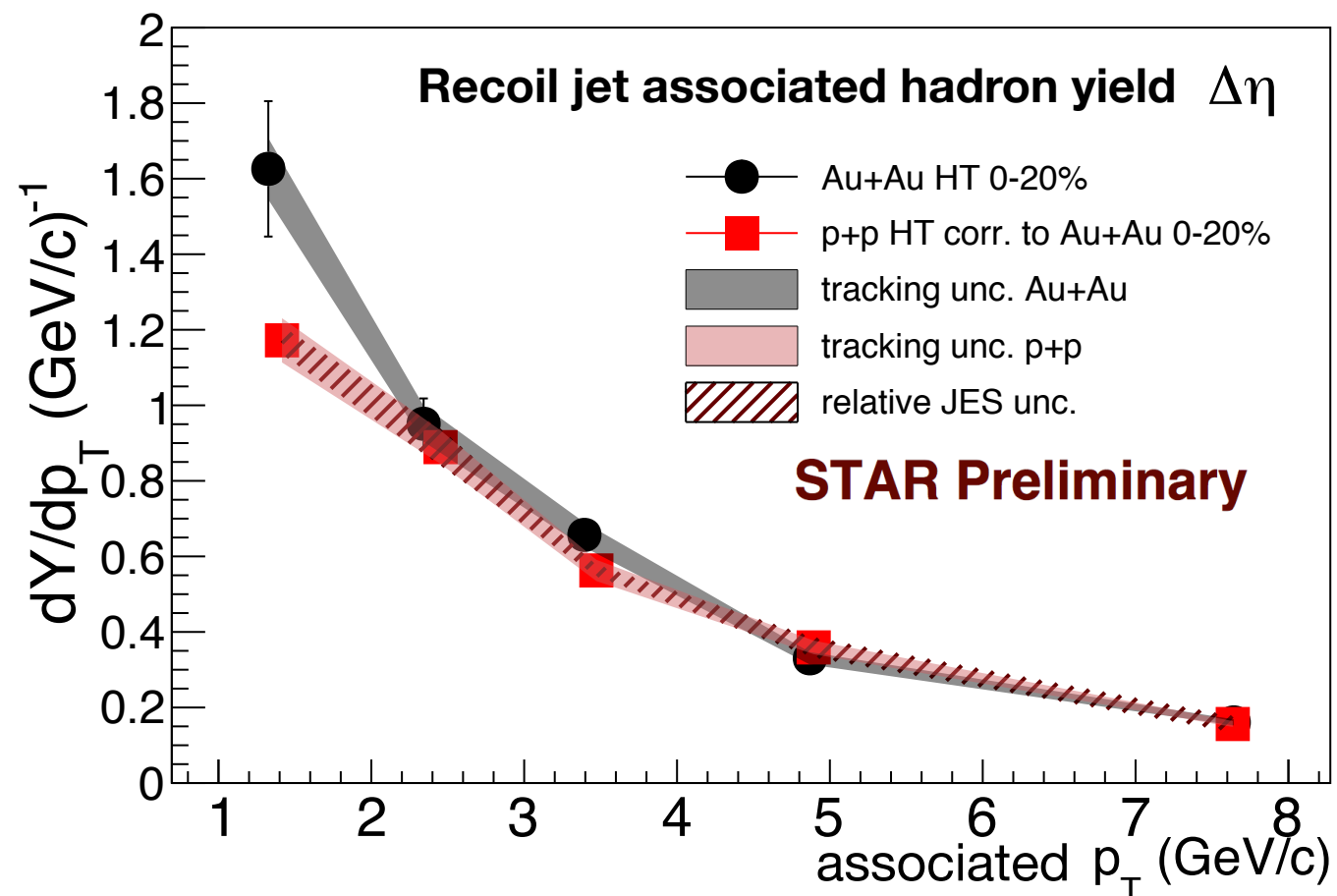
yields consistent between
 $\Delta\phi$ & $\Delta\eta$

→ yield contained within $R=0.4$
for all p_T , consistent with A_J

→ trigger jet: p+p like
"surface bias"

→ recoil jet: hint of modification
enhancement in yield
for $p_T^{\text{assoc}} < 2.0$ GeV/c

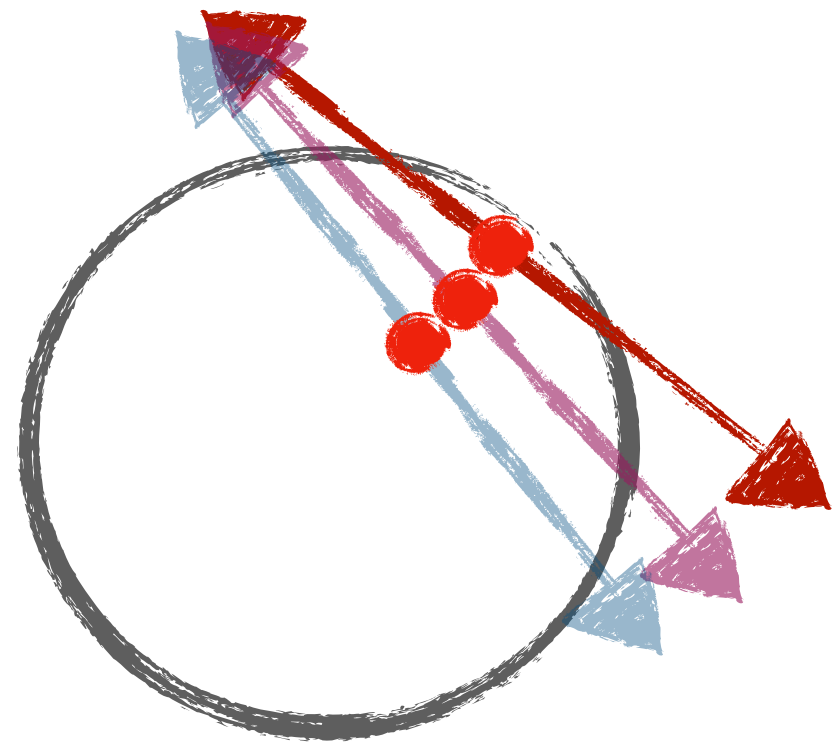
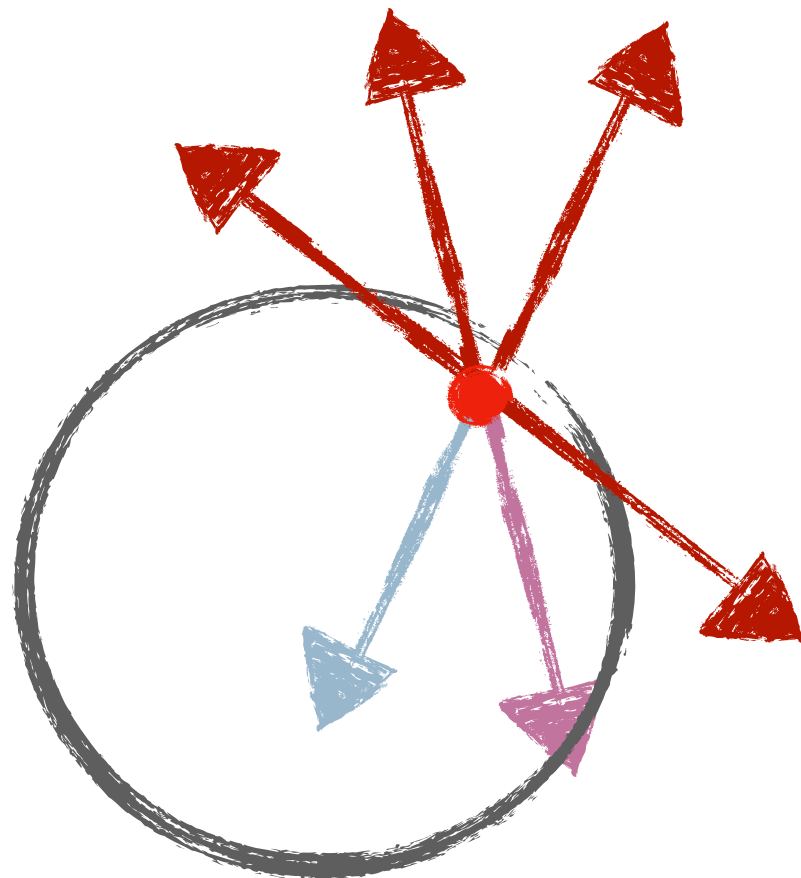
for this p_T^{hard} const selection
(> 2.0 GeV/c), modification
appears to be mainly in recoil jet



Jet geometry engineering

we have a set of jets with specific kinematics that we understand well

- can varying the jet definition select more or less modified jets?
- modification $\rightarrow$ path length



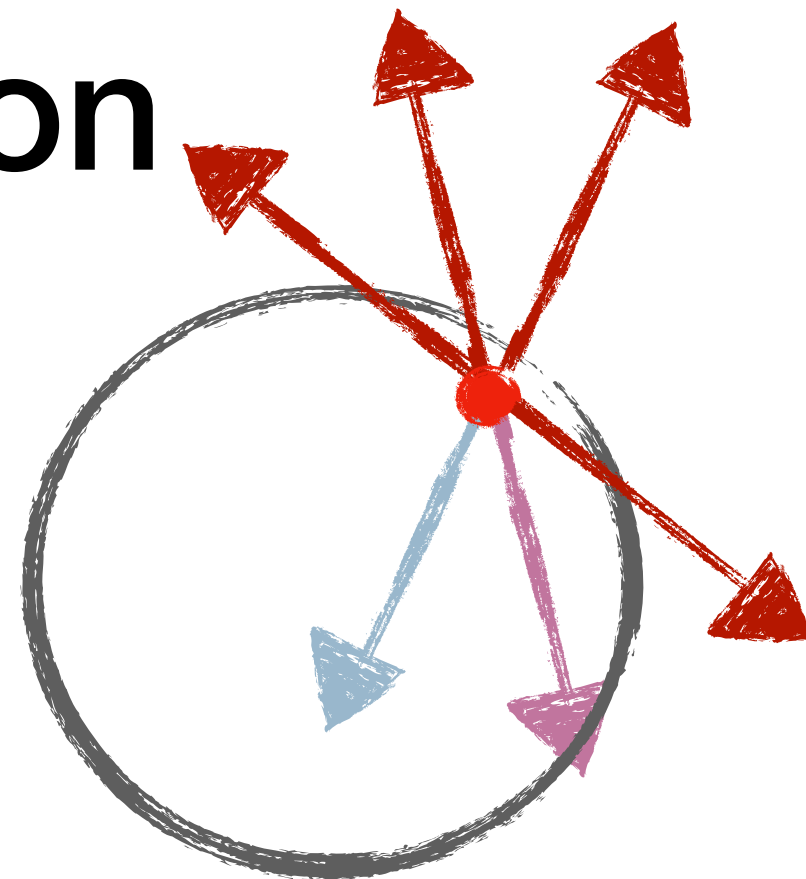
Quantifying modification

vary the jet definition

→ jet p_T

→ hard constituent p_T cut

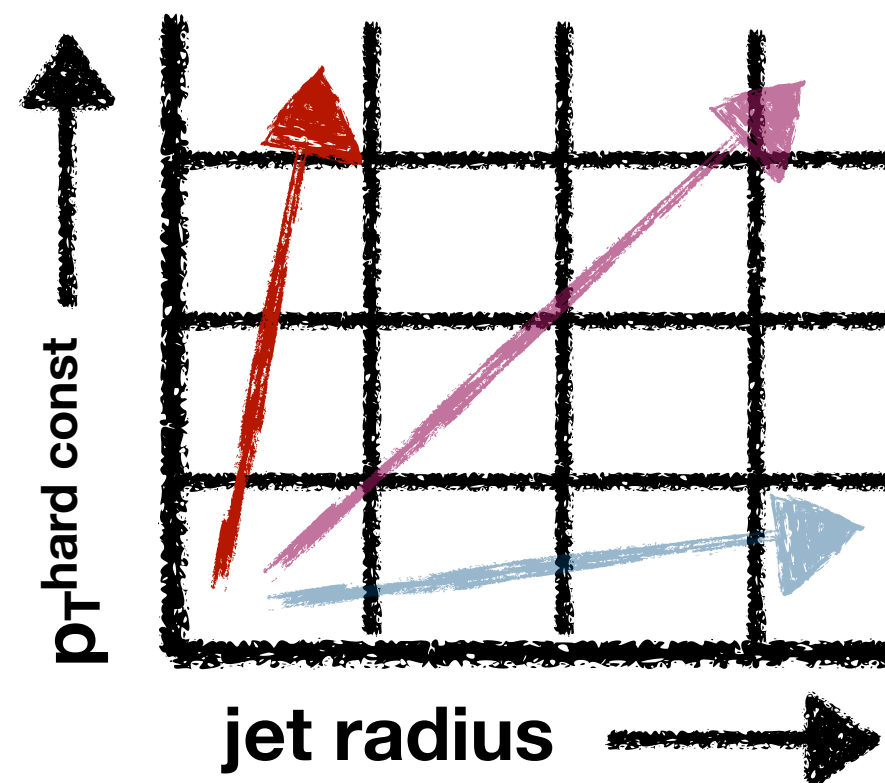
→ jet radius R



use hard core and matched A_J
as our observables

compare Au+Au to p+p embedded
using a binned two-sample
Kolmogorov-Smirnov (K-S) test

KS value = measure of statistical
similarity between distributions

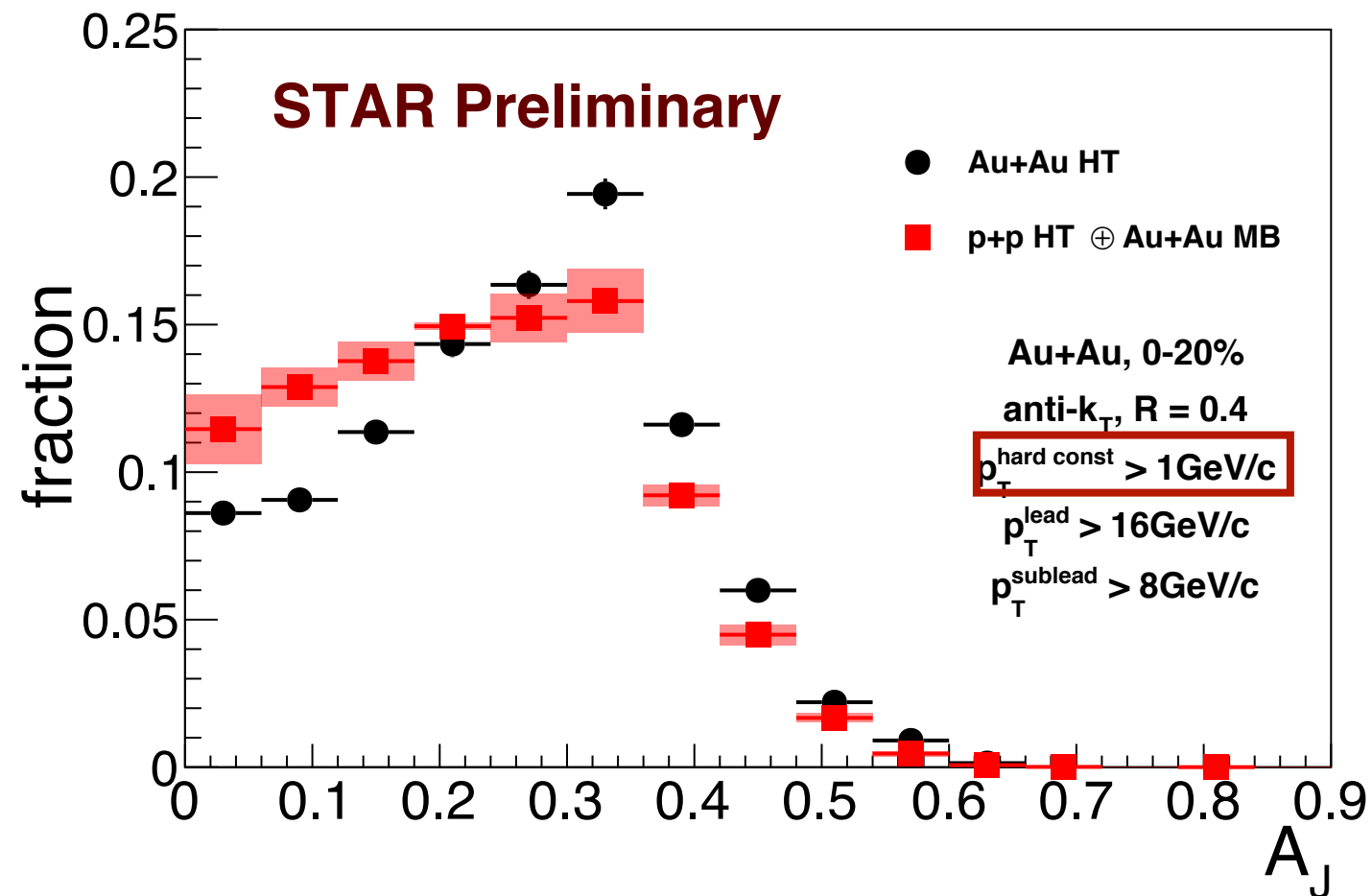


Differential di-jet imbalance

➔ **hard core di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
 $p_T^{\text{hard const}} > 1 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



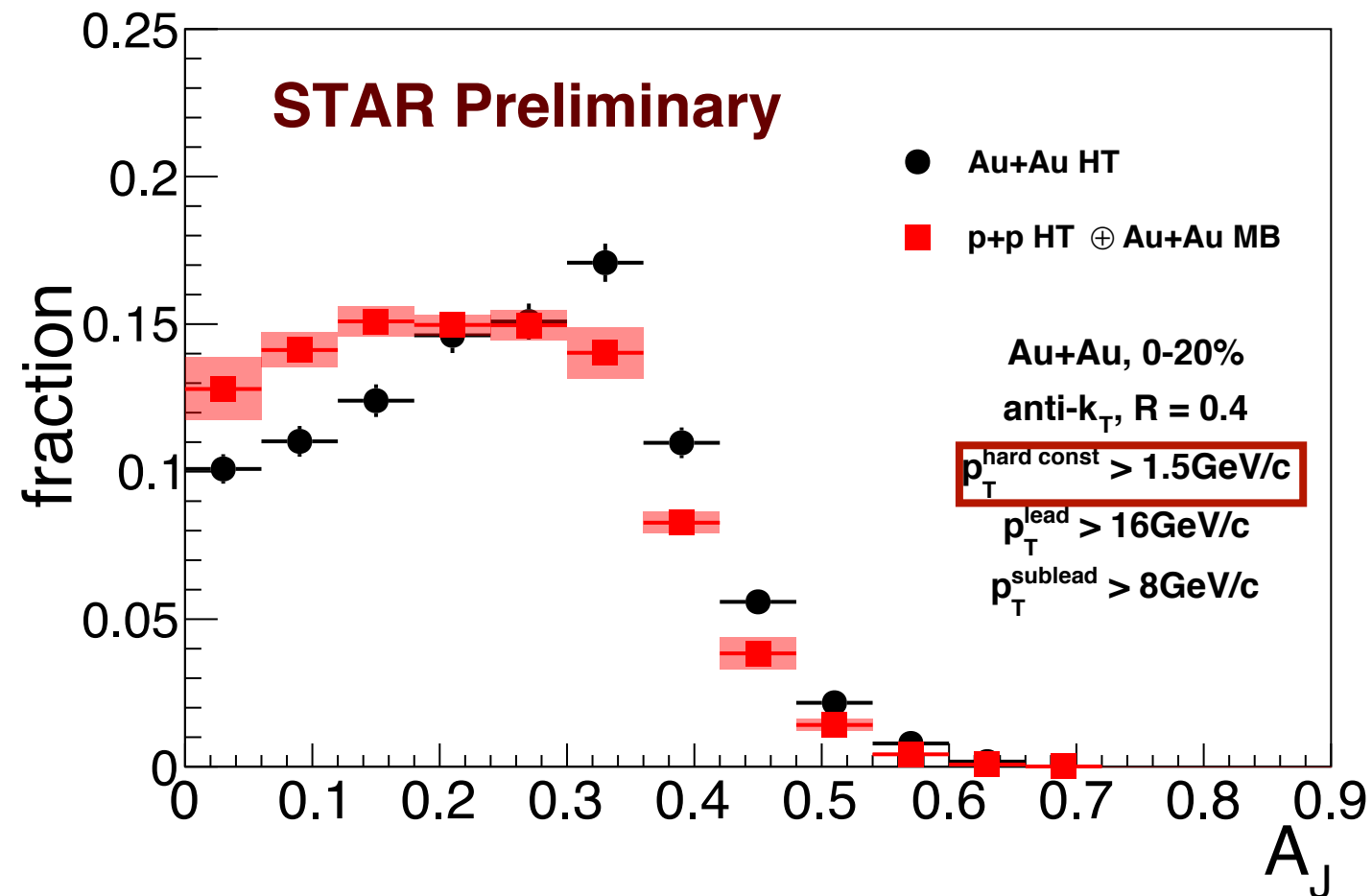
K-S value $\ll 1.0$

Differential di-jet imbalance

➔ **hard core di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
 $p_T^{\text{hard const}} > 1.5 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



