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

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

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WAYNE STATE

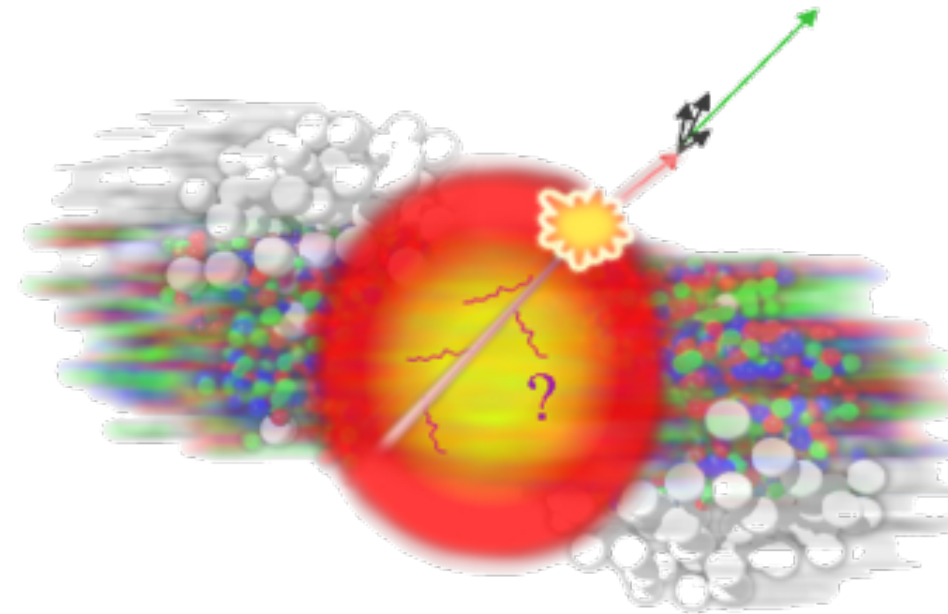
STAR

Jet quenching in a nutshell

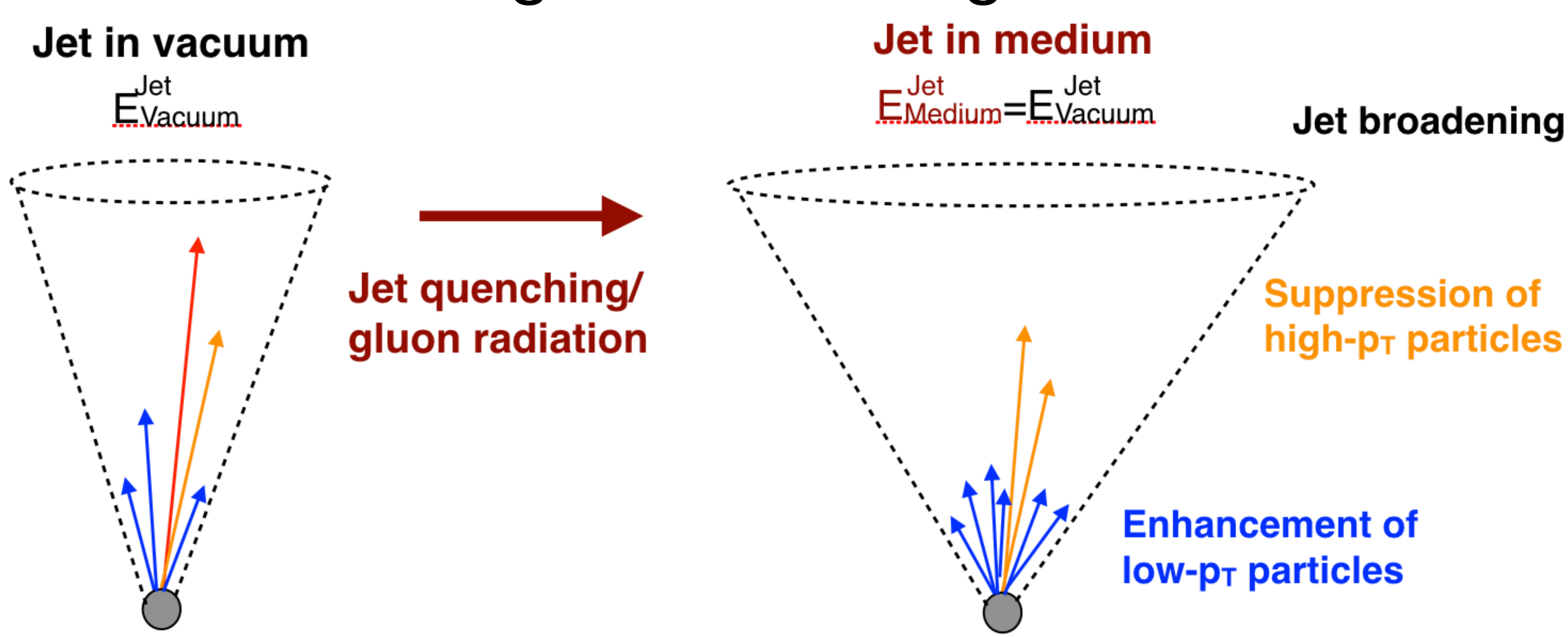
partonic energy loss

gluon radiation (**primary**)

collisional energy loss (small)



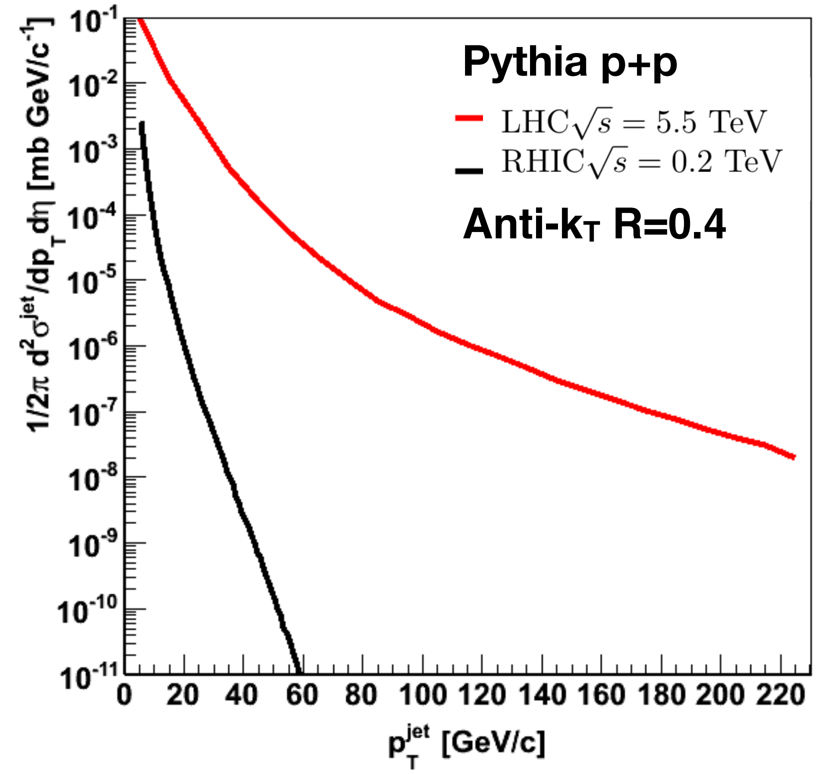
broadening and softening



Jet production at RHIC & LHC

orders of magnitude difference in jet production cross section

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



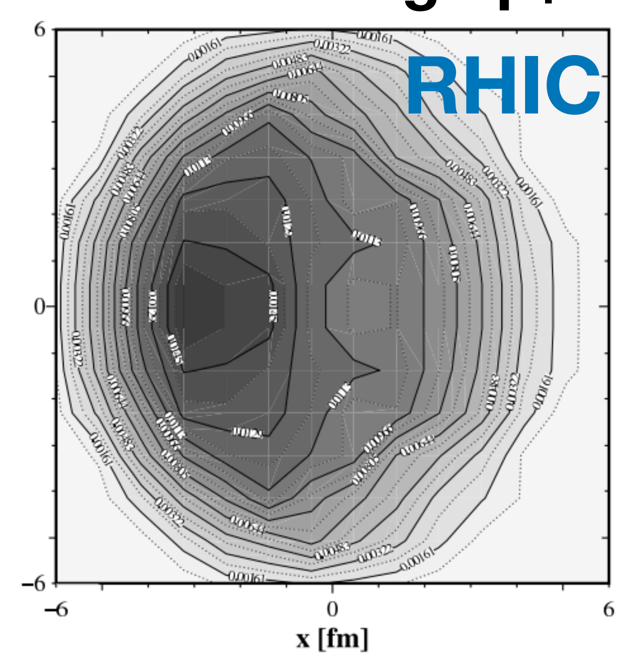
models (Renk, Zapp,…) predict that with the softer **RHIC** spectrum

trigger ➔ surface bias

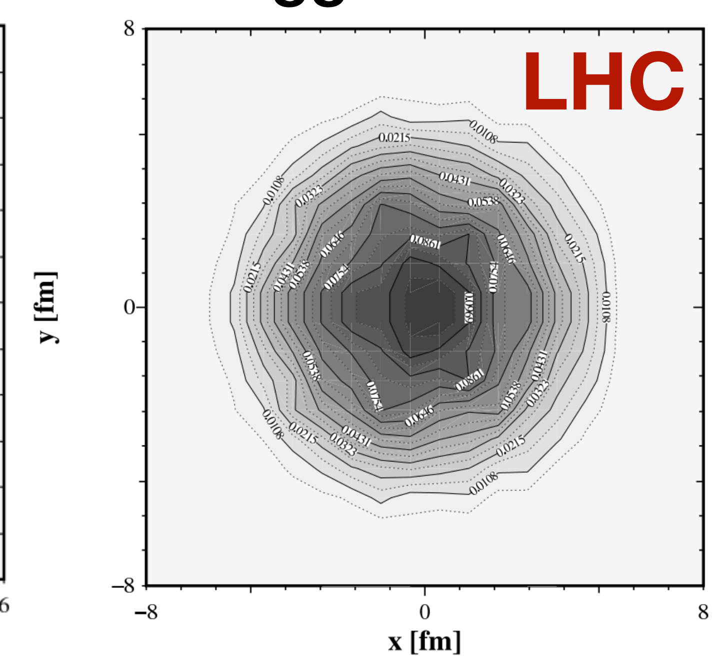
however, at the higher **LHC** energies,

trigger ➔ no surface bias

high p_T hadron trigger



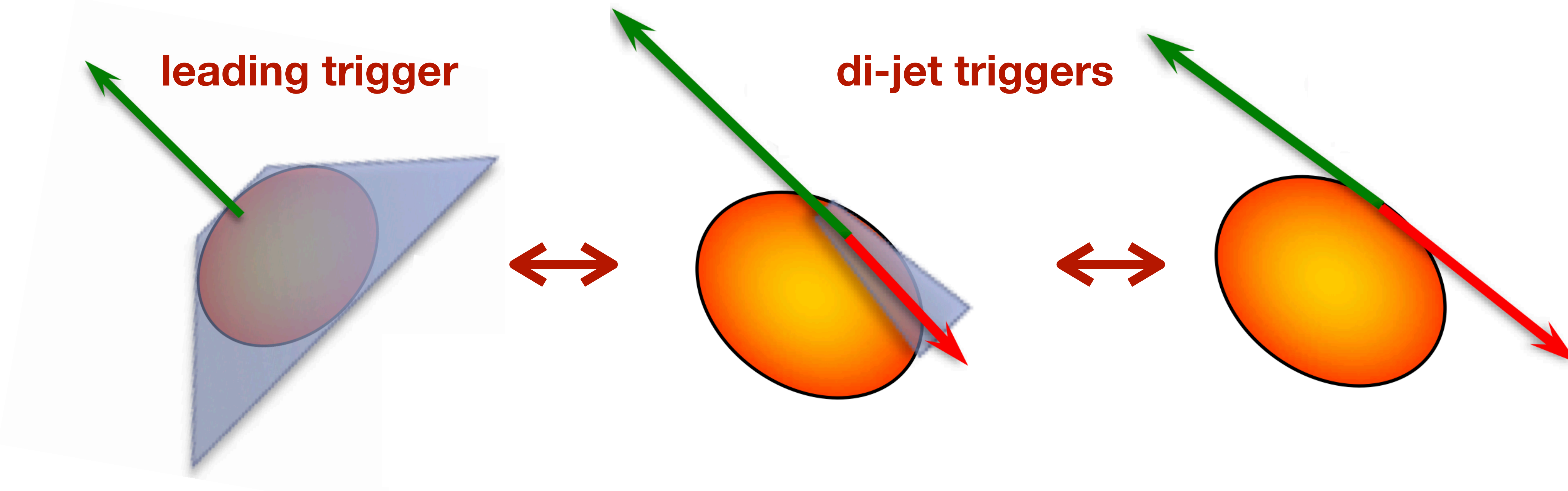
Renk, Phys.Rev. C 87, 024905 (2013)



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

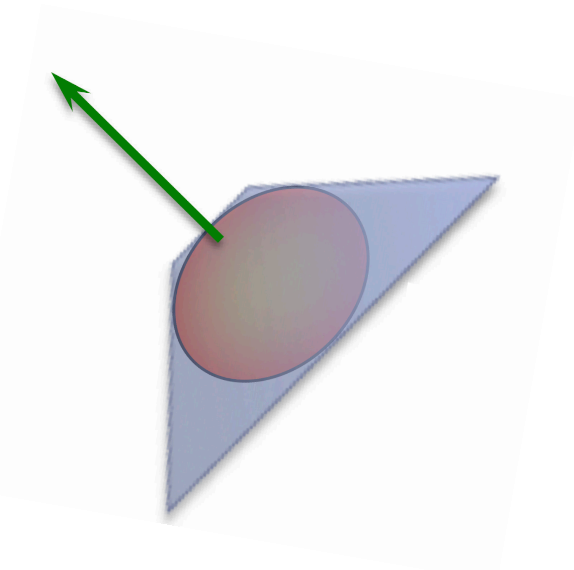
STAR, Phys. Rev. Lett. 119, 062301 (2017)

2+1 correlations

STAR, PRC 83 061901 (2011)

STAR, PRC 87 44903 (2013)

Outline

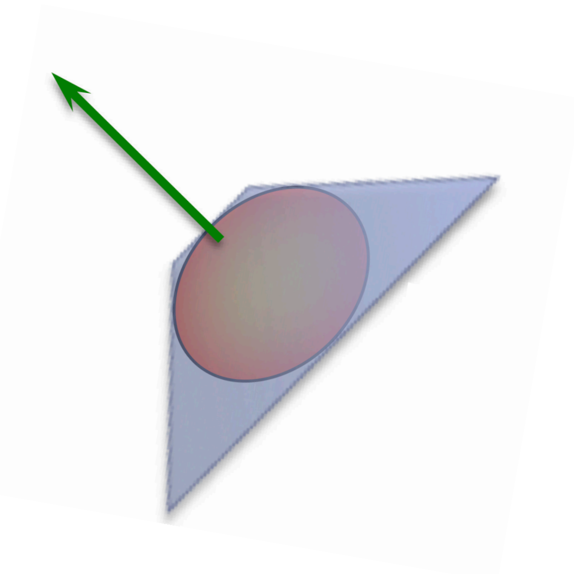


jet-like triggers

jet-hadron correlations

hadron-jet spectra

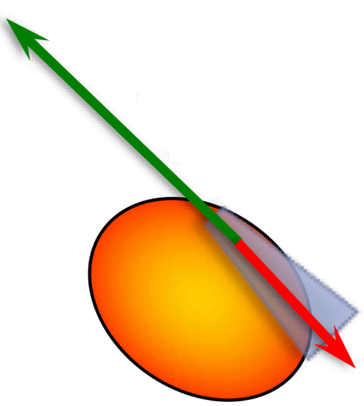
Outline



jet-like triggers

jet-hadron correlations

hadron-jet spectra

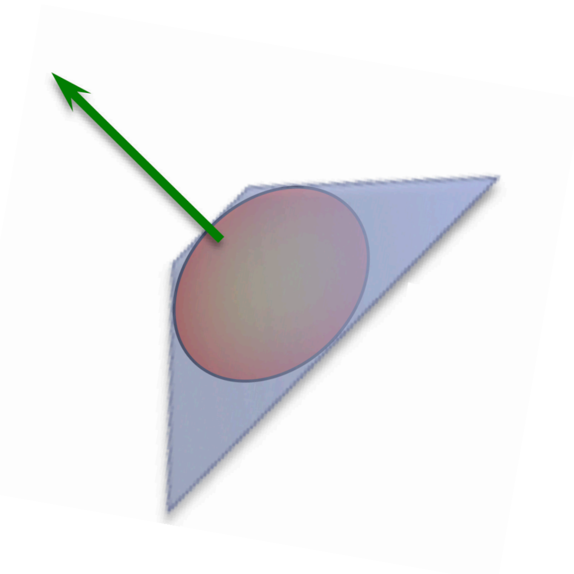


di-jet triggers

di-jet imbalance

di-jet hadron correlations

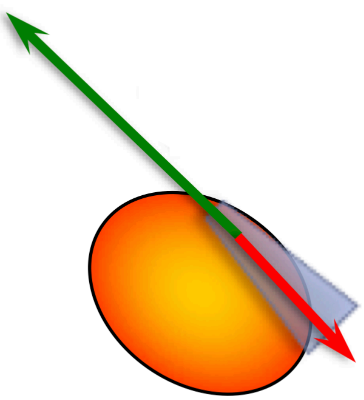
Outline



jet-like triggers

jet-hadron correlations

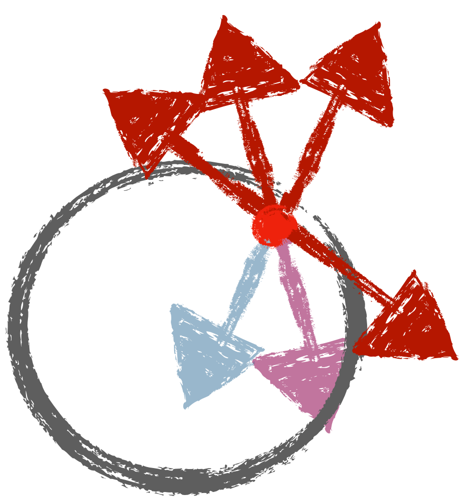
hadron-jet spectra



di-jet triggers

di-jet imbalance

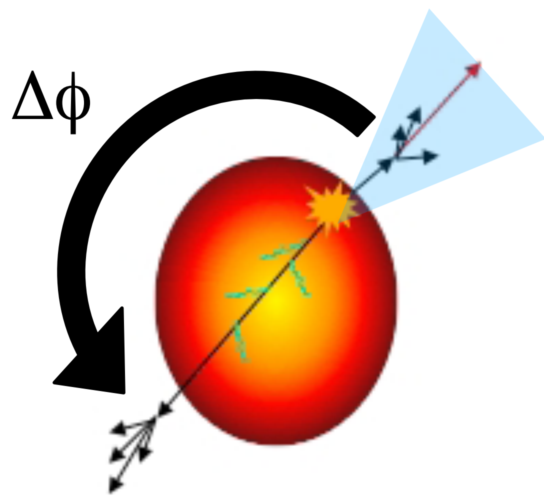
di-jet hadron correlations



jet geometry engineering

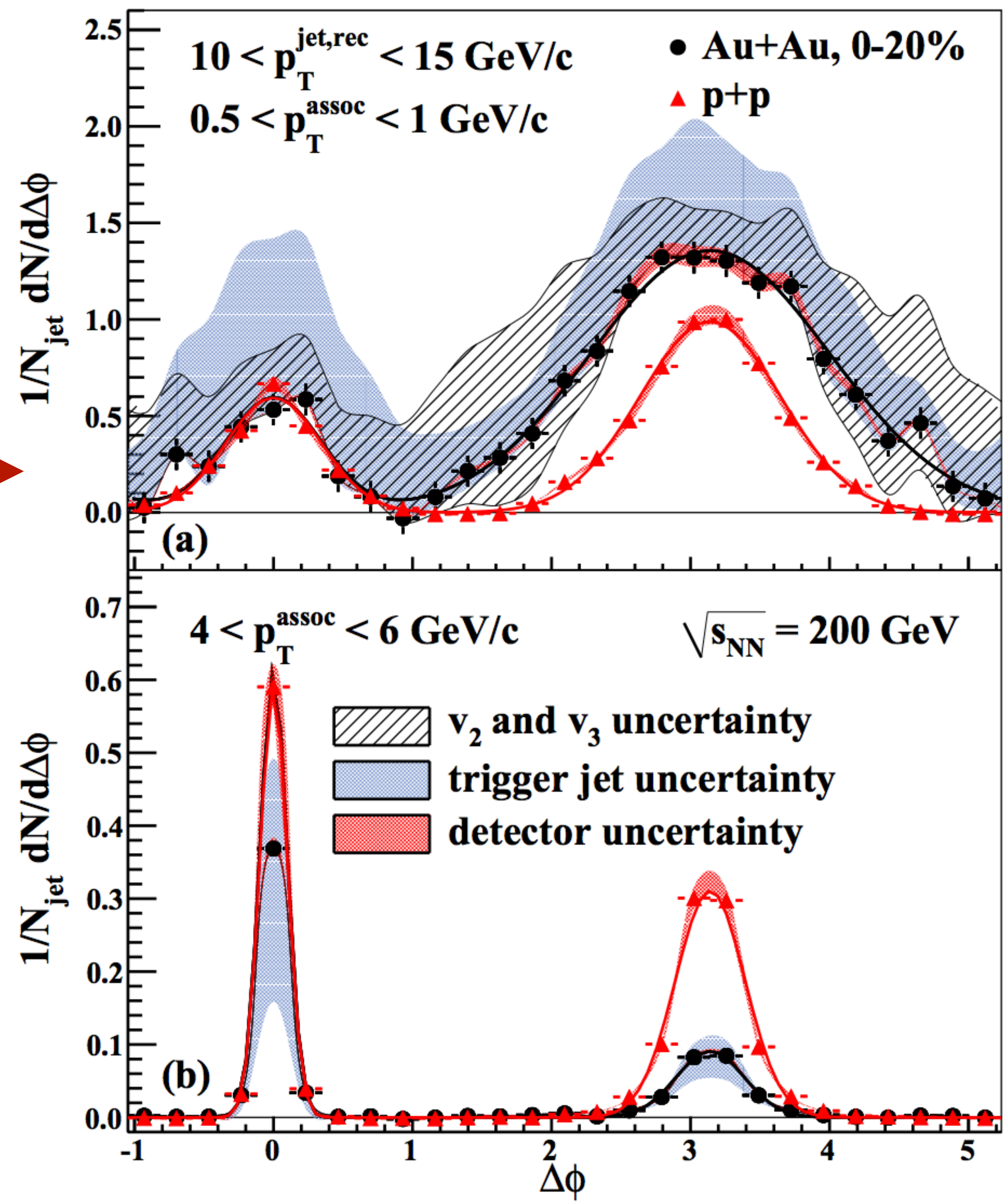
differential di-jet imbalance

Jet+hadron correlations



enhancement of recoil jet low-p_T constituents, broadening

suppression of recoil jet high-p_T constituents

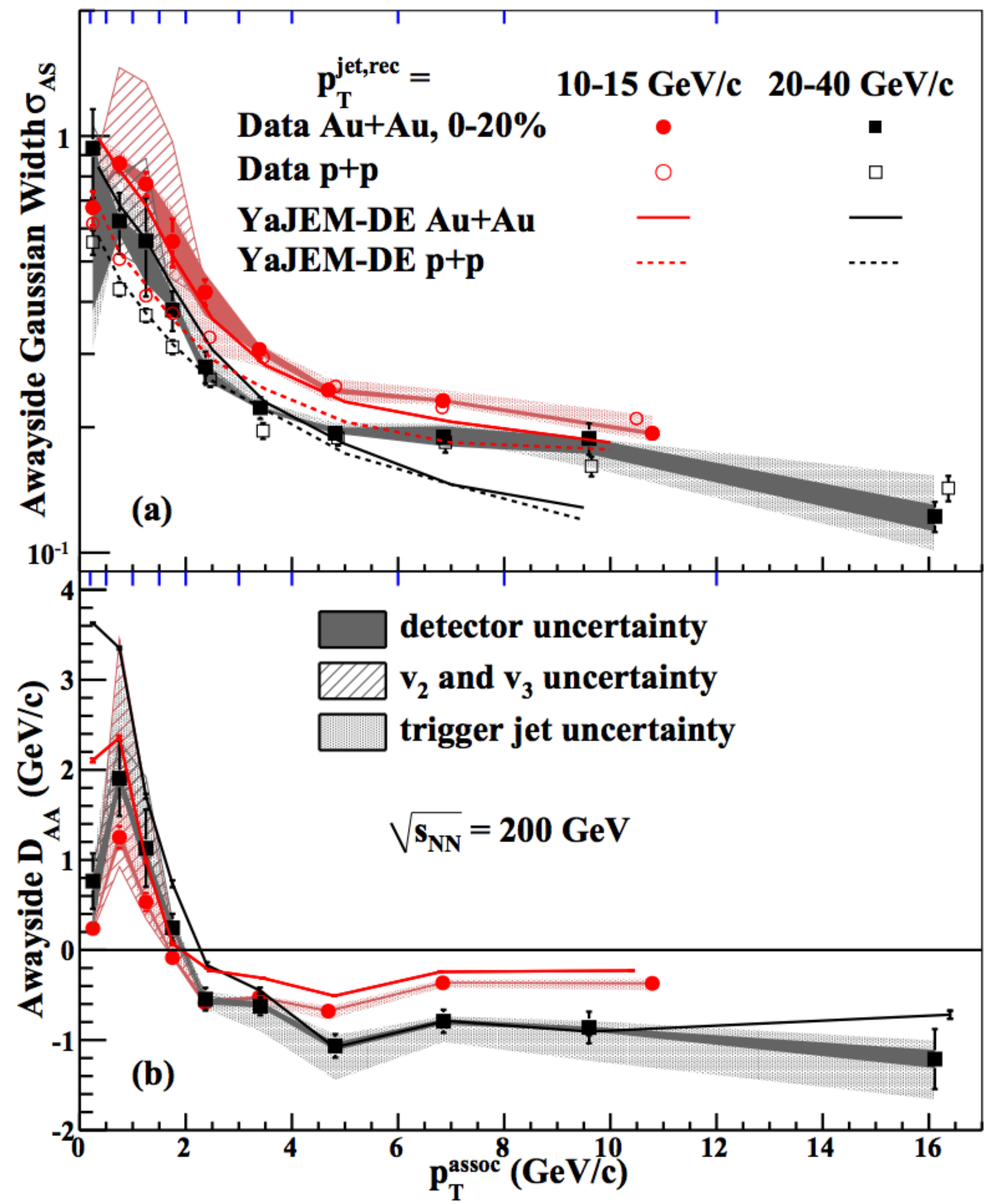


STAR, PRL **112**, 122301 (2014)

