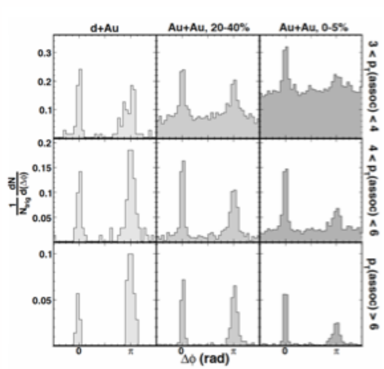
Di-Jet Imbalance Measurements and Semi-Inclusive Recoil Jet Distributions in Central Au+Au Collisions in STAR

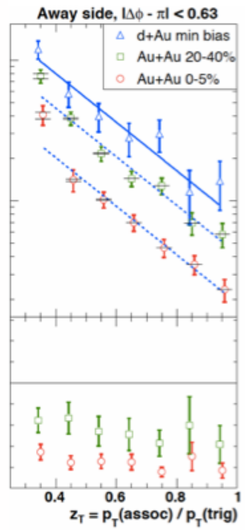
Jörn Putschke
for the STAR Collaboration
(Wayne State University)

Jet Quenching via triggered correlations at RHIC

Di-hadron

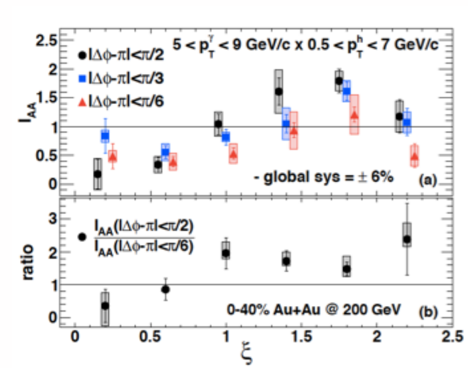
STAR, PRL ***97****, 162301 (2006)*

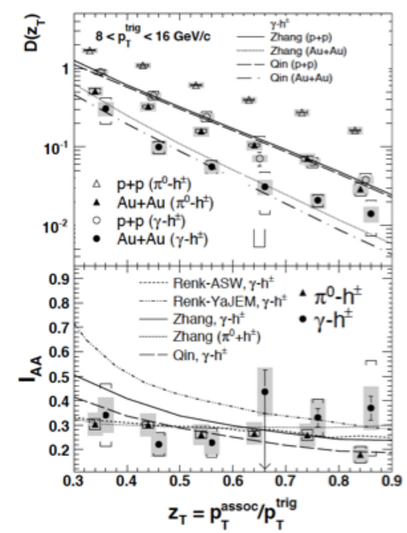




γ-hadron

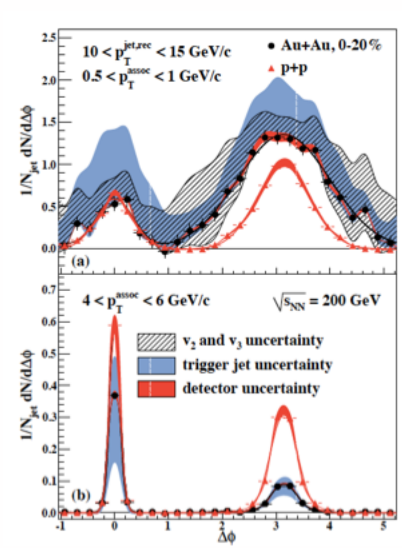
STAR, PRC ***82****, 034909 (2010)*
PHENIX, PRL ***111****, 032301 (2013)*

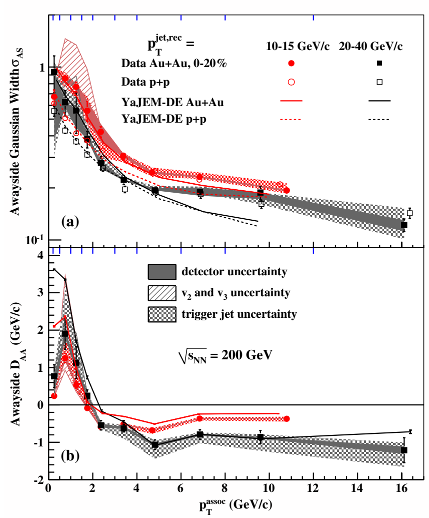




Jet-hadron

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





Different triggers → different biases

Observations:

- high-z suppression
- low-z enhancement
- *modest* azimuthal broadening at low p_T

Jet Quenching via triggered correlations at RHIC

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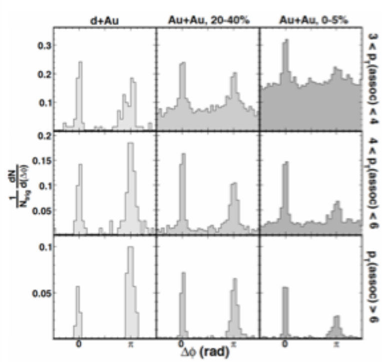

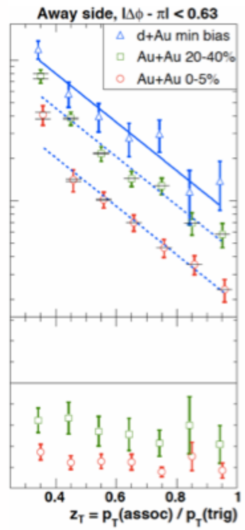

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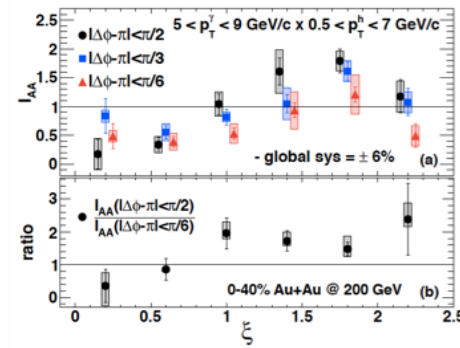

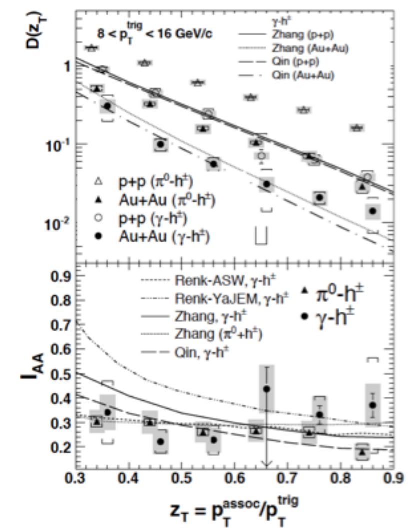

Jet-hadron

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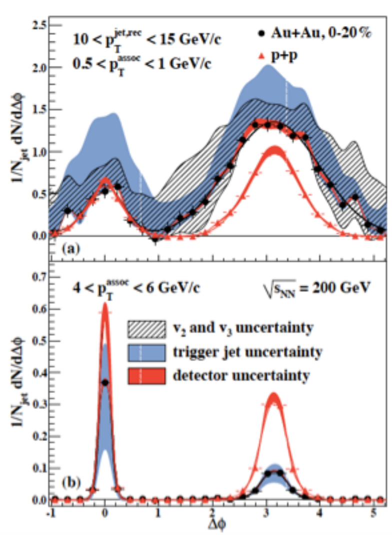
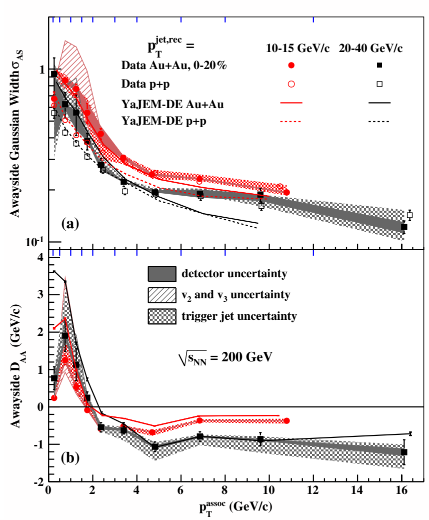




Different triggers → different biases

Observations:

- high-z suppression
- low-z enhancement
- *modest* azimuthal broadening at low p_T

But recoil hadrons only probe jet structure *statistically*!

Next Chapter:

Reconstruction of recoil jets;
again utilize different triggers and biases

Jets in STAR

Online Trigger
E_T > 5.4 GeV
in one tower
$\Delta\phi \times \Delta\eta = 0.05 \times 0.05$

<u>Data sets:</u>

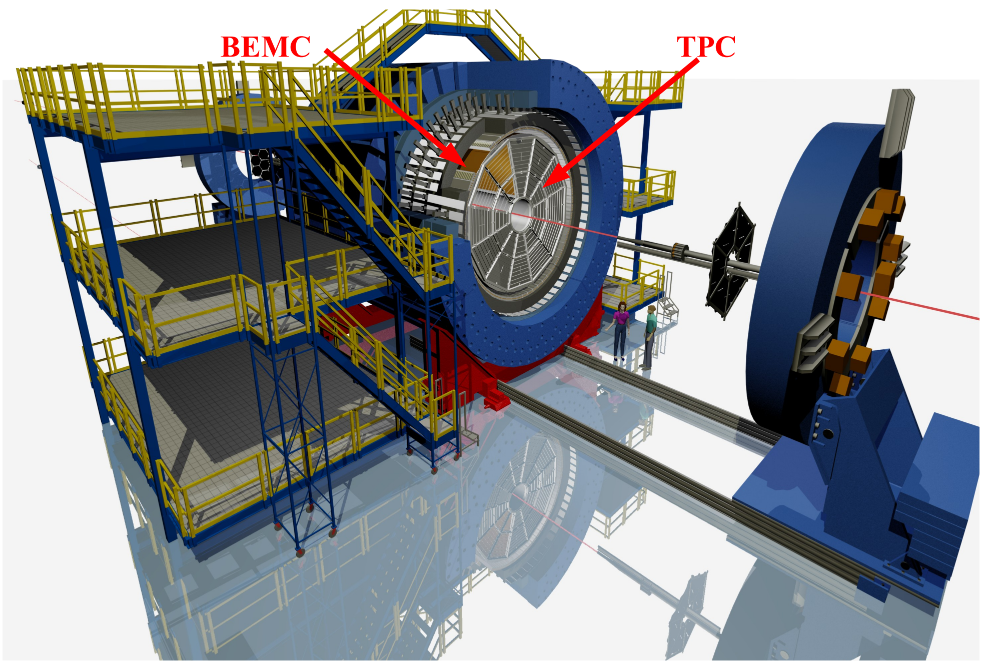
(i) Run 7 Au+Au and Run 6 p+p
$\sqrt{s_{NN}}$ = 200 GeV, High Tower (HT) Trigger
TPC+BEMC (charged+neutral) → ***Di-Jet Imbalance A_J***

(ii) Run 11 Au+Au $\sqrt{s_{NN}}$ = 200 GeV Minimum Bias
TPC (charged only in this analysis)
→ ***Recoil Jets***

<u>Jet-Finding Algorithm:</u>

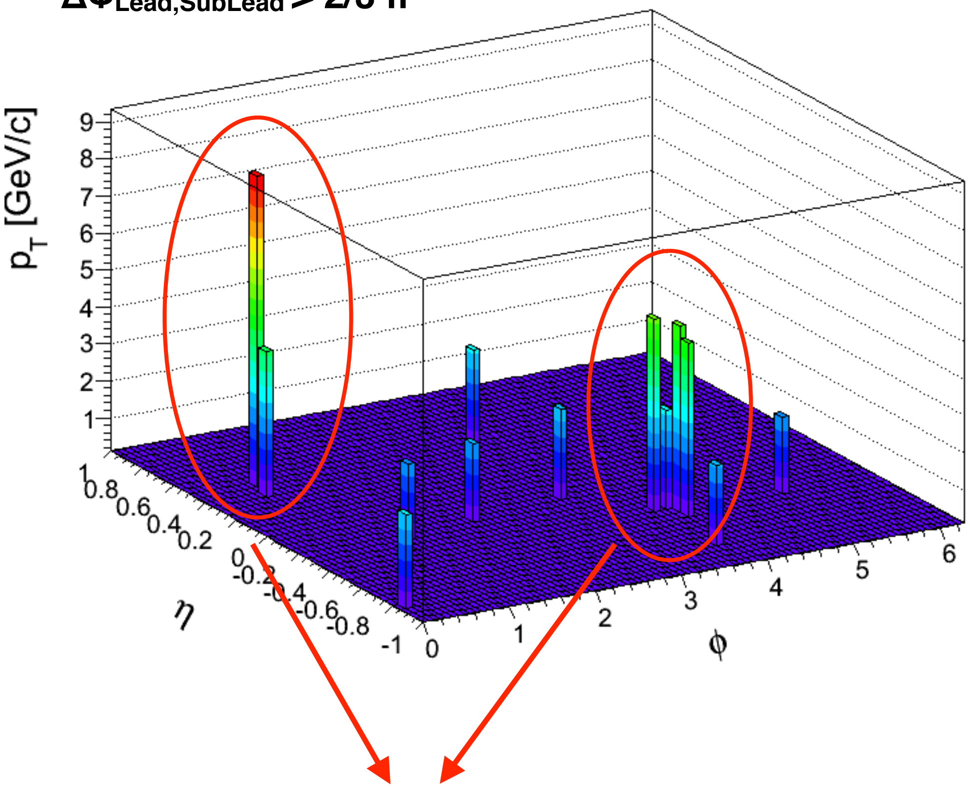
Anti-k_T algorithm (R=0.2-0.4)

M. Cacciari and G. Salam
*Phys. Lett. B **641**, 57 (2006)*



A_J: (Biased) Di-Jet Selection and "Notation"

$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π



Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

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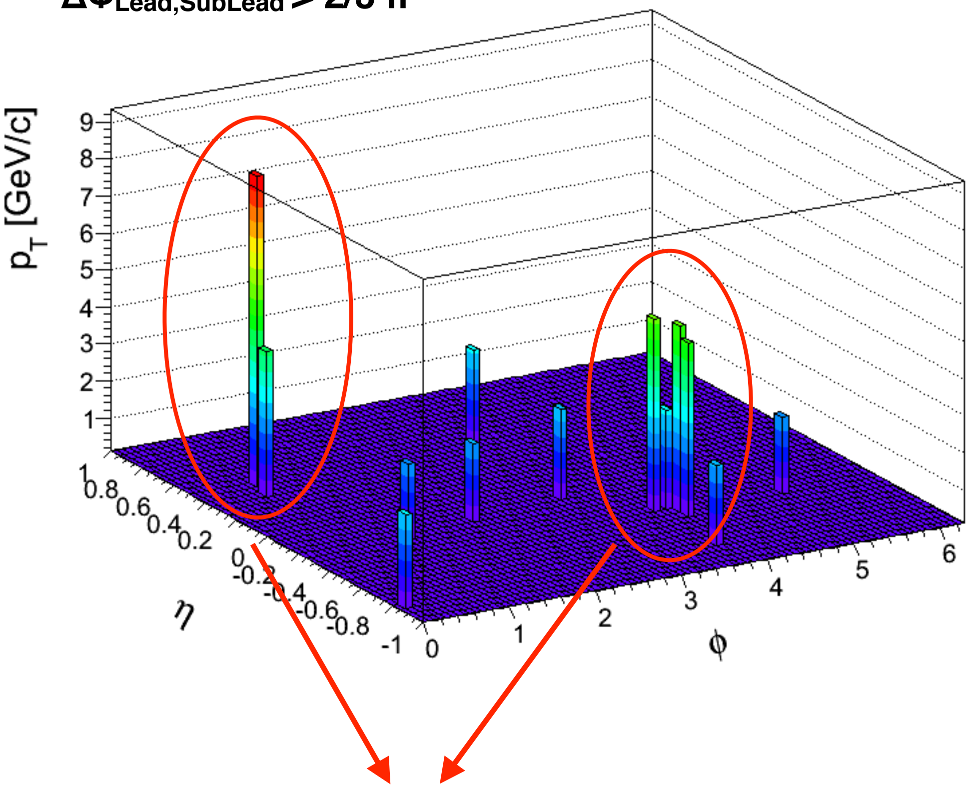

Rerun jet-finding algorithm anti-k_T on these events ...

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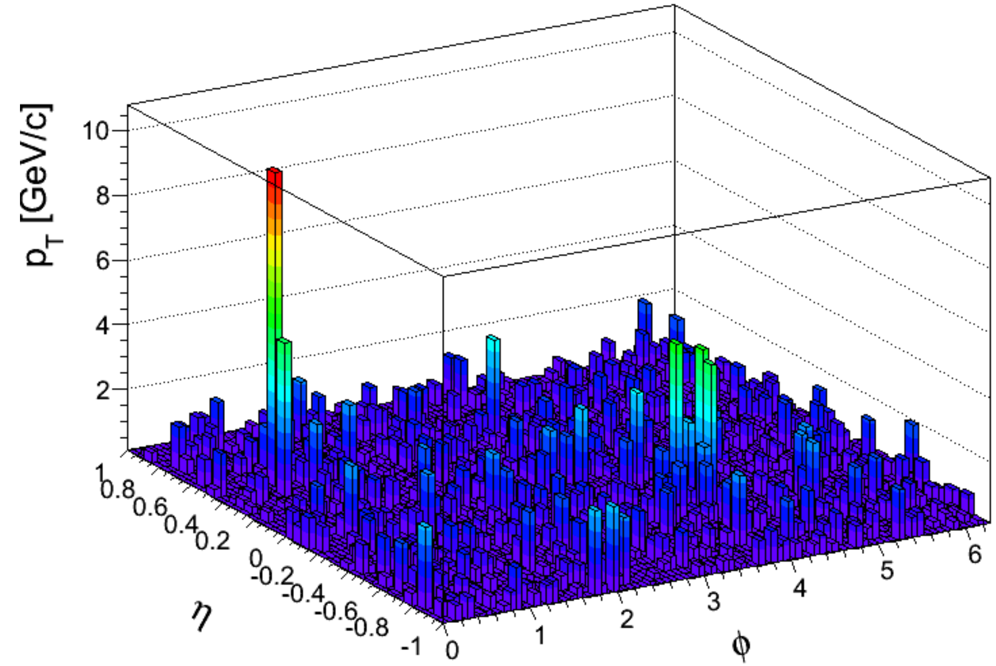