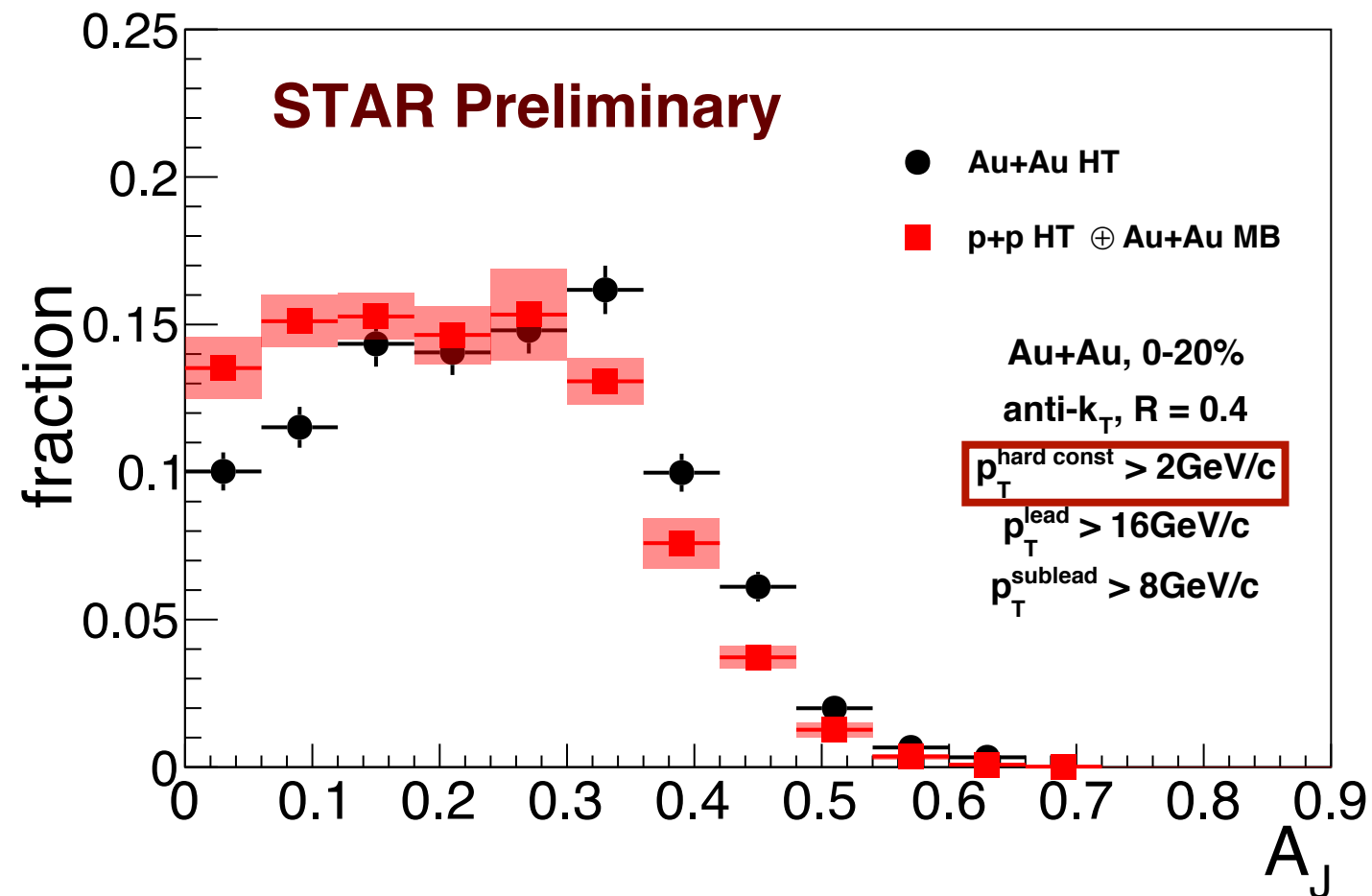
K-S value $\ll 1.0$

Differential di-jet imbalance

➔ **hard core di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
 $p_T^{\text{hard const}} > 2.0 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



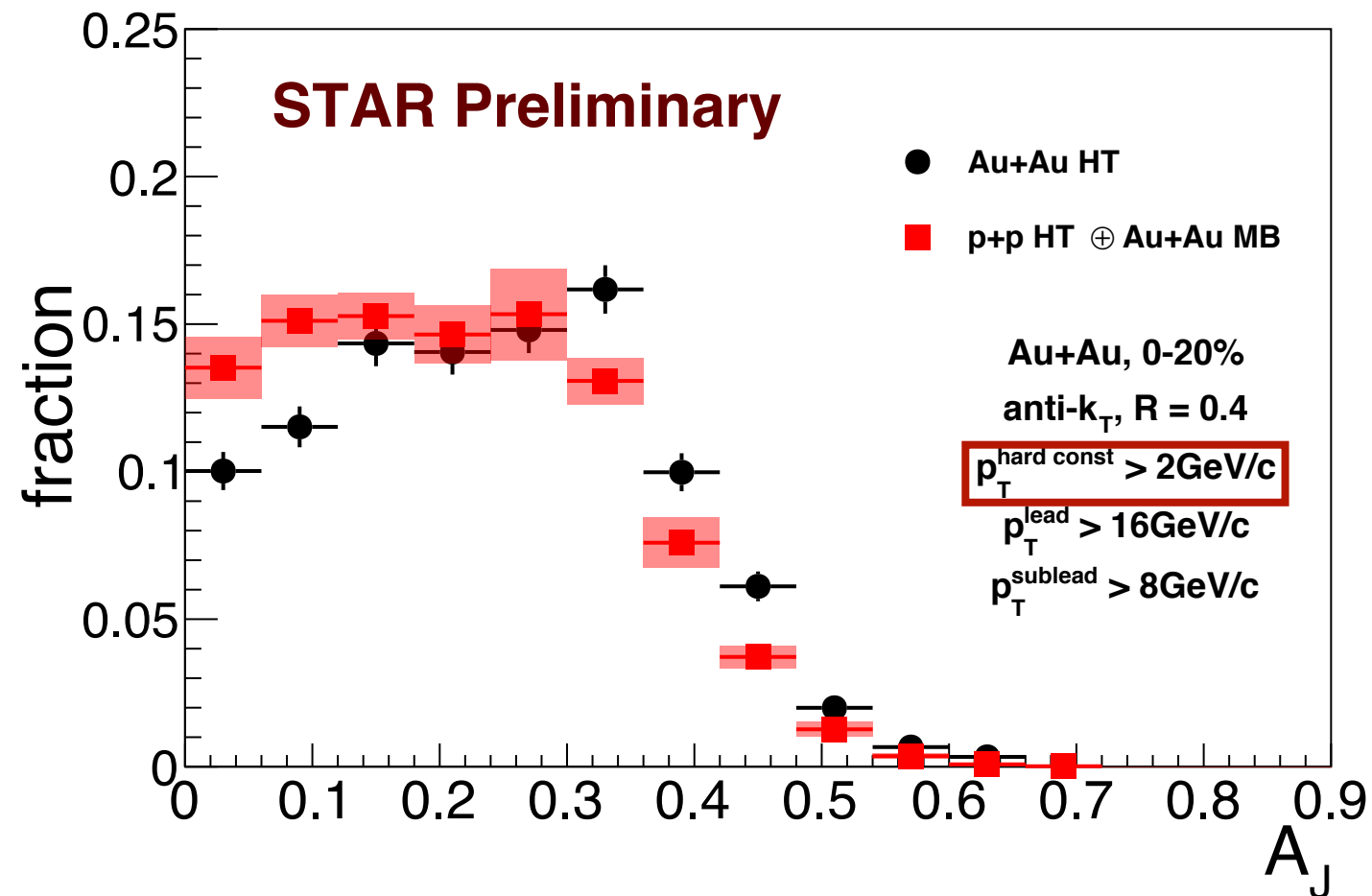
K-S value $\ll 1.0$

Differential di-jet imbalance

➔ **hard core di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
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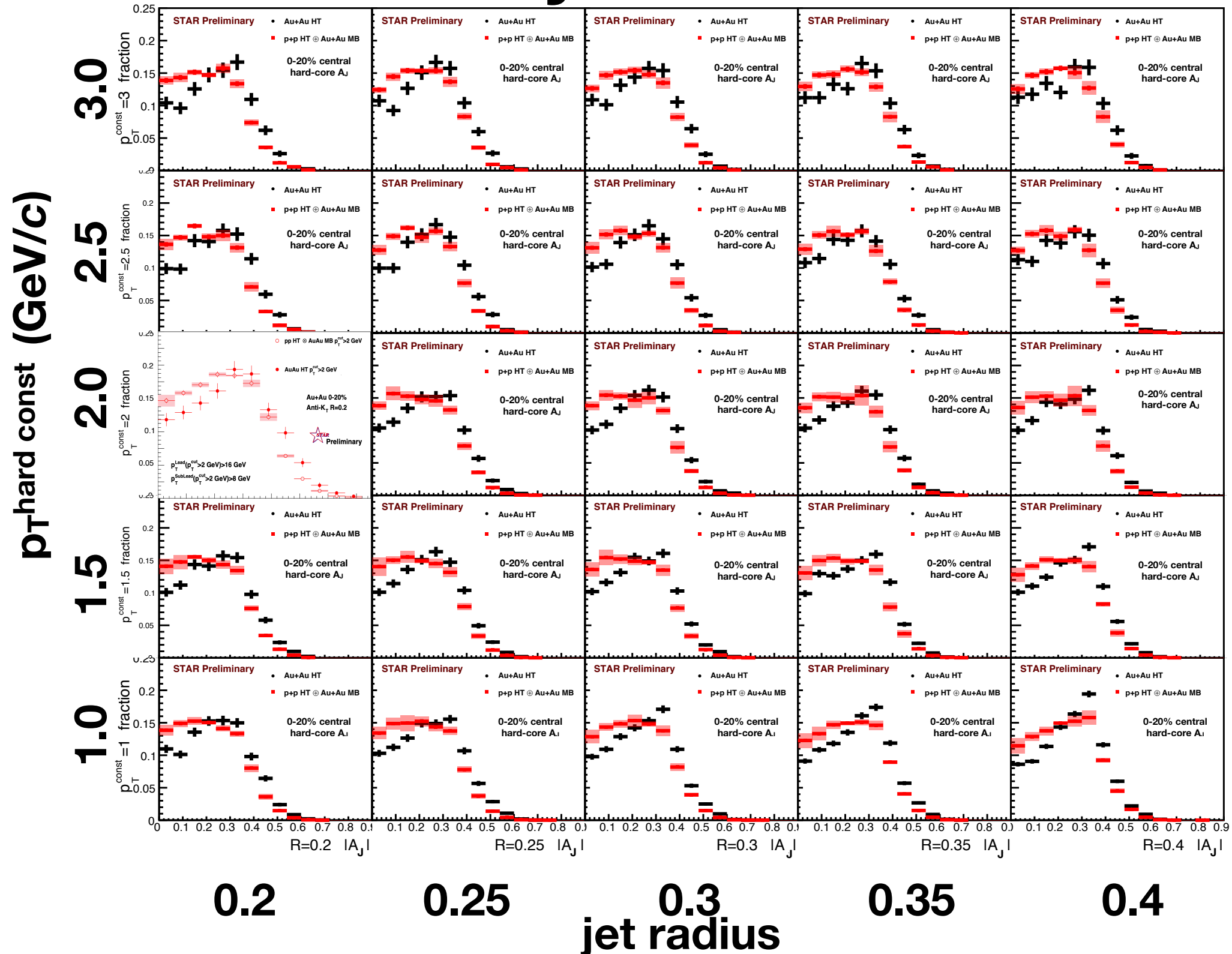
0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



K-S value $\ll 1.0$

Now, we can repeat the procedure with the jet radius

Differential di-jet imbalance



Significant difference in all bins

Differential di-jet imbalance

hard core di-jets

→ modified for all kinematic selections

three distinct classes
using K-S test ($p = \text{K-S value}$)



balanced ($p > 0.01$)

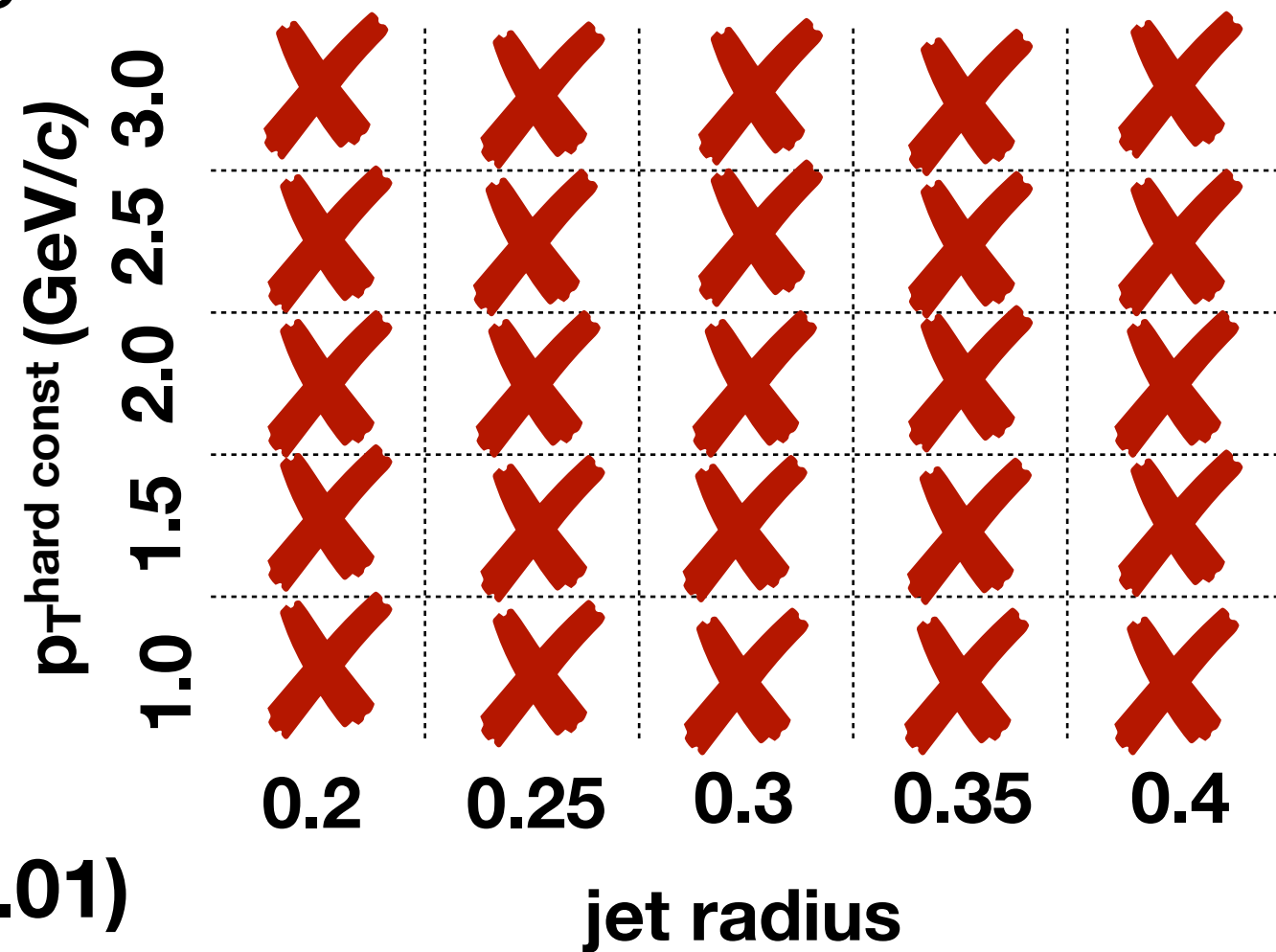


semi-balanced ($10^{-4} < p < 0.01$)



imbalanced ($p < 10^{-4}$)

Hard core di-jets



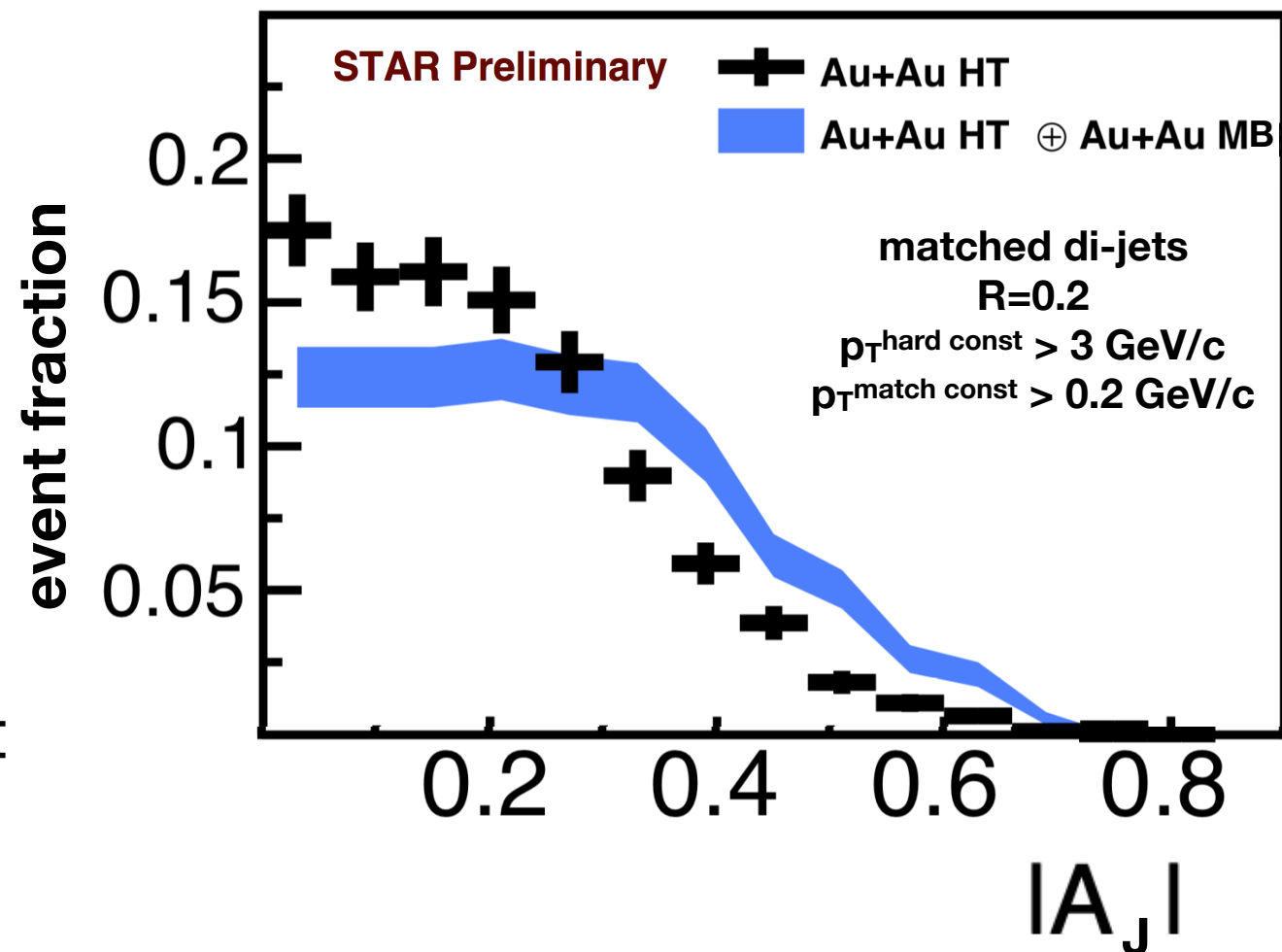
Estimate of the effect of background on balancing

