EUROPEAN PHYSICAL SOCIETY HEP2015

European Physical Society
Conference on High Energy Physics

22-29 July 2015
Vienna

Semi-Inclusive Jet Measurements in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR

STAR

Jan Rusňák for the STAR Collaboration

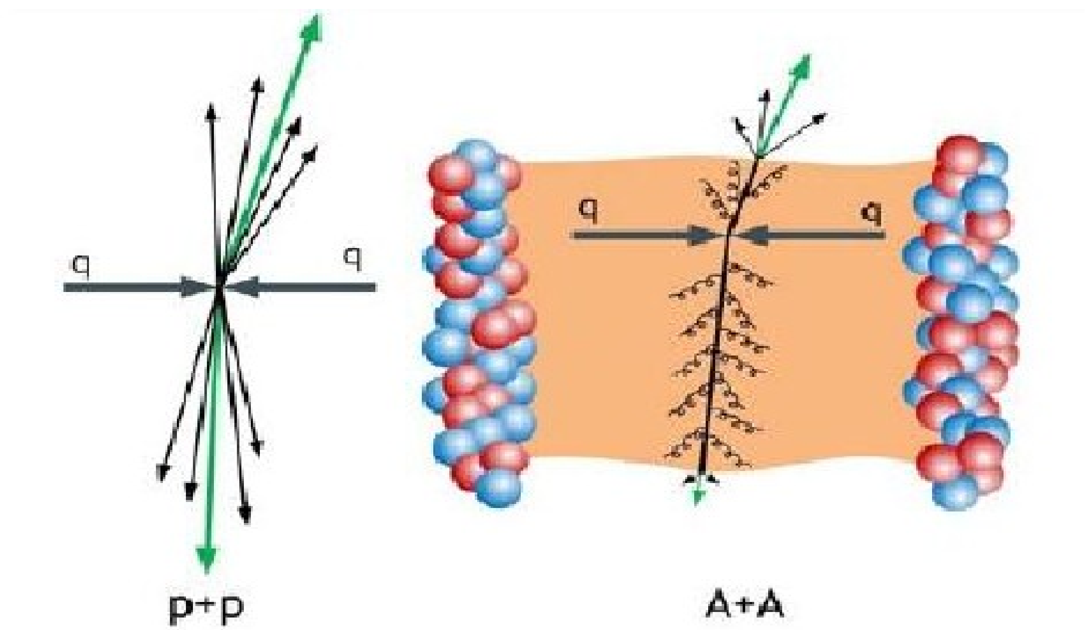
Nuclear Physics Institute ASCR

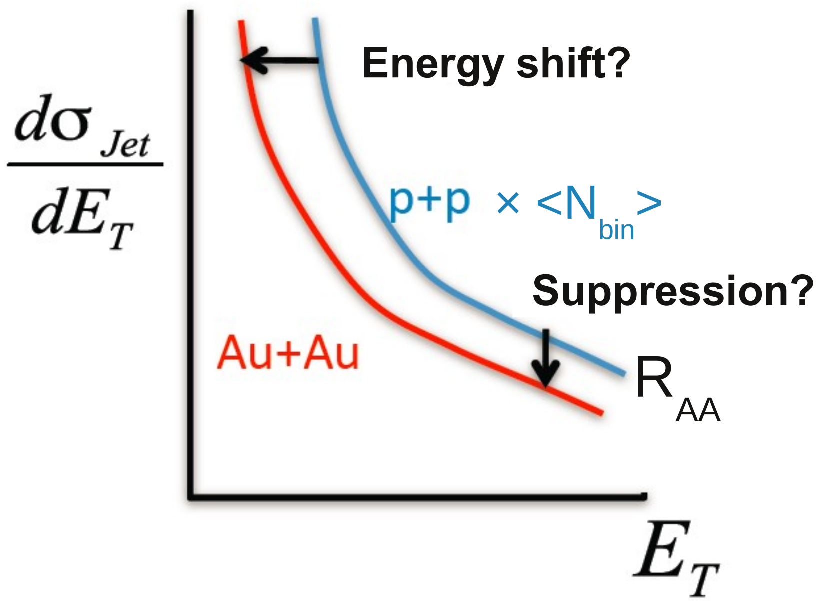
Motivation for Jet Studies

Jets: collimated sprays of hadrons created by fragmentation and hadronization of hard-scattered partons