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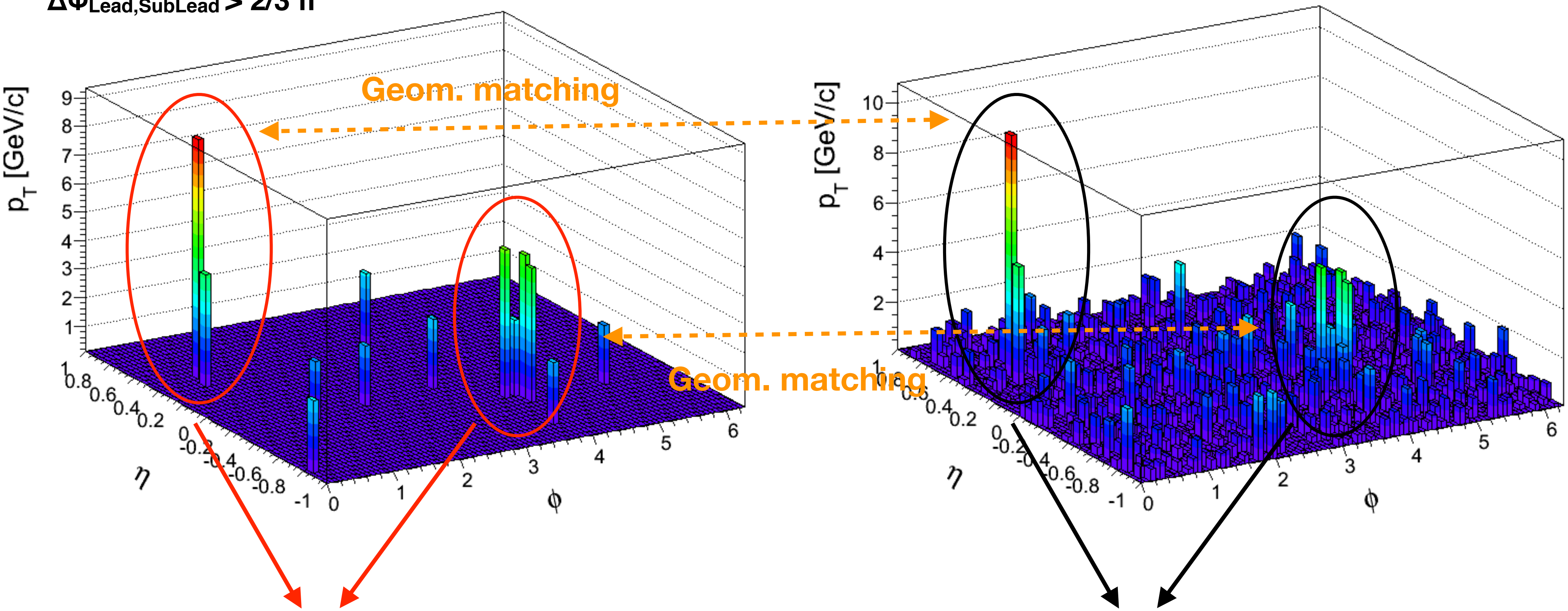

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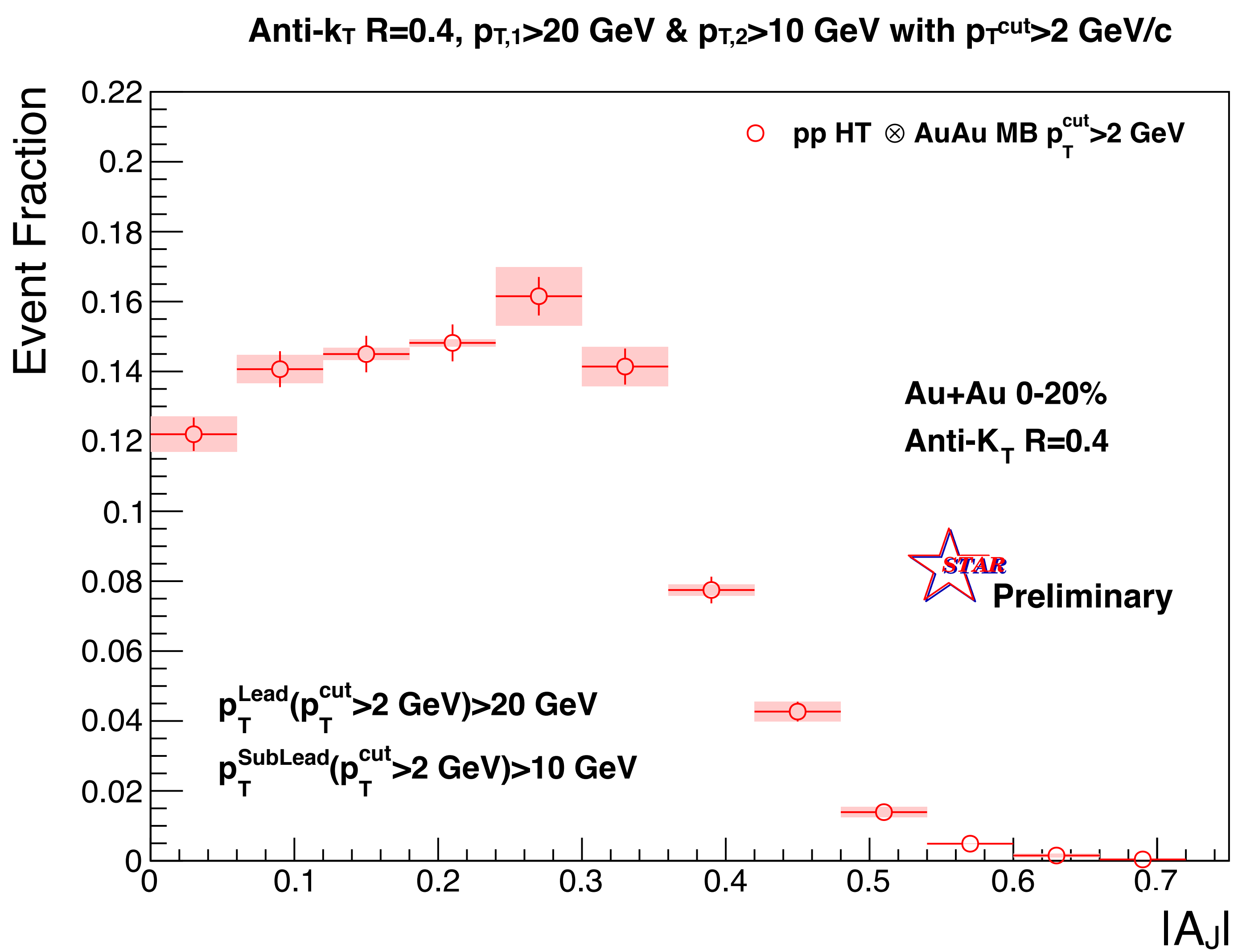
Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

Di-Jet Imbalance A_J Au+Au 0-20% R=0.4



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

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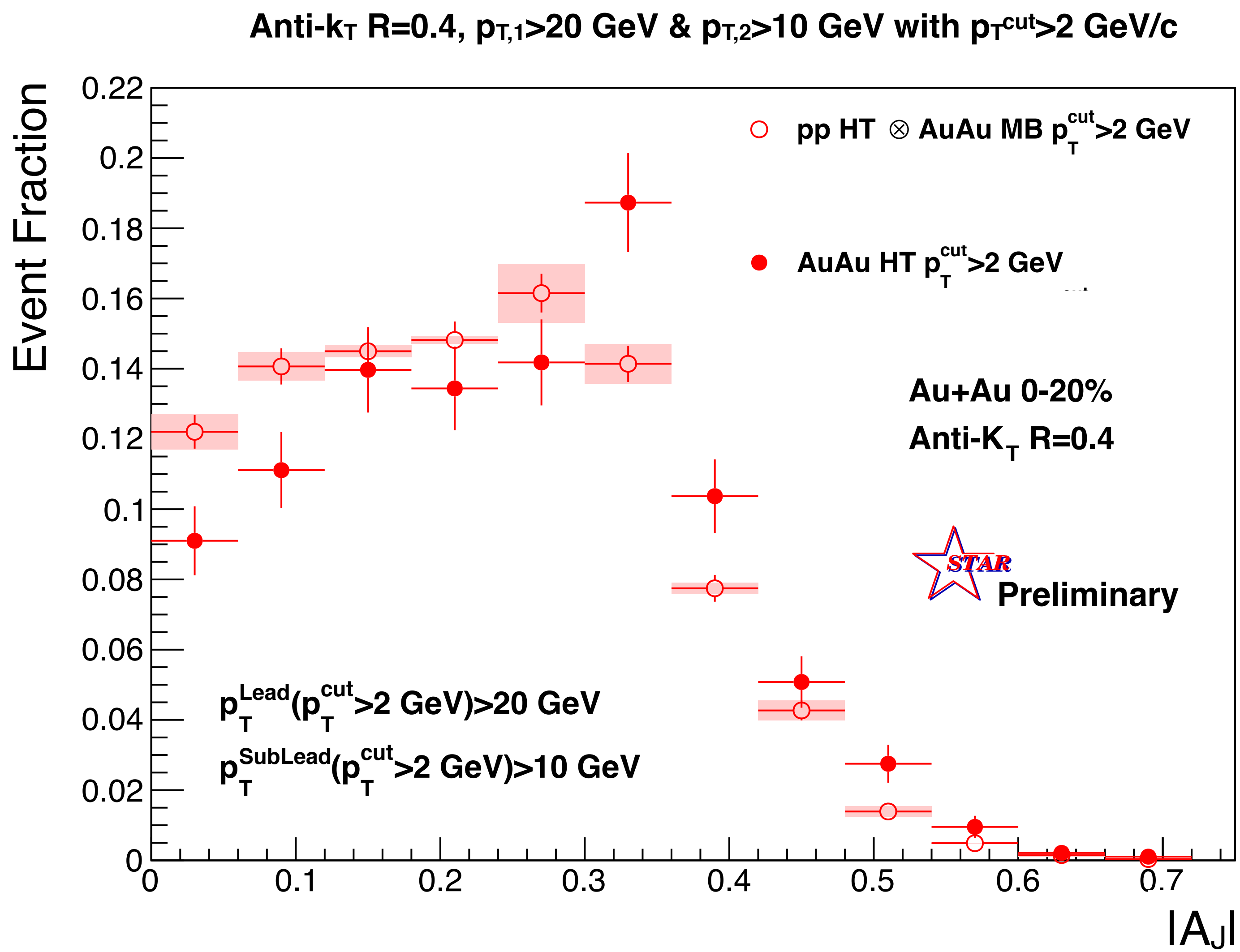

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p-value<10^{-5}
(stat. error only)

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

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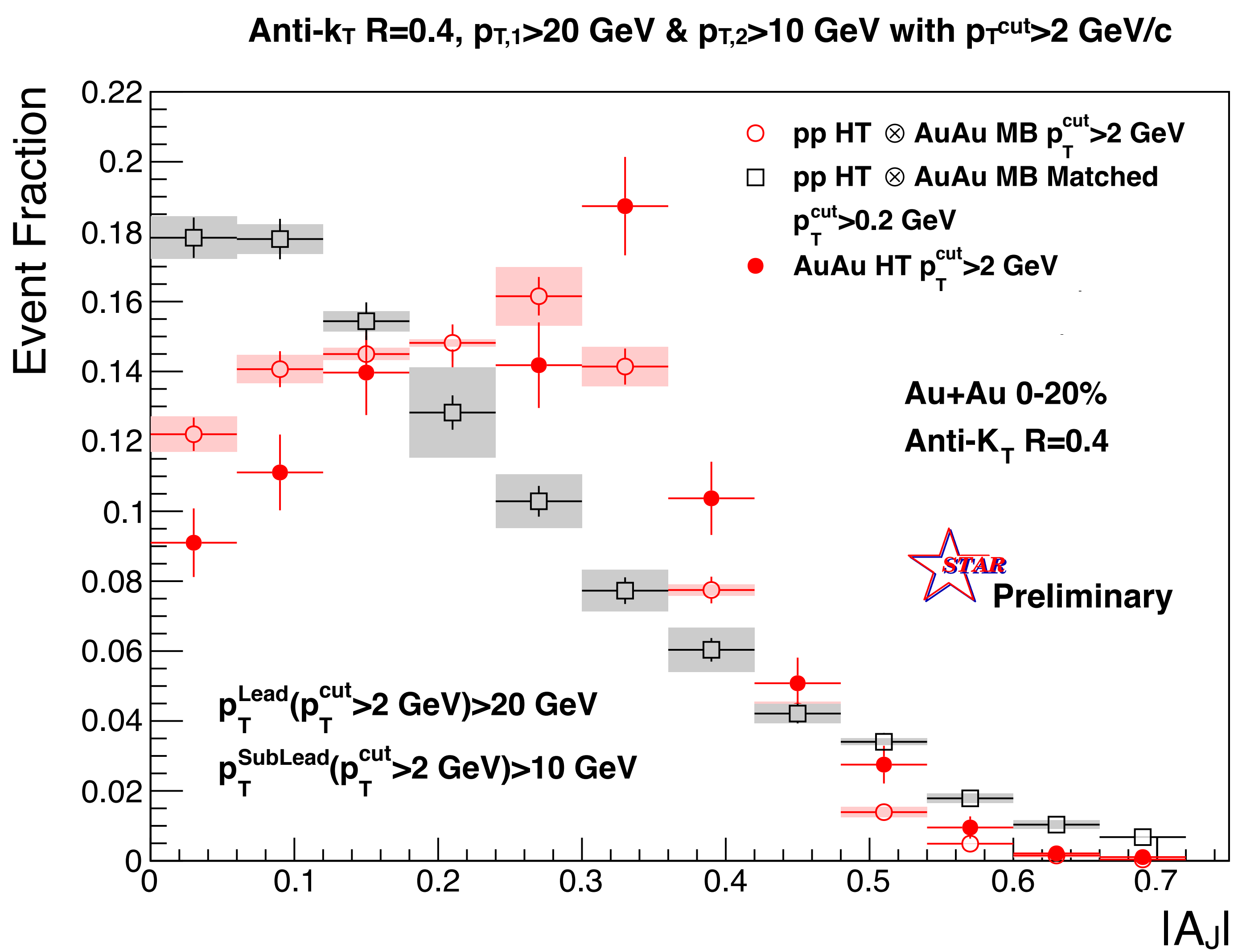

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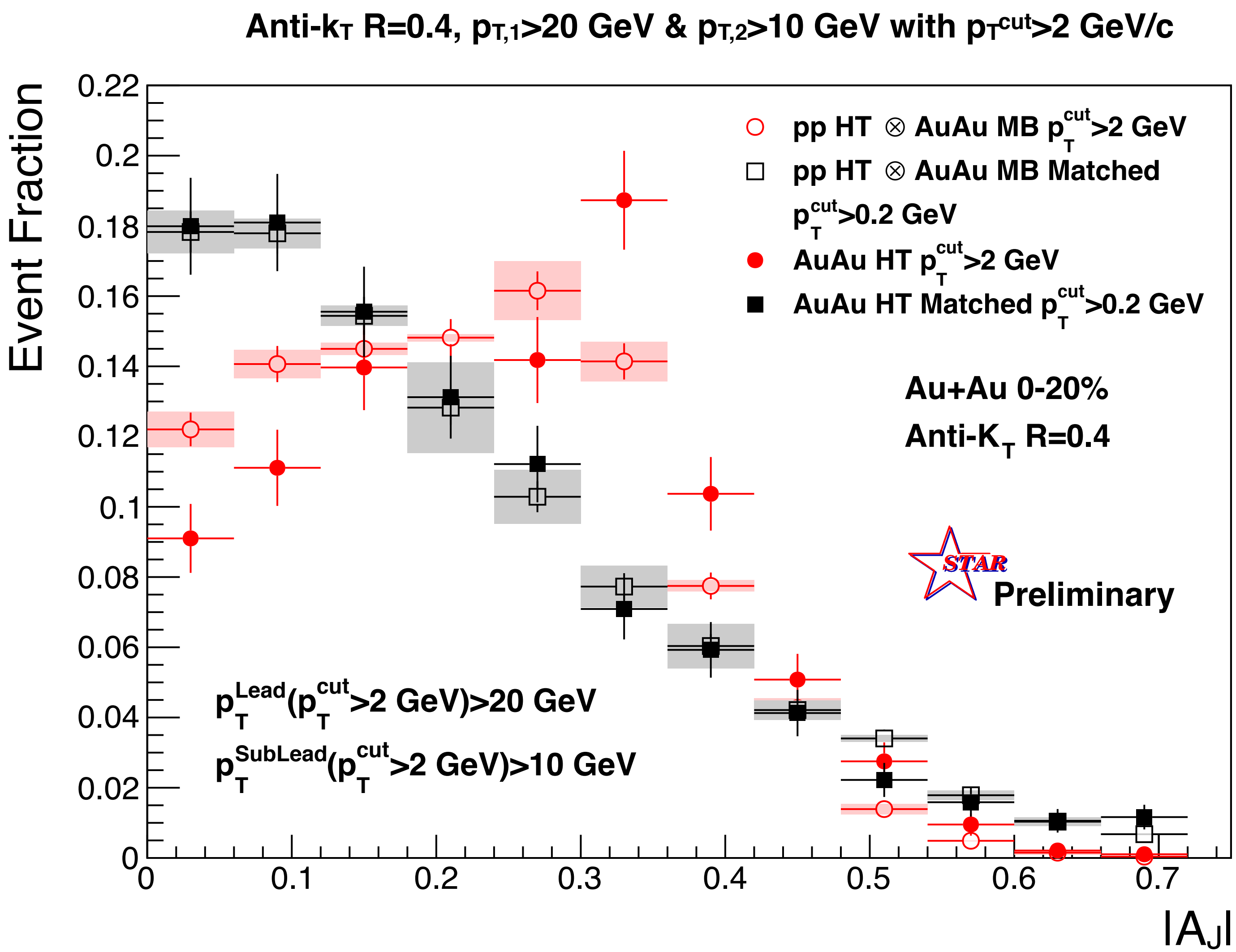

Sys. Uncertainties:
- tracking eff. 6%
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p-value<10^{-5}
(stat. error only)

p-value~0.8
(stat. error only)

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

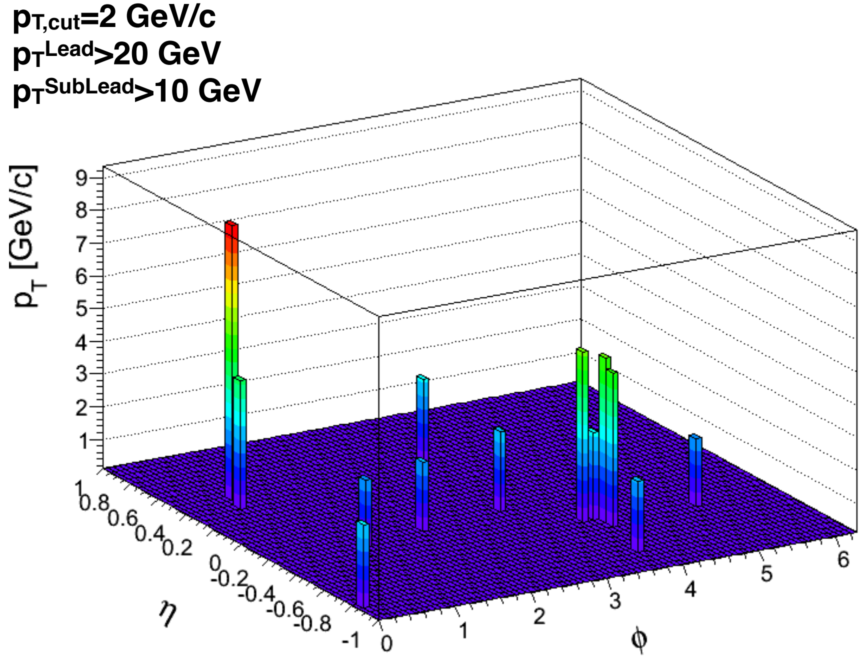
Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

Null-Hypothesis

Assumption: **Observed di-jet balancing for matched jets is only due to background fluctuations, not due to correlated signal yield!**

Method 1: Random Cone (RC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)