→ intra-event fluctuations in background density can shift the A_J distribution

→ estimate the sensitivity of our measurement to correlated signal yield by **embedding hard-core jets into random MB events**

quantify sensitivity using K-S test to evaluate the difference

→ between **Au+Au** and **Au+Au hard-core embedded in random MB events**



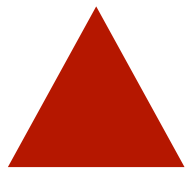
Differential di-jet imbalance

matched jets can get some
“balance” from background
fluctuations

→ compare matched jets to
hard-core jets embedded
in Au+Au MB

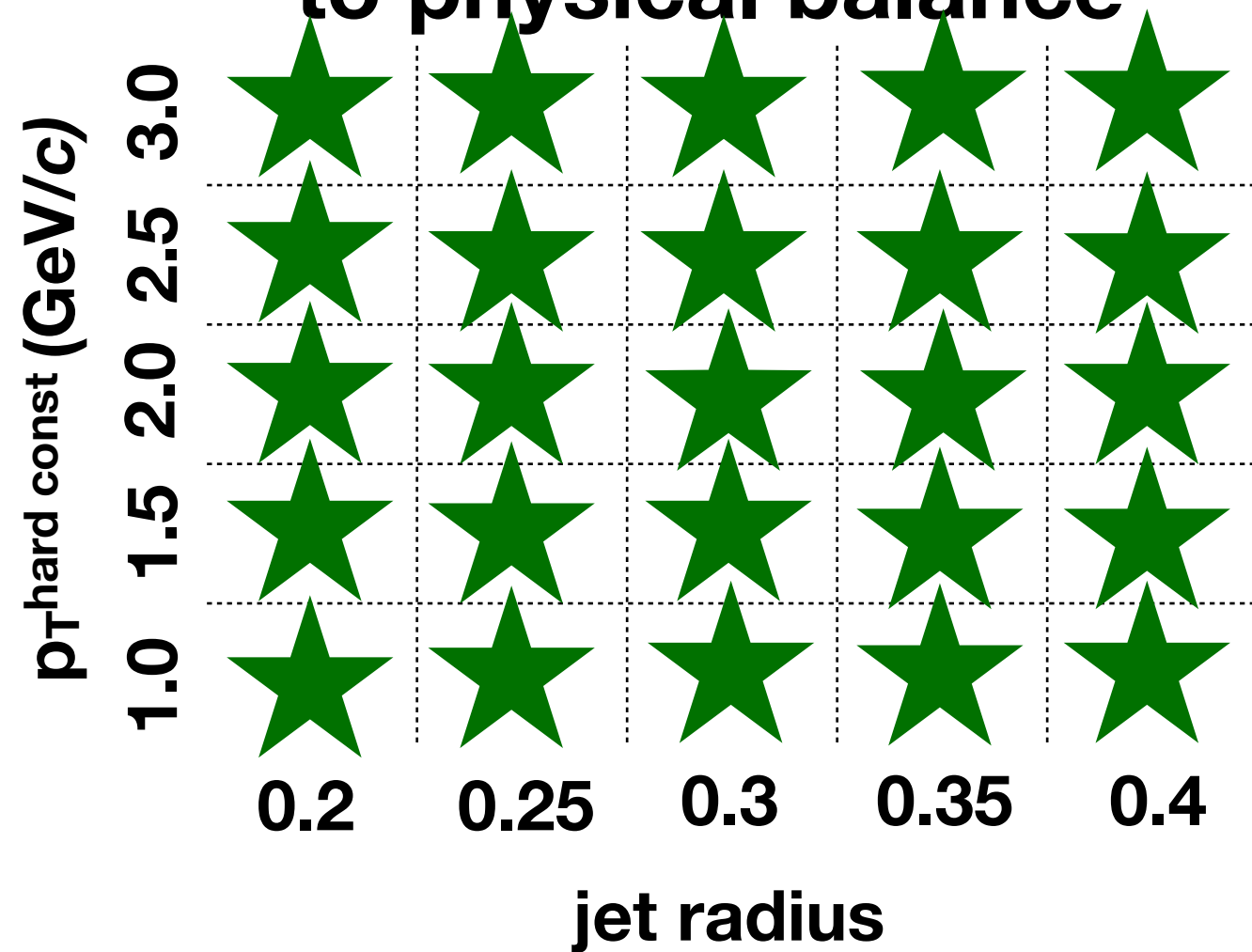


sensitive ($p < 0.01$)



insensitive ($p > 0.01$)

**Estimate of sensitivity
to physical balance**

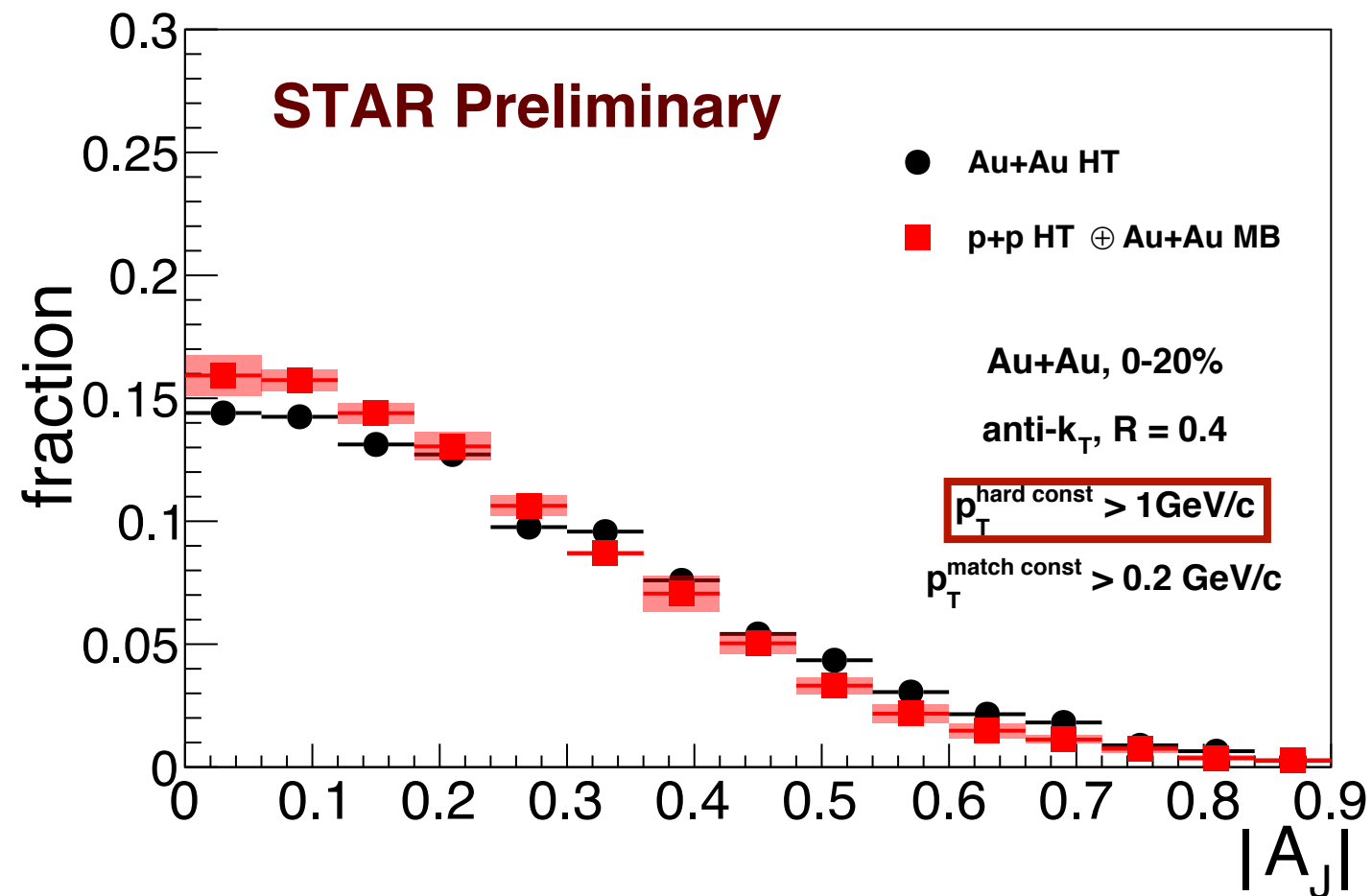


Differential di-jet imbalance

➔ **matched di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
 $p_T^{\text{hard const}} > 1 \text{ GeV}/c$
 $p_T^{\text{match const}} > 0.2 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



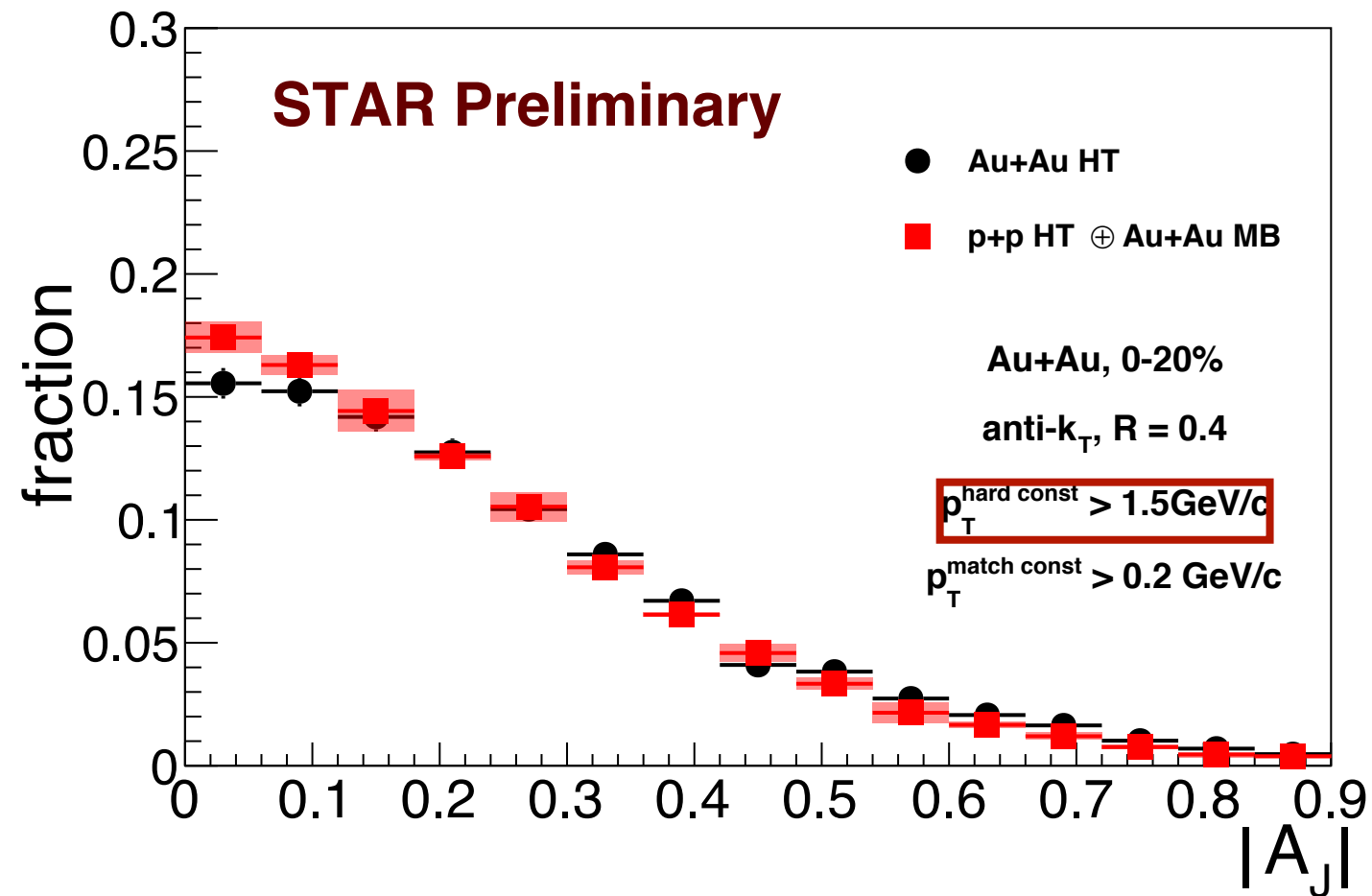
K-S value $\ll 1.0$

Differential di-jet imbalance

➔ **matched di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
 $p_T^{\text{hard const}} > 1.5 \text{ GeV}/c$
 $p_T^{\text{match const}} > 0.2 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm



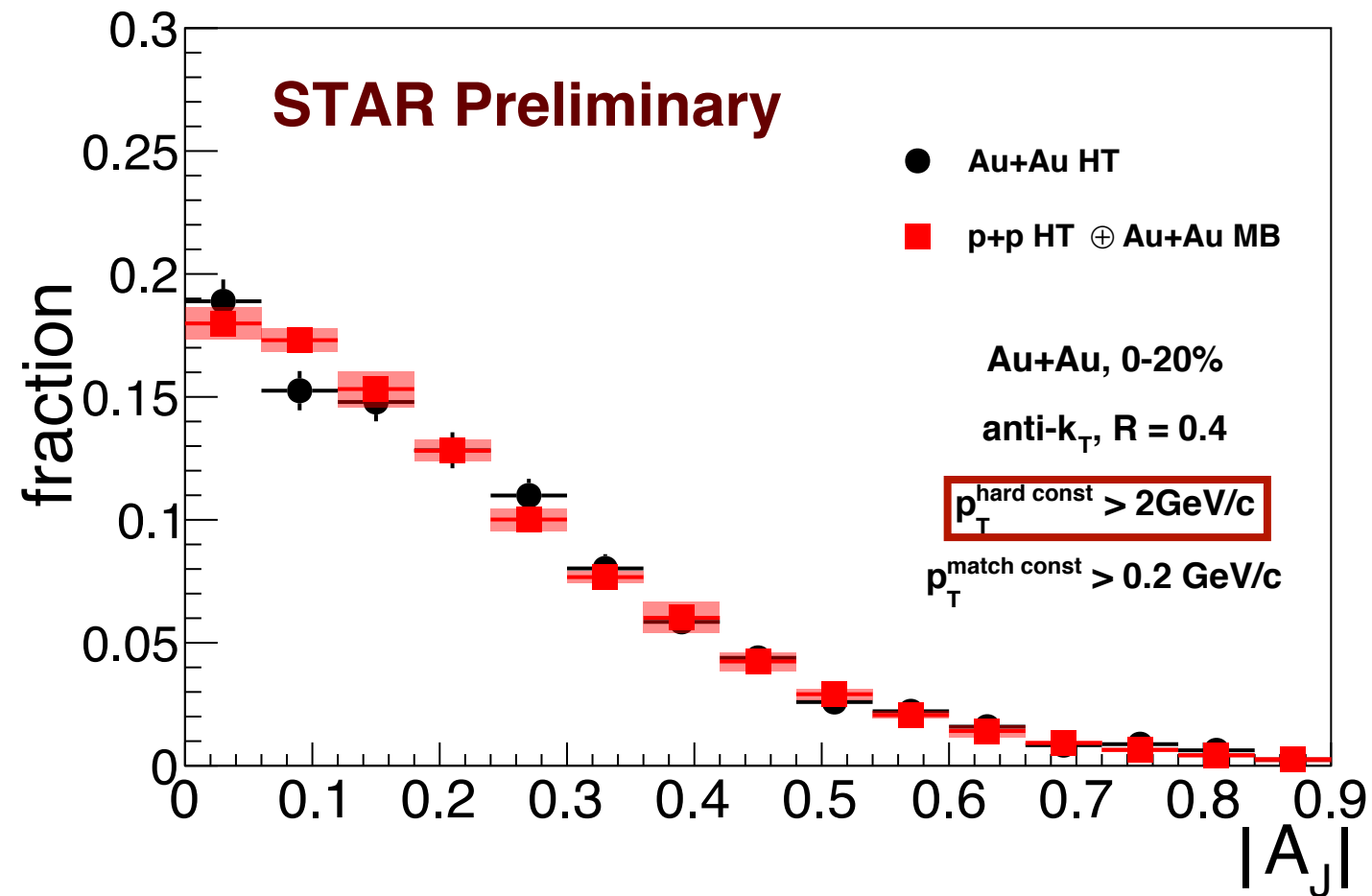
K-S value = 0.0006

Differential di-jet imbalance

➔ **matched di-jets**
for $R=0.4$, scan $p_T^{\text{hard const}}$

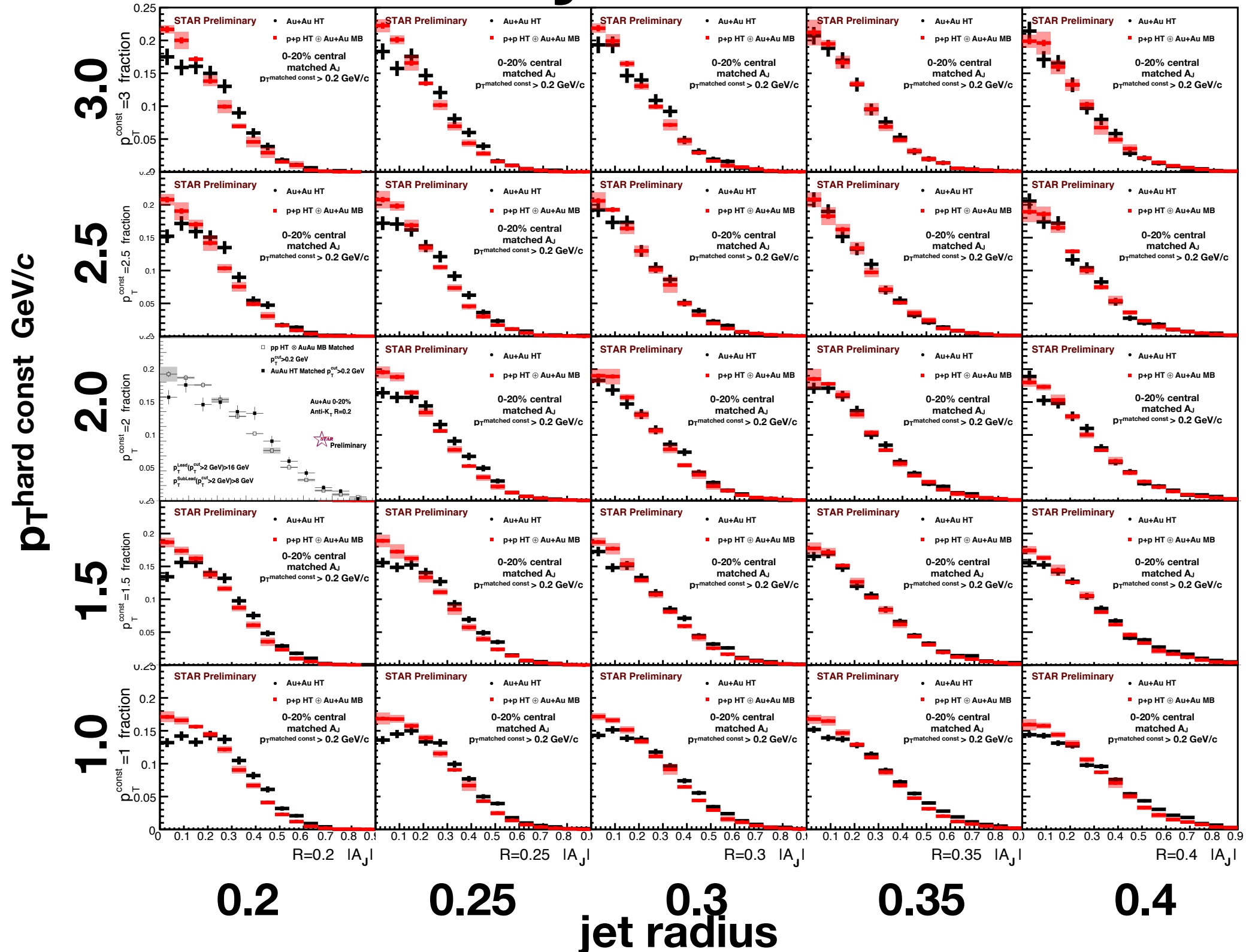
$R = 0.4$
 $p_T^{\text{hard const}} > 2.0 \text{ GeV}/c$
 $p_T^{\text{match const}} > 0.2 \text{ GeV}/c$