Elementary collisions: fundamental test of pQCD

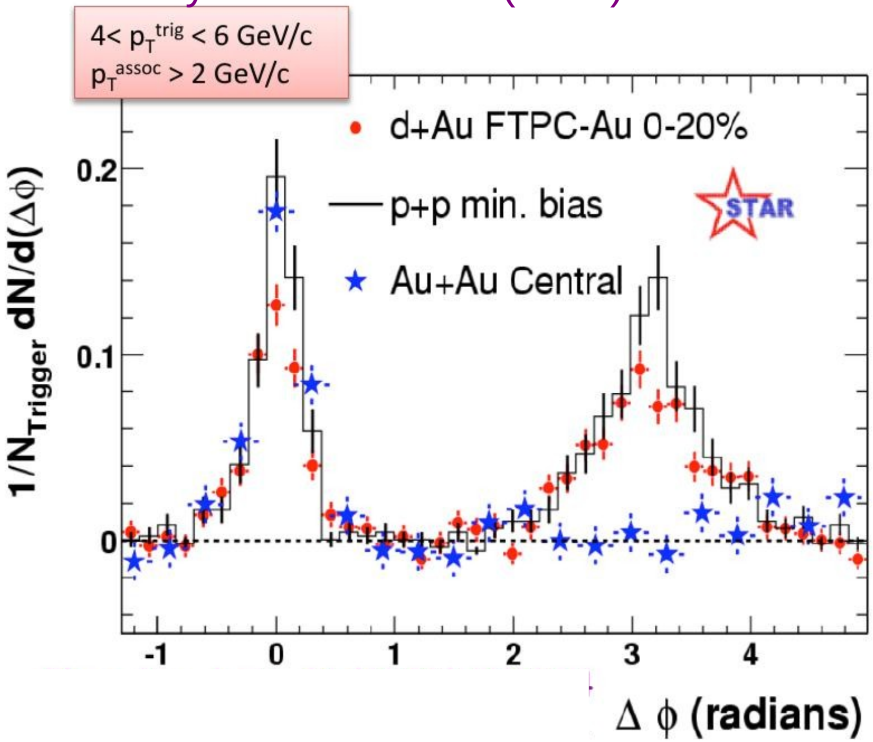
Heavy-ion collisions: energy loss mechanism in Quark Gluon Plasma (QGP)