Embed randomly the 2 Jet vectors into a Au+Au 0-20% Minimum Bias event

Calculate $|A_J|$ with p_T^{Cut}>0.2 GeV/c using cone of R

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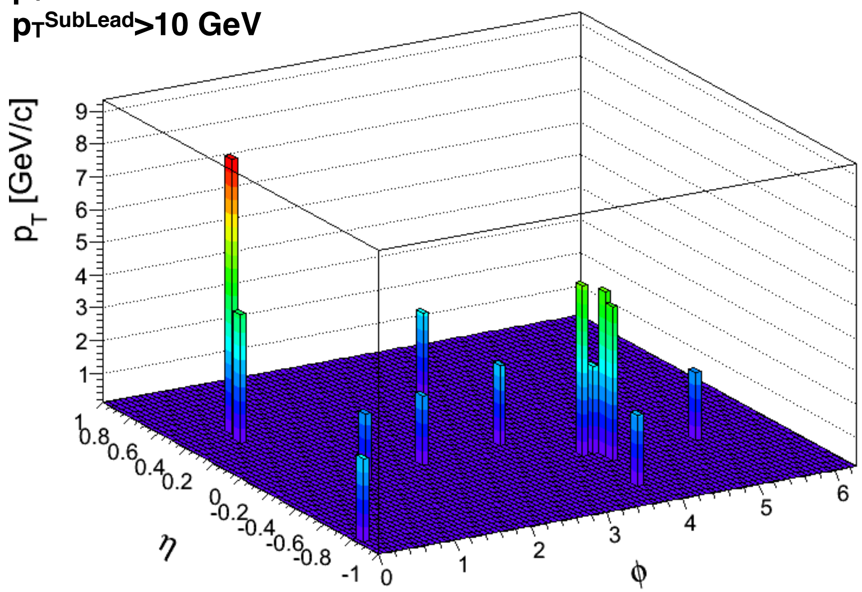

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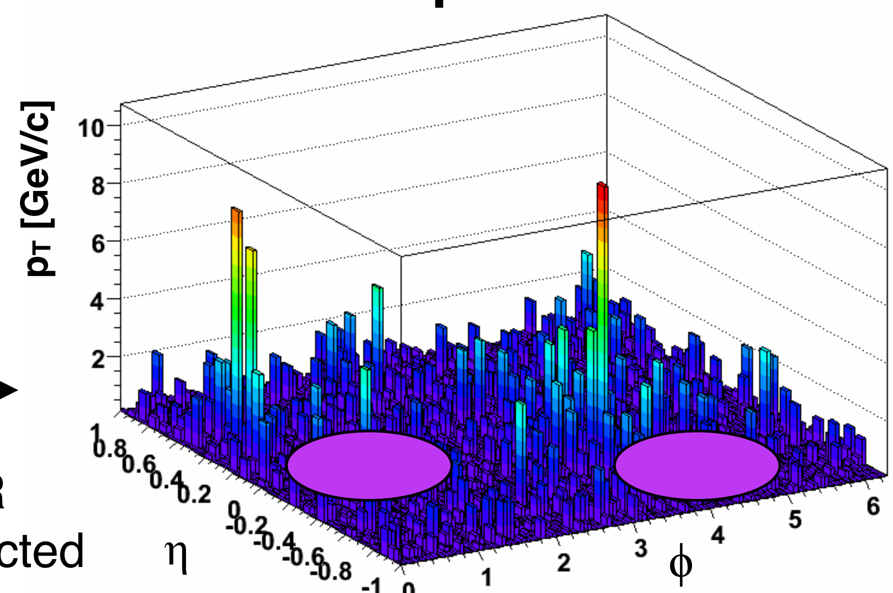
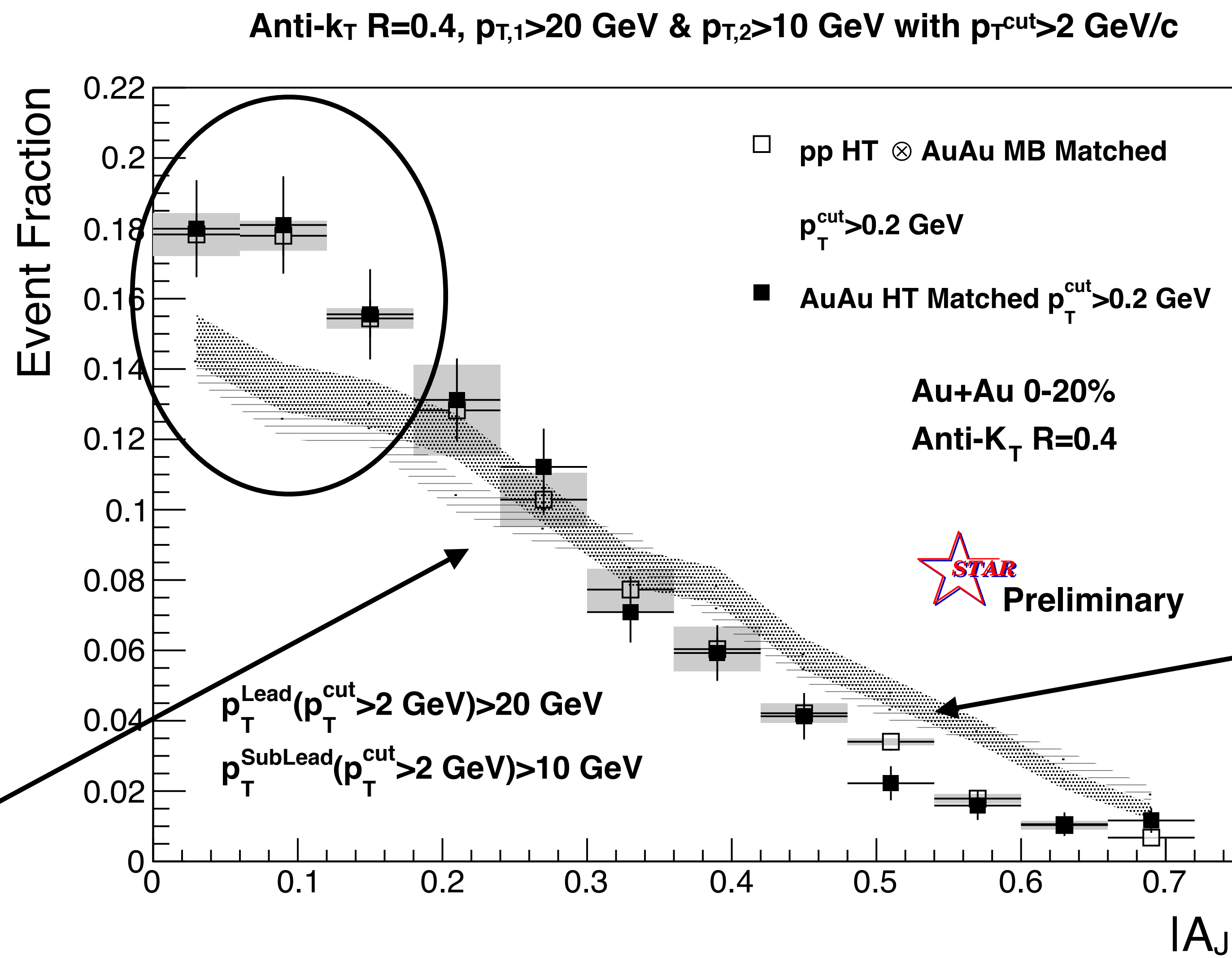


Method 2: EtaCone (EC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)

Embed the two Jet vectors into 0-20% Au+Au HT event 2*R away from reconstructed di-jet pair in that event

Null-Hypothesis



Sys. Uncertainties:
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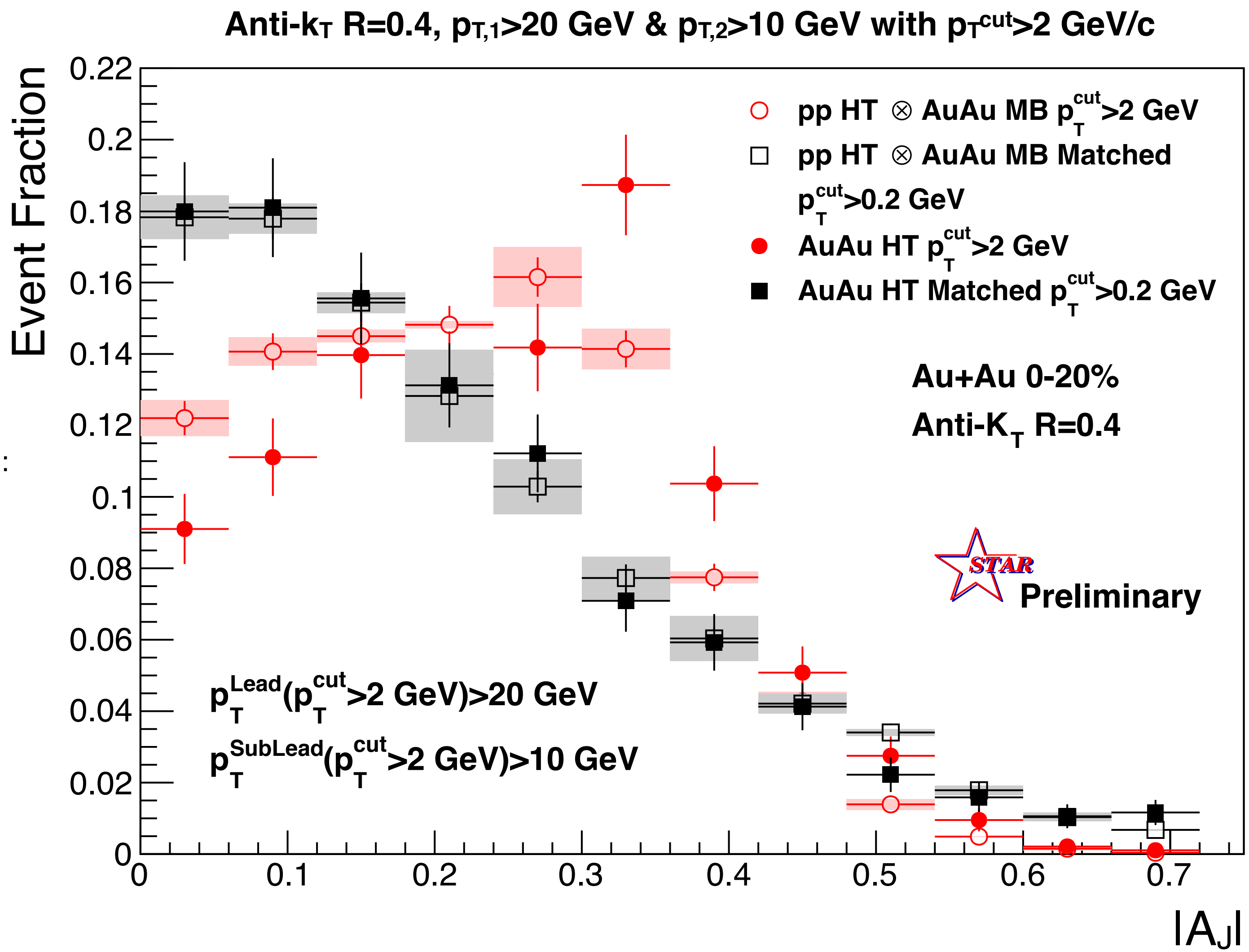
Method 1 (RC)

Method 2 (EC)

Balancing of Au+Au matched di-jets due to correlated signal yield in a cone of R=0.4

Di-Jet Imbalance A_J Au+Au 0-20% R=0.4



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

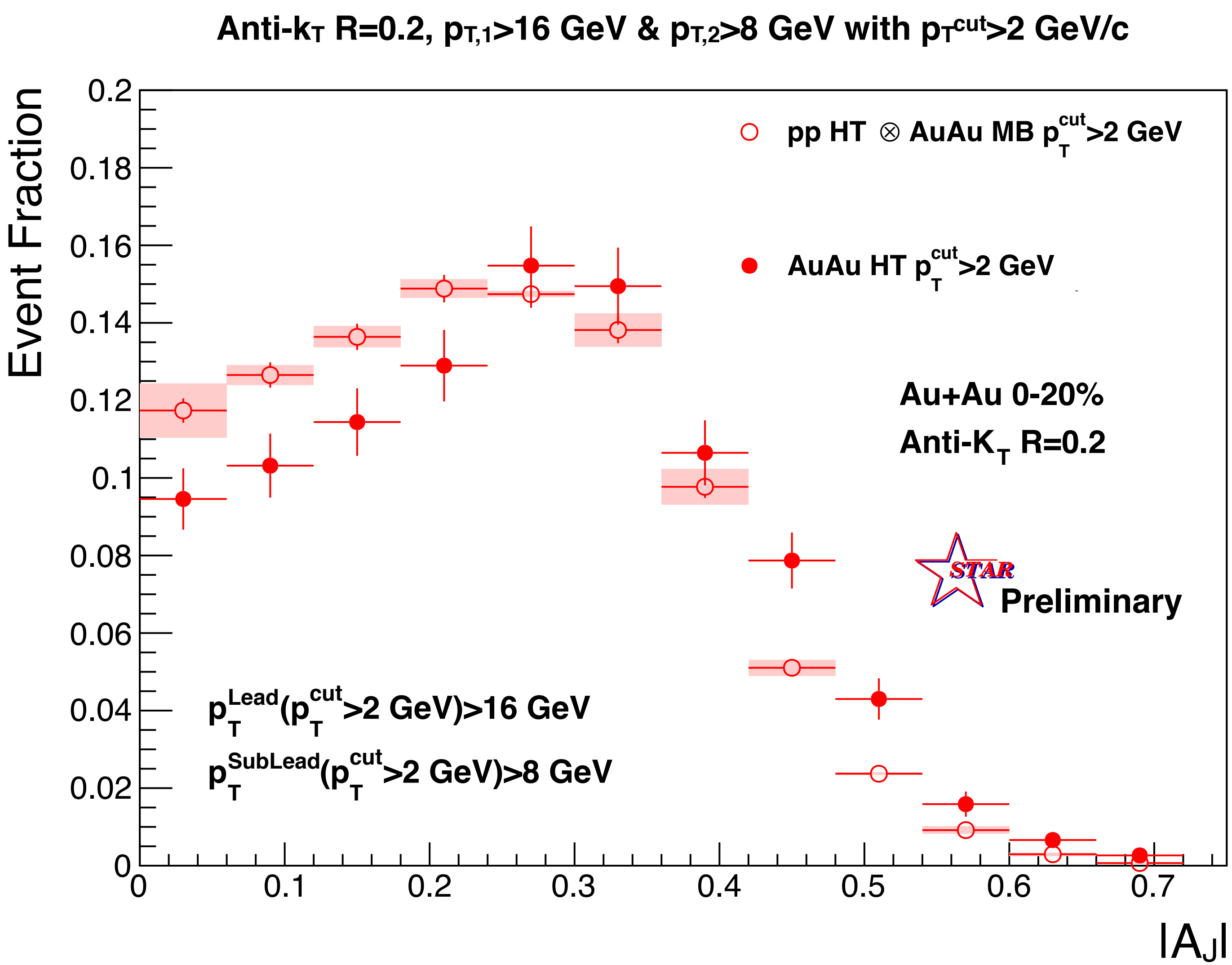
p-value<10^{-5} (stat. error only)

p-value~0.8 (stat. error only)

Select modified di-jet pairs with p_T^{cut}>2 GeV/c in Au+Au

→ quenched jet energy is recovered at low p_T within a cone of R=0.4 – consistent with Jet-Hadron results

Di-Jet Imbalance A_J Au+Au 0-20% R=0.2



Sys. Uncertainties:
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p-value<10^{-10}
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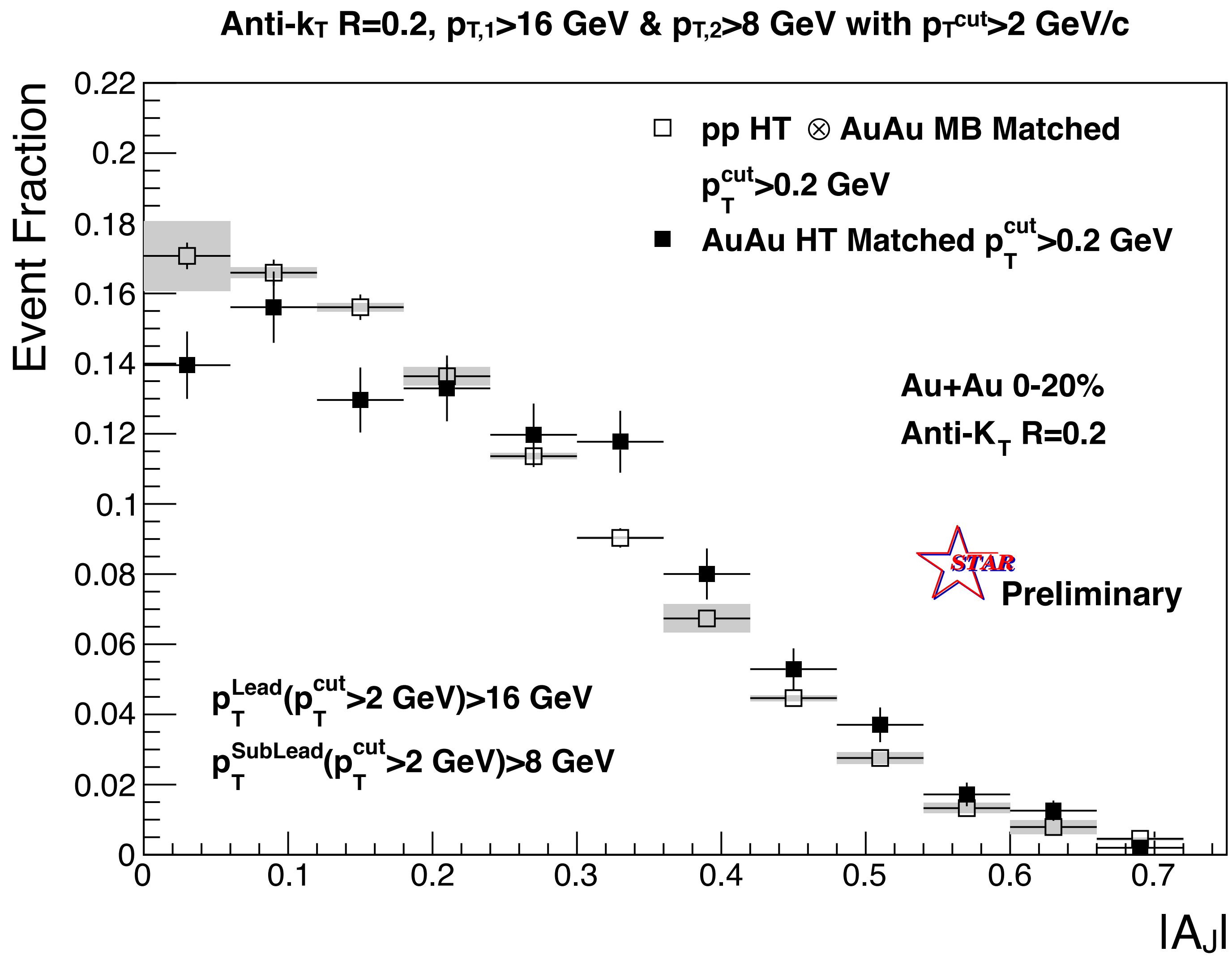
Di-Jet Imbalance A_J Au+Au 0-20% R=0.2