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
anti- k_T algorithm

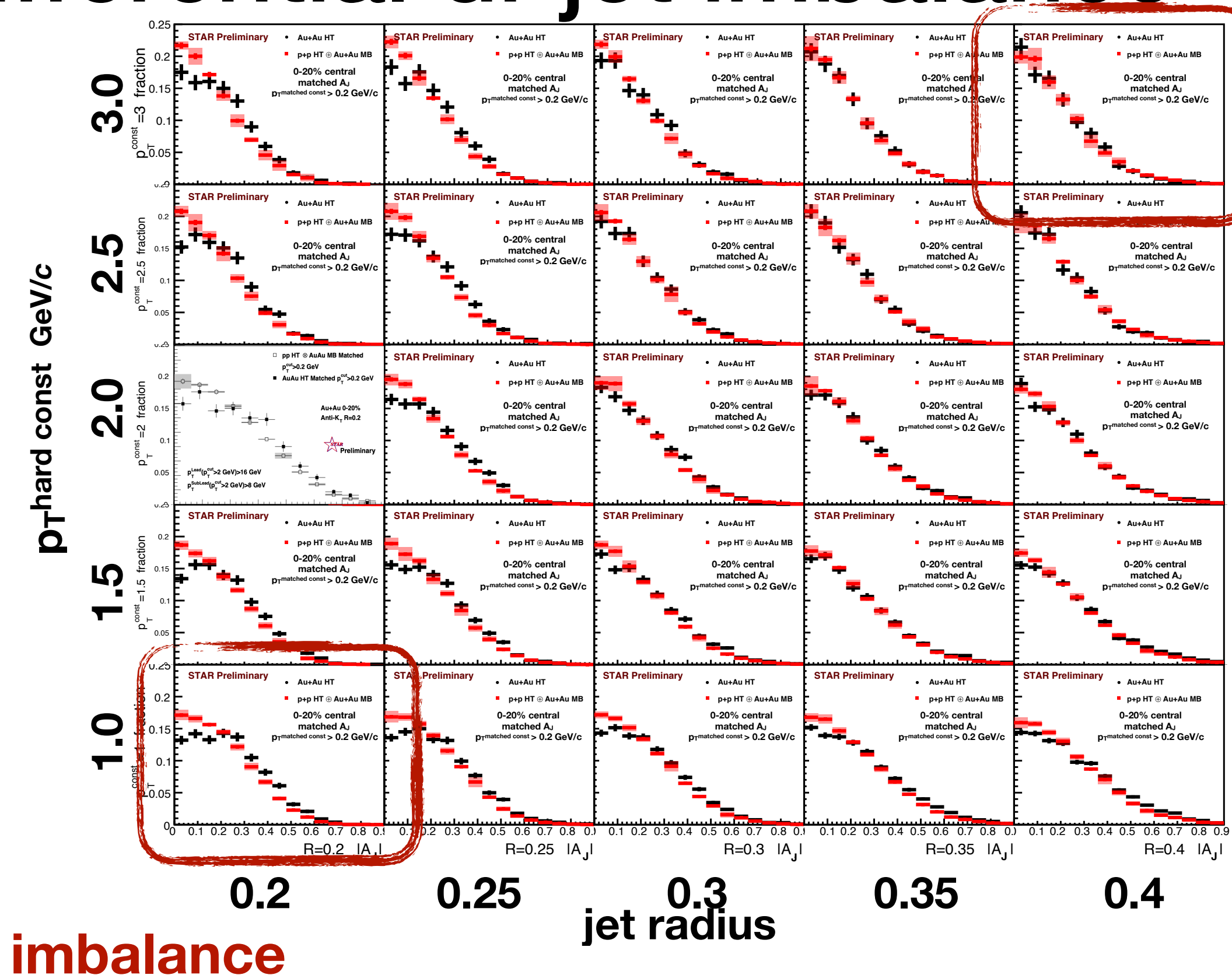


K-S value = 0.17

Differential di-jet imbalance



Differential di-jet imbalance balance

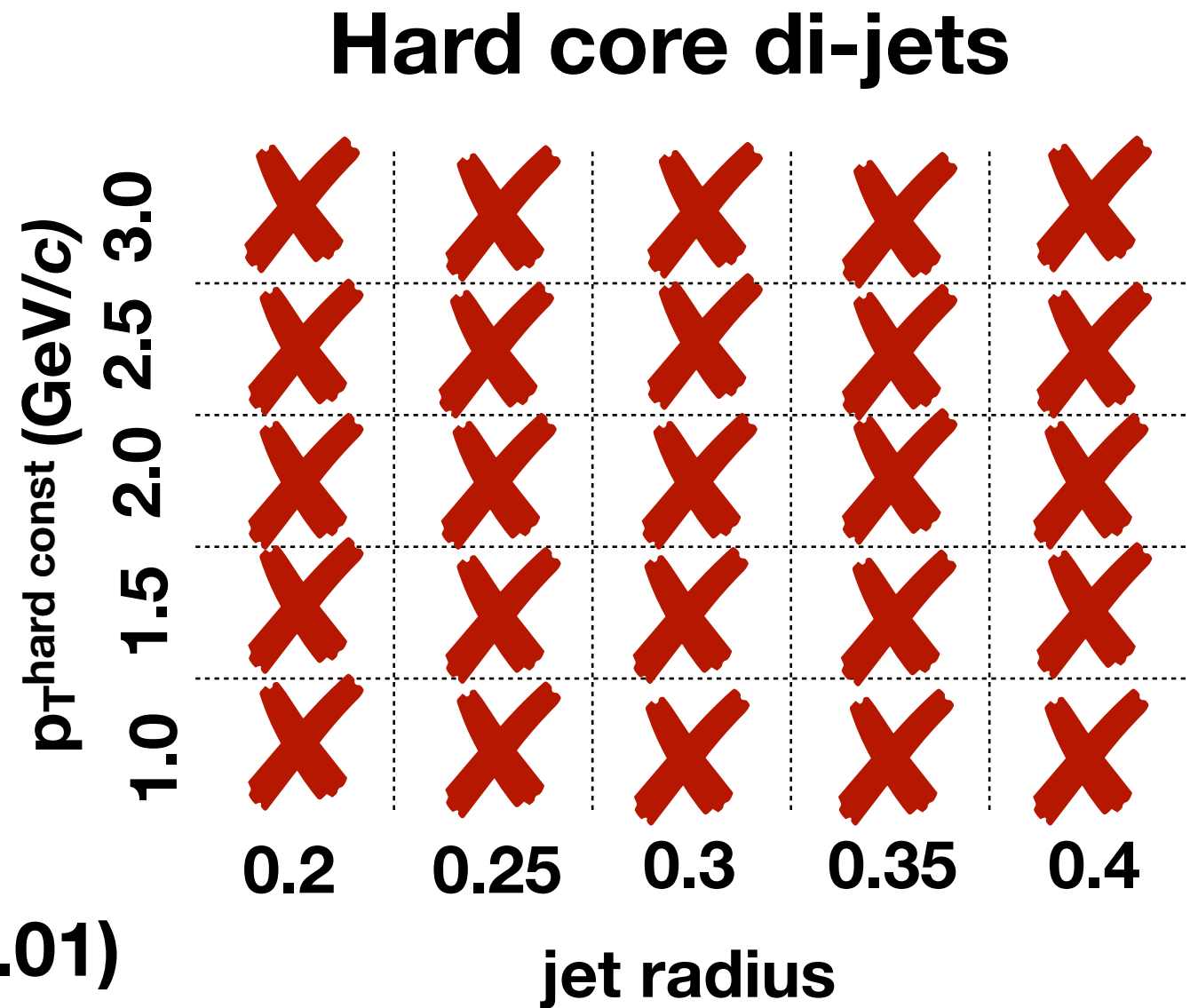


Differential di-jet imbalance

hard core di-jets

modified for all kinematic
selections

- ✓ balanced ($p > 0.01$)
- semi-balanced ($10^{-4} < p < 0.01$)
- ✗ imbalanced ($p < 10^{-4}$)



Differential di-jet imbalance

hard core di-jets

modified for all kinematic
selections

matched di-jets

→ reducing $p_{\text{T}}^{\text{hard const}}$
can increase modification
beyond $R=0.4$



balanced ($p > 0.01$)

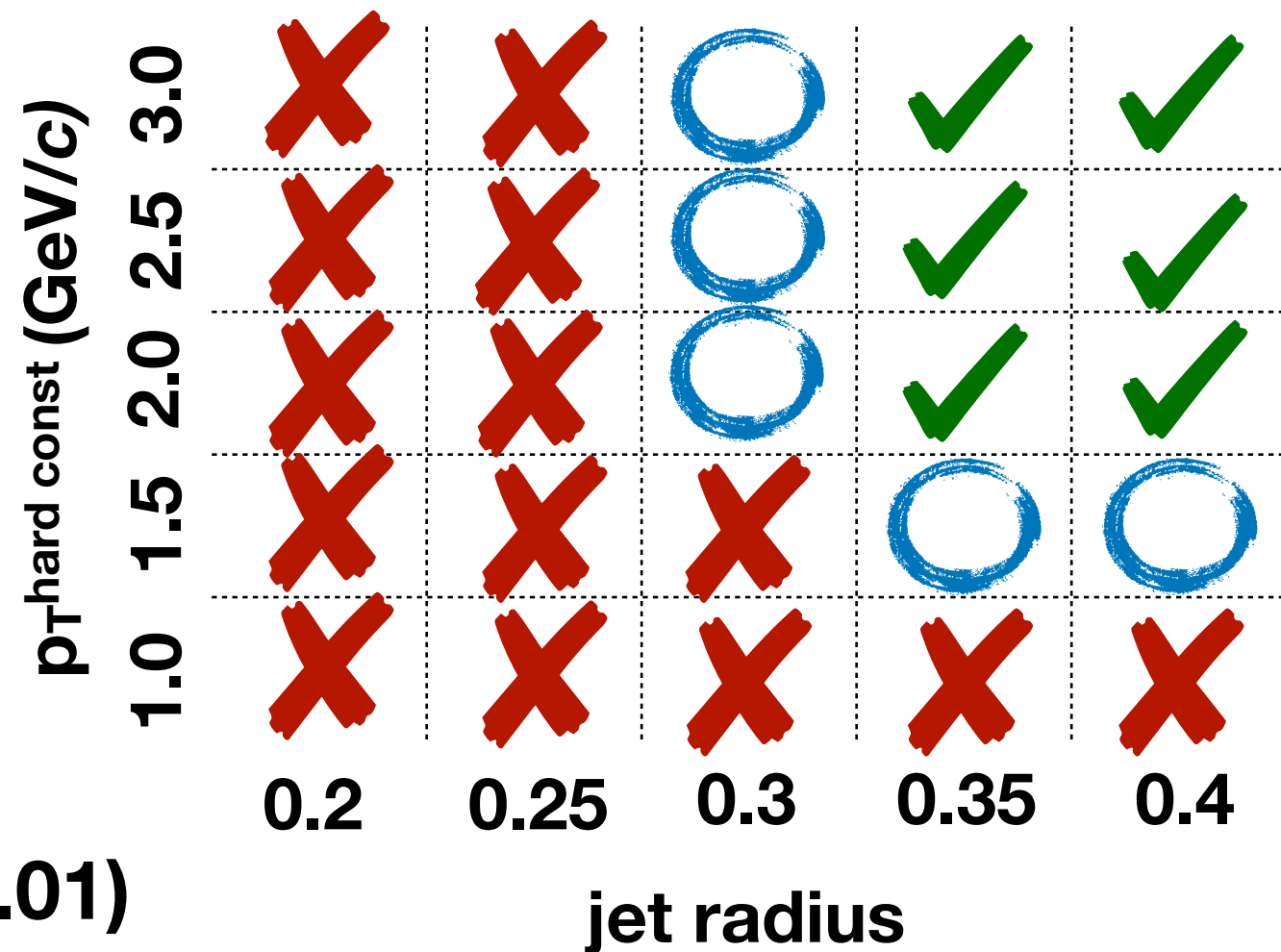


semi-balanced ($10^{-4} < p < 0.01$)

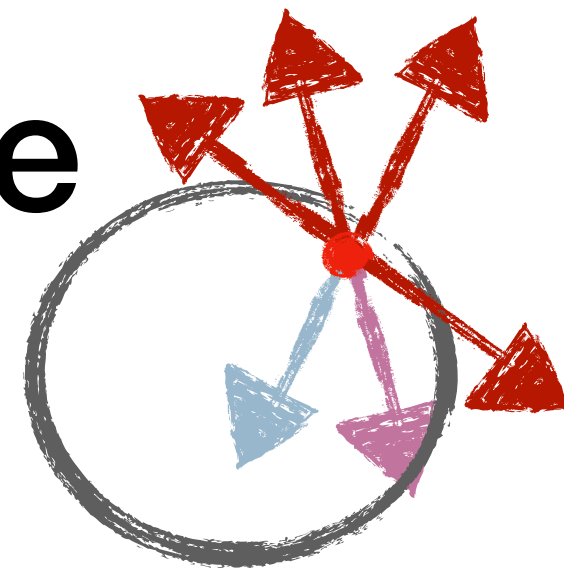


imbalanced ($p < 10^{-4}$)

Matched di-jets



Differential di-jet imbalance



hard core di-jets

modified for all kinematic
selections

matched di-jets

→ reducing $p_{T}^{\text{hard const}}$
can increase modification
beyond $R=0.4$



balanced ($p > 0.01$)

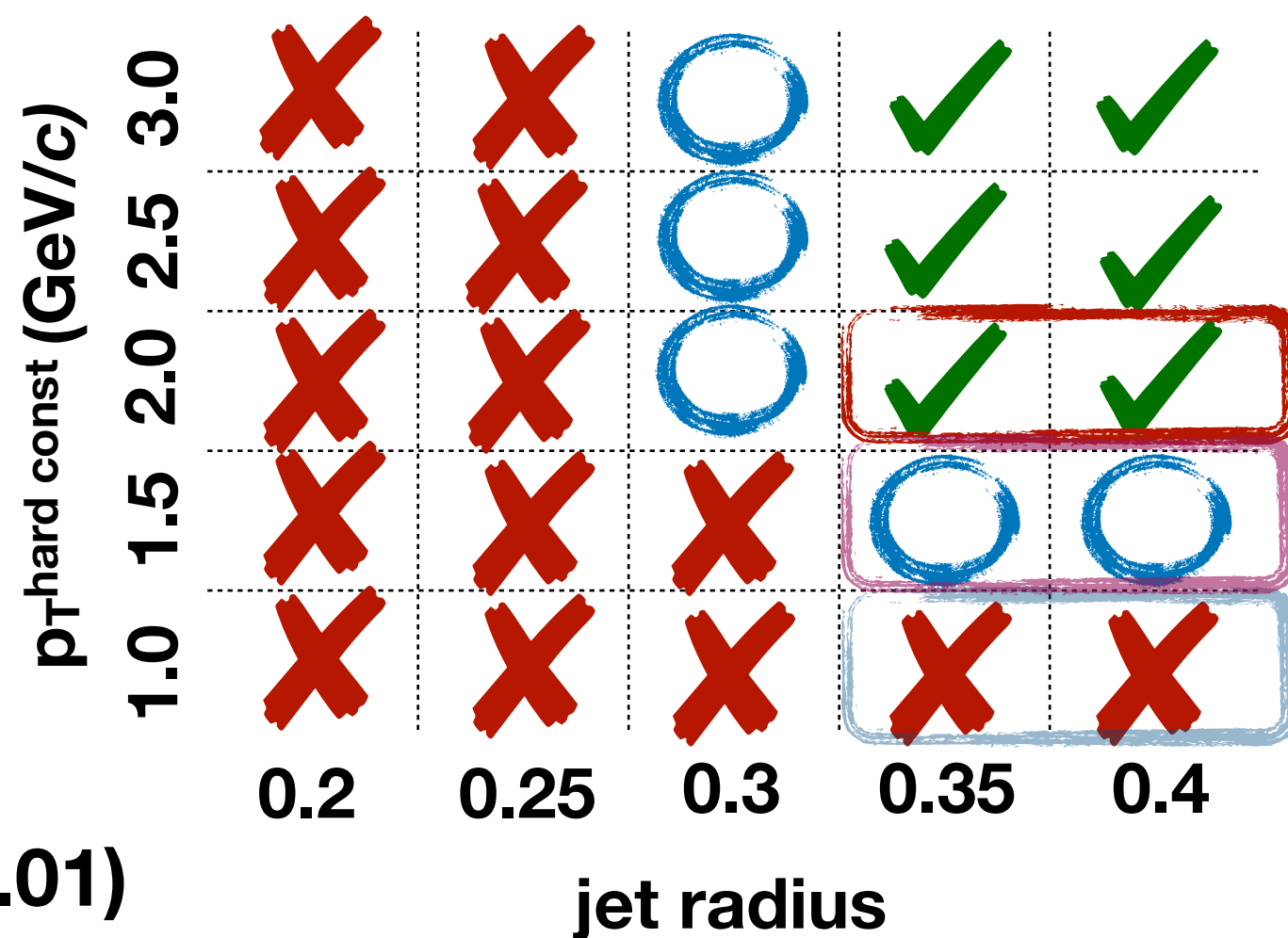


semi-balanced ($10^{-4} < p < 0.01$)



imbalanced ($p < 10^{-4}$)

