Systematic studies of di-jet imbalance measurements at STAR

- Jet geometry engineering -

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WAYNE STATE

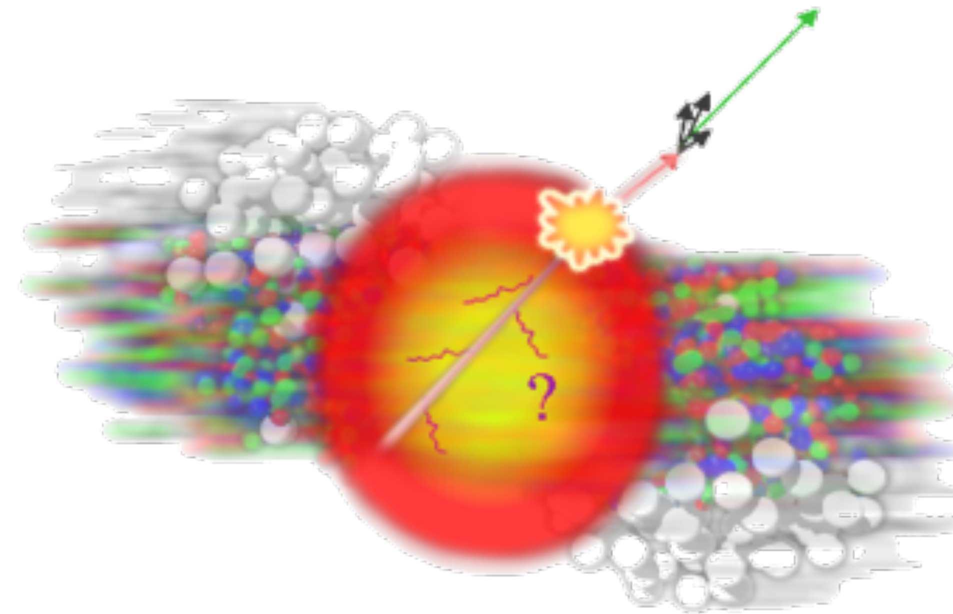
STAR

Jet quenching in a nutshell

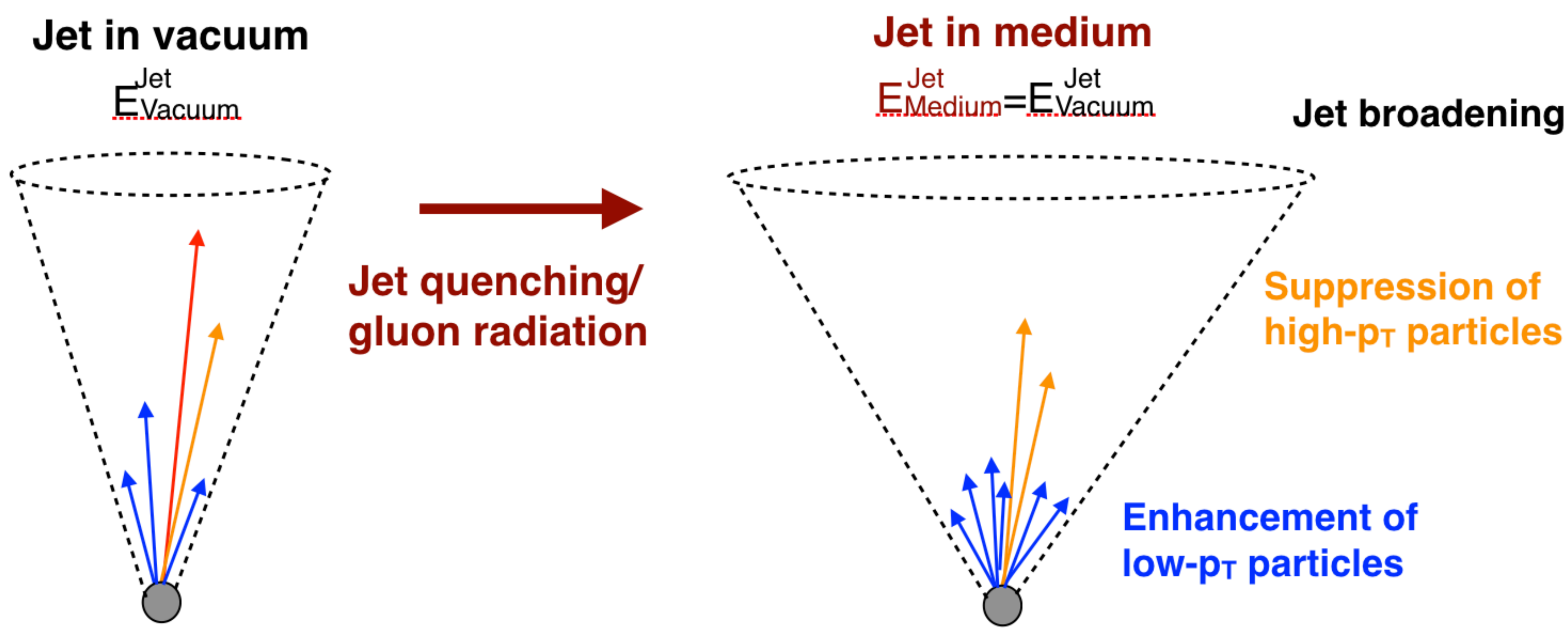
partonic energy loss

→ gluon radiation (**primary**)

→ collisional energy loss (small)



→ broadening and softening



Jet production at RHIC & LHC

orders of magnitude difference in jet production cross section

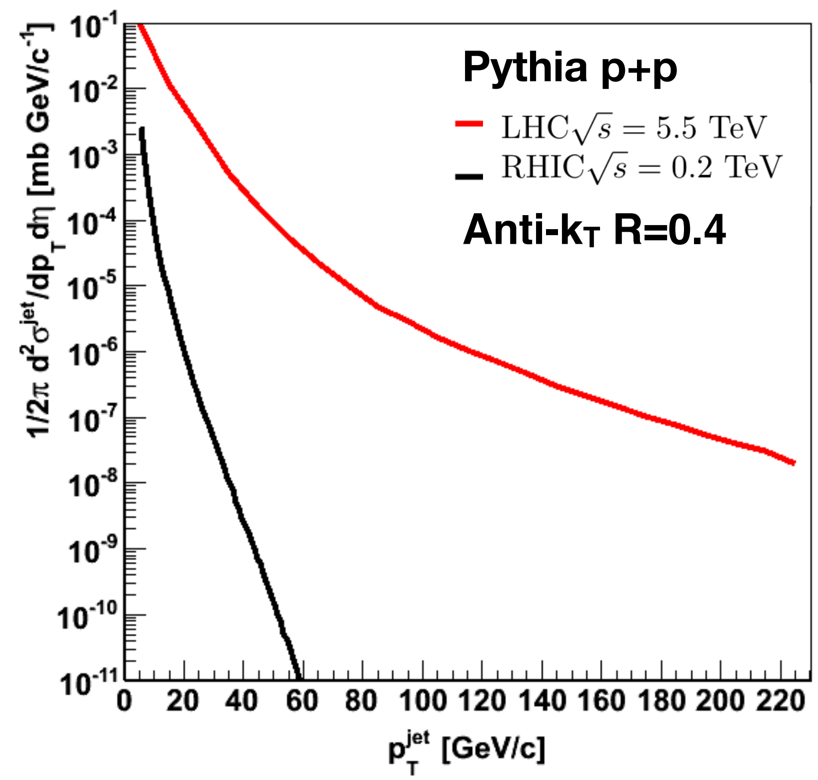
trigger: high-p_T hadron, jet w/ constituent cut, etc

models (Renk, Zapp,…) predict that with the softer **RHIC** spectrum

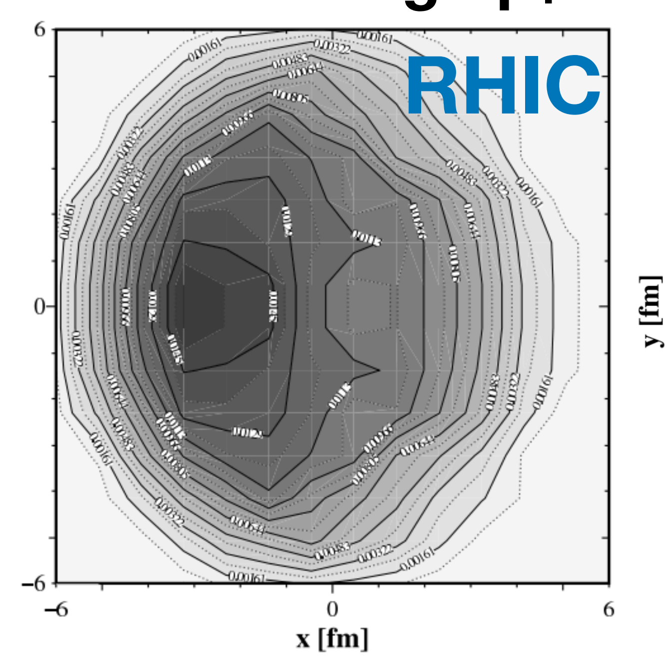
trigger → surface bias

however, at the higher **LHC** energies,

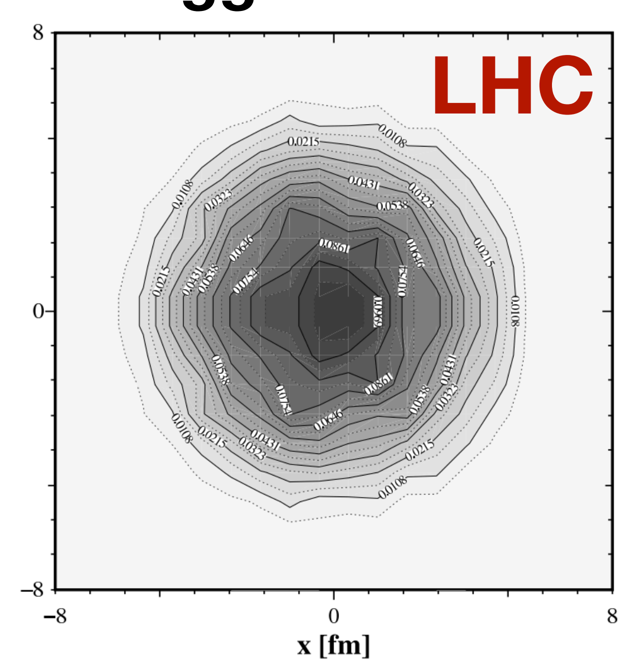
trigger → no surface bias



high p_T hadron trigger



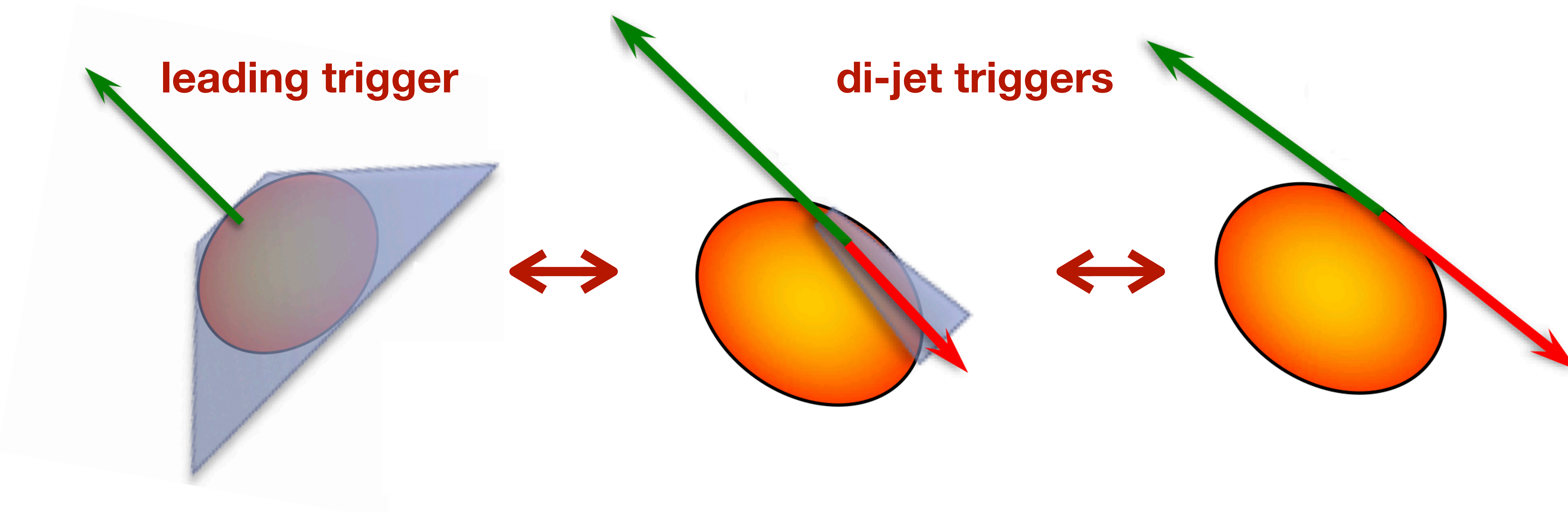
Renk, Phys.Rev. C 87, 024905 (2013)



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)

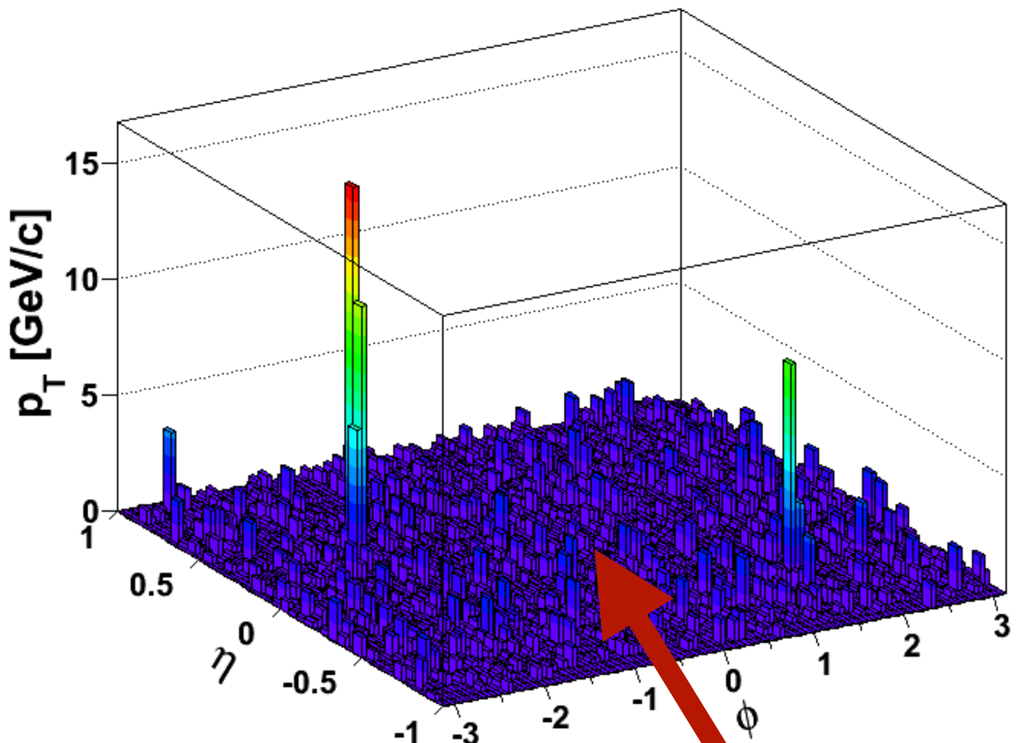
di-jet imbalance, di-jet hadron correlations

2+1 correlations

STAR, PRC 83 061901 (2011)
STAR, PRC 87 44903 (2013)

Hard core jets at STAR

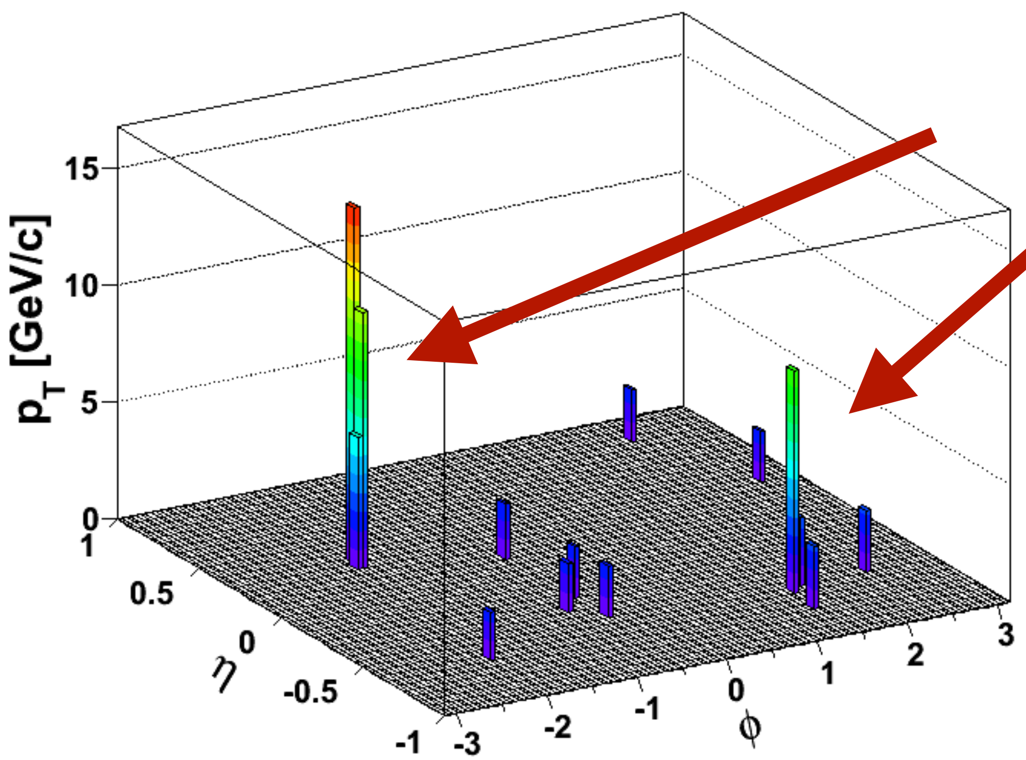
in a heavy-ion collision



large background energy density

Hard core jets at STAR

in a heavy-ion collision



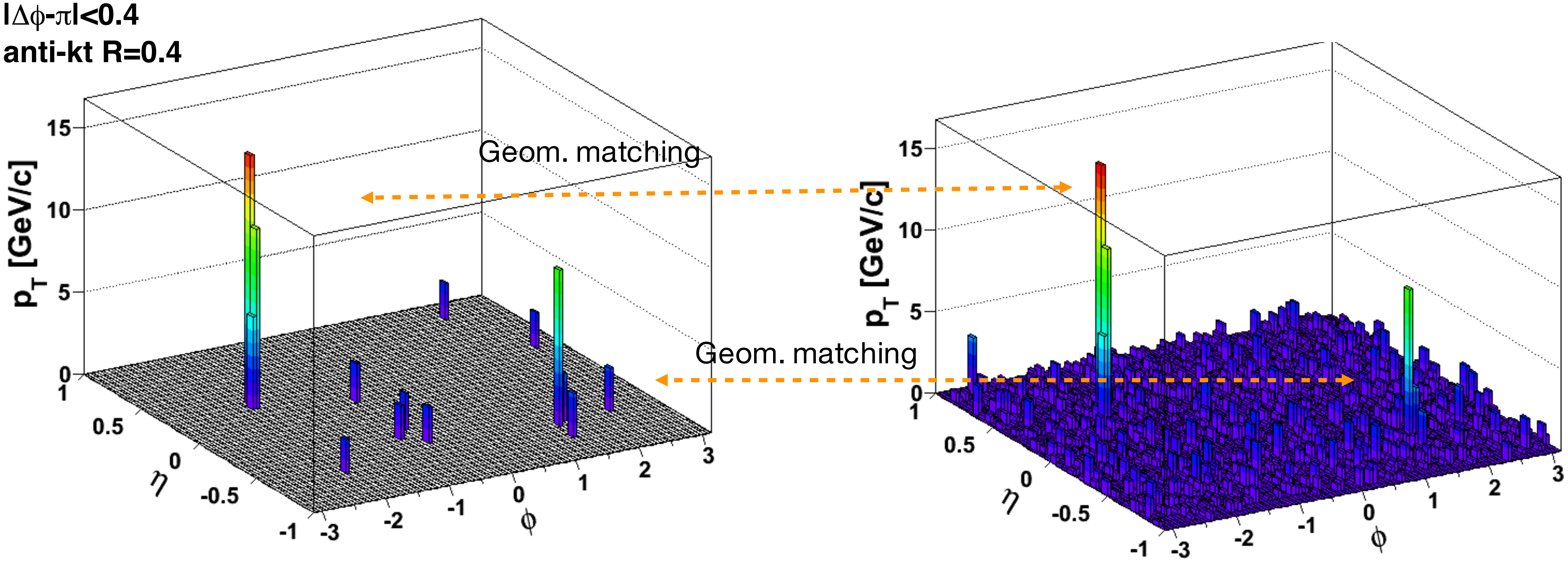
clear jet signal

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

Hard core jets at STAR

in a heavy-ion collision

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



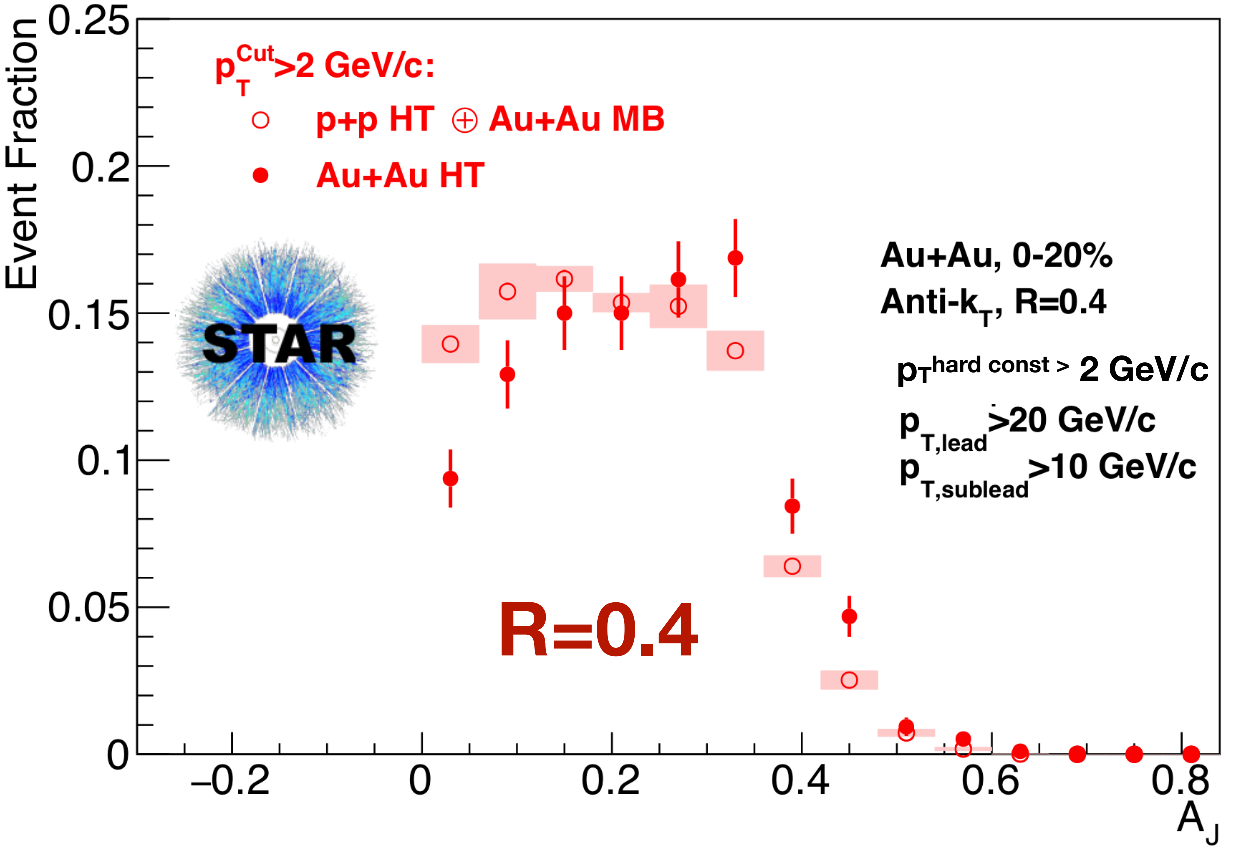
$p_T^{hard\ const} > 2$ GeV/c cut → removes almost all background

geometric matching $p_T^{match\ const} > 0.2$ GeV/c → no combinatoric jets, recover all constituents

Di-jet asymmetry at STAR

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

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



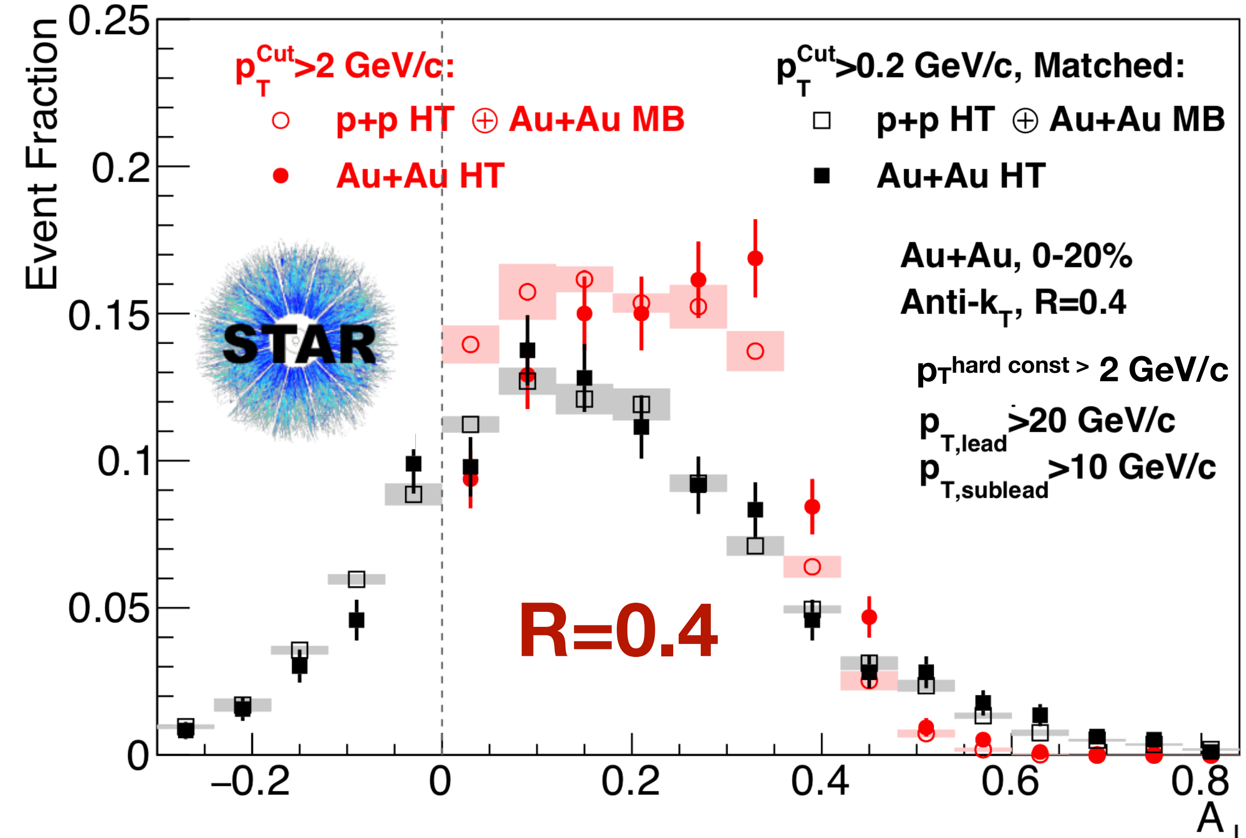
STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Di-jet asymmetry at STAR

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

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

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



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

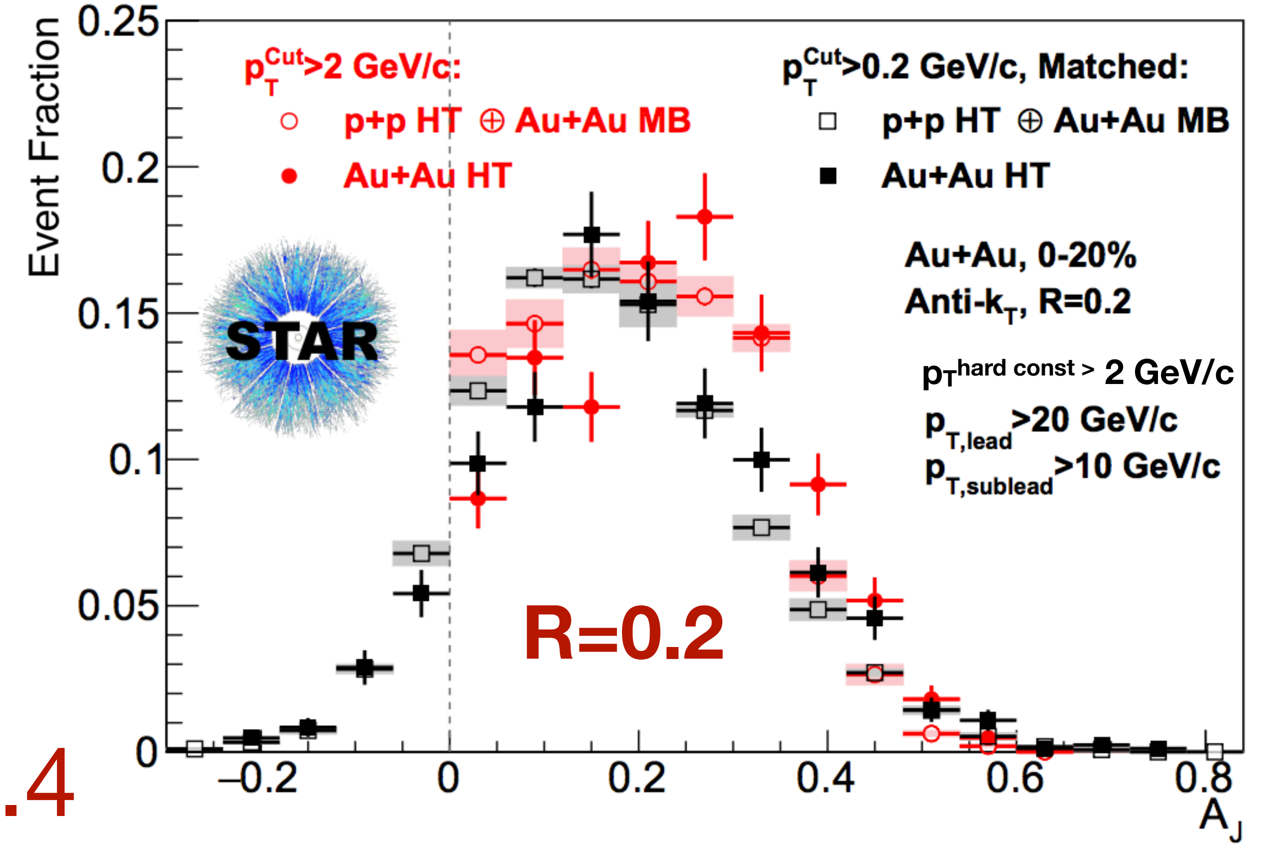
Di-jet asymmetry at STAR

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

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



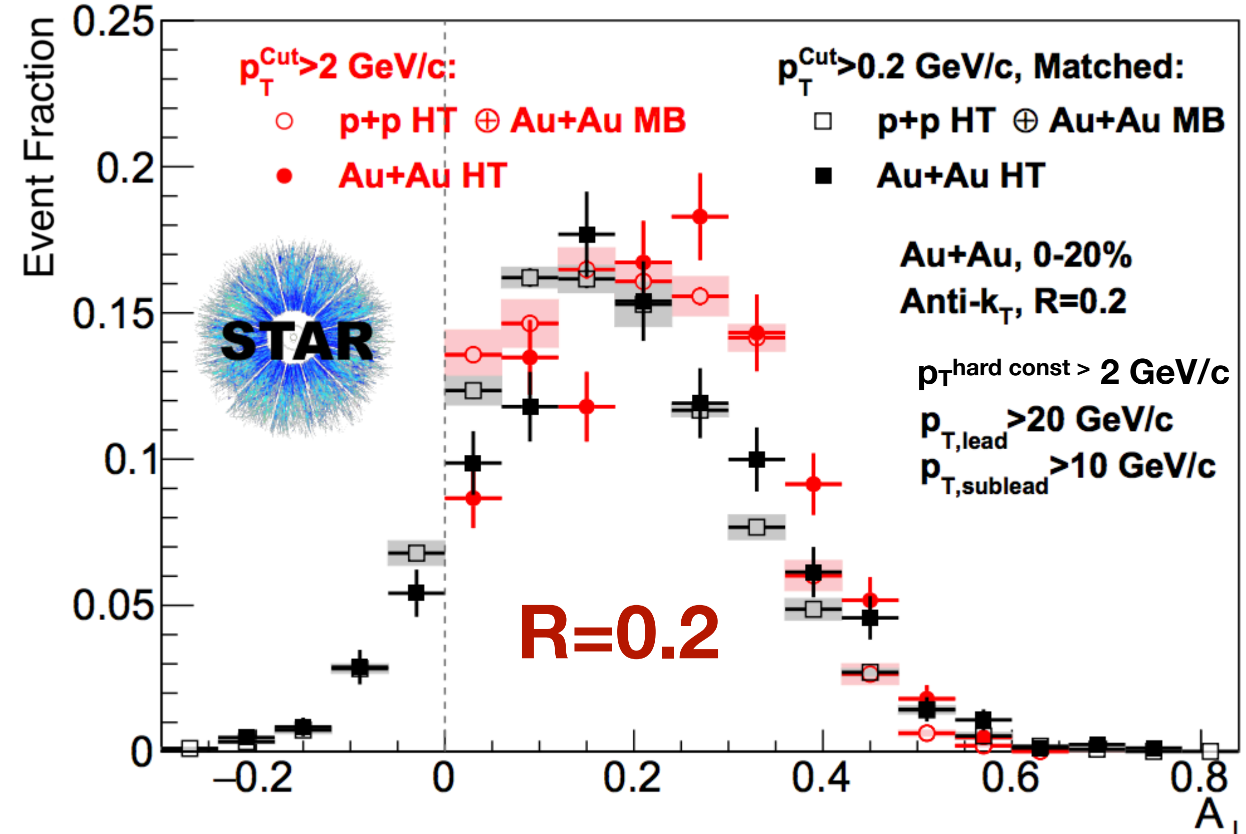
STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Di-jet asymmetry at STAR

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

A_J is insensitive to the details of which jet is modified

→ di-jet hadron correlations



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

Di-jet hadron correlations

di-jet definition

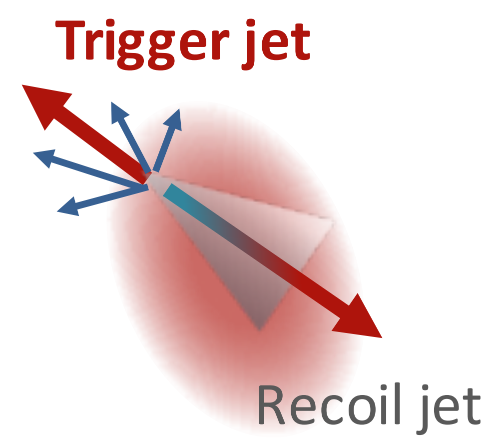
$p_T^{hard\ const} > 2$ GeV/c

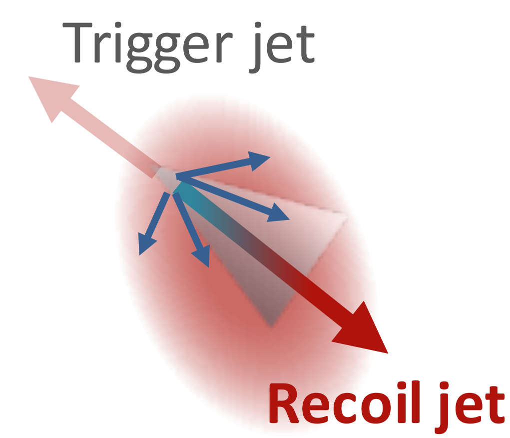
$p_T^{Lead} > 20$ GeV/c

$p_T^{SubLead} > 10$ GeV/c

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

anti-k_T R = 0.4





correlations

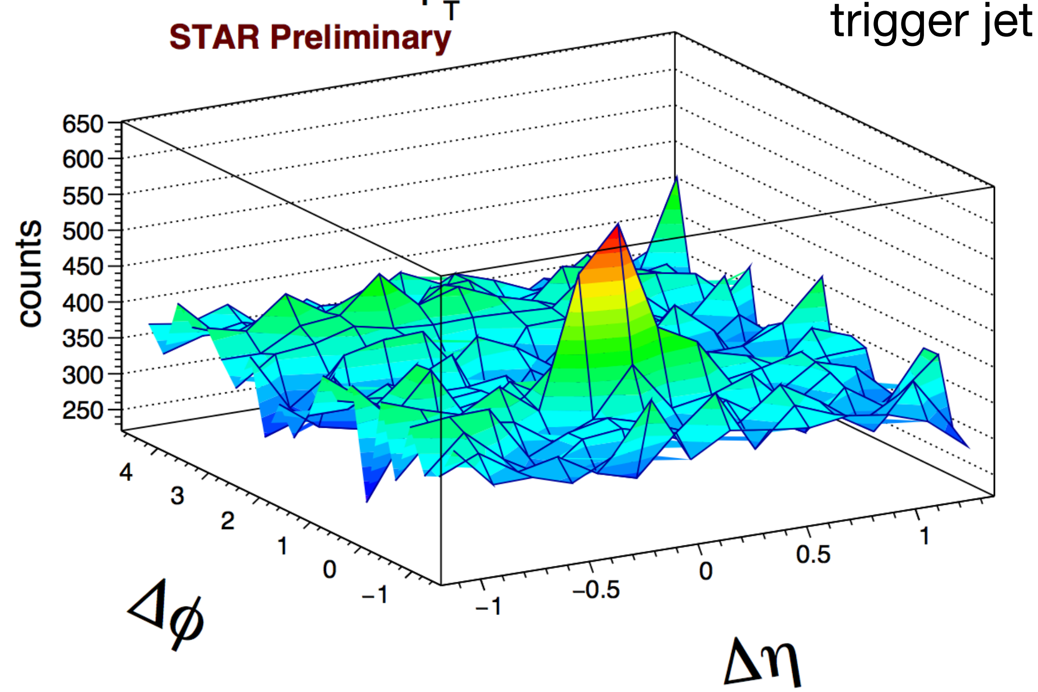
$\Delta\eta = \eta^{jet} - \eta^{track}$

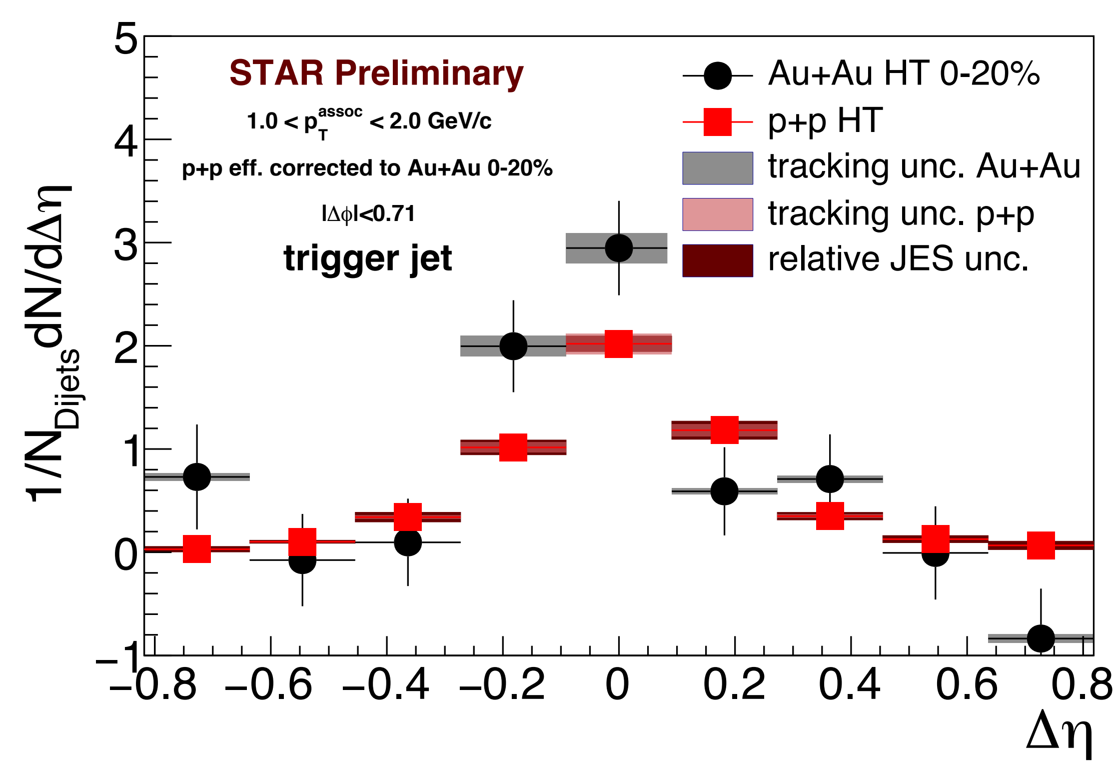
$\Delta\varphi = \varphi^{jet} - \varphi^{track}$

trigger jet: require EMCal hit w/ $E_T > 5.4$ GeV

recoil jet: back-to-back with trigger jet

Au+Au
0-20% central



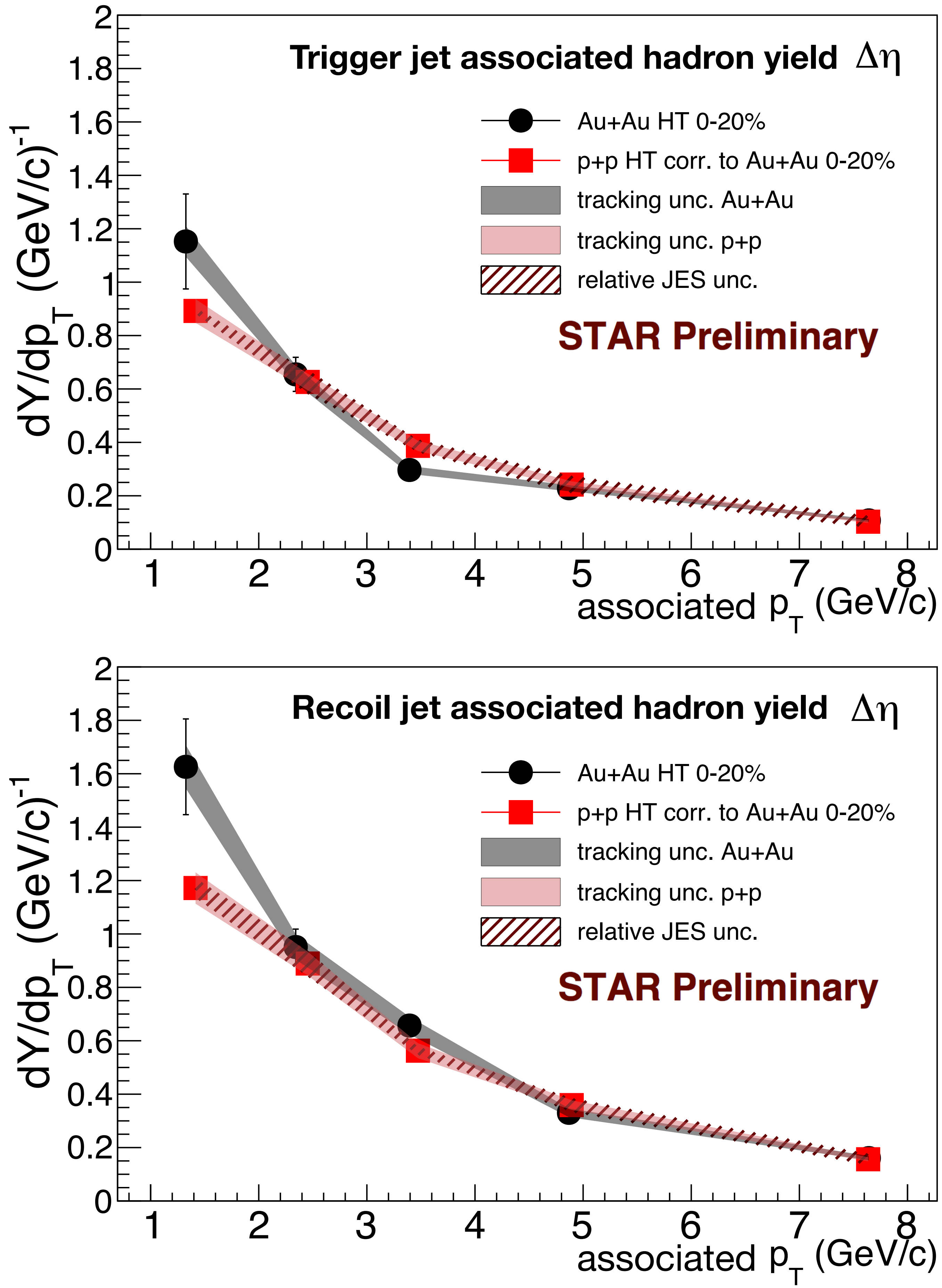


Correlated jet yield

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^{assoc}<2.0 GeV/*c*

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

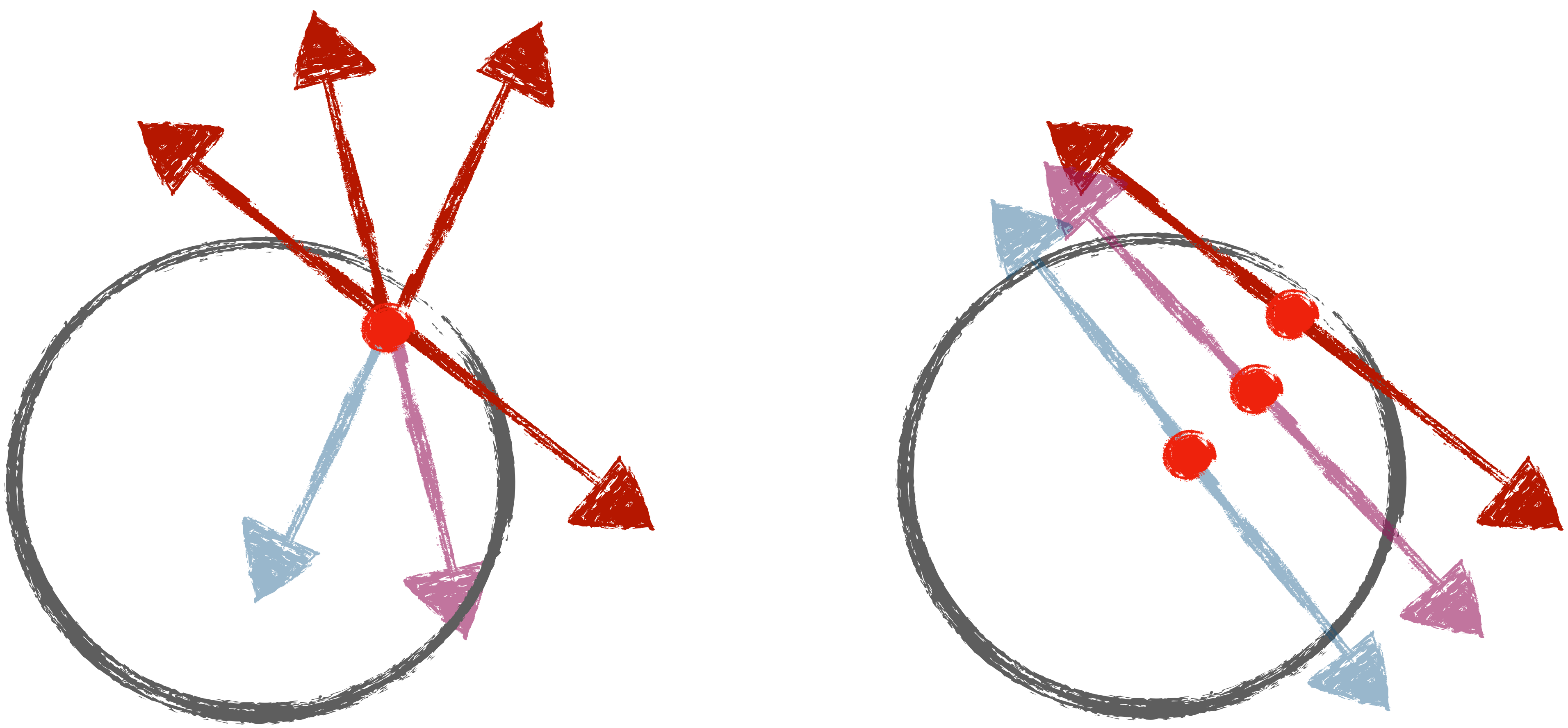


Jet geometry engineering

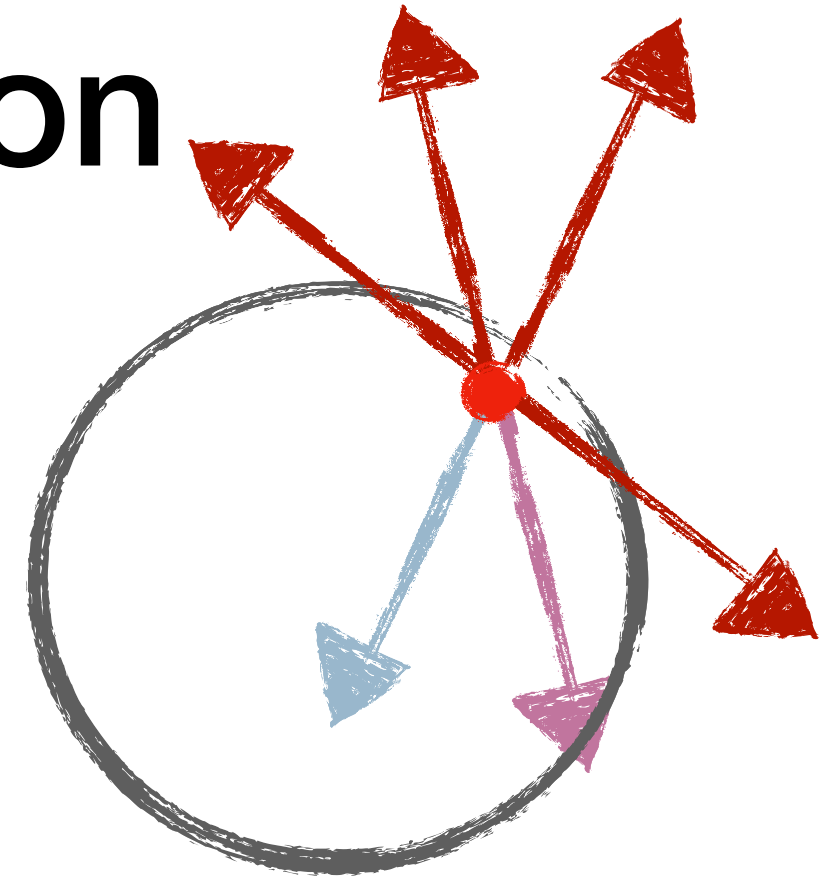
we have a set of jets with specific kinematics that we understand well

→ can varying the jet definition select more or less modified jets?

→ modification —> path length



Quantifying modification

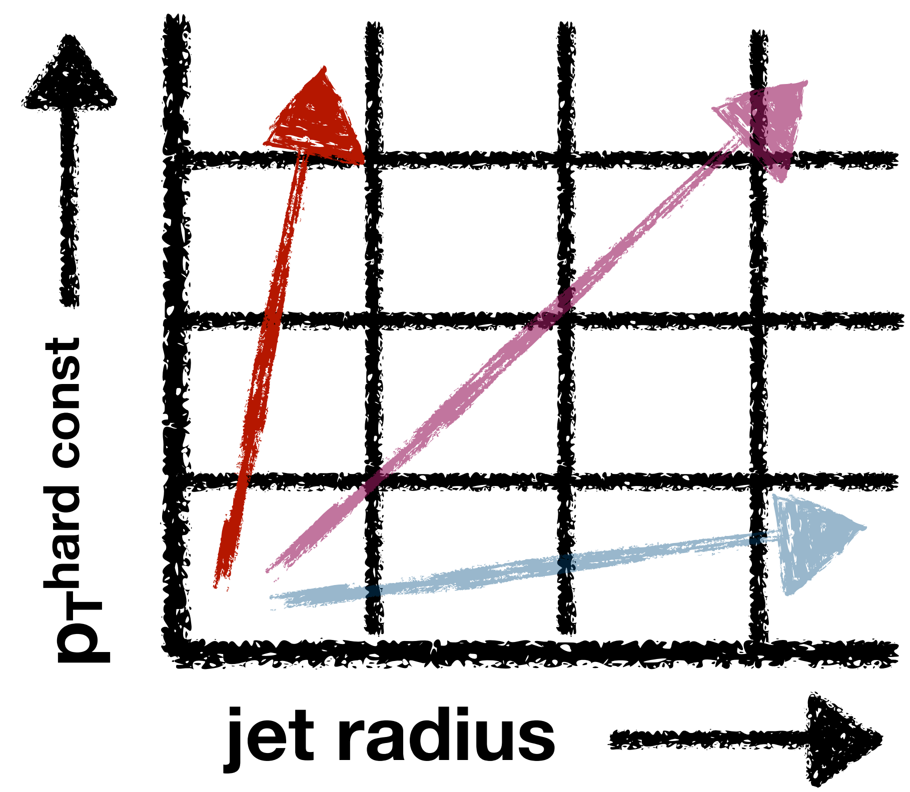


vary the jet definition

- 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



p-value= probability that data came from same probability distribution

Differential di-jet imbalance

hard core di-jets

for R=0.4, scan $p_T^{hard\ const}$

R = 0.4

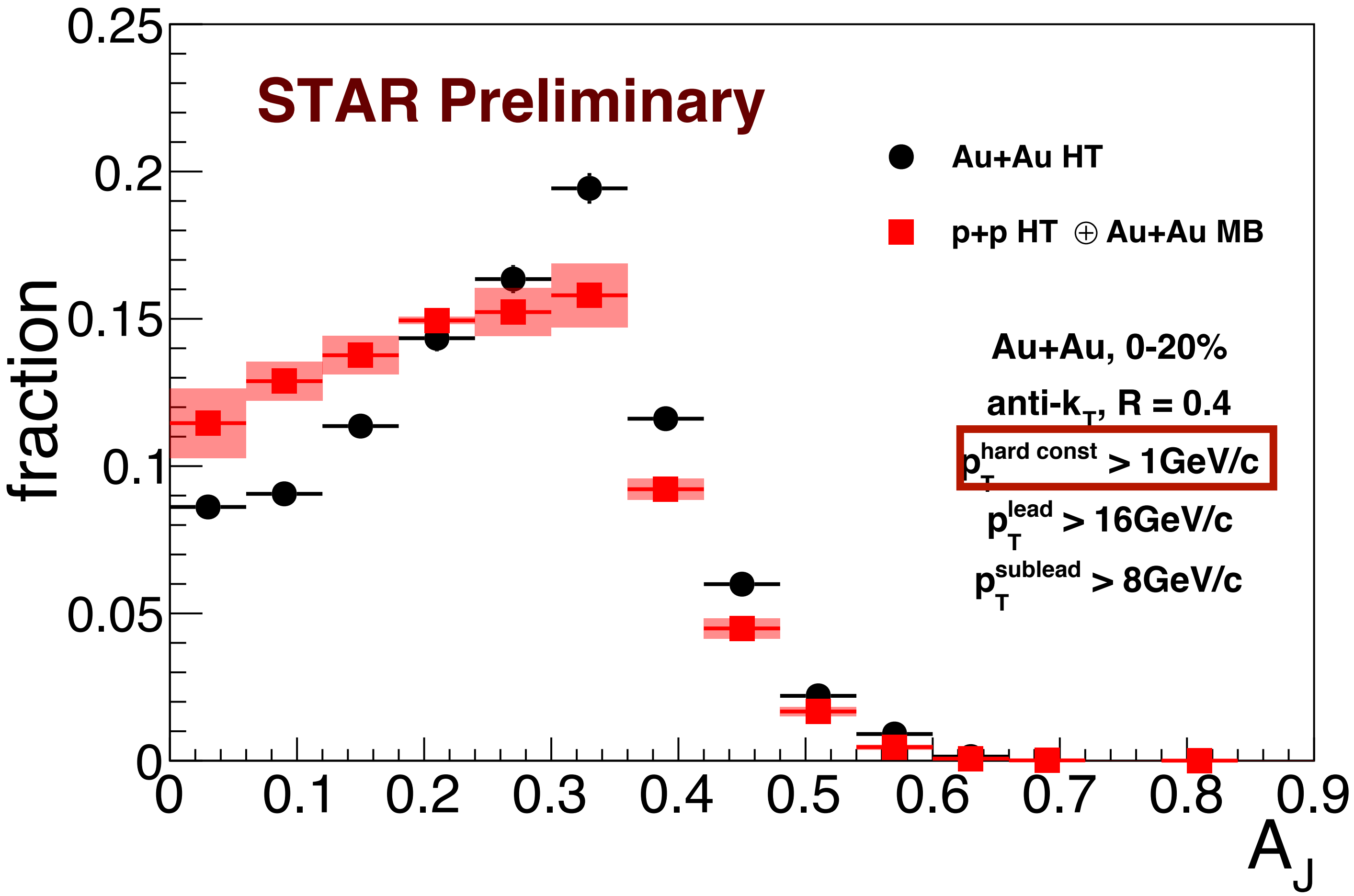
$p_T^{hard\ const} > 1$ GeV/*c*

0-20% central

$p_T^{lead} > 16$ GeV/c

$p_T^{sublead} > 8$ GeV/c

anti-k_T algorithm



K-S p-value << 1.0

Differential di-jet imbalance

hard core di-jets

for R=0.4, scan $p_T^{hard\ const}$

R = 0.4

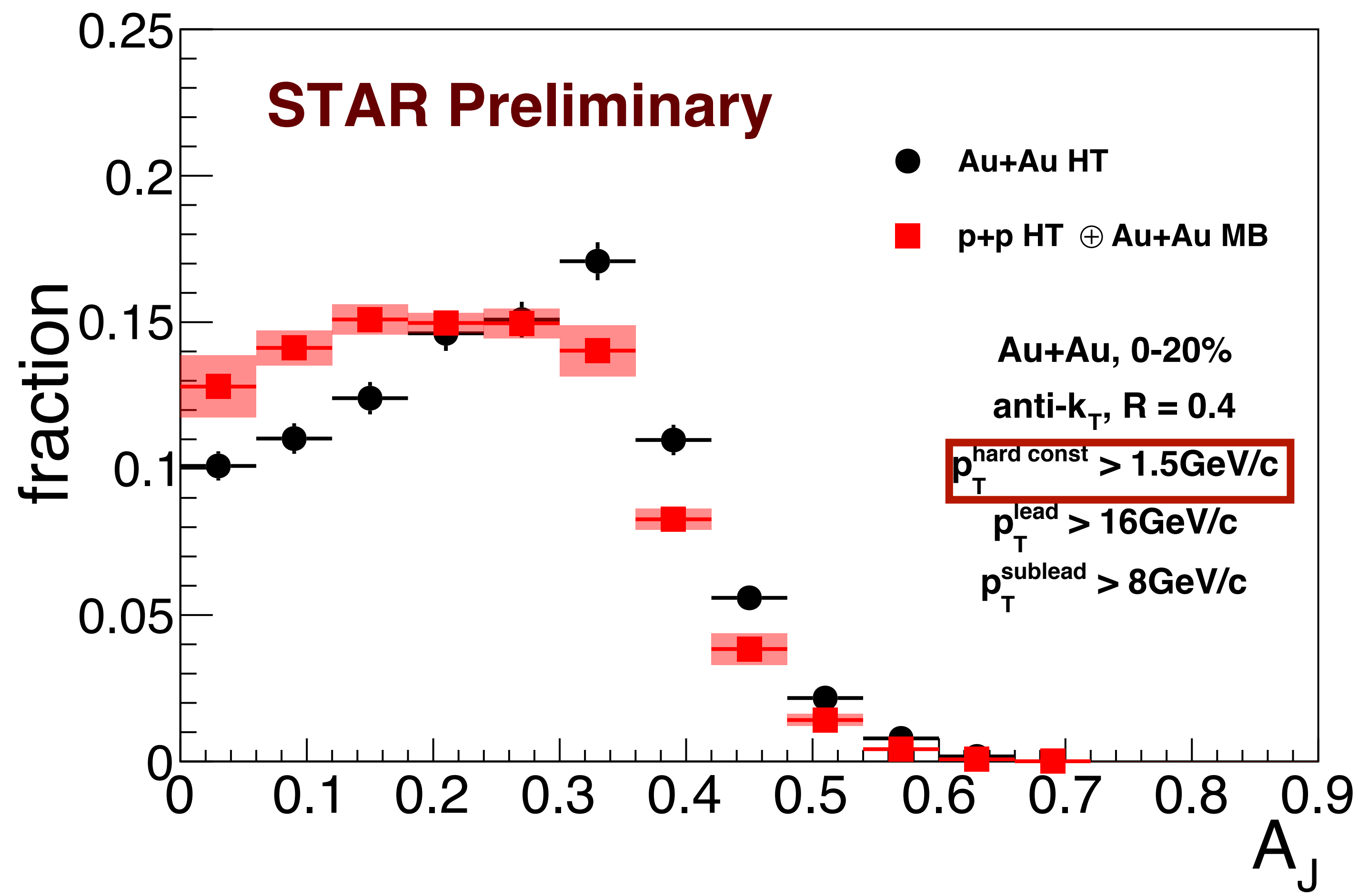
$p_T^{hard\ const} > 1.5$ GeV/*c*

0-20% central

$p_T^{lead} > 16$ GeV/c

$p_T^{sublead} > 8$ GeV/c

anti-k_T algorithm



K-S p-value << 1.0

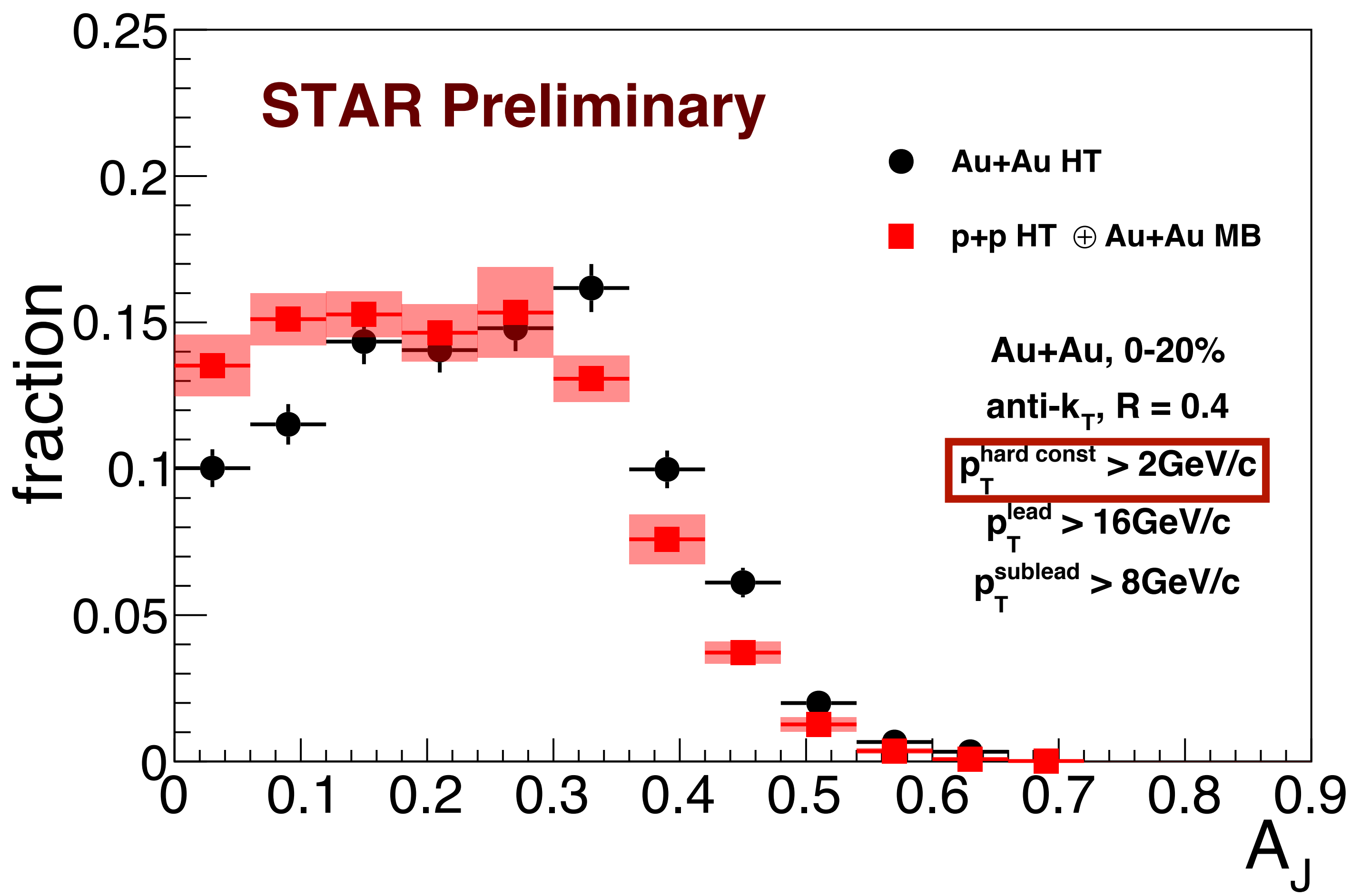
Differential di-jet imbalance

→ **hard core di-jets**

for R=0.4, scan $p_T^{hard\ const}$

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

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



K-S p-value << 1.0

Differential di-jet imbalance

hard core di-jets

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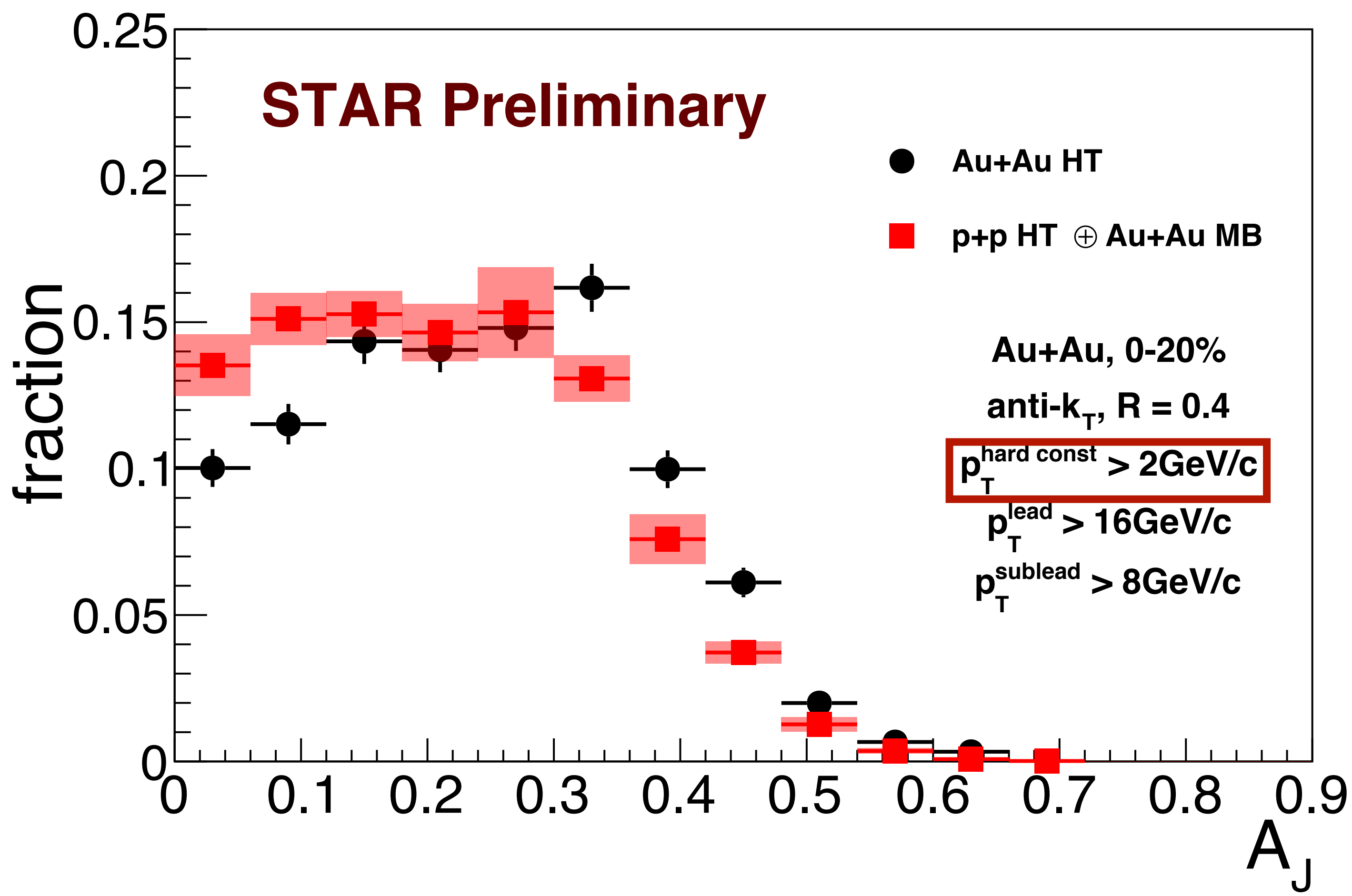
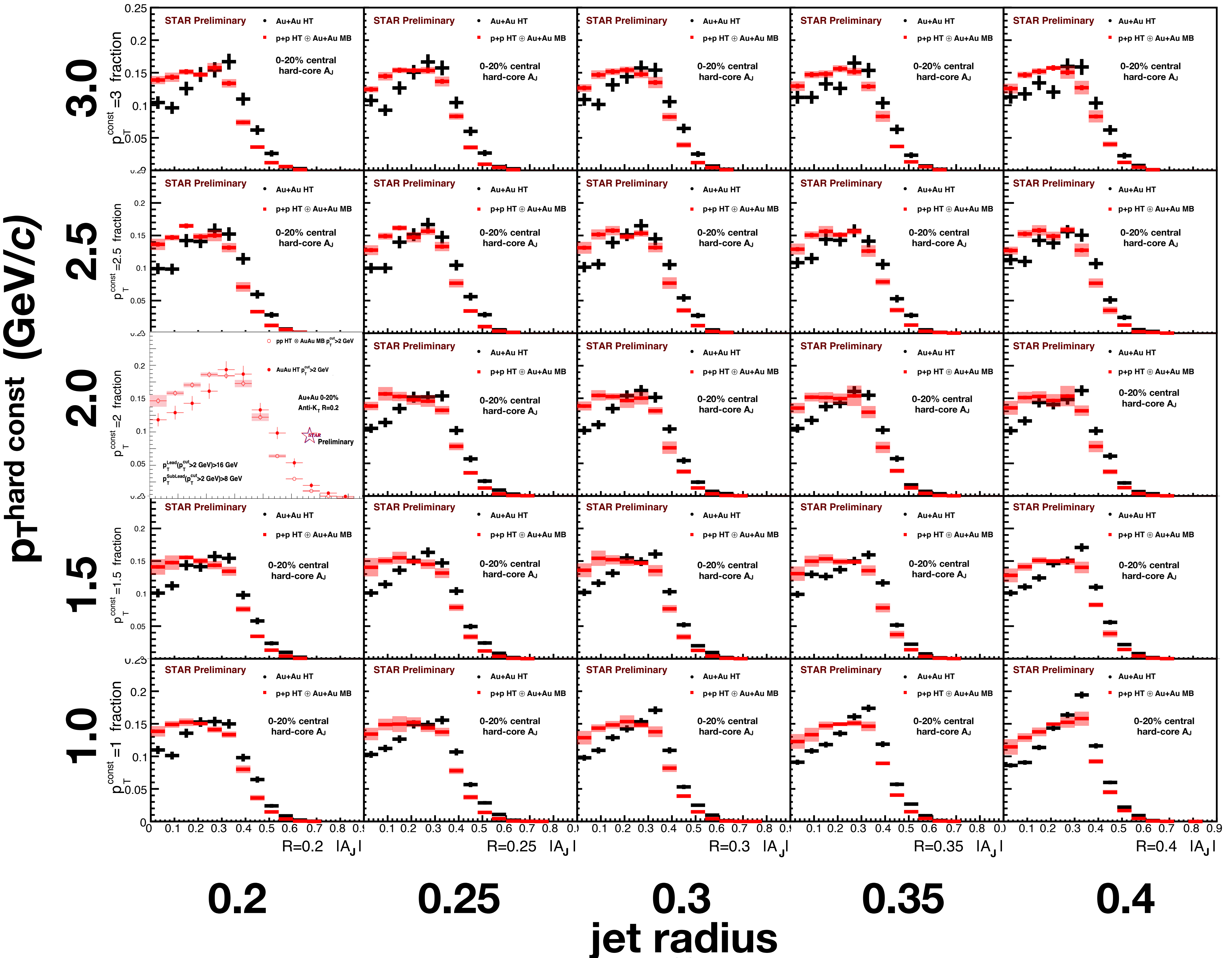


K-S p-value << 1.0

Now, we can repeat the procedure with the jet radius

Differential di-jet imbalance



Nick Elsey, STAR - Hard Probes 2018, France

Differential di-jet imbalance

hard core di-jets

→ modified for all kinematic selections

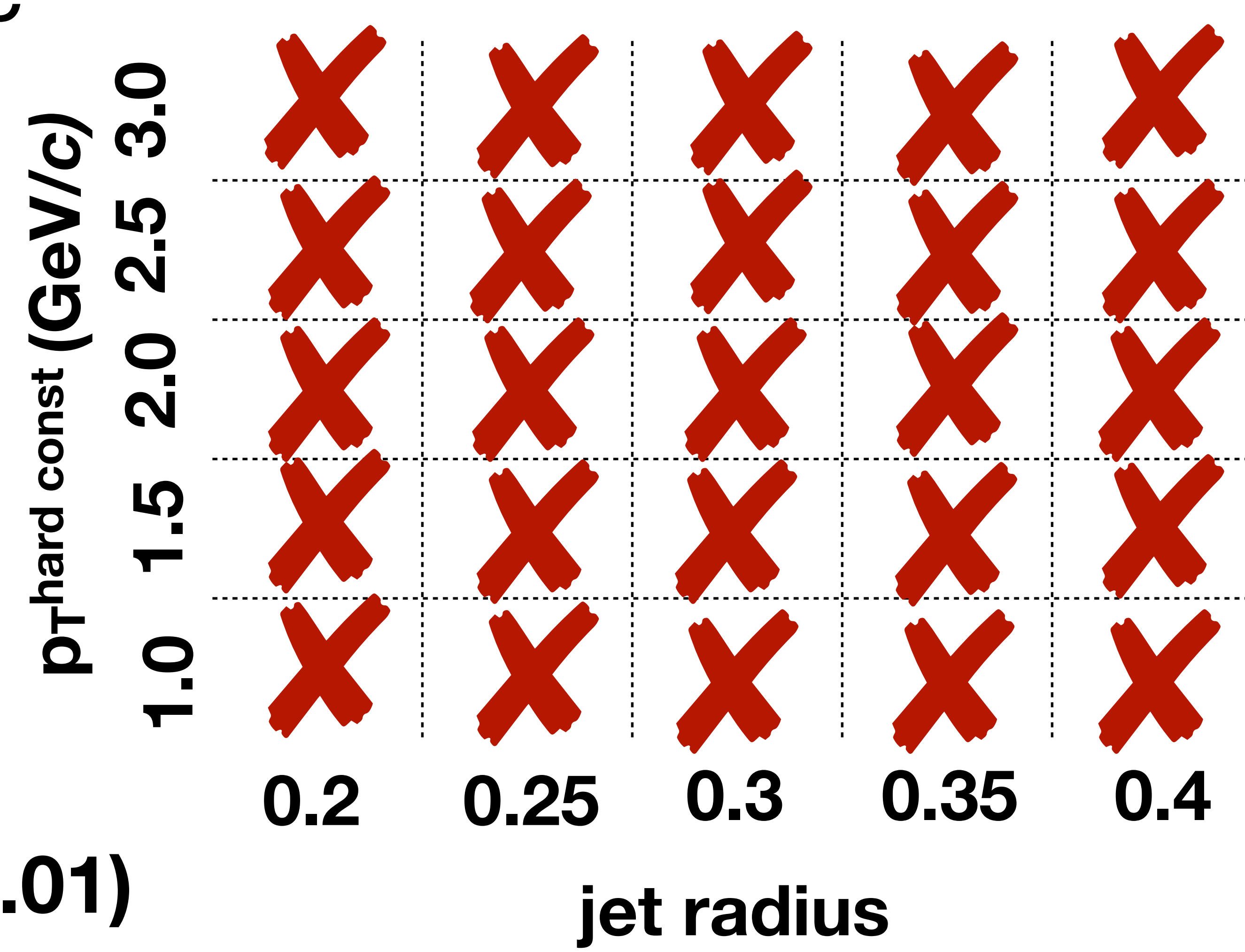
three distinct classes using K-S test (p = K-S p-value)

✓ **balanced ($p > 0.01$)**

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

✗ **imbalanced ($p < 10^{-4}$)**

Hard core di-jets



Differential di-jet imbalance

matched di-jets

for R=0.4, scan $p_T^{hard\ const}$

R = 0.4

$p_T^{hard\ const}$ > 1 GeV/*c*

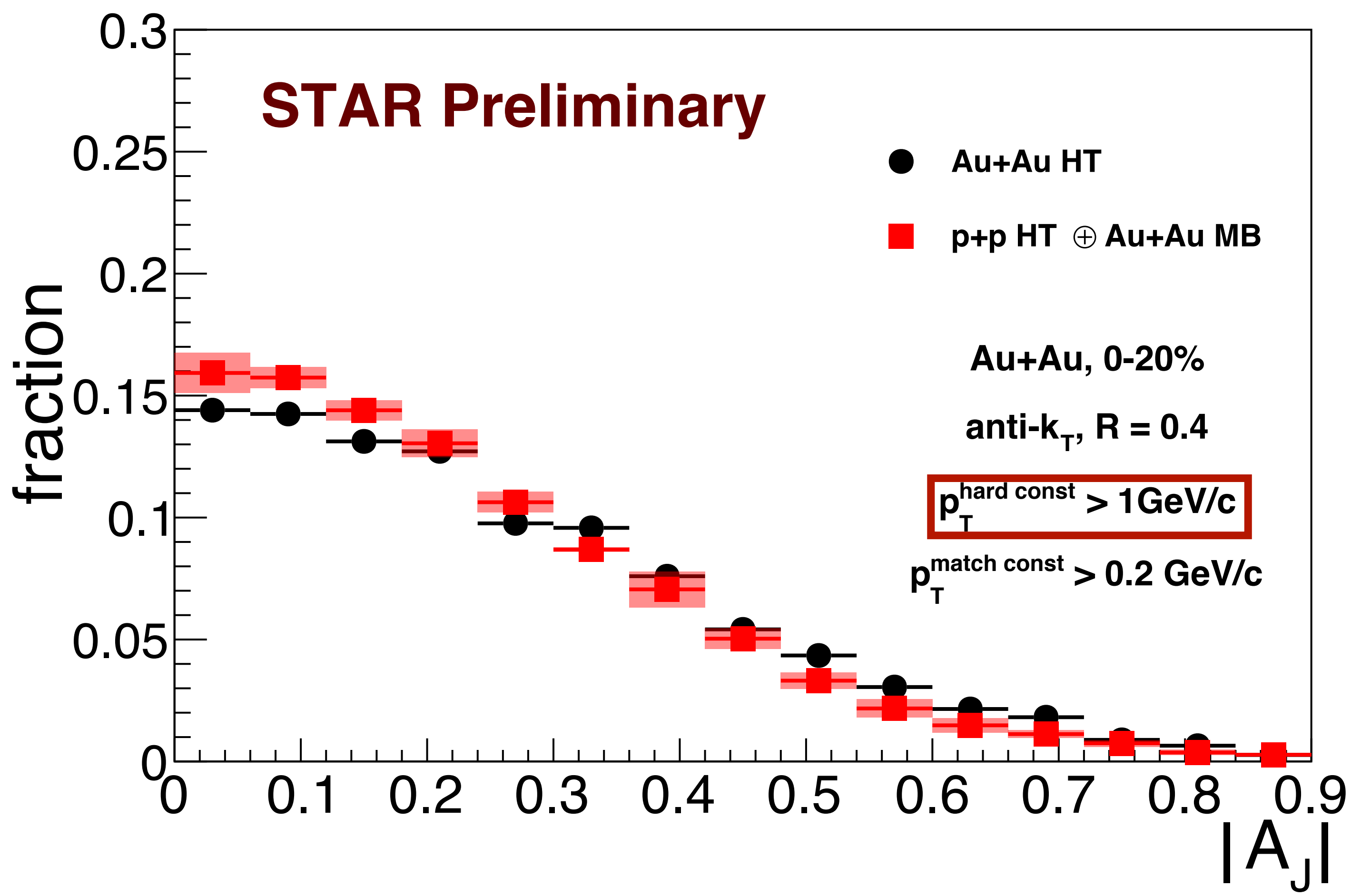
$p_T^{match\ const}$ > 0.2 GeV/*c*

0-20% central

p_T^{lead} > 16 GeV/c

$p_T^{sublead}$ > 8 GeV/c

anti-k_T algorithm



K-S p-value << 1.0

Differential di-jet imbalance

→ **matched di-jets**

for R=0.4, scan $p_T^{hard\ const}$

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

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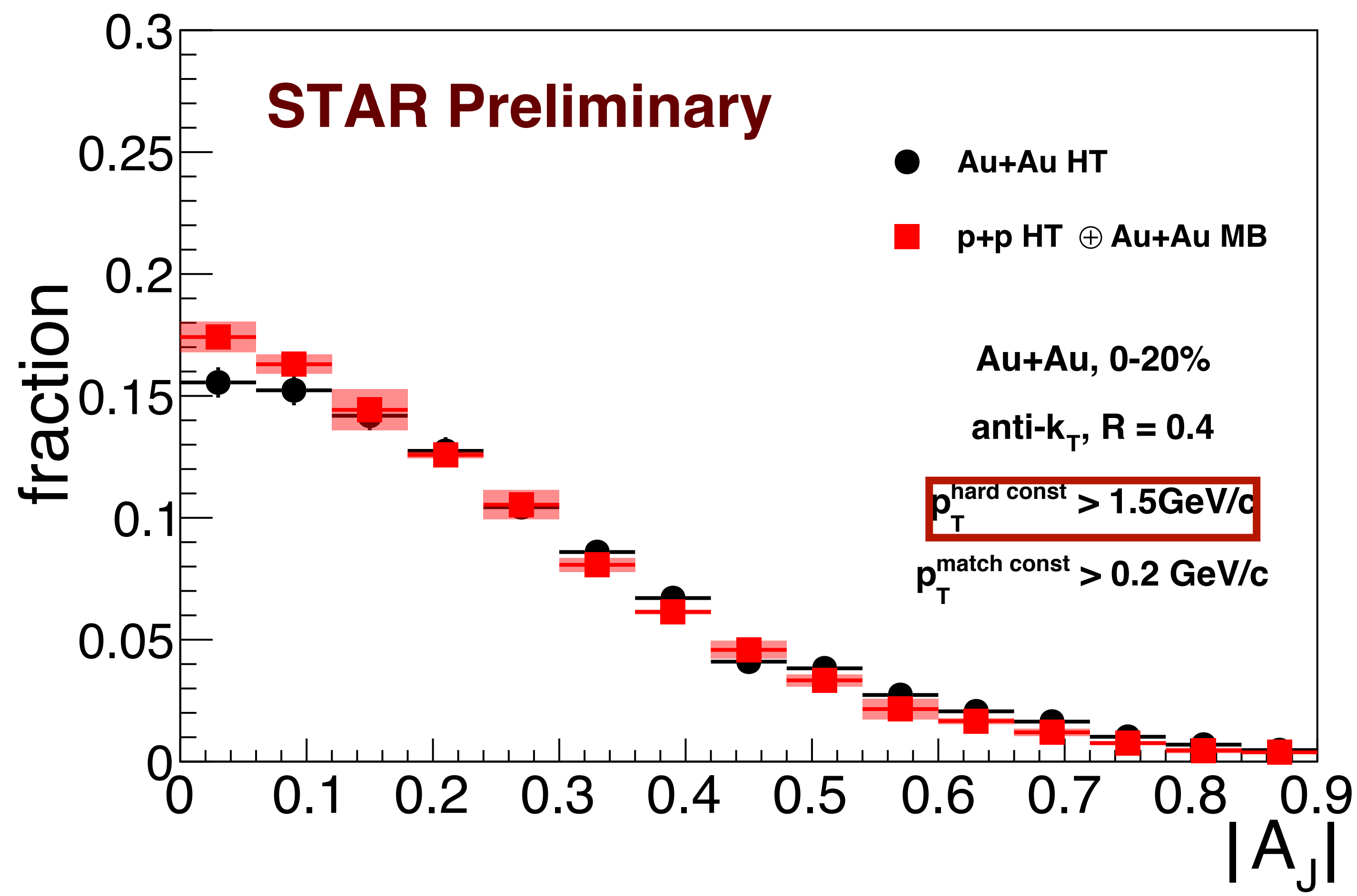
anti-k_T algorithm



K-S p-value = 0.0006

Differential di-jet imbalance

matched di-jets

for R=0.4, scan $p_T^{hard\ const}$

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

0-20% central
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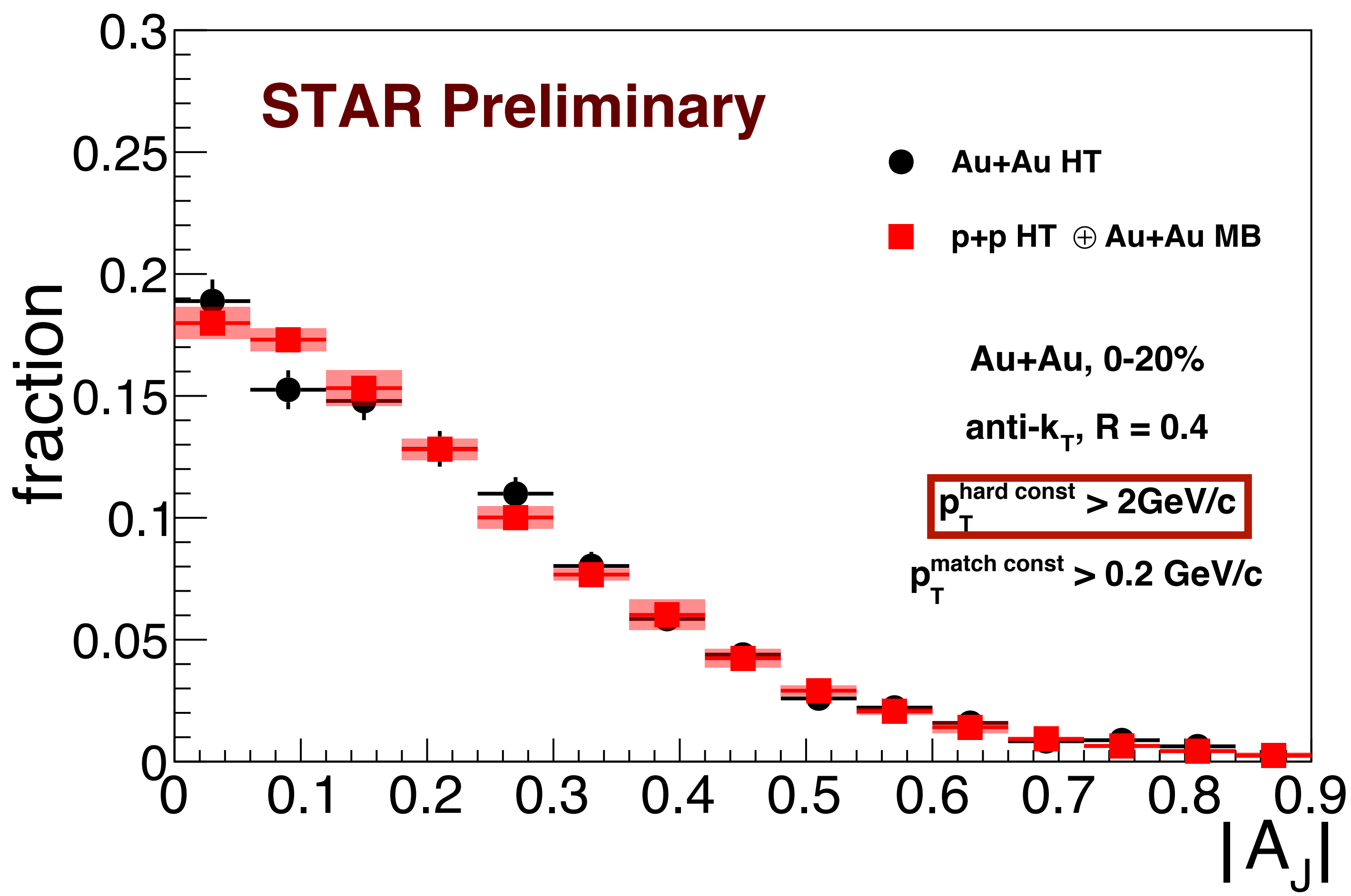
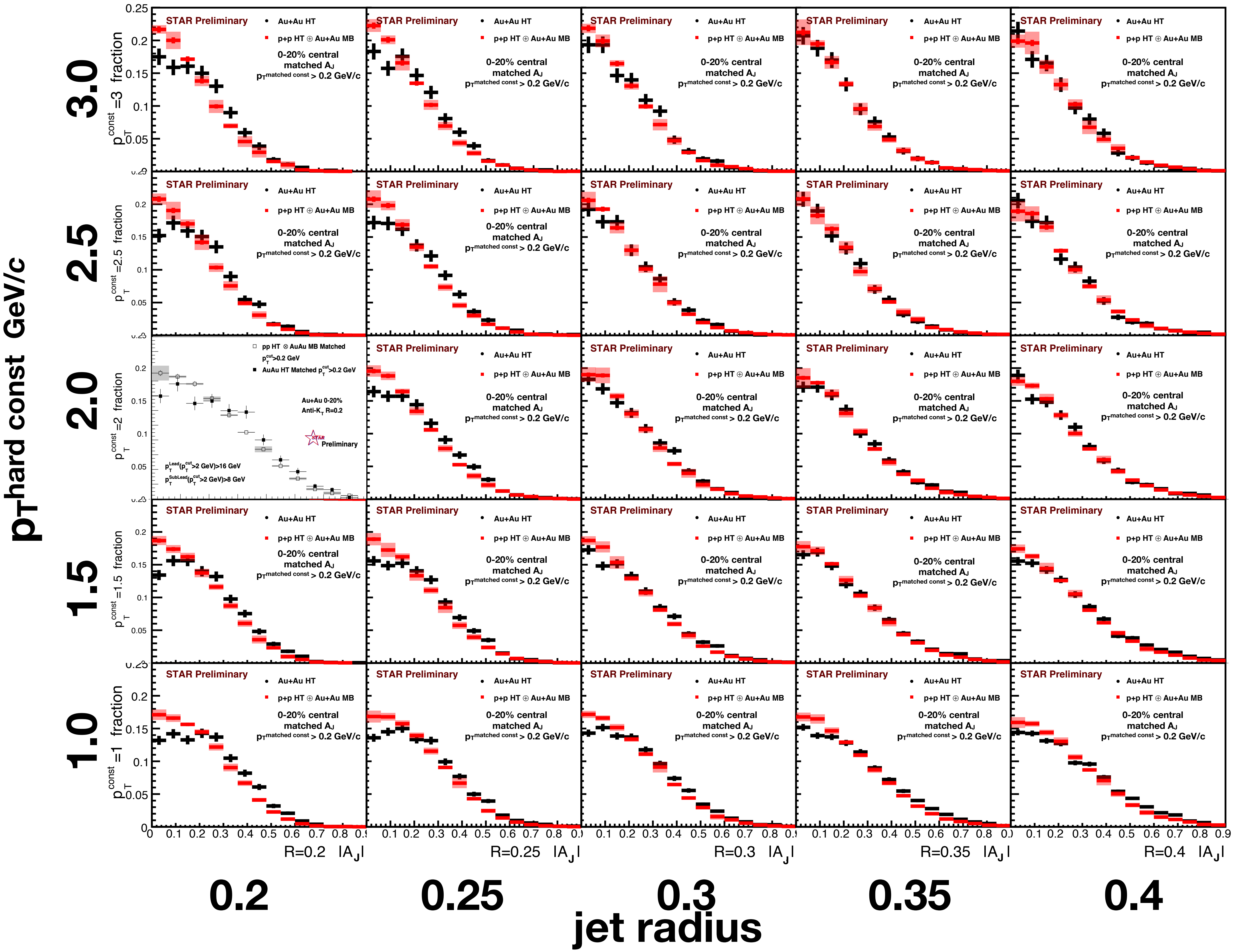
anti-k_T algorithm



K-S p-value = 0.17

Differential di-jet imbalance



Nick Elsey, STAR - Hard Probes 2018, France

Differential di-jet imbalance

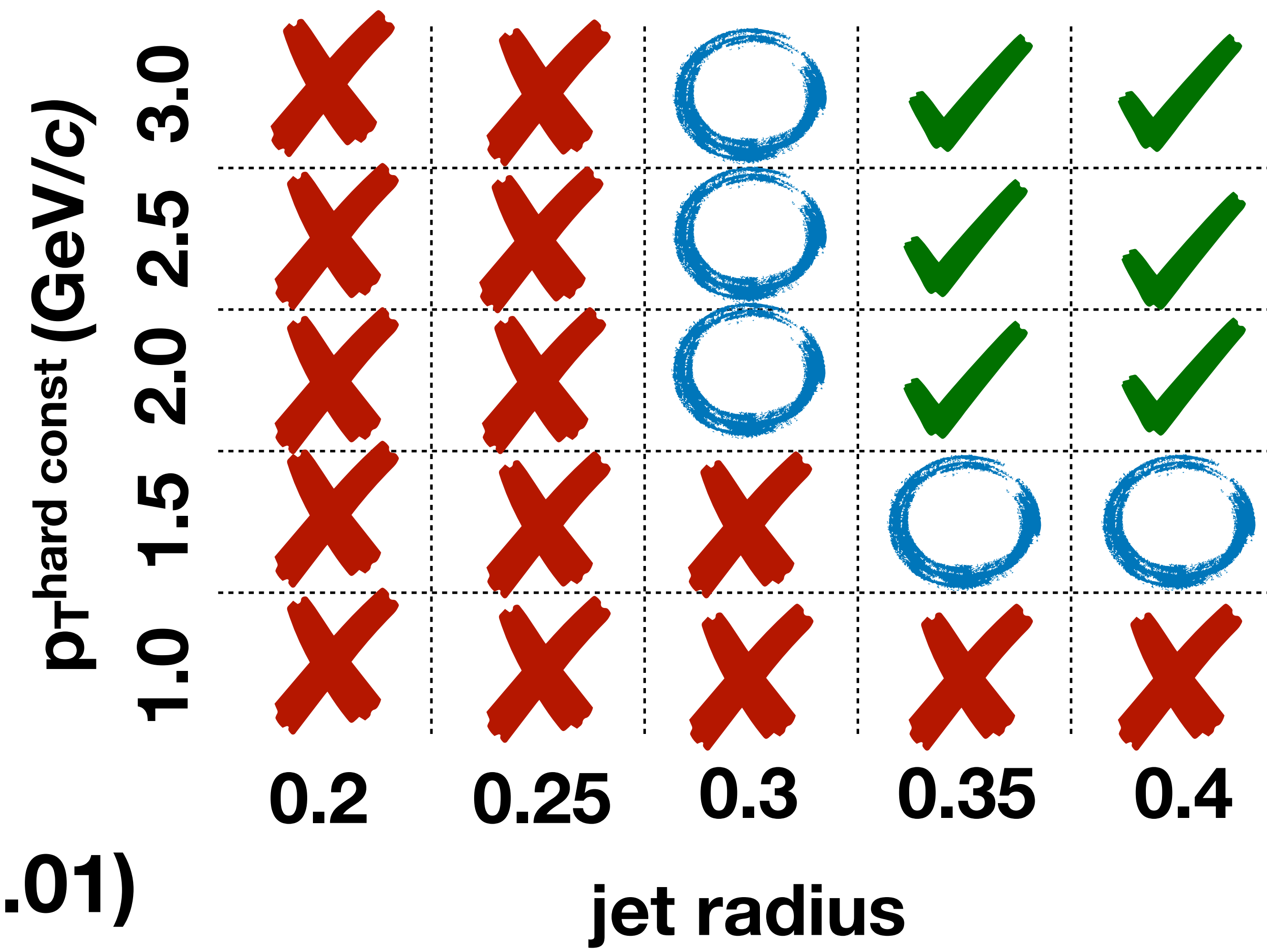
hard core di-jets

modified for all kinematic selections

matched di-jets

reducing $p_T^{hard\ const}$ can increase modification beyond R=0.4

Matched di-jets



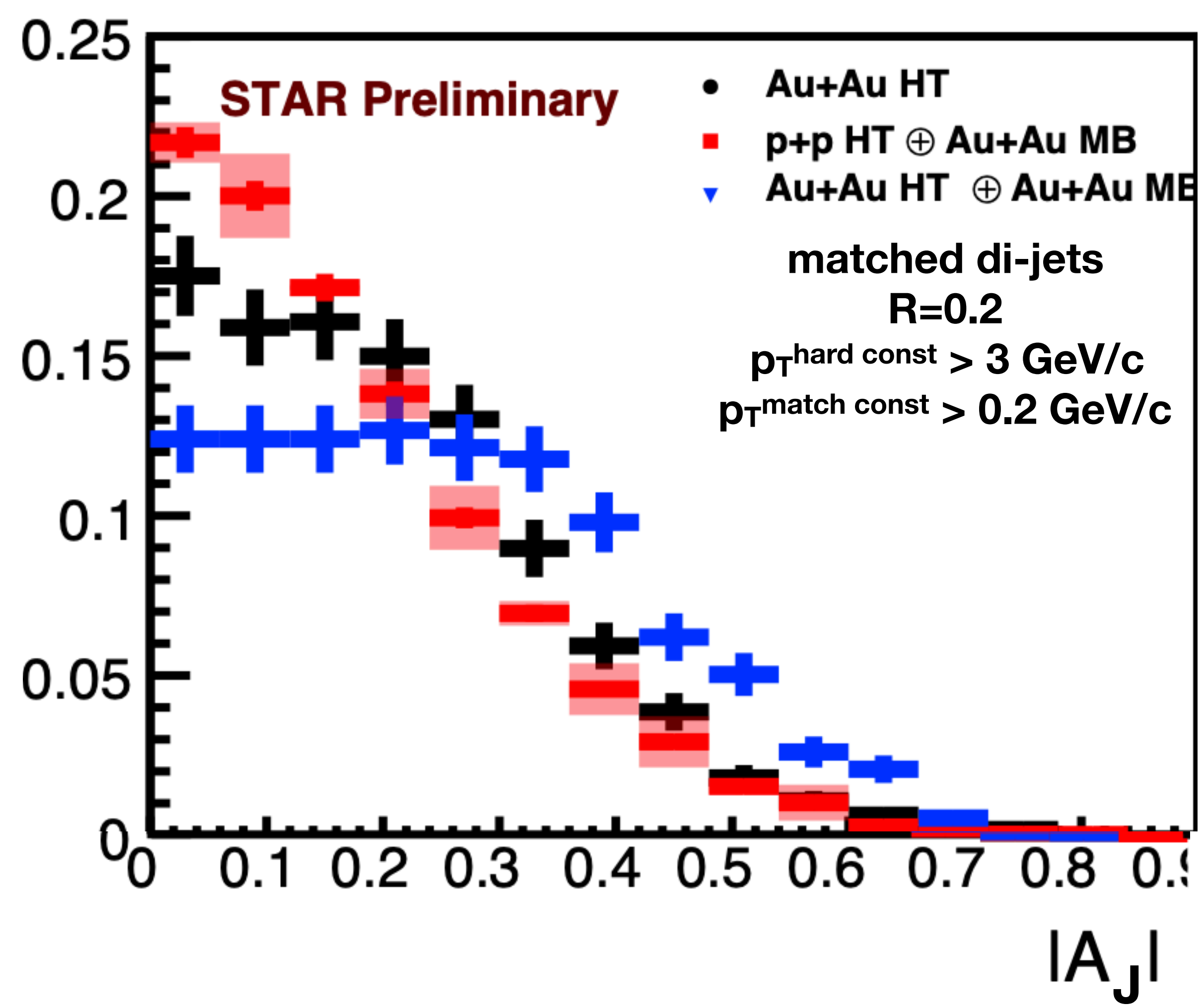
balanced ($p > 0.01$)

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

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

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**



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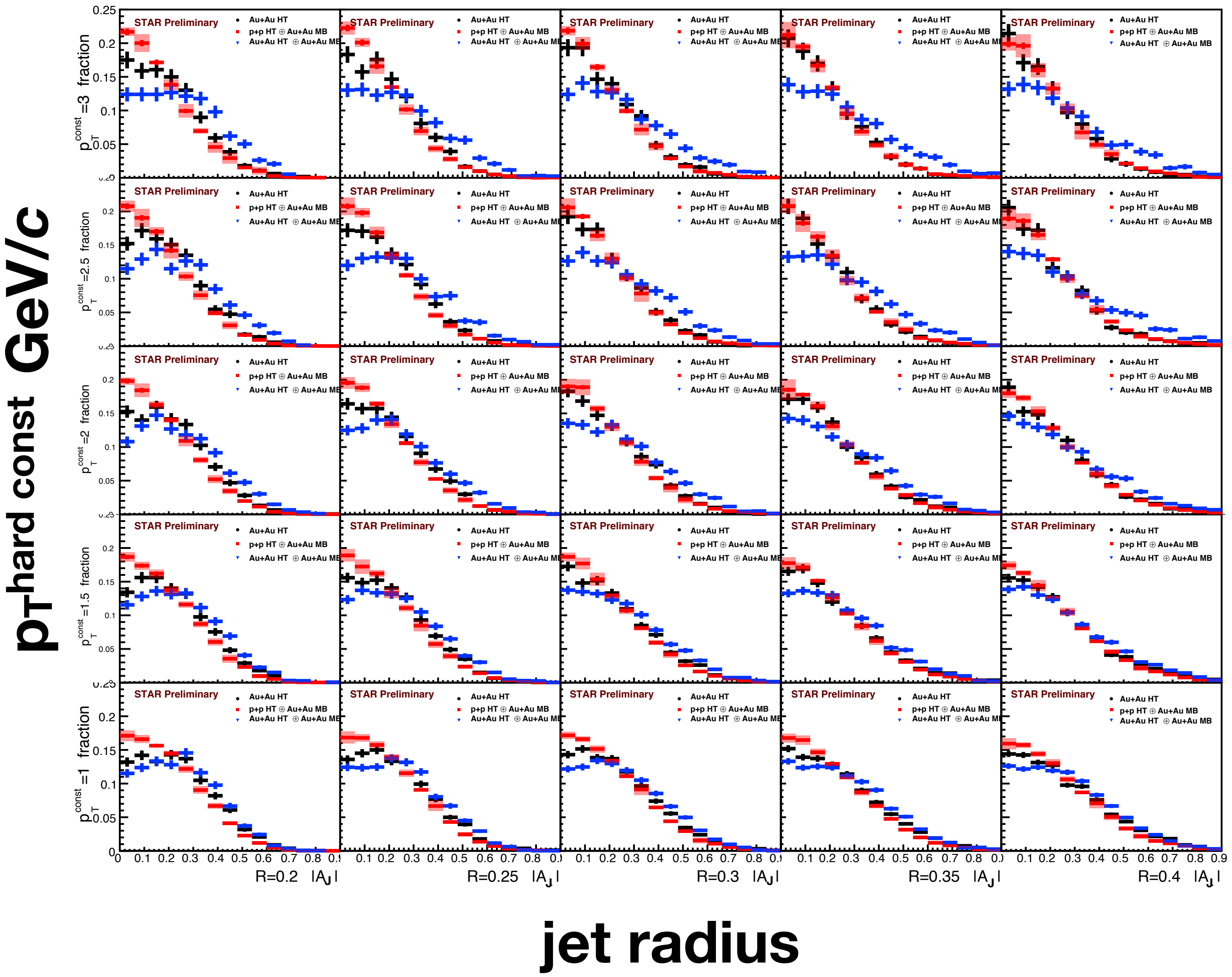
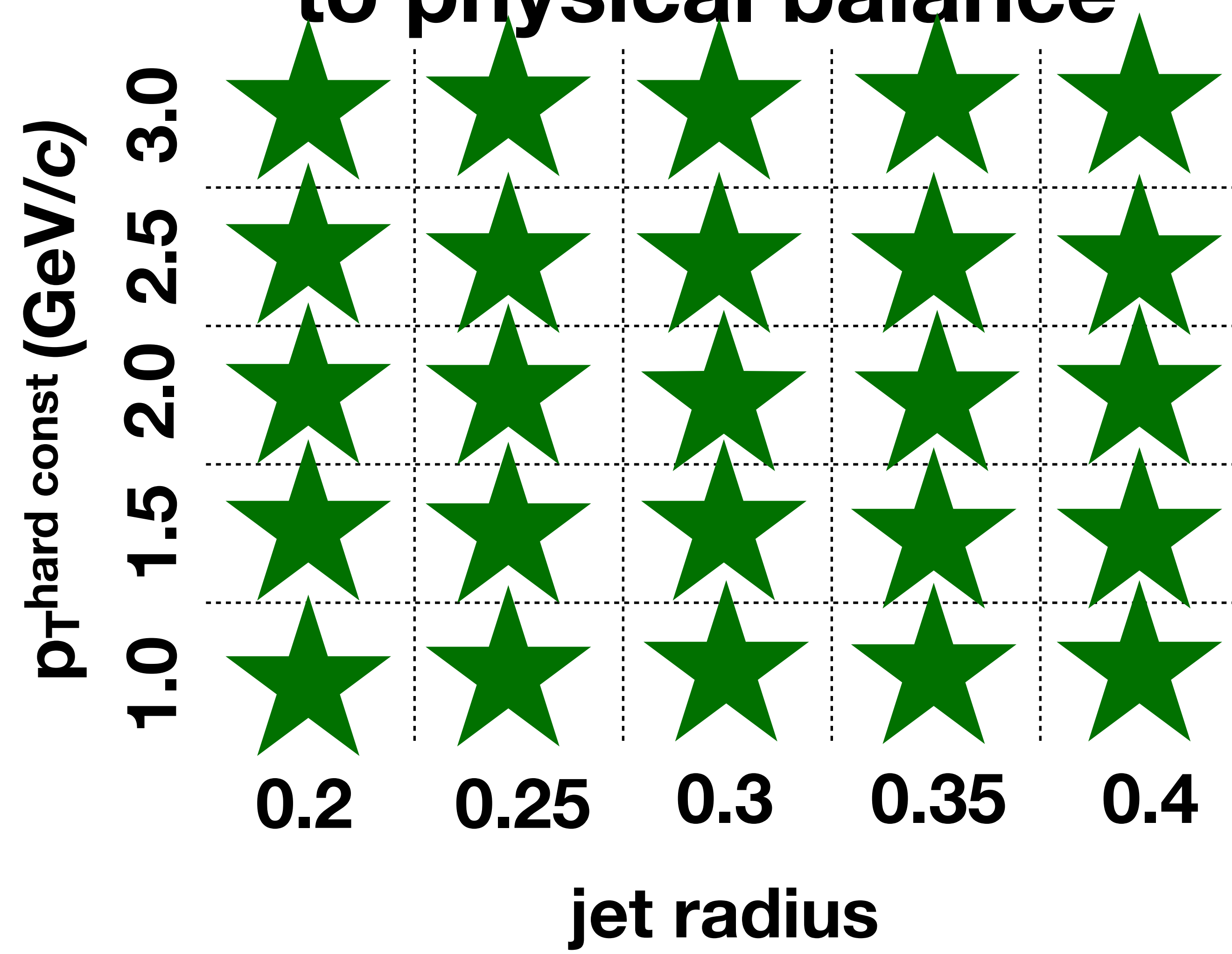


Differential di-jet imbalance

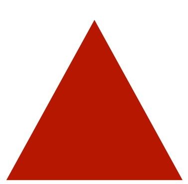
matched jets can get some "balance" from background fluctuations

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

Estimate of sensitivity to physical balance



sensitive ($p < 0.01$)

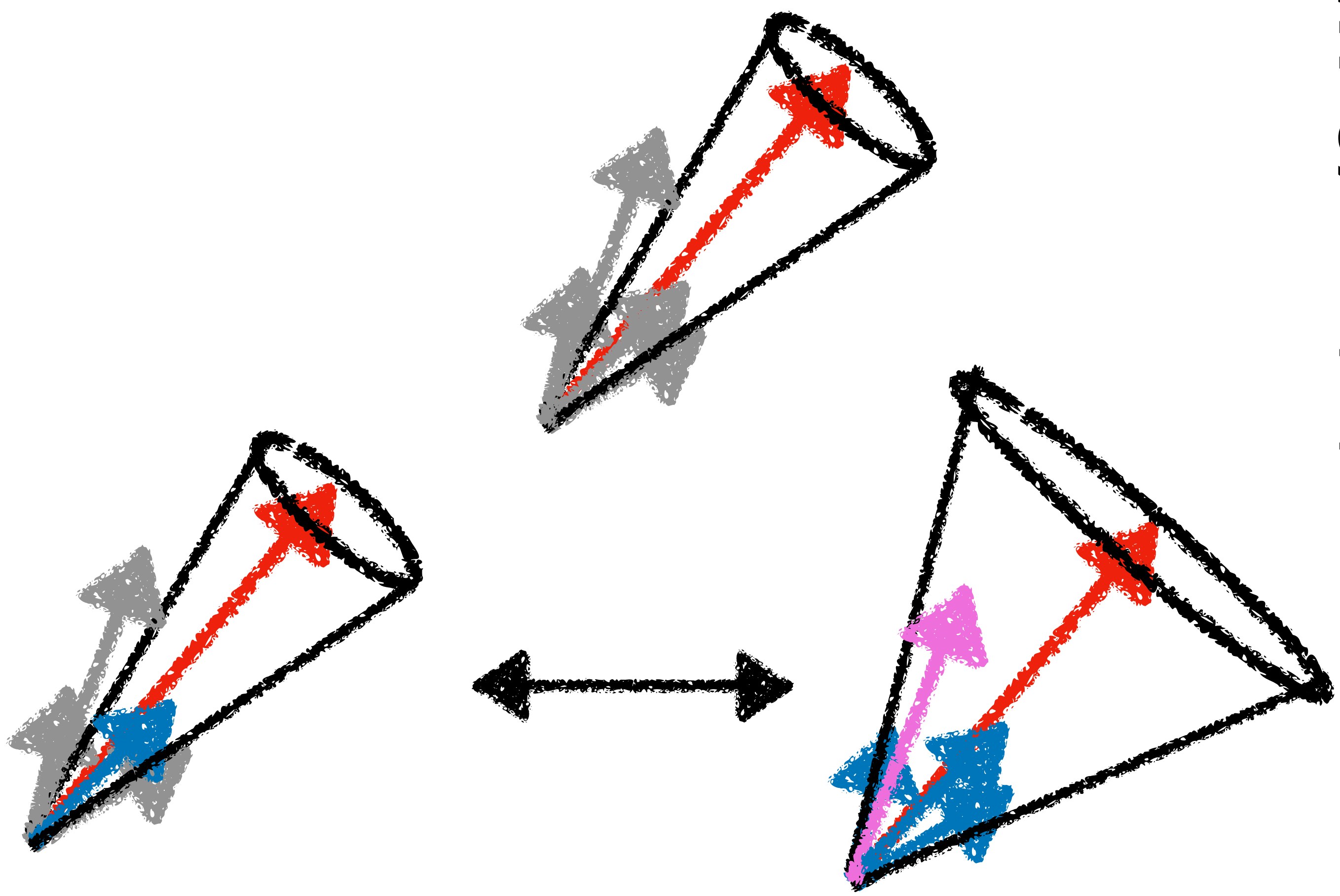


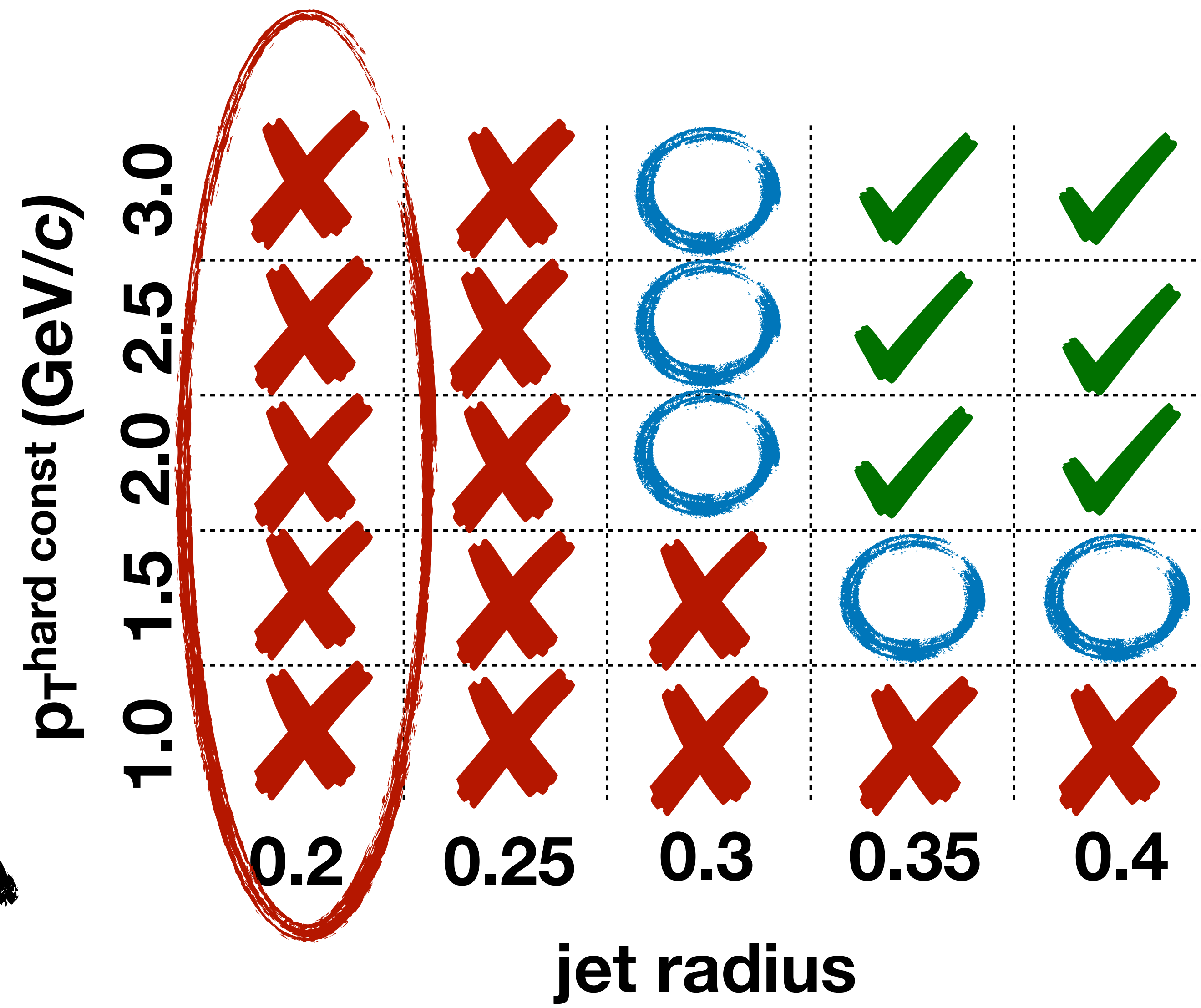
insensitive ($p > 0.01$)

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





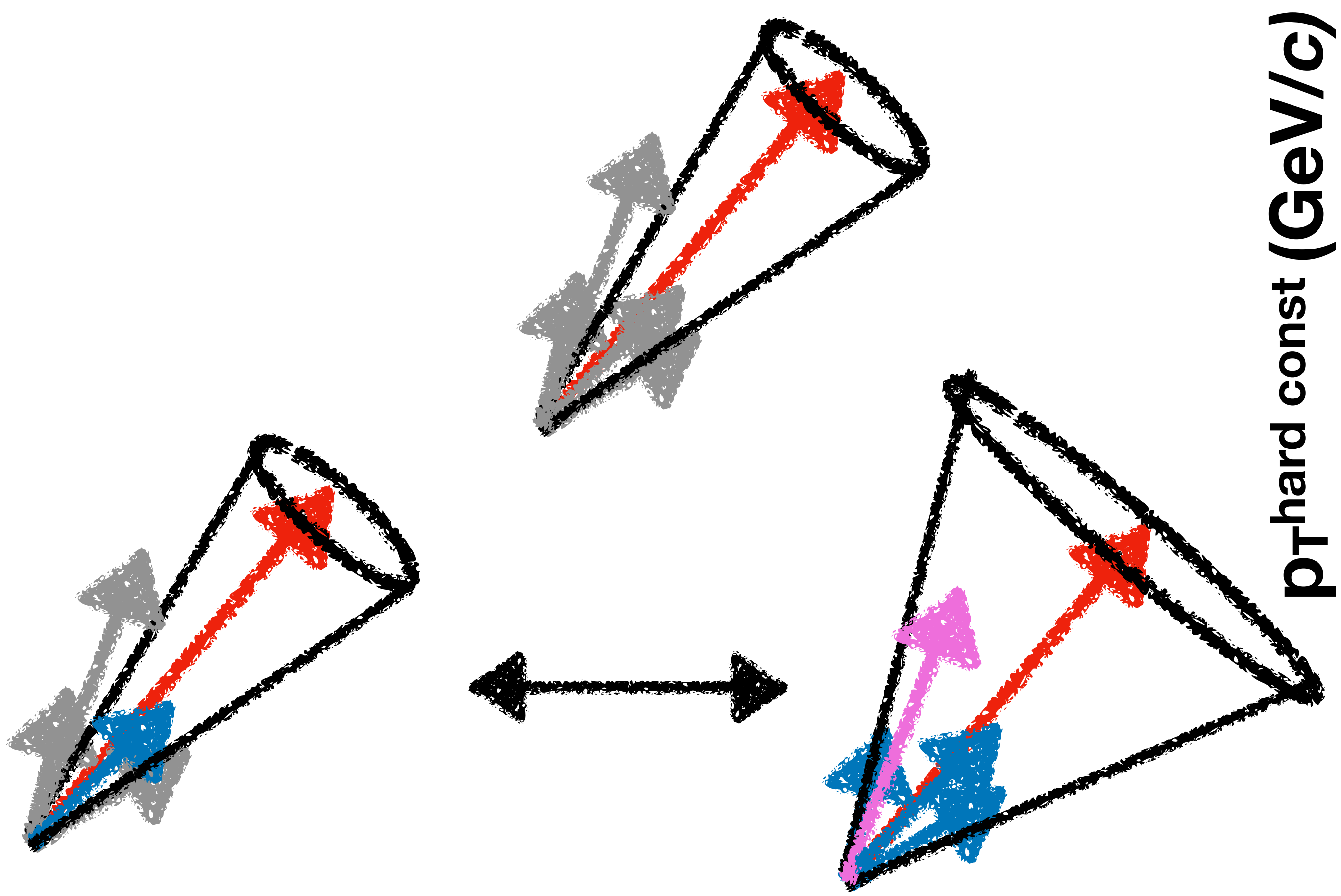
scan through matched jet radii (R=0.2 → 0.4)

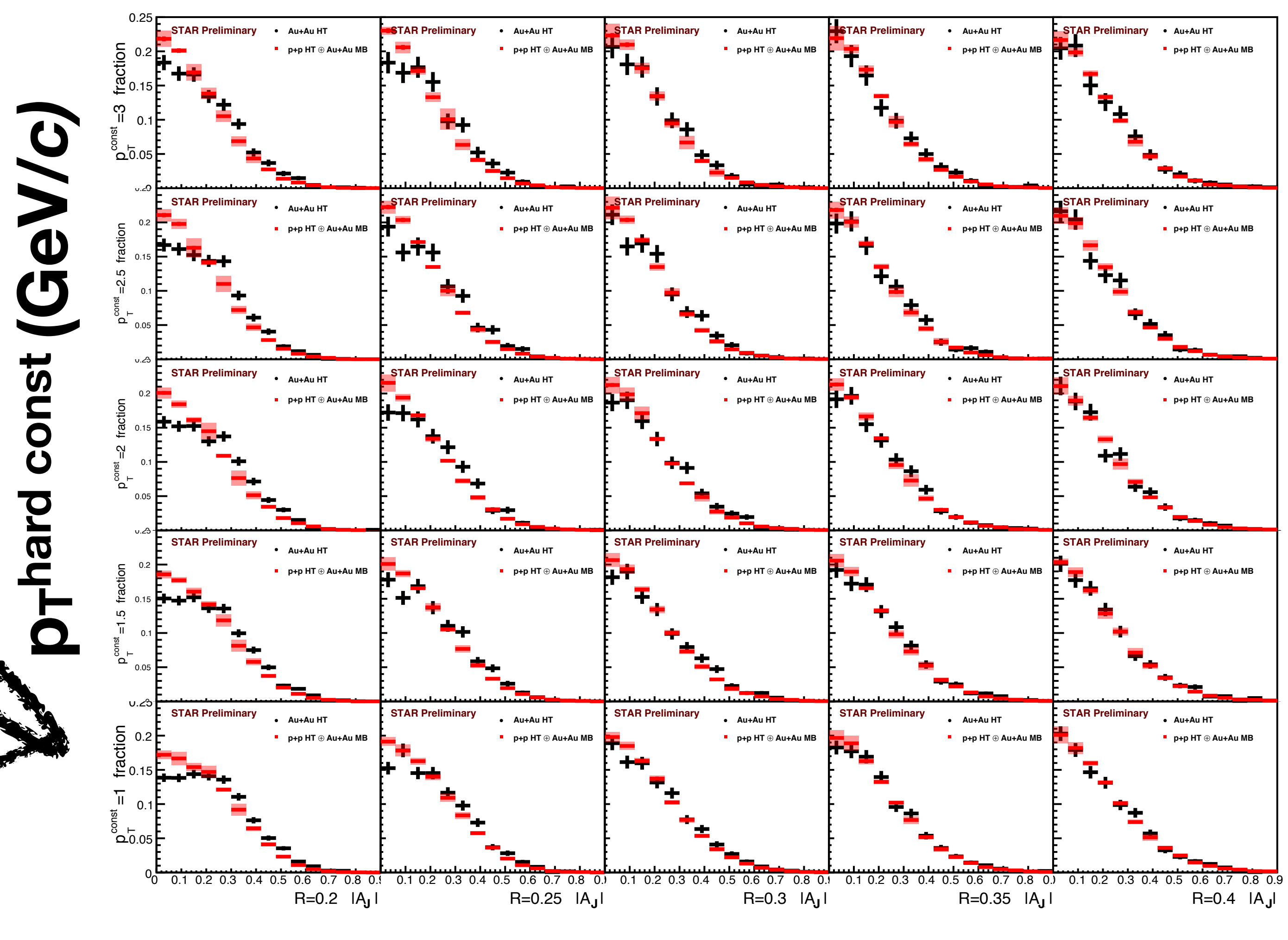
Radial scan of matched jets

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

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

start with a narrow hard core jet





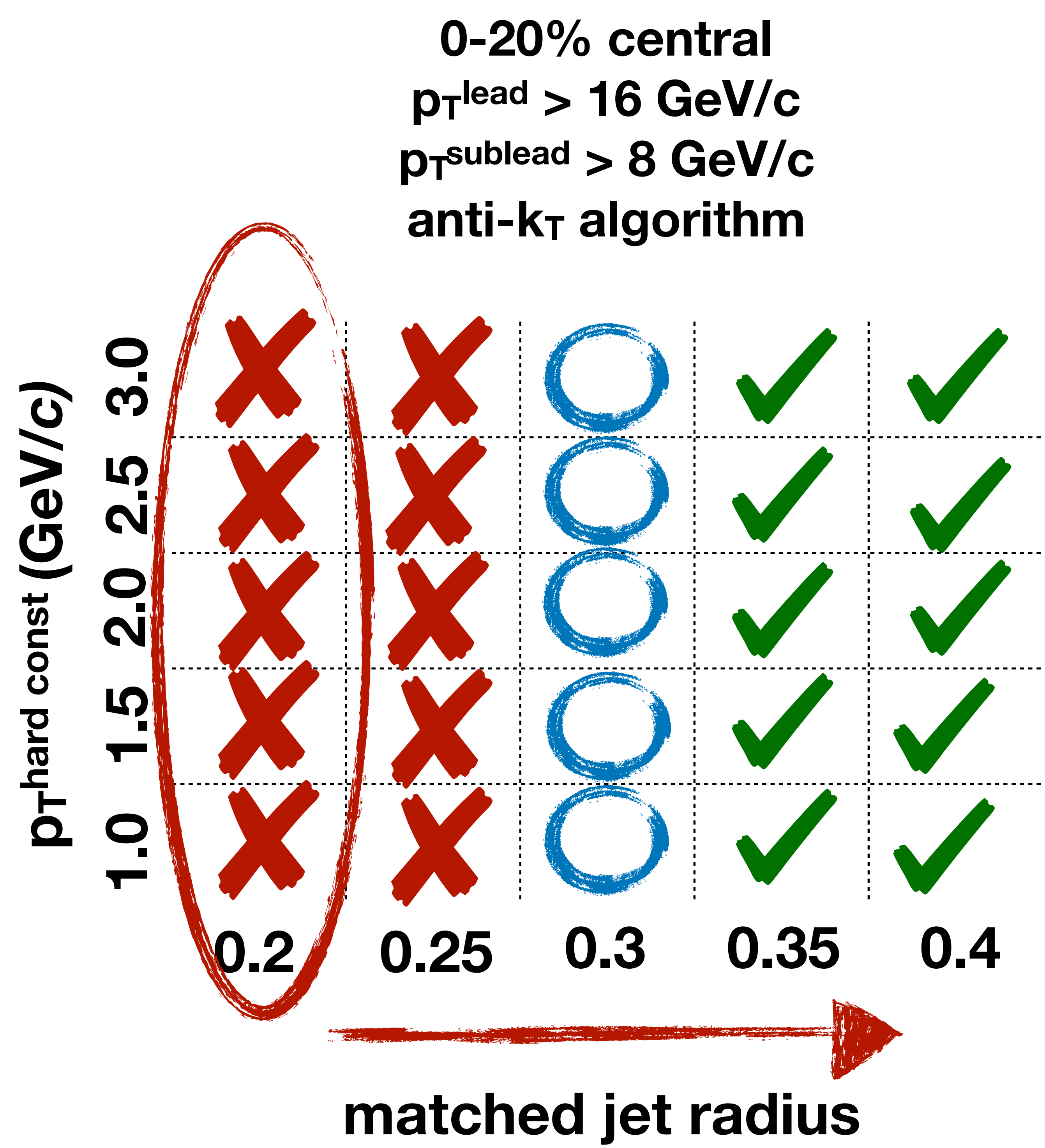
scan through matched jet radii (R=0.2 -> 0.4)

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 $p_T^{hard\ const}$

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



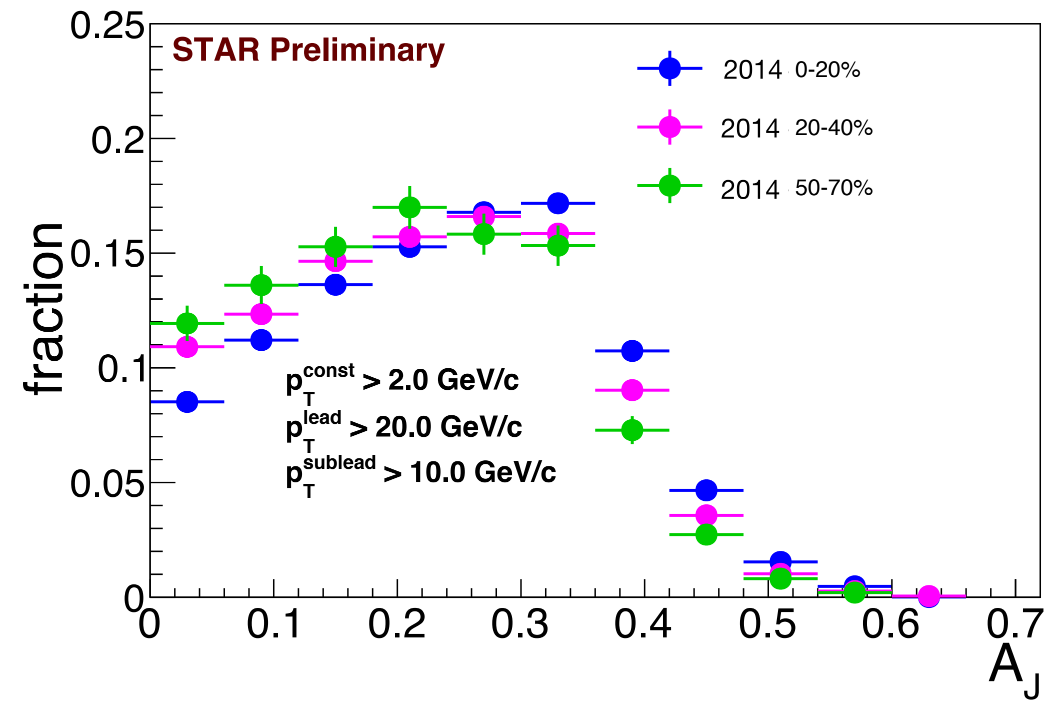
Moving forward

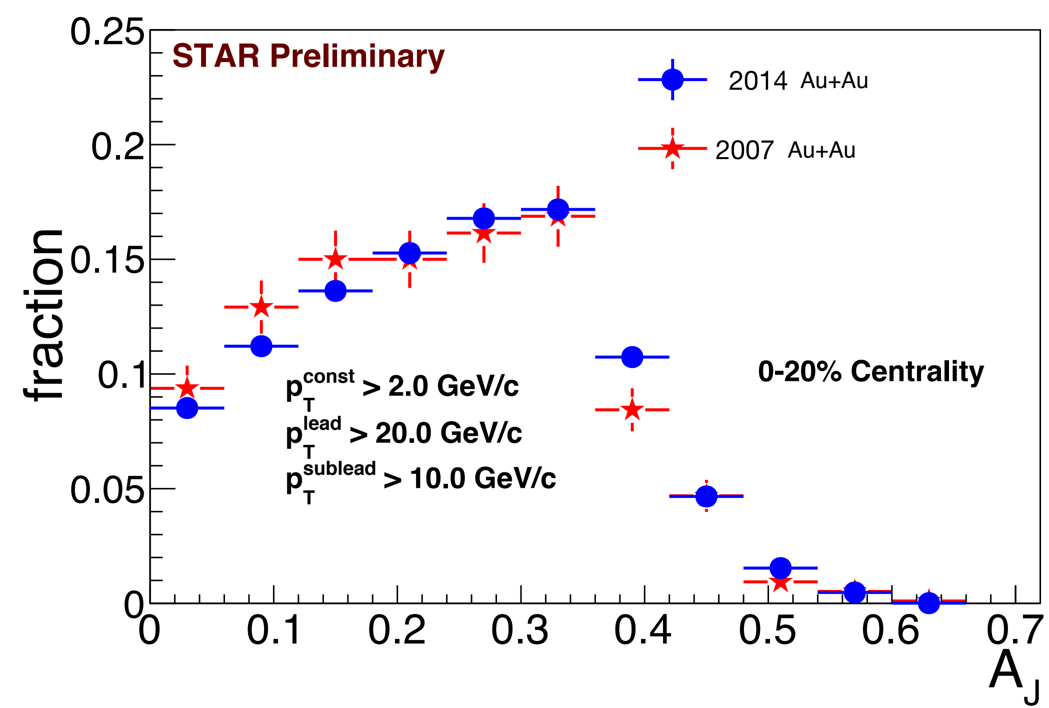
2014 Au+Au 200 GeV

20x increase in statistics

→ allow for wider jet kinematic range

→ centrality dependence



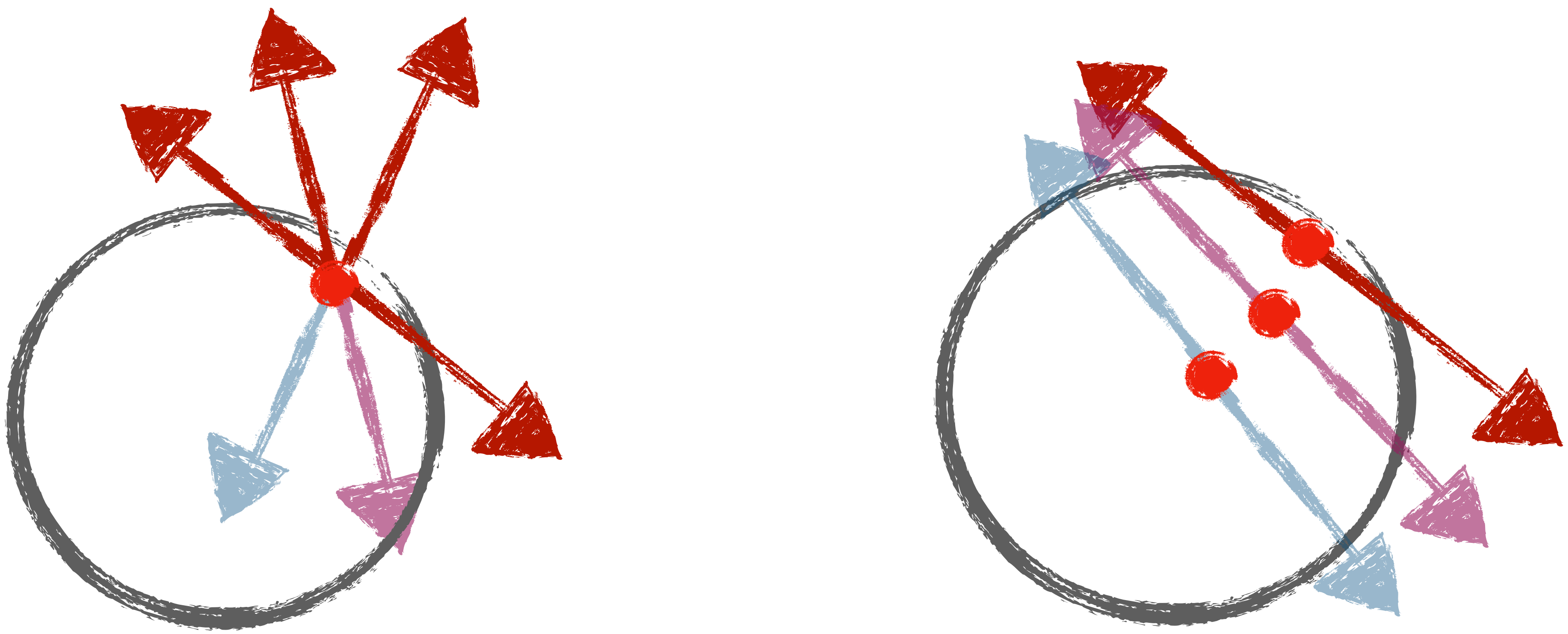


STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Conclusions

- using hard core di-jets, we've 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

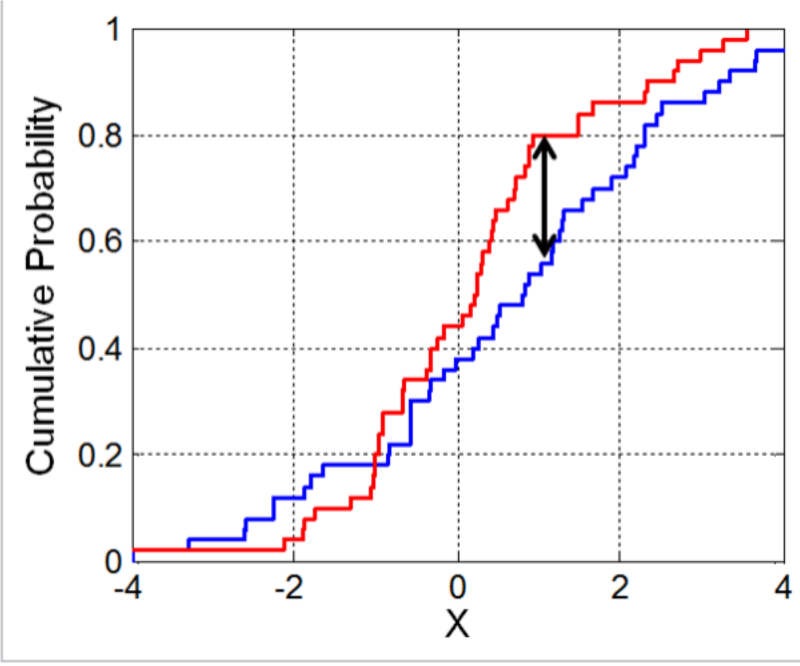


Qualitatively consistent picture of partonic energy loss emerging at RHIC. Observed difference in broadening of jet structure can be related to in-medium path length/ amount of diffusion of medium-induced soft gluon radiation in the QGP.

Thank You

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



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

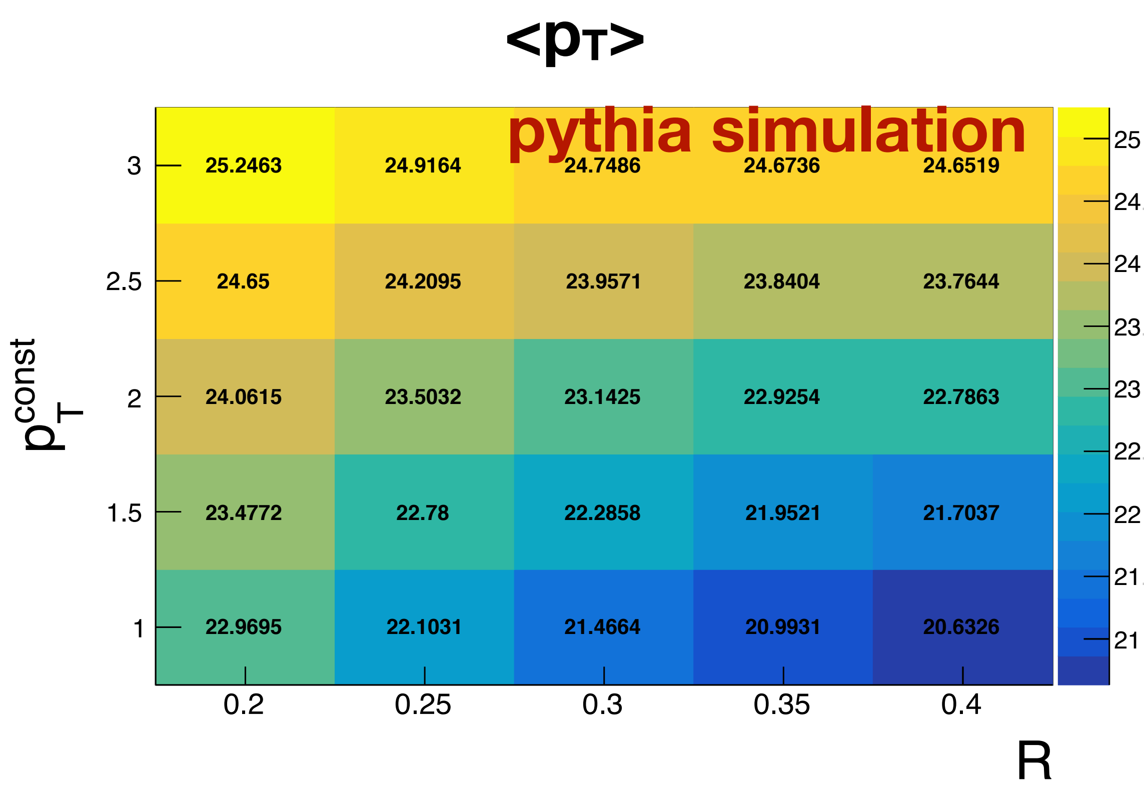
$$D_{n,m} > c(\alpha)\sqrt{\frac{n+m}{nm}}.$$

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

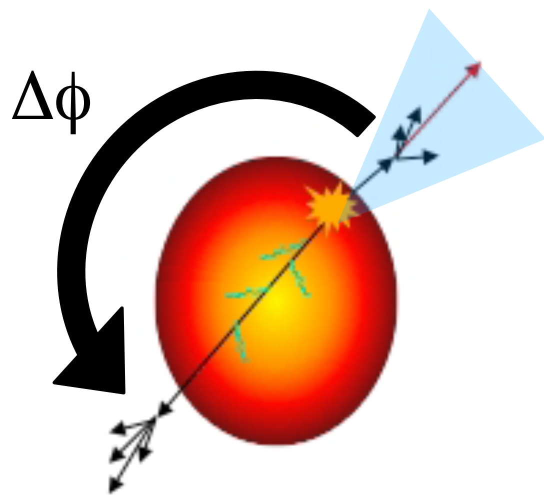
α	0.10	0.05	0.025	0.01	0.005	0.001
$c(\alpha)$	1.22	1.36	1.48	1.63	1.73	1.95

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

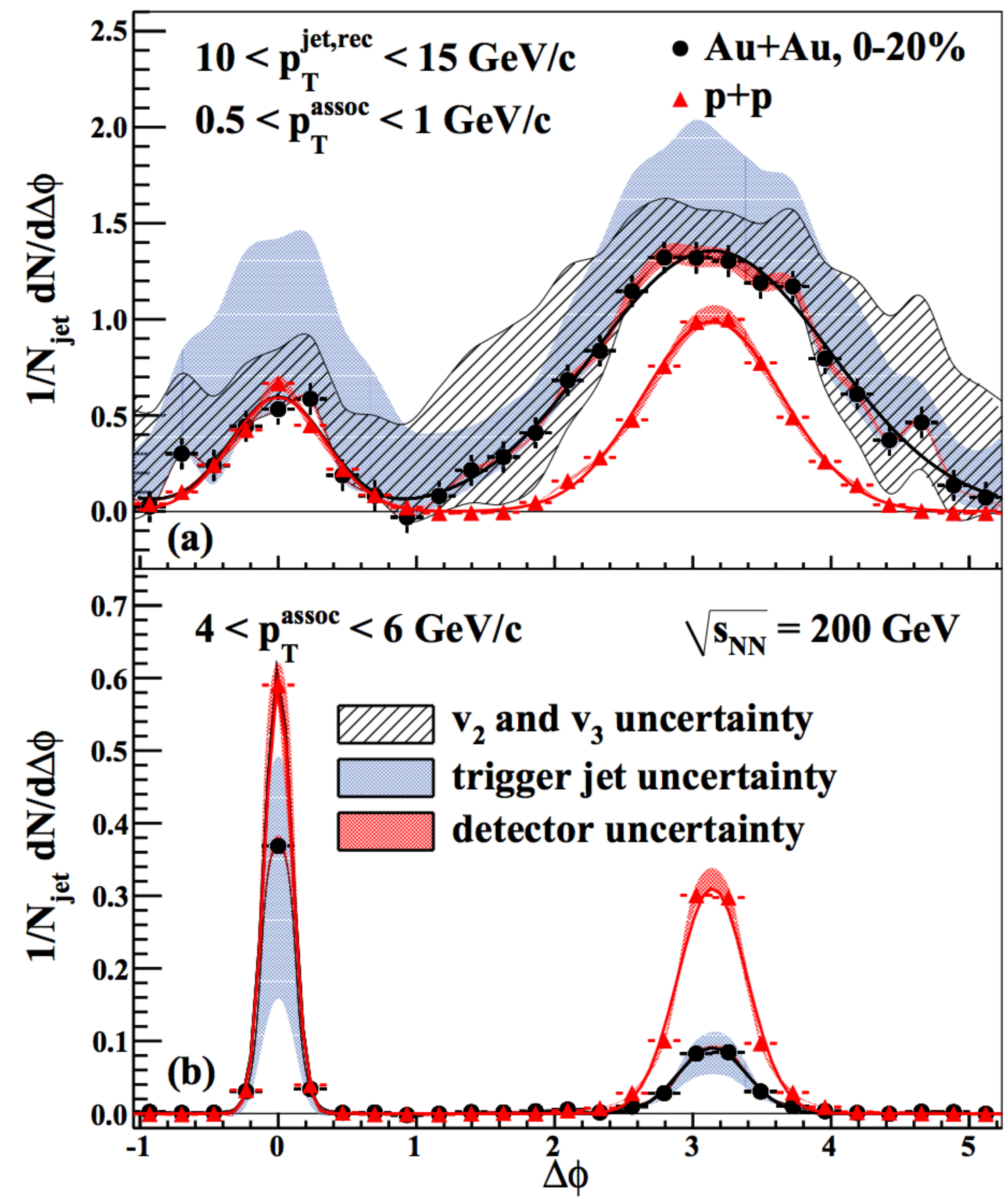


Jet+hadron correlations



enhancement of recoil jet low-p_T constituents, broadening

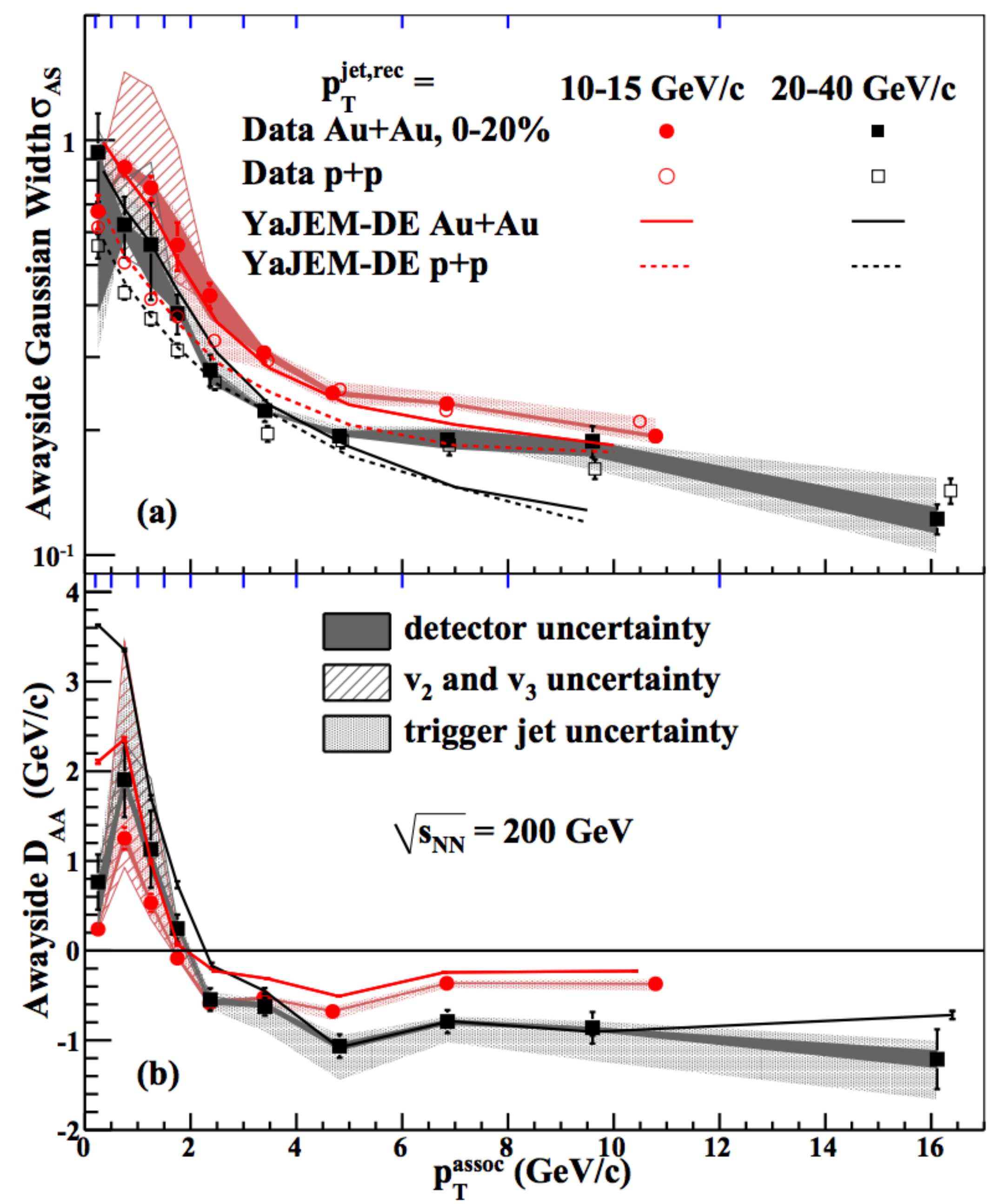
suppression of recoil jet high-p_T constituents



STAR, PRL ***112****, 122301 (2014)*

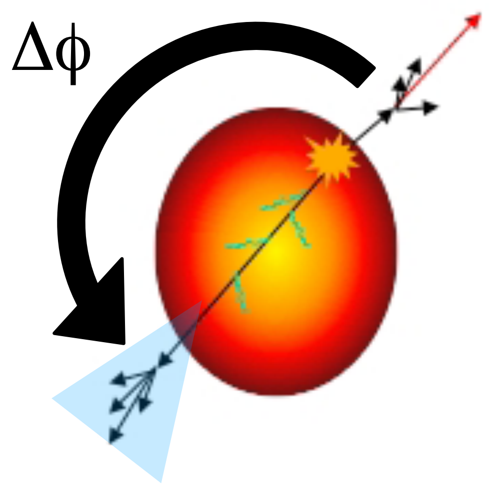
Jet+hadron correlations

- clear signal of **softening** and **broadening** in recoil jet
- energy loss in high-p_T region balanced by low-p_T excess



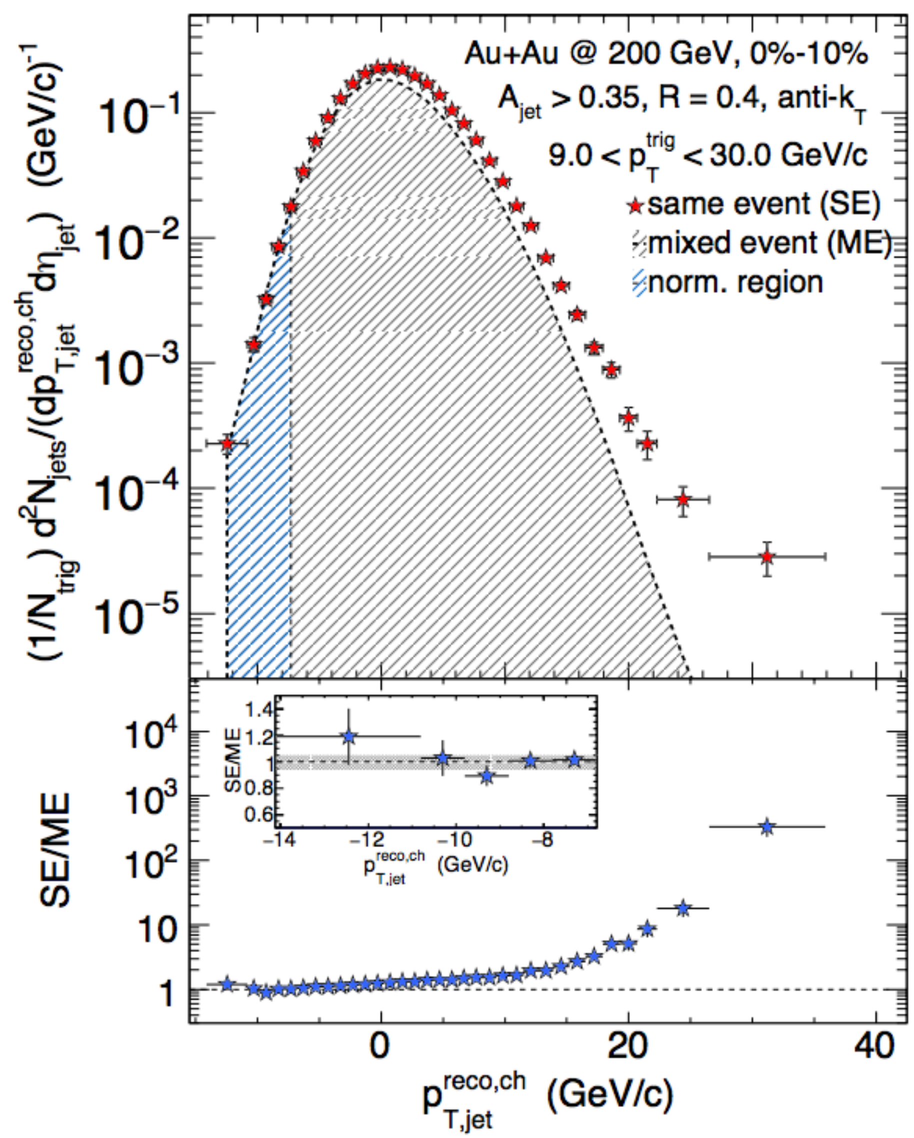
*STAR, PRL **112**, 122301 (2014)*

Hadron+jet spectra



semi-inclusive hadron-triggered recoil jet spectra

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



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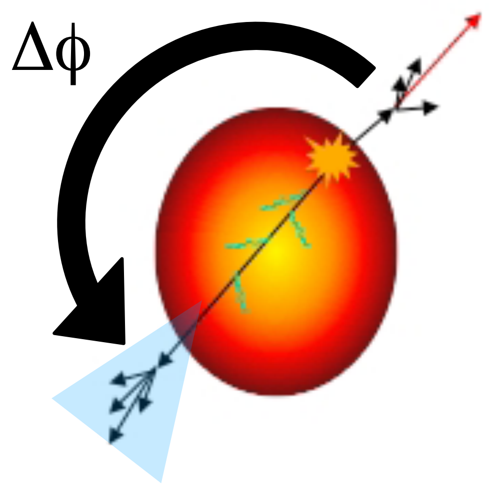
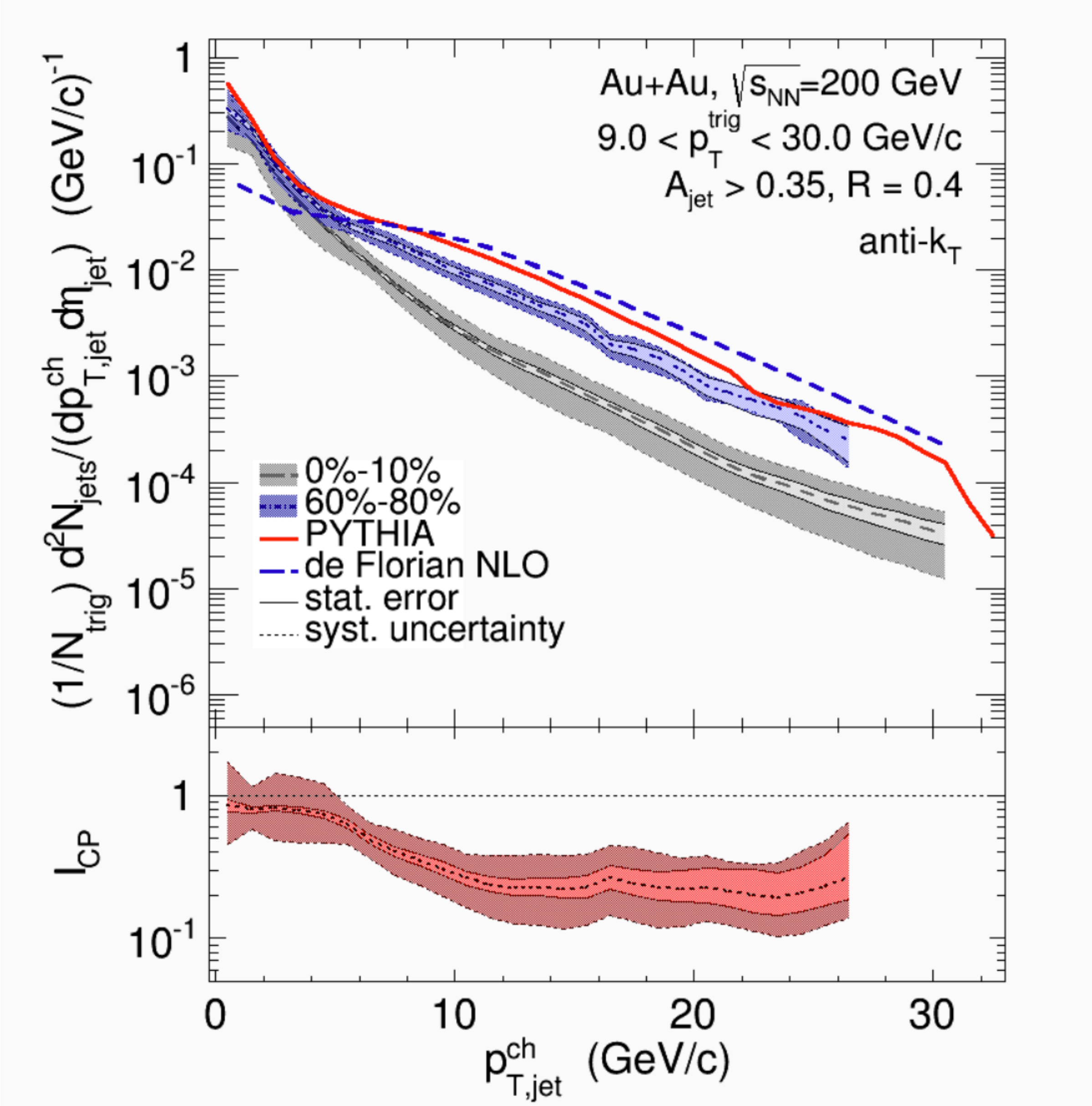
Hadron+jet spectra



yield of jets recoiling from high p_T hadron

suppression of recoil jet in central collisions compared to peripheral



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