Jet+hadron correlations

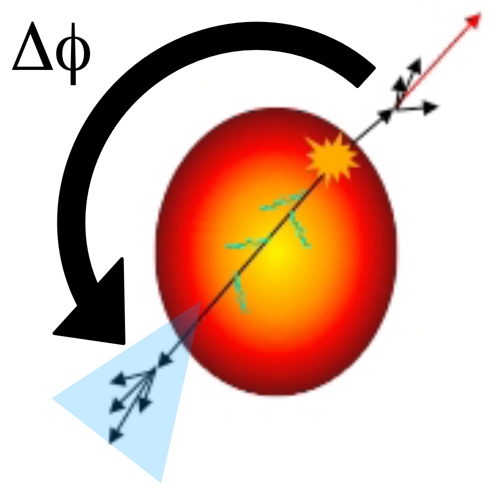
- clear signal of **softening** and **broadening** in recoil jet
- "energy loss" in high-p_T region balanced by low-p_T excess

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



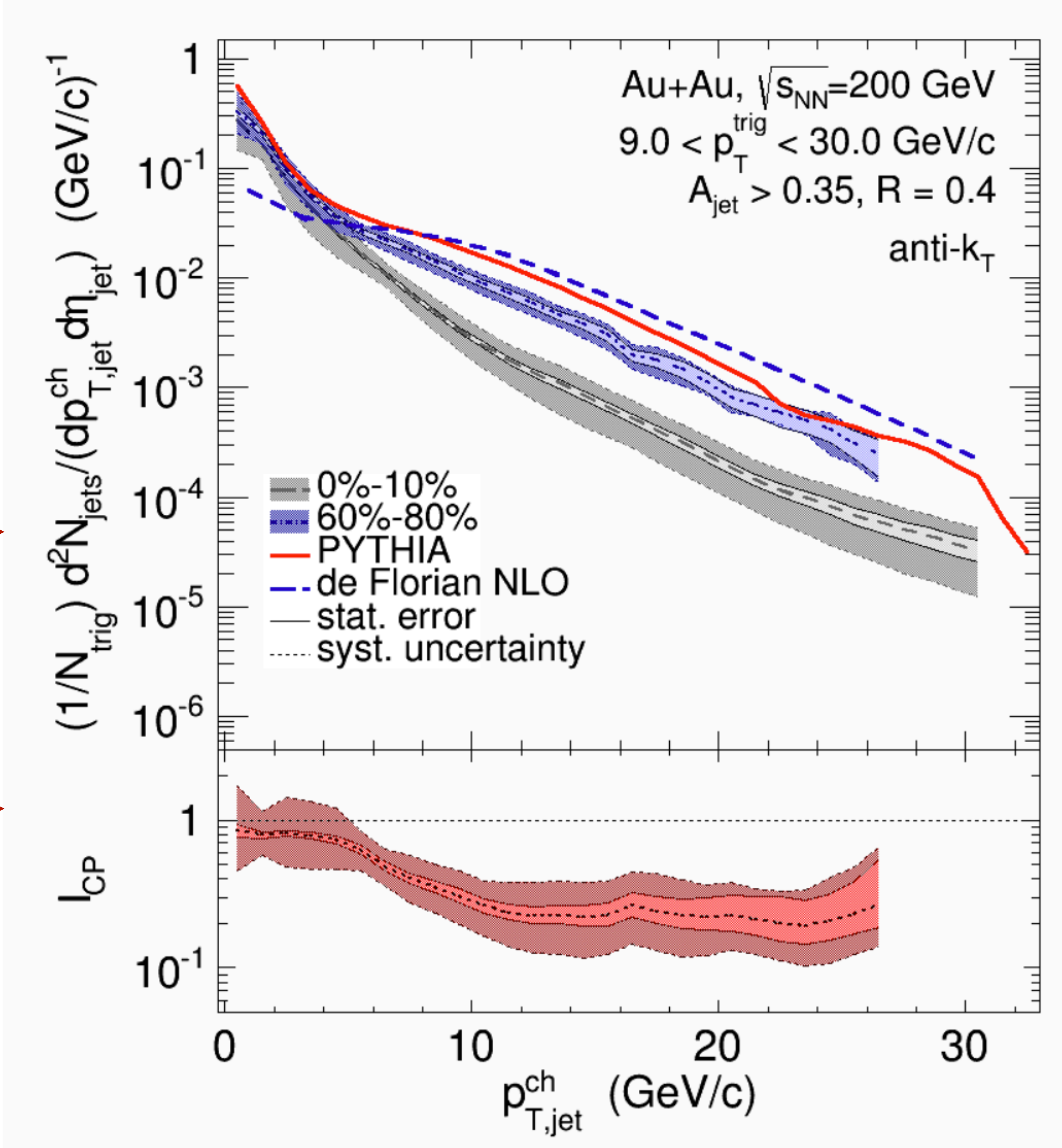
*STAR, PRL **112**, 122301 (2014)*

Hadron+jet spectra



yield of jets recoiling from high p_T hadron

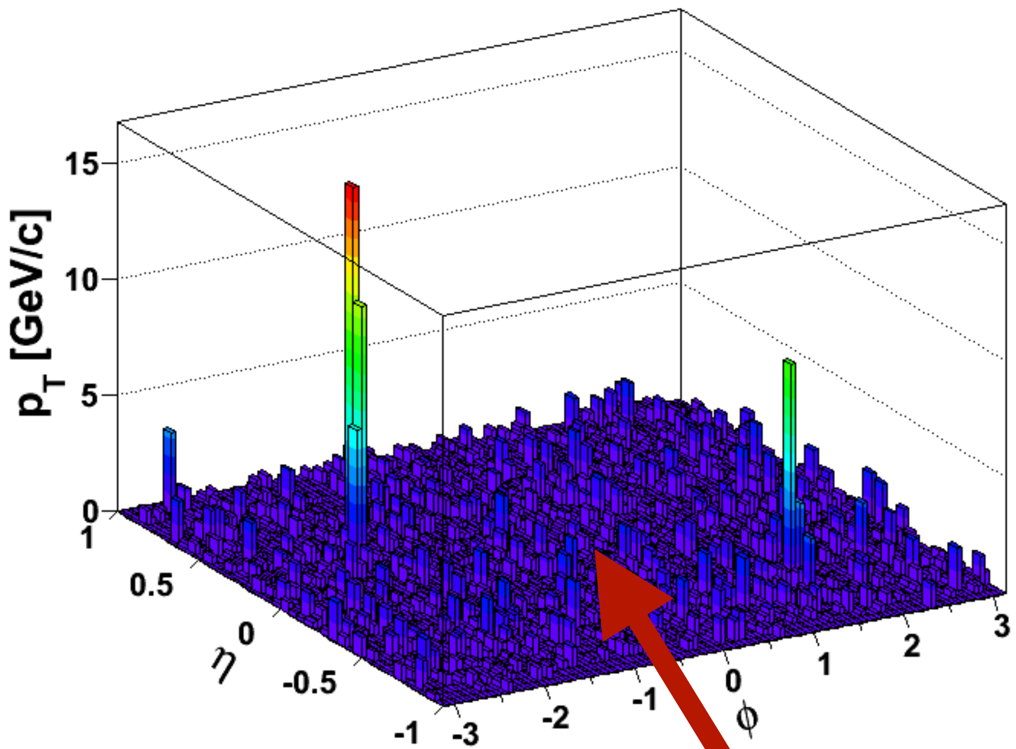
suppression of recoil jet in central collisions compared to peripheral



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

Hard core jets at STAR

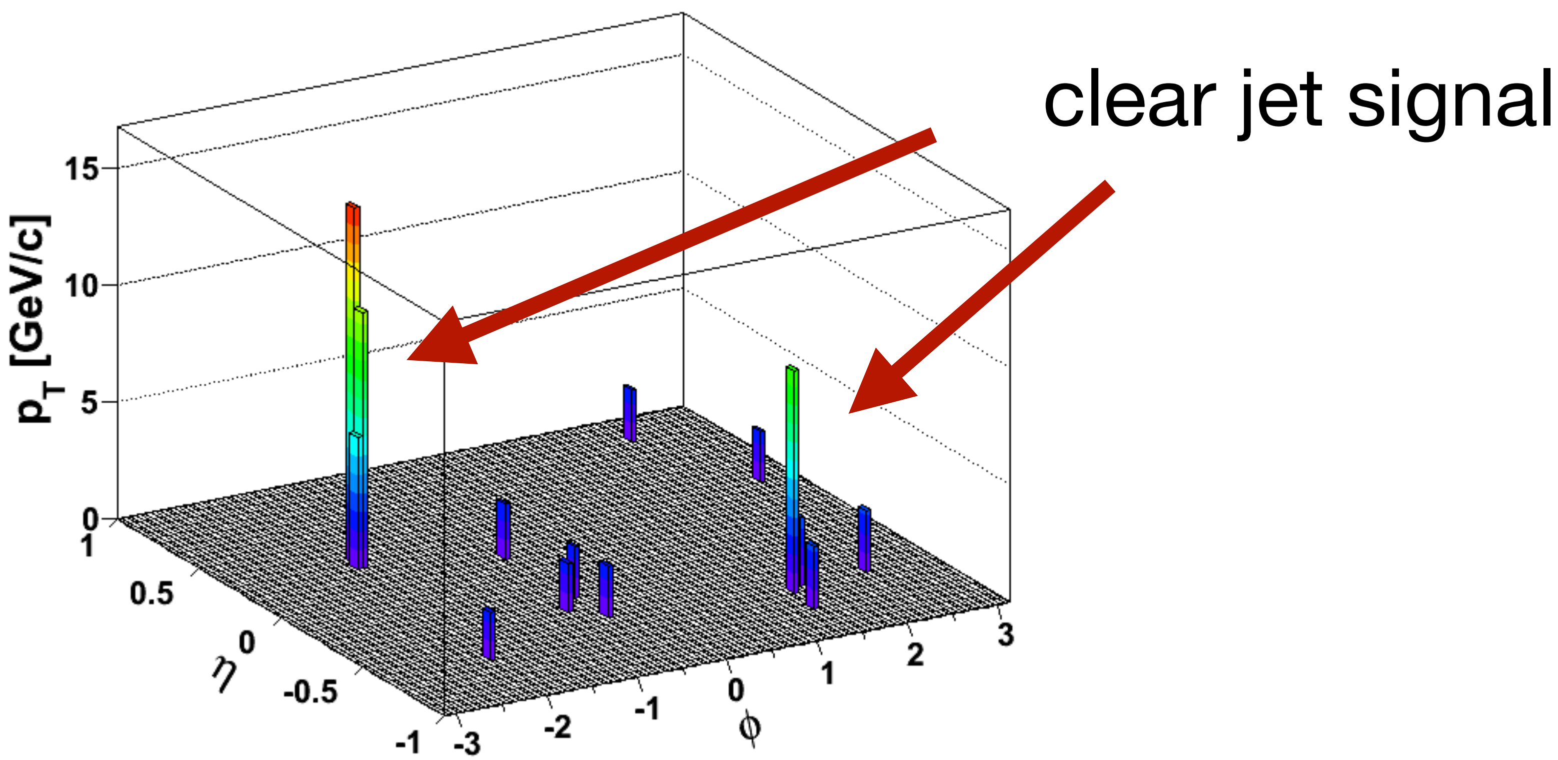
in a heavy-ion collision



large background energy density

Hard core jets at STAR

in a heavy-ion collision

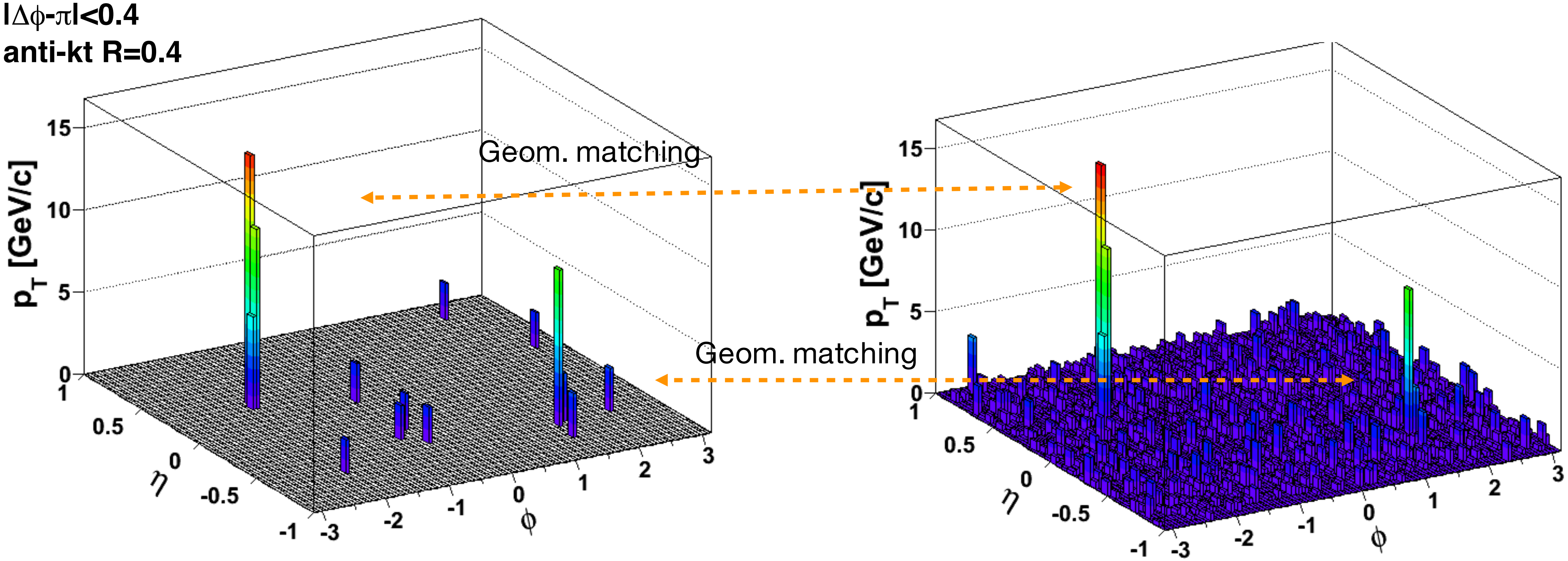


$p_T^{hard\ const} > 2$ GeV/c cut → removes almost all background

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



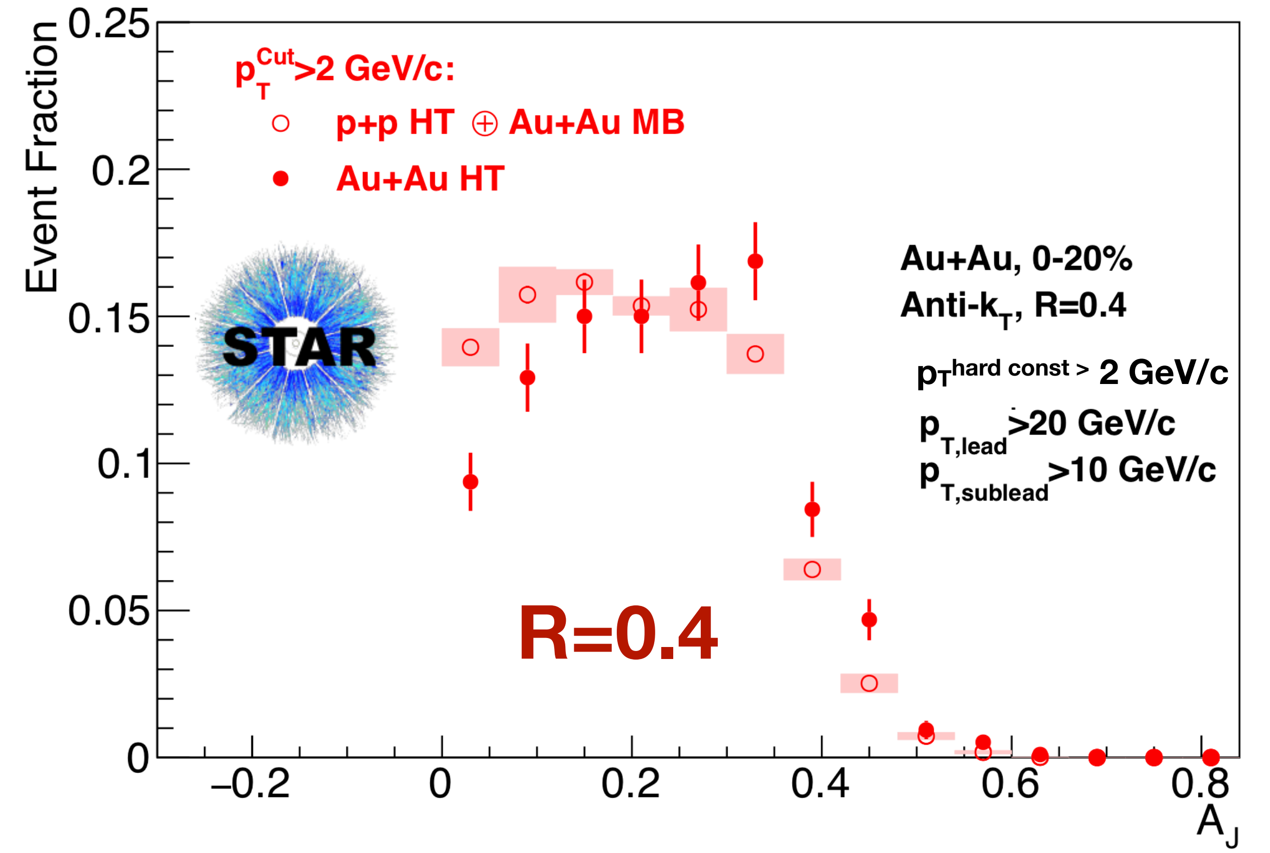
$p_T^{hard\ const}$ > 2 GeV/*c* cut → removes almost all background

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

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



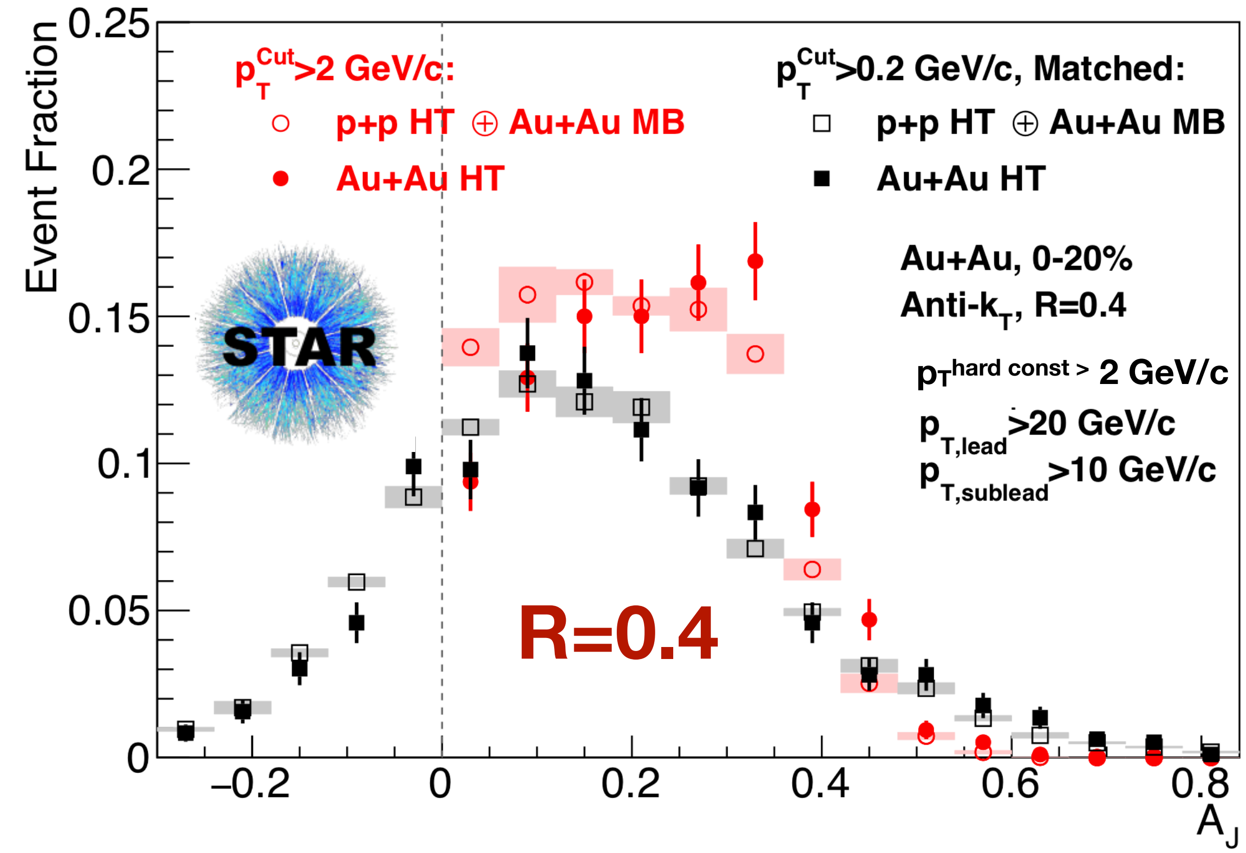
STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Di-jet asymmetry at STAR

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

when soft constituents are included: balance 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)

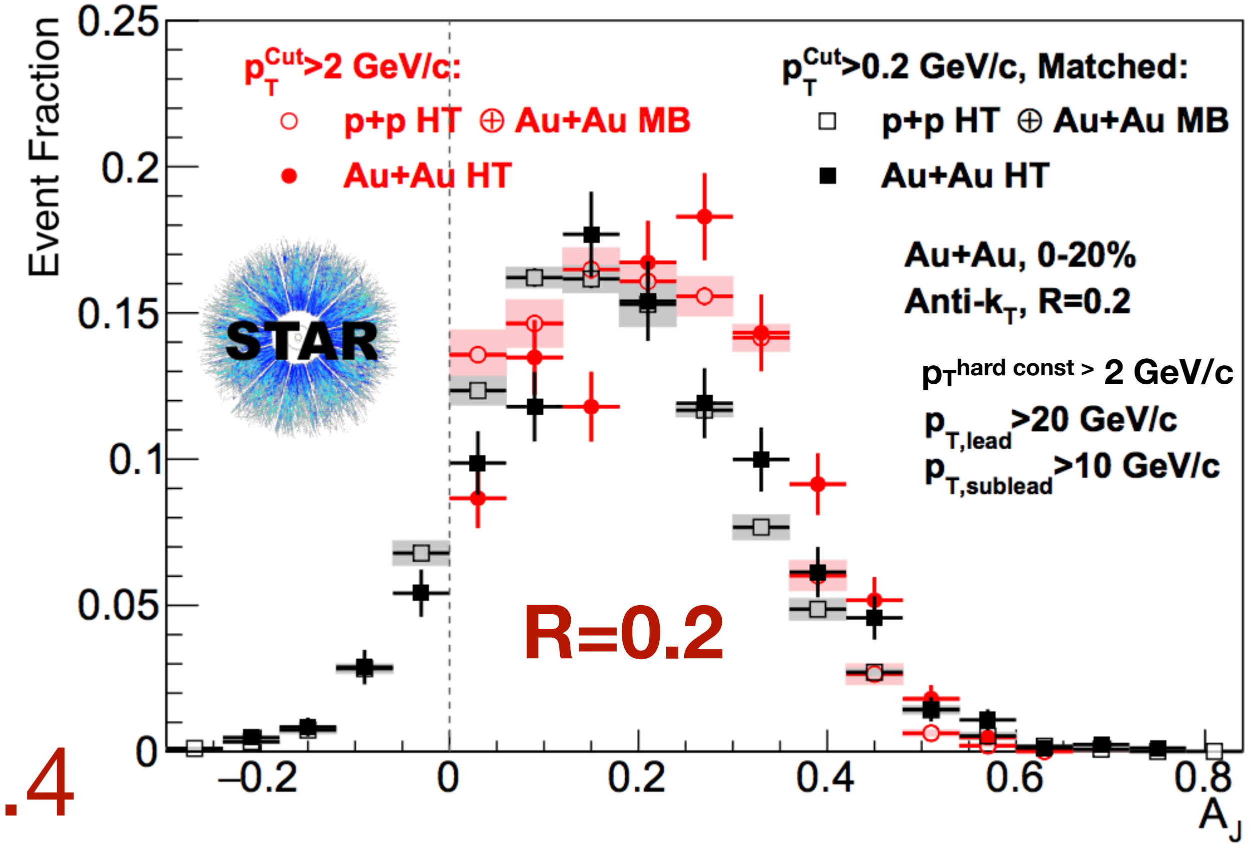
Di-jet asymmetry at STAR

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

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



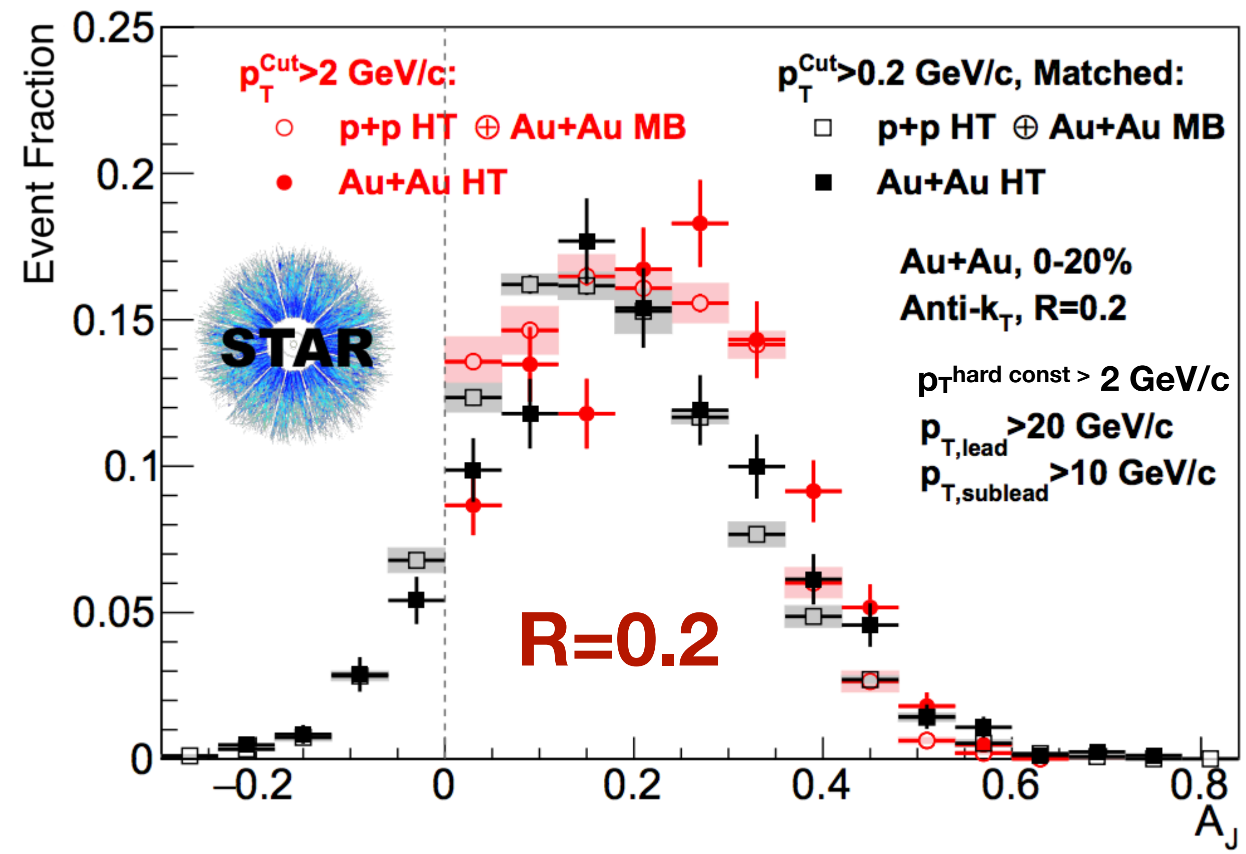
STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