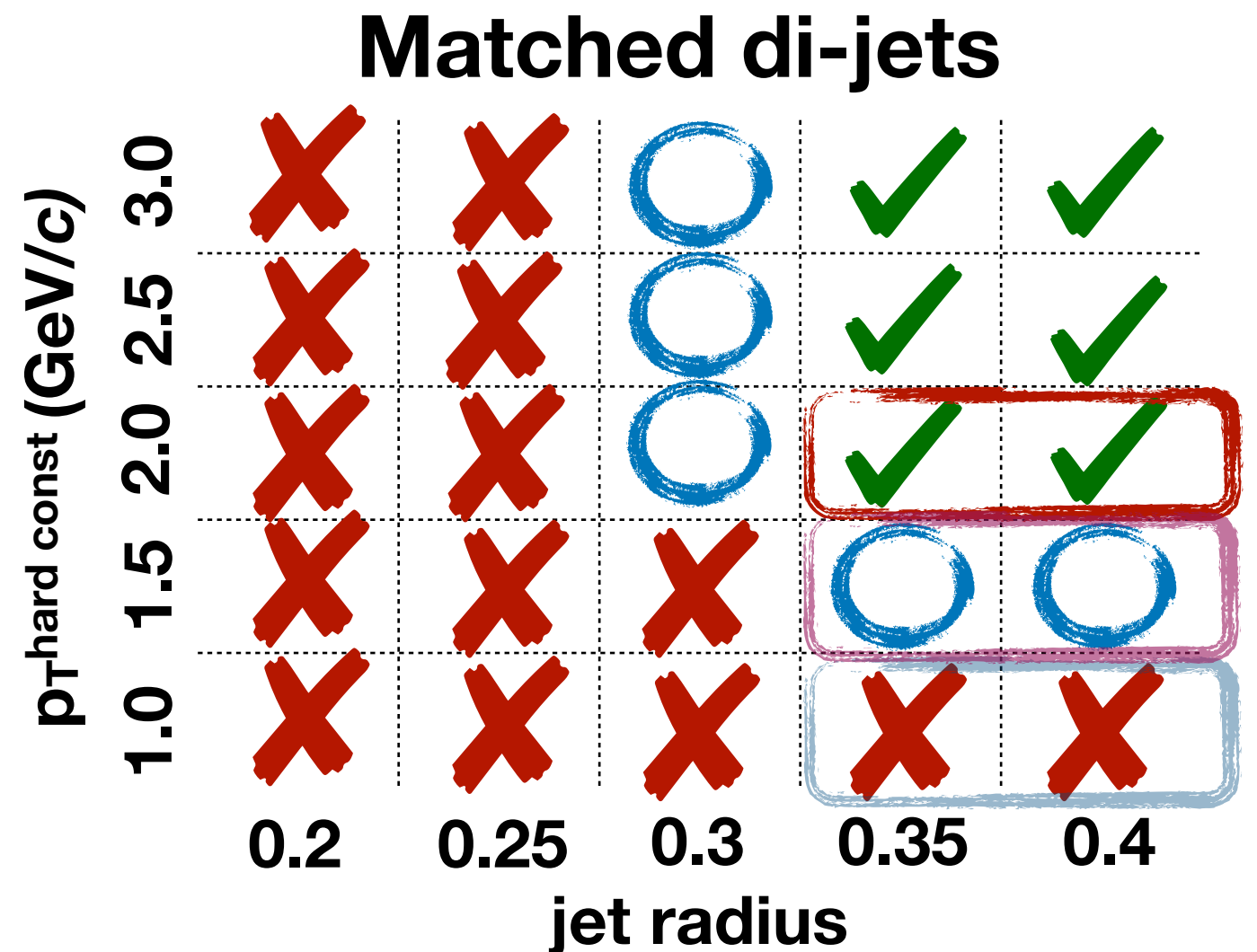
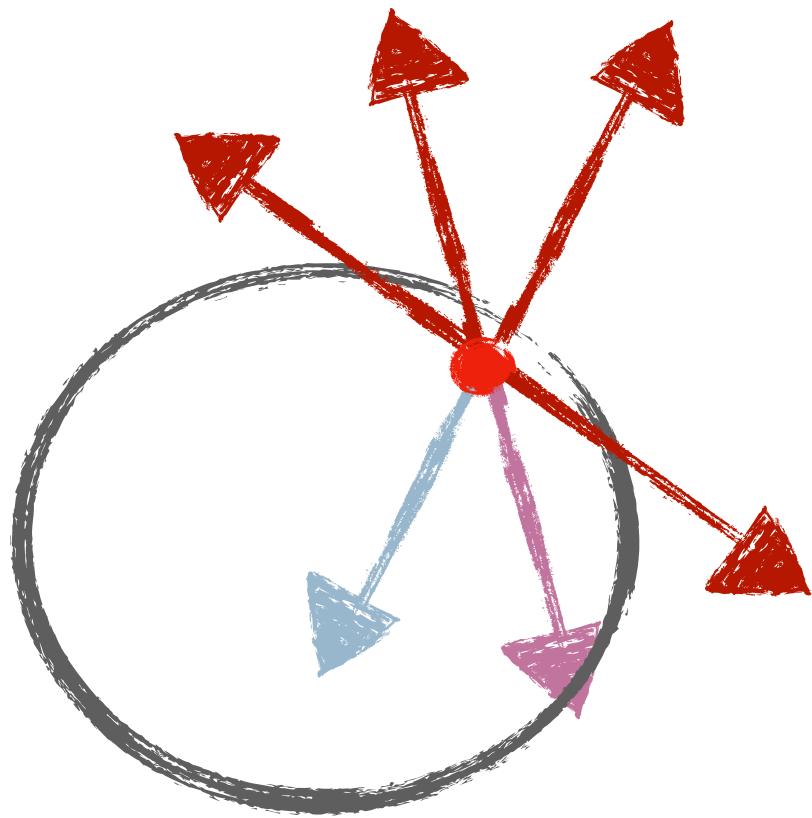
Matched di-jets



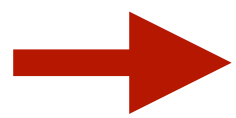
Jet geometry engineering

Conclusions

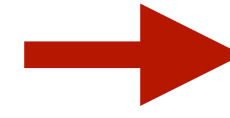
- using hard core di-jets, we have measured energy loss, and we can define jet selections where we recover energy in our original cone - allows for calculation of fragmentation functions
- demonstrated jet geometry engineering, and the ability to control the extent of the energy loss using jet kinematic cuts



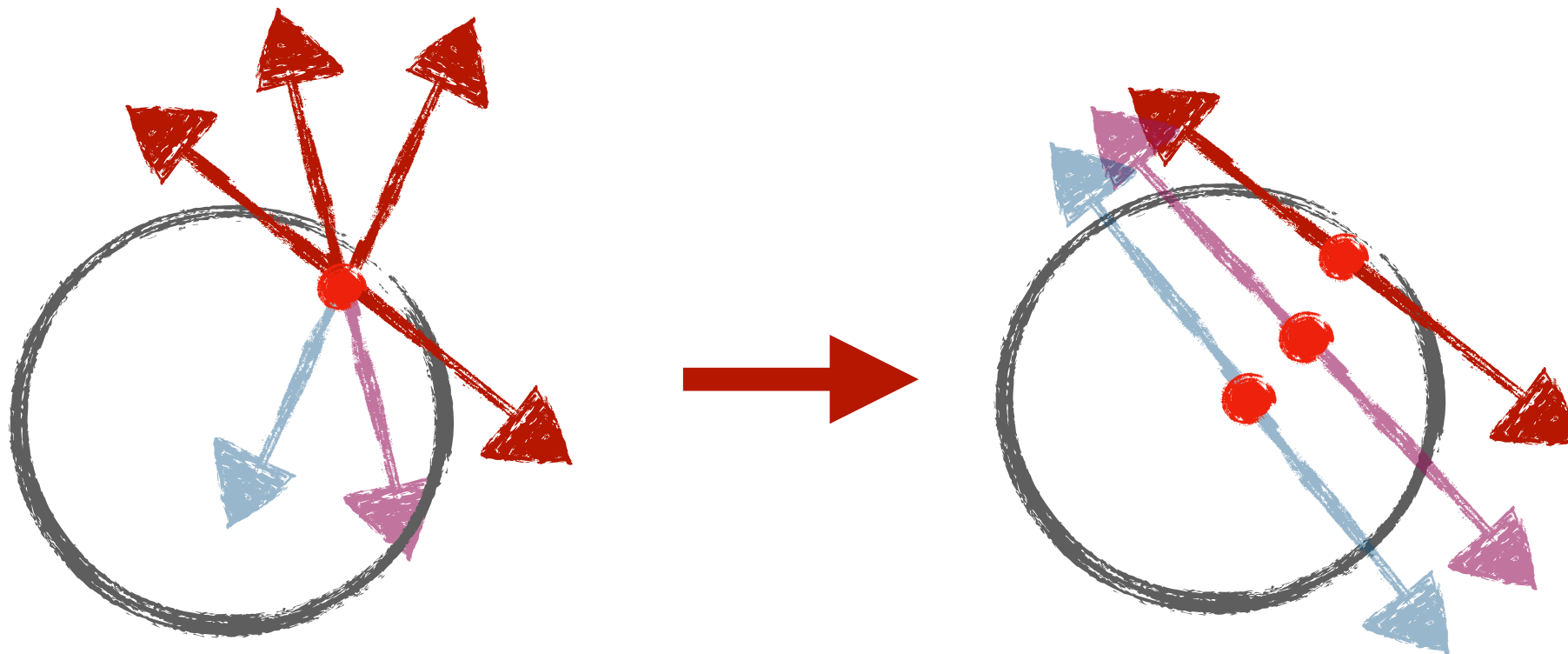
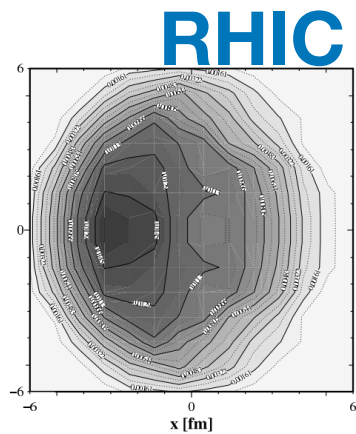
Conclusions



high-energy online calorimeter trigger



large surface bias



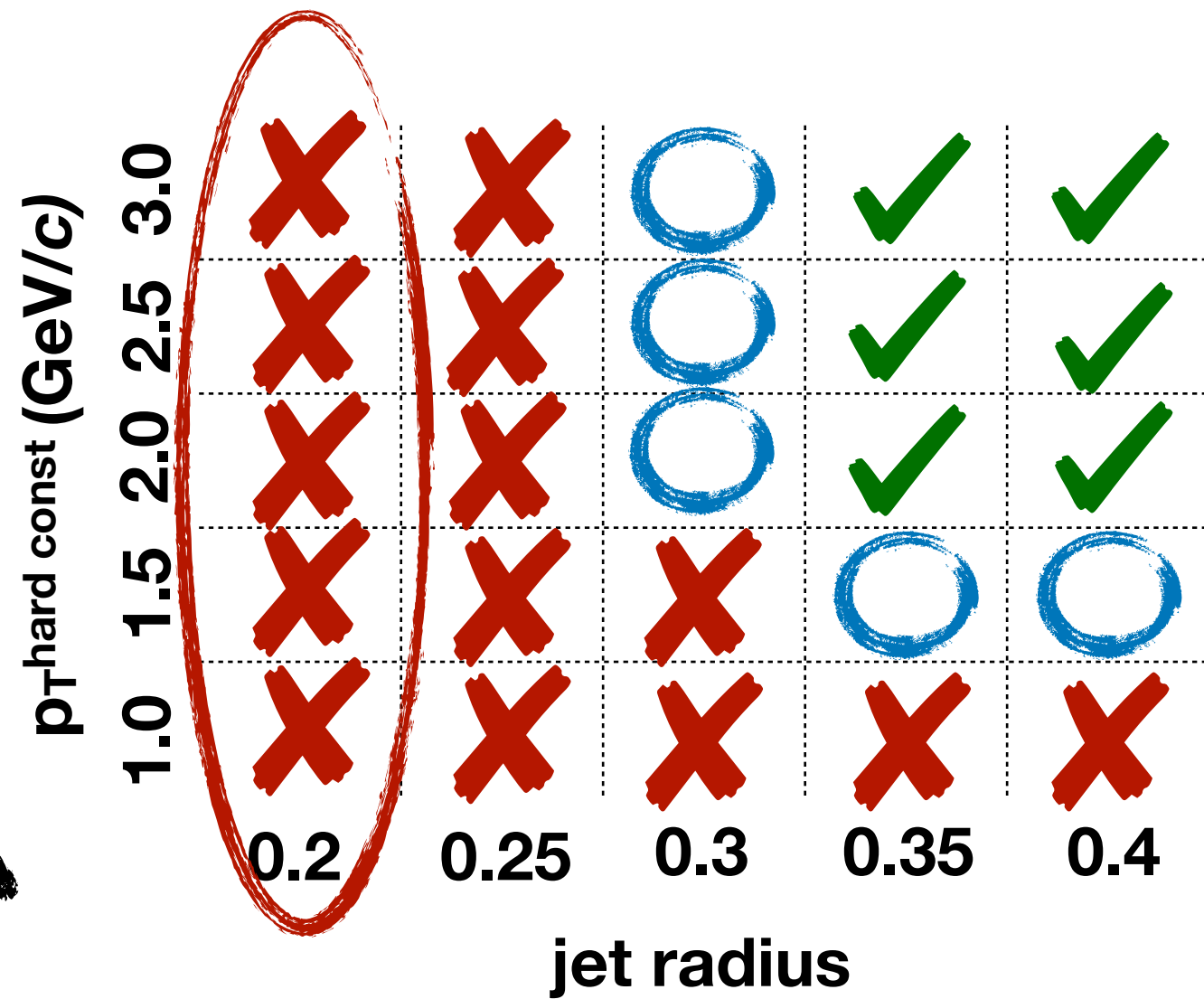
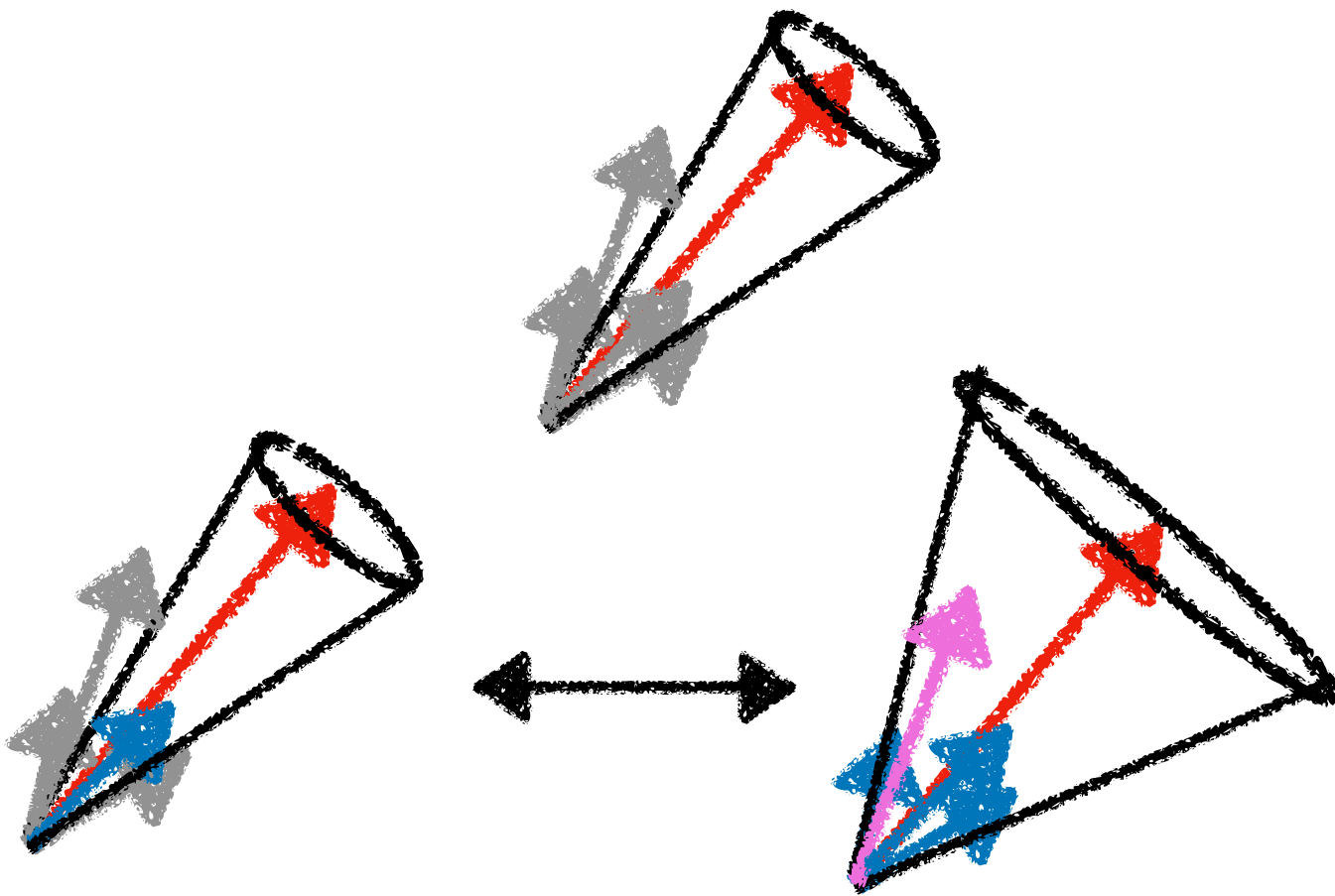
Qualitatively consistent picture of partonic energy loss emerging at RHIC. Observed difference in broadening of jet structure can be related to in-medium path length/ amount of diffusion of medium-induced soft gluon radiation in the QGP.

Thank You

Radial scan of matched jets

at what radius does a set of imbalanced hard core jets ($R=0.2$) recover its energy?

fix hard-core jet at $R = 0.2$



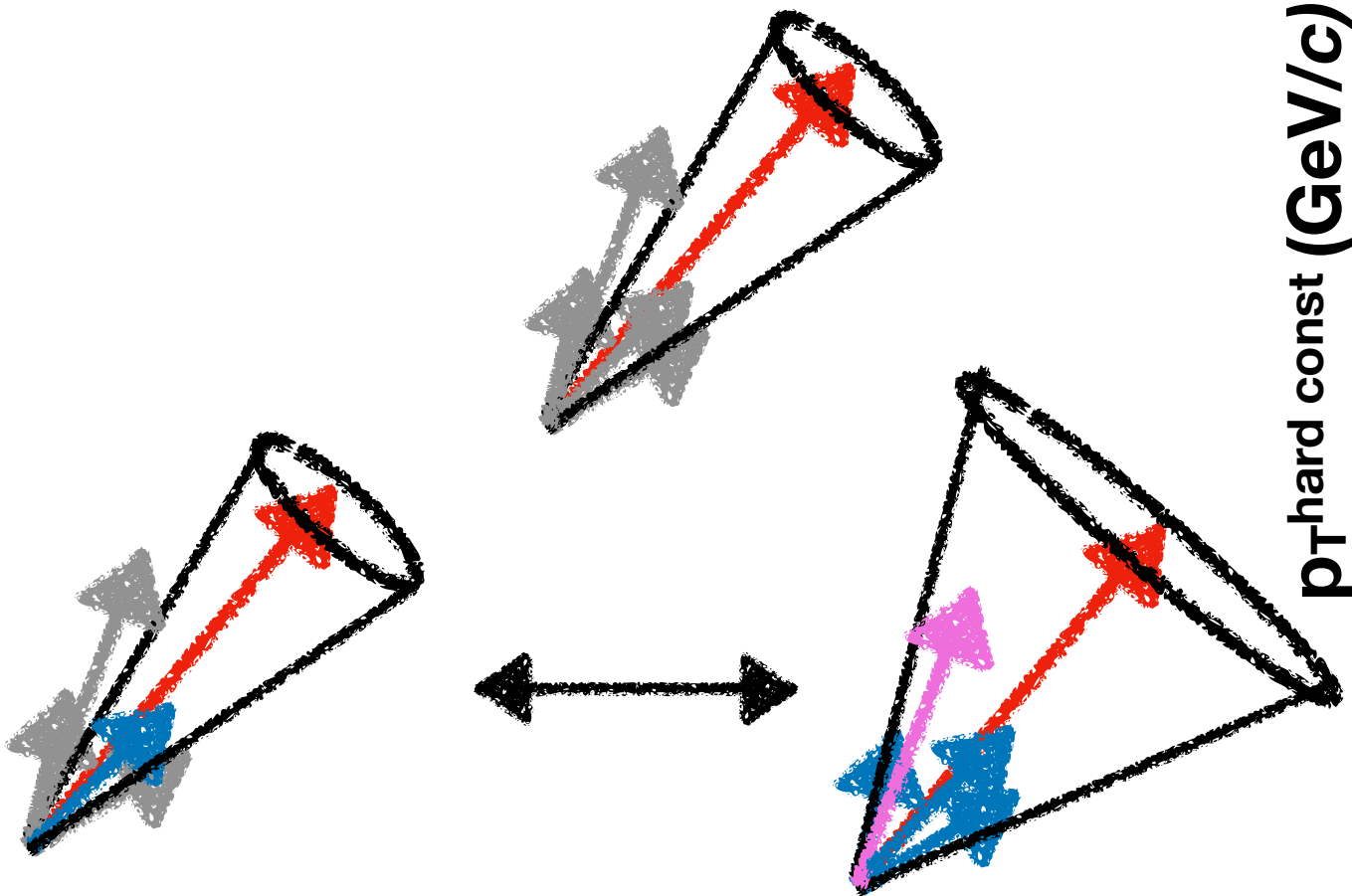
scan through matched jet radii ($R=0.2 \rightarrow 0.4$)

Radial scan of matched jets

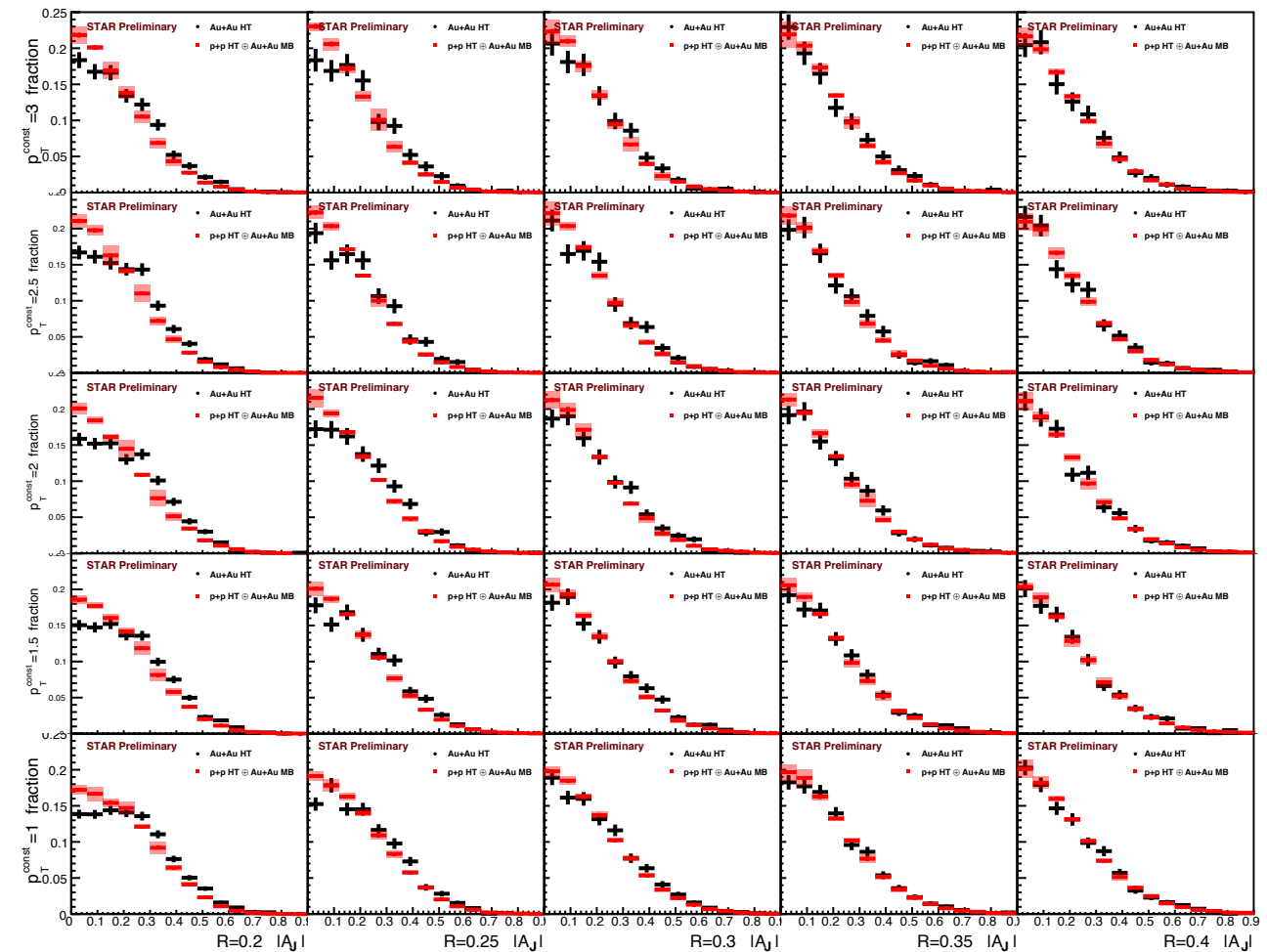
at what radius does a set of imbalanced hard core jets (R=0.2) recover its energy?

0-20% central
 $p_T^{\text{lead}} > 16 \text{ GeV}/c$
 $p_T^{\text{sublead}} > 8 \text{ GeV}/c$
 anti- k_T algorithm

fix hard-core jet at $R = 0.2$



$p_T^{\text{hard const}} (\text{GeV}/c)$



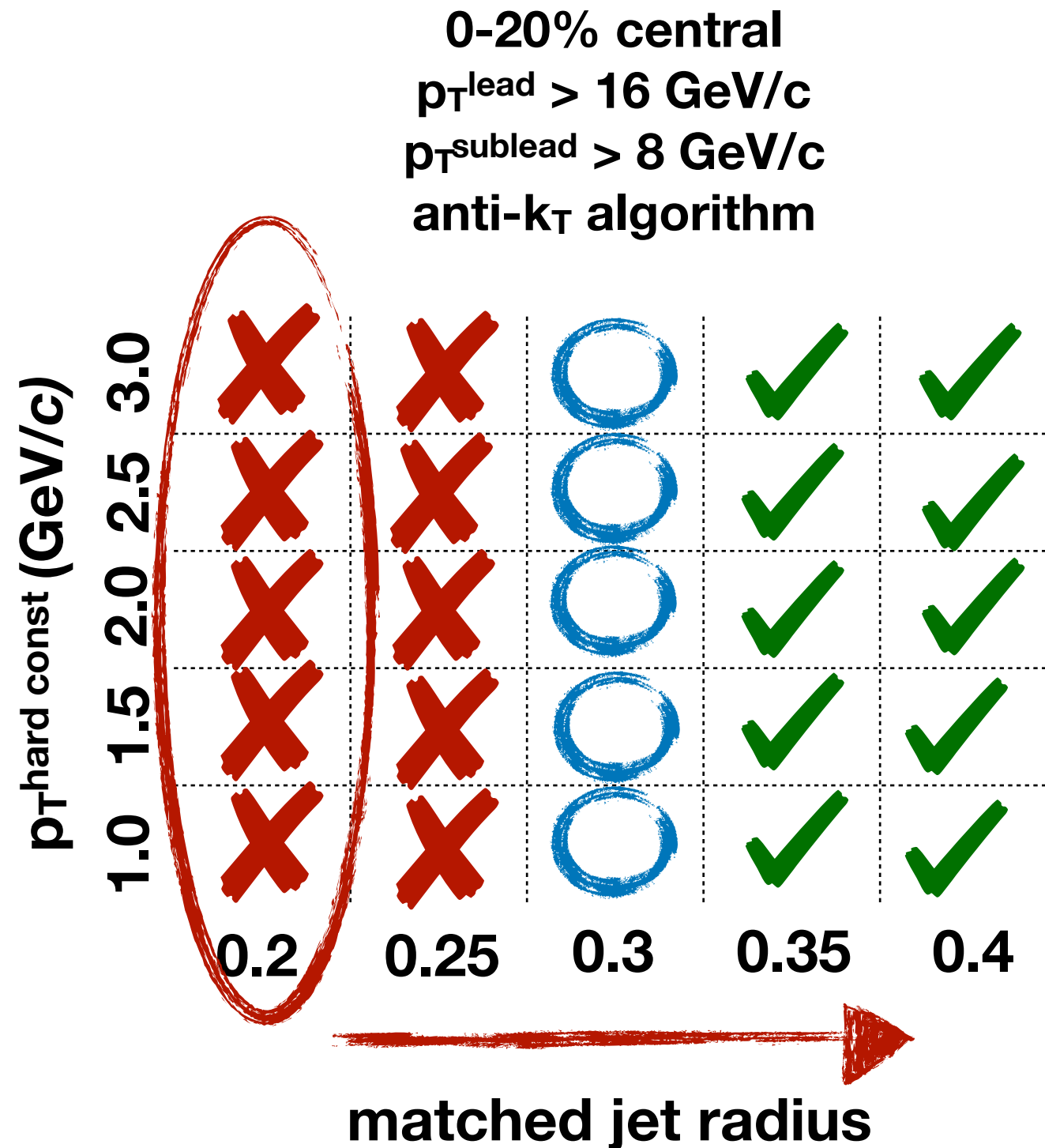
scan through matched jet radii (R=0.2 $\Rightarrow$ 0.4) matched jet radius

Radial scan of matched jets

at what radius does a set of imbalanced hard core jets ($R=0.2$) recover its energy?

→ radial modification is relatively independent on $p_{T\text{hard const}}$

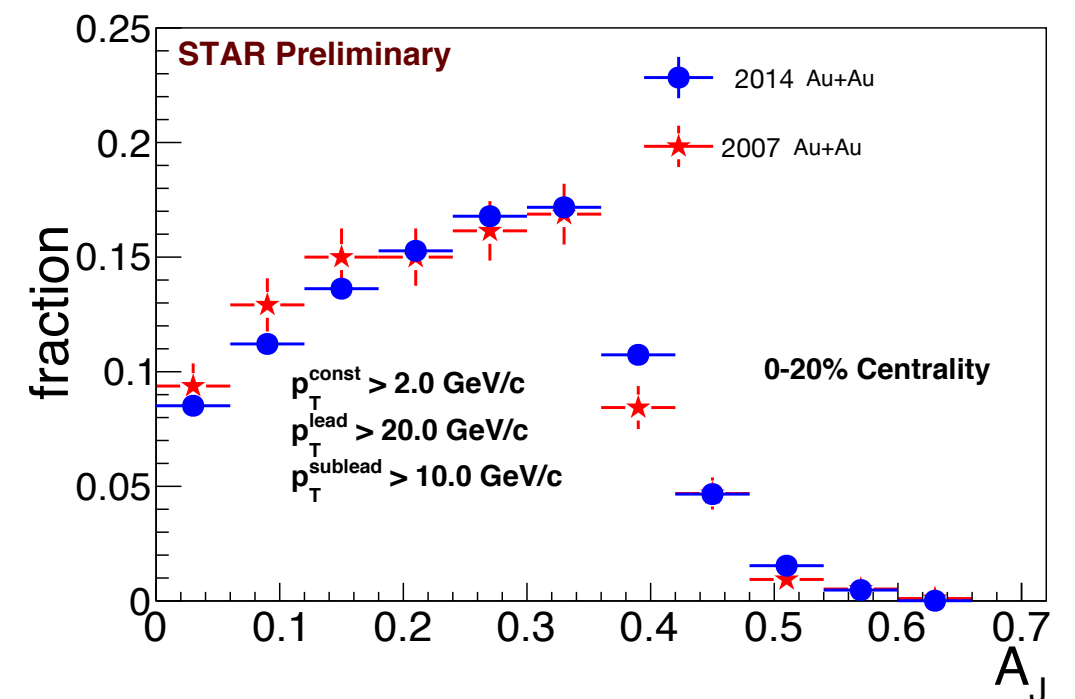
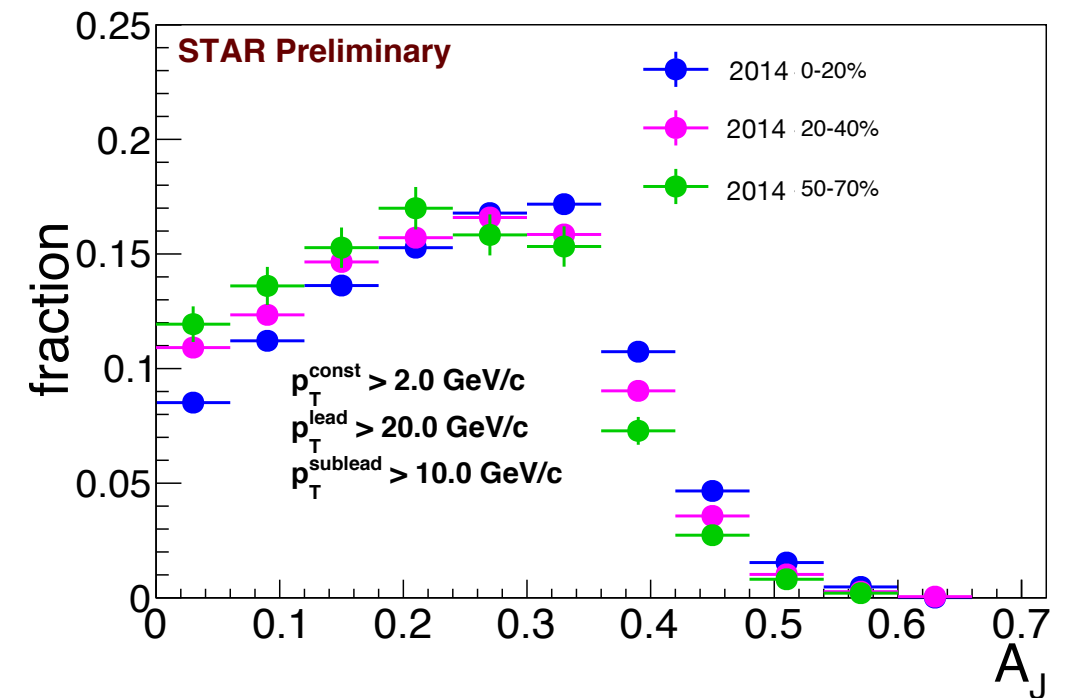
→ selecting narrower/harder/higher energy jets with $R = 0.2$



Moving forward

2014 Au+Au 200 GeV
20x increase in statistics

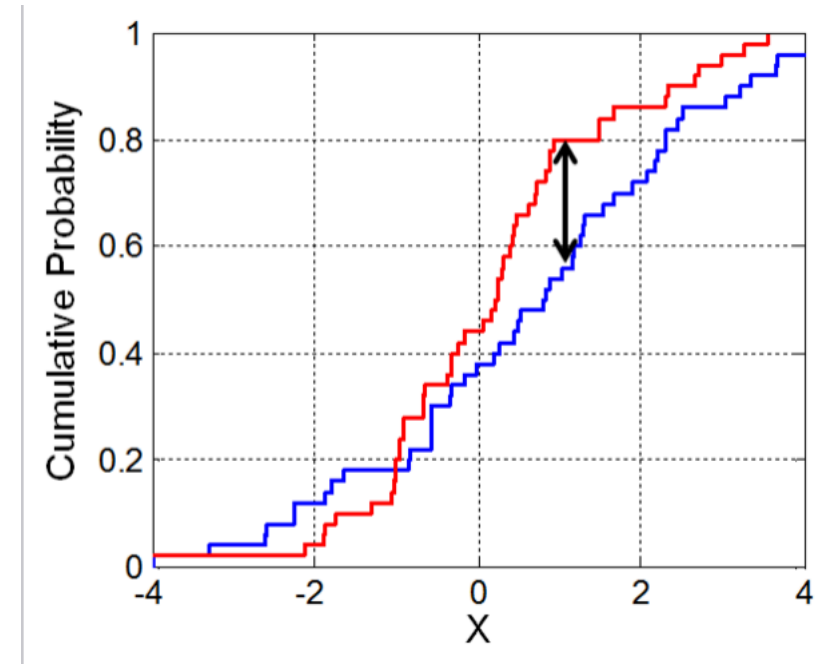
- allow for wider jet kinematic range
- centrality dependence



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

Kolmogorov-Smirnov two-sample test

- estimate the probability two data samples came from the same underlying distribution
- build the empirical distribution function (~CDF) for each dataset & find the maximal deviation between the two
- scale by an appropriate factor to generate a probability



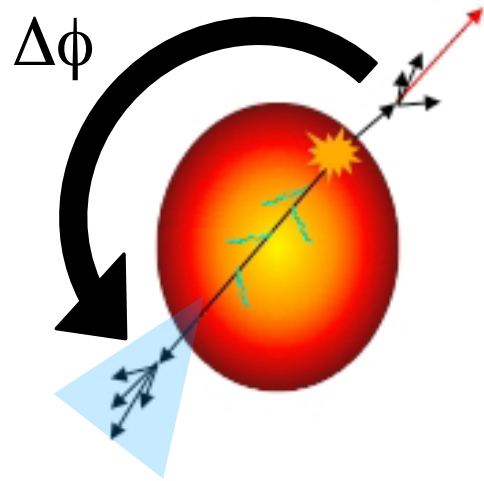
$$D_{n,m} = \sup_x |F_{1,n}(x) - F_{2,m}(x)|,$$

$$D_{n,m} > c(\alpha) \sqrt{\frac{n+m}{nm}}.$$

$$c(\alpha) = \sqrt{-\frac{1}{2} \ln\left(\frac{\alpha}{2}\right)}.$$

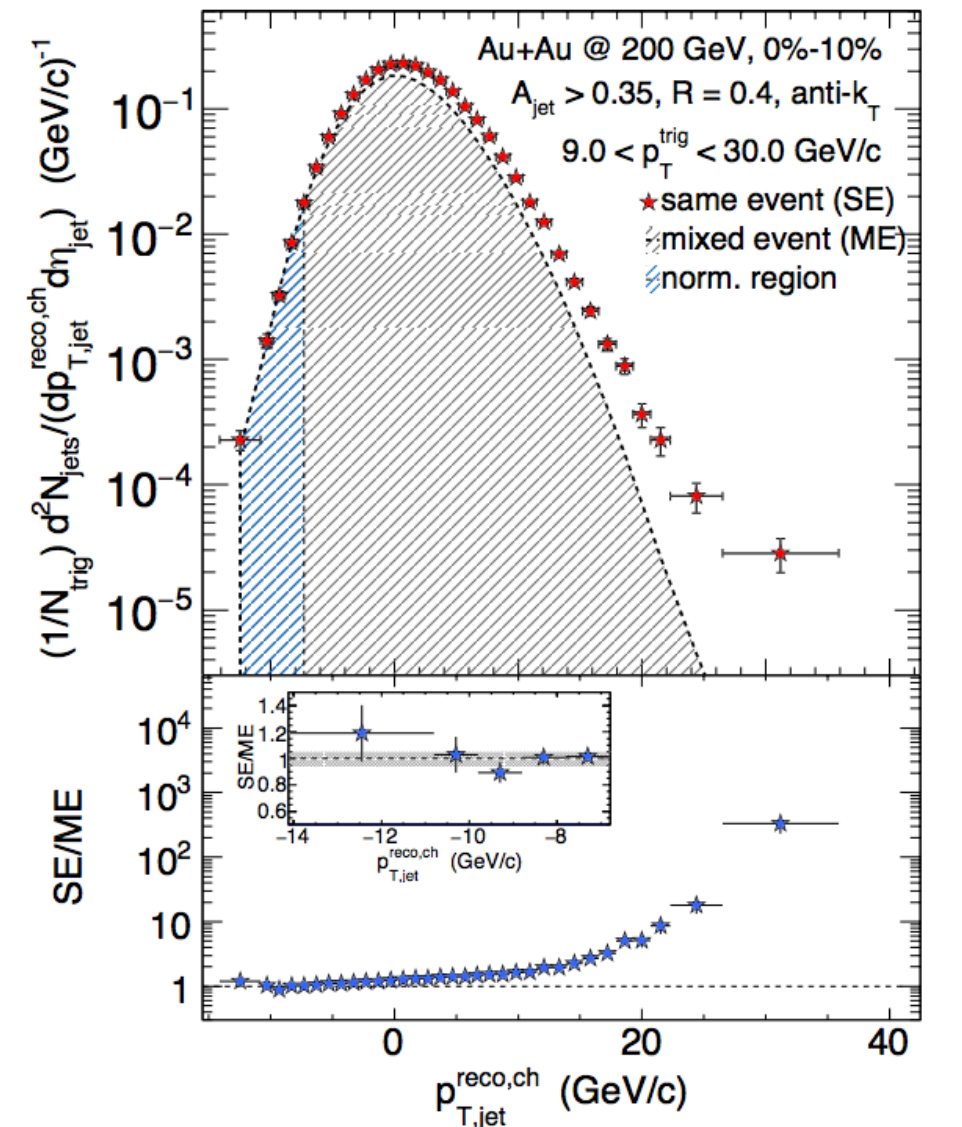
α	0.10	0.05	0.025	0.01	0.005	0.001
$c(\alpha)$	1.22	1.36	1.48	1.63	1.73	1.95

Hadron+jet spectra



semi-inclusive hadron-triggered
recoil jet spectra

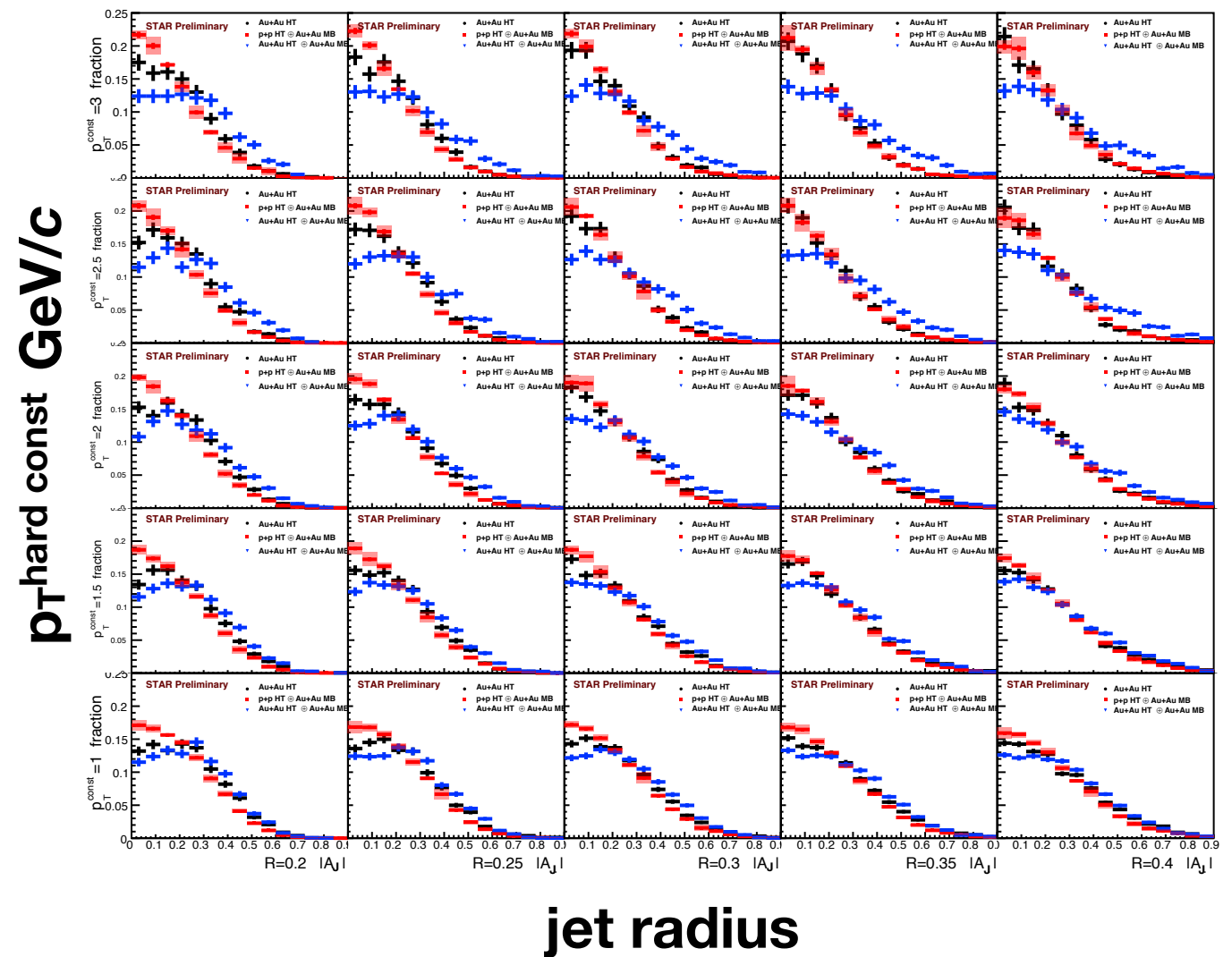
use of mixed-event
method to extend kinematic
reach to low jet p_T



STAR, Phys.Rev. C96, 024905 (2017)

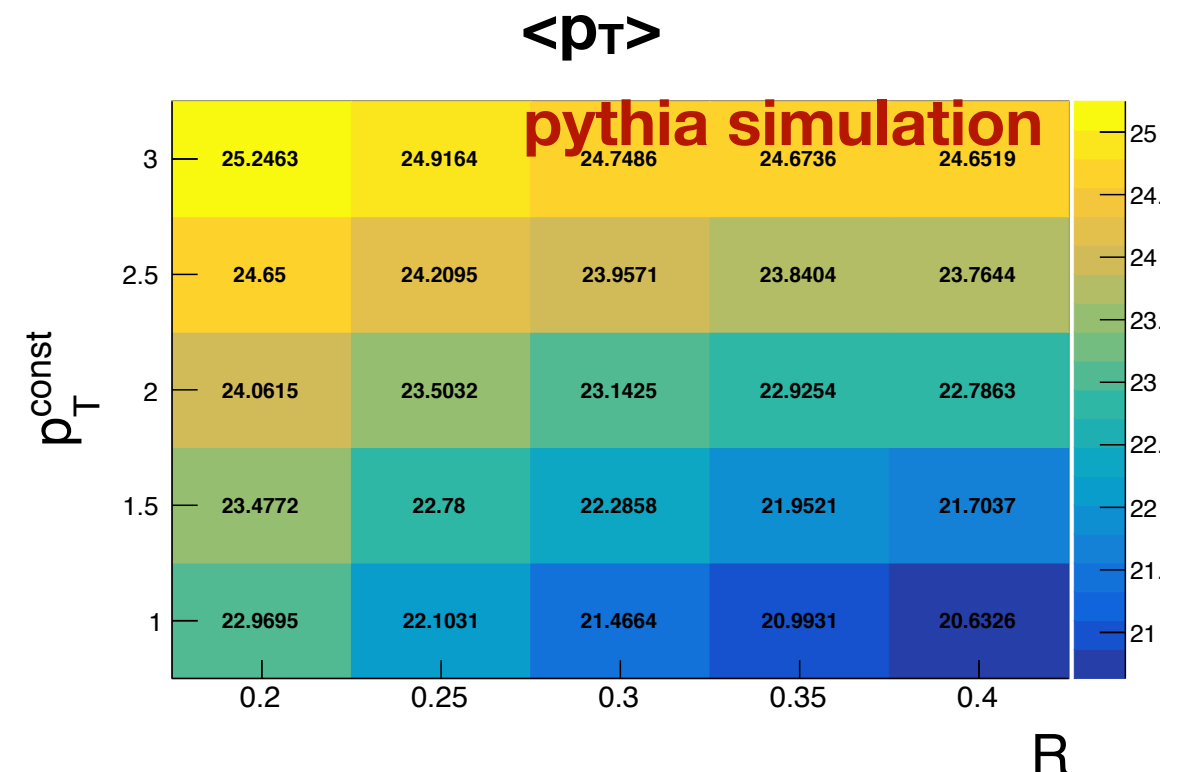
Estimate of the effect of background on balancing

- fluctuations in the background density can shift the A_J distribution
- estimate the sensitivity of our measurement to correlated signal yield by **embedding hard-core jets into random MB events**
- quantify sensitivity using K-S test to evaluate the difference between **Au+Au** and **Au+Au hard-core embedded in random MB events**

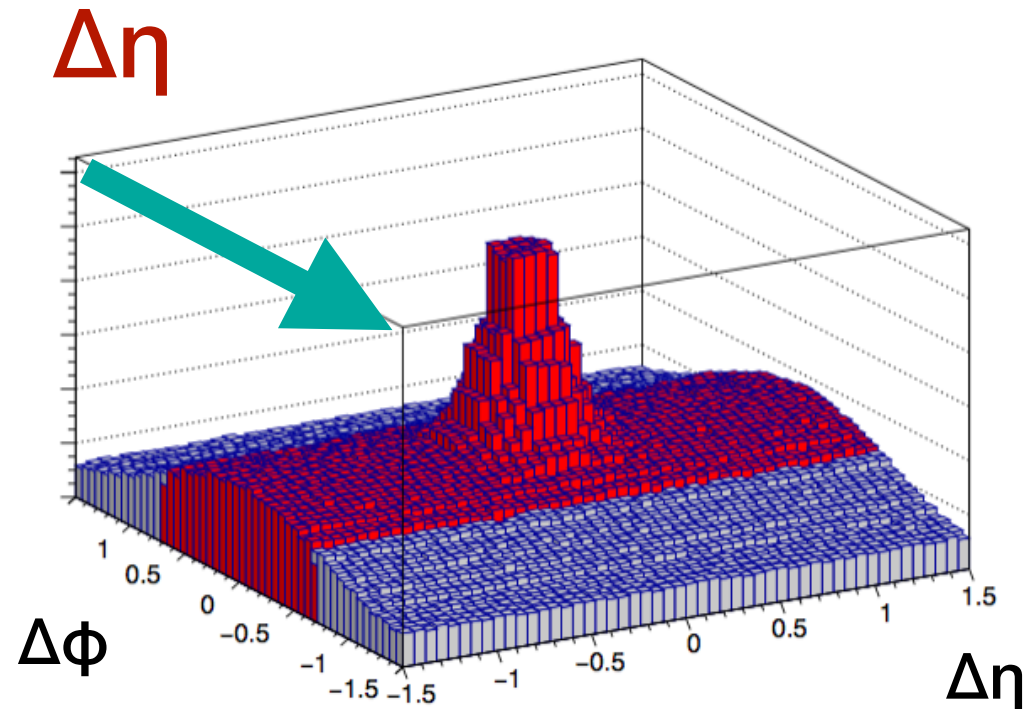


Estimation of the effect of jet definition on jet kinematics in vacuum

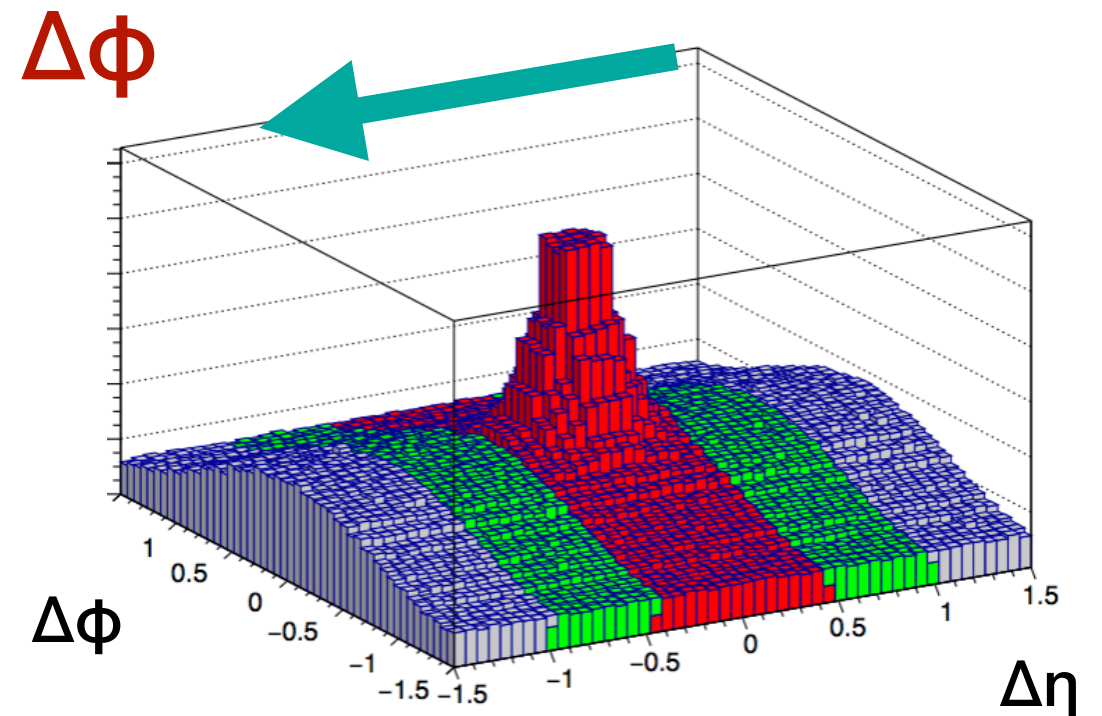
- using pythia, estimate the average p_T^{hat} for each jet definition
- narrower, harder constituent cut jets on average come from higher energy processes



Background subtraction in di-jet hadron correlations

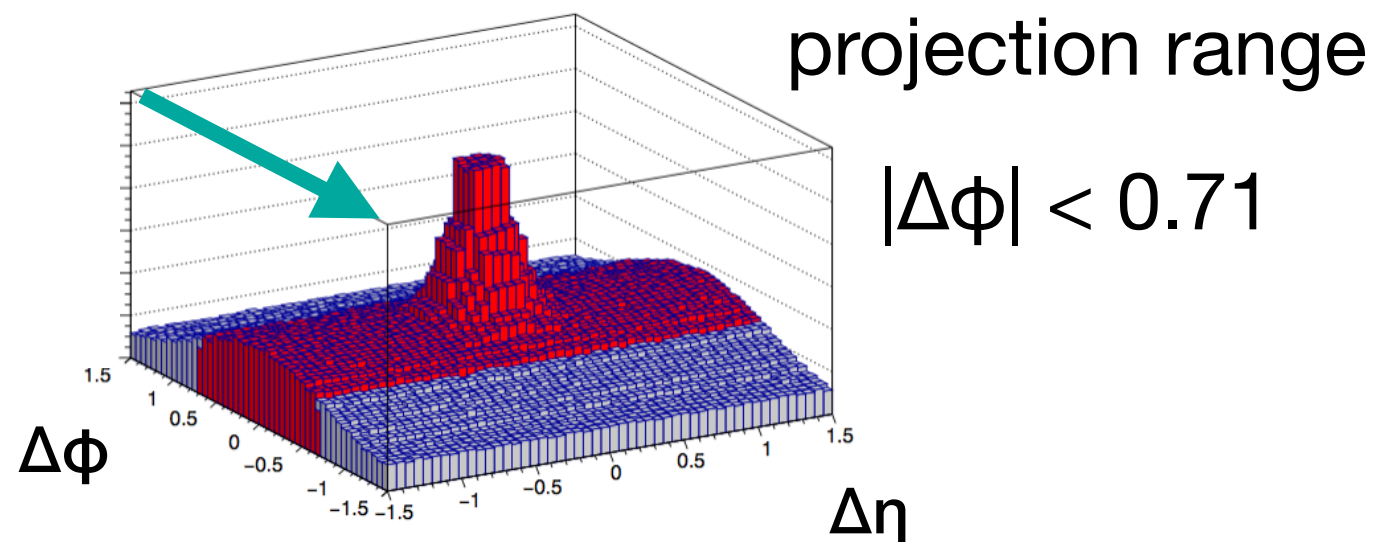


fit with a constant+gaussian
constant subtracted as
background

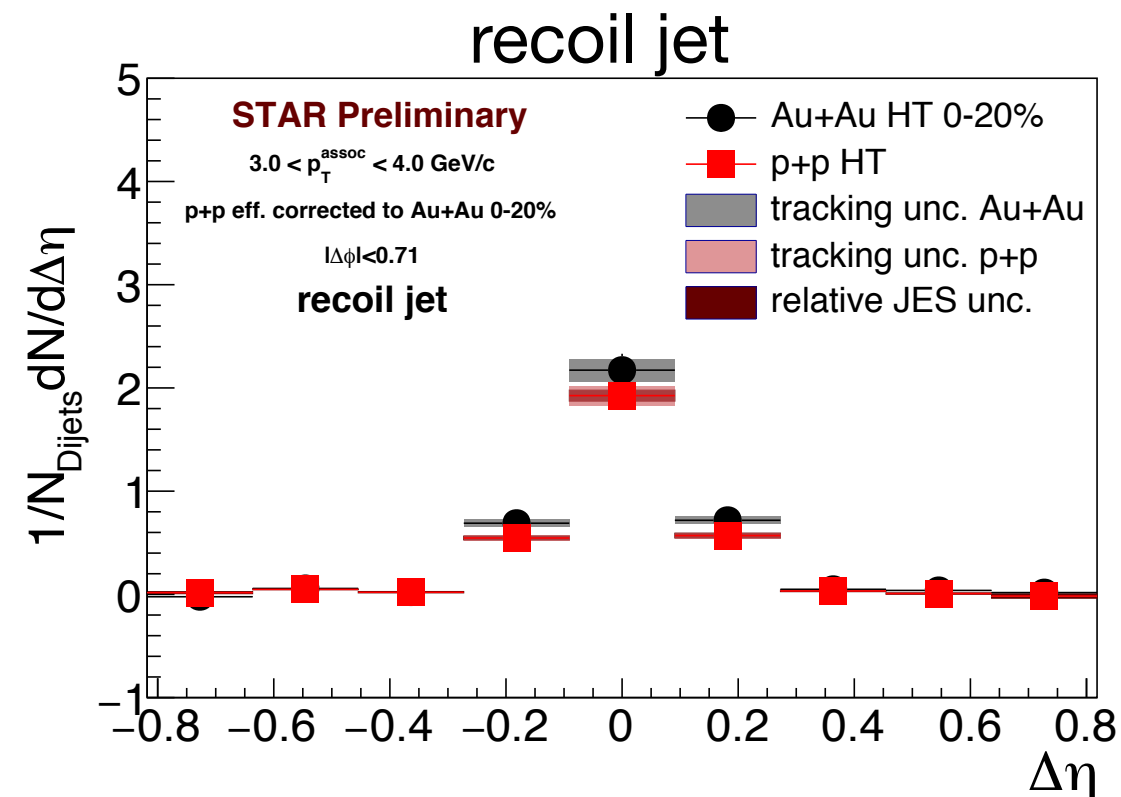
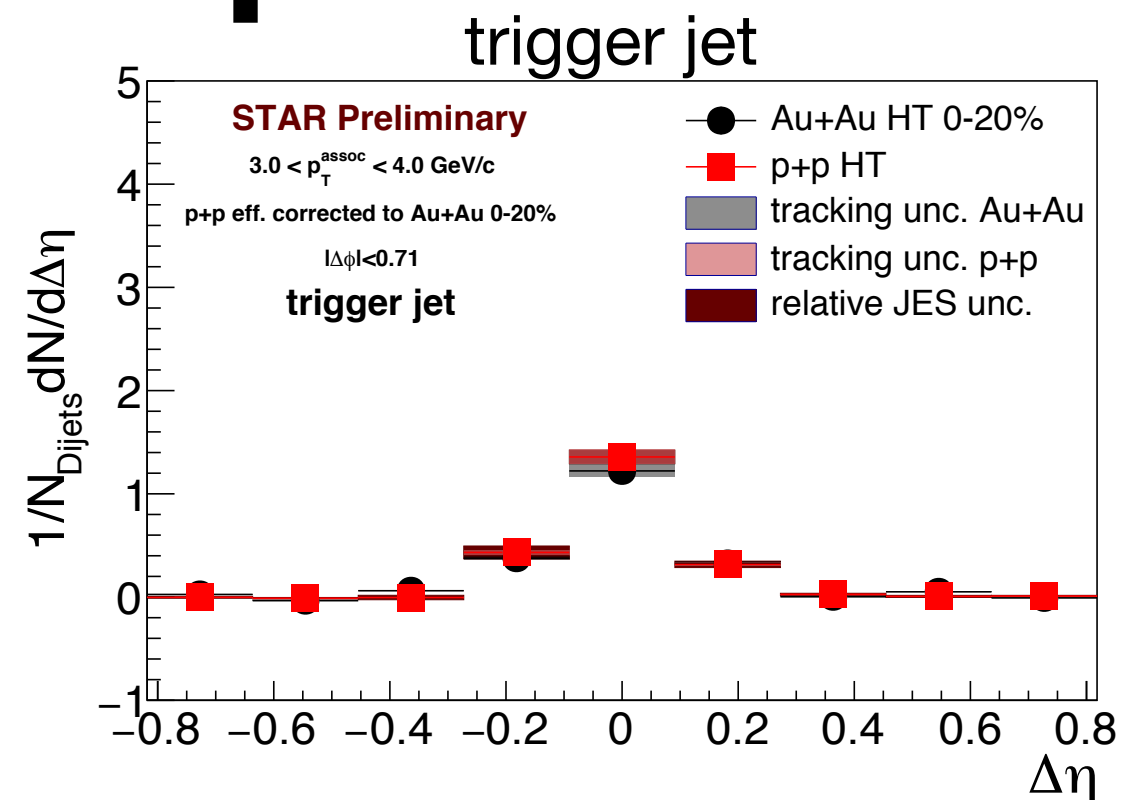


use sideband subtraction to
account for flow in underlying
event

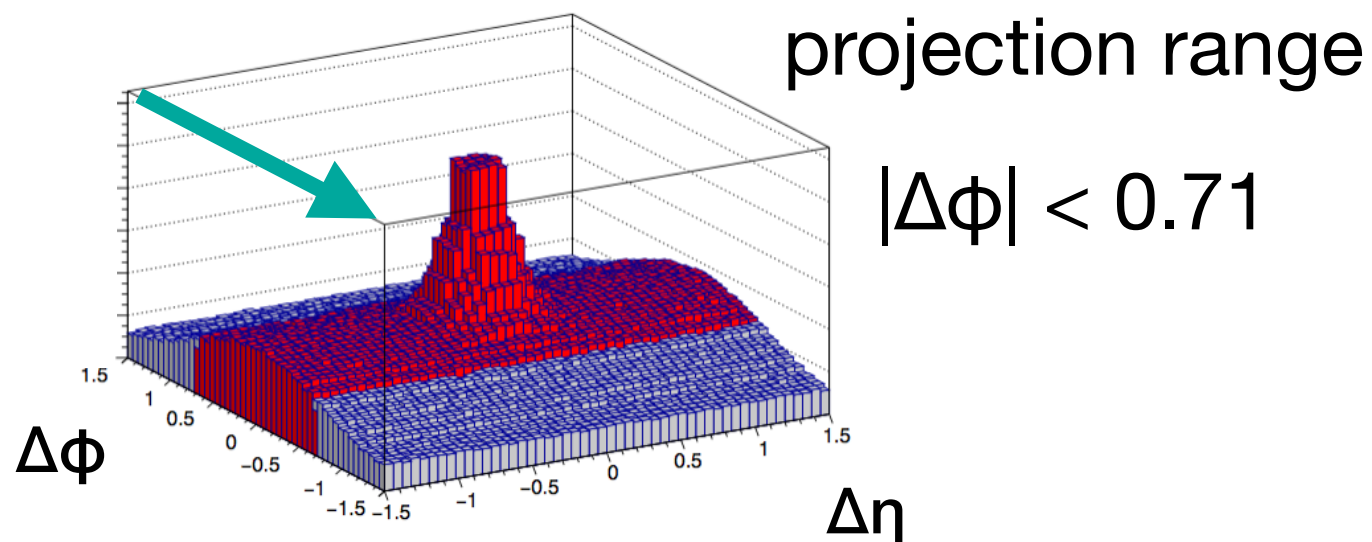
Correlations in $\Delta\eta$ $3.0 < p_T^{\text{assoc}} < 4.0 \text{ GeV/c}$



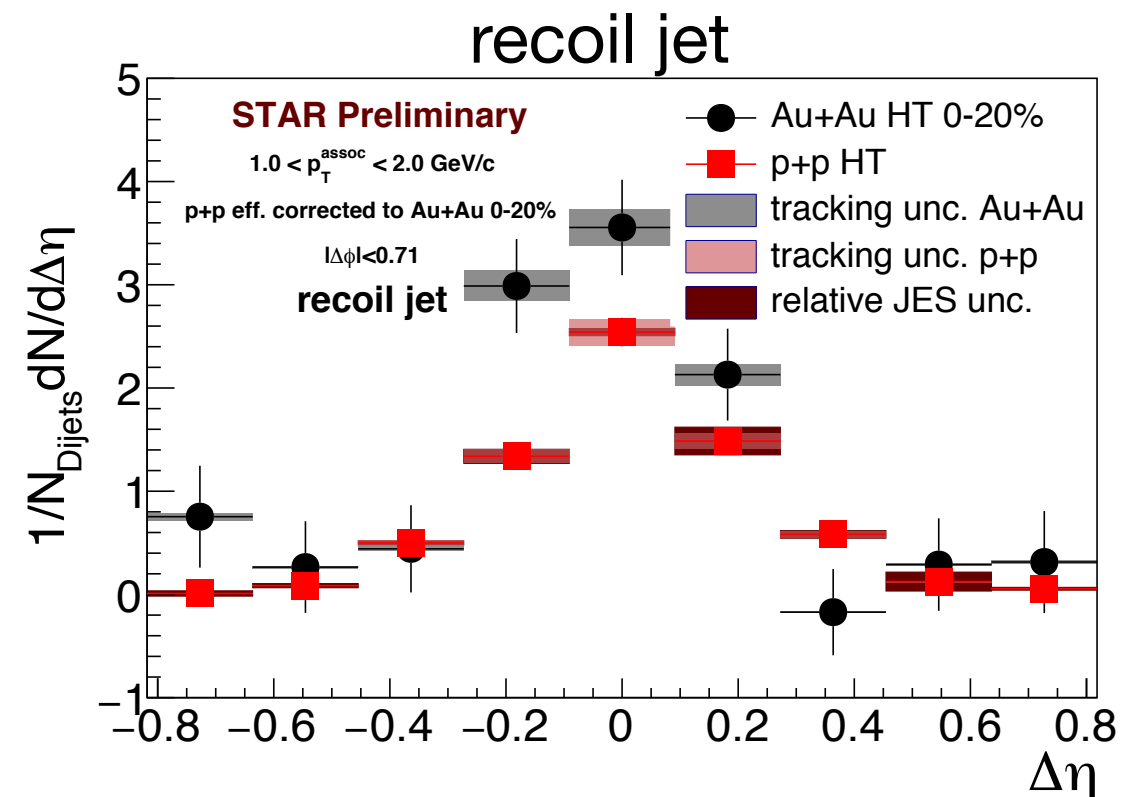
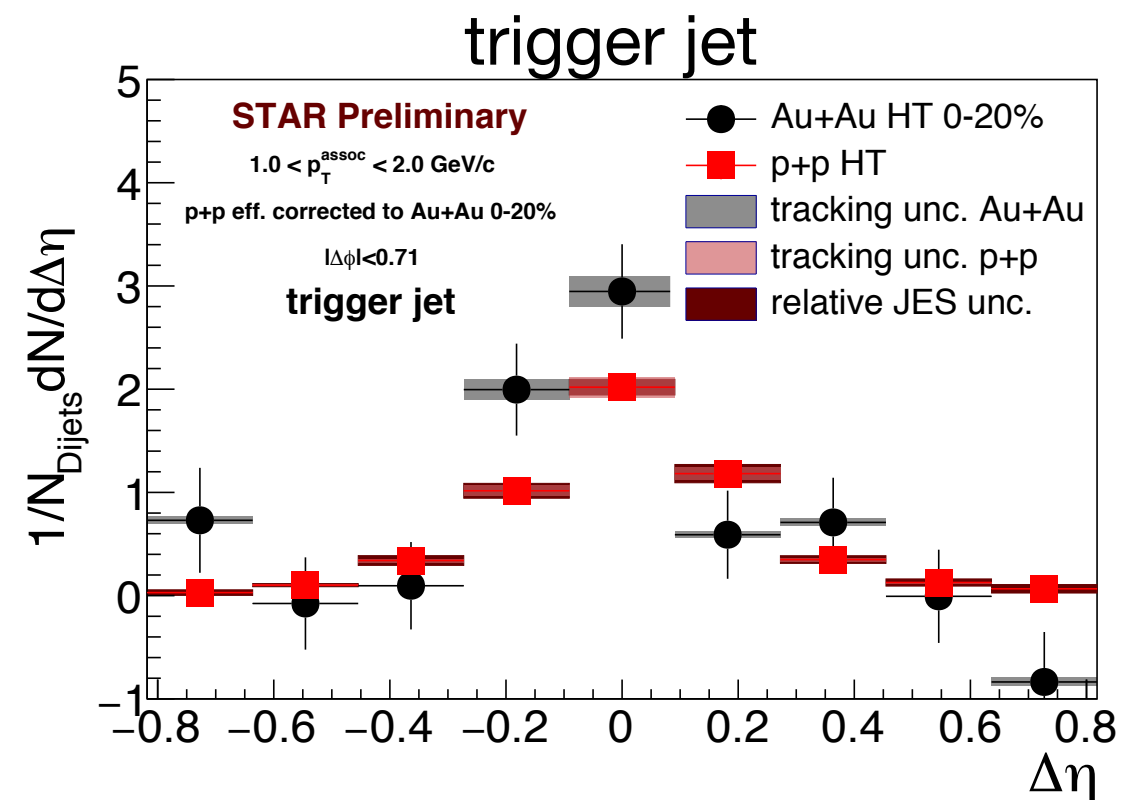
yield contained within
jet radius $R=0.4$



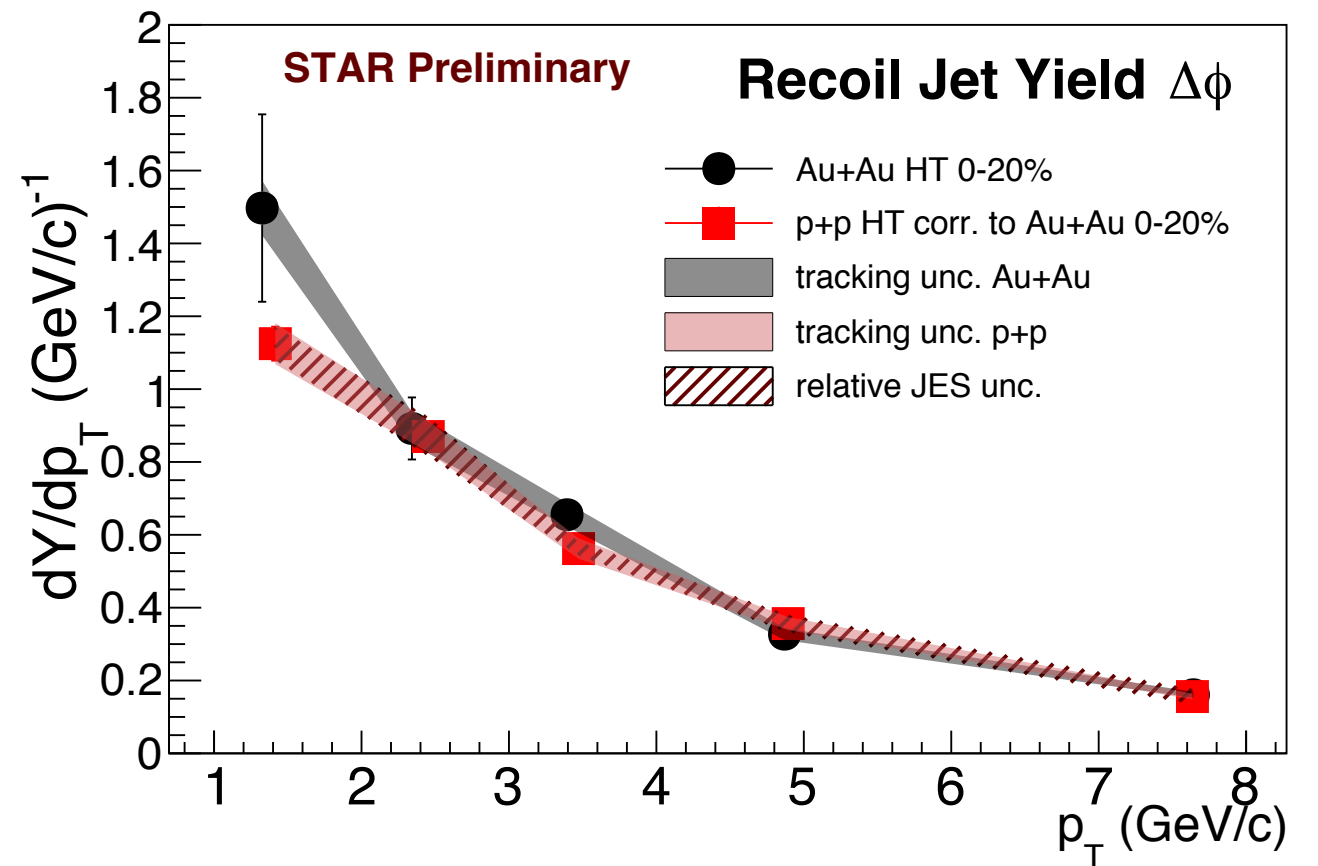
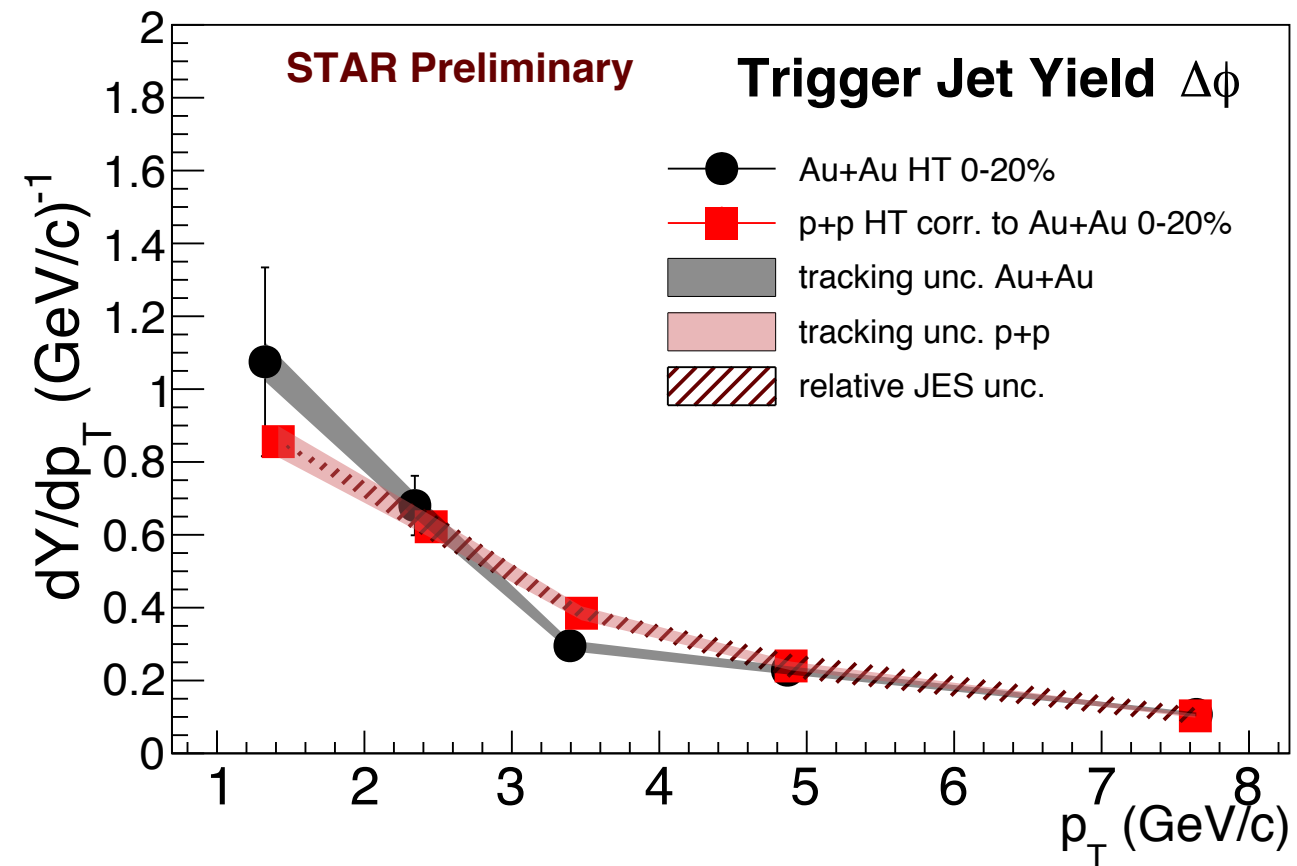
Correlations in $\Delta\eta$ $1.0 < p_T^{\text{assoc}} < 2.0 \text{ GeV}/c$



yield contained within
jet radius $R=0.4$



Yields in $\Delta\phi$



Consistent with A_J ?

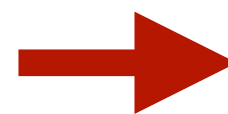
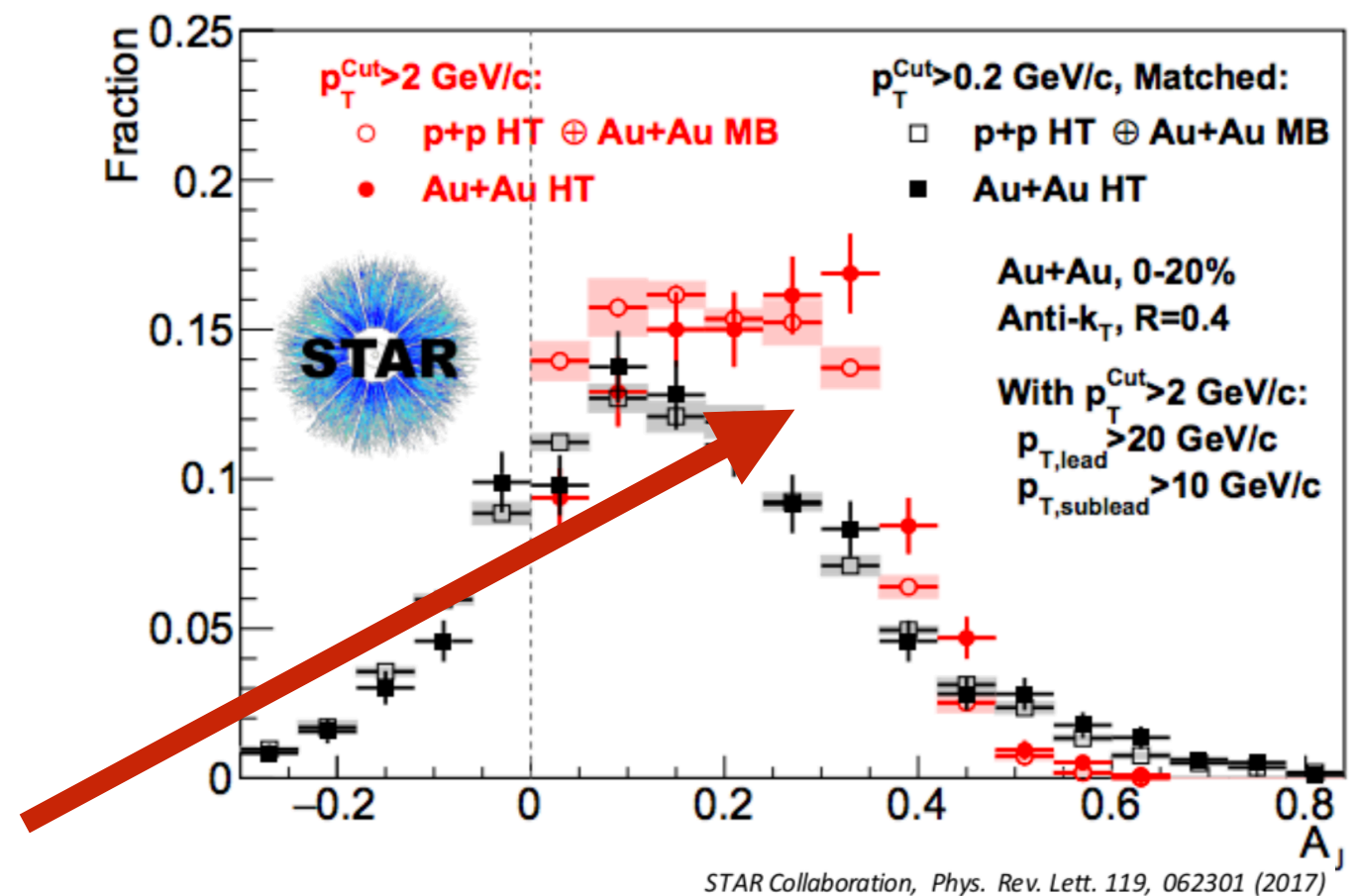
minimal modification
at high p_T for both trigger
& recoil jets

possible enhancement at
low p_T in recoil jet

A_J enhances sensitivity
to modification

effect is diluted in ensemble
measurements like
di-jet hadron correlations

Why a small effect?



more differential:
select on A_J ?