Sys. Uncertainties:
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p-value<10^{-10}
(stat. error only)

p-value<10^{-4}
(stat. error only)

Matched Au+Au A_J ≠ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

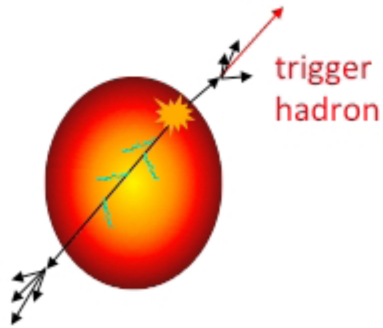
Quick Summary of A_J Measurements

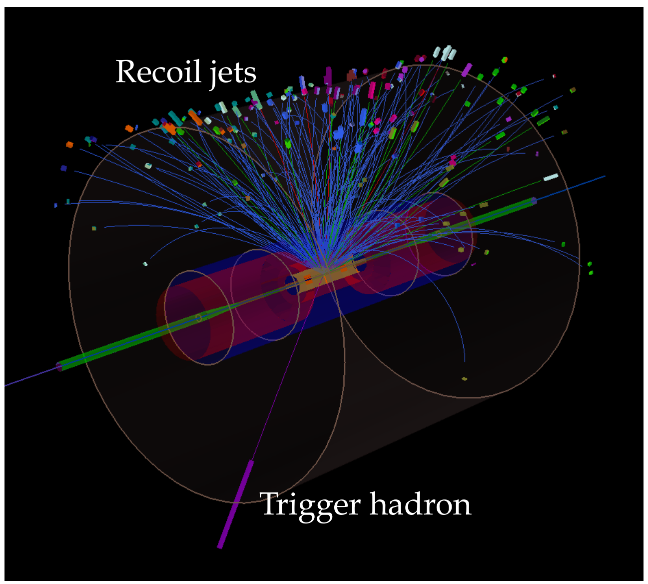
	R=0.4	R=0.2
Au+Au vs. p+p p_T^{Cut}>2 GeV/c	X	X
Matched Au+Au vs. p+p (p_T^{Cut}>0.2 GeV/c)	O	X

X = "*Non-identical*" A_J distribution (Au+Au vs. p+p)

O = "*Identical*" A_J distribution (Au+Au vs. p+p)

Semi-inclusive Recoil Jets





Charged hadron trigger: $9<p_T<19$ GeV/c

Charged particle jets:

- Anti-k_T R=0.3
- Constituent tracks: $p_T > 0.2$ GeV/c

Recoil jet azimuth: $|\varphi-\pi|<\pi/4$

Semi-inclusive Observable:
Recoil jets per trigger

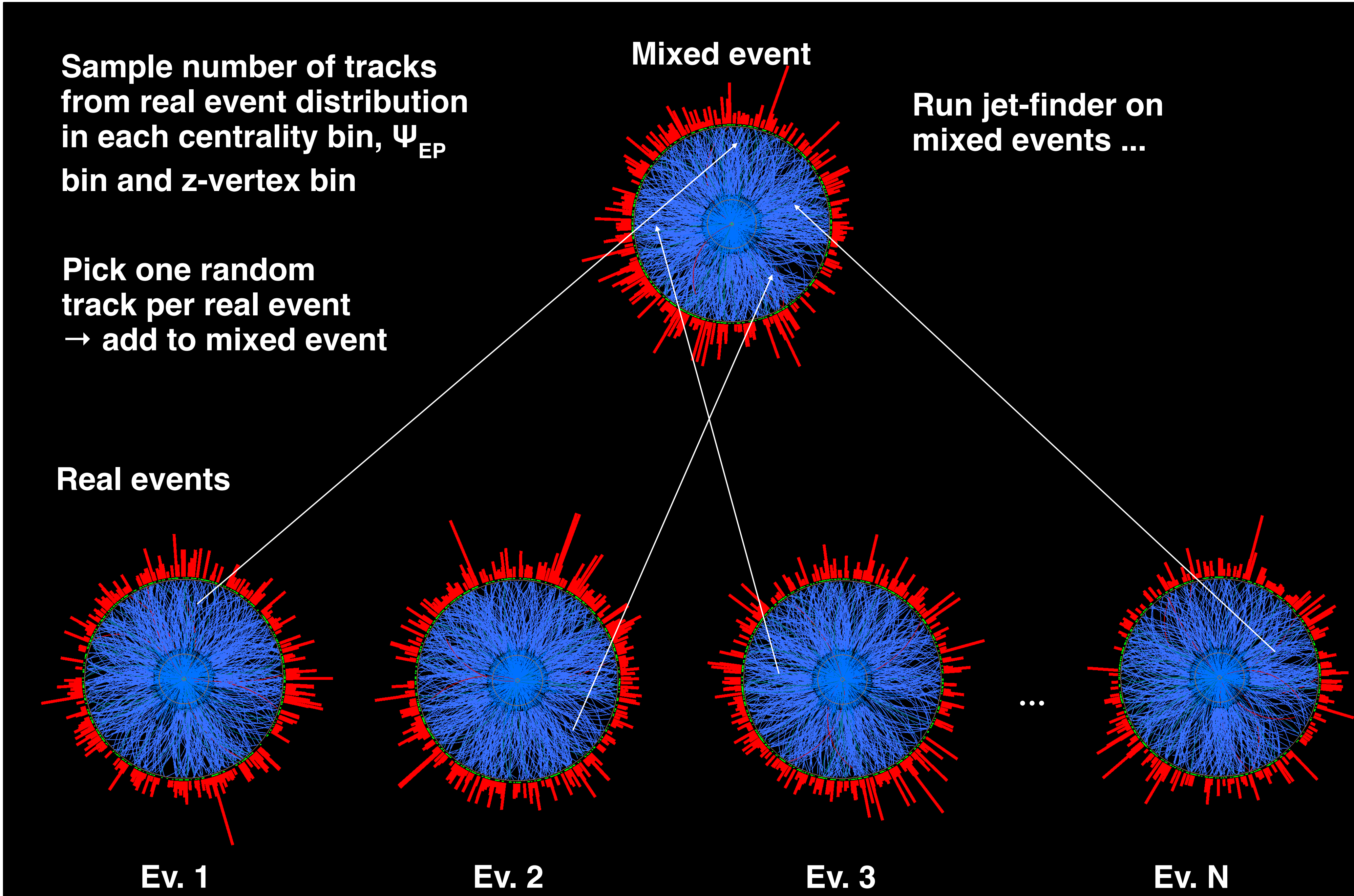
$$\frac{1}{N^{h}_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA\rightarrow h+X}}\frac{d\sigma^{AA\rightarrow h+jet+X}}{dp_{T,jet}}$$

Measured — Calculable in fixed-order pQCD

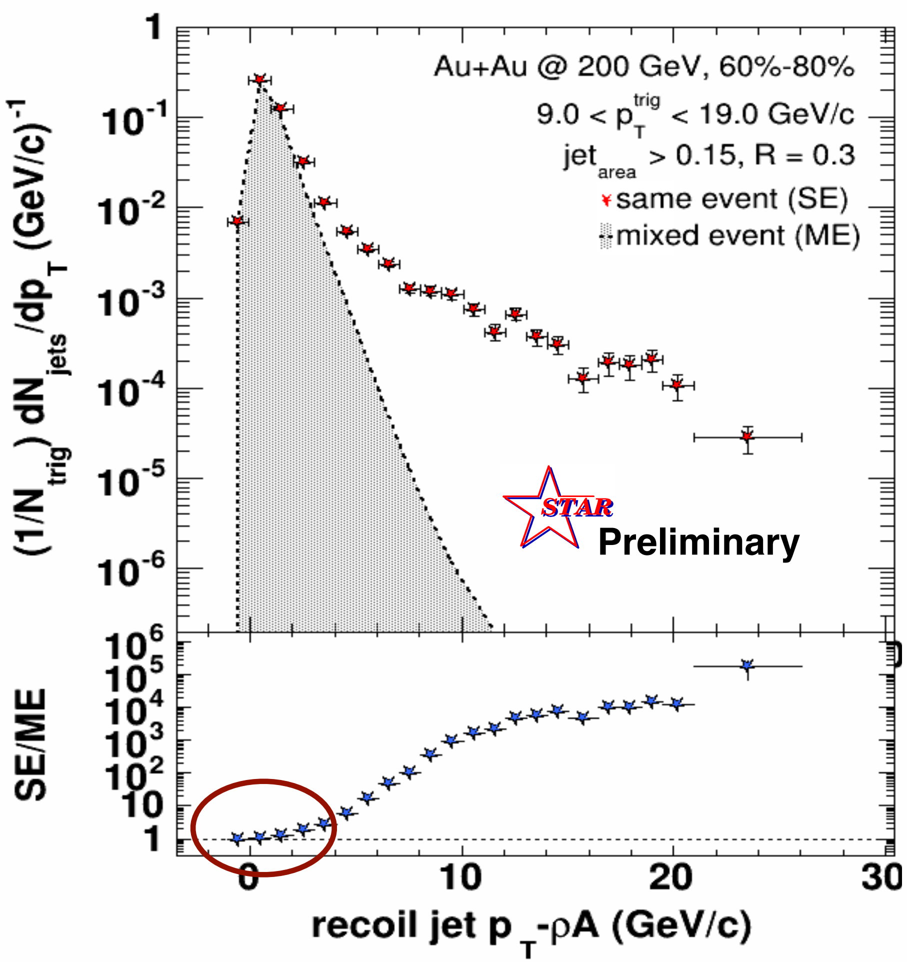
Ensemble-averaged analysis:

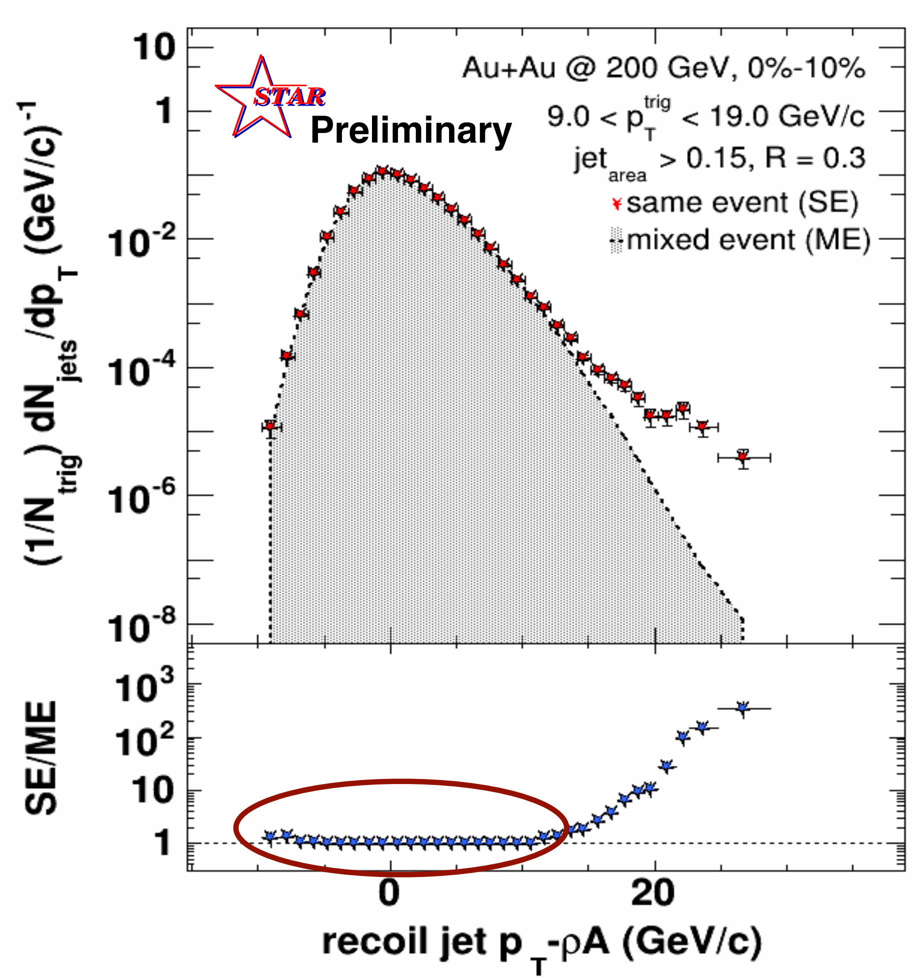
- No rejection of jet candidates on a jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)

New Method: Combinatorial Jets via Mixed Events



Semi-inclusive Recoil Jets SE and ME p_T^{trig}>9 GeV/c





Excellent description of combinatorial jets background via new event mixing method!

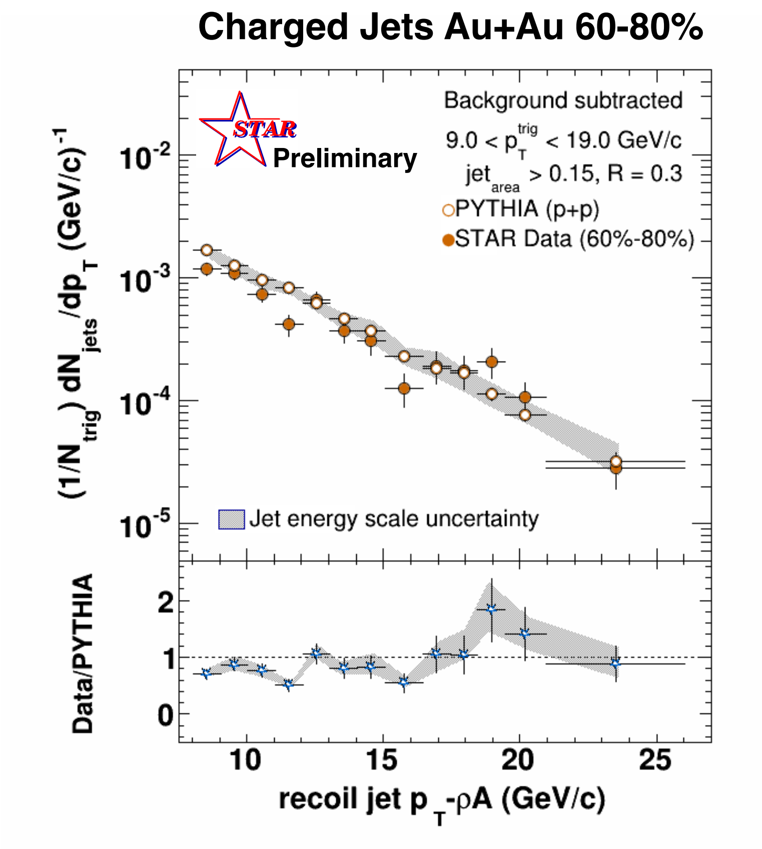
→ **Triggered Recoil jet distribution: SE-ME**

Semi-inclusive Recoil Jets (SE-ME) p_T^{trig}>9 GeV/c

Au+Au background subtracted distributions (SE-ME):

- *Ultimately:* Correct to particle level via unfolding of bkgd fluctuations and detector effects
- *Currently:* Compare to PYTHIA p+p distribution "smeared" by these effects

Dominant sys uncertainty: Tracking eff. → Jet energy scale (JES) uncertainty ~7%



Peripheral Au+Au: Good agreement between data and PYTHIA

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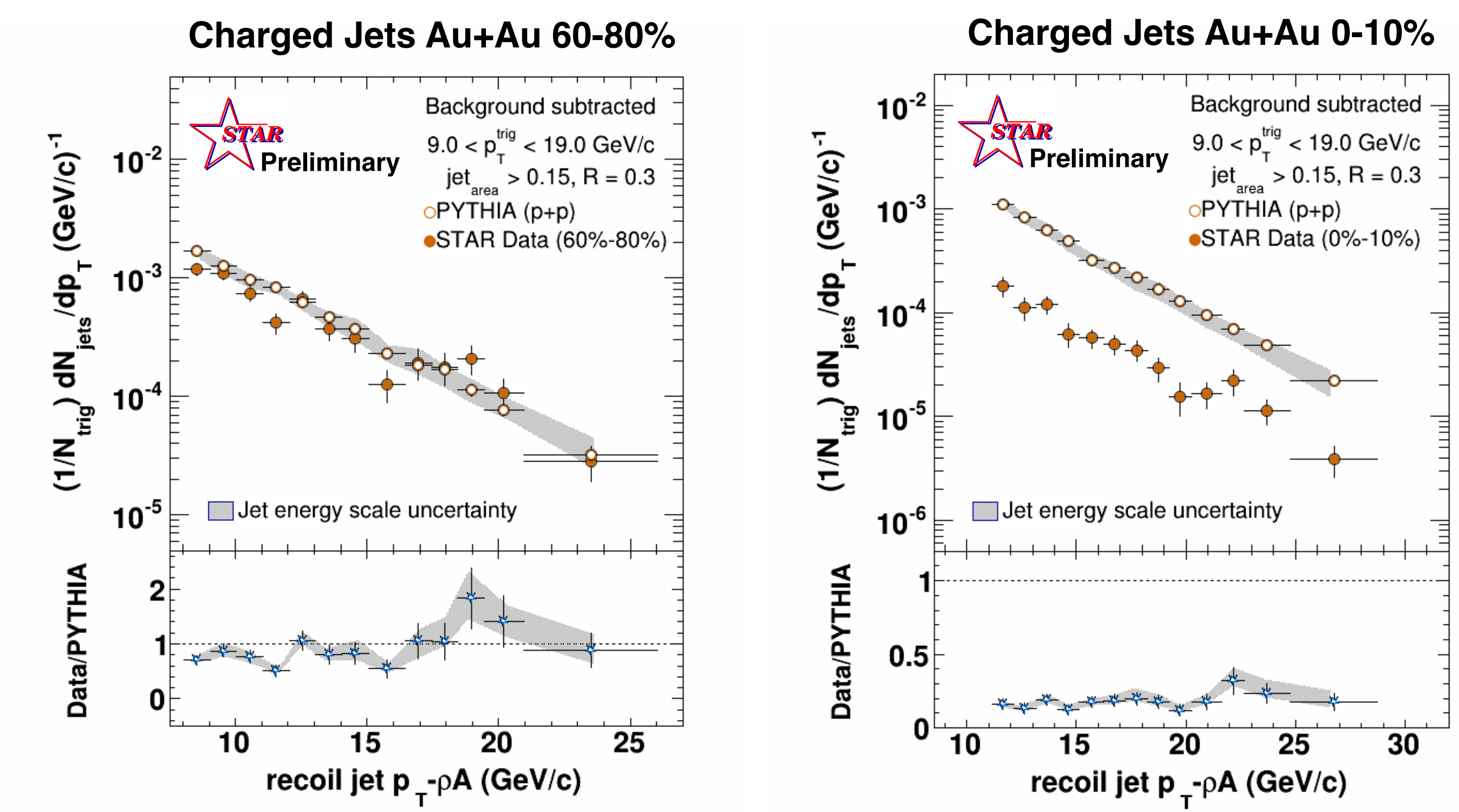
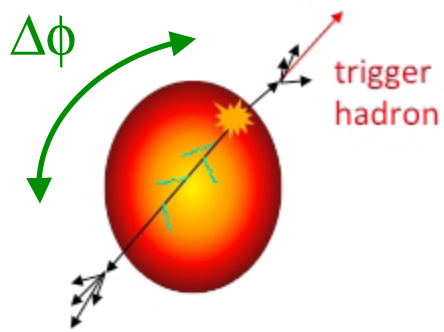


Peripheral Au+Au: Good agreement between data and PYTHIA

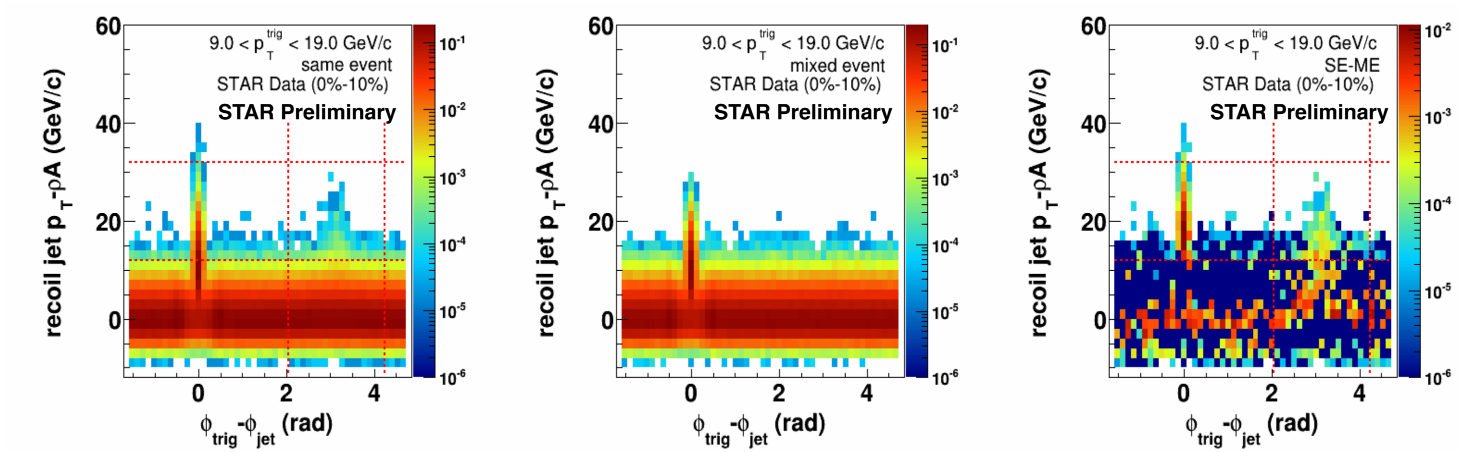
Central Au+Au: Strong suppression (relative to PYTHIA)

First Look: Medium Induced Acoplanarity?

Charged Jets Au+Au 0-10%



SE **ME** **SE-ME**



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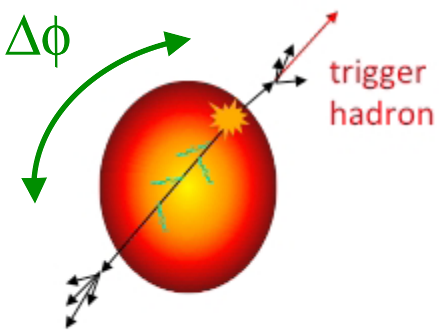
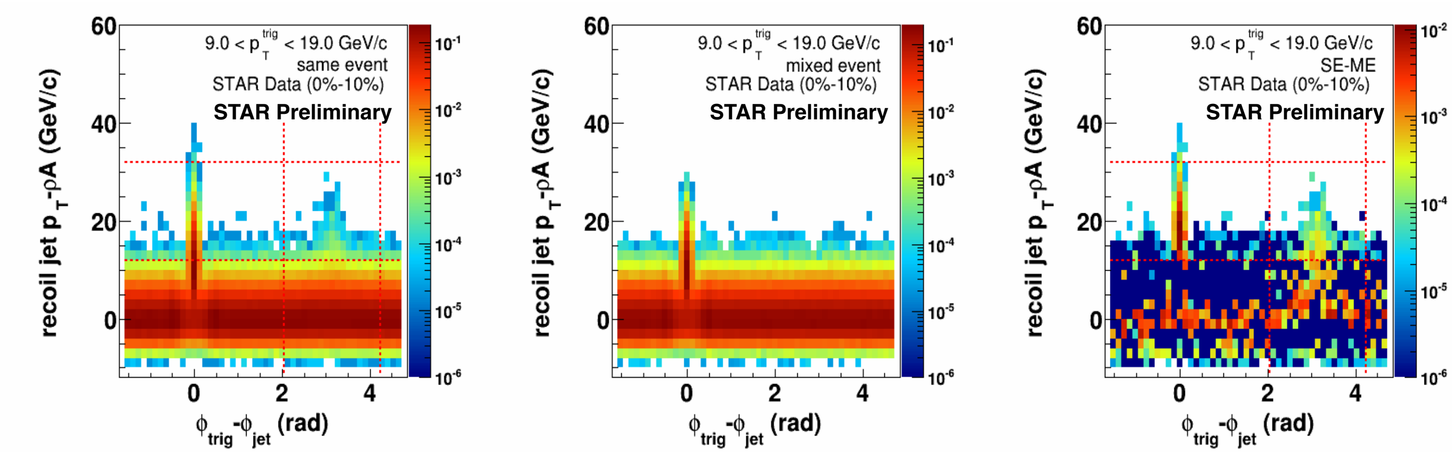
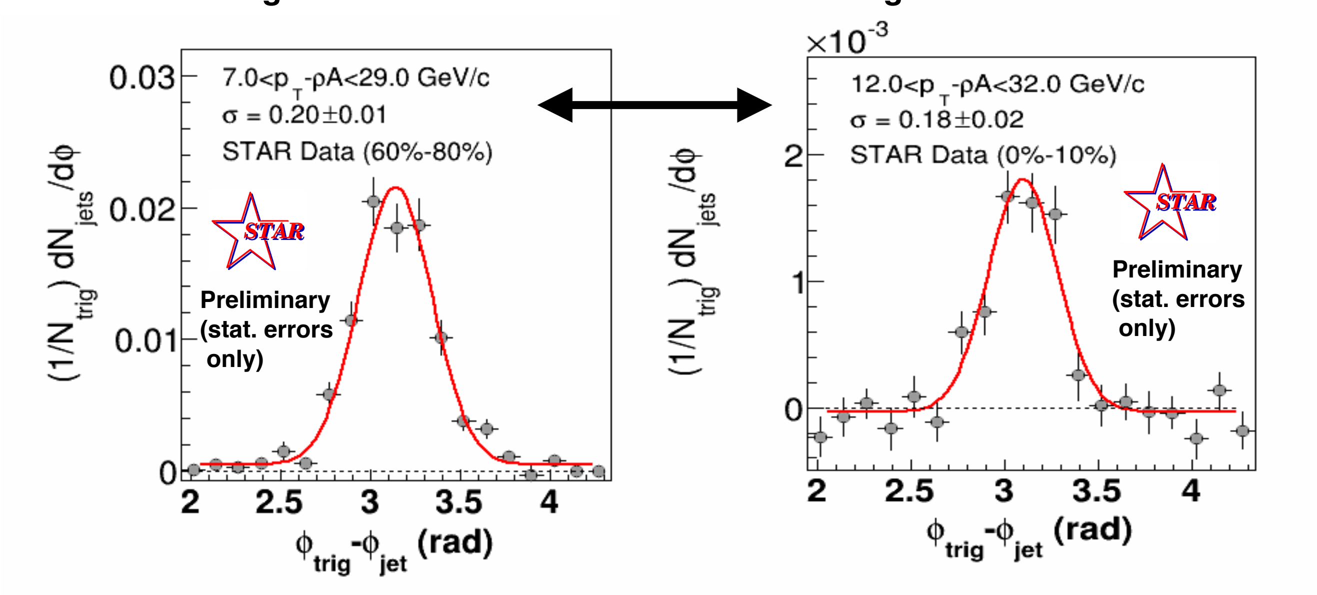


SE **ME** **SE-ME**



Charged Jets Au+Au 60-80% **Charged Jets Au+Au 0-10%**



AuAu central vs peripheral: Similar widths; can measure large angle radiation

First Look: Medium Induced Acoplanarity?

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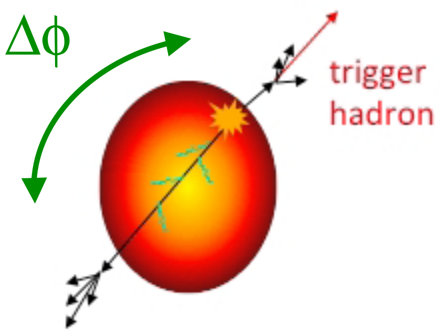
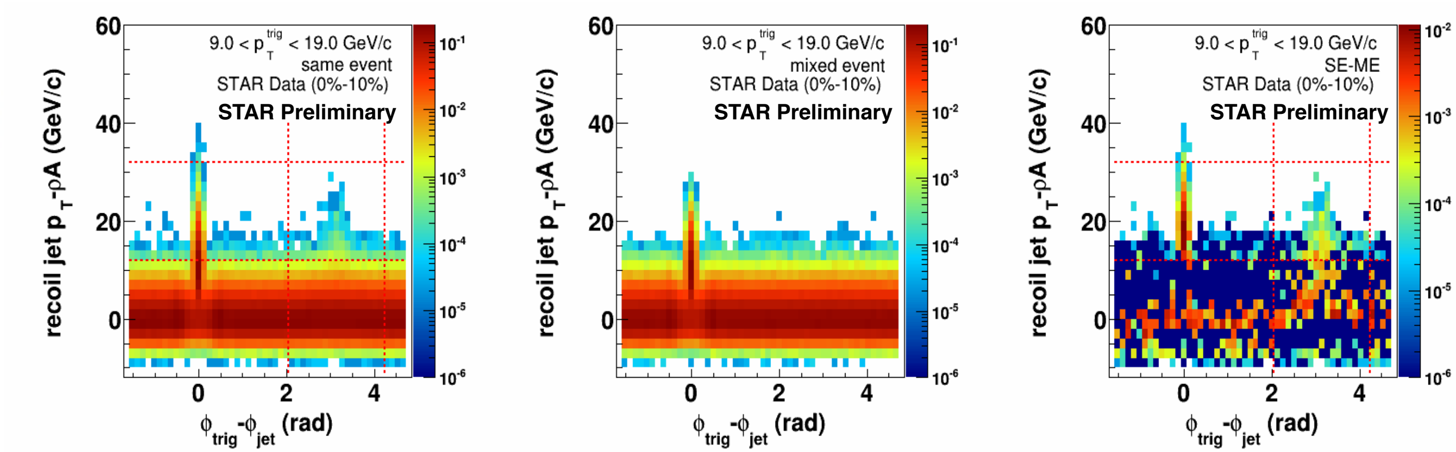


SE | ME | SE-ME



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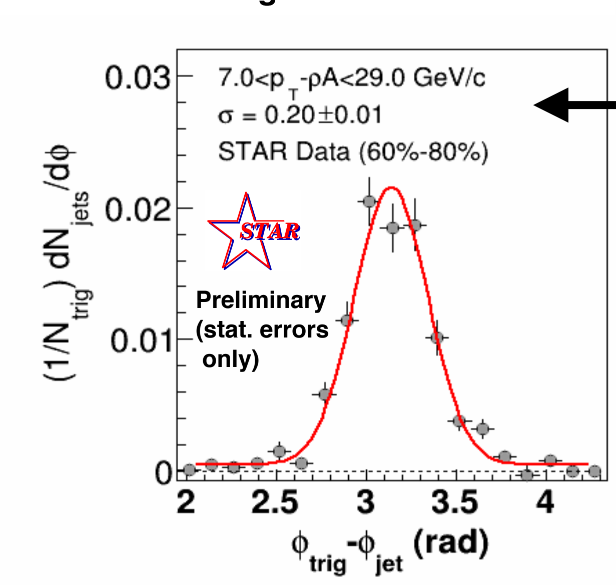

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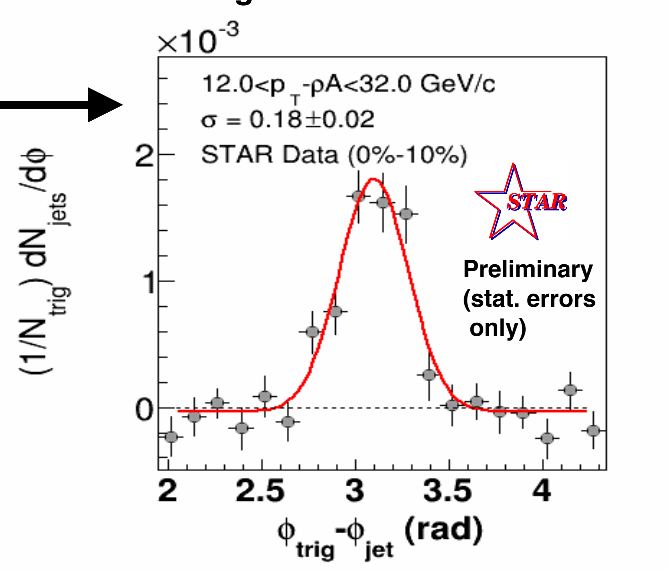
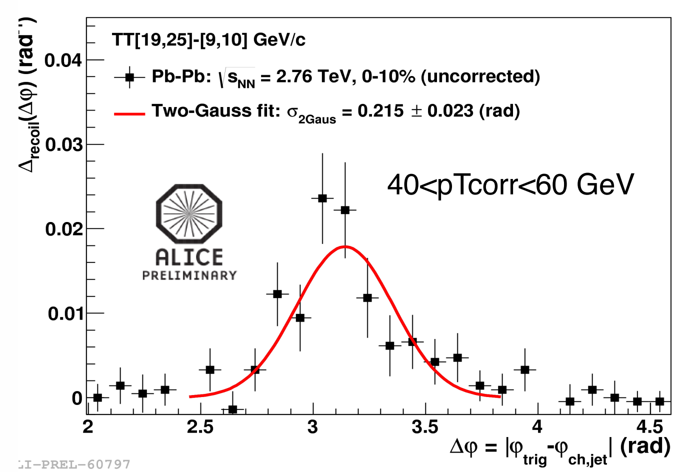


Pb+Pb 2.76 TeV 0-10%

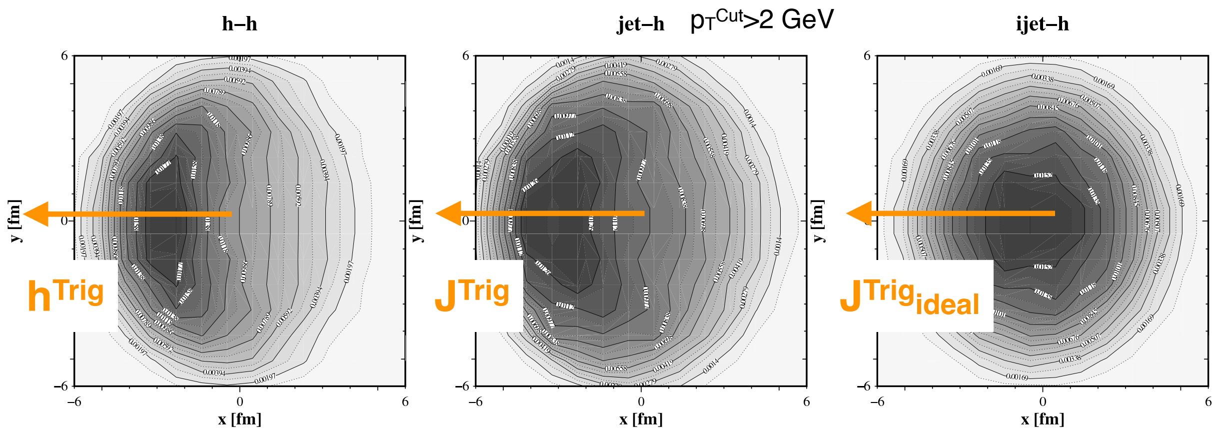


AuAu central vs peripheral: Similar widths; can measure large angle radiation

RHIC vs LHC: Comparable widths

Discussion: The Role of *Biases*

*T. Renk, PRC **87** (2013) 024905 and PRC **88** (2013) 054902*



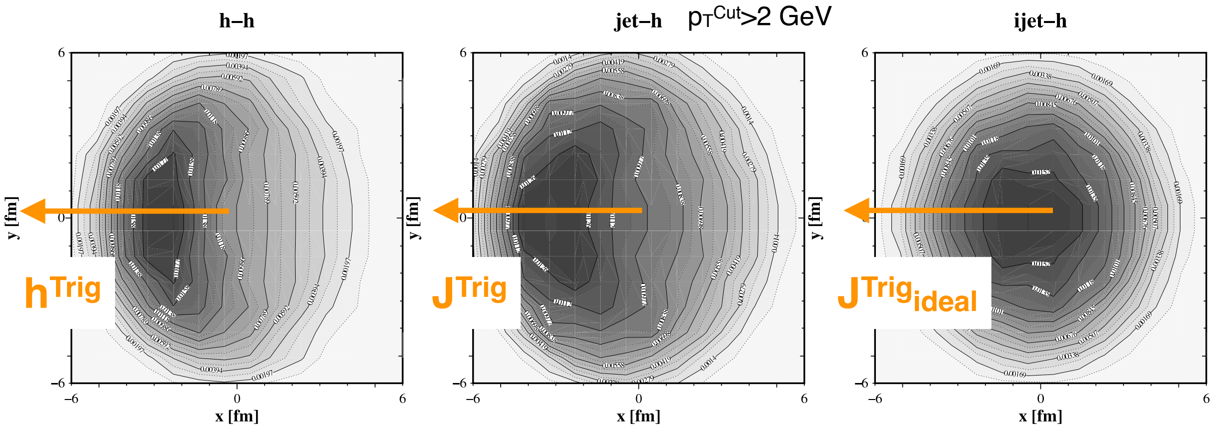
Biases **(p_T^{Cut}, R, ...) can be used to change *systematically* the *pathlength* of the recoil jet**

(even more when also applied on recoil jet definition)

<u>Further *advantage* at RHIC:</u> Steeply falling spectrum at RHIC → good correlation to the *initial parton energy*

Discussion: The Role of *Biases*

*T. Renk, PRC **87** (2013) 024905 and PRC **88** (2013) 054902*



Biases **(p_T^{Cut}, R, ...) can be used to change *systematically* the *pathlength* of the recoil jet**

(even more when also applied on recoil jet definition)

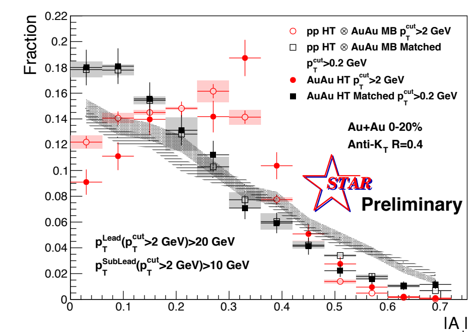
<u>Further *advantage* at RHIC:</u> Steeply falling spectrum at RHIC → good correlation to the *initial parton energy*

<u>Di-Jet Imbalance A_J:</u>

Biased **initial di-jet selection also on recoil jet (p_T^{cut}>2 GeV)**

→ smaller pathlength/energy loss at later times

→ balance restored including low p_T constituents for R=0.4 wrt p+p (broadening observed within R=0.4; consistent with Jet-Hadron)



Discussion: The Role of *Biases*

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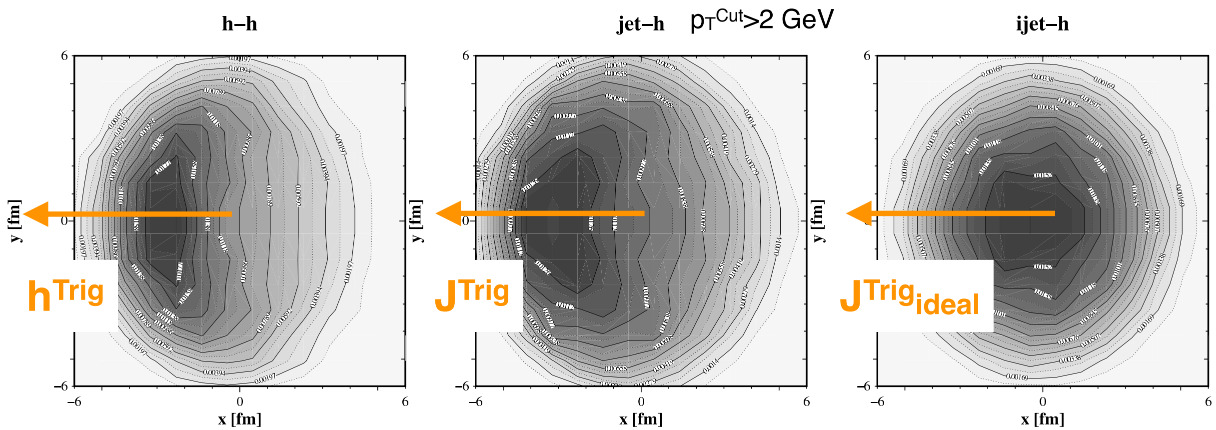

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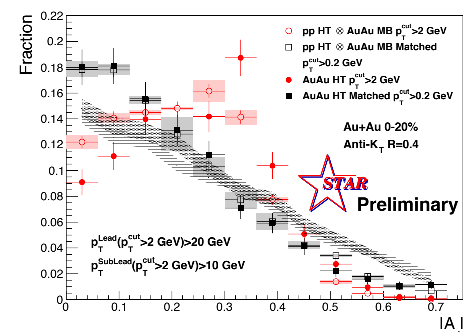


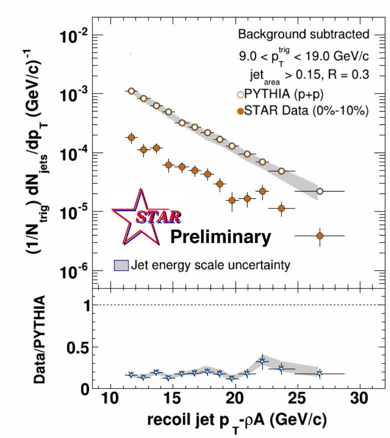
<u>Semi-inclusive Recoil Jets (h-Jet):</u>

No bias **on recoil jet**

→ larger (maximized) pathlength for recoil jets

→ more energy loss combined with jet broadening (Jet-Hadron)

→ (strong) suppression wrt Pythia (R=0.3)



Summary

<u>New di-jet measurements from STAR:</u>

A_J : Balance restored for R=0.4 wrt p+p (for *biased* di-jets)

h-Jet : (Strong) suppression wrt Pythia (R=0.3); no evidence of large angle scattering

More data available (6x more HT triggered data wrt Run 7) and full jet analysis in Run 11.

<u>Coherent Jet Quenching Program in STAR:</u>

Statistically: Di-Hadron, γ-Jet, Jet-Hadron and 2+1 Correlations

<u>*Extension* via new/future jet Measurements:</u>

Explore systematically and differentially biases (p_T^{cut}, R, ..) in particular utilizing di-jet coincidence measurements at RHIC

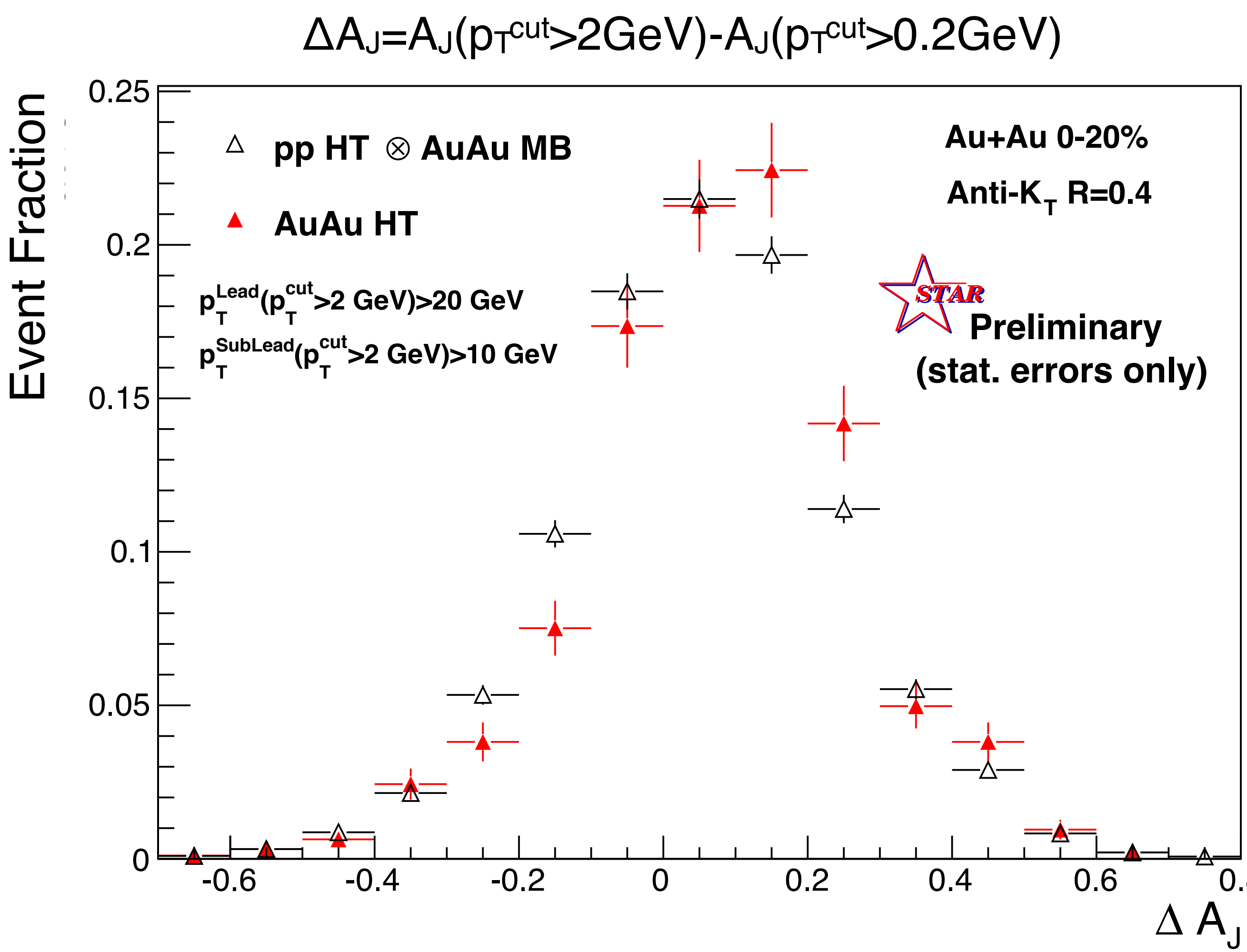
→ engineer geometrical biases

→ "jet - tomography"

→ study evolution of soft gluon radiation

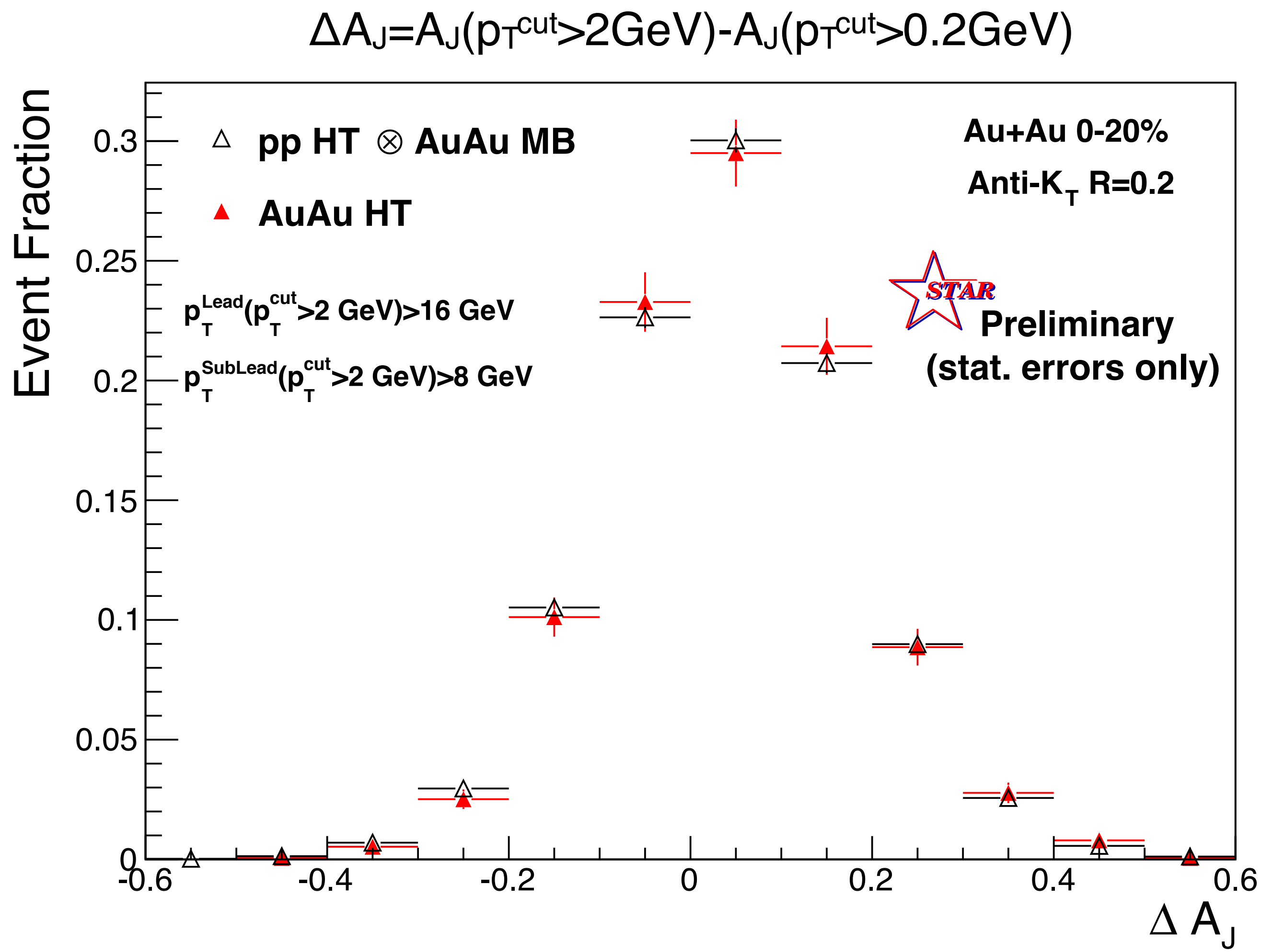
Backup

E-by-E A_J Difference: ΔA_J Au+Au 0-20% R=0.4 & R=0.2



R=0.4: ΔA_J larger for Au+Au than p+p
→ more energy recovered at low p_T

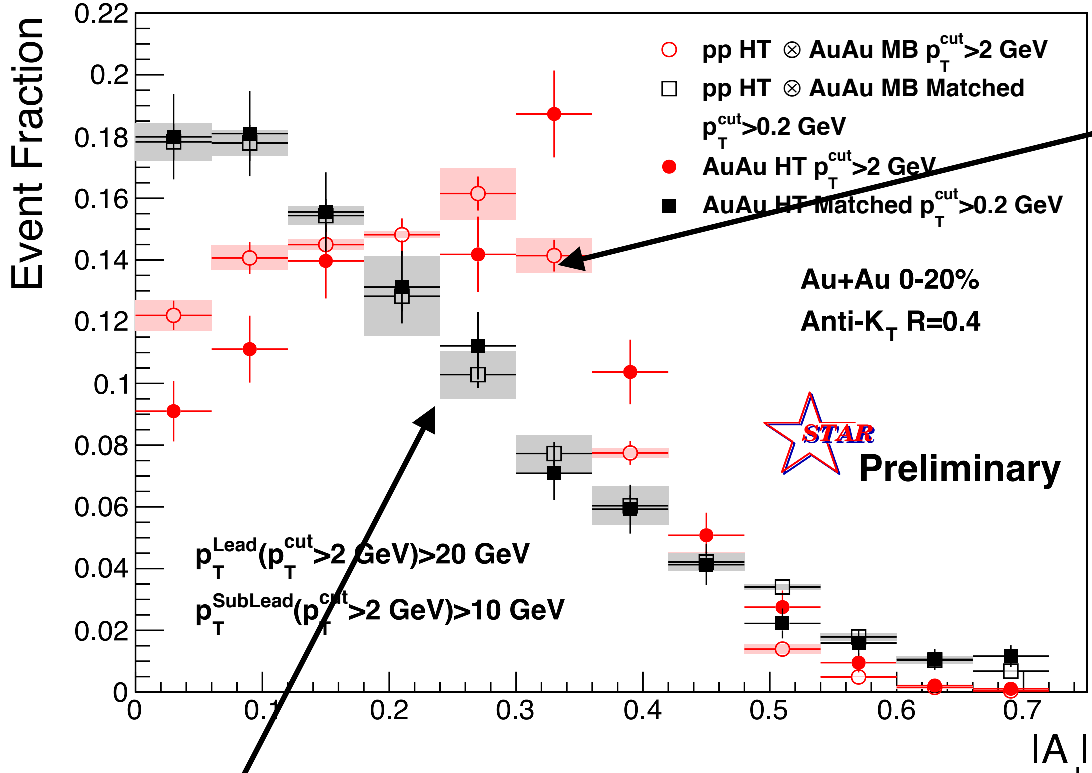
E-by-E A_J Difference: ΔA_J Au+Au 0-20% R=0.4 & R=0.2



R=0.4: ΔA_J larger for Au+Au than p+p
→ more energy recovered at low p_T

R=0.2: ΔA_J Au+Au ~ ΔA_J p+p
→ similar energy recovered at low p_T

pp HT Reference and Systematic Errors



Reference:

pp HT ⊗ AuAu MB

Embed pp HT randomly into AuAu 0-20% minimum bias event, adjusted for relative tracking efficiency between pp HT Y06 and AuAu HT Y07

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

Systematic Uncertainties (Analogous to Jet-Hadron Corr.)

- Tracking efficiency uncertainties 6%
- Relative Tower energy scale uncertainty 2%
- Background/vn: Null-Hypothesis Method1 vs. Method2
- Remaining uncertainties negligible

Systematic uncertainties of the h+jet distribution

Jet Energy Scale (JES) uncertainty: 7%

Dominant contribution: tracking efficiency

- studied via embedding in Run11 data
- average charged track reconstruction efficiency is about 68% at high p_T
- the p_T-dependent efficiencies were varied by +/-10% (relative) and applied to the PYTHIA tracks as a systematic uncertainty on reference (instead of unfolding of data, TBD)

Track momentum resolution: negligible contribution to JES resolution (~1-2%)

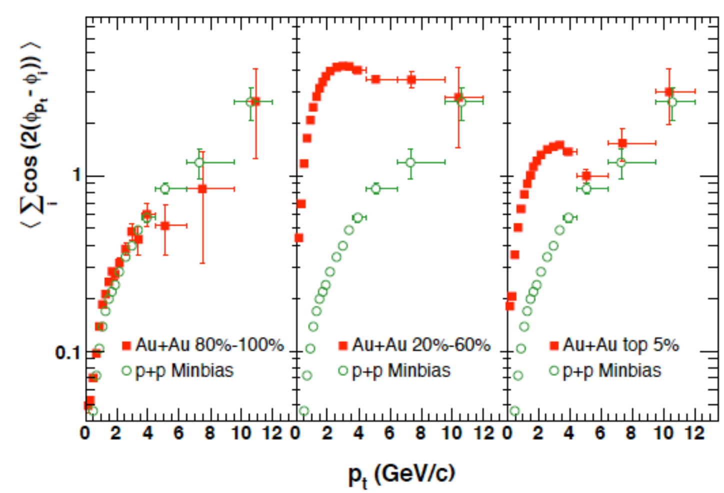
Event plane correlations

No evidence of a correlation of high p_T particles with the event plane

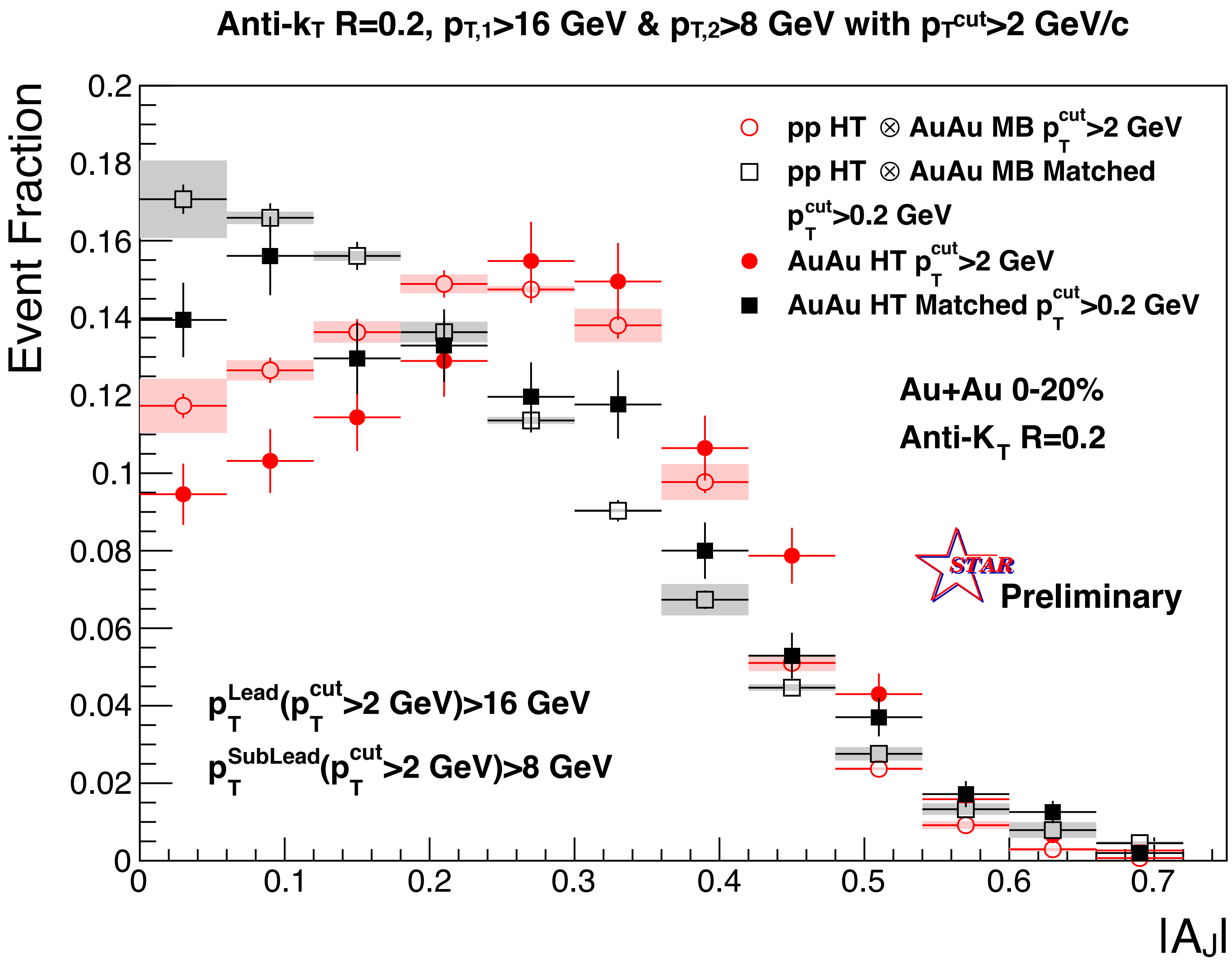
(e.g.: STAR Phys.Rev.Lett. 93 (2004) 252301)

→ a bias of the jet spectrum due to event plane correlations with the trigger particle are unlikely.

→ an upper limit was estimated by using two different Delta p_T distributions which were calculated in and out of plane.



Di-Jet Imbalance A_J Au+Au 0-20% R=0.2 (I)

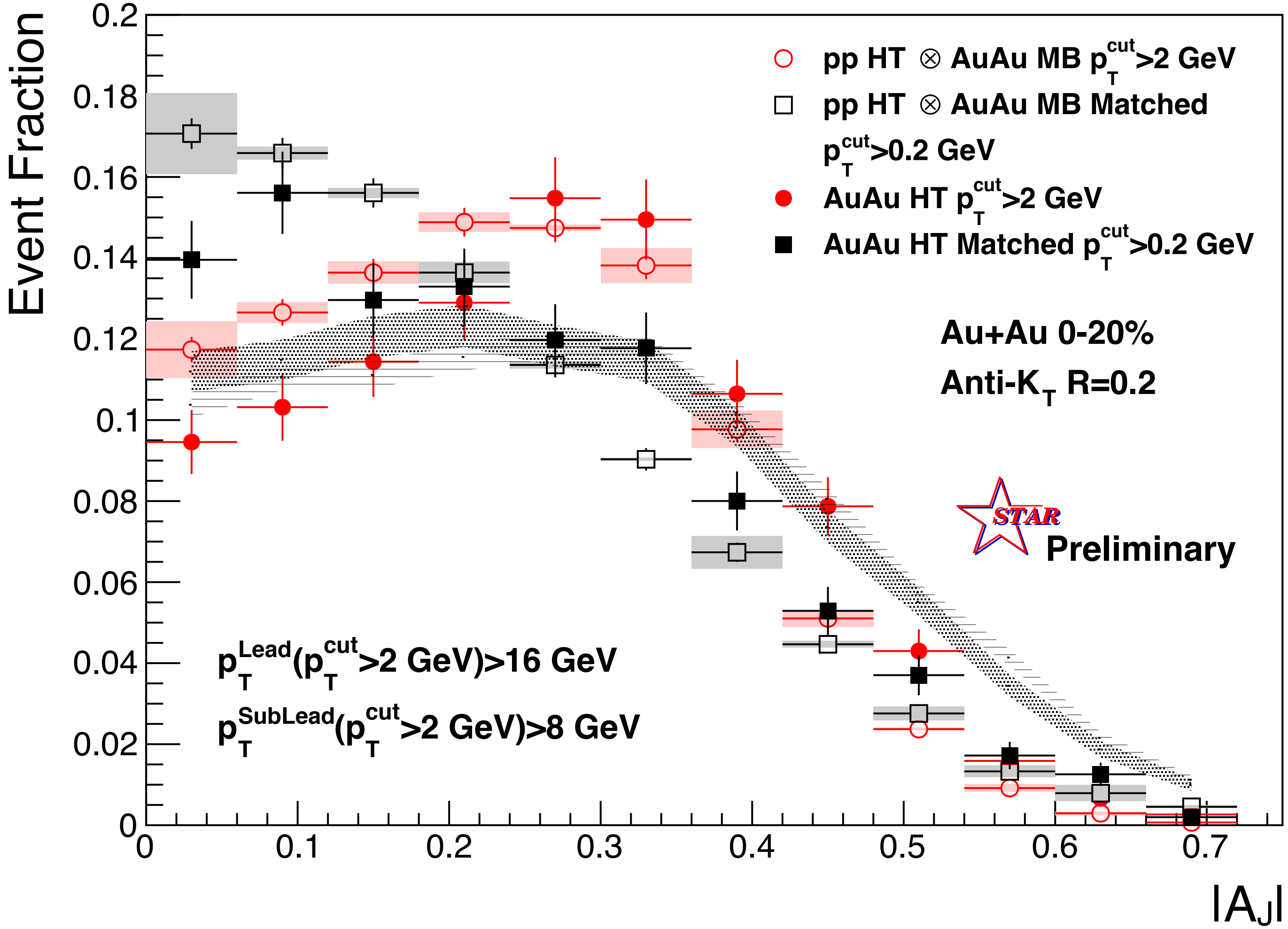


Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Di-Jet Imbalance A_J Au+Au 0-20% R=0.2 (I)

Anti-k_T R=0.2, $p_{T,1}$>16 GeV & $p_{T,2}$>8 GeV with p_T^{cut}>2 GeV/c

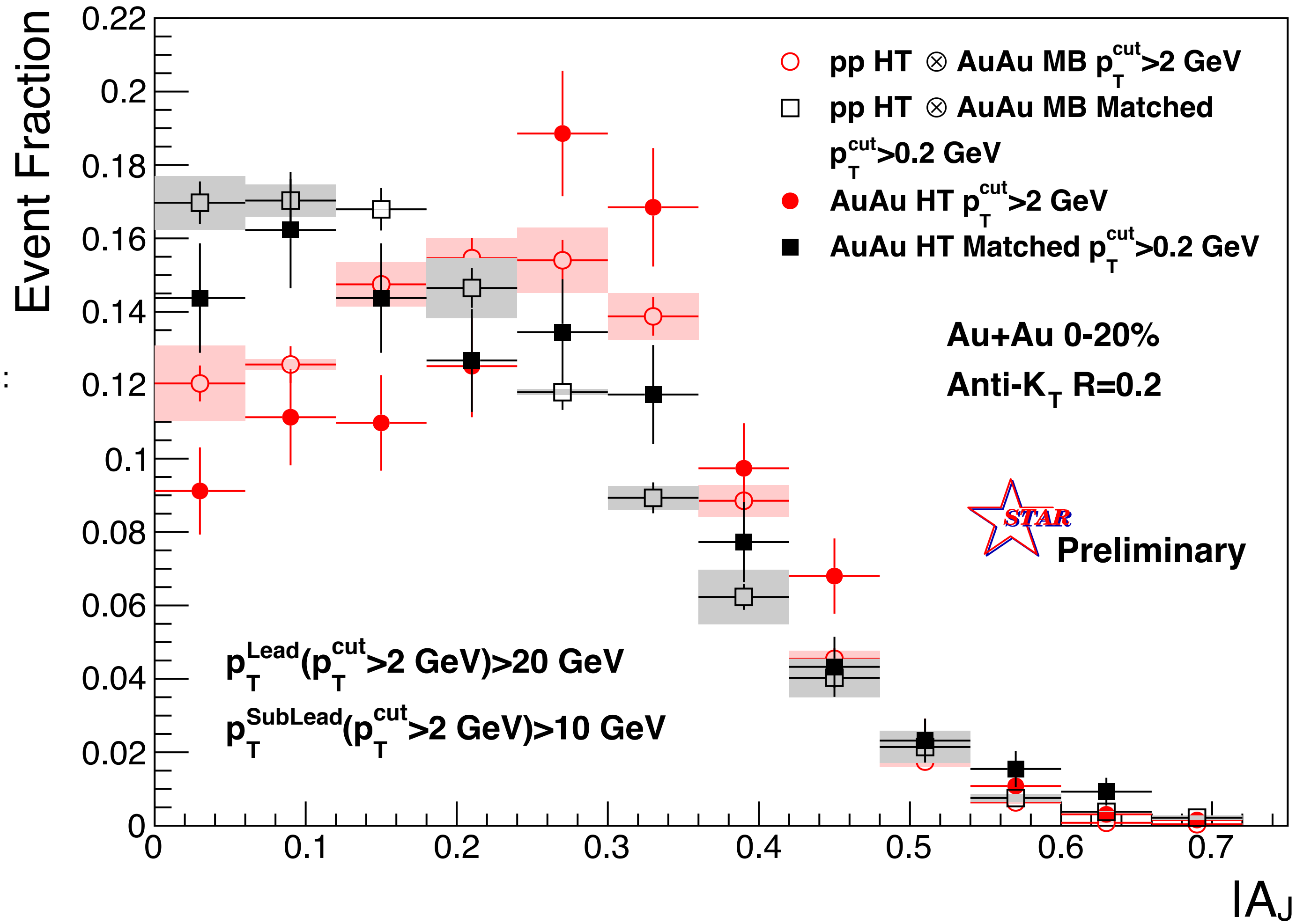
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



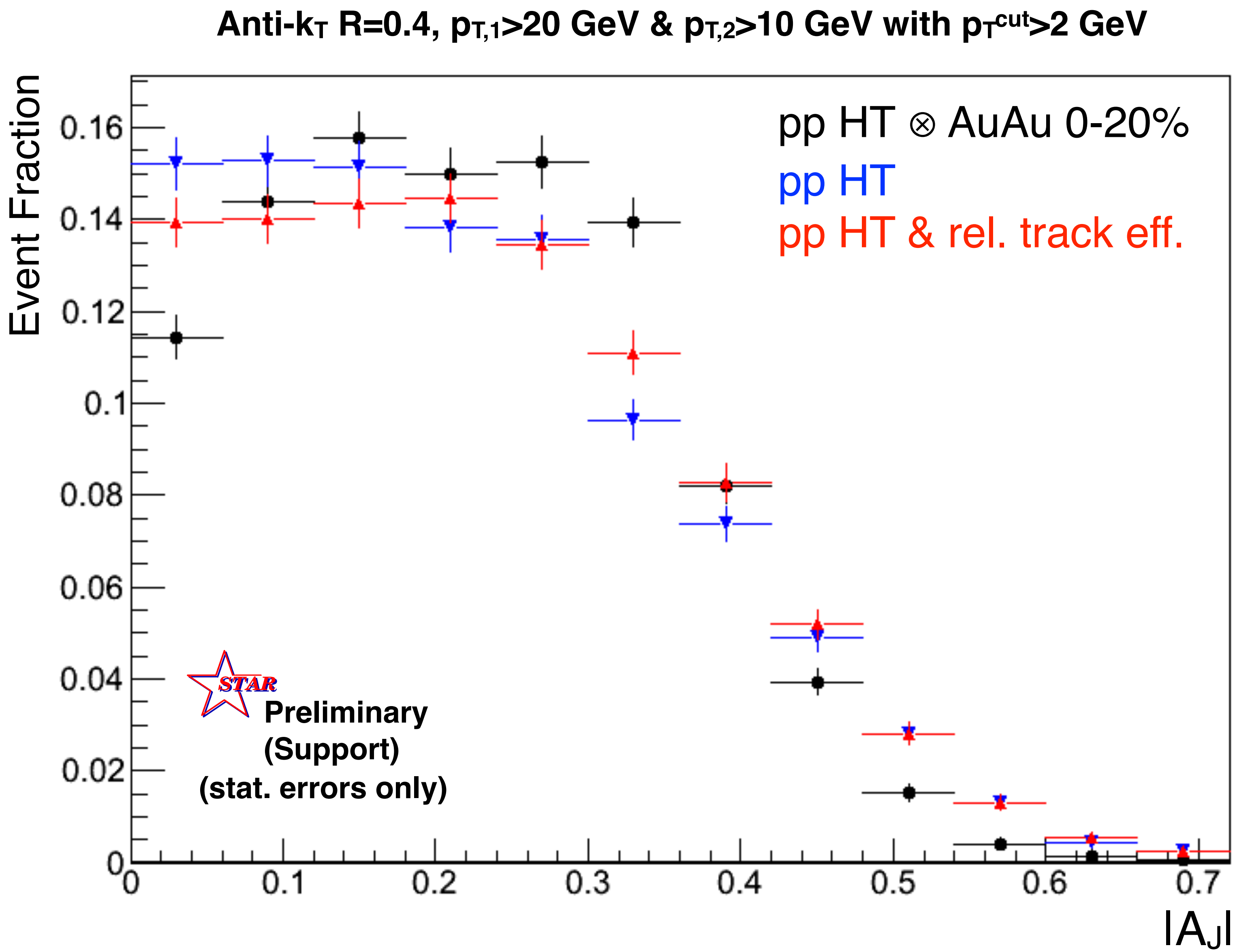
Di-Jet Imbalance A_J AuAu 0-20% R=0.2 (II)

Anti-k_T R=0.2, $p_{T,1}$>20 GeV & $p_{T,2}$>10 GeV with p_T^{cut}>2 GeV

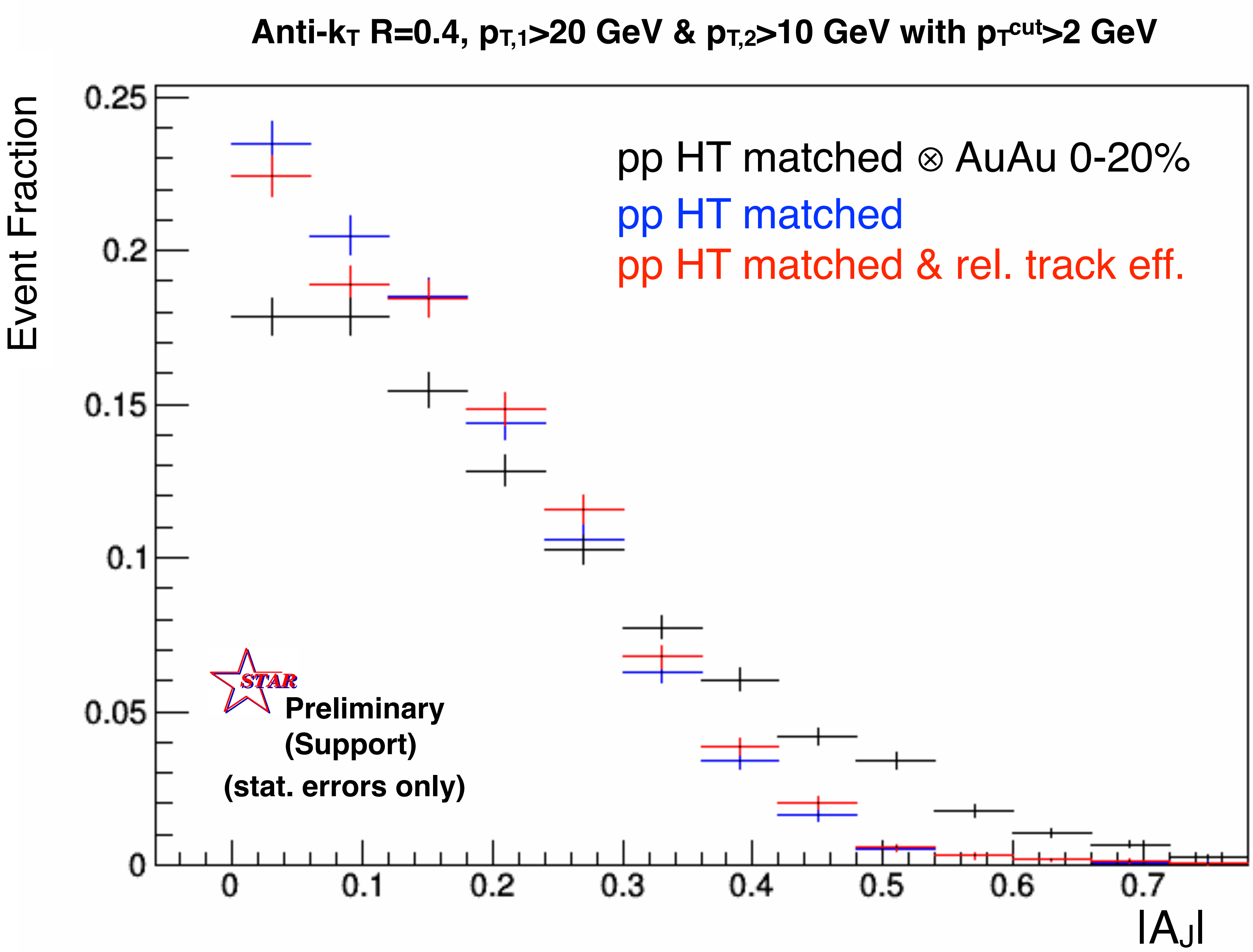
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



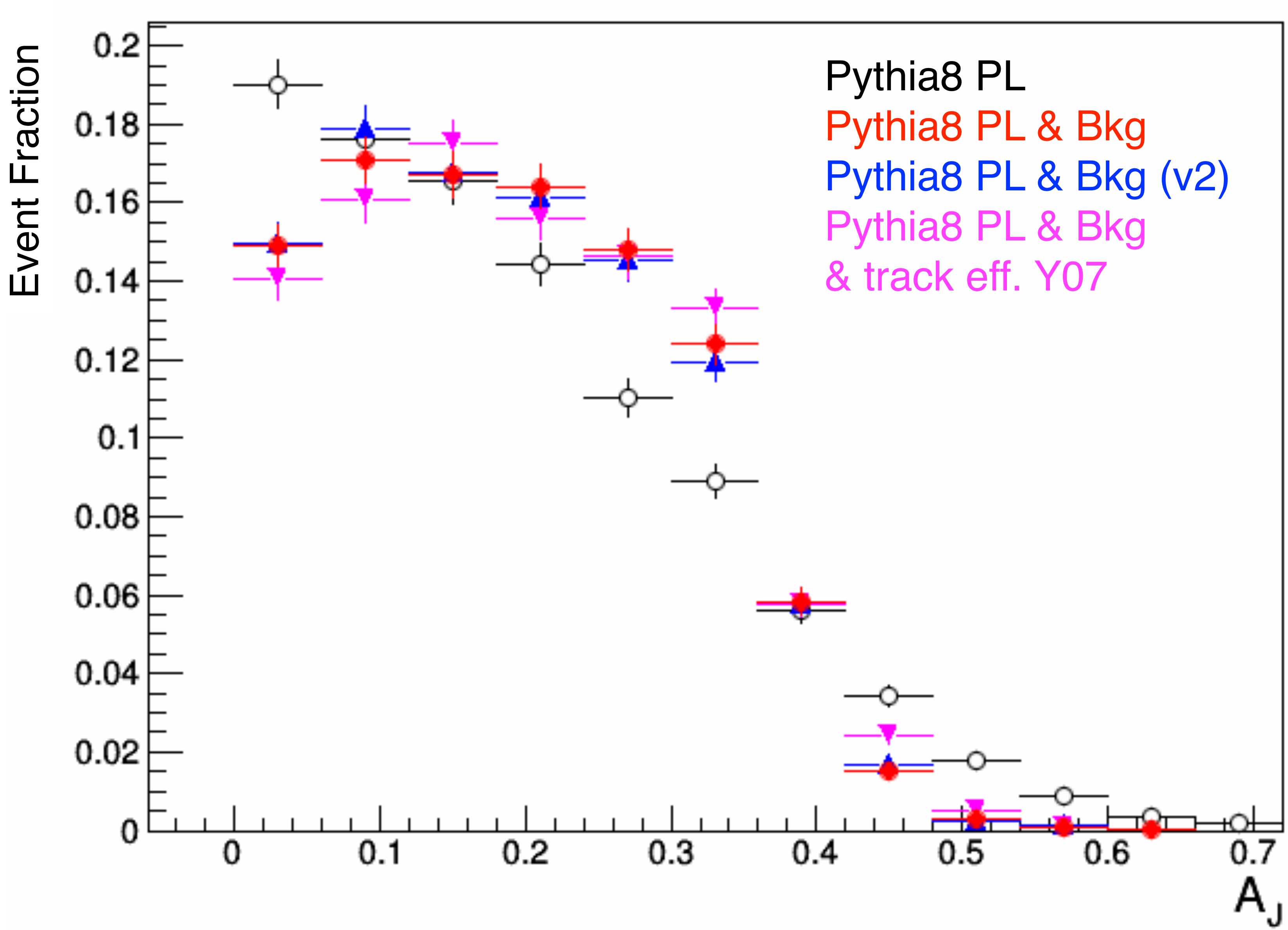
AuAu Embedding: p_T^{Cut}>2 GeV



AuAu Embedding: Matched jets with p_T^{cut}>0.2 GeV

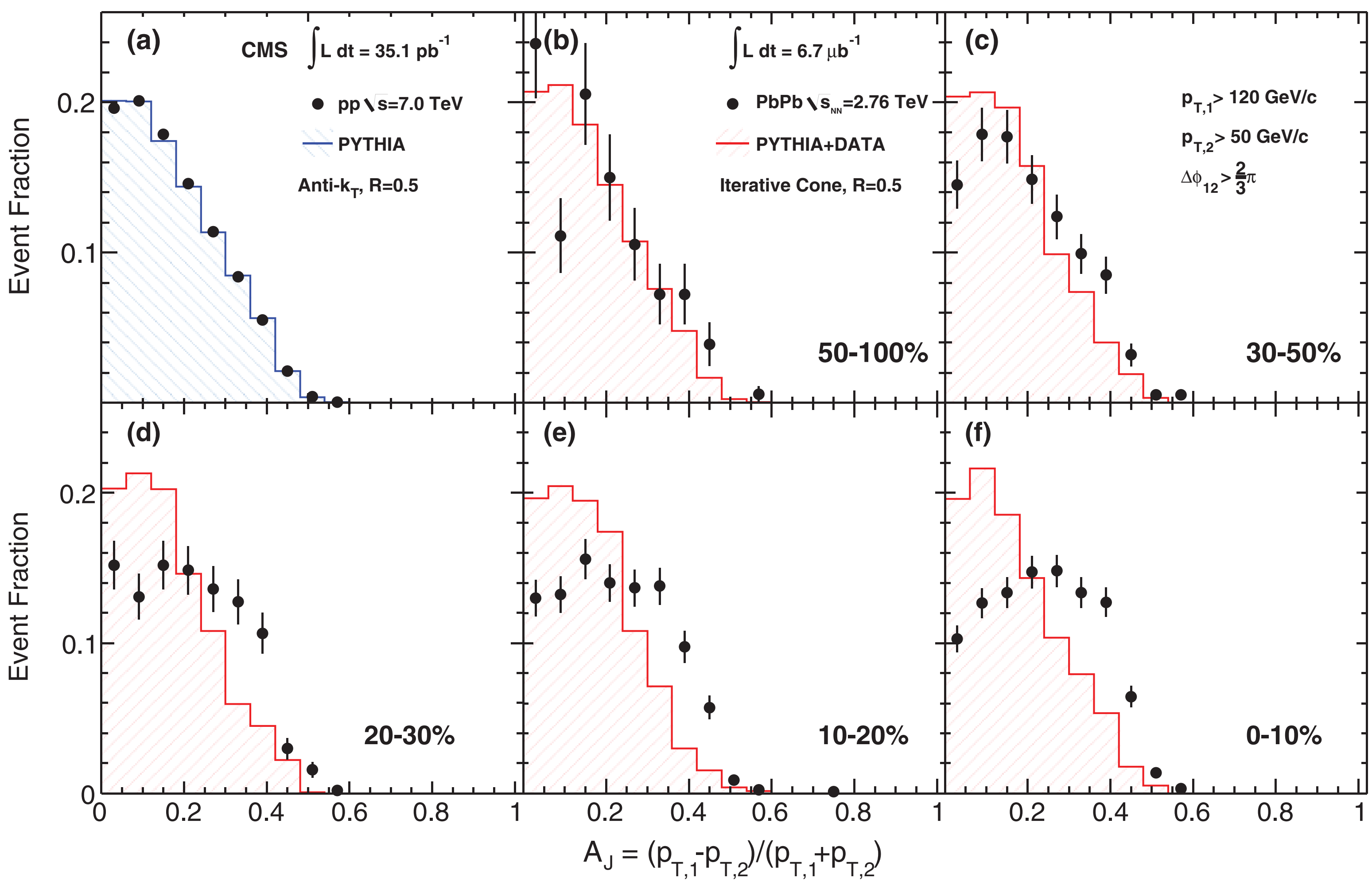


PYTHIA8 Particle Level (PL) and Toy Bkg. Model



A_J at the LHC

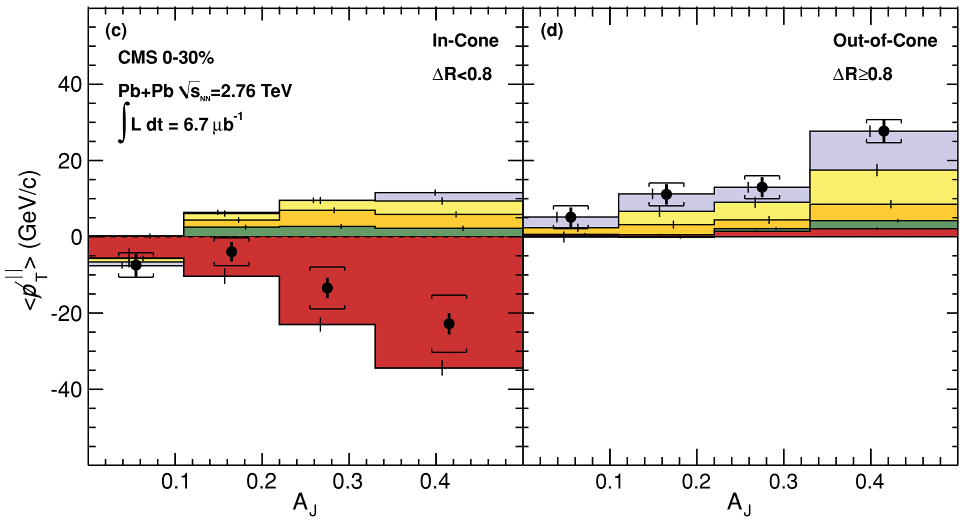
*CMS, PRC **84**, 024906 (2011)*



Significant di-jet momentum imbalance A_J observed in central Pb+Pb

Discussion: RHIC vs LHC

*CMS, PRC **84**, 024906 (2011)*



The momentum difference in the di-jets is balanced by low p_T particles at large angles relative to the away side jet axis

Discussion: RHIC vs LHC

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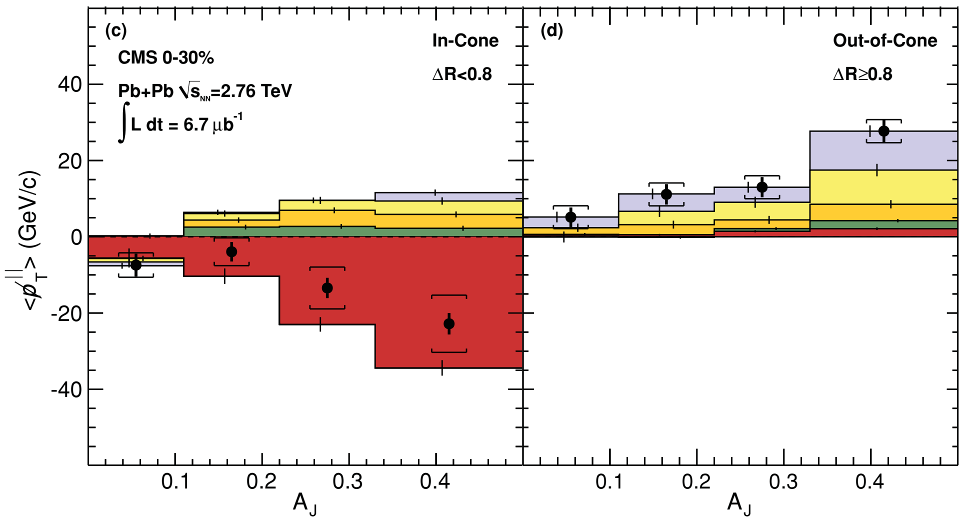

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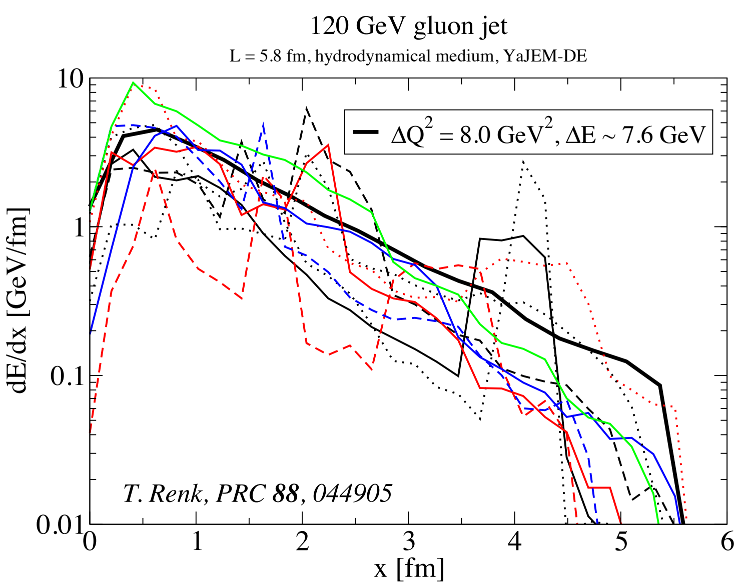

LHC:

Larger energy loss at early times

→ more diffusion in medium

→ larger angles

Discussion: RHIC vs LHC

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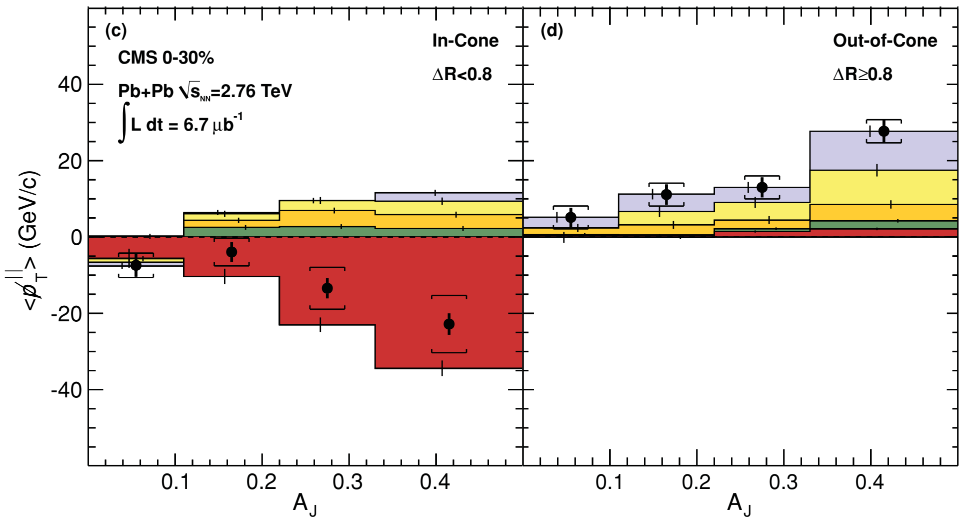

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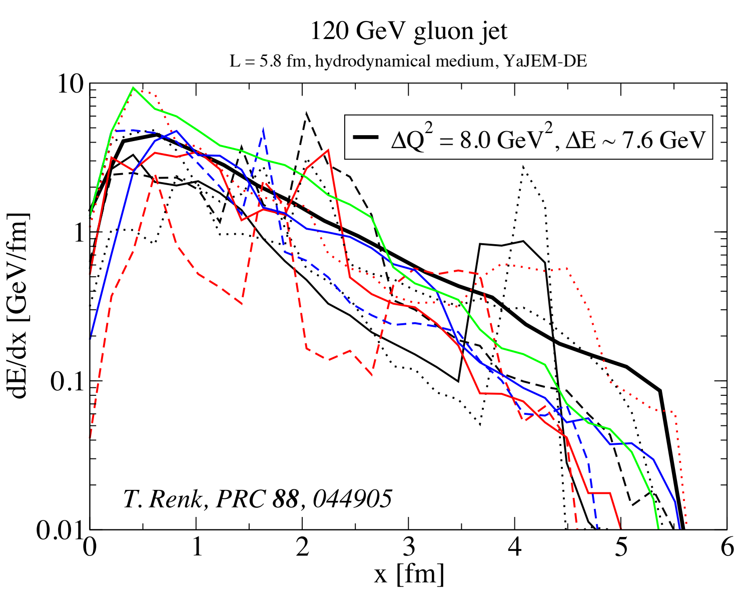


LHC:

Larger energy loss at early times
→ more diffusion in medium
→ larger angles

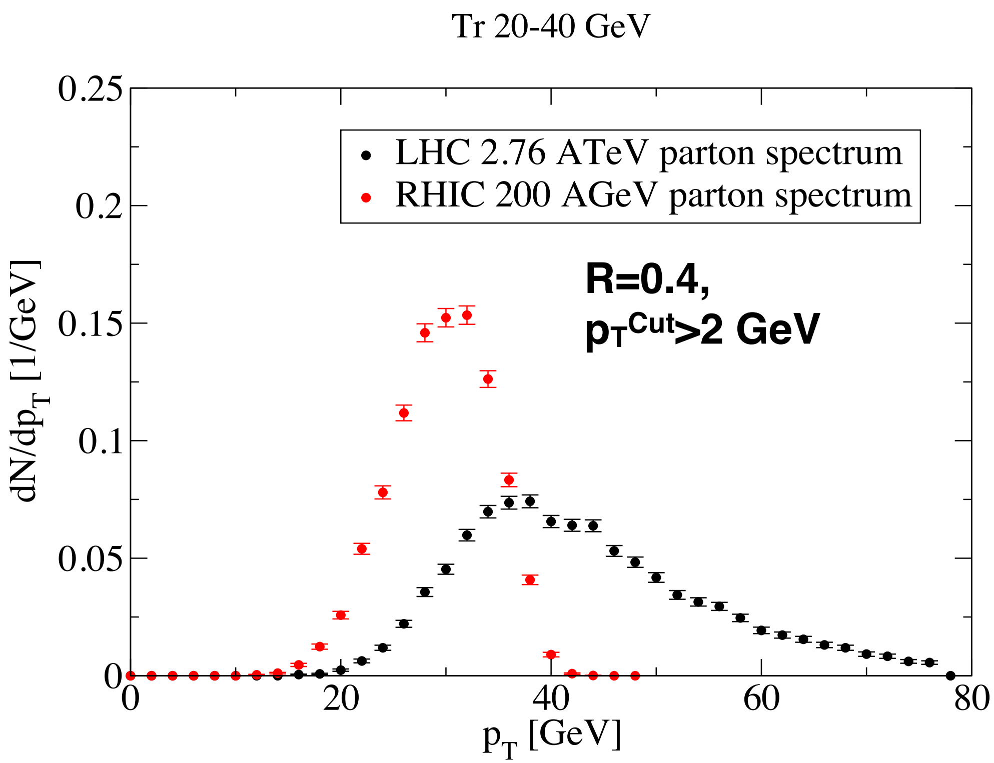
RHIC:

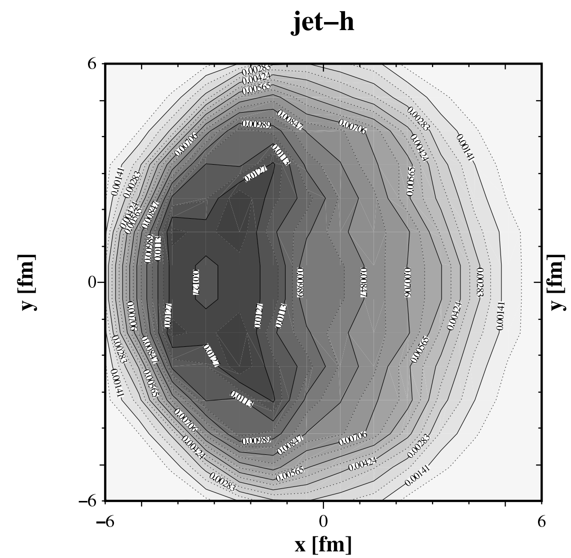
Quenched energy closer to initial parton/jet direction. Can utilize biases for systematic exploration.

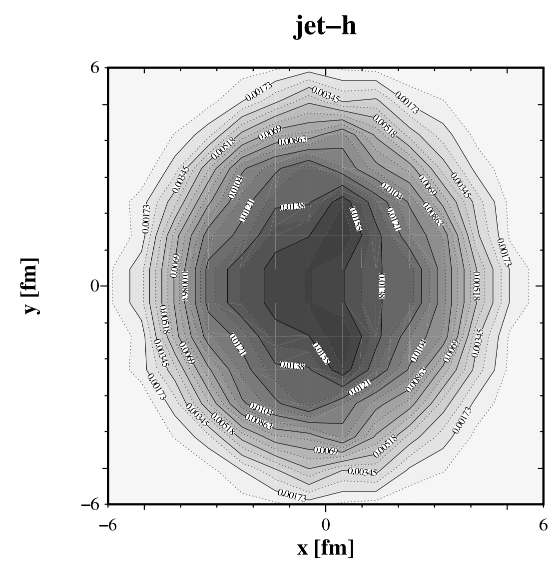
→ (easier) to study soft gluon radiation

Biases are not always bad - actually a strength of RHIC

T. Renk, Phys.Rev. C87 (2013) 024905







Due to the steeply falling spectrum at RHIC, even with imposing biases (p_T^{Cut}, ...), a good correlation to the initial parton energy is preserved

Biases (p_T^{Cut}, ...) can be used to change systematically the pathlength of the recoil jet

Biases (p_T^{Cut}, ...) can be further utilized to favor gluon recoil jets