Di-Jet Measurements with STAR

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U.S. DEPARTMENT OF ENERGY | Office of Science

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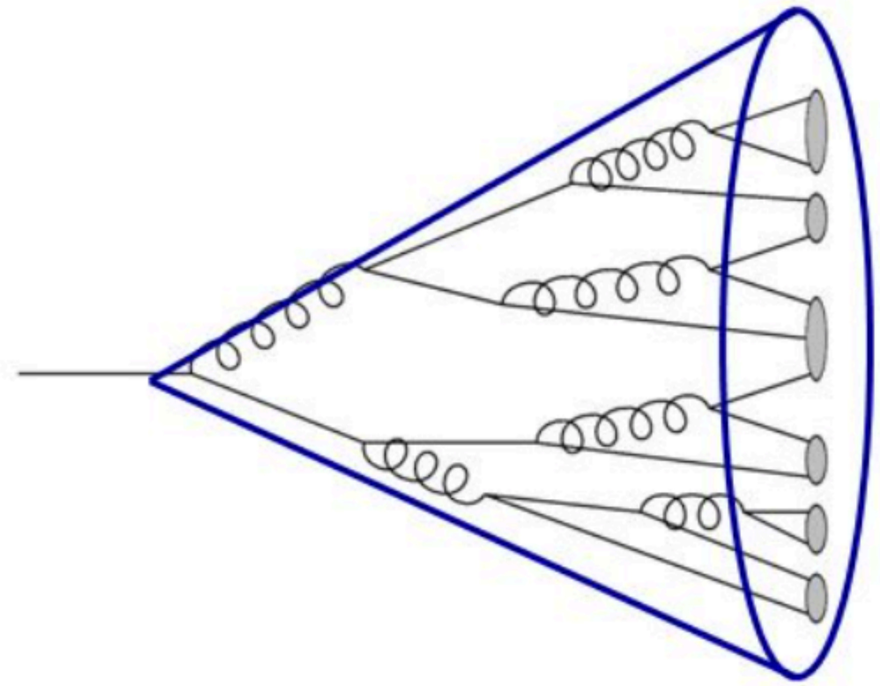
STAR

Jets

theory: X —> $q\bar{q}$ (or g)

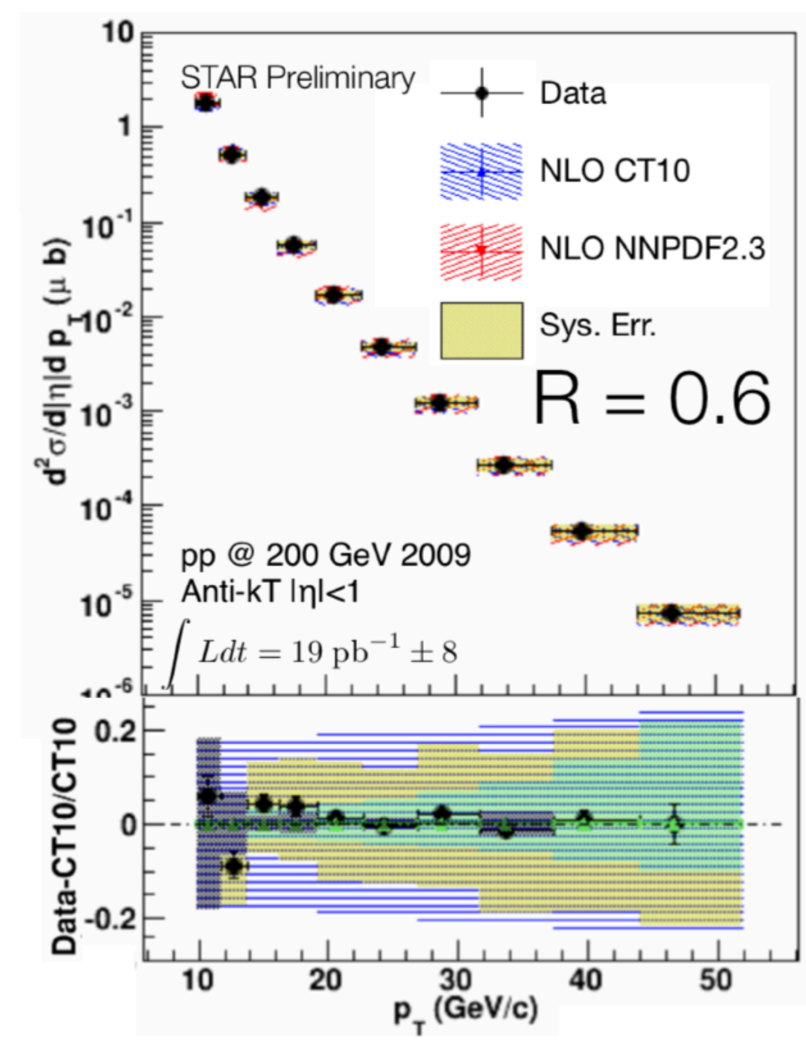


experiment: collimated shower of hadrons

theory ⟷ jet-finding ⟷ experiment

jets are calculable: pQCD

extremely good agreement over several orders of magnitude



[arXiv:1506.06314]

FastJet

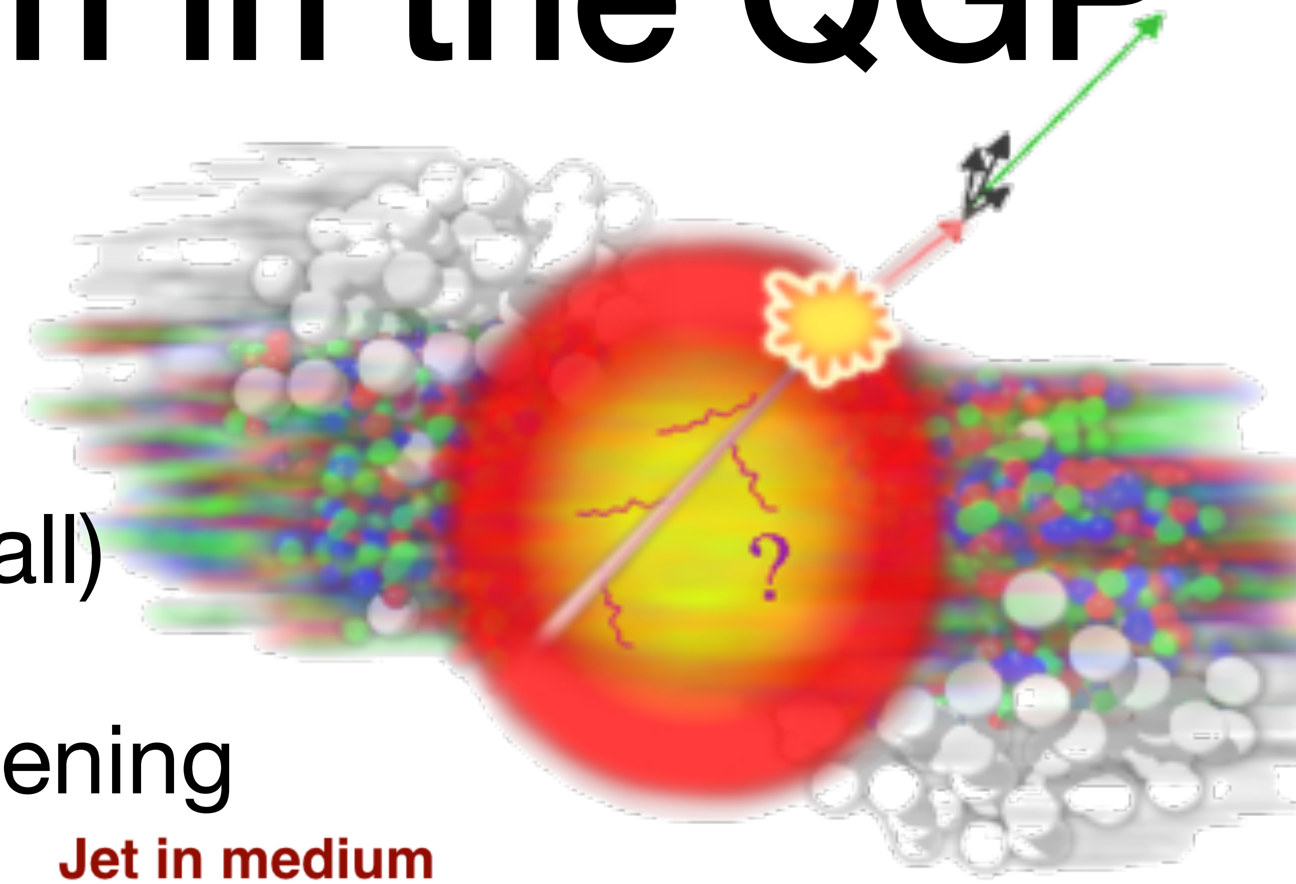
M. Cacciari, G.P. Salam and G. Soyez, Eur.Phys.J. C72 (2012) 1896 [arXiv:1111.6097]

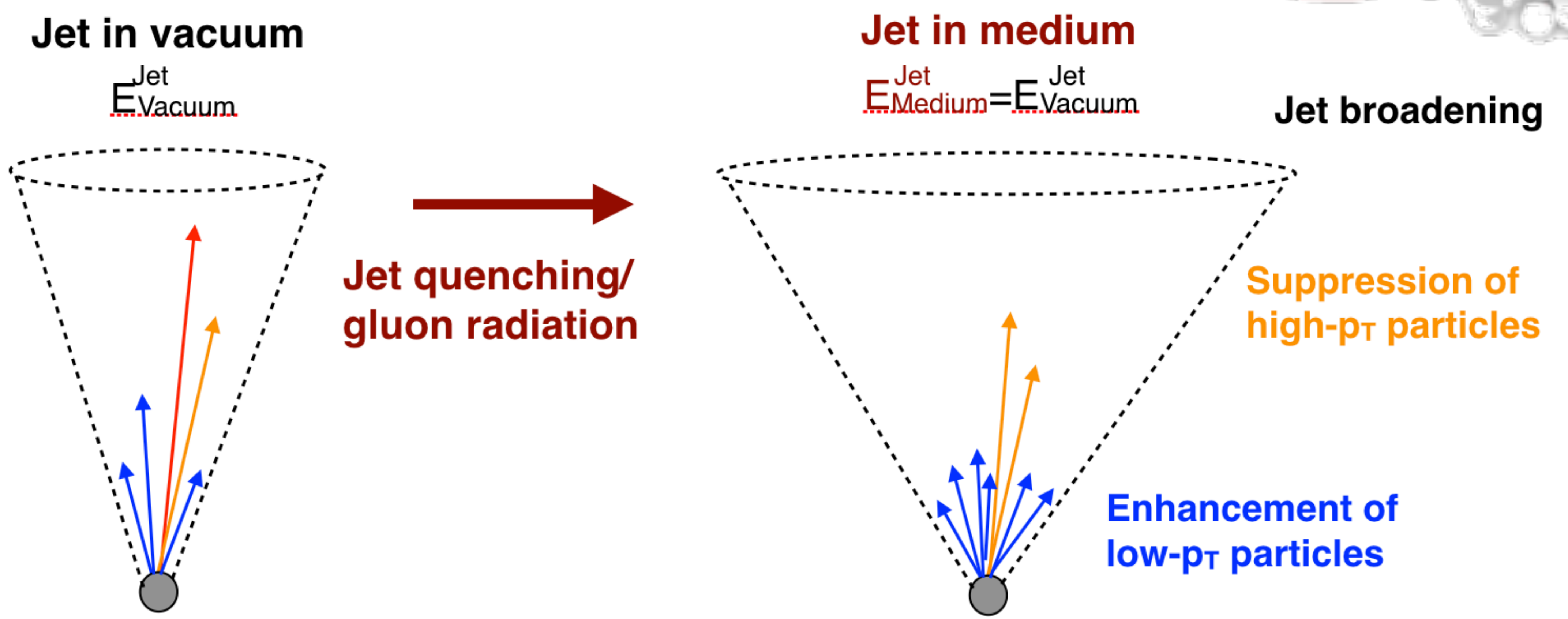
Jet modification in the QGP

partonic energy loss

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

  - broadening and softening

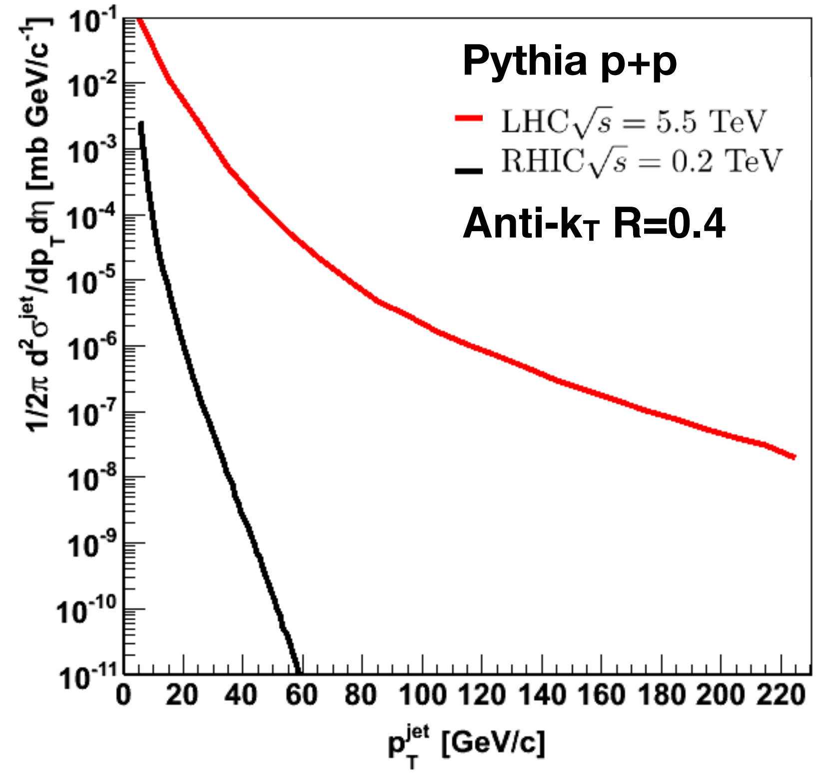




Jet production at RHIC & LHC

orders of magnitude difference in jet production cross section

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



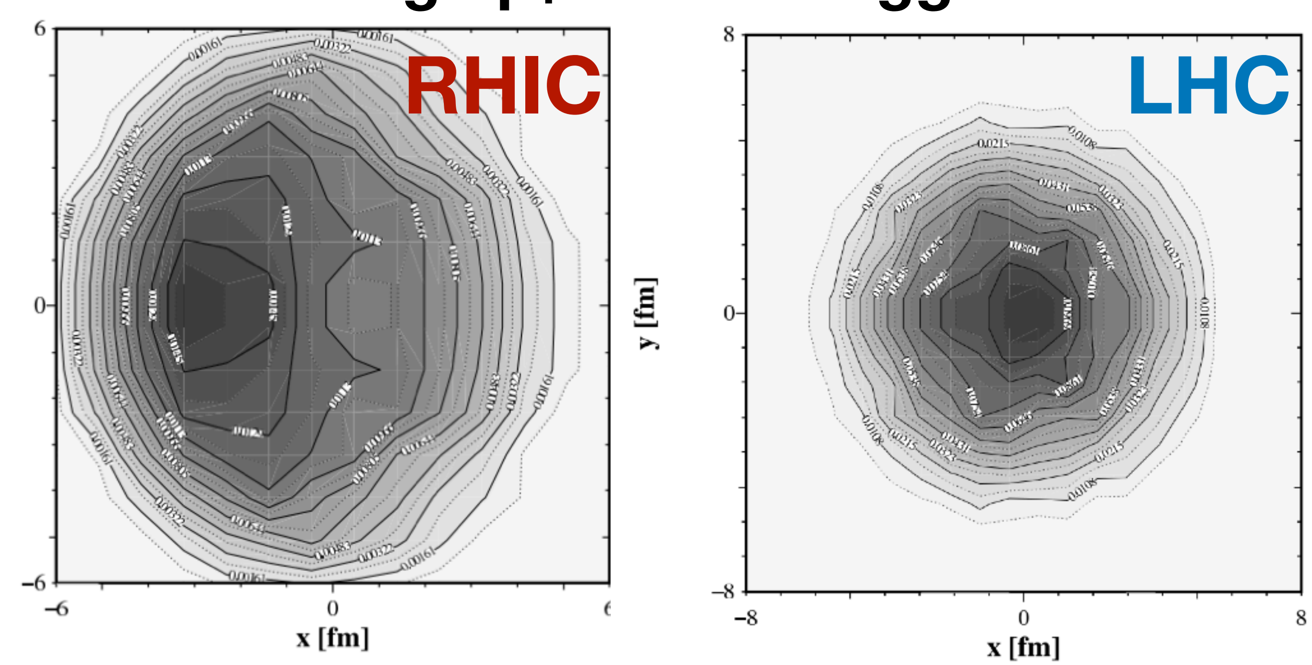
models predict that with the softer **RHIC** spectrum

trigger → surface bias

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

trigger → no surface bias

high p_T hadron trigger

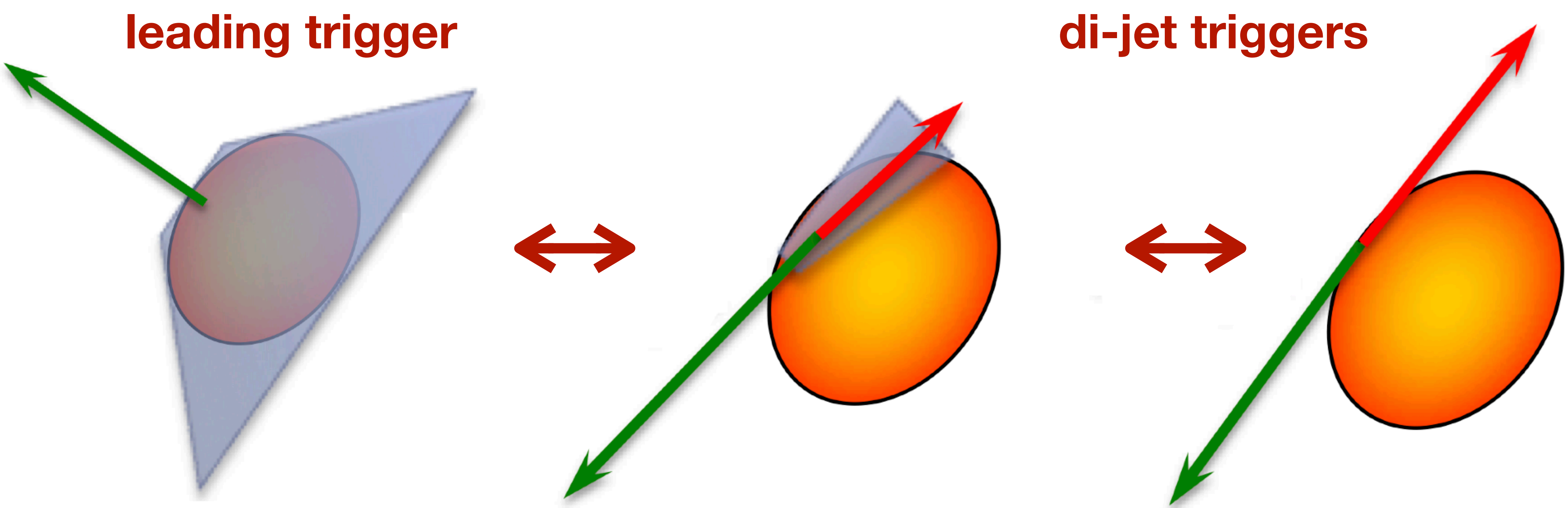


Renk, Phys.Rev. C 87, 024905 (2013)

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

Jet trigger bias

however, this bias can be useful - opportunity to use jet cuts to select jet production vertex and di-jet orientation

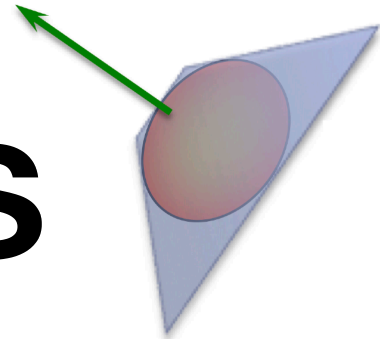


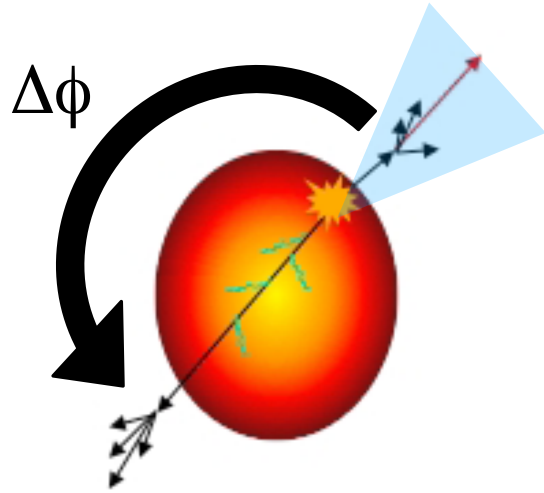
jet+hadron correlations, hadron+jet spectra

di-jet imbalance, di-jet hadron correlations

2+1 correlations

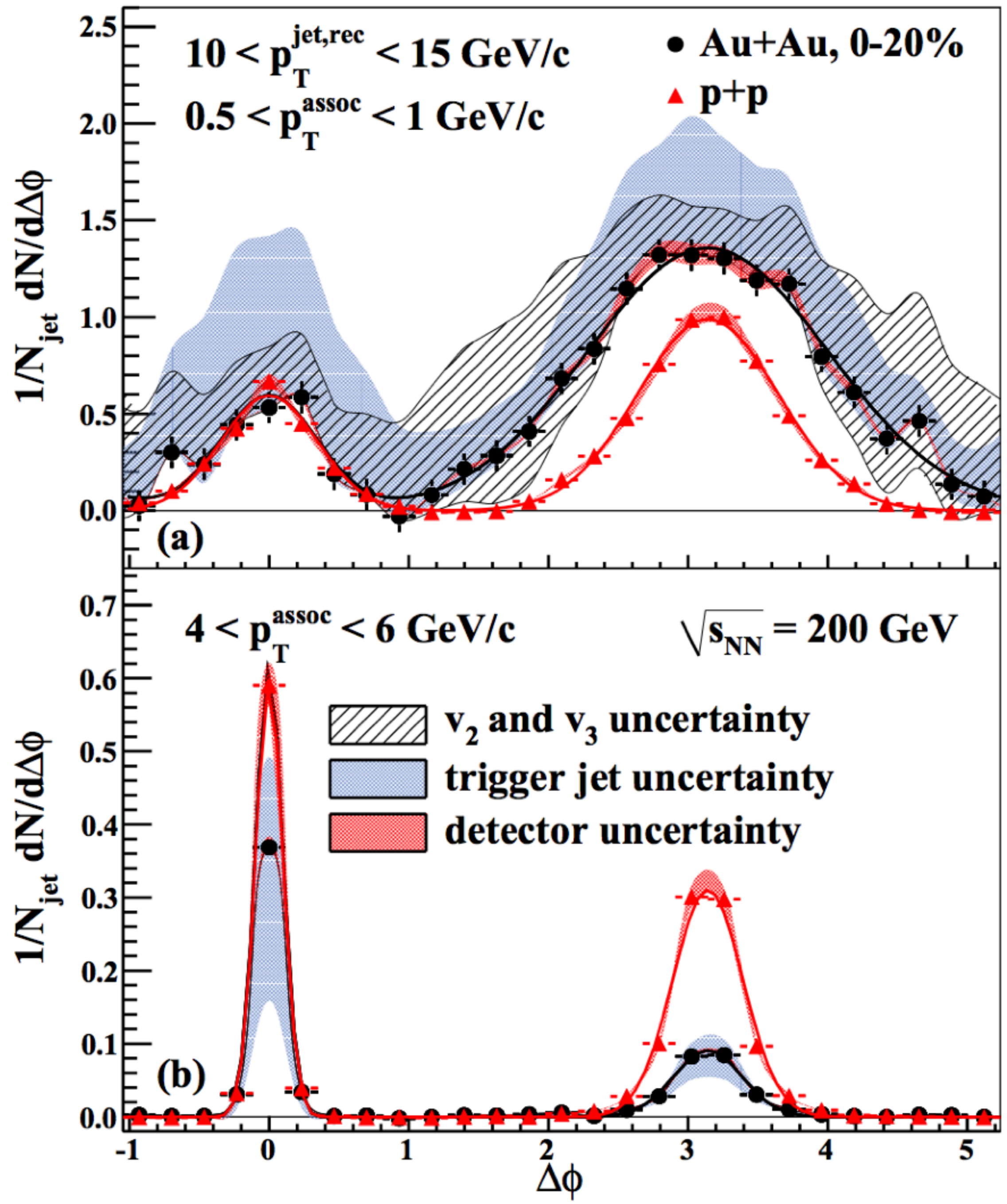
Jet+hadron correlations





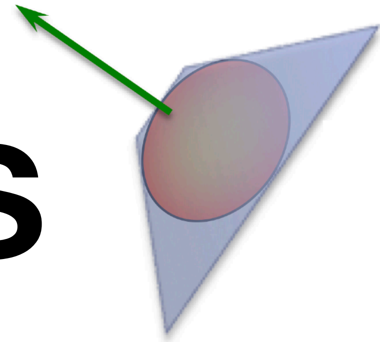
enhancement of recoil jet
low-p_T constituents,
broadening

suppression of recoil jet
high-p_T constituents

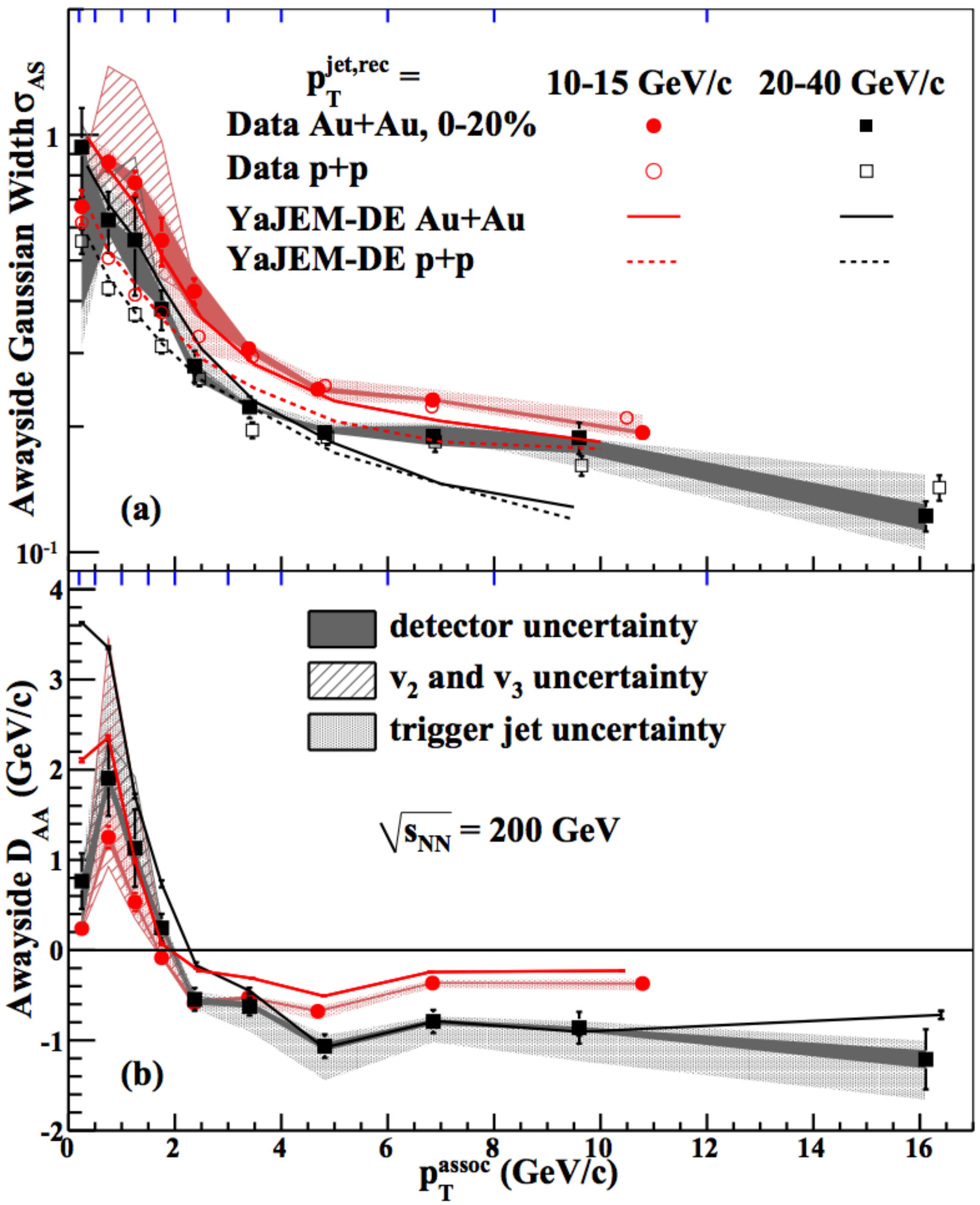


STAR, PRL ***112****, 122301 (2014)*

Jet+hadron correlations

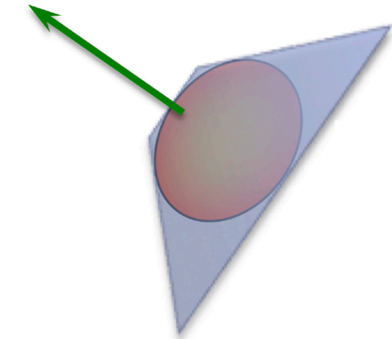


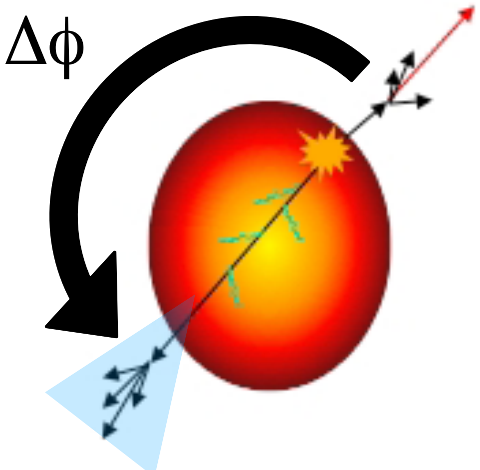
- clear signal of **softening** and **broadening** in recoil jet
- energy loss in high-p_T region balanced by low-p_T excess



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

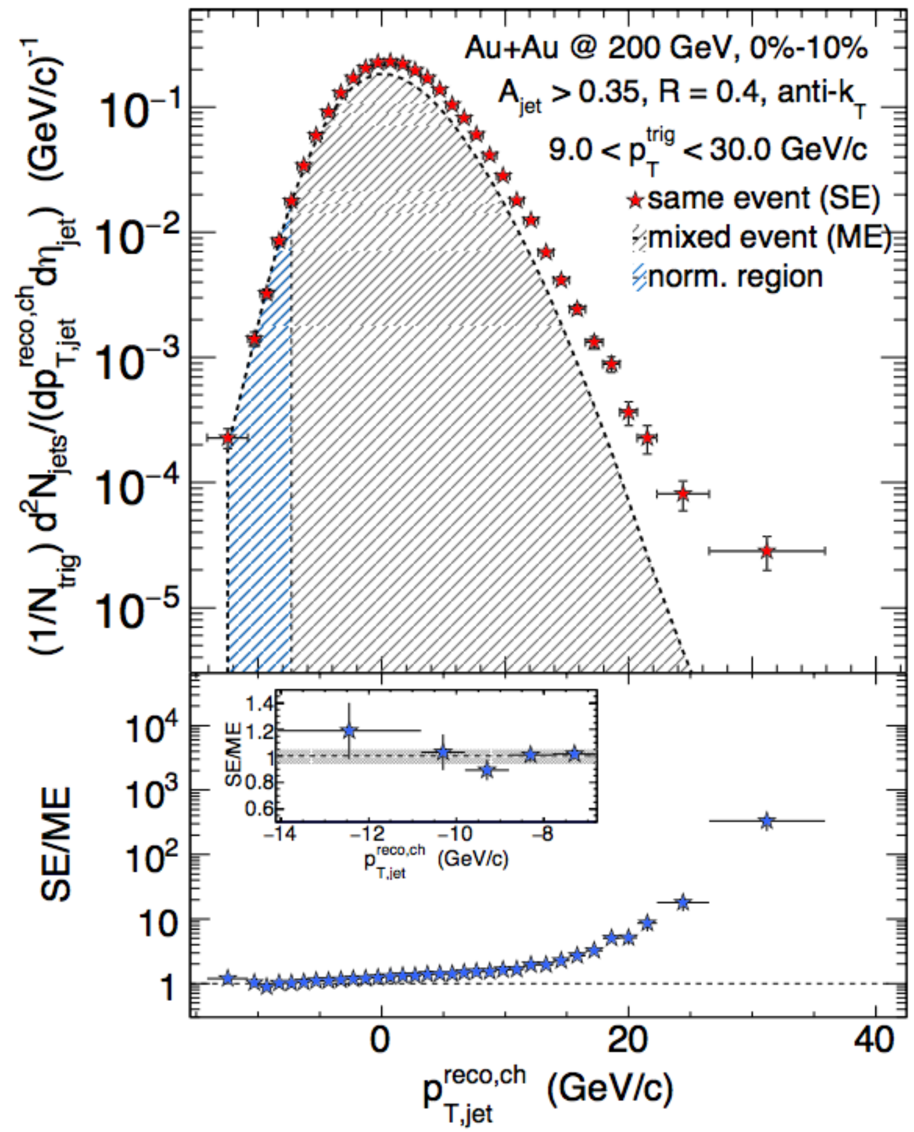
Hadron+jet spectra





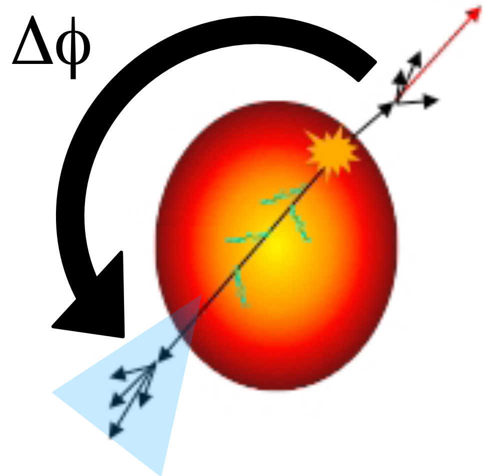
semi-inclusive hadron-triggered recoil jet spectra

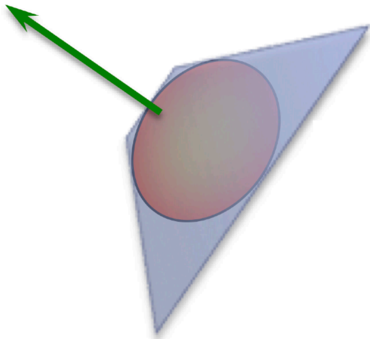
use of novel mixed-event method to extend kinematic reach to low jet p_T



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

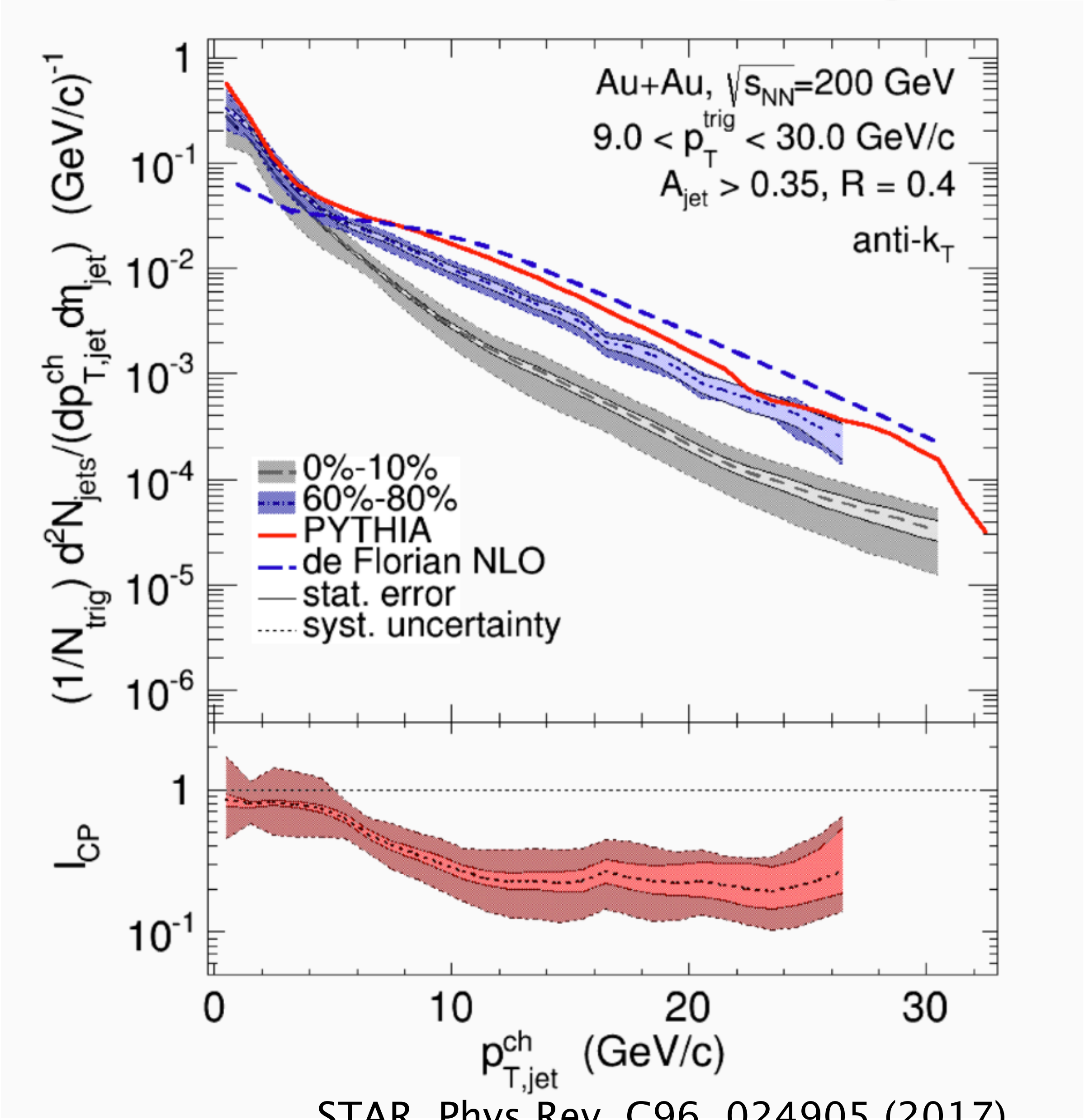
Hadron+jet spectra





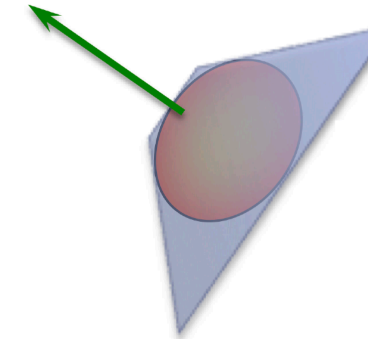
yield of jets recoiling from high p_T hadron

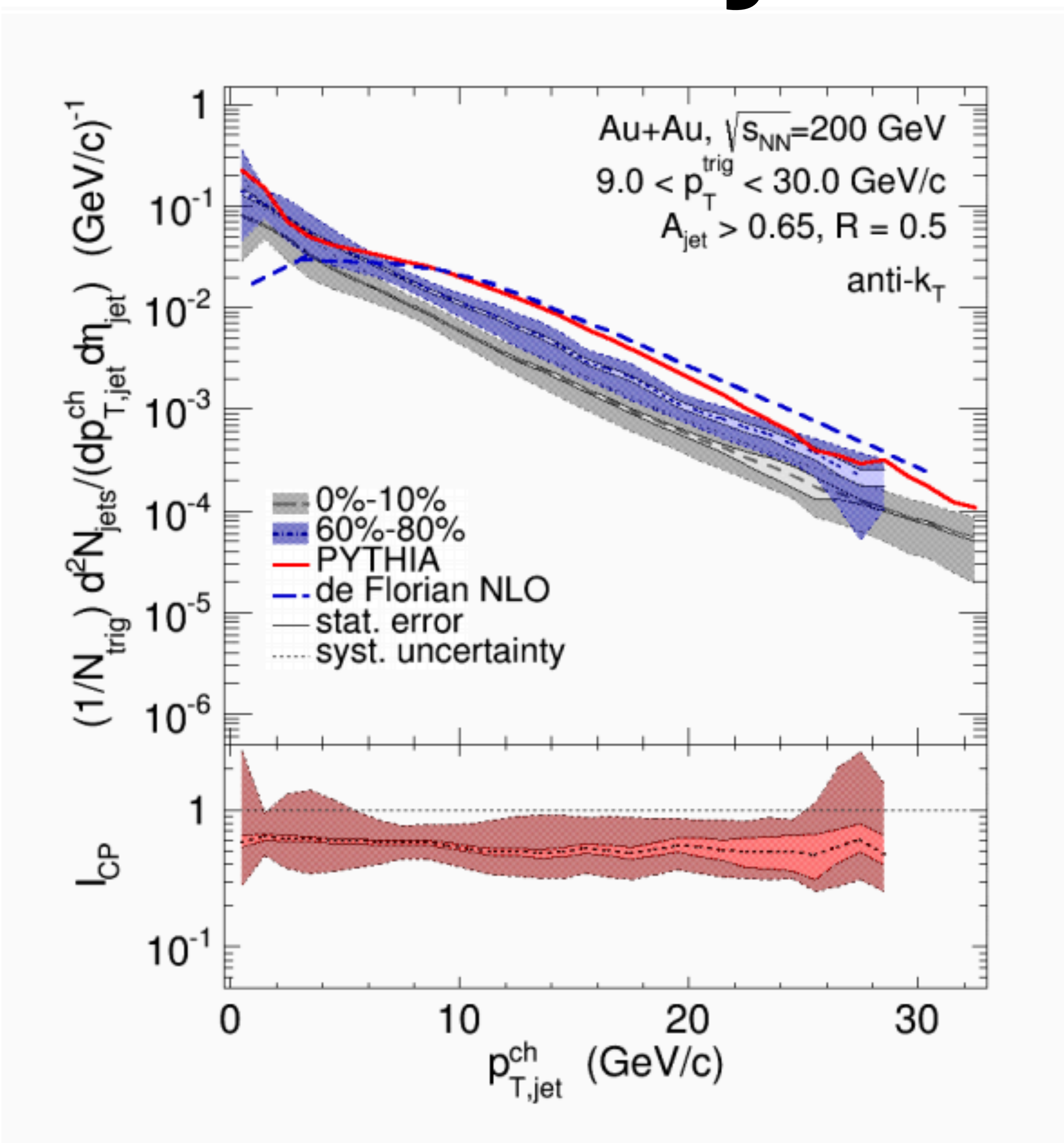
suppression of recoil jet in central collisions compared to peripheral

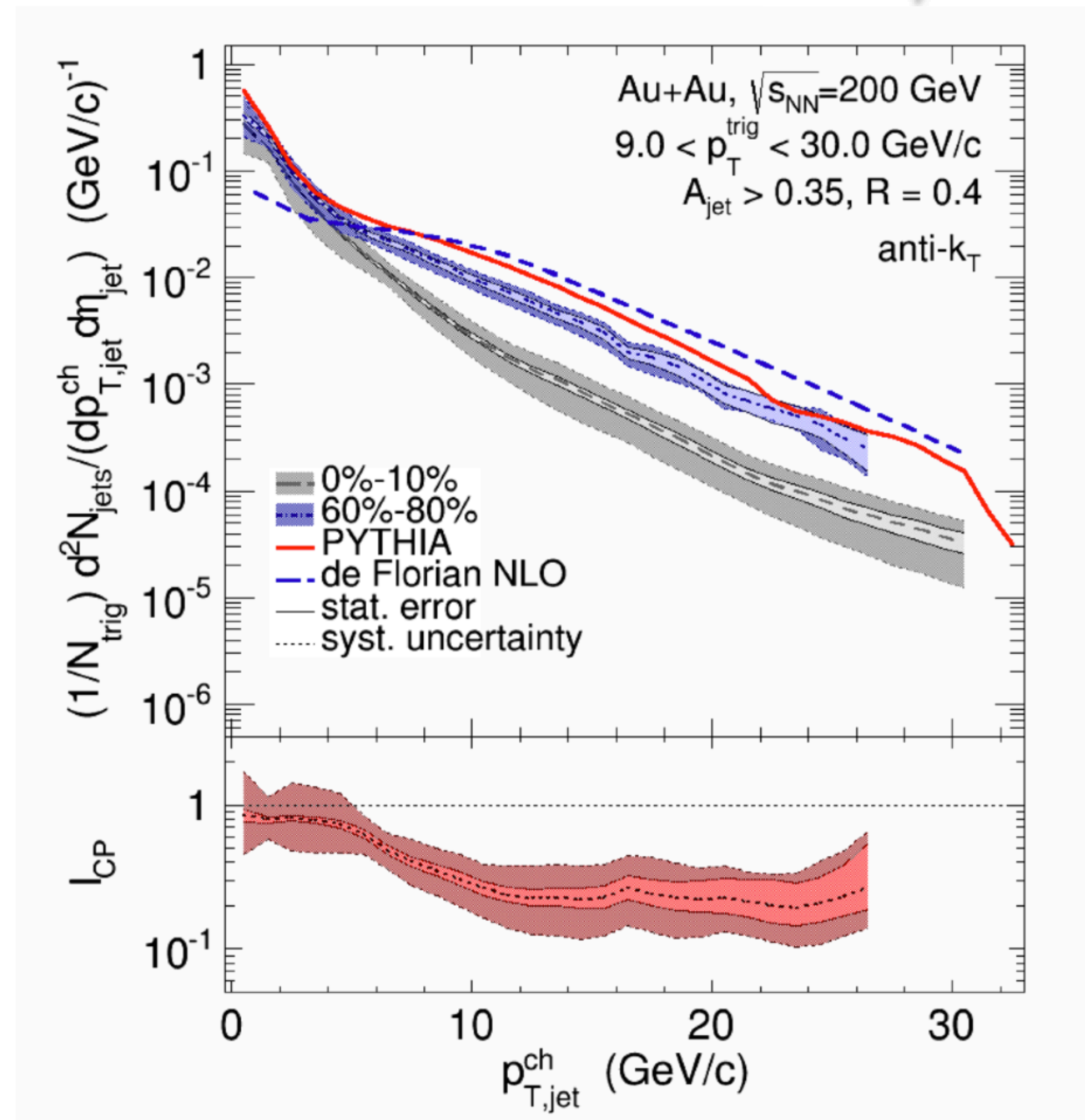


STAR, Phys.Rev. C96, 024905 (2017)

Hadron+jet spectra





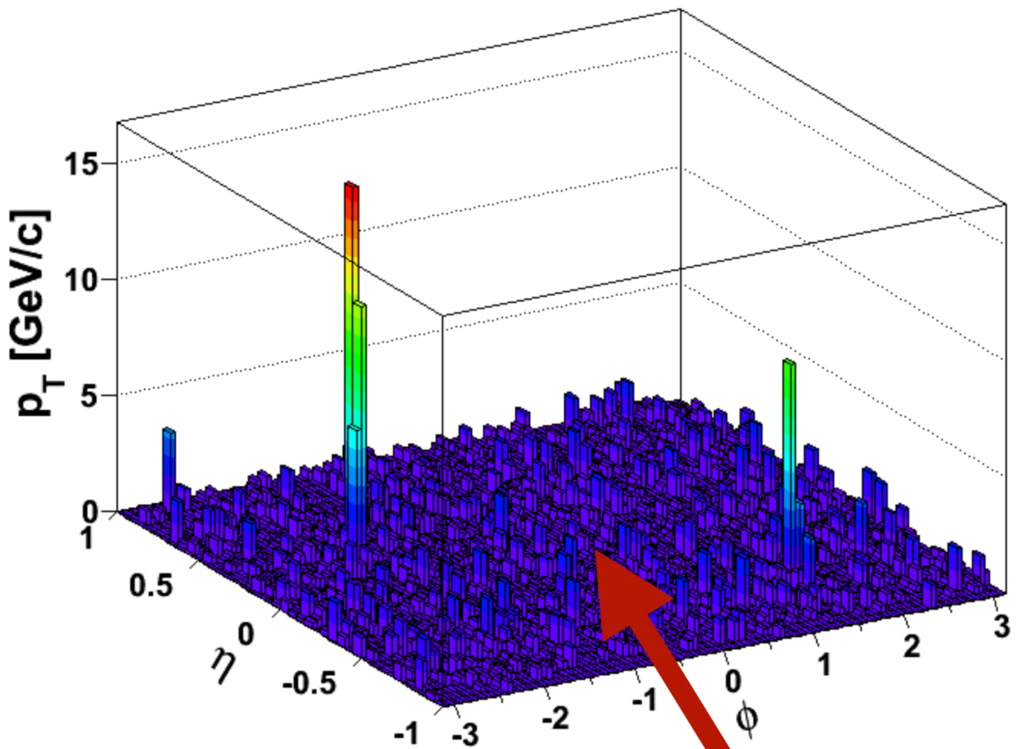


Phys.Rev. C96 no.2, 024905 (2017)

increasing R → increasing I_{CP} → broadening

Hard core jets at STAR

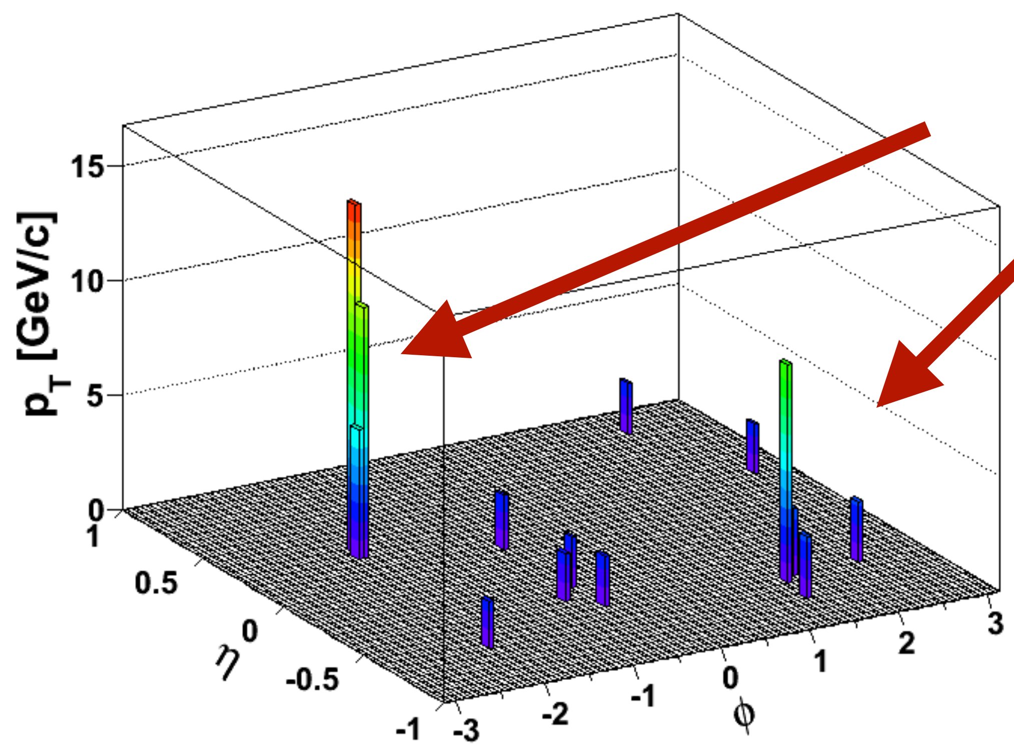
in a heavy ion background



large background energy density

Hard core jets at STAR

in a heavy ion background



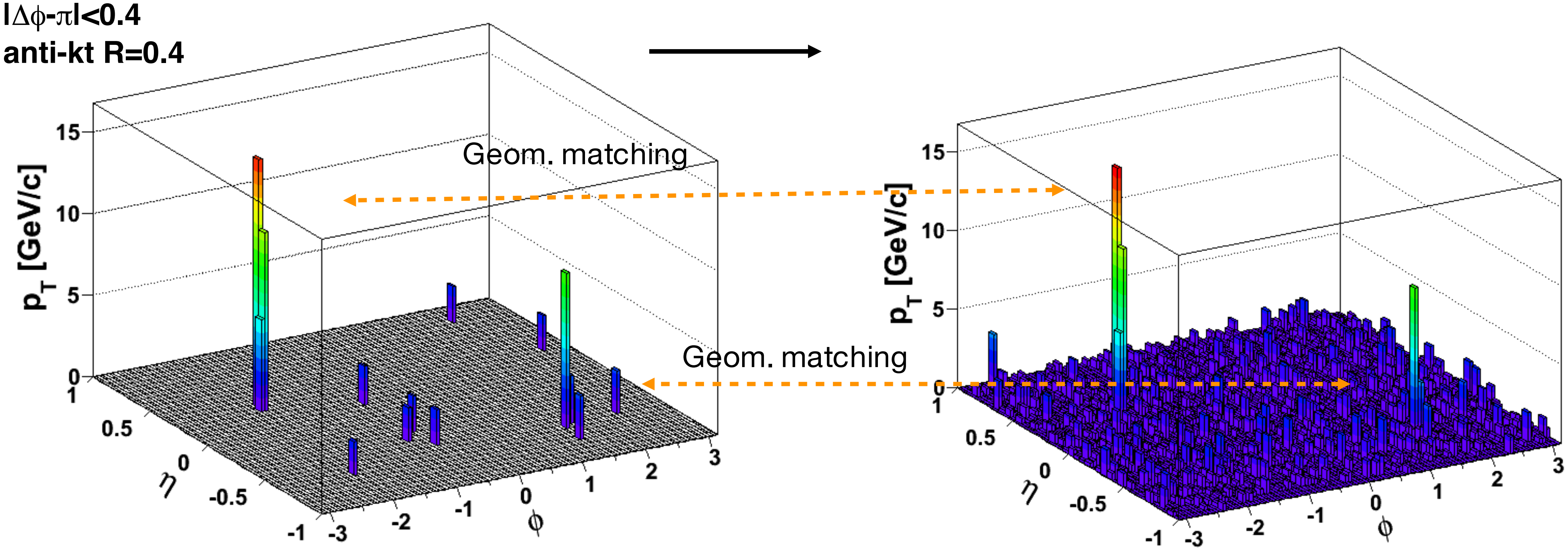
clear jet signal

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

Hard core jets at STAR

in a heavy ion background

p_T^{Cut}=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



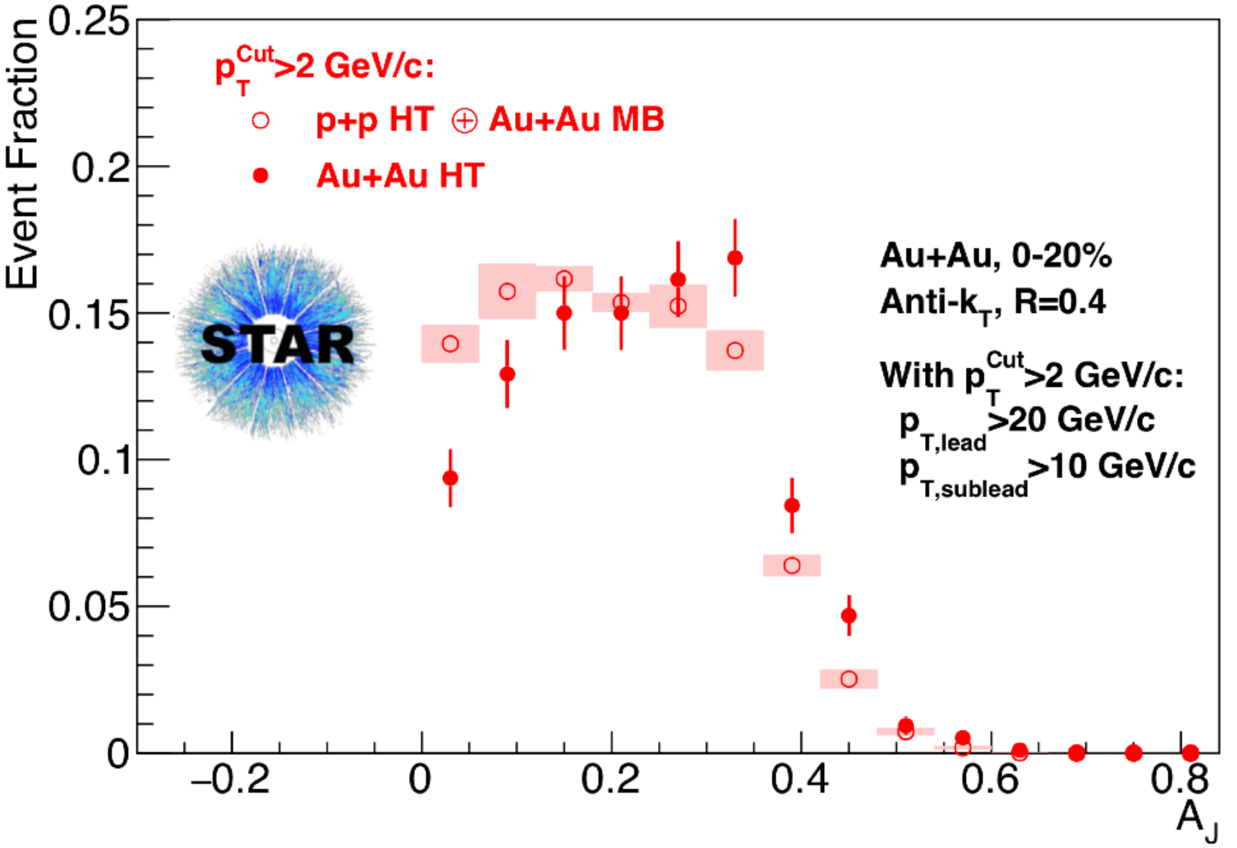
p_T^{const}>2 GeV/c cut → removes almost all background

geometric matching → no combinatoric jets, recover all constituents

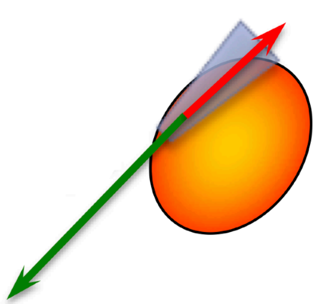
Di-jet asymmetry at STAR

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)

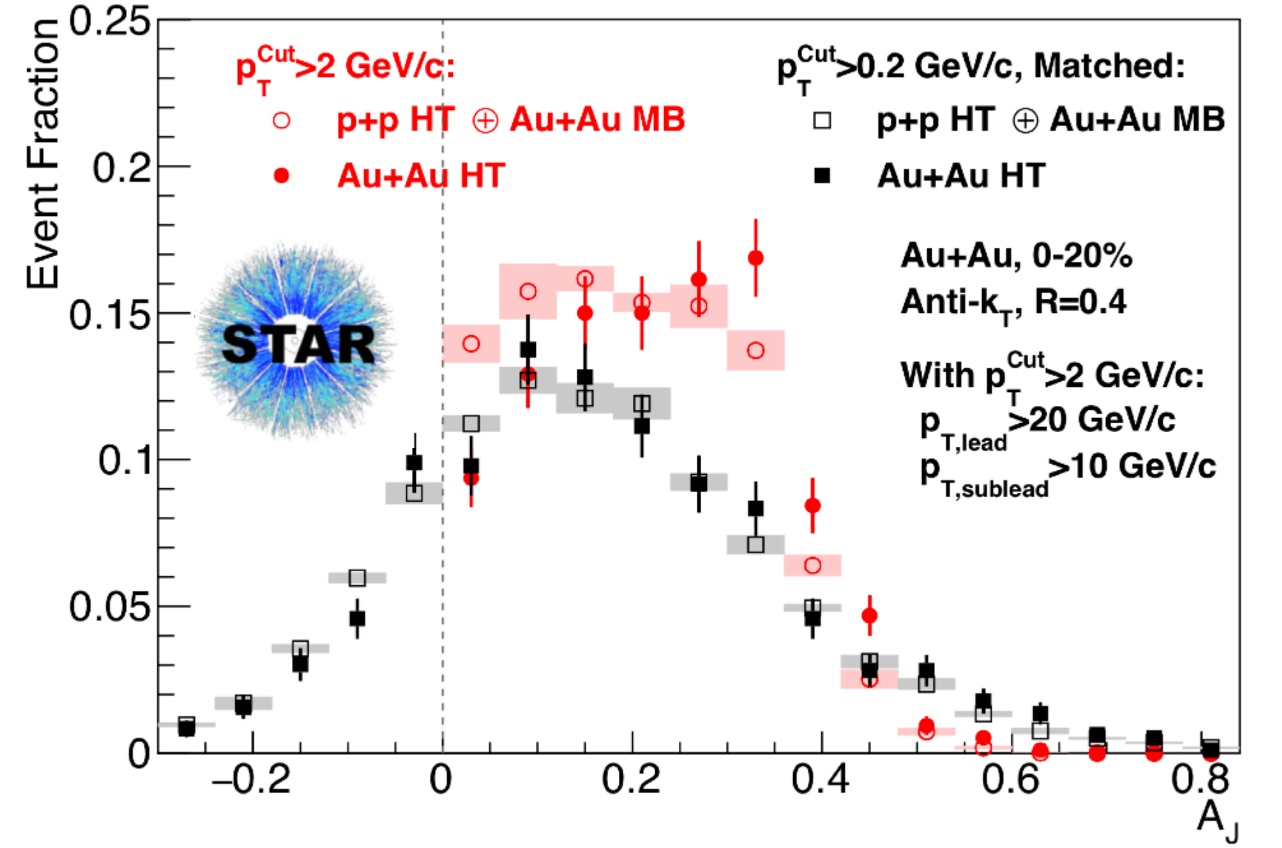


Di-jet asymmetry at STAR

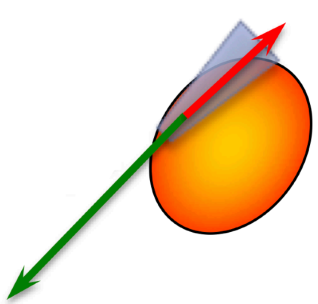
hard core di-jets more imbalanced with respect to p+p

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)



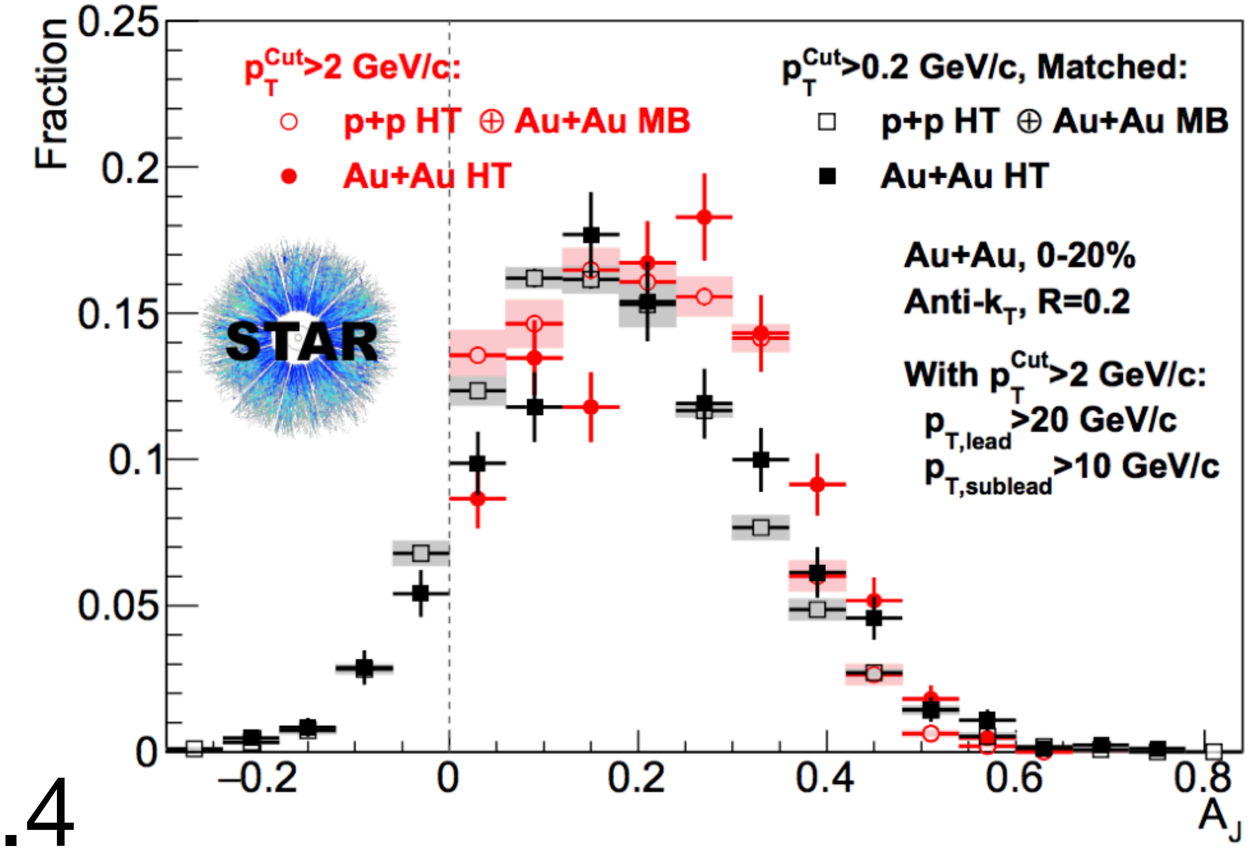
Di-jet asymmetry at STAR

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

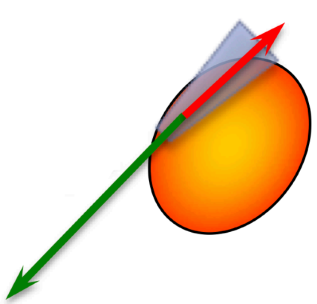
when soft constituents are included: balance no longer restored to the level of p+p in R=0.2

broadening of jet from 0.2 to 0.4

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



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

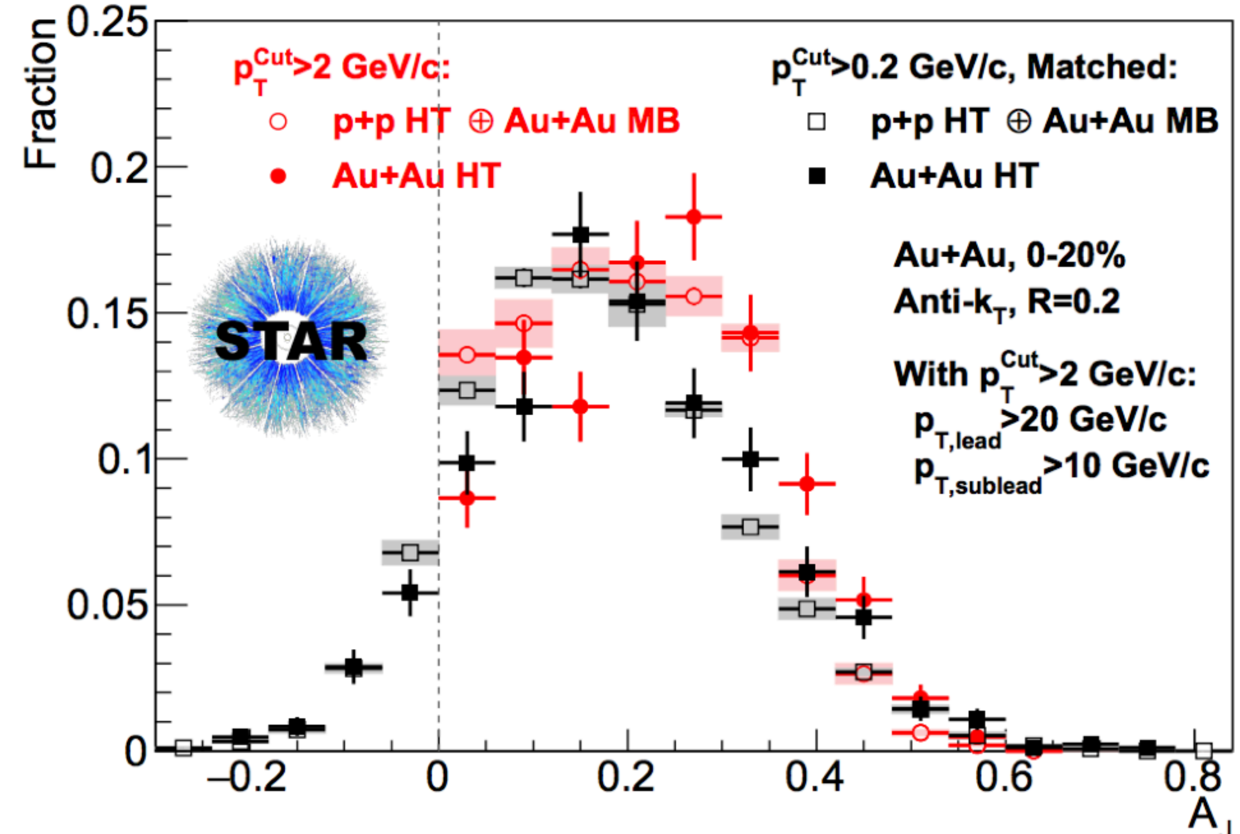


Di-jet asymmetry at STAR

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

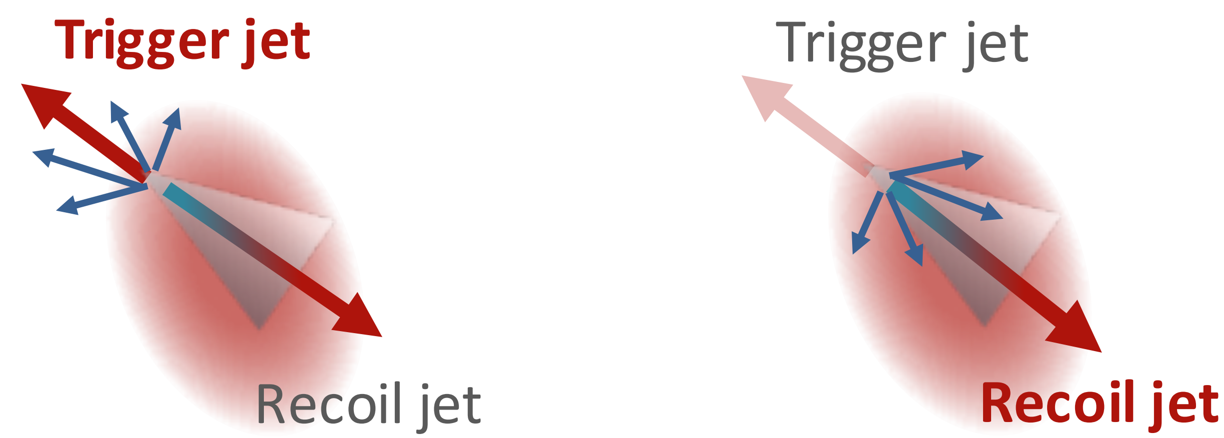
$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$



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

more differential → di-jet hadron correlations

Di-jet hadron correlations



di-jet definition

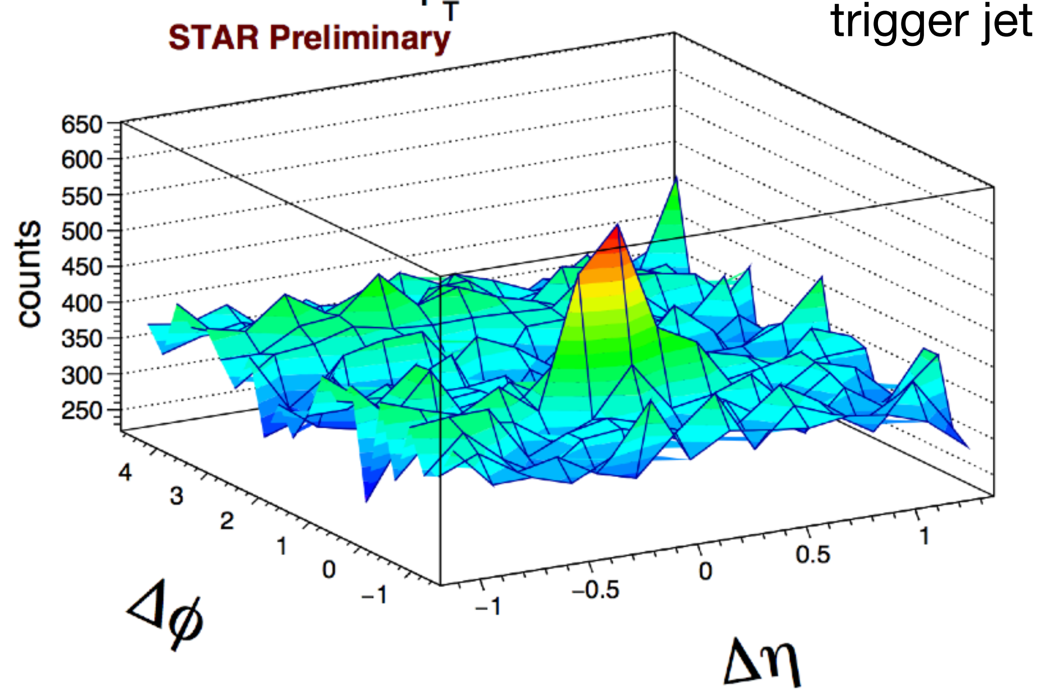
p_T^{Cut}=2 GeV/c
p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$|\Delta\phi-\pi|<0.4$
anti-k_T R = 0.4

jet-finding → detector level

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

correlations & yields → particle level

Au+Au
0-20% central



systematic uncertainties

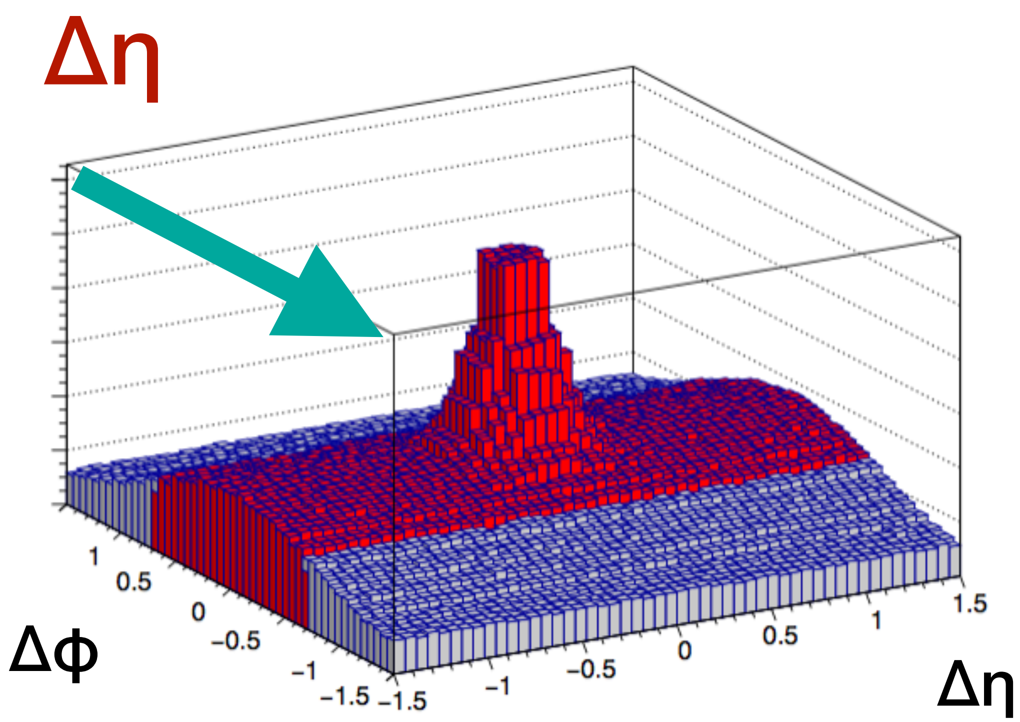
→ tracking efficiency (±5%)

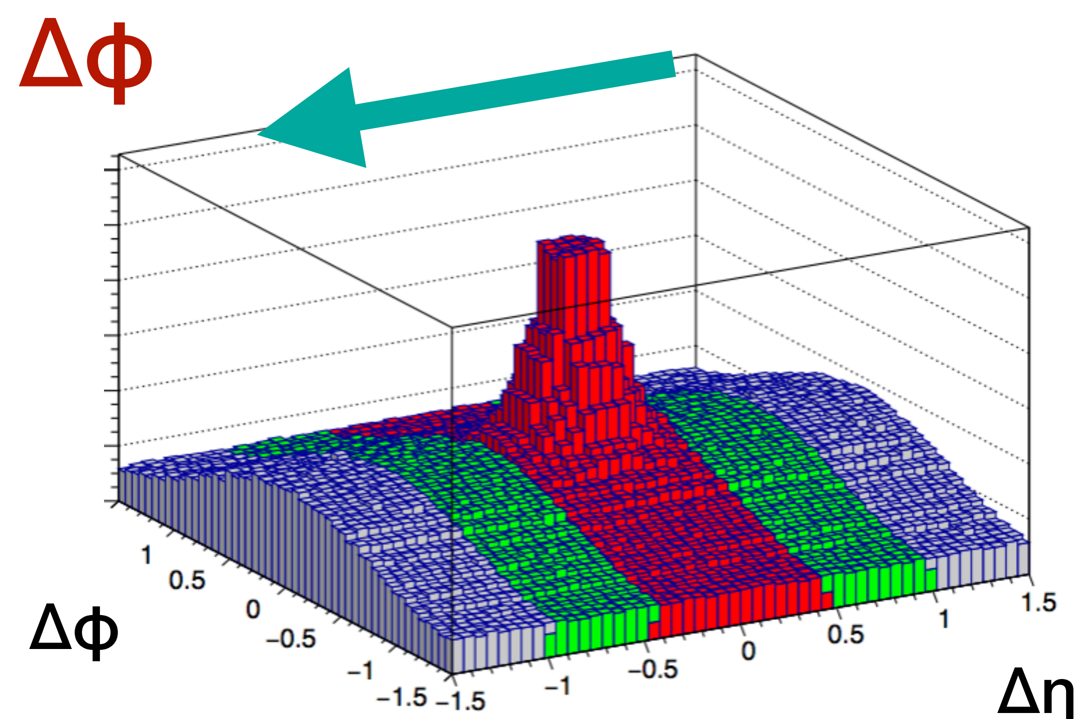
→ relative jet energy scale

relative tracking efficiency (±7%)

relative tower energy scale (±2%)

Background subtraction in di-jet hadron correlations



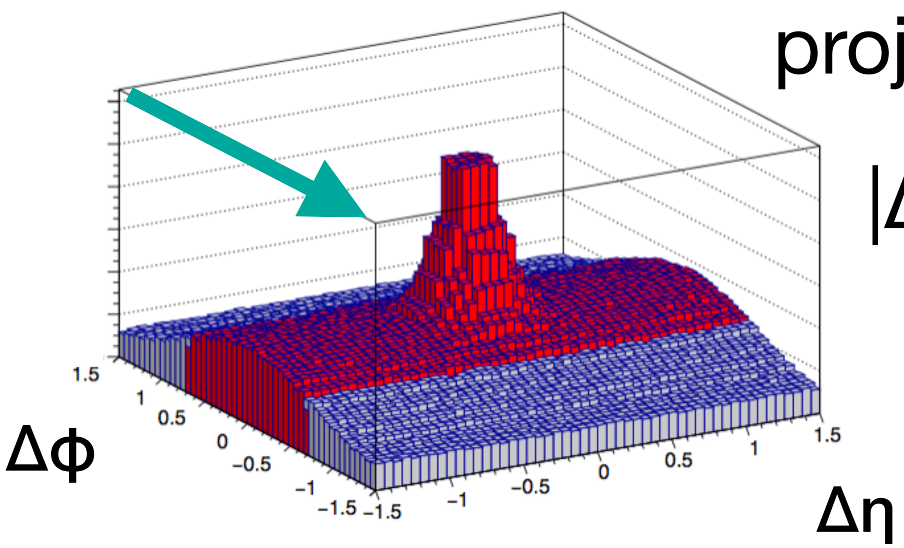


fit with a constant+gaussian constant subtracted as background

use sideband subtraction to account for flow in underlying event

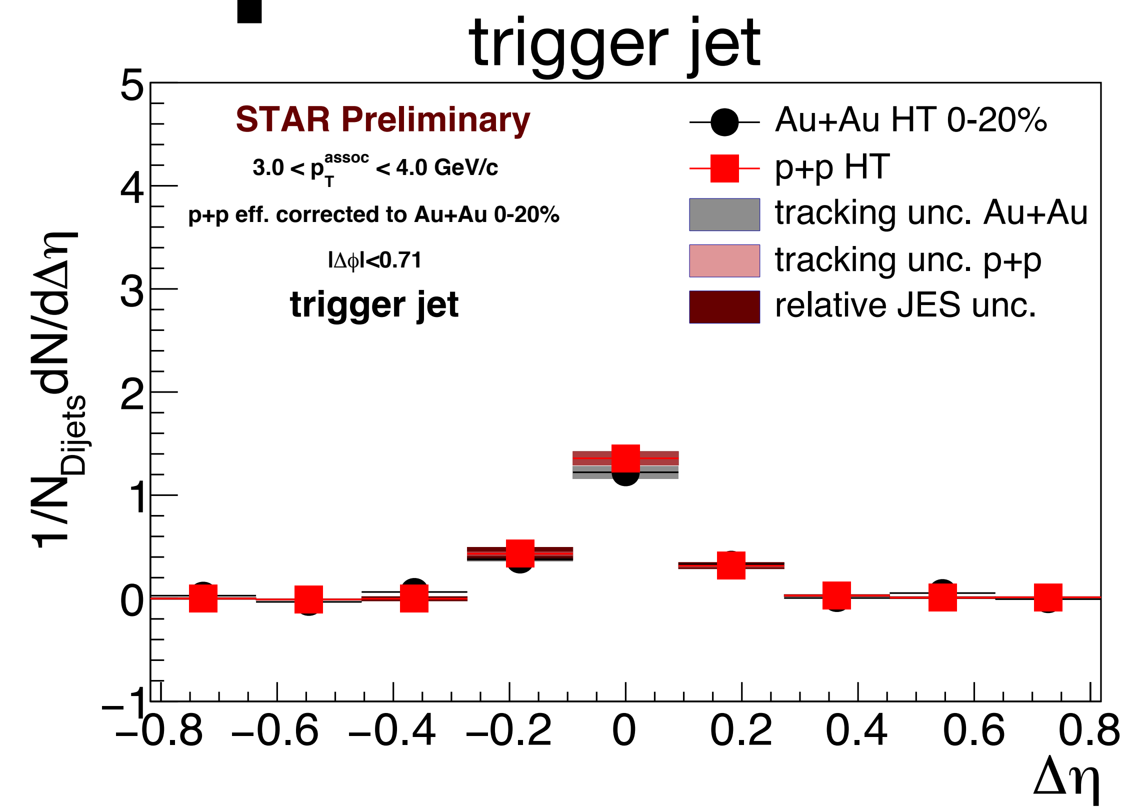
Correlations in Δη

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

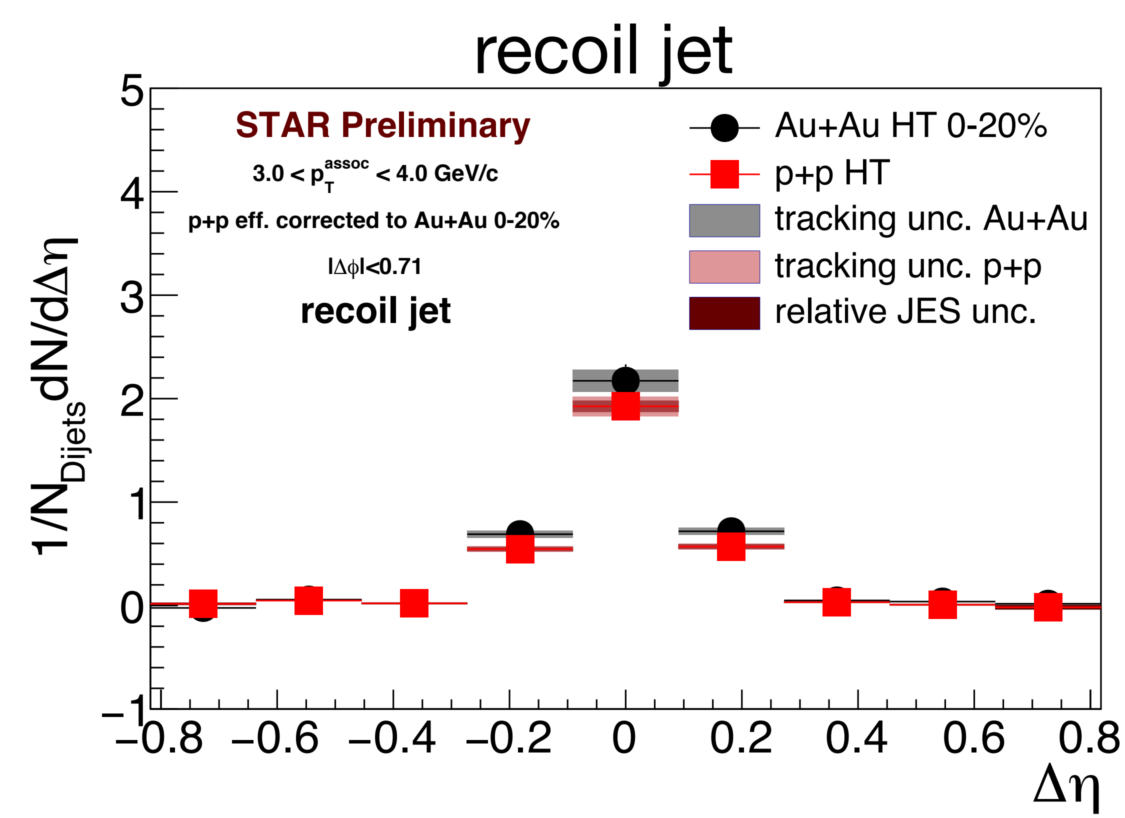


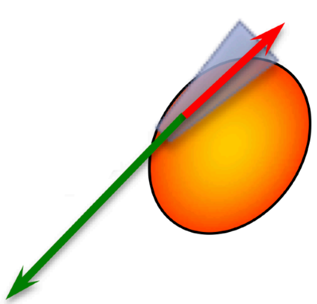
projection range

$|\Delta\phi| < 0.71$



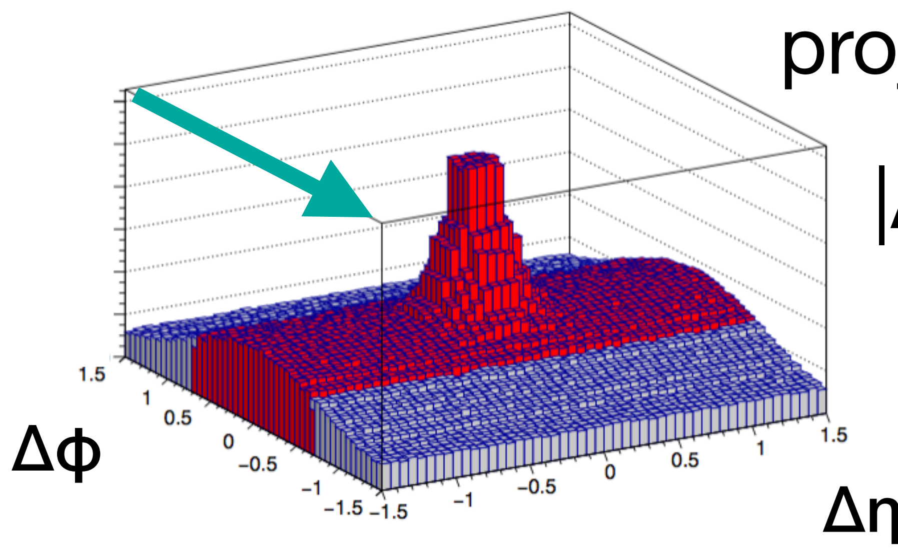
yield contained within jet radius R=0.4





Correlations in $\Delta\eta$

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



projection range

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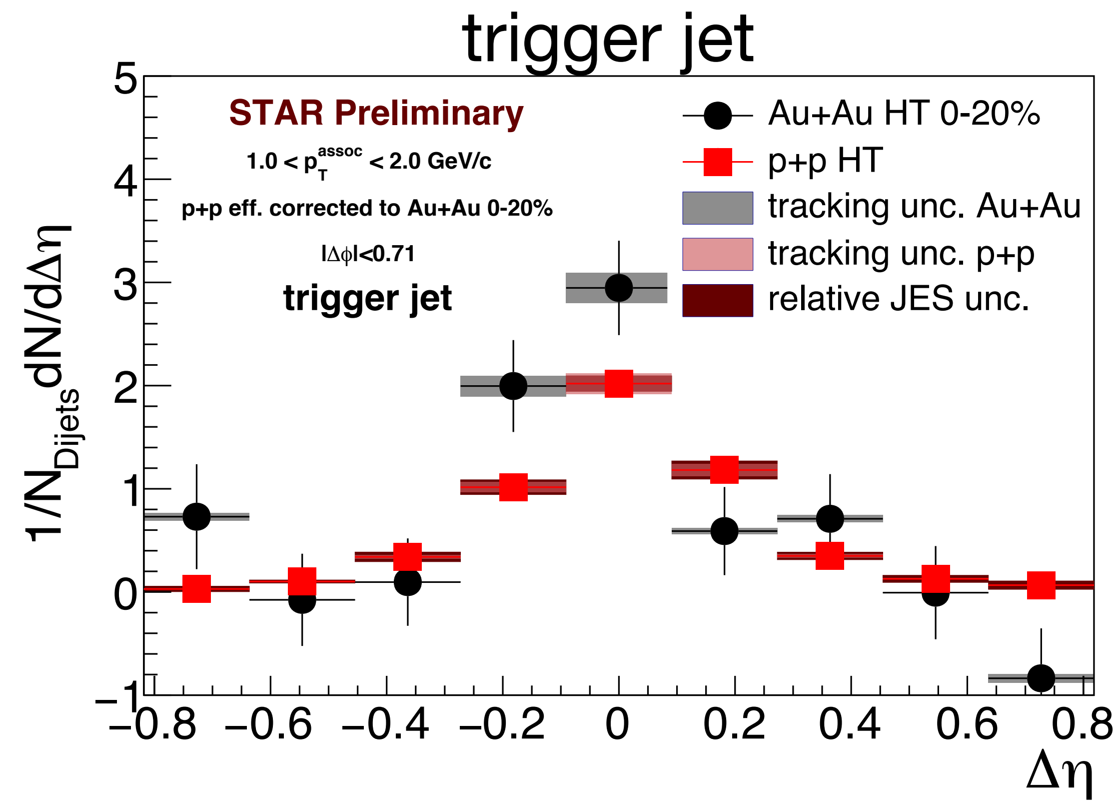
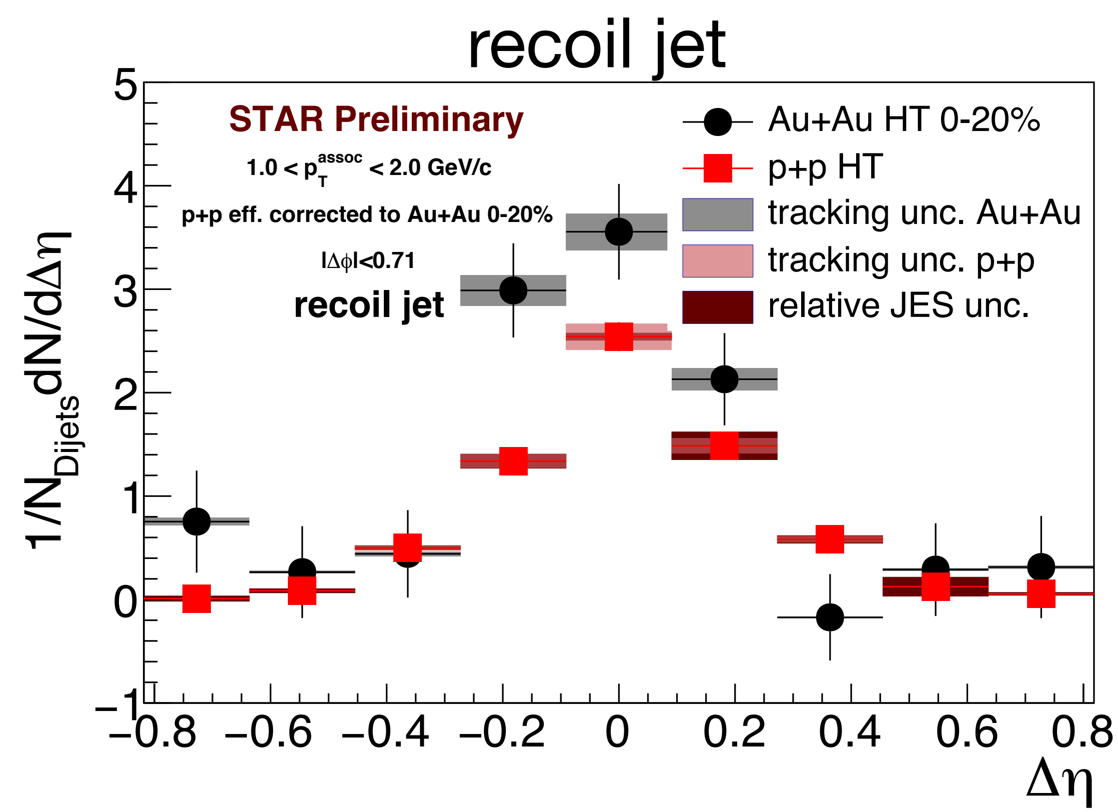
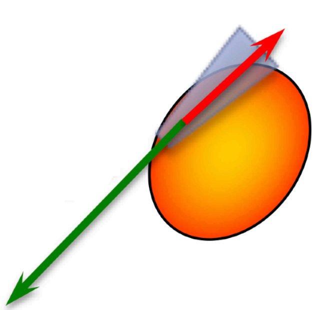




→ yield contained within jet radius R=0.4



Jet constituent Yields

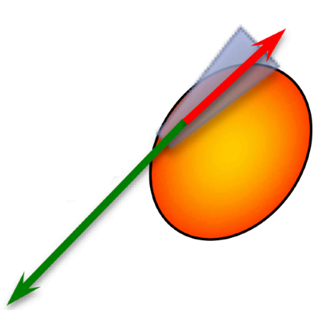
yields consistent between
$\Delta\phi$ & $\Delta\eta$

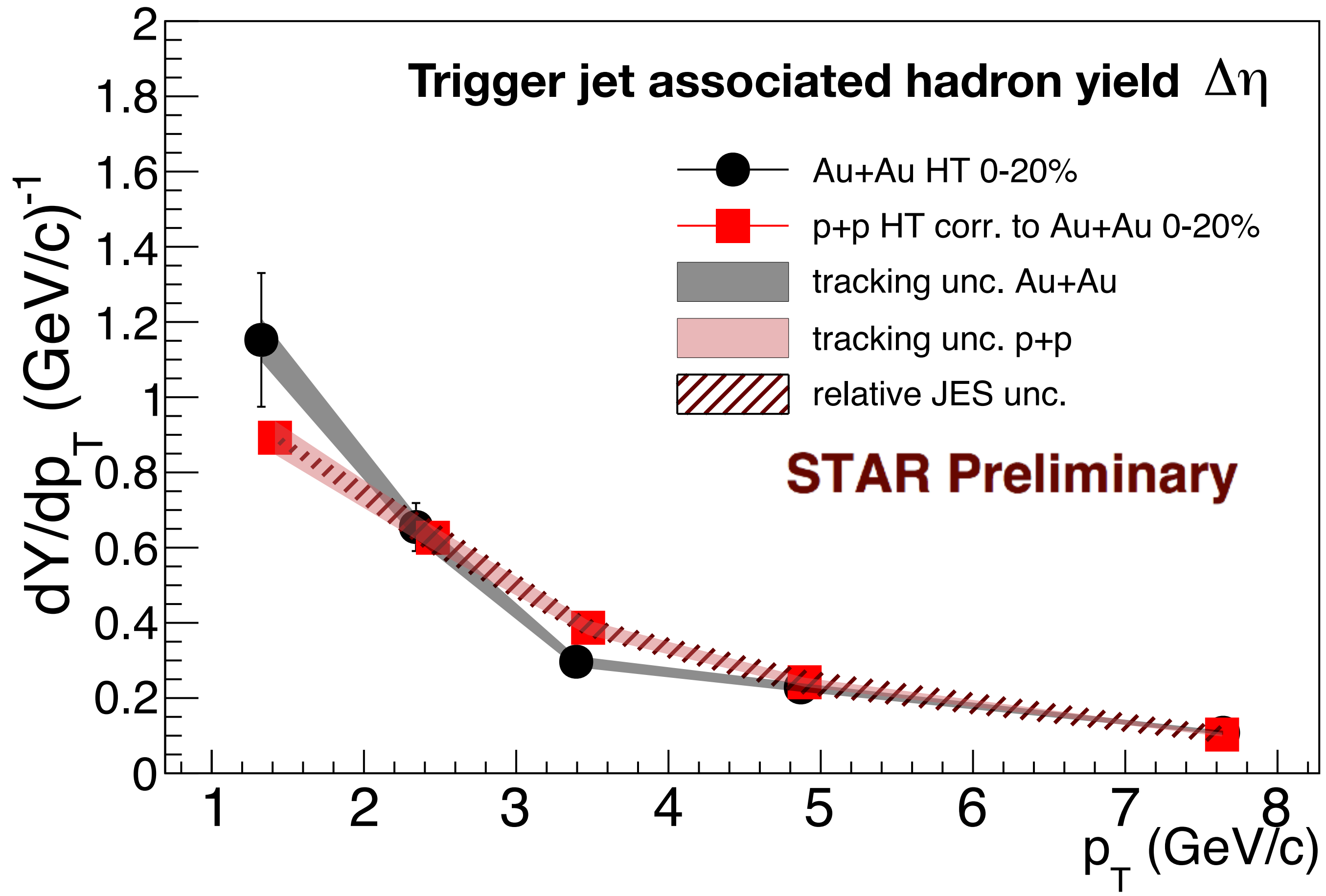
→ yield contained within R=0.4 for all p_T, consistent with A_J

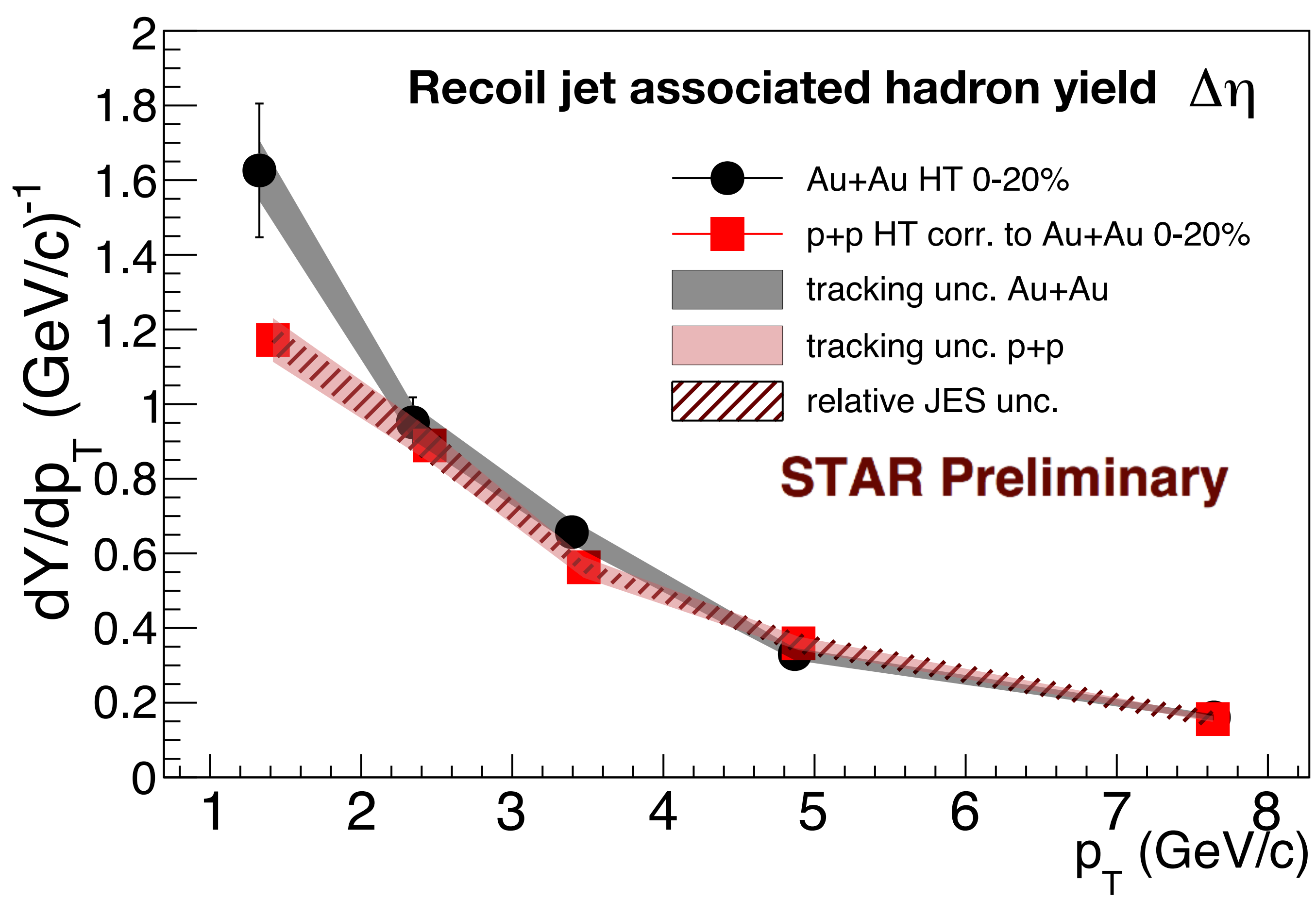
trigger jet: unmodified

→ "surface bias"

recoil jet: hint of modification for p_T^{assoc}<2.0 GeV/c







Consistent with A_J?

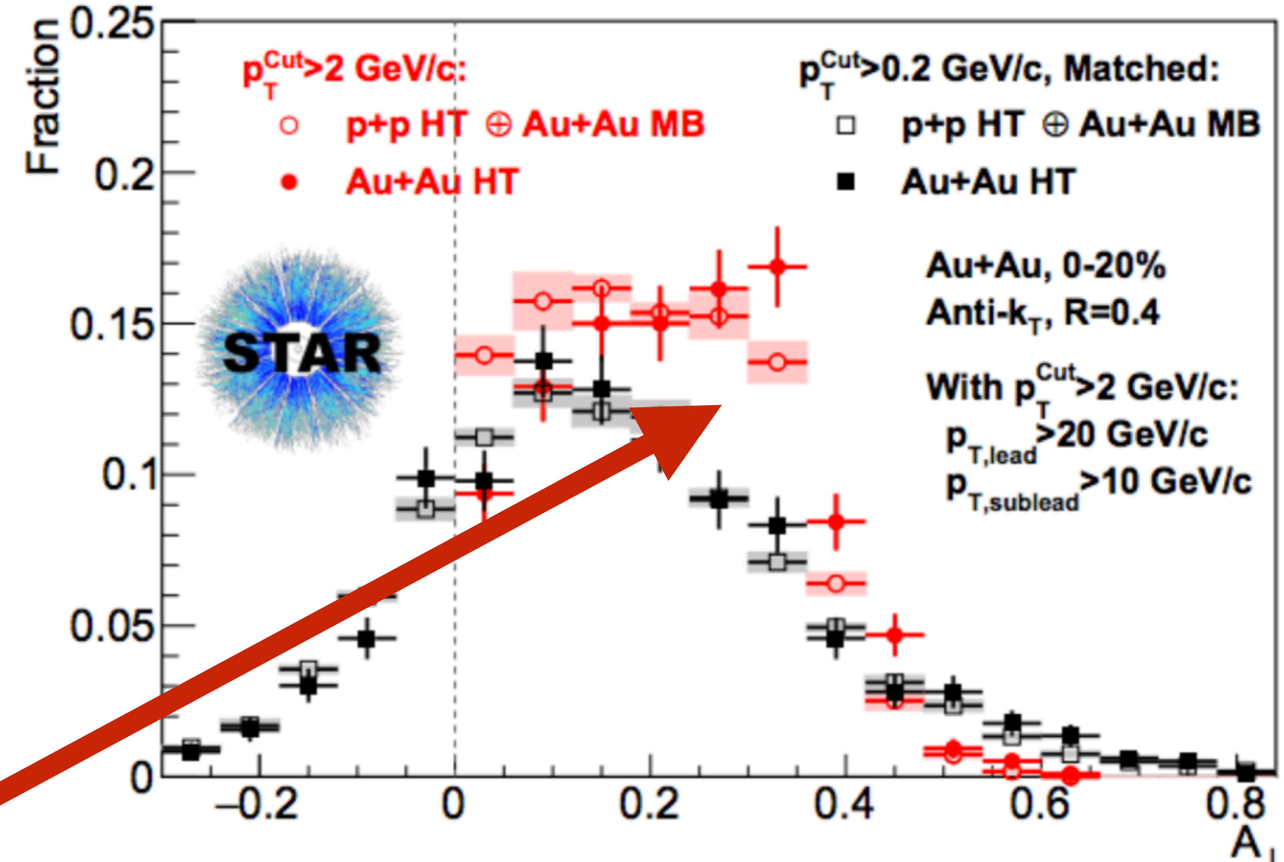
minimal modification at high p_T for both trigger & recoil jets

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?

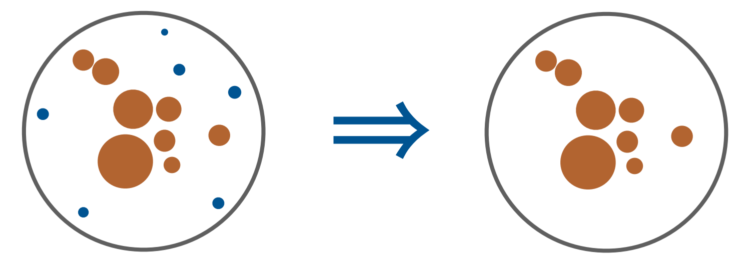


STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

more differential: select on A_J?

Soft-drop grooming

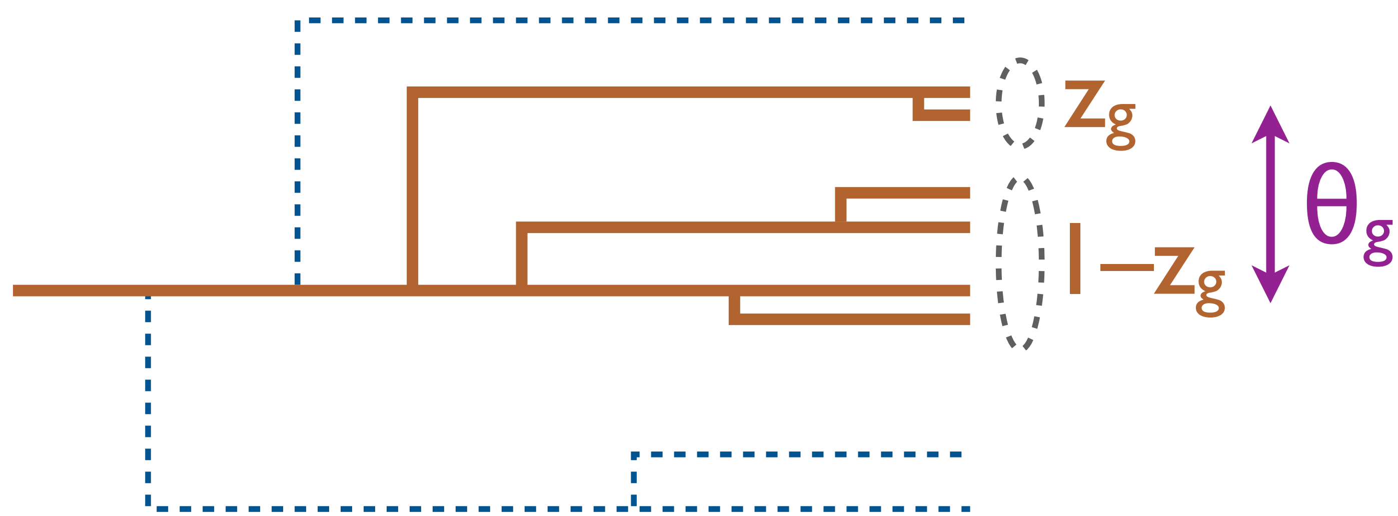
→ remove wide angle, soft radiation



Soft Drop Condition:

$$z > z_{\text{cut}}\, \theta^{\beta}$$

energy threshold (z_{cut}), angular exponent (β)



Based on declustering an angular-ordered tree

Many applications, such as:
groomed energy, groomed radius
pp, jet mass, …
Focus here (with β=0):

"Groomed Momentum Sharing"

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

p_T fraction carried by less-energetic sub-jet after grooming

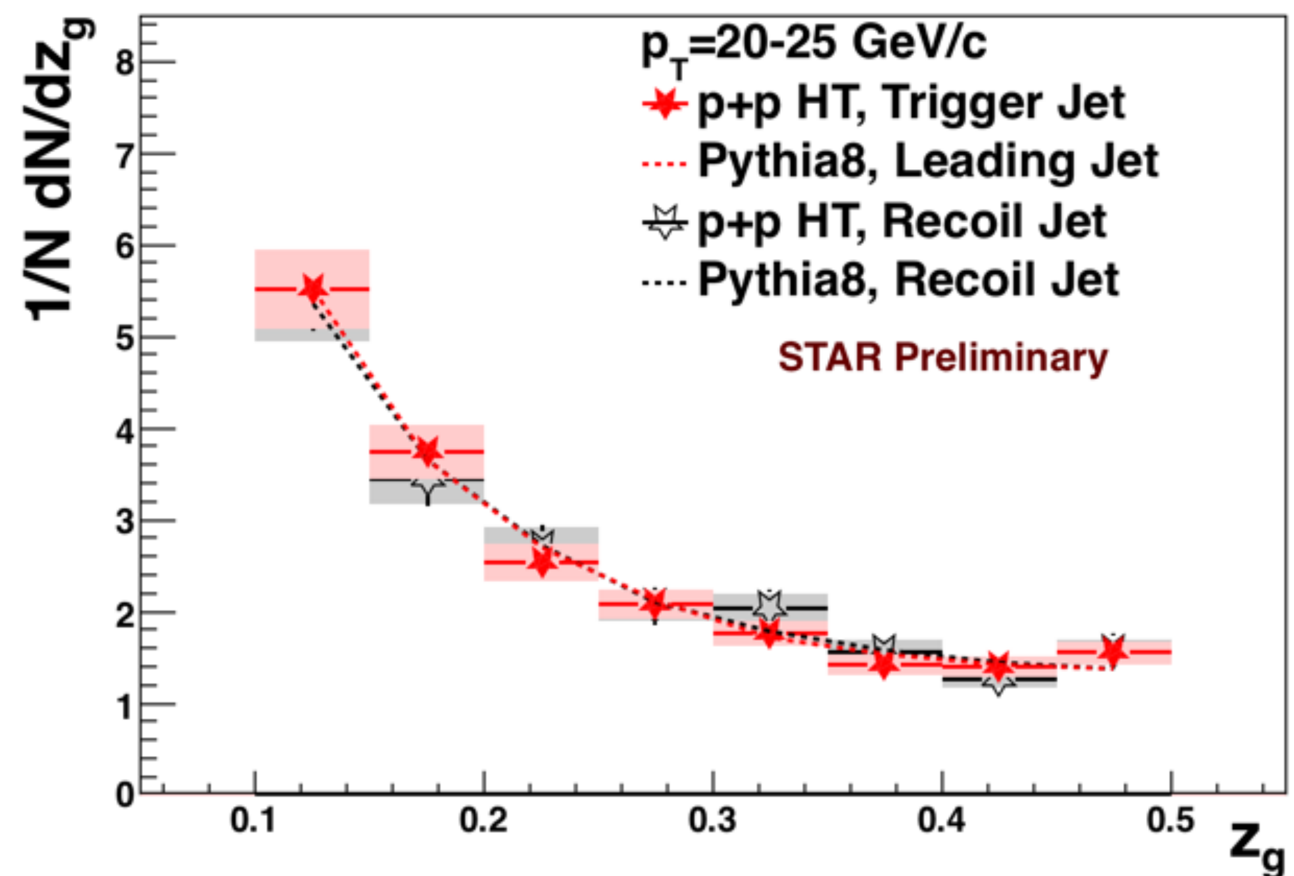
slide from: J. Thaler, ALICE Jet Workshop, Yale,
K. Kauder, LBNL, STAR analysis meeting

Jet shape - z_g

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

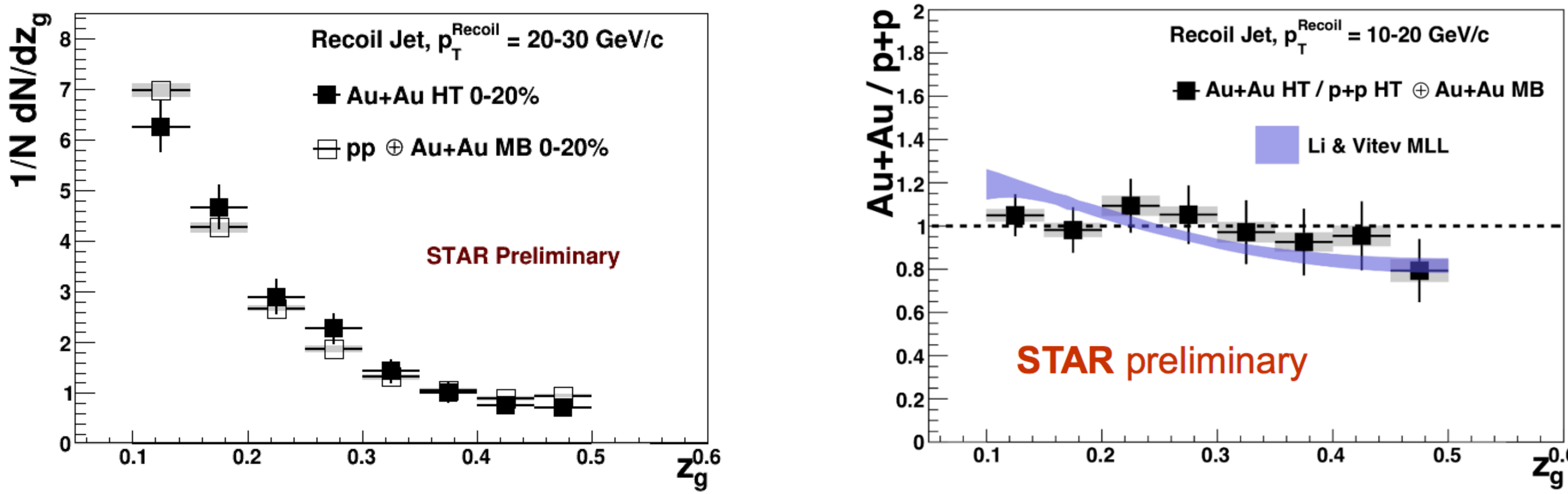
good agreement
between p+p and Pythia

but is there measurable
modification in the hard core
di-jets?



Jet shape - z_g

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



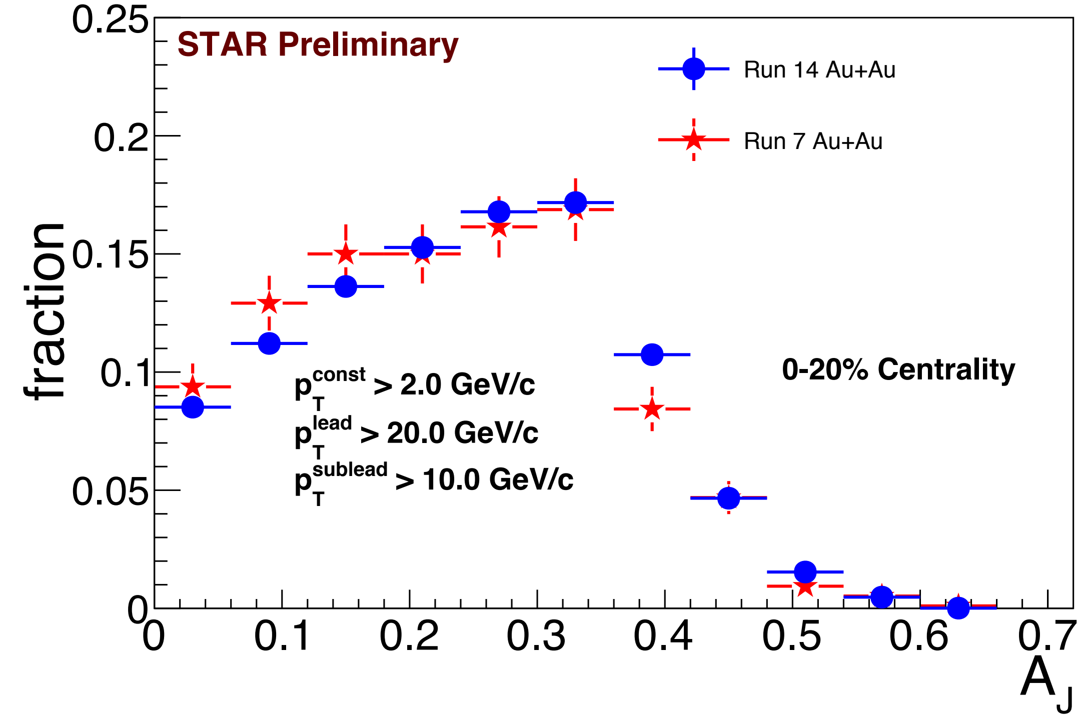
Li & Vitev arXiv: 1801.00008

compare recoil jets in central Au+Au and p+p

no modification of z_g for hard
core selected recoil (and trigger) jets

Differential di-jet asymmetry

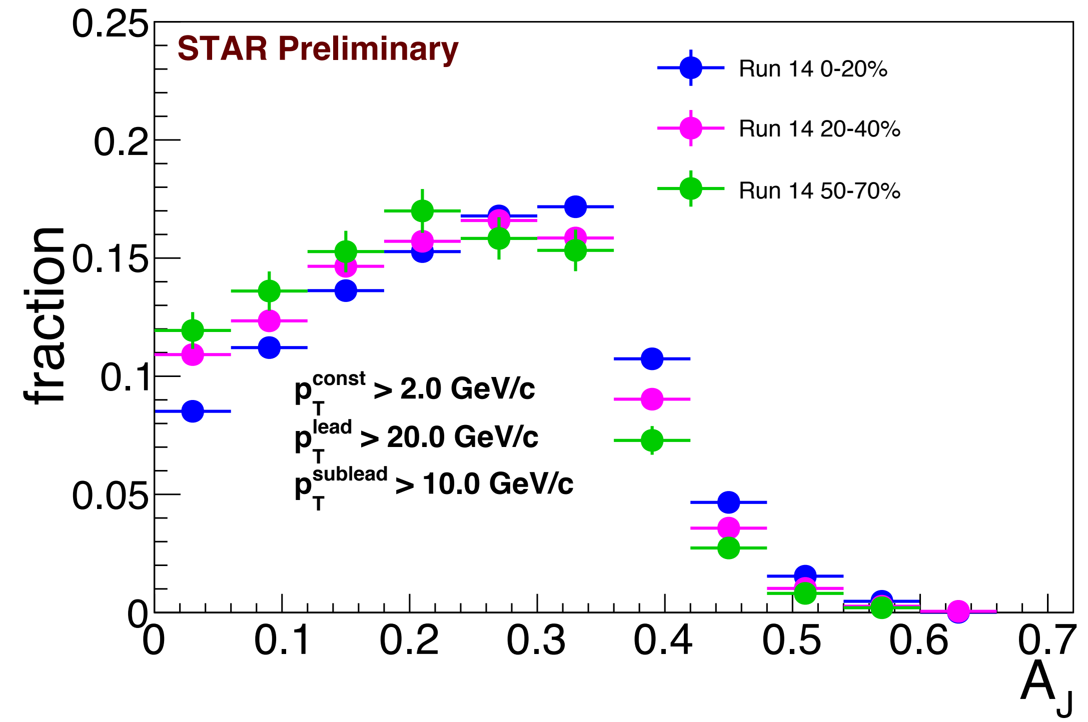
STAR Run 14 ⟶ 20x increase in di-jet pairs allows for differential A_J measurement



Goals

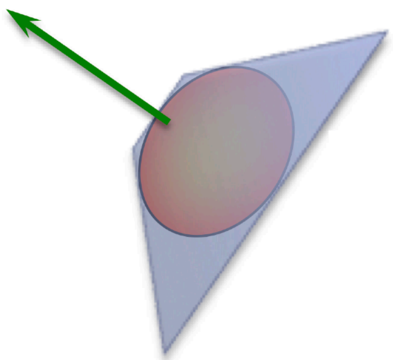
centrality dependence of A_J

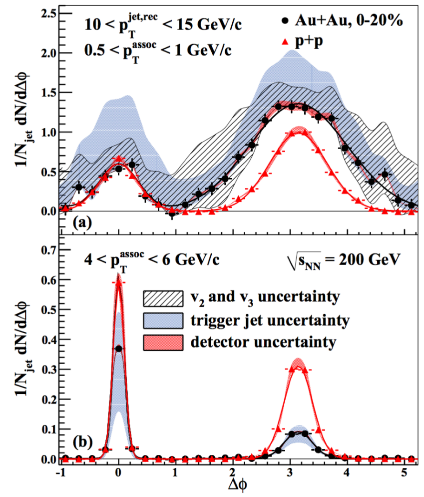
scan parameter space (R, p_T^{Lead}, p_T^{Sub}, p_T^{Const})

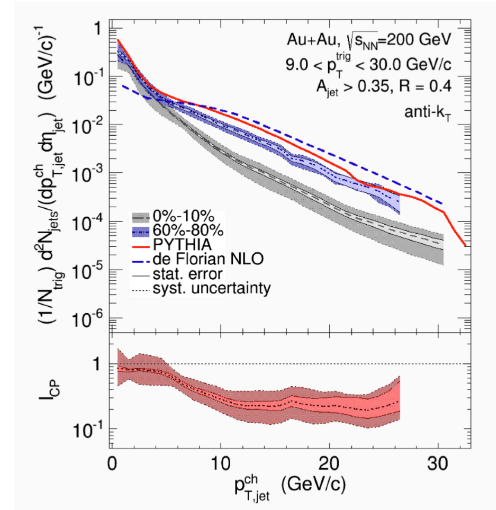


→ "jet geometry engineering"

Nick Elsey, RHIC AGS Users Meeting 2018, BNL

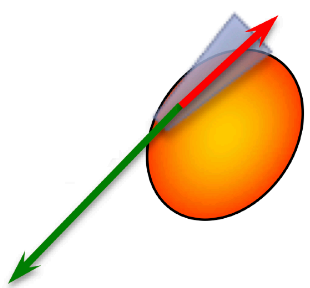


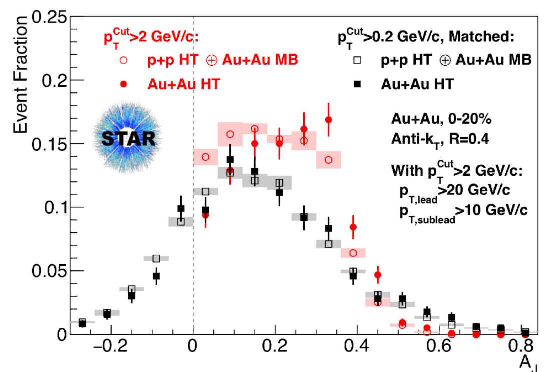


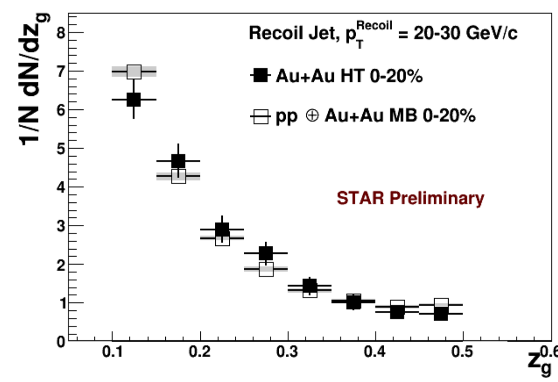


Summary

“softening” (p_T < 2 GeV) & broadening beyond R=0.4







modified hard core di-jet pairs (softening & broadening)

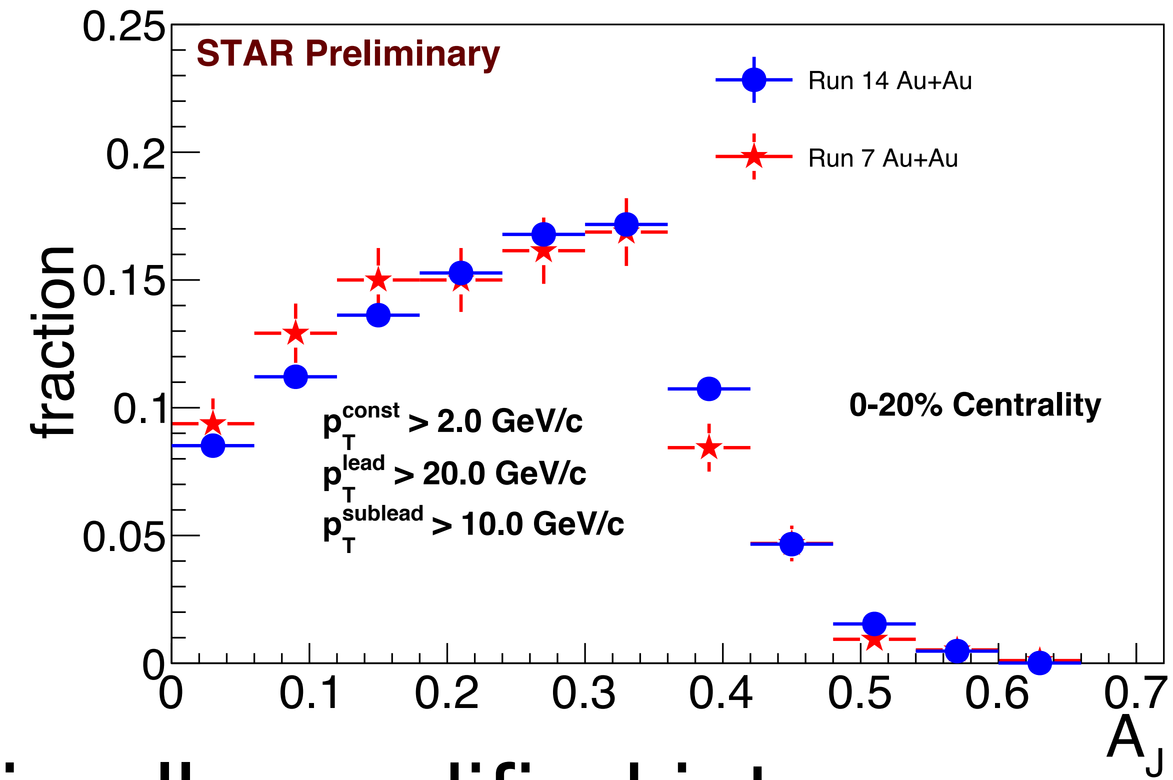
energy recovered in narrow cone (R=0.4)

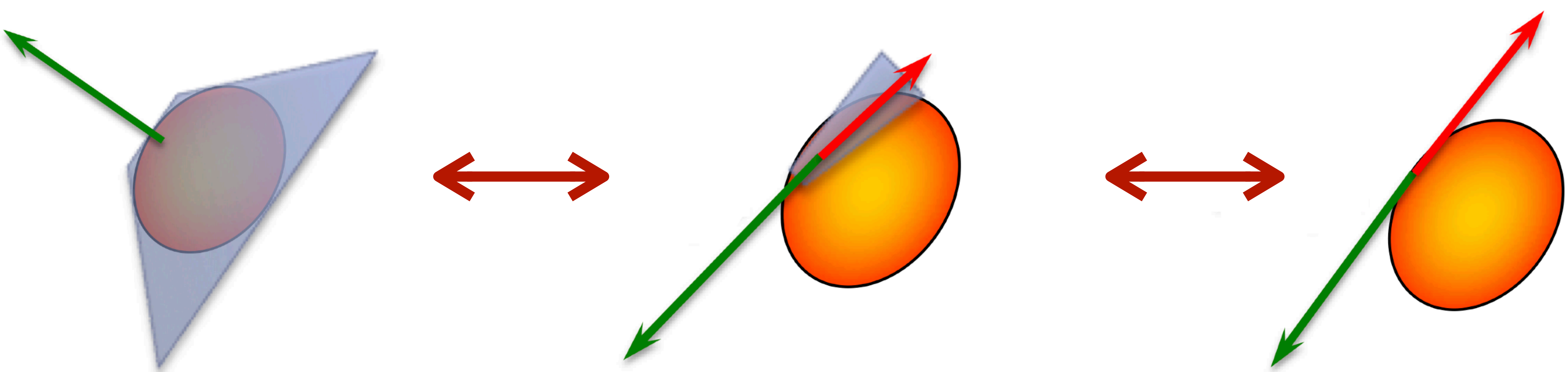
no modification seen in z_g; indicates split/shower outside medium (formation time)

→ 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 (enhancement at fixed p_T < 2 GeV) in the QGP.

Future

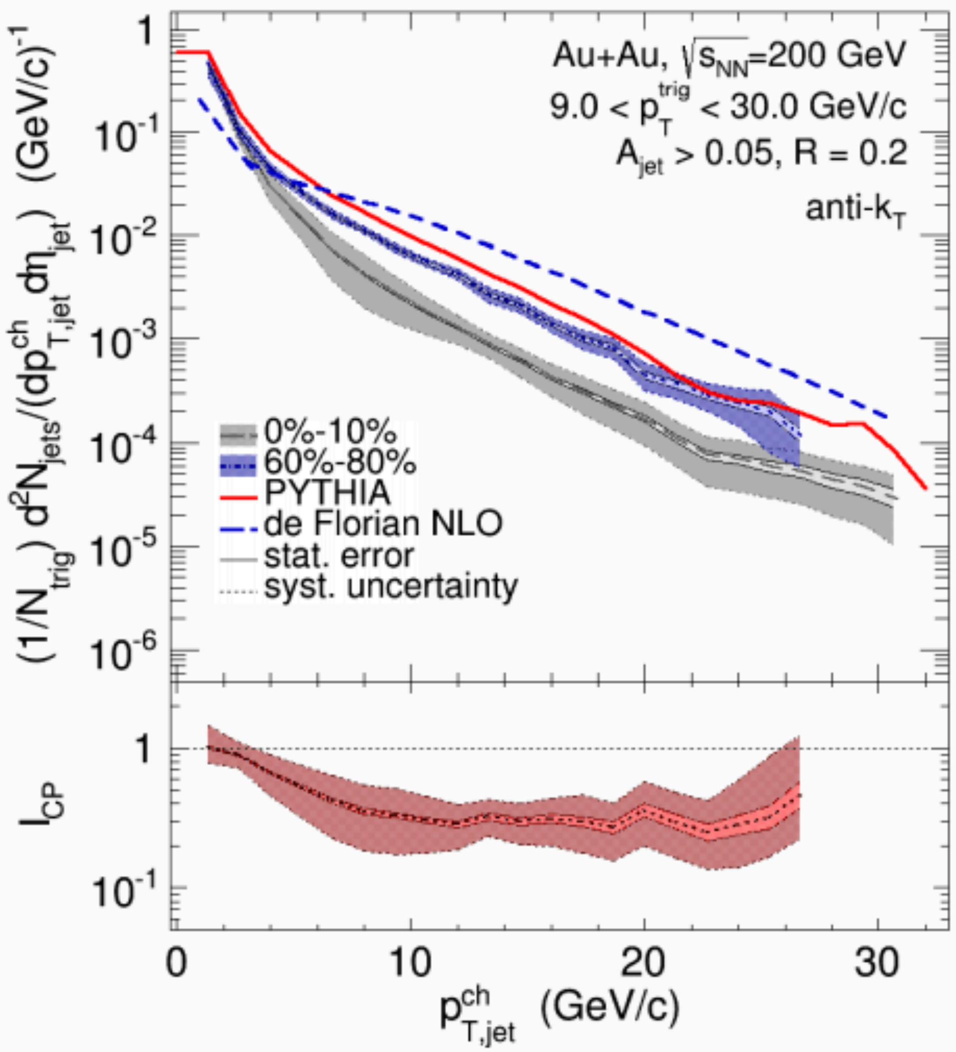
- new, large dataset
- differential measurements
- scan from minimally to maximally modified jets, connect biased and unbiased measurements
- strongly constrain energy loss models

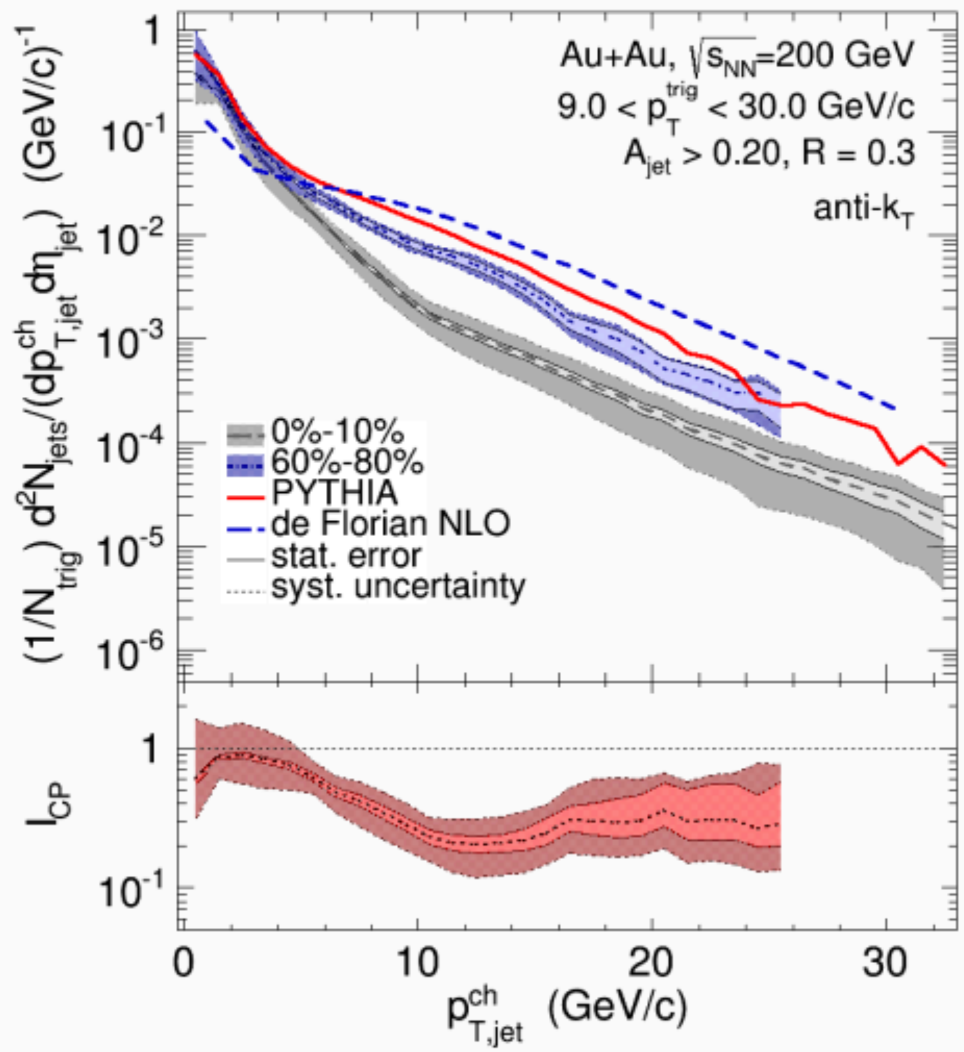




Thank you :)

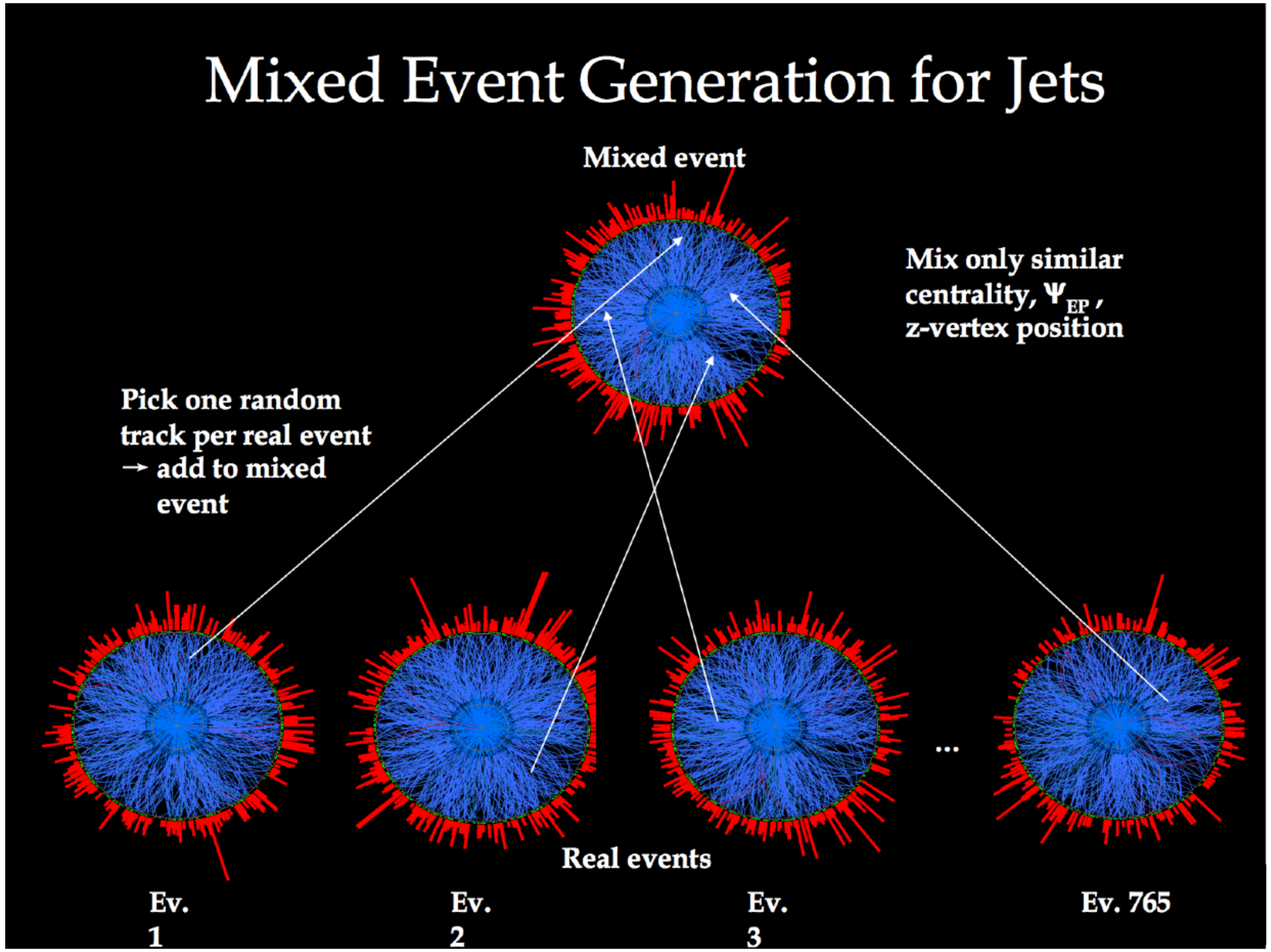
Hadron+jet - differing R





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

Hadron+jet - event mixing



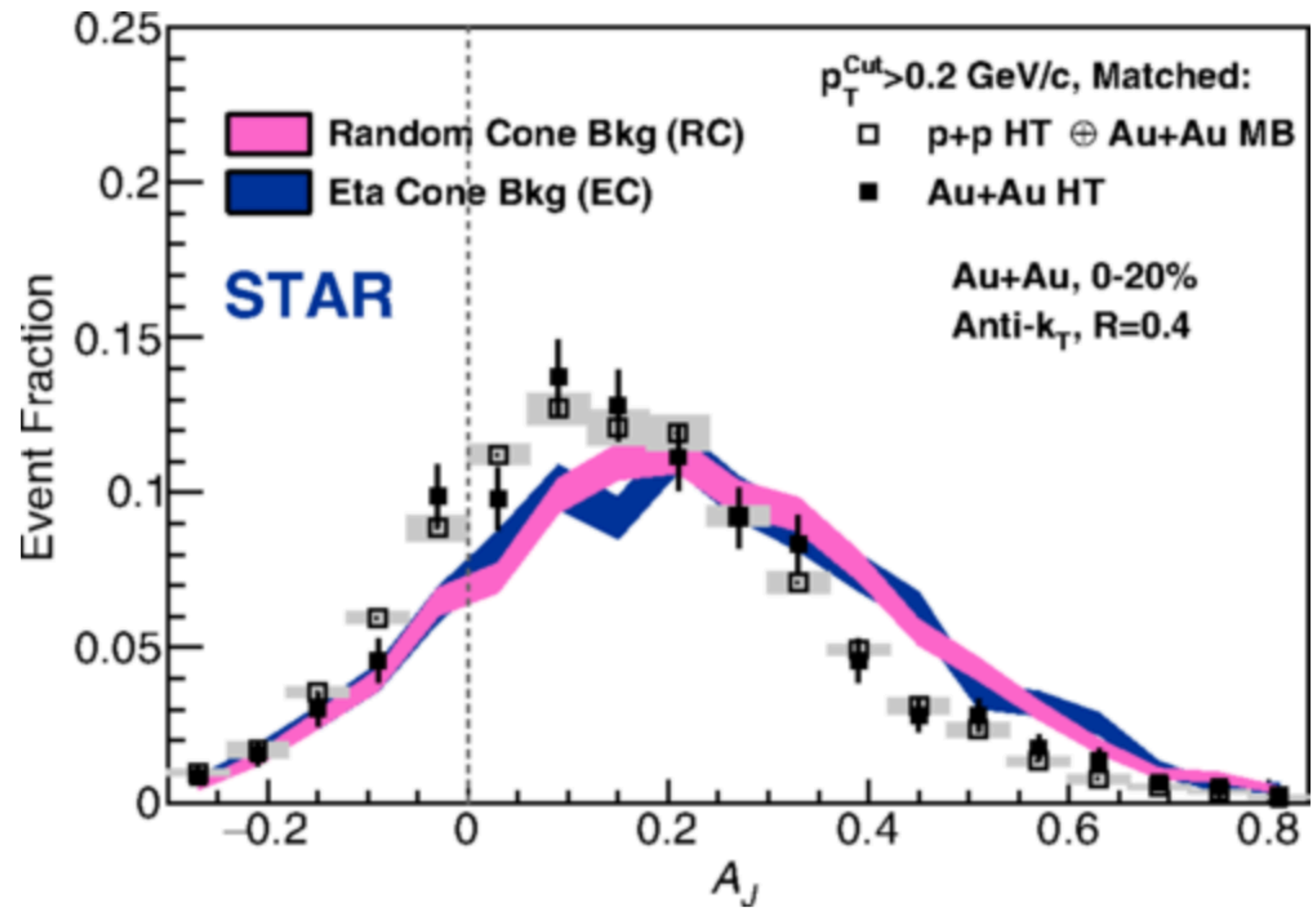
Schmah, Symposium on Jet & Electromagnetic Tomography of Dense Matter, 2015

these events only carry information about background fluctuations, and can be used to estimate background contribution to jet distribution

Di-jet imbalance & effect of background

can background fluctuations balance jets to p+p level?

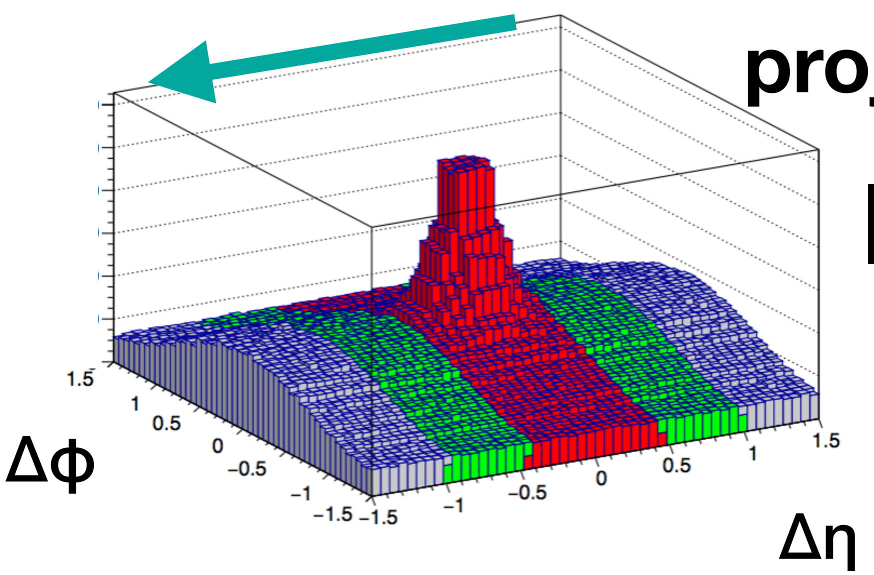
A_J calculated with random eta cone, balance **not** recovered to p+p level



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

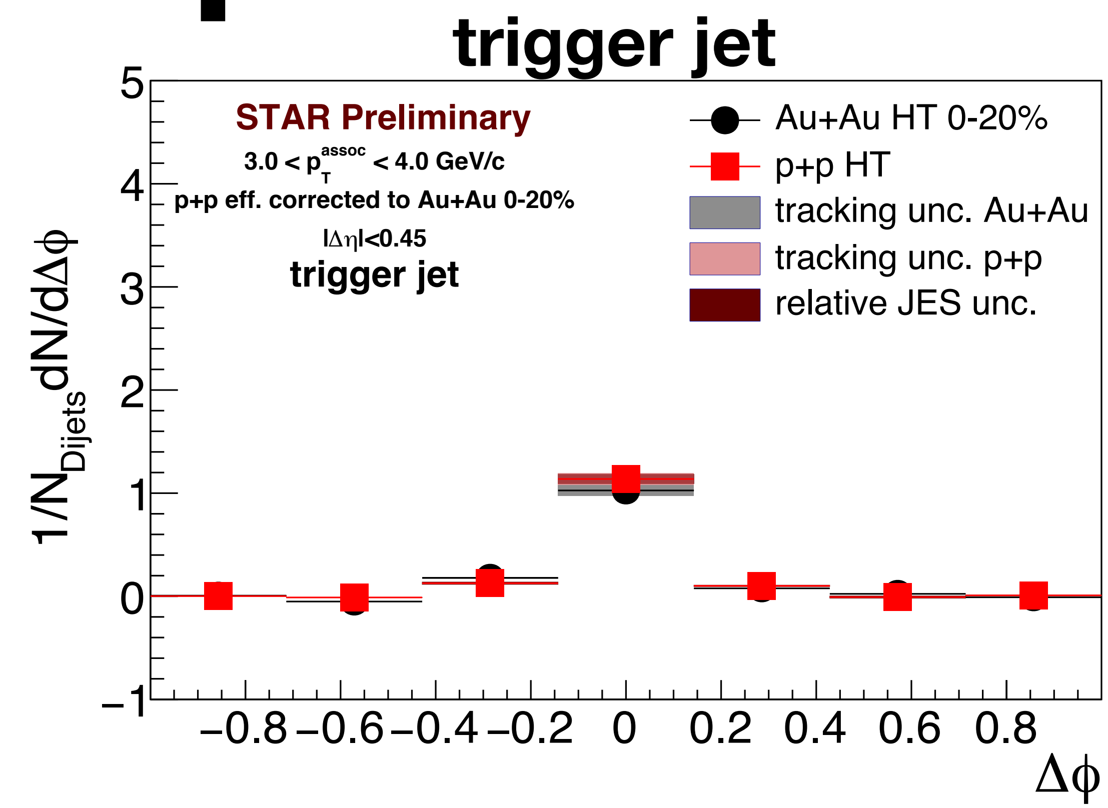
Correlations in Δϕ

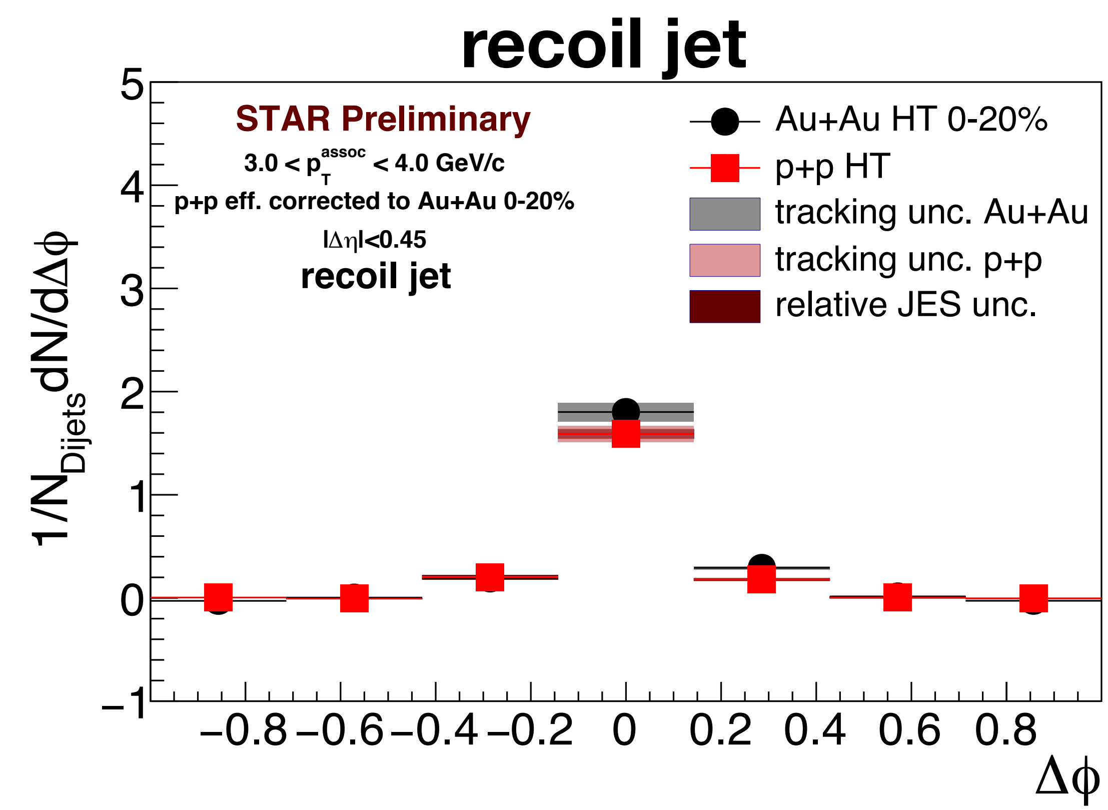
$3.0 < p_T^{assoc} < 4.0$ GeV/c



projection range

|Δη| < 0.45

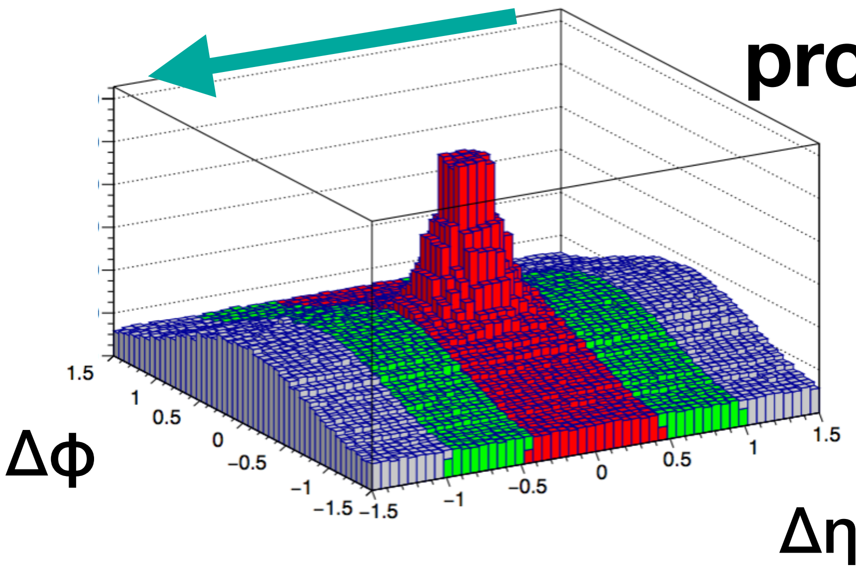




- **yield contained within jet radius R=0.4**
- **similar to Δη ~ circular jets**

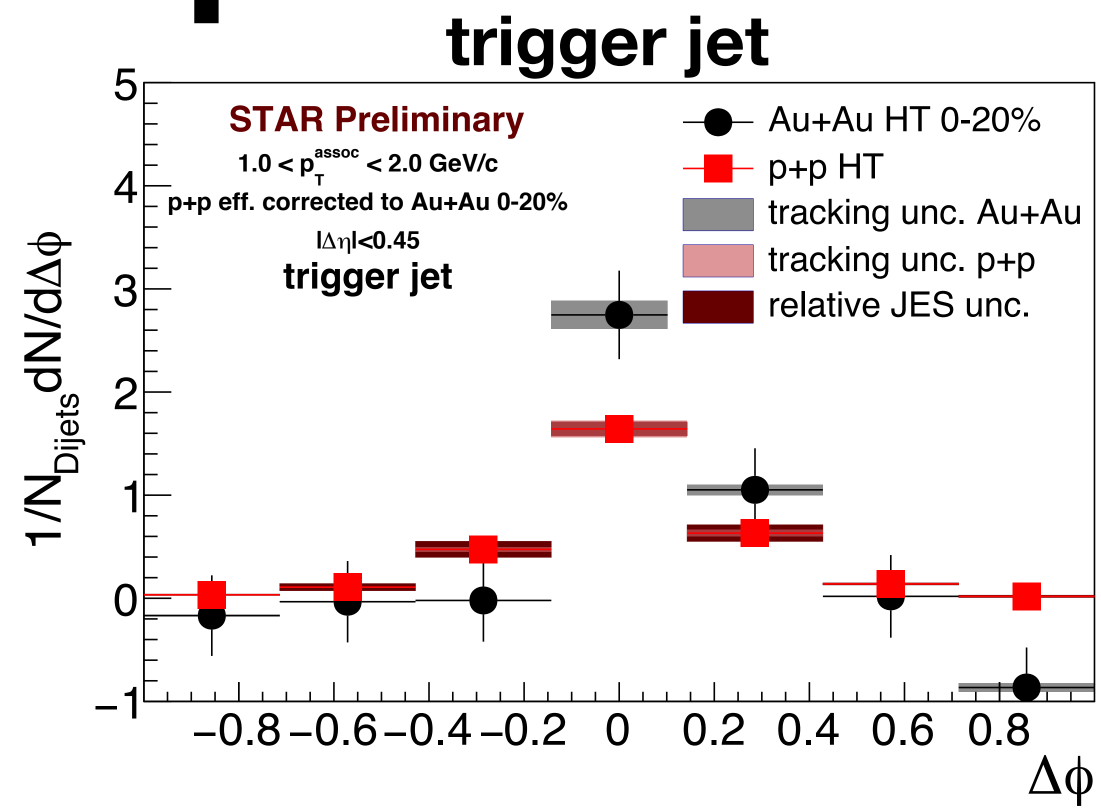
Correlations in Δφ

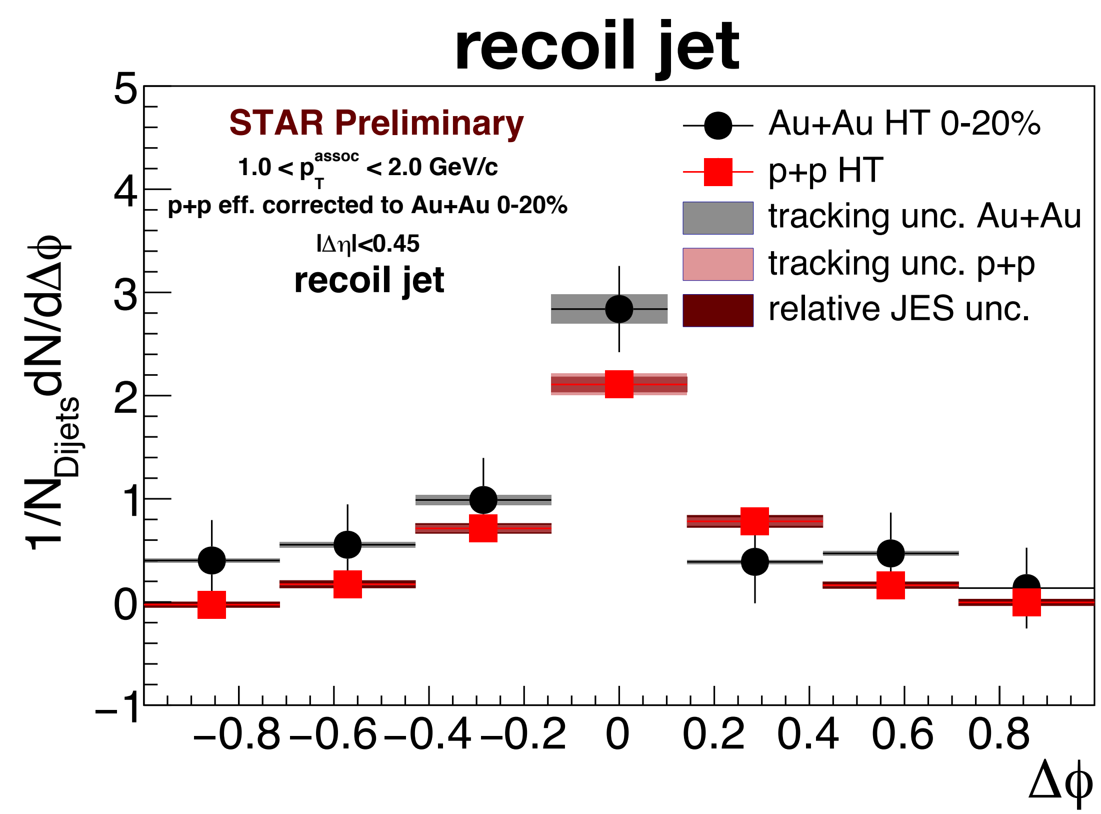
$1.0 < p_T^{assoc} < 2.0$ GeV/c



projection range

$|\Delta\eta| < 0.45$





- **yield contained within jet radius R=0.4**
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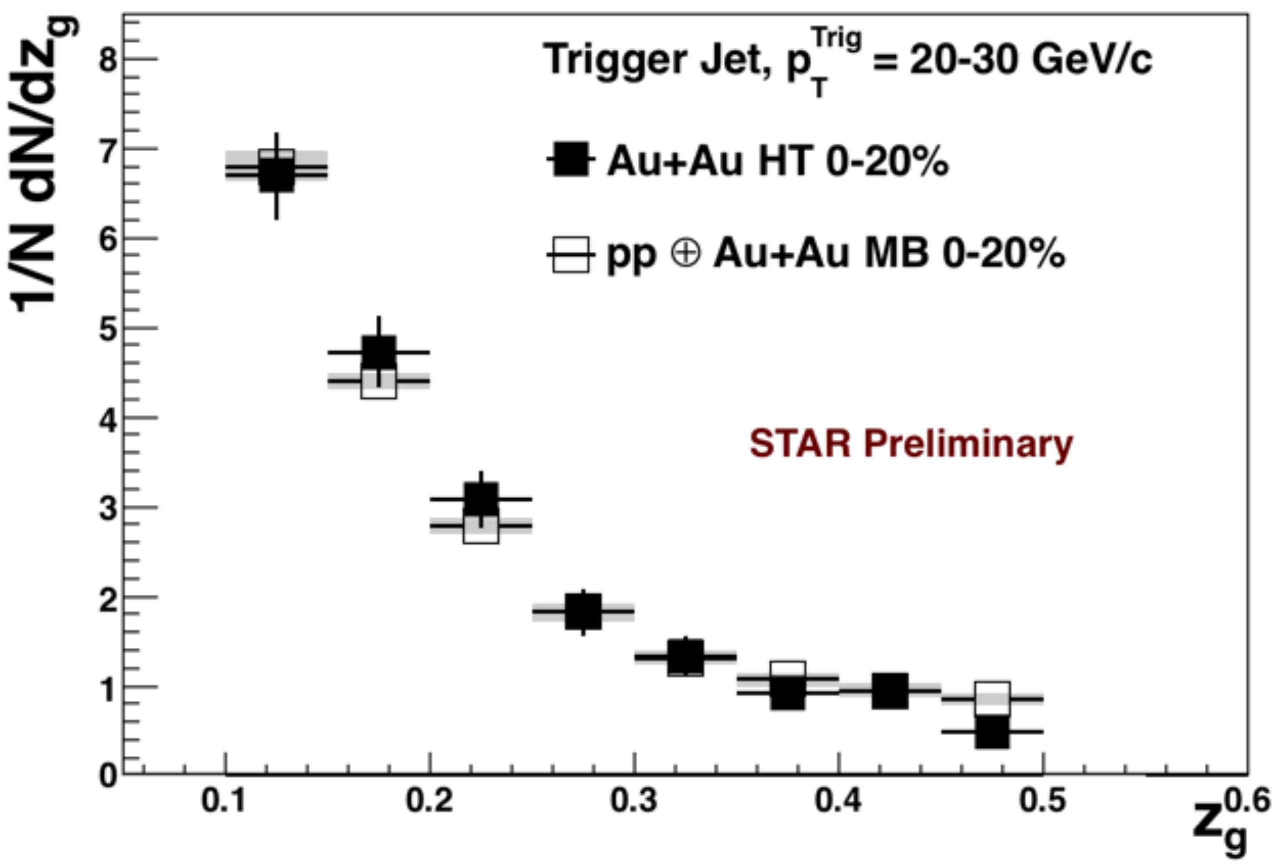
Further z_g results



no significant modification of
hard core selected trigger jets
in Au+Au

Nick Elsey, RHIC AGS Users Meeting 2018, BNL

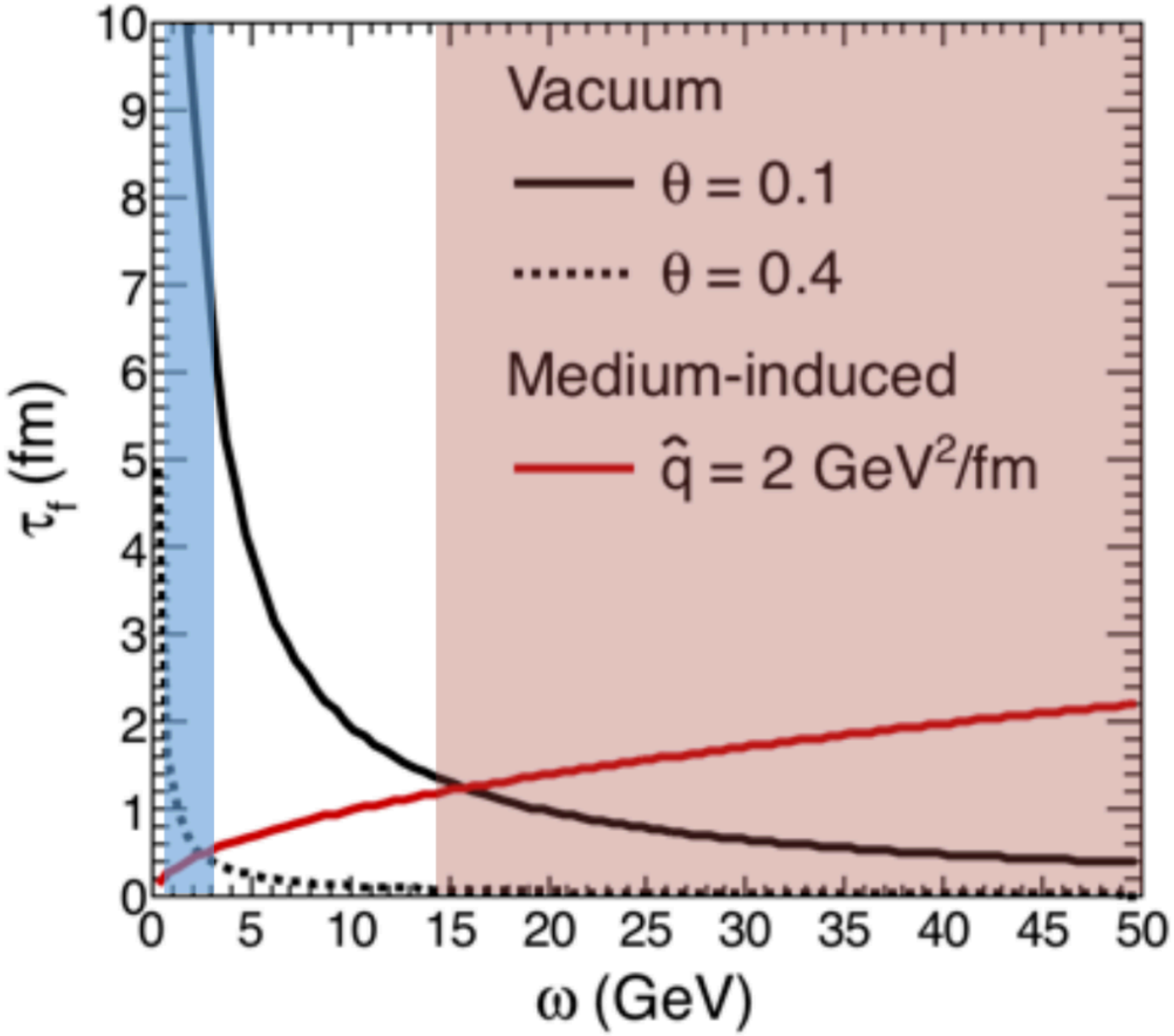
Z_g and Formation Time

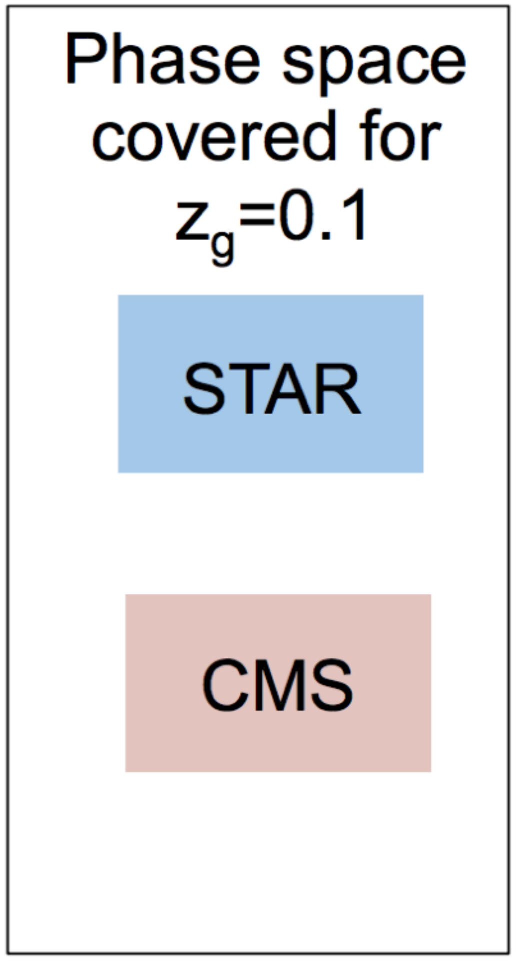
Vacuum and medium formation times

Hard medium-induced radiation happens late in the shower

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$





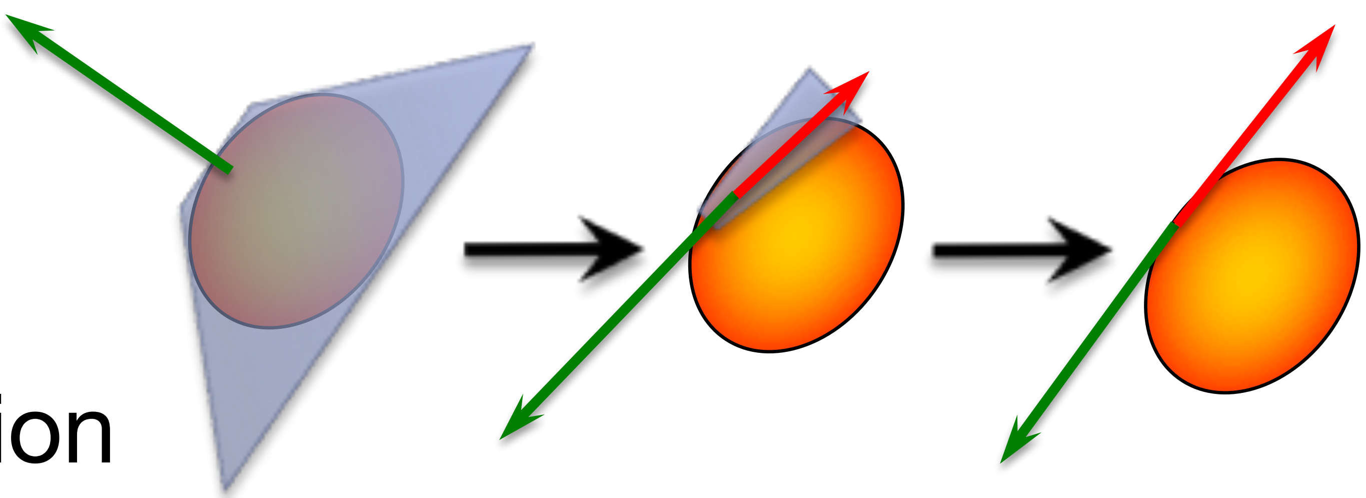
At RHIC can only see medium for rare large angle emissions or even splittings. Larger z_{cut} and/or ΔR_{12} selection would increase sensitivity

Conclusions

- qualitatively consistent picture of energy loss measured in jet+hadron, hadron+jet, di-jet imbalance
- yield enhancement at low p_T, suppression at high p_T
- in hard core di-jets, no significant broadening or modification in z_g

towards the future:

differential selection of jets based on geometry



- directly measure attenuation
- strongly constrain energy loss models
- systematically connect our biased and unbiased measurements