Di-hadron Measurements: Proxy to Jets

Phys. Rev. Lett. 91 (2003) 072304



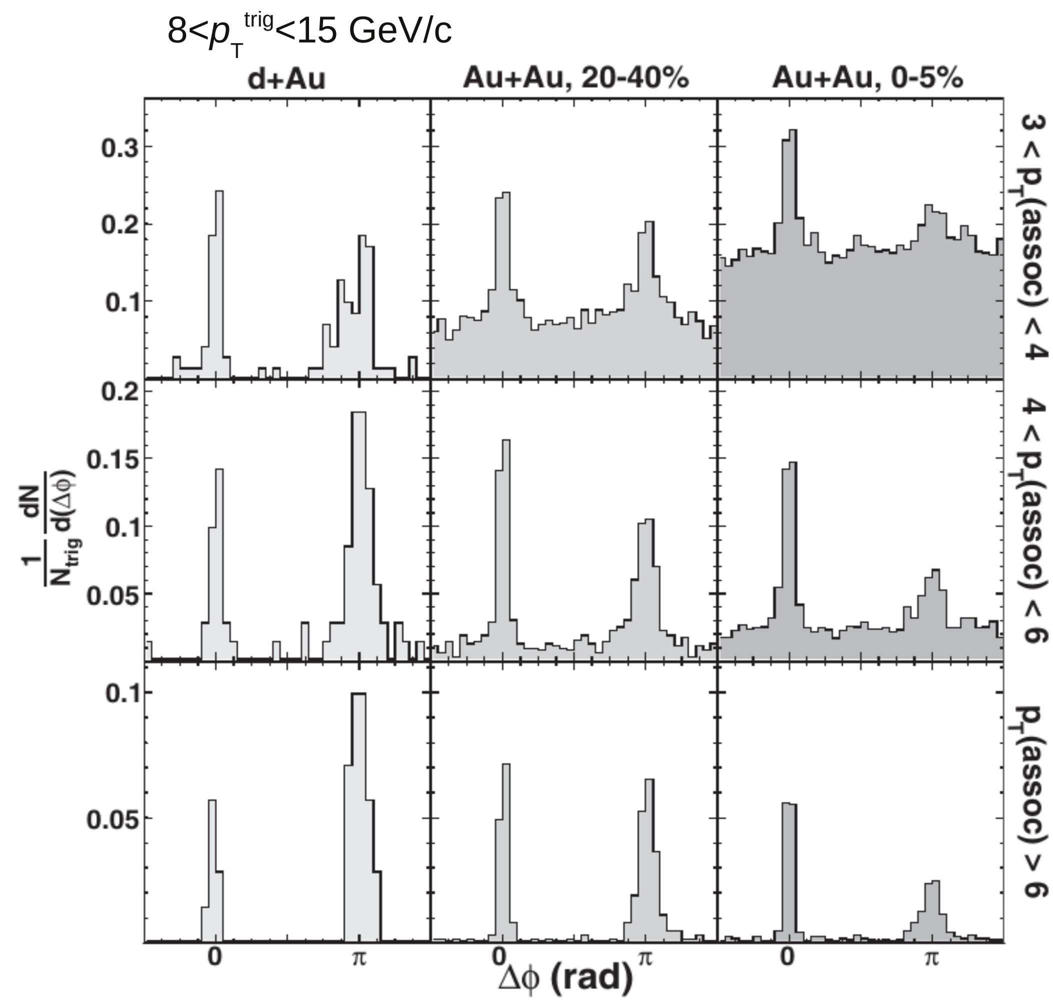
intermediate trigger momentum:

Central Au+Au collisions: suppression of away side jet - "jet quenching"

d+Au: no suppression -> medium effect

Better understanding of jet quenching
=> fully reconstructed jets

Phys. Rev. Lett. 97 (2006) 162301

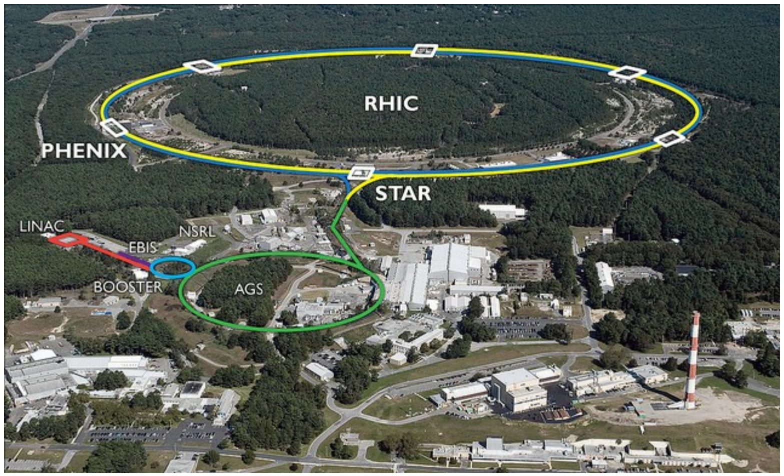


high trigger momentum:

Central Au+Au: away-side "jet" suppression of the order of charged hadrons suppression

STAR Experiment

Relativistic Heavy Ion Collider (RHIC)



Unique machine:
polarized *p+p* collisions, wide range of species,
$\sqrt{s_{NN}}$ from 5.5 to 510 GeV, asymmetric collision...