Di-jet asymmetry at STAR

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

A_J is insensitive to the details of which jet is modified

→ di-jet hadron correlations

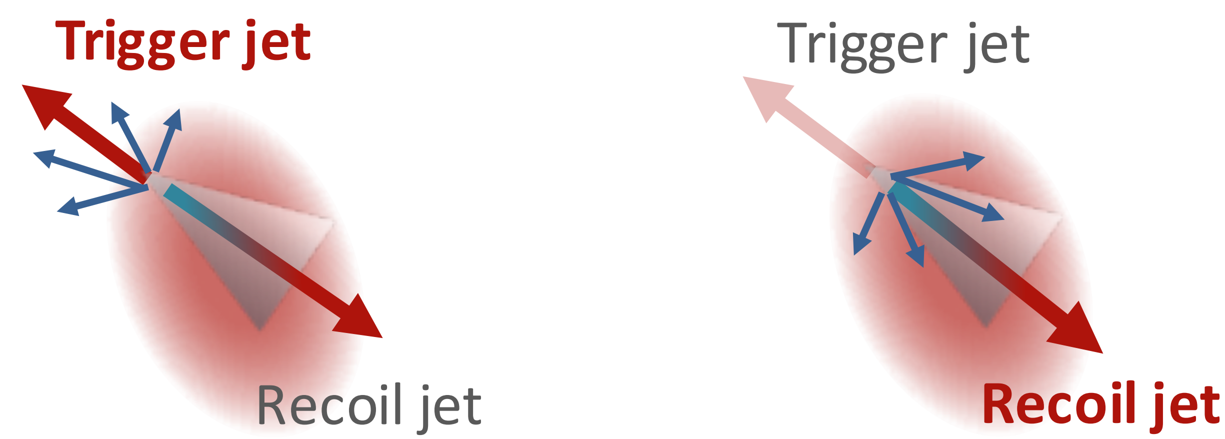


STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

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

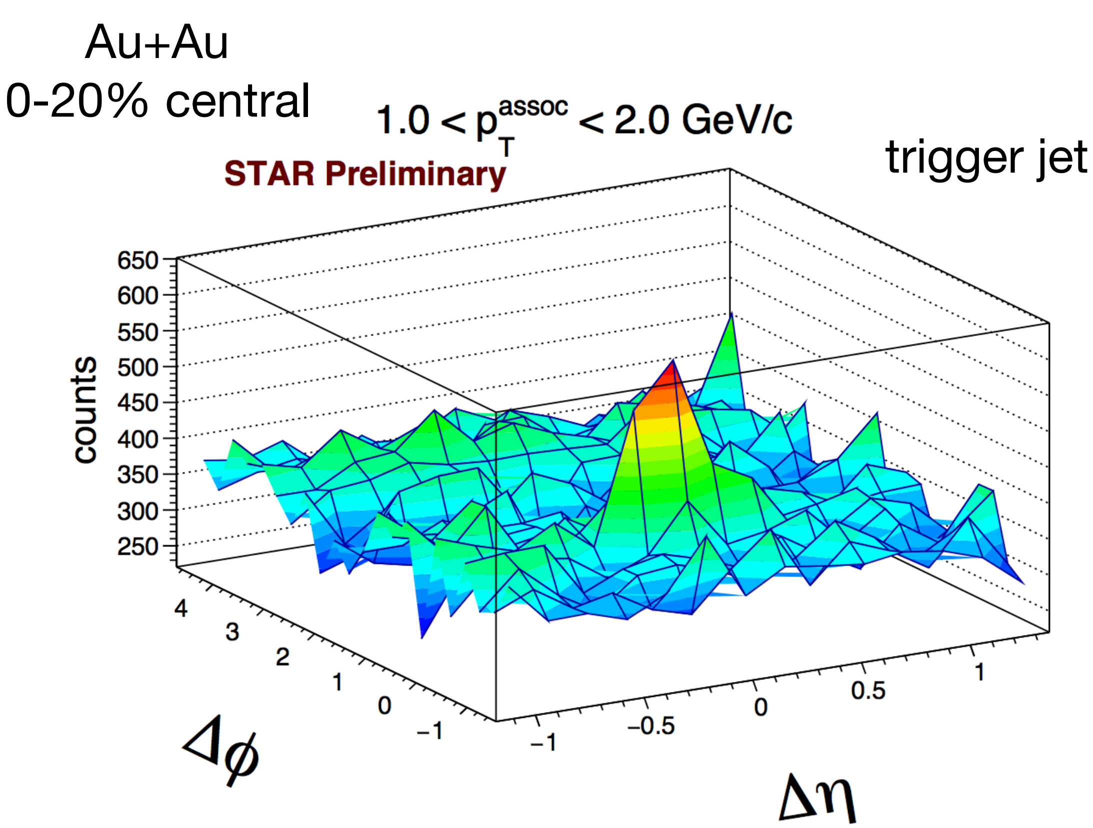


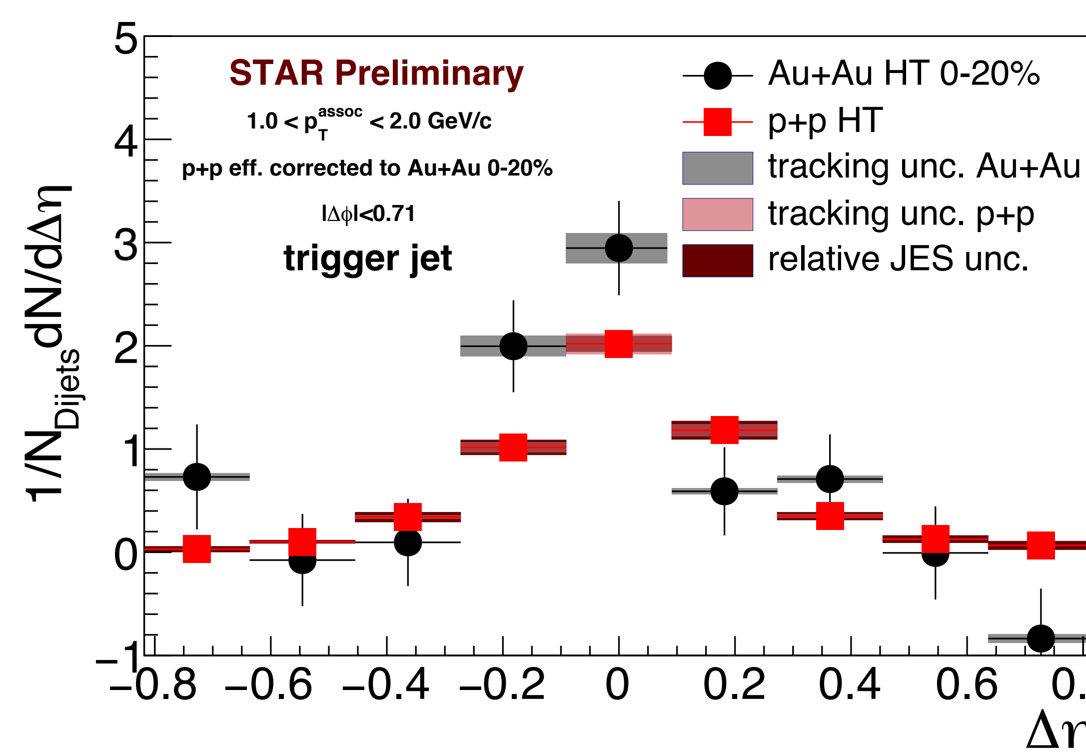
correlations

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

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

recoil jet: back-to-back with trigger jet

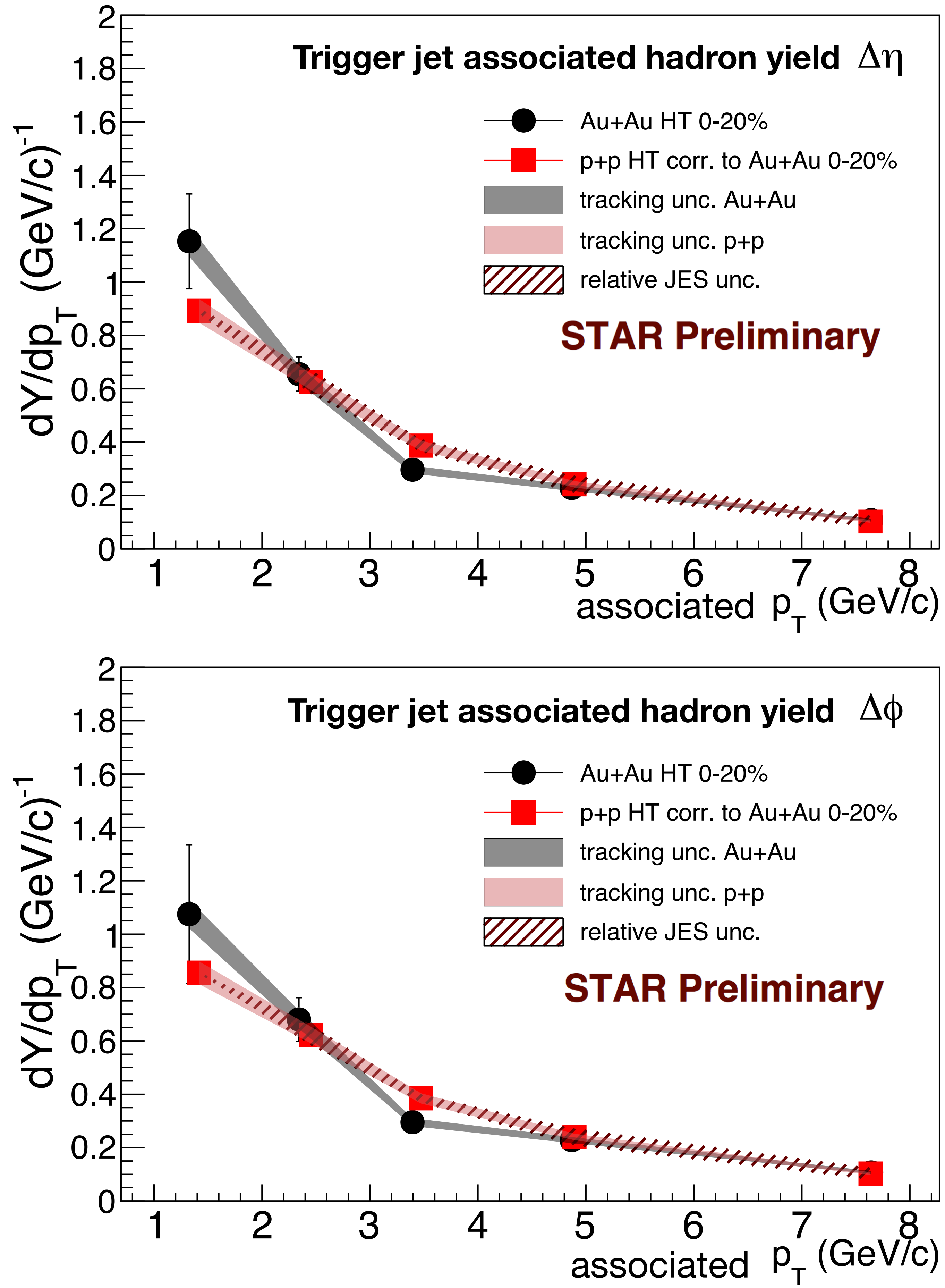




Correlated jet yield

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"

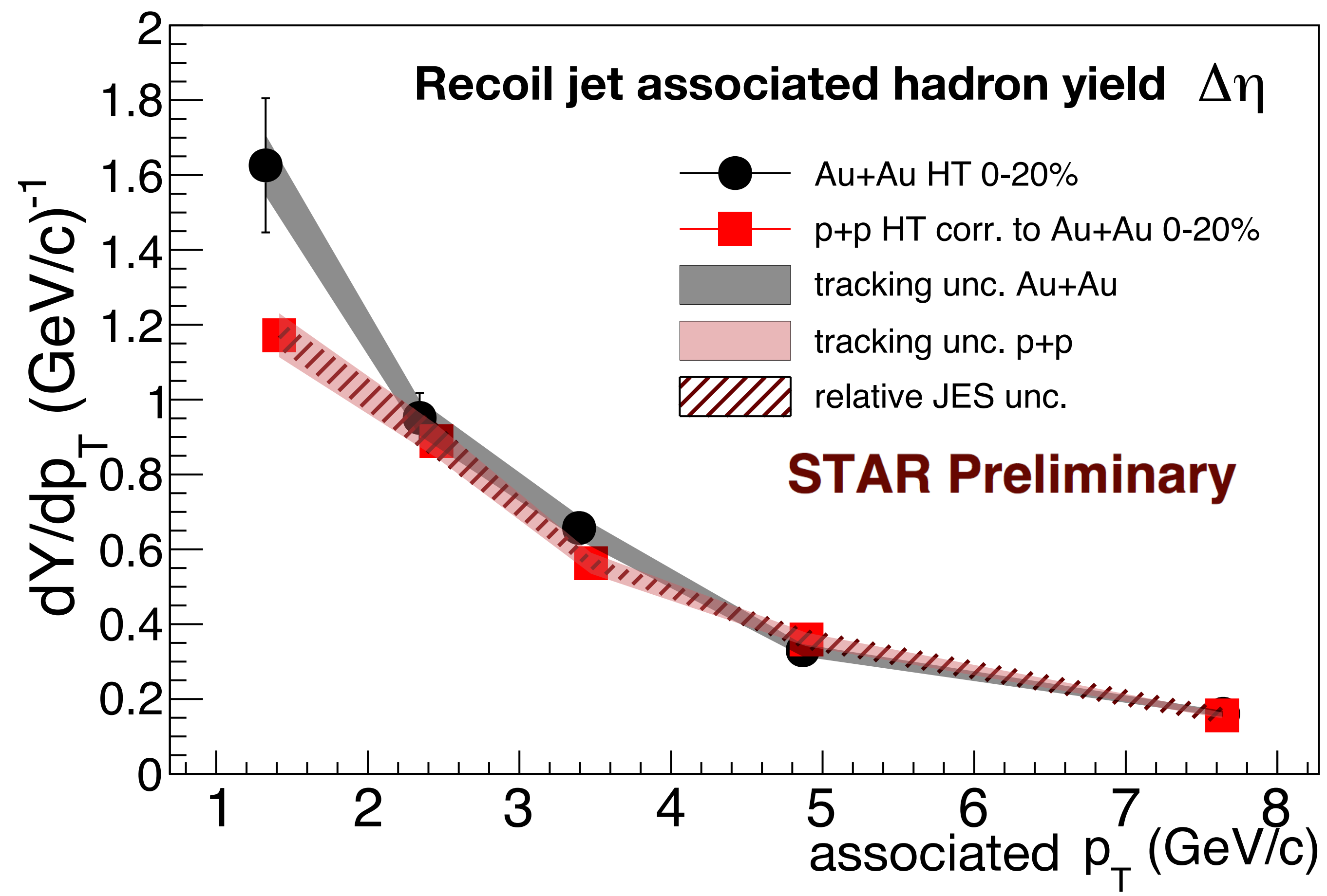


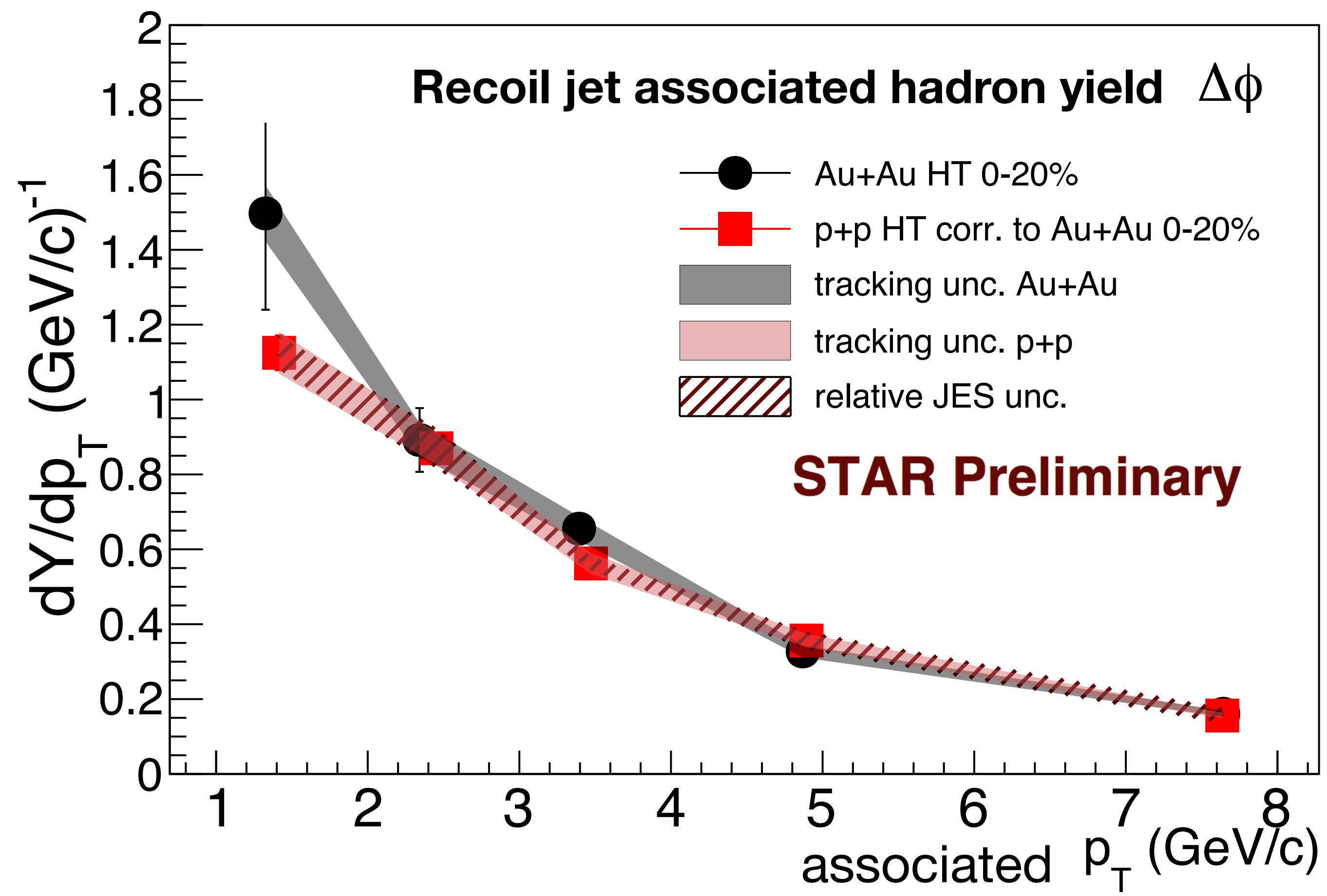
Correlated jet yield

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^{assoc}<2.0 GeV/c

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



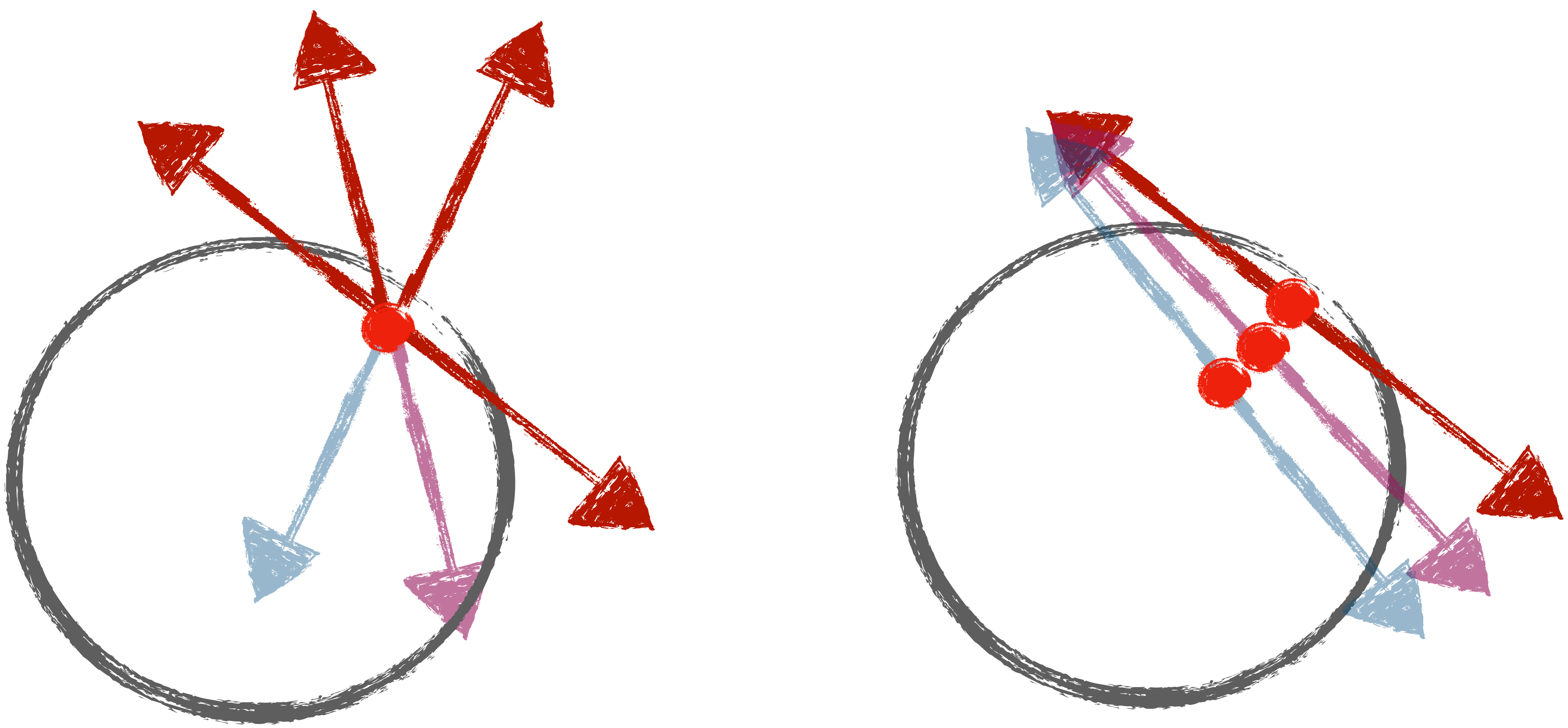


Jet geometry engineering

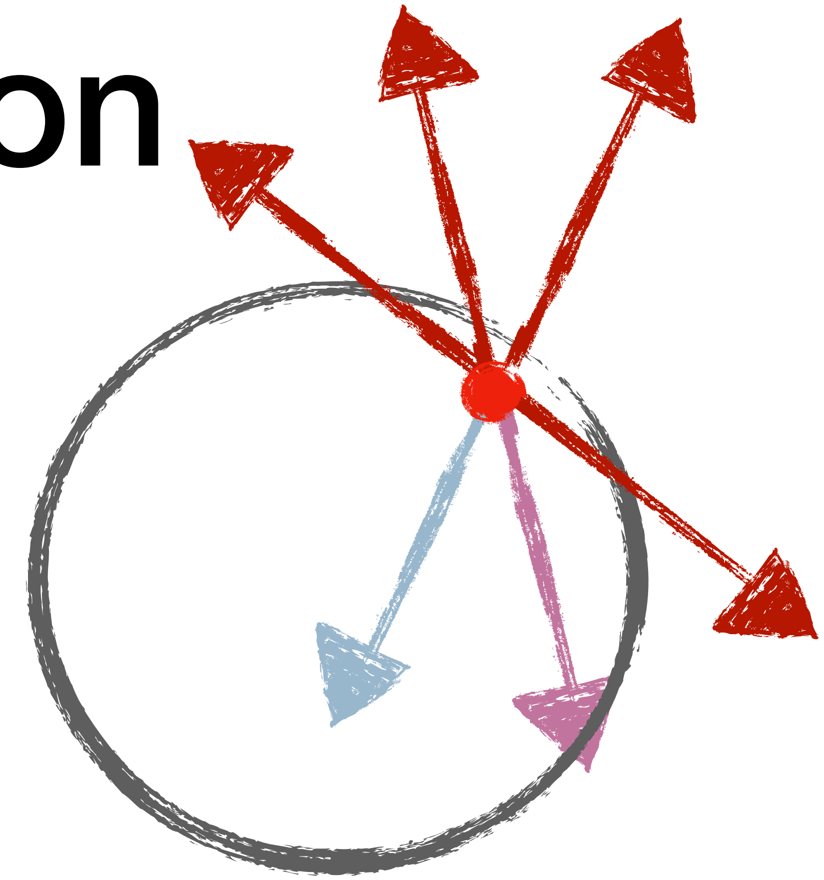
we have a set of jets with specific kinematics that we understand well

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

→ modification —> path length



Quantifying modification

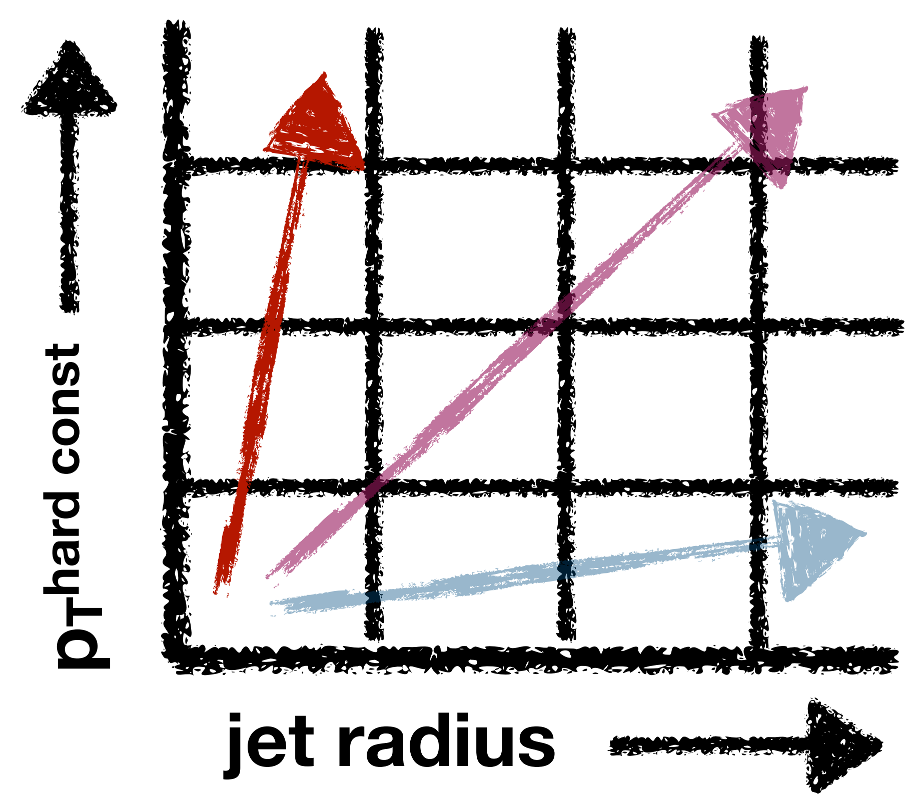


vary the jet definition

- 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



KS value = measure of statistical similarity between distributions

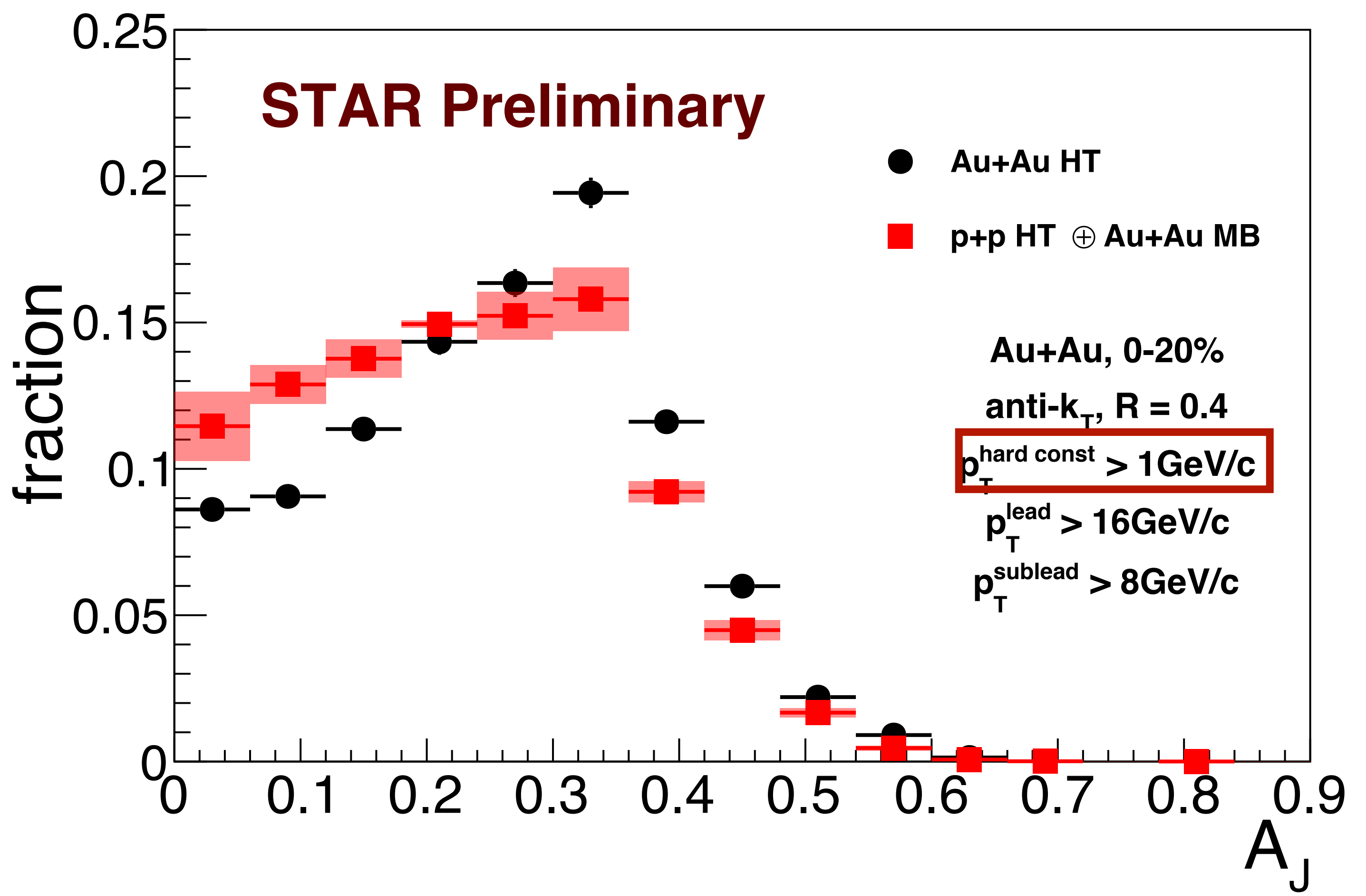
Differential di-jet imbalance

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 value << 1.0

Differential di-jet imbalance

→ **hard core di-jets**

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

R = 0.4

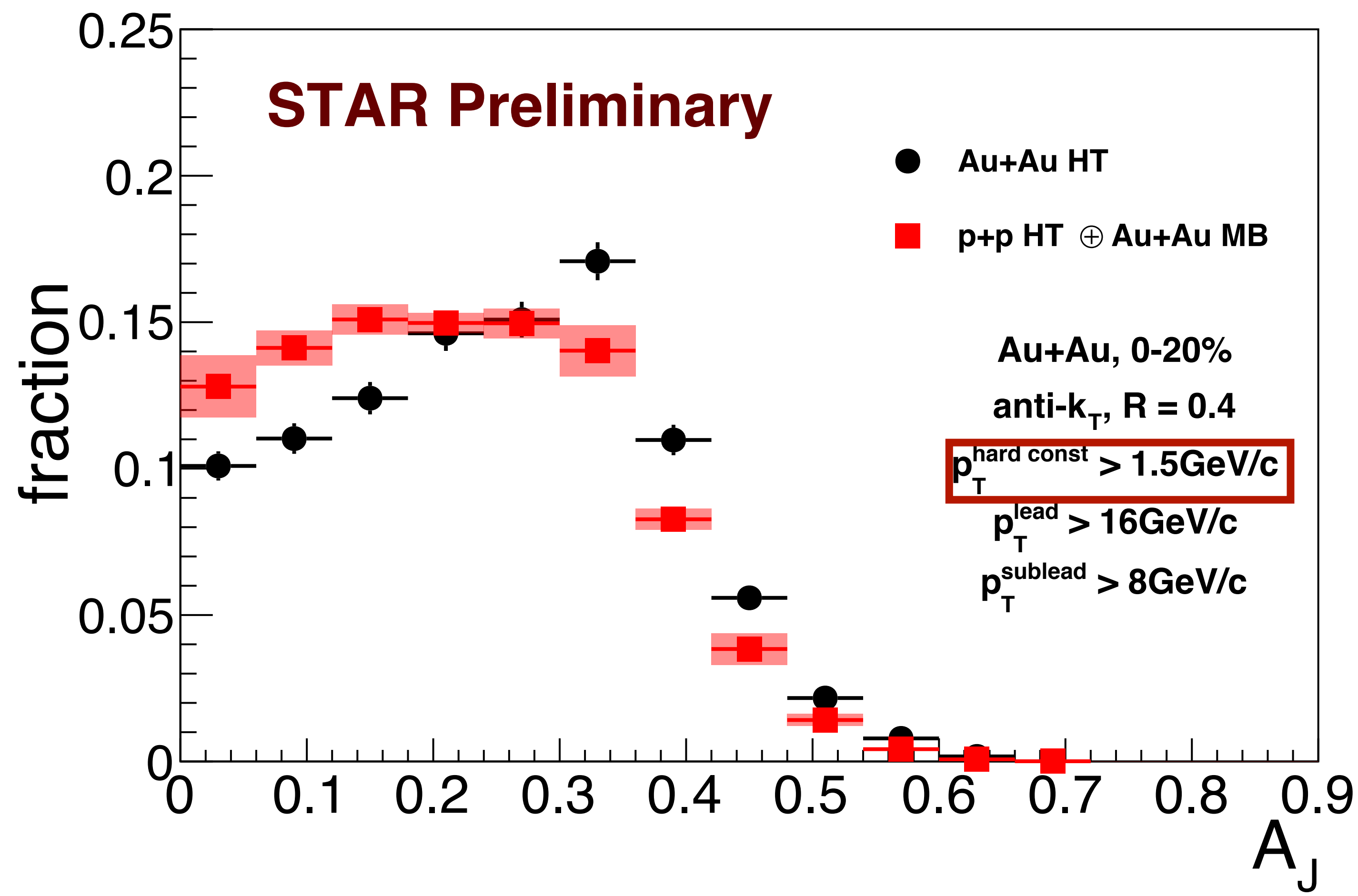
$p_T^{hard\ const}$ > 1.5 GeV/*c*

0-20% central

p_T^{lead} > 16 GeV/c

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

anti-k_T algorithm



K-S value << 1.0

Differential di-jet imbalance

hard core di-jets

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

R = 0.4

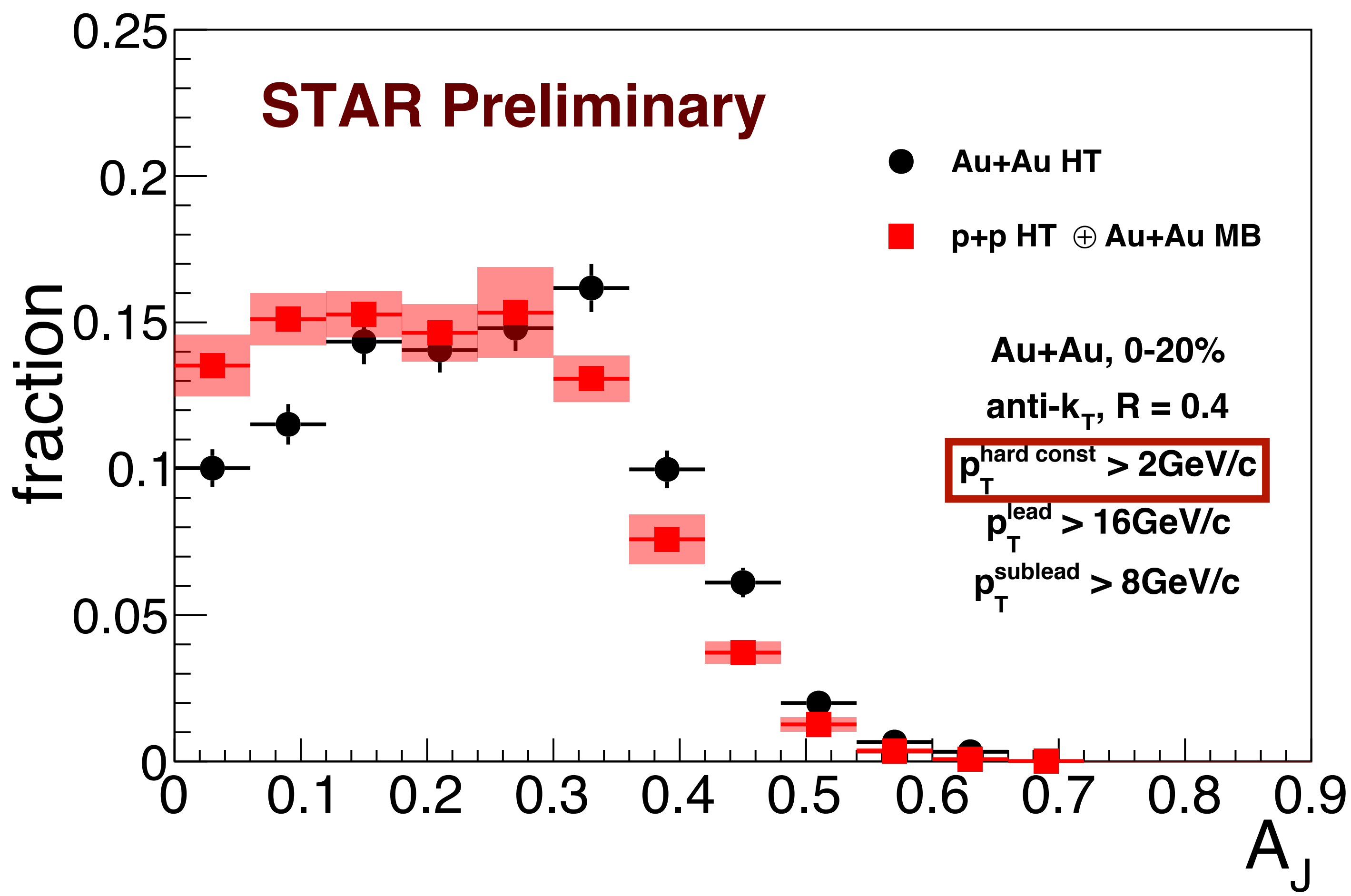
$p_T^{hard\ const}$ > 2.0 GeV/*c*

0-20% central

p_T^{lead} > 16 GeV/c

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

anti-k_T algorithm



K-S value << 1.0

Differential di-jet imbalance

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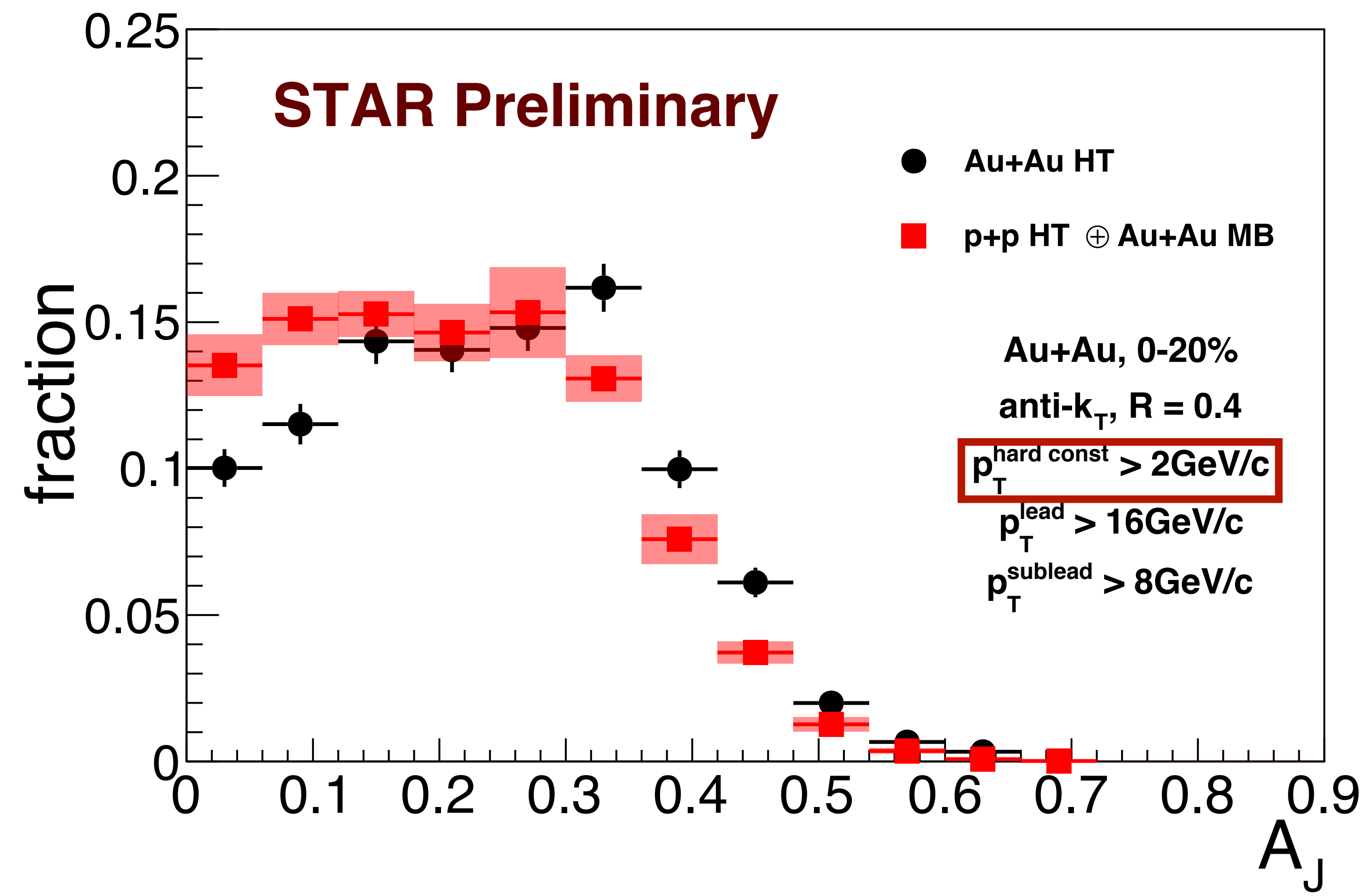
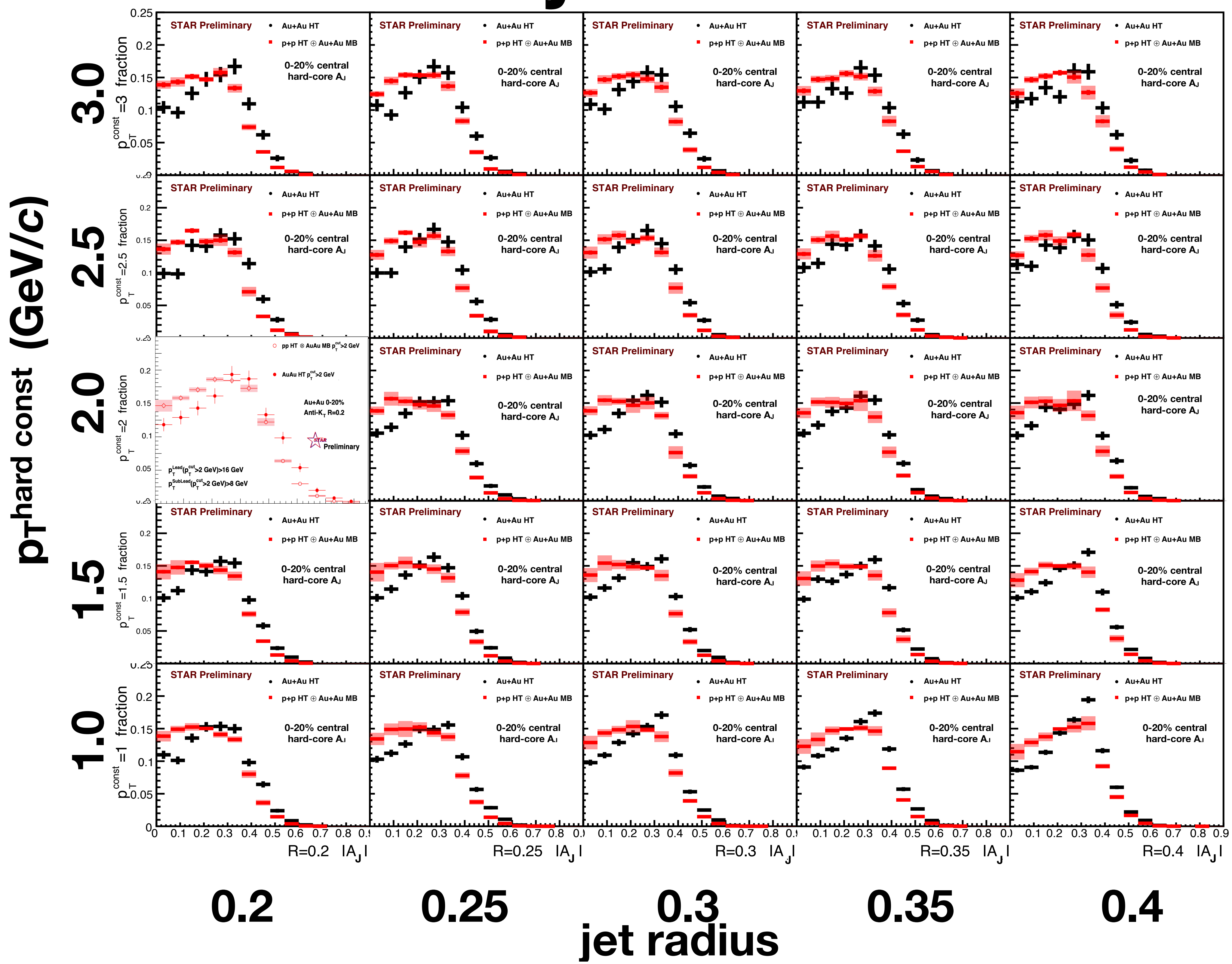


K-S value << 1.0

Now, we can repeat the procedure with the jet radius

Differential di-jet imbalance



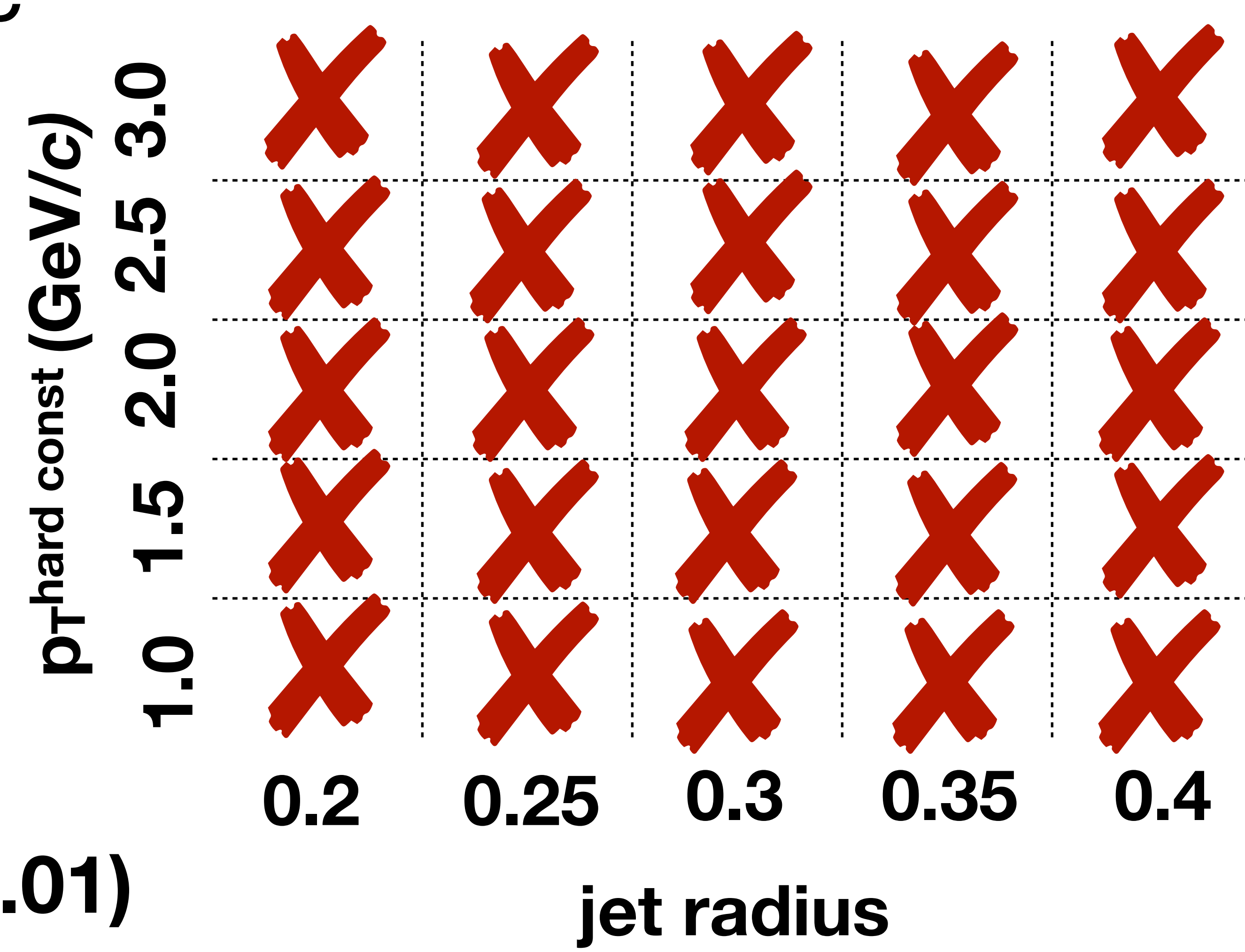
Significant difference in all bins

Differential di-jet imbalance

hard core di-jets

→ modified for all kinematic selections

Hard core di-jets



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

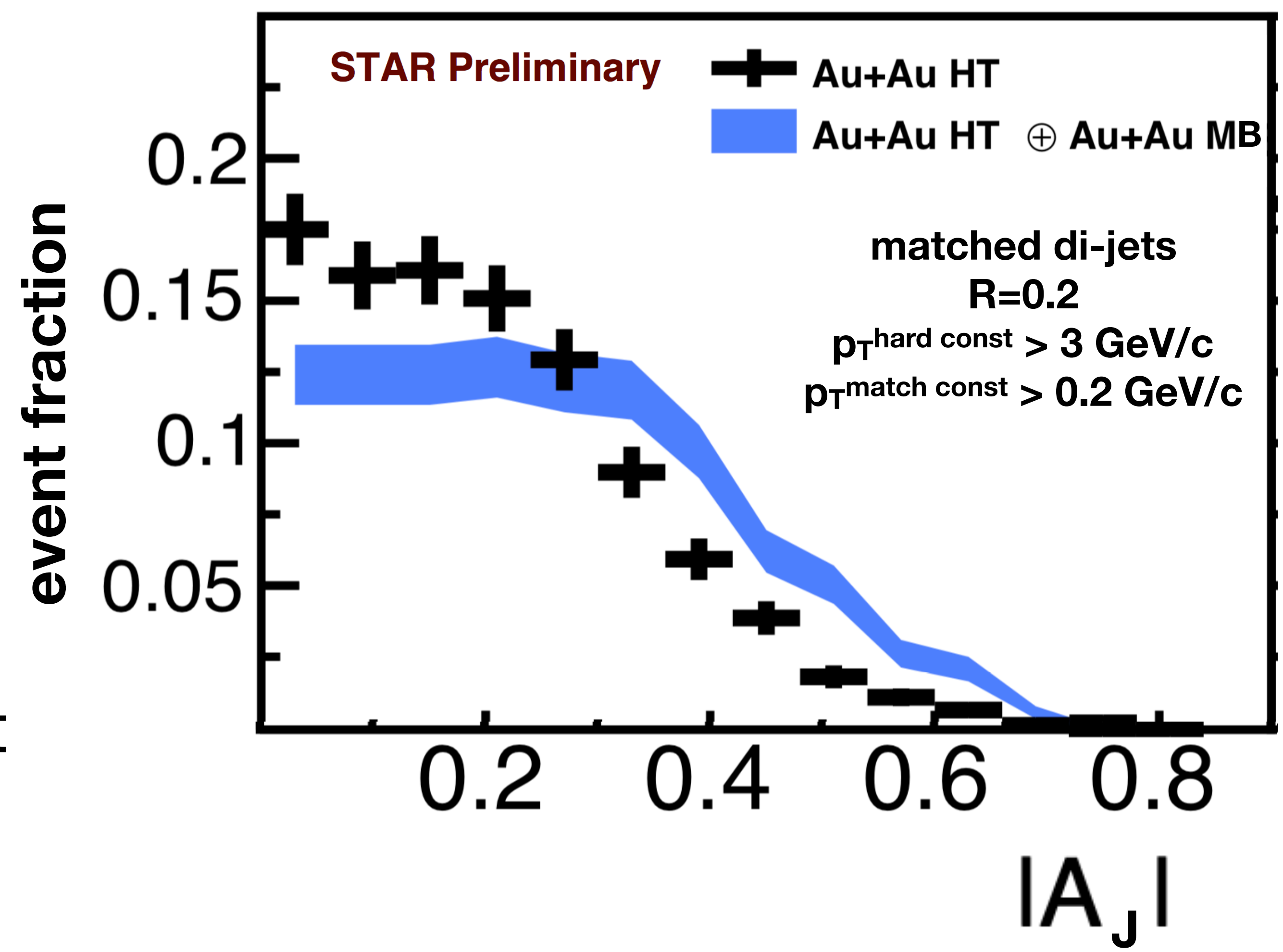
✓ **balanced ($p > 0.01$)**

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

✗ **imbalanced ($p < 10^{-4}$)**

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 signa 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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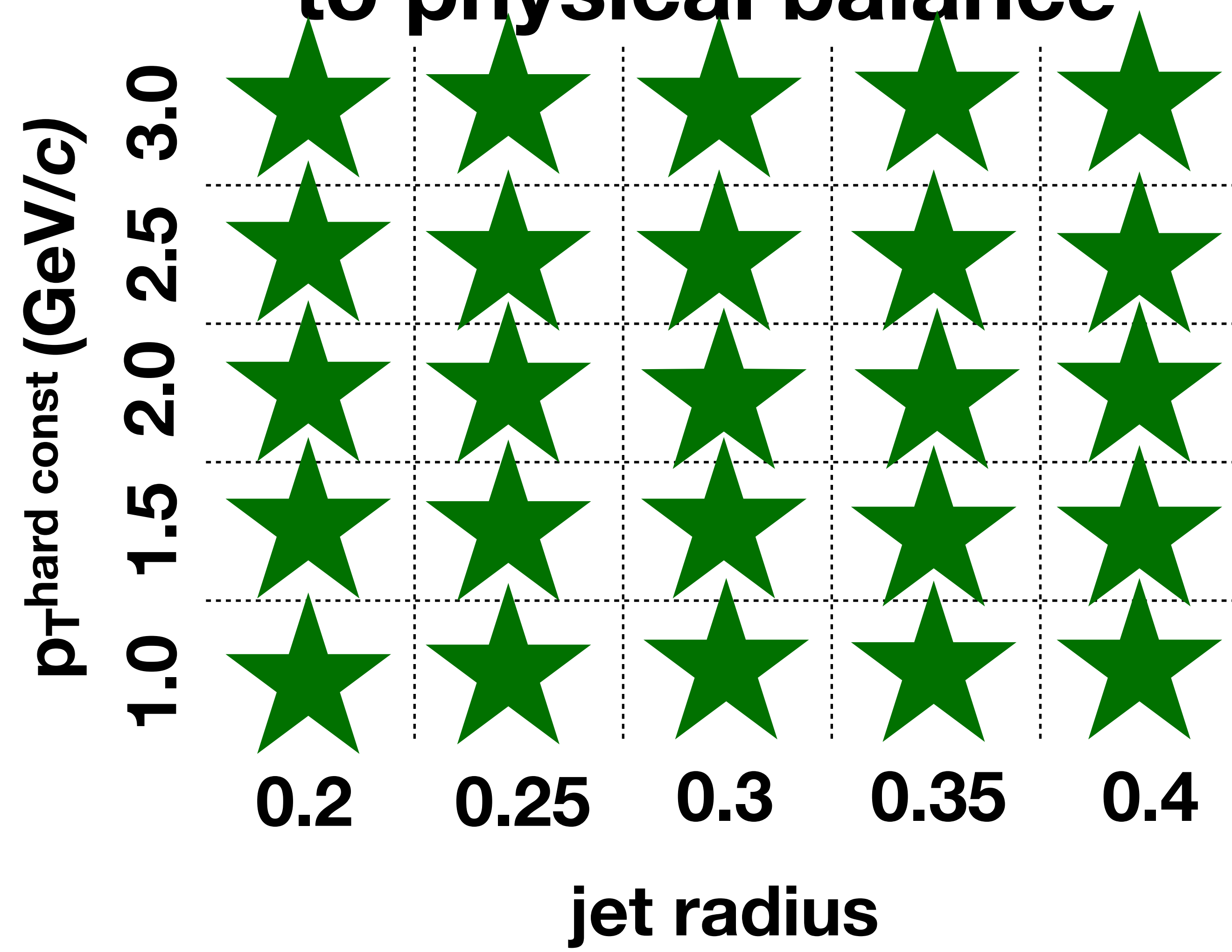
Differential di-jet imbalance

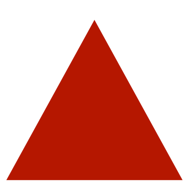
matched jets can get some “balance” from background fluctuations

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

Estimate of sensitivity to physical balance



sensitive ($p < 0.01$)



insensitive ($p > 0.01$)

Differential di-jet imbalance

matched di-jets

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

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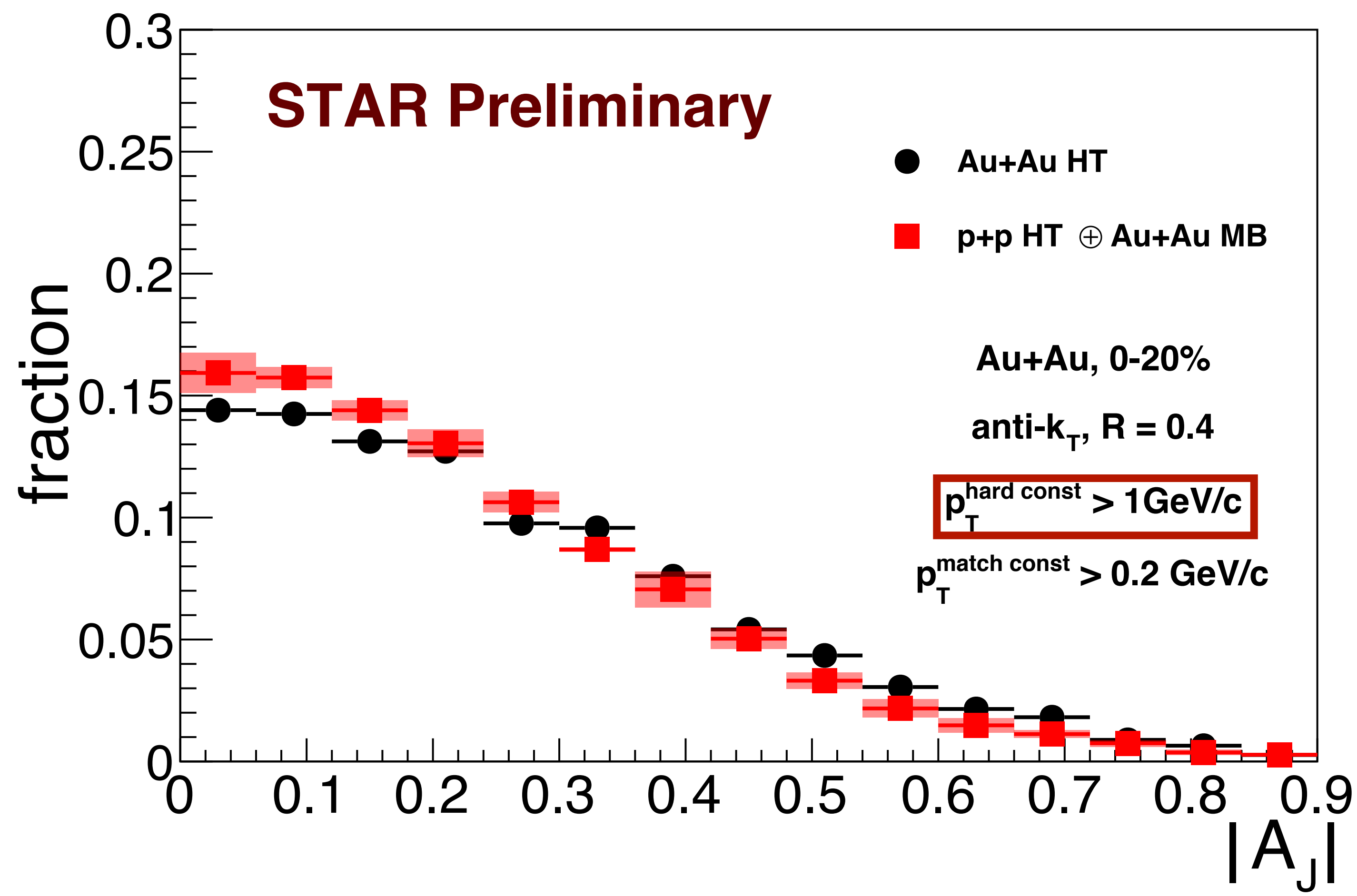
$p_T^{match\ const}$ > 0.2 GeV/*c*

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



K-S value << 1.0

Differential di-jet imbalance

matched di-jets

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

R = 0.4

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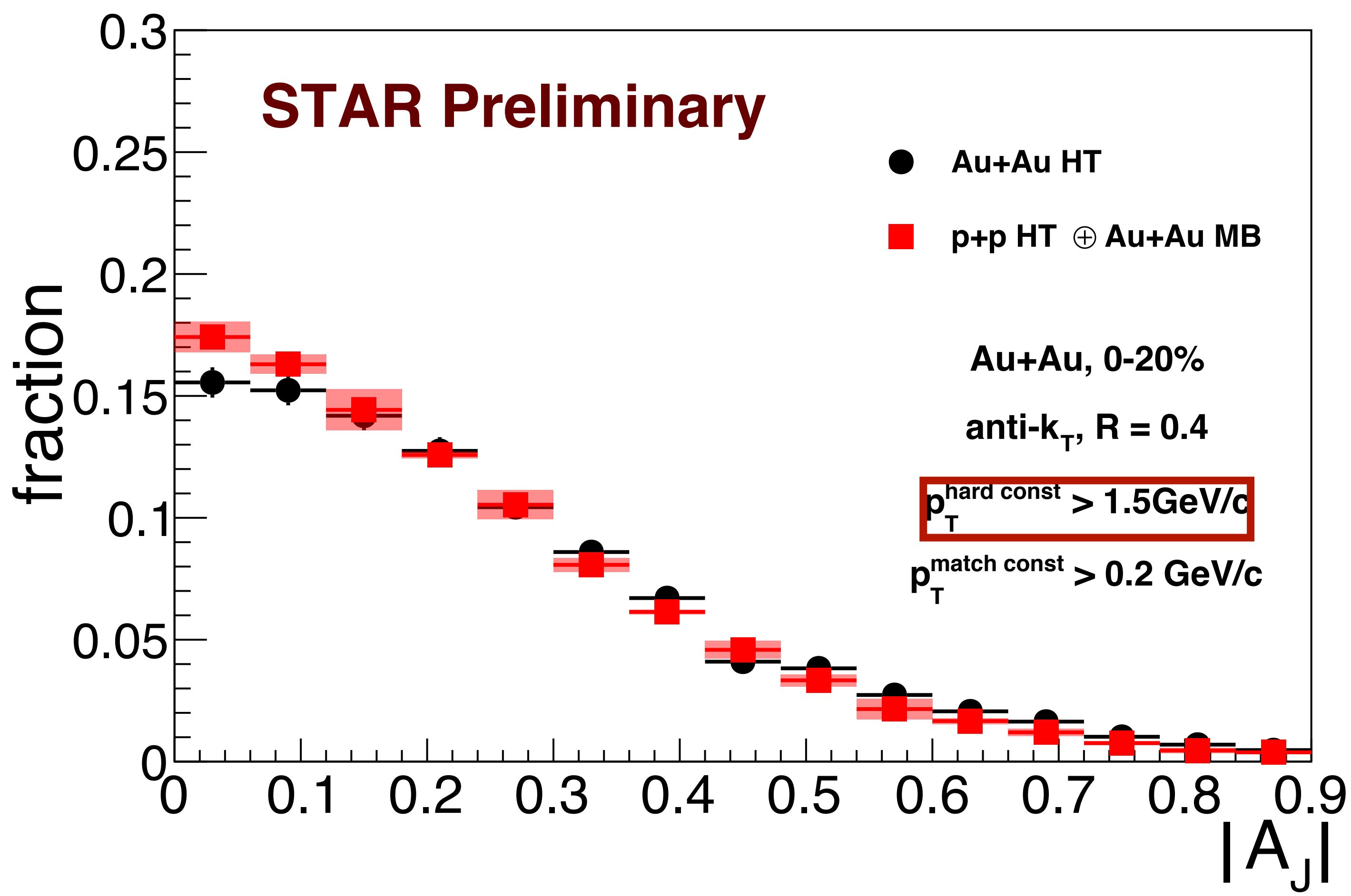
anti-k_T algorithm



K-S 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*

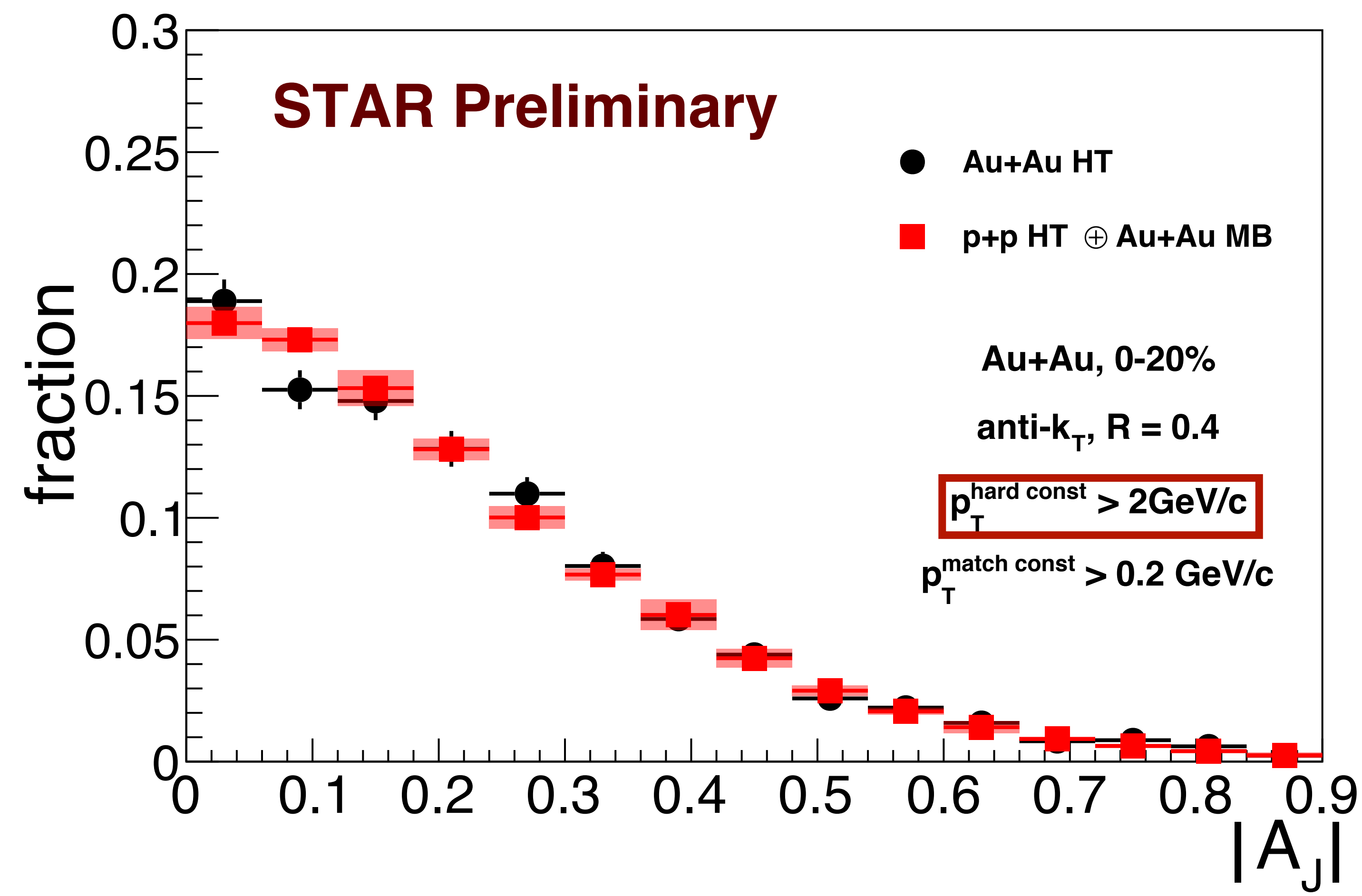
$p_T^{match\ const}$ > 0.2 GeV/*c*

0-20% central

p_T^{lead} > 16 GeV/c

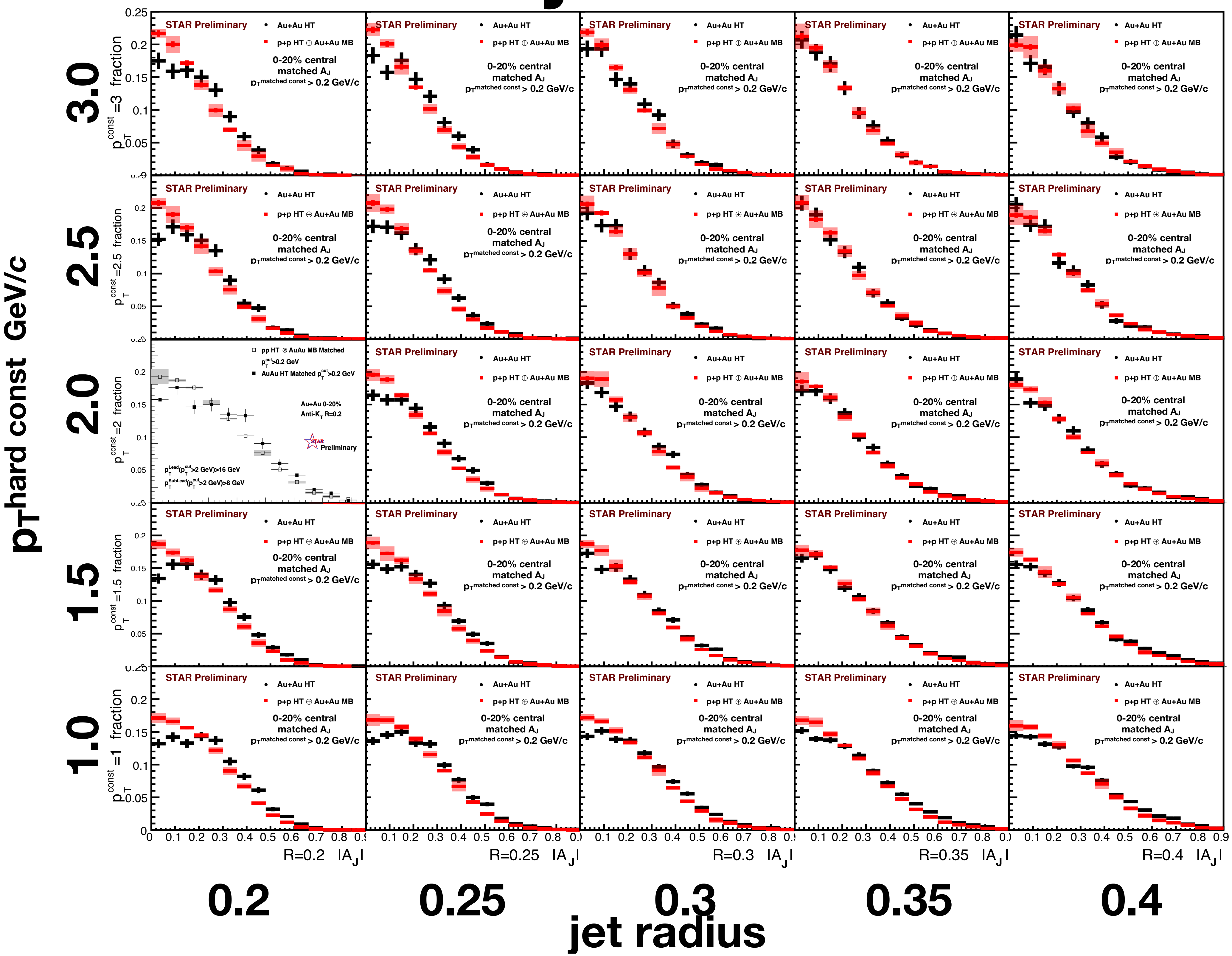
$p_T^{sublead}$ > 8 GeV/c

anti-k_T algorithm



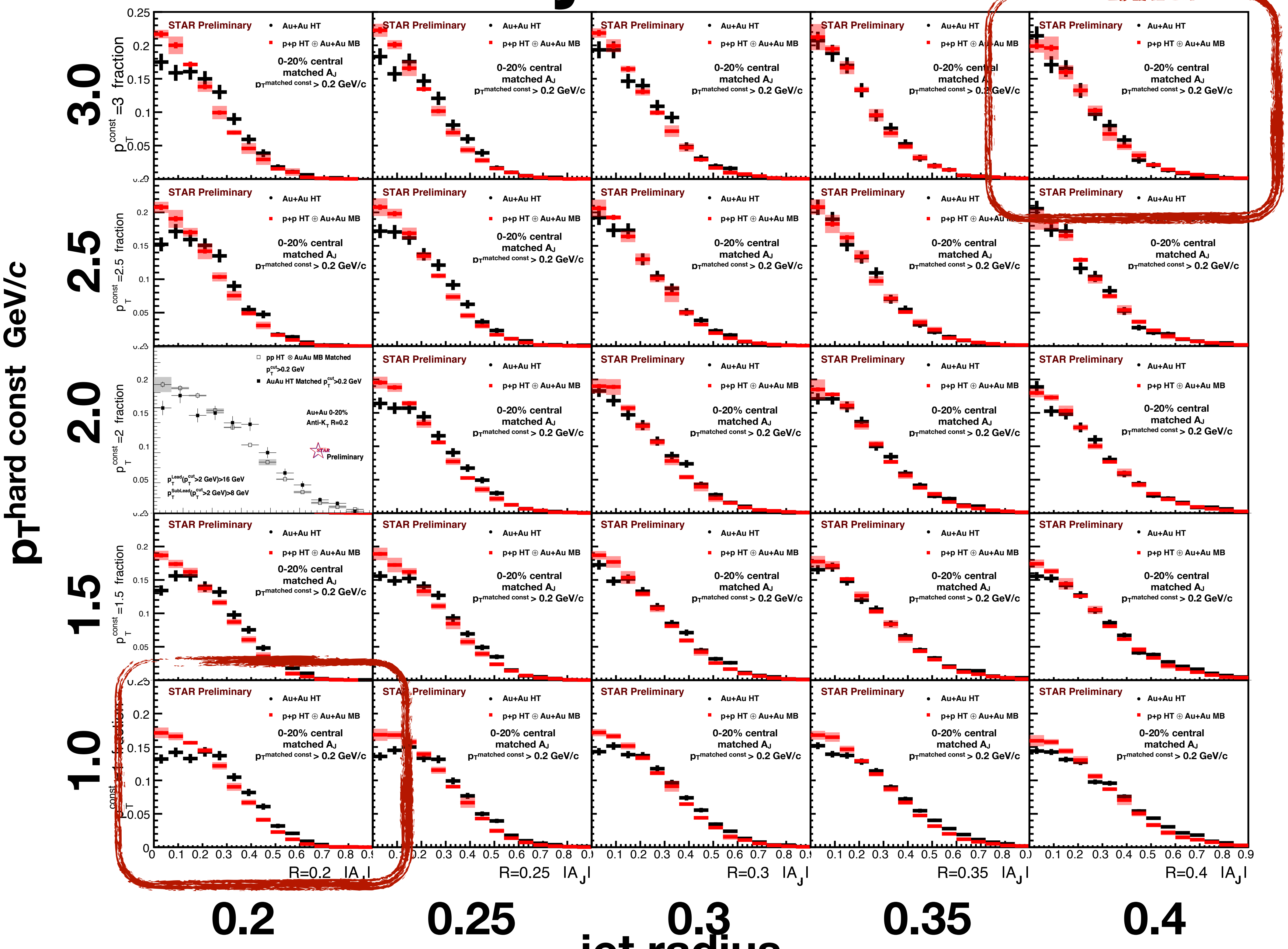
K-S value = 0.17

Differential di-jet imbalance



Differential di-jet imbalance

balance



imbalance

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Differential di-jet imbalance

hard core di-jets

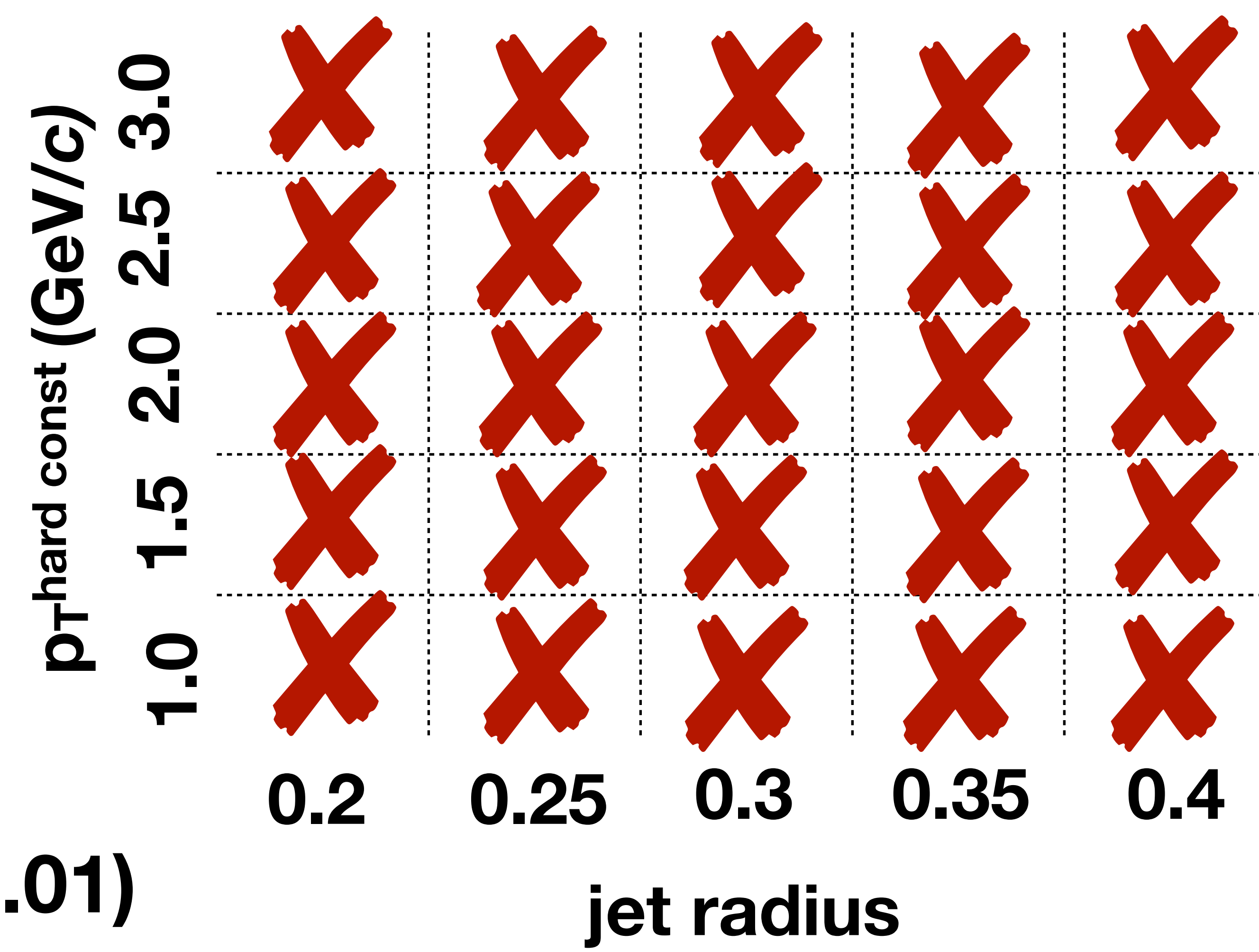
modified for all kinematic selections

balanced ($p > 0.01$)

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

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

Hard core di-jets



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

✓ **balanced ($p > 0.01$)**

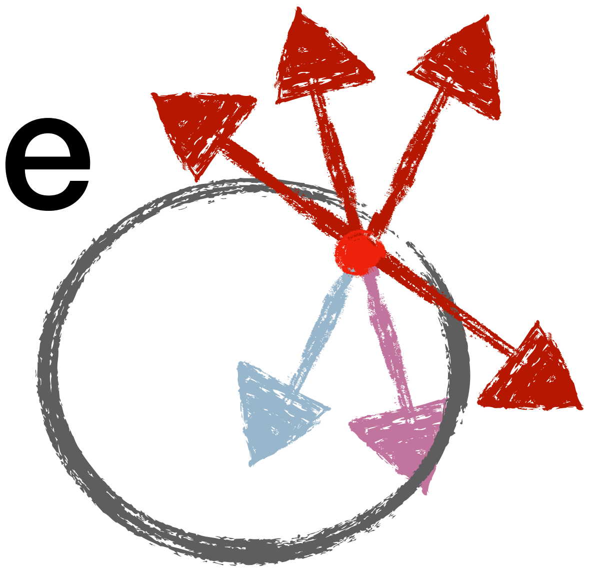
○ **semi-balanced ($10^{-4} < p < 0.01$)**

✗ **imbalanced ($p < 10^{-4}$)**

Matched di-jets

$p_T^{hard\ const}$ (GeV/c) \ jet radius	0.2	0.25	0.3	0.35	0.4
3.0	✗	✗	○	✓	✓
2.5	✗	✗	○	✓	✓
2.0	✗	✗	○	✓	✓
1.5	✗	✗	✗	○	○
1.0	✗	✗	✗	✗	✗

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

✓ **balanced ($p > 0.01$)**

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

✗ **imbalanced ($p < 10^{-4}$)**

Matched di-jets

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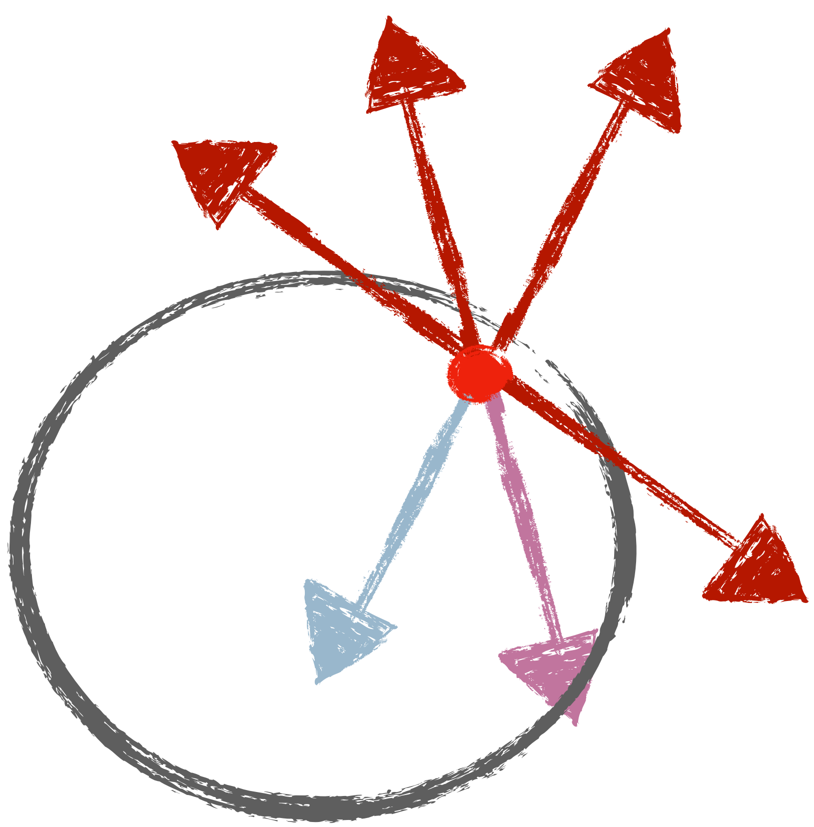
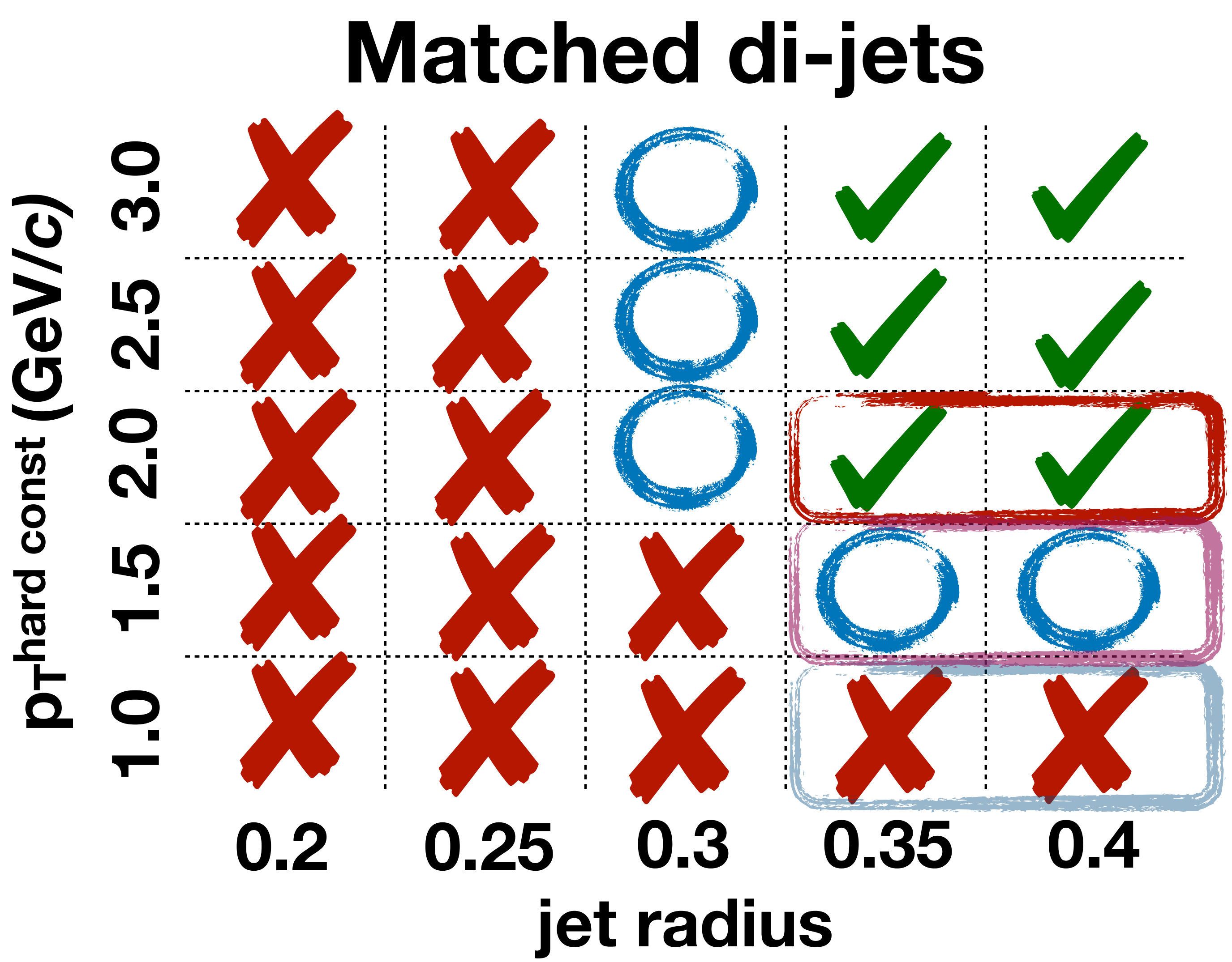
2.5	✗	✗	○	✓	✓
2.0	✗	✗	○	✓	✓
1.5	✗	✗	✗	○	○
1.0	✗	✗	✗	✗	✗

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

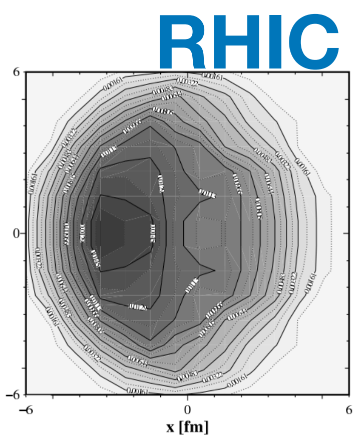


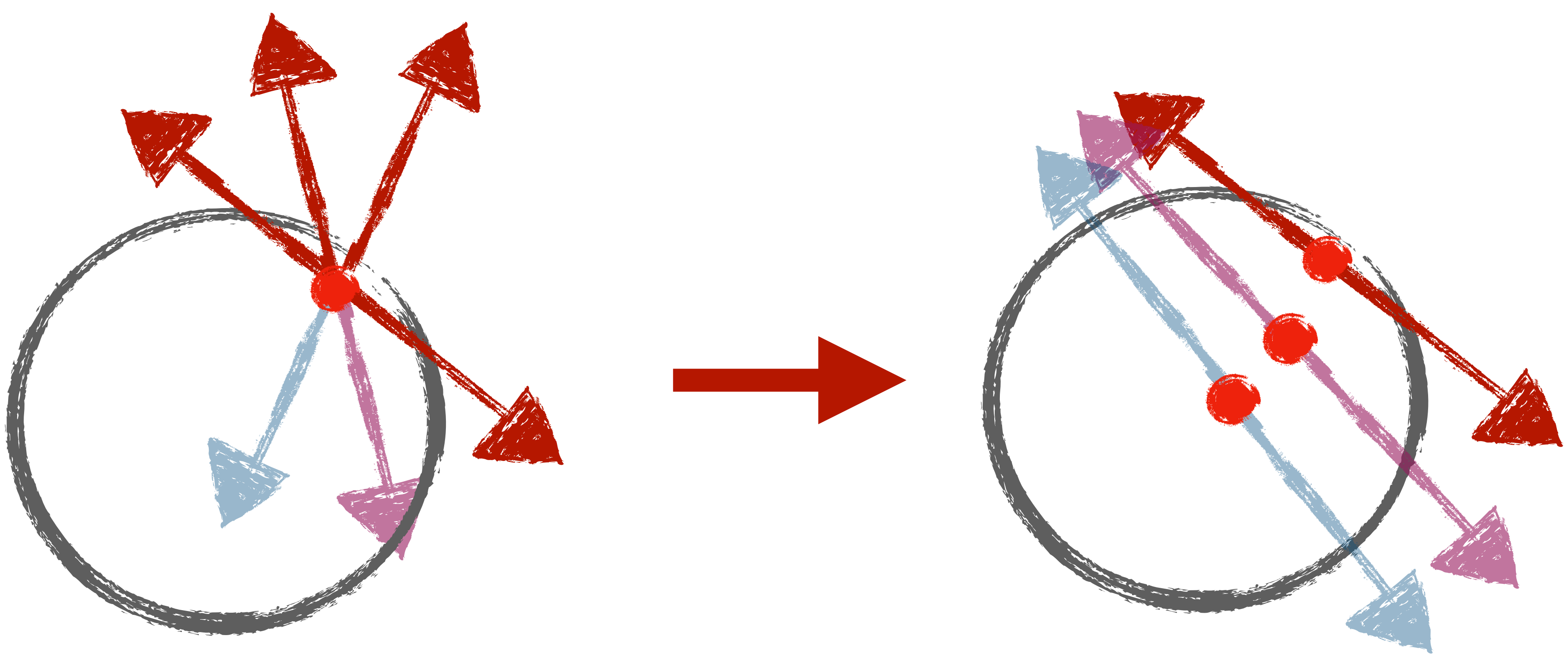


*See Raghav's talk: Wednesday, 9:30

Conclusions

→ high-energy online calorimeter trigger → large surface bias





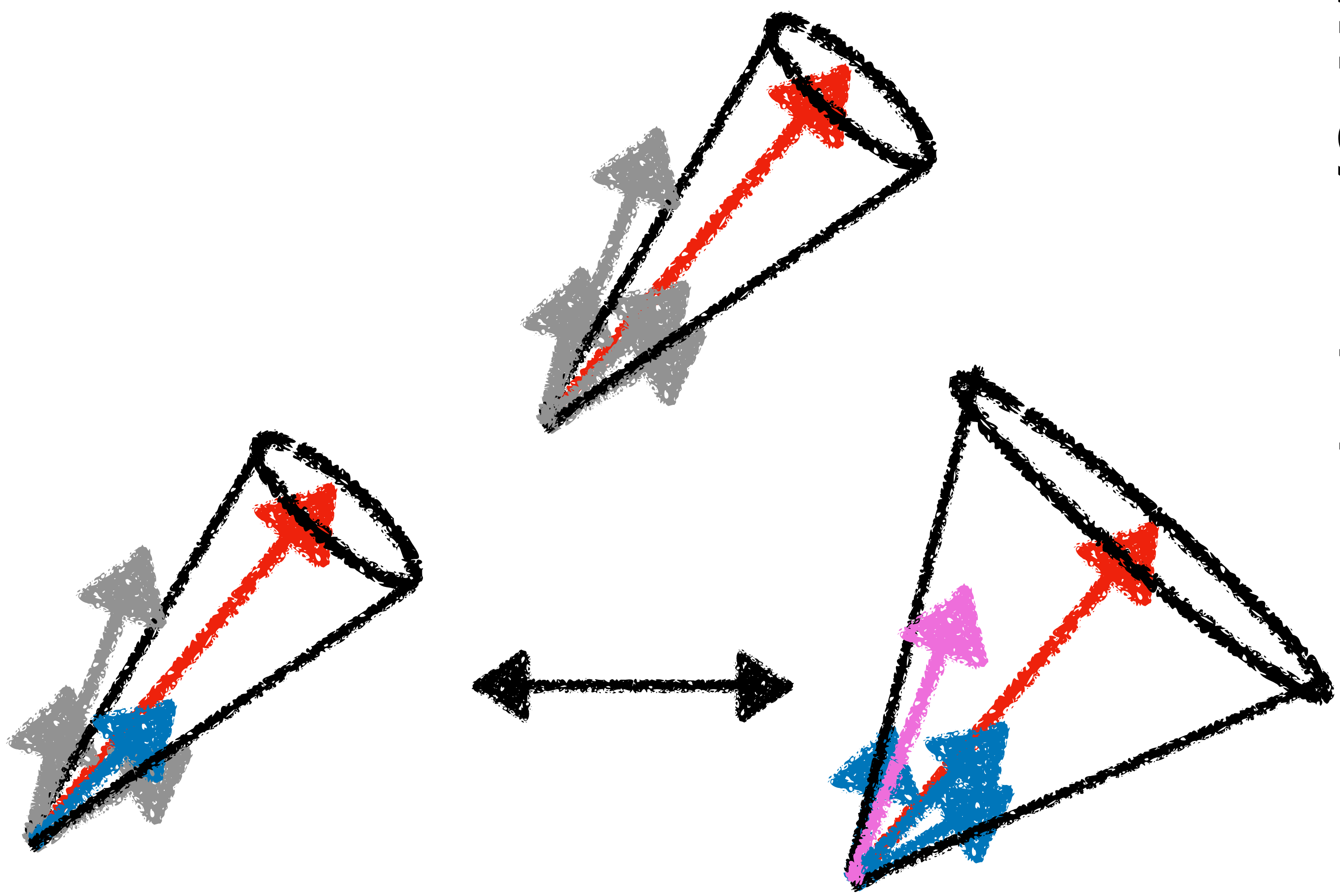
Qualitatively consistent picture of partonic energy loss emerging at RHIC. Observed difference in broadening of jet structure can be related to in-medium path length/ amount of diffusion of medium-induced soft gluon radiation in the QGP.

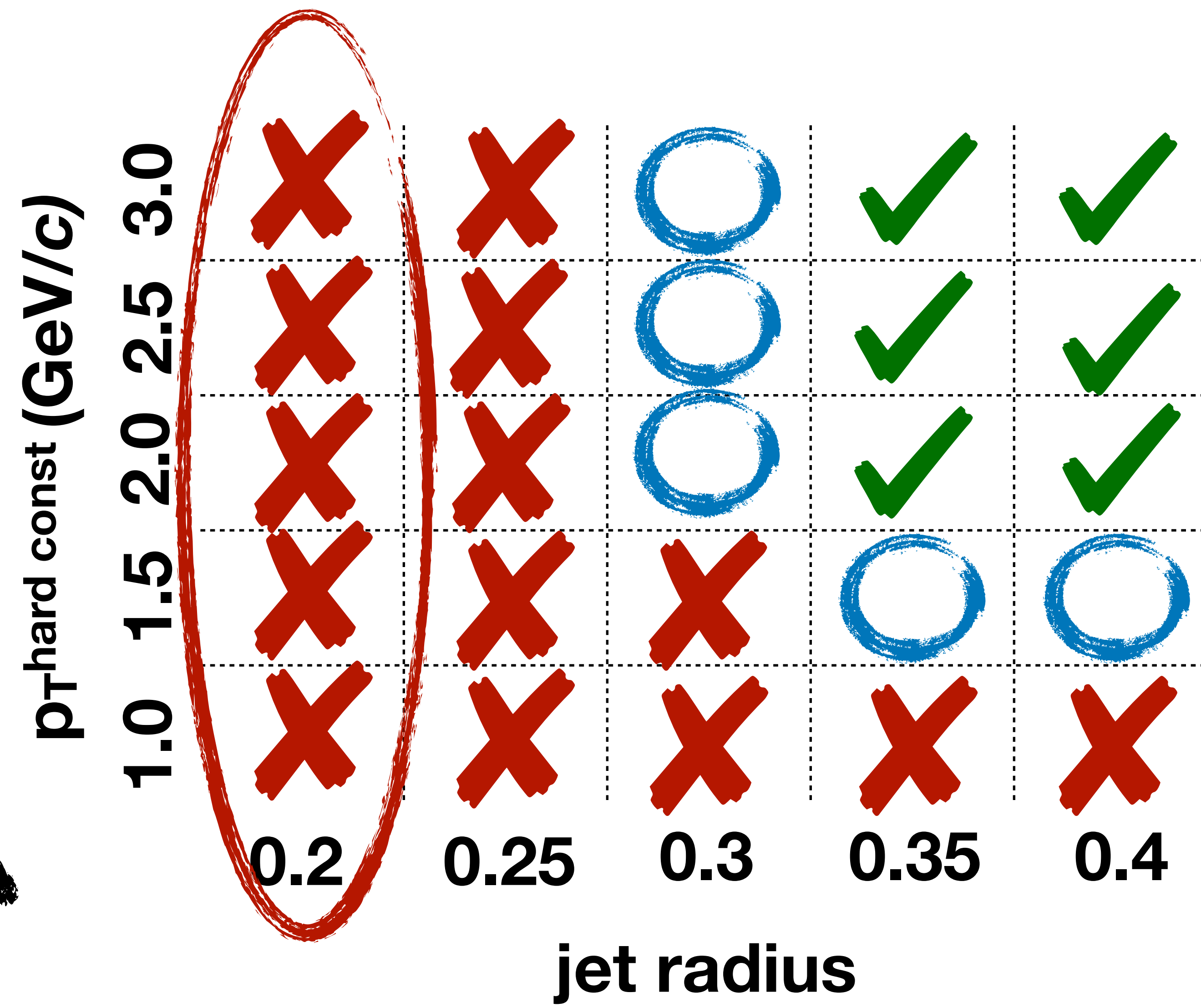
Thank You

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 → 0.4)

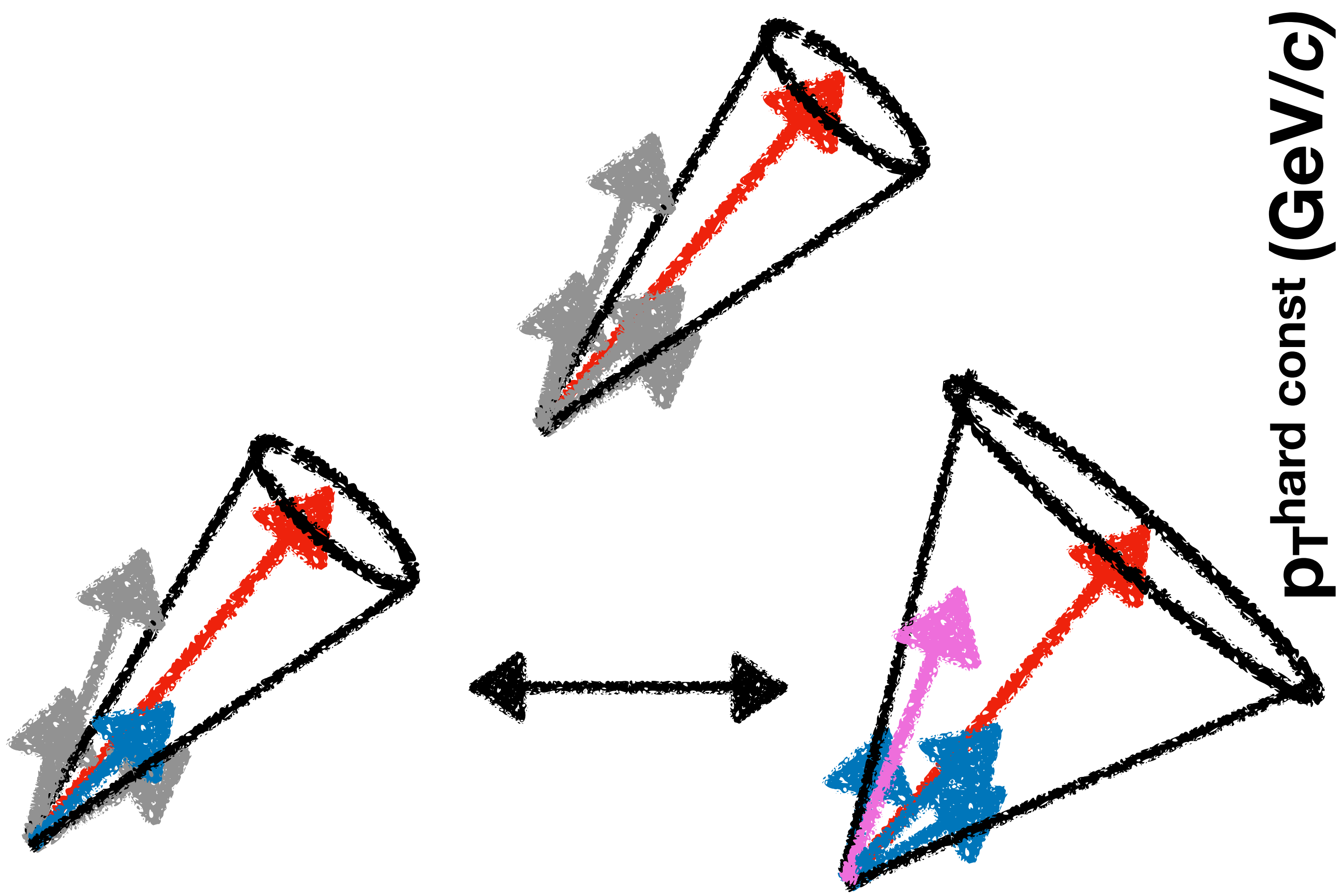
Nick Elsey, STAR - High p_T Workshop, Knoxville 2019

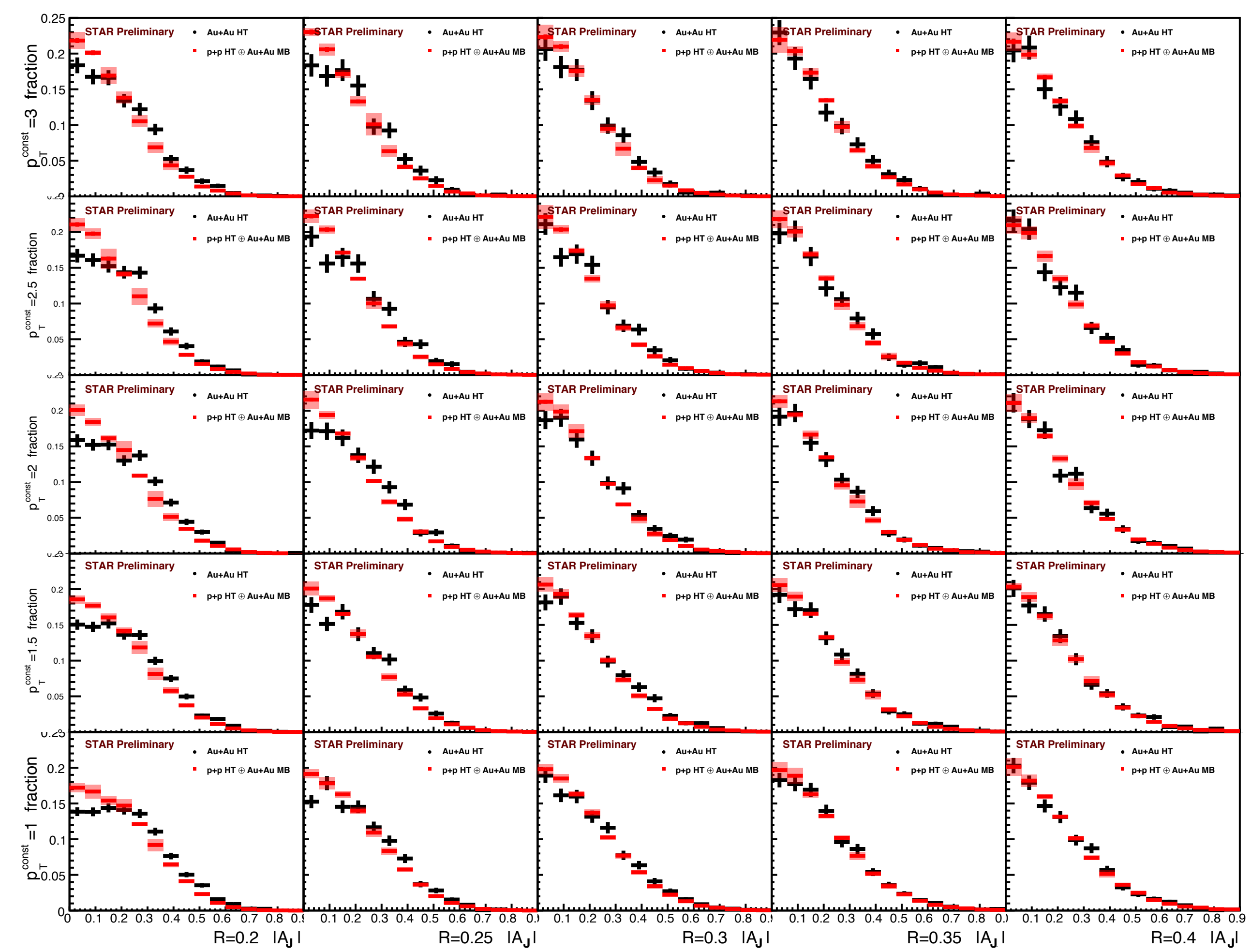
Radial scan of matched jets

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

fix hard-core jet at R = 0.2





p_T hard const (GeV/*c*)

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

Nick Elsey, STAR - High p_T Workshop, Knoxville 2019

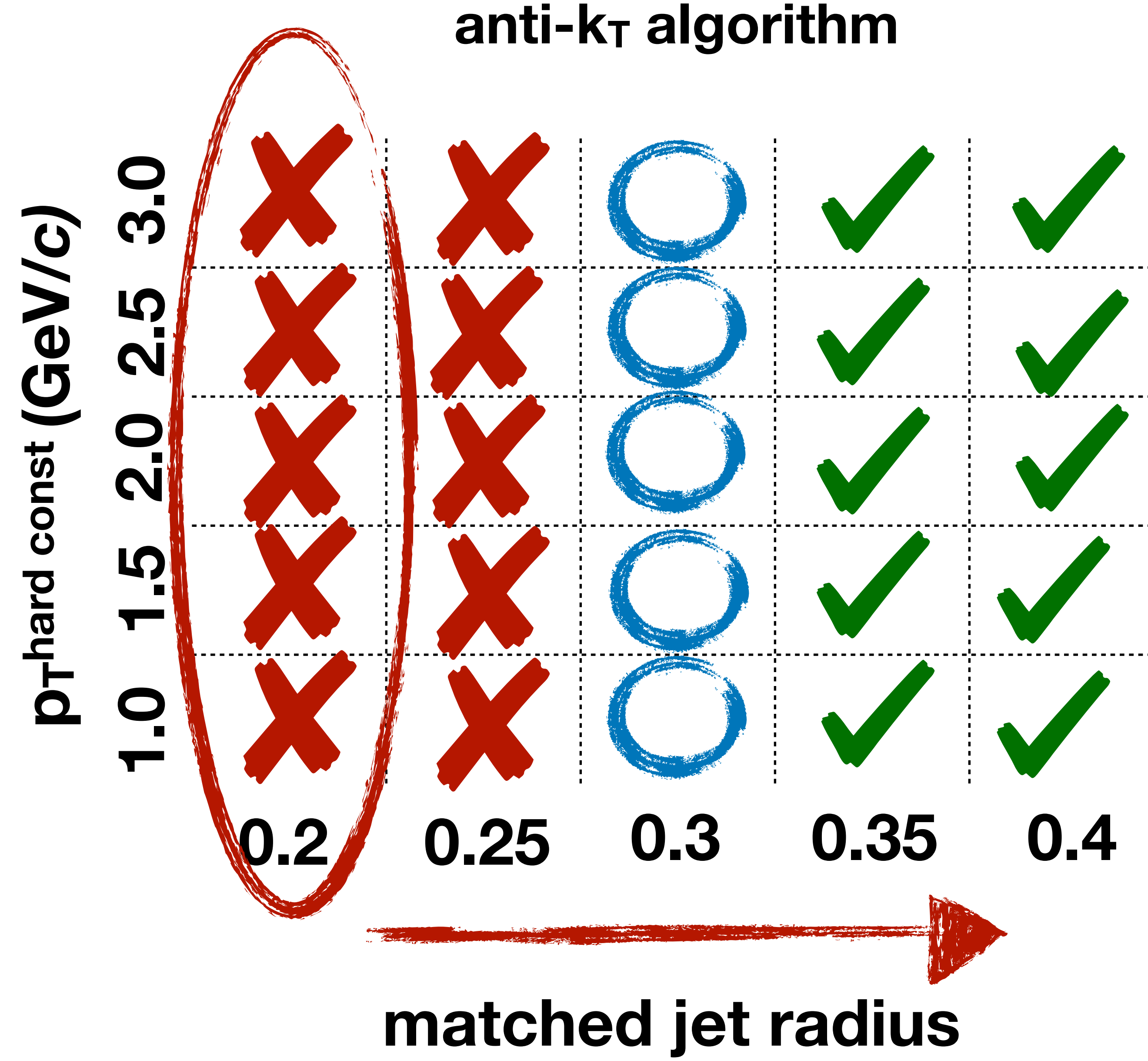
Radial scan of matched jets

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

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



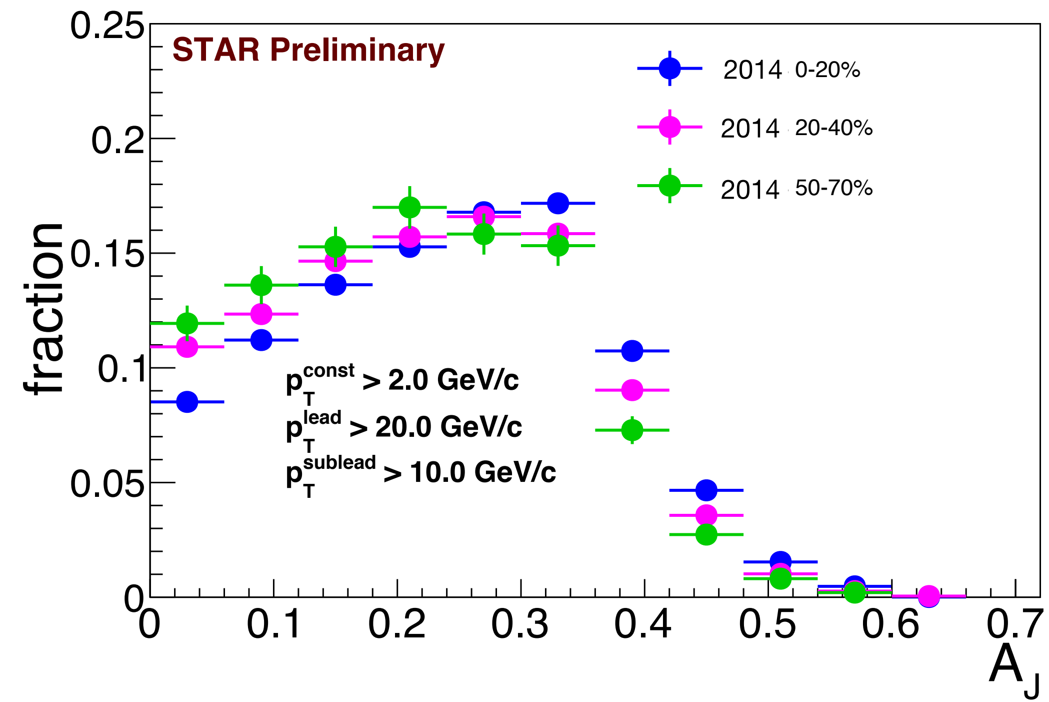
Moving forward

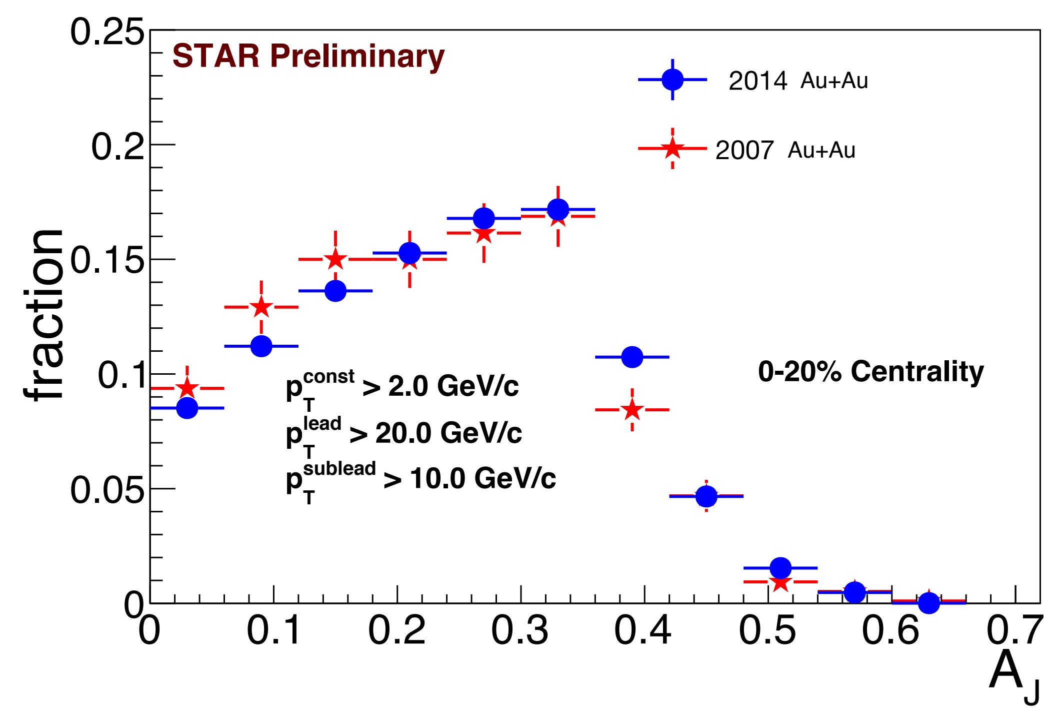
2014 Au+Au 200 GeV

20x increase in statistics

→ allow for wider jet kinematic range

→ centrality dependence





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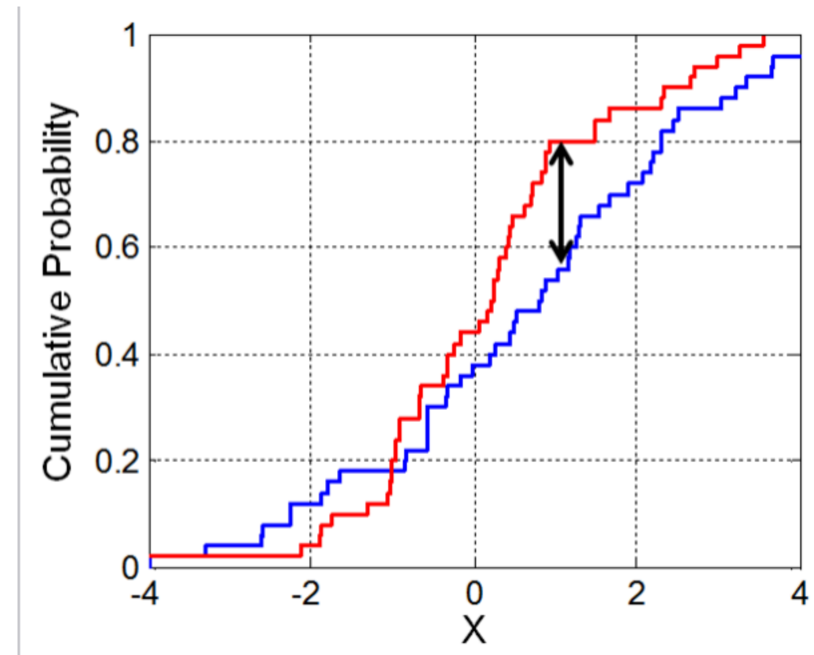
Kolmogorov-Smirnov two-sample test

- 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



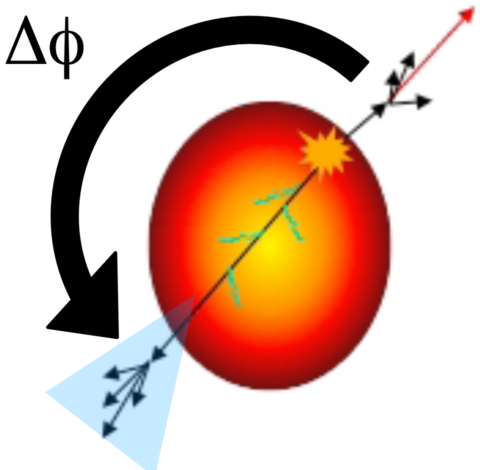
$$D_{n,m} = \sup_x |F_{1,n}(x) - F_{2,m}(x)|,$$

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

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

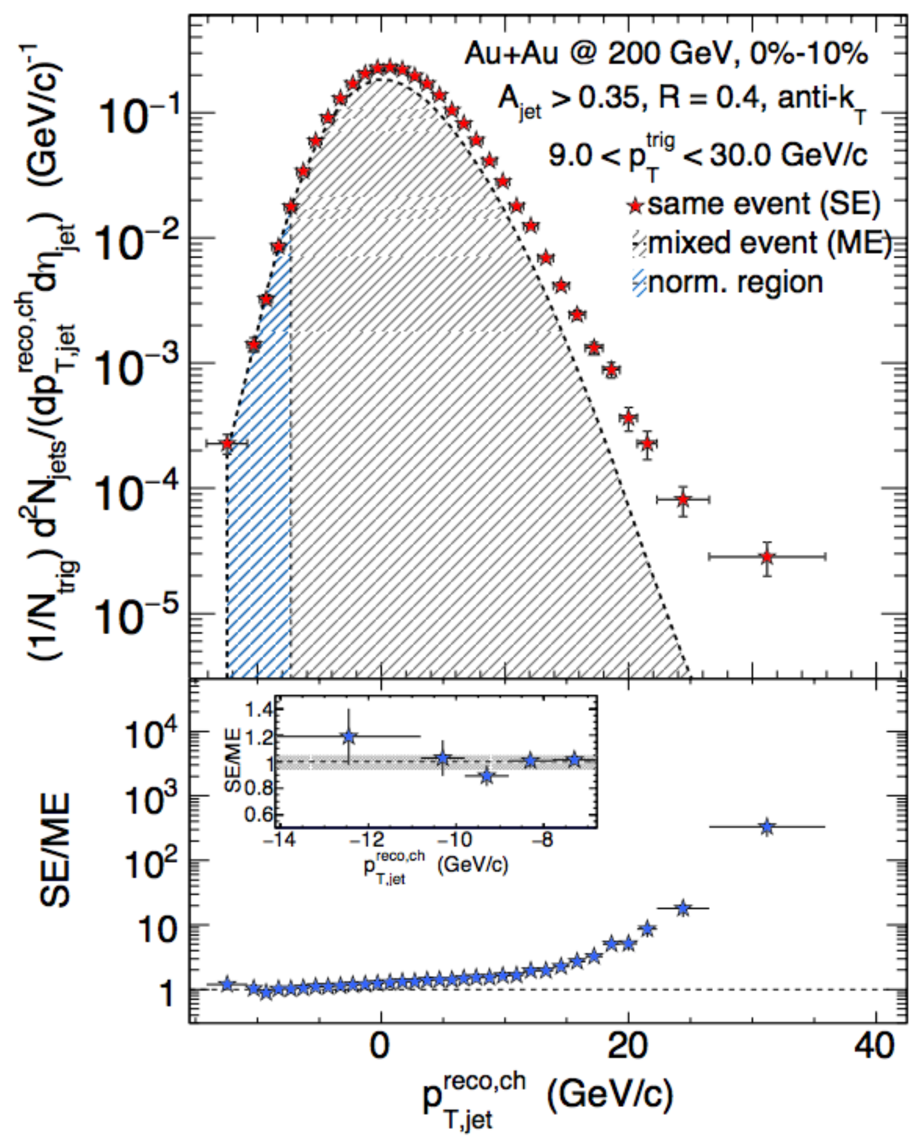
α	0.10	0.05	0.025	0.01	0.005	0.001
$c(\alpha)$	1.22	1.36	1.48	1.63	1.73	1.95

Hadron+jet spectra



semi-inclusive hadron-triggered recoil jet spectra

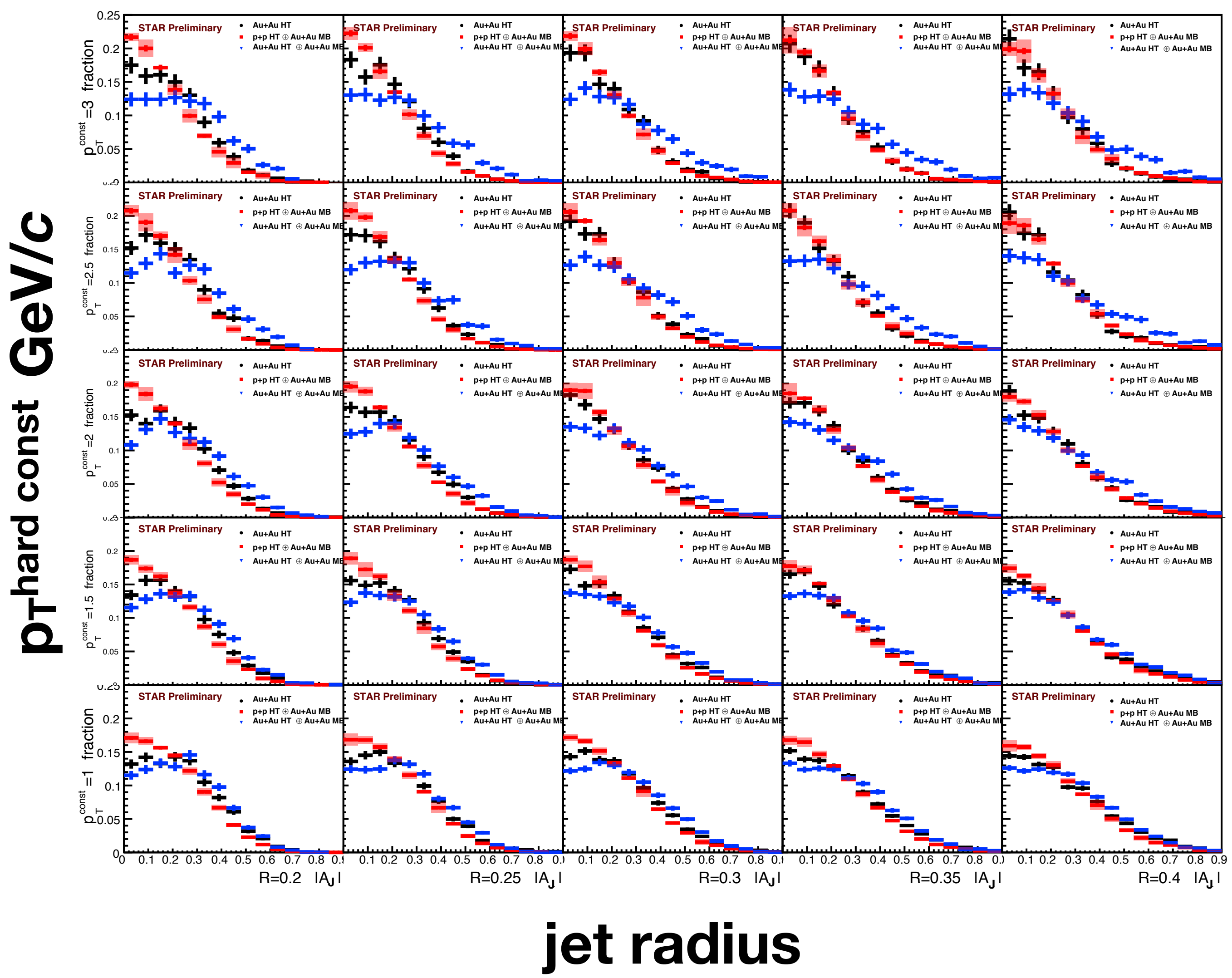
use of mixed-event method to extend kinematic reach to low jet p_T



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

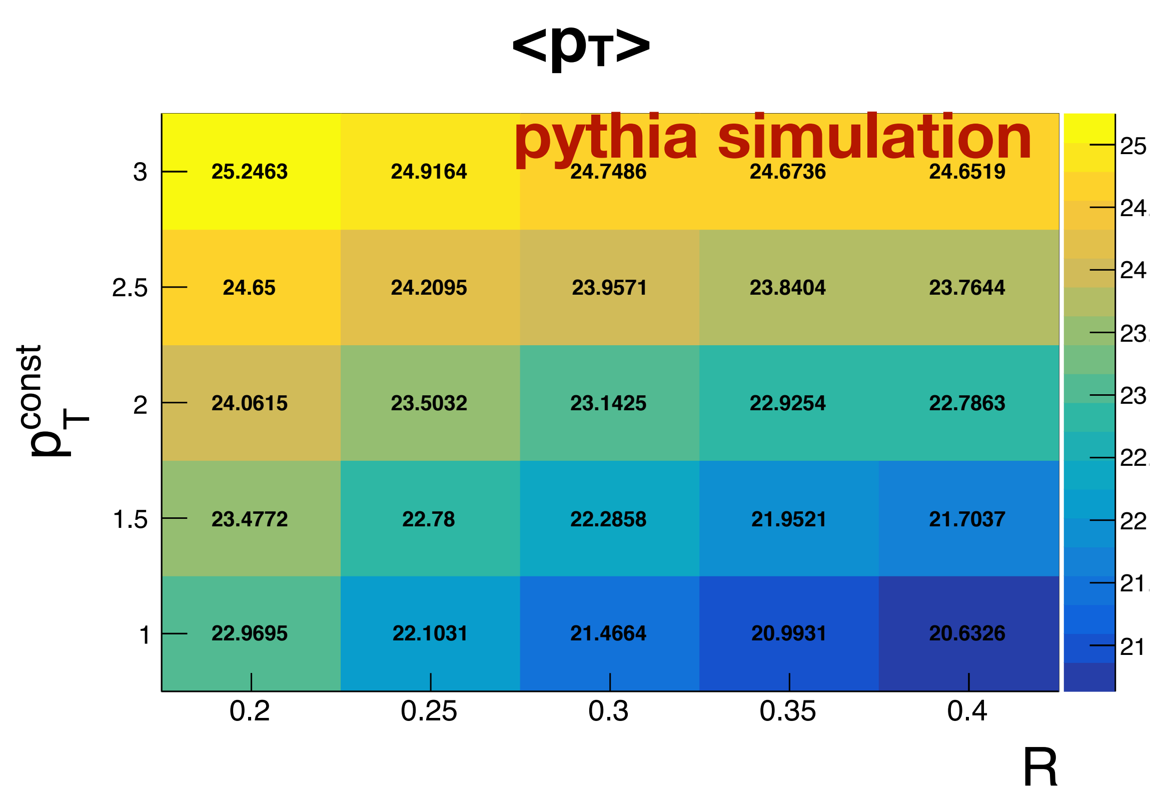
Estimate of the effect of background on balancing

- 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**

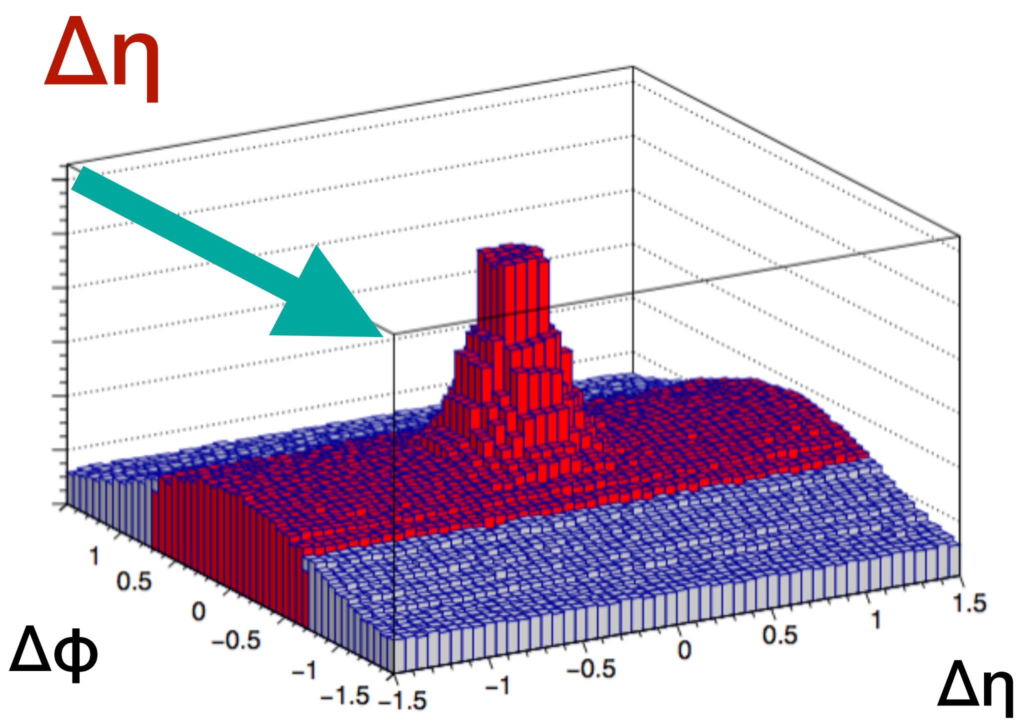


Estimation of the effect of jet definition on jet kinematics in vacuum

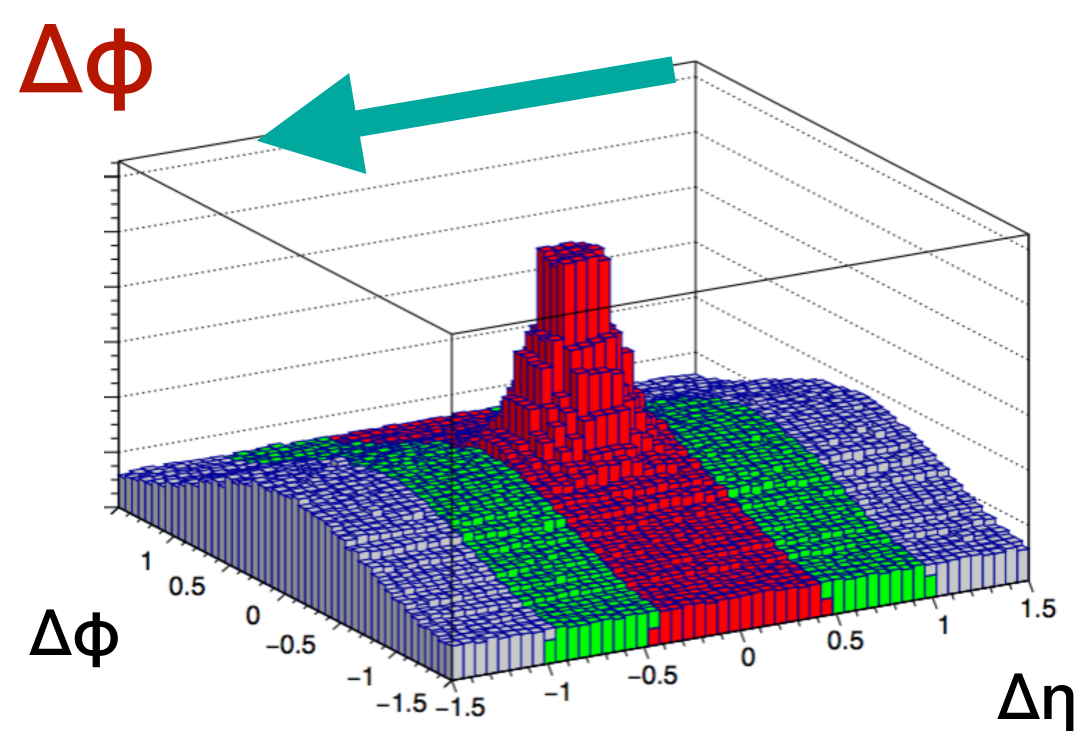
- using pythia, estimate the average p_T^{hat} for each jet definition
- narrower, harder constituent cut jets on average come from higher energy processes



Background subtraction in di-jet hadron correlations



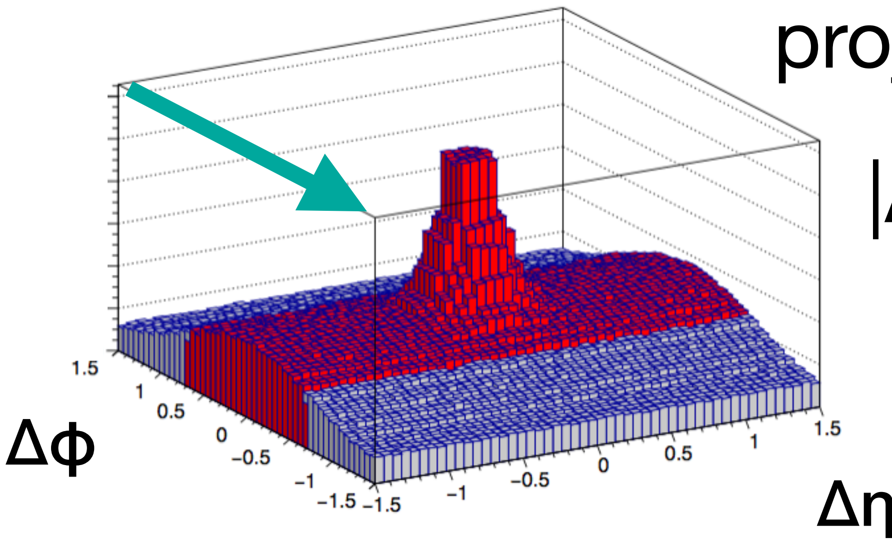
fit with a constant+gaussian constant subtracted as background



use sideband subtraction to account for flow in underlying event

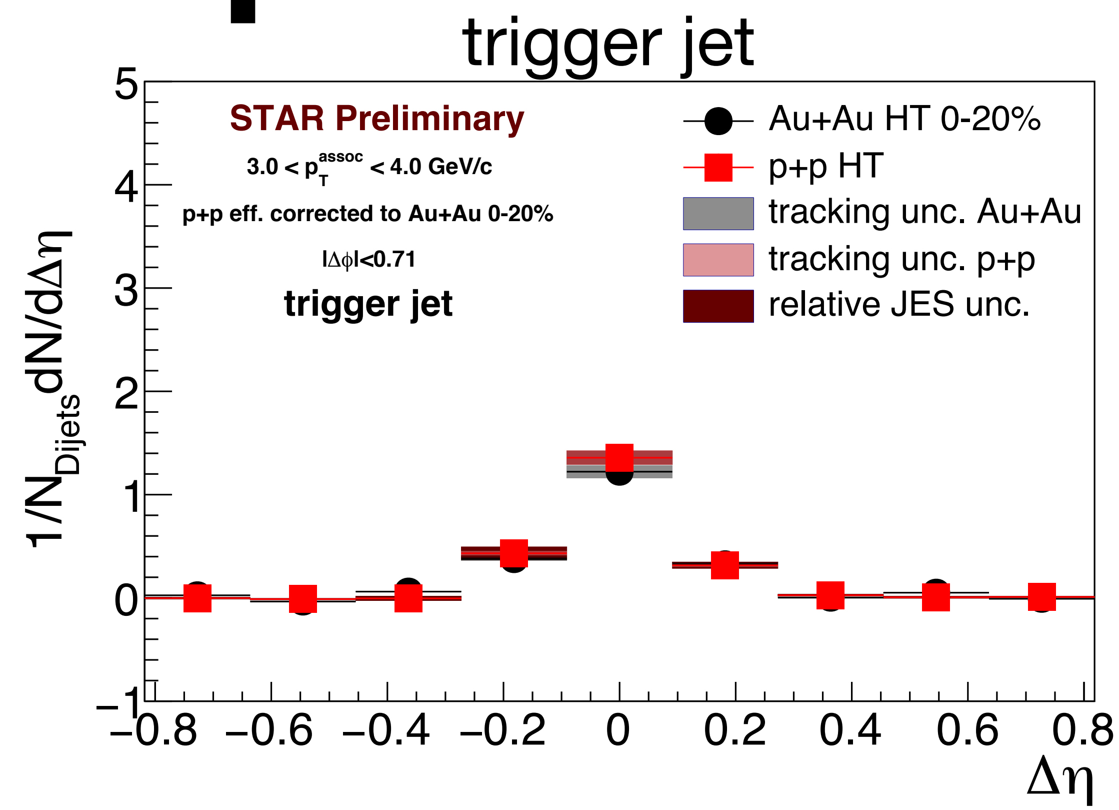
Correlations in Δη

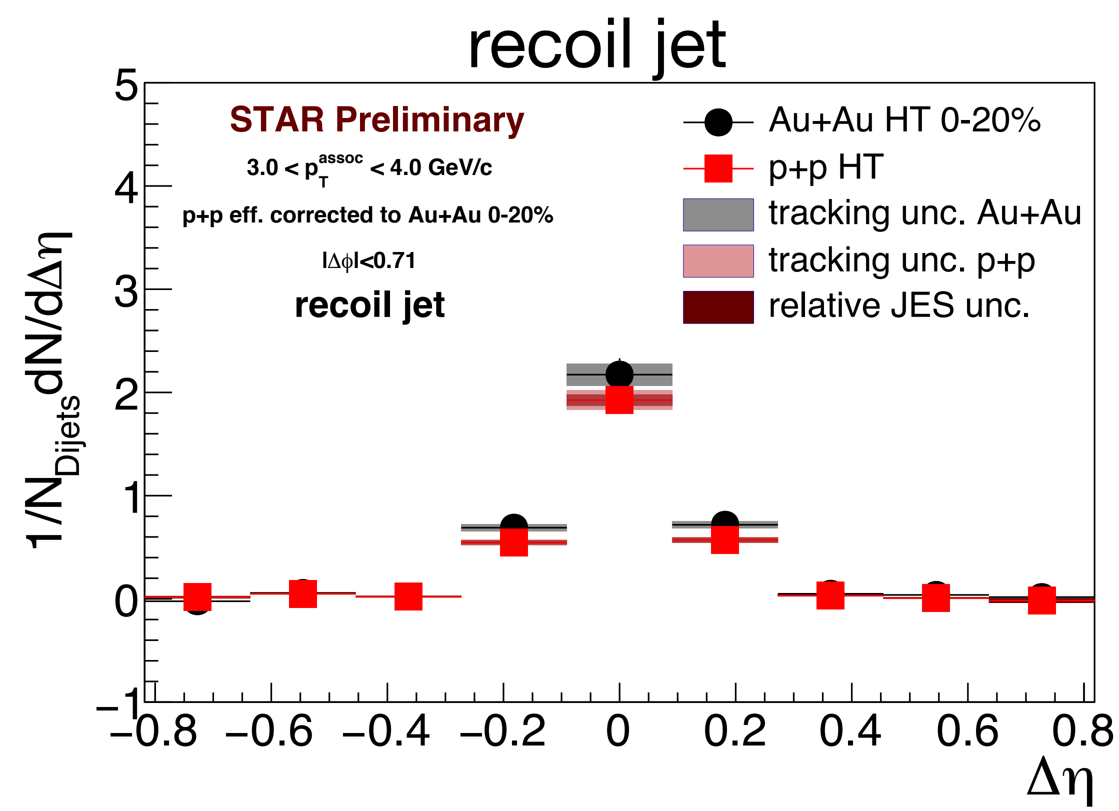
3.0 < p_T^{assoc} < 4.0 GeV/c



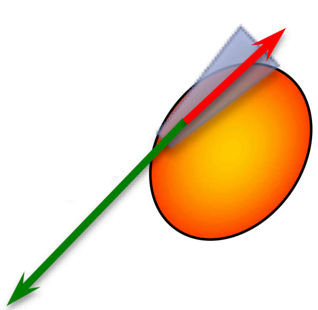
projection range

|Δϕ| < 0.71



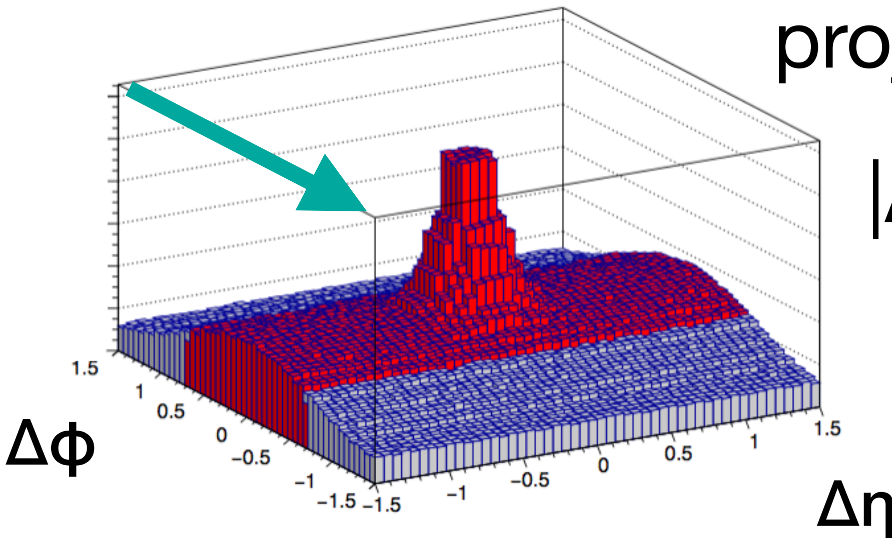


→ yield contained within jet radius R=0.4



Correlations in Δη

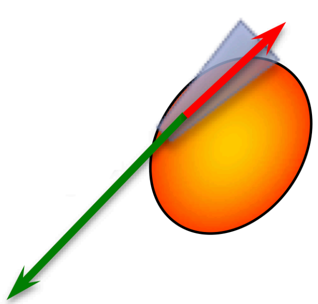
$1.0 < p_T^{assoc} < 2.0$ GeV/c

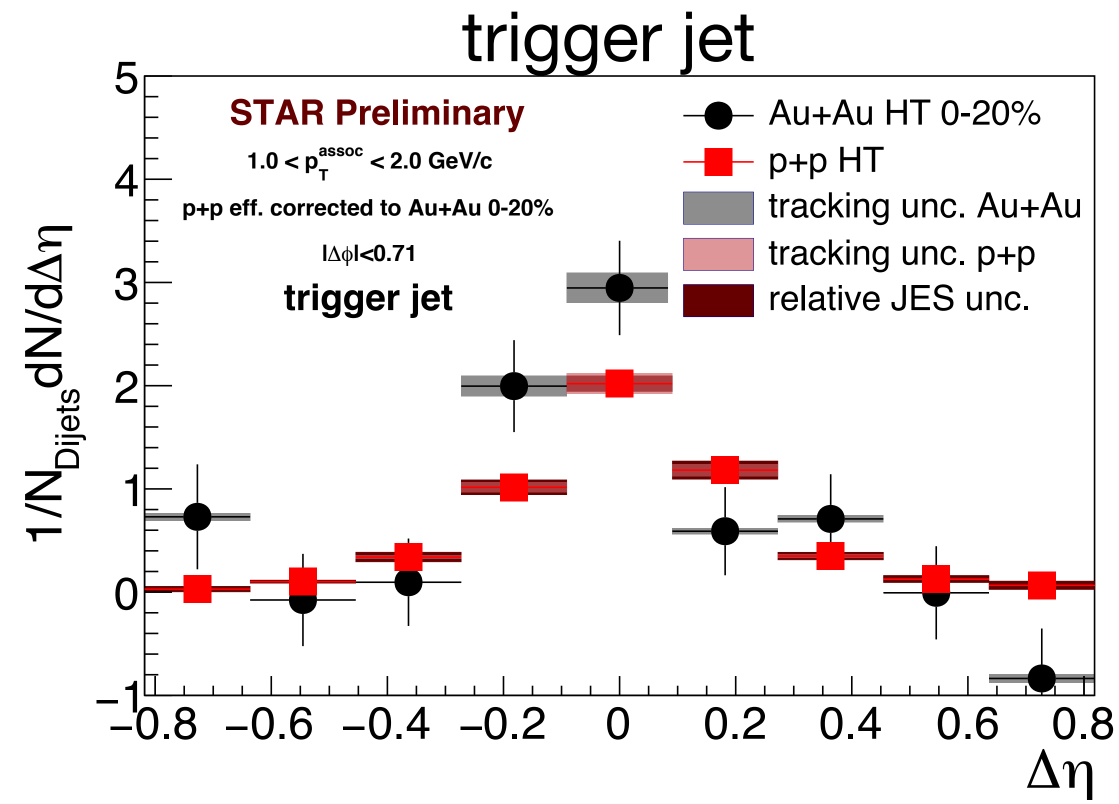


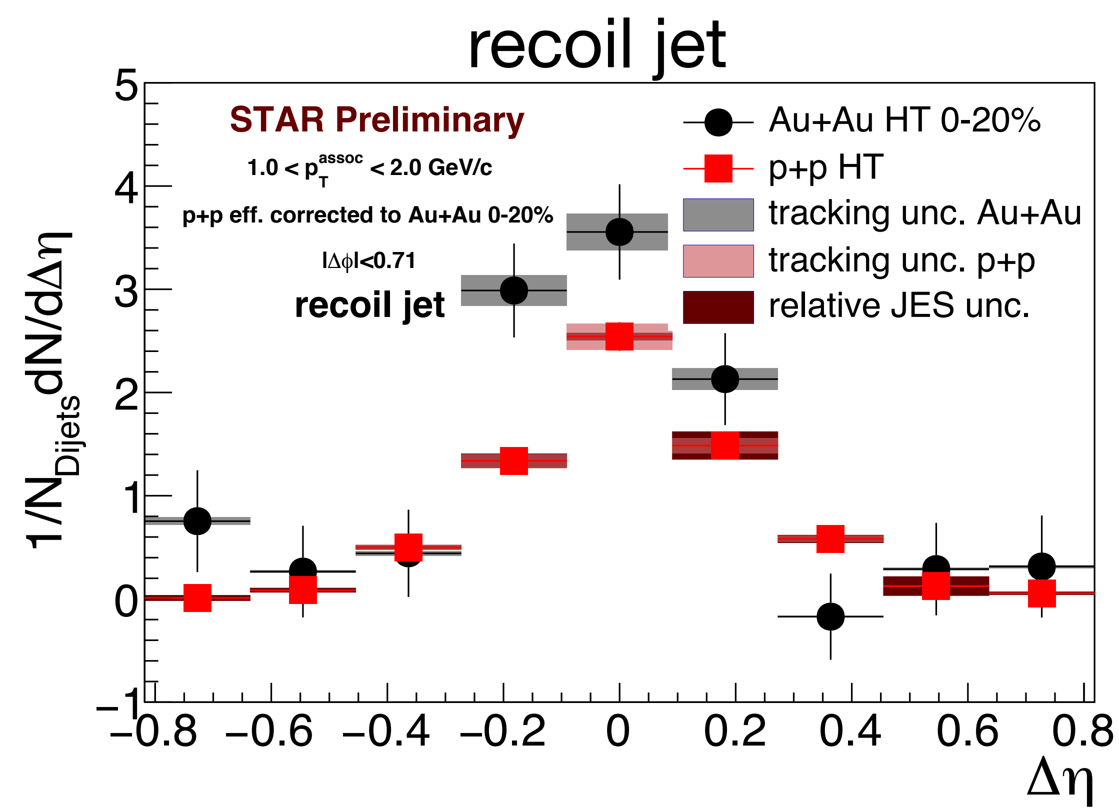
projection range

$|\Delta\phi| < 0.71$

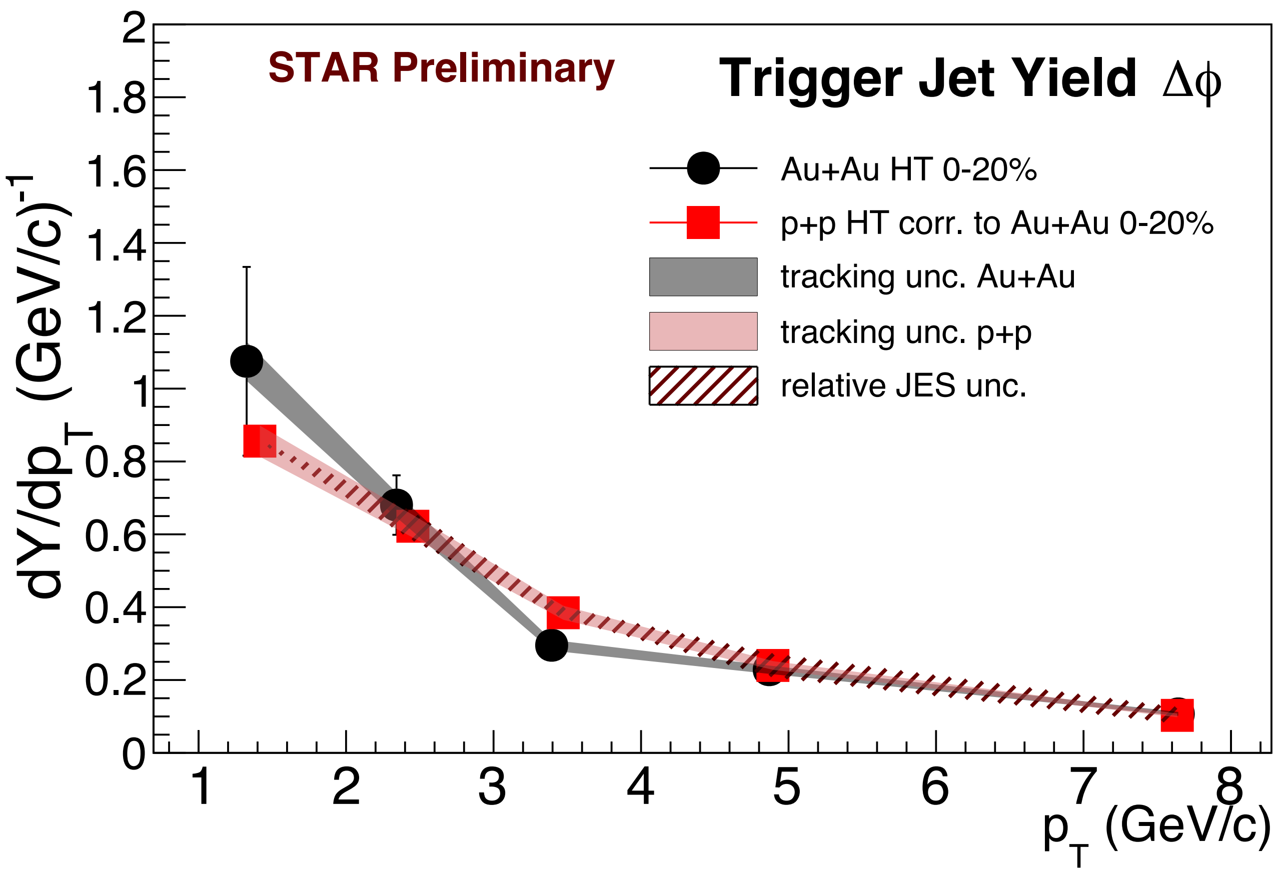
yield contained within jet radius R=0.4

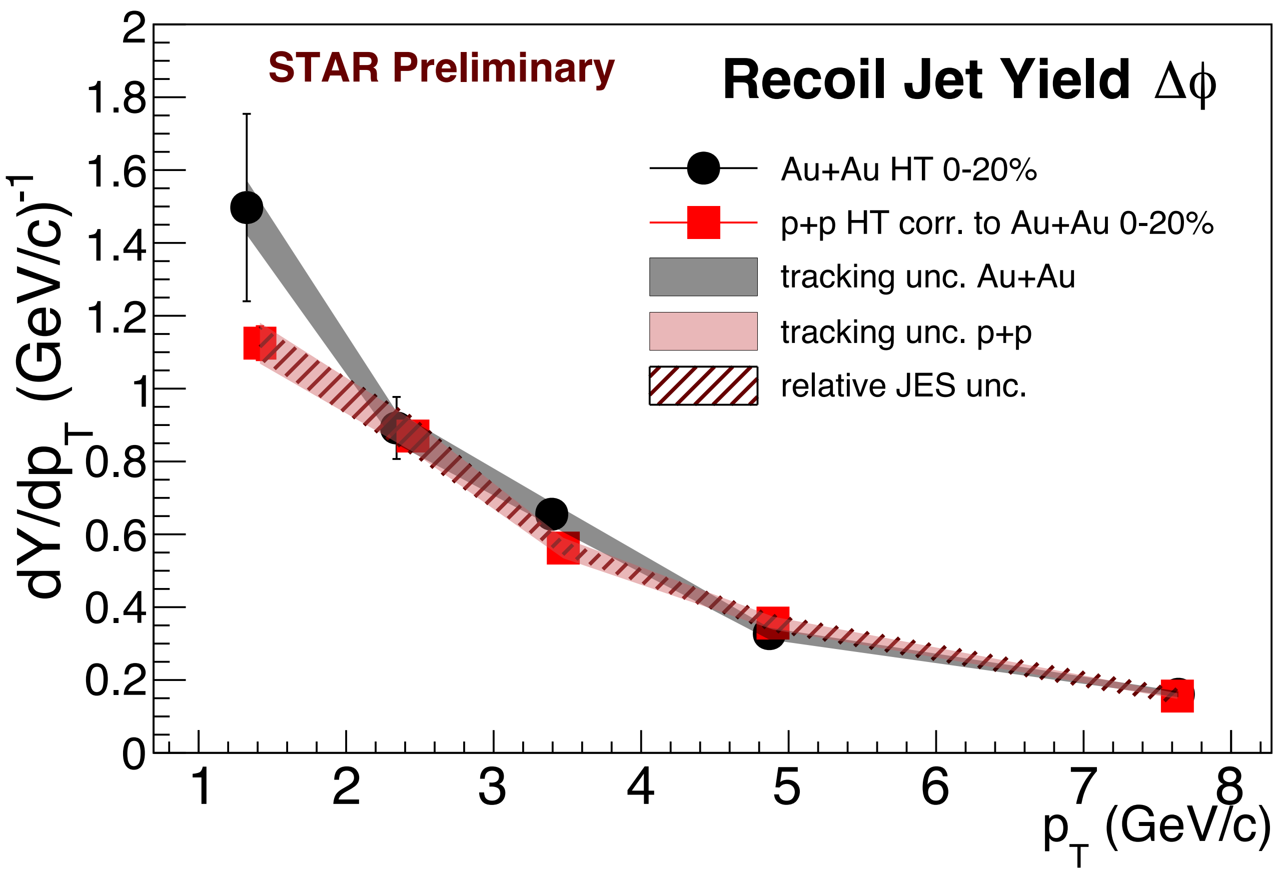






Yields in Δϕ


STAR Preliminary
Trigger Jet Yield Δϕ
Au+Au HT 0-20%
p+p HT corr. to Au+Au 0-20%
tracking unc. Au+Au
tracking unc. p+p
relative JES unc.
dY/dp_T (GeV/c)^-1
p_T (GeV/c)


STAR Preliminary
Recoil Jet Yield Δϕ
Au+Au HT 0-20%
p+p HT corr. to Au+Au 0-20%
tracking unc. Au+Au
tracking unc. p+p
relative JES unc.
dY/dp_T (GeV/c)^-1
p_T (GeV/c)

Consistent with A_J?

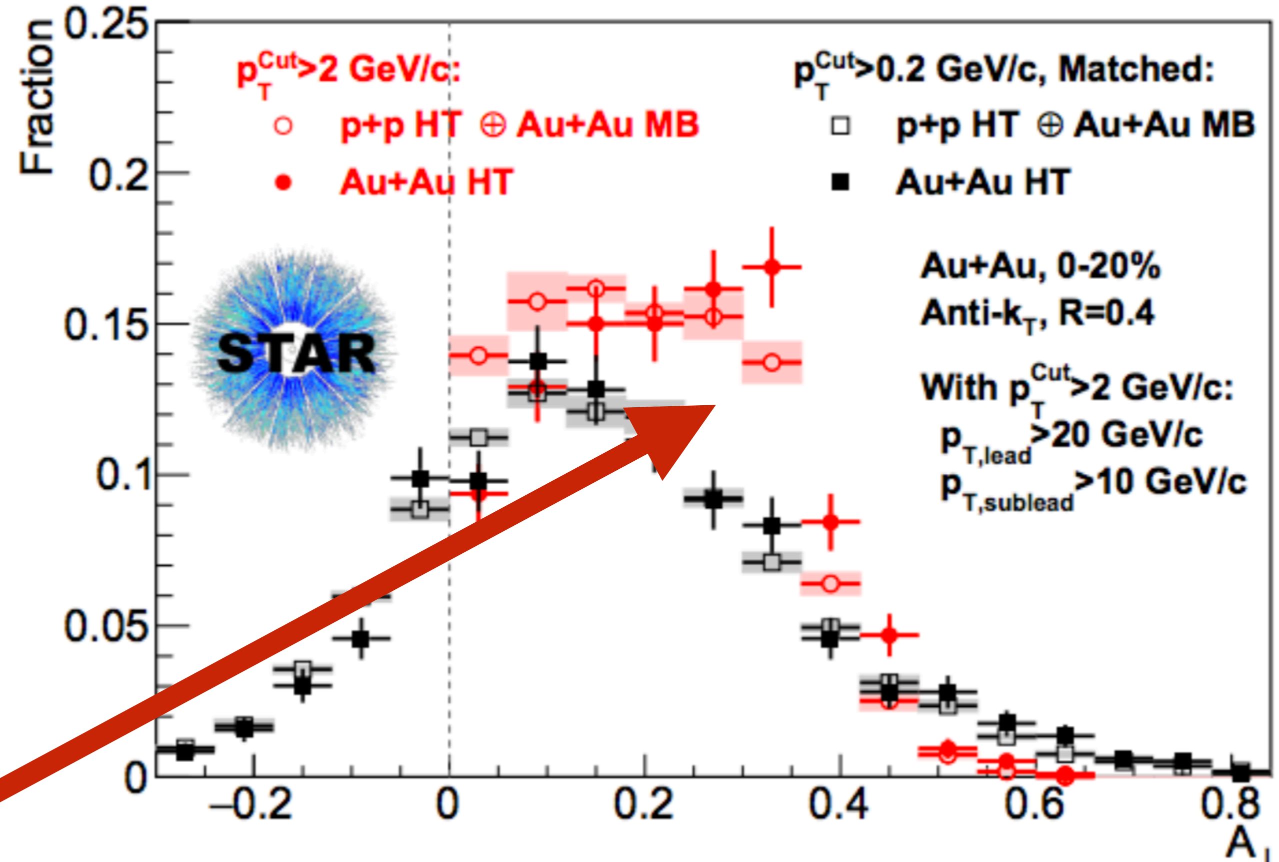
minimal modification at high p_T for both trigger & recoil jets

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?



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

more differential: select on A_J?