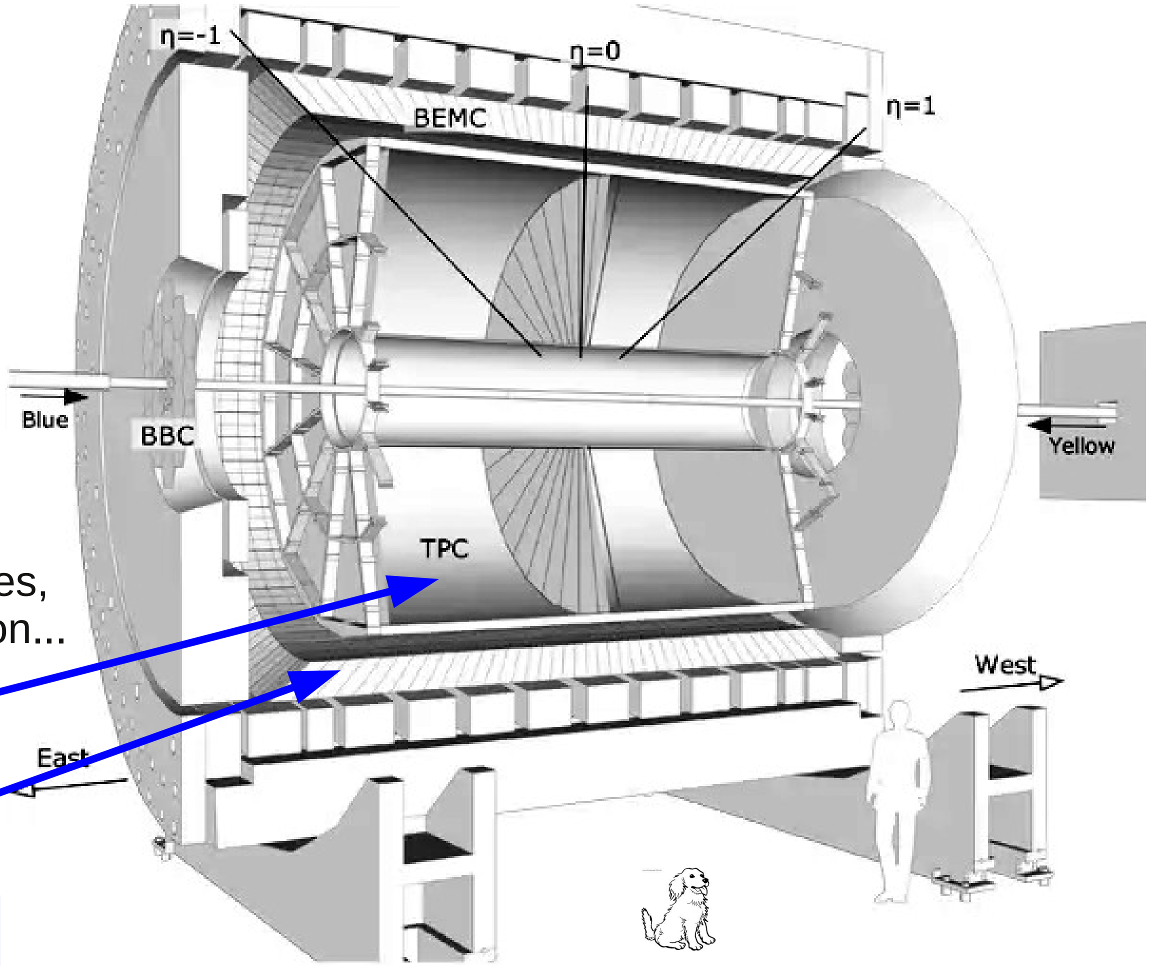
Time Projection Chamber

Barrel ElectroMagnetic Calorimeter

Data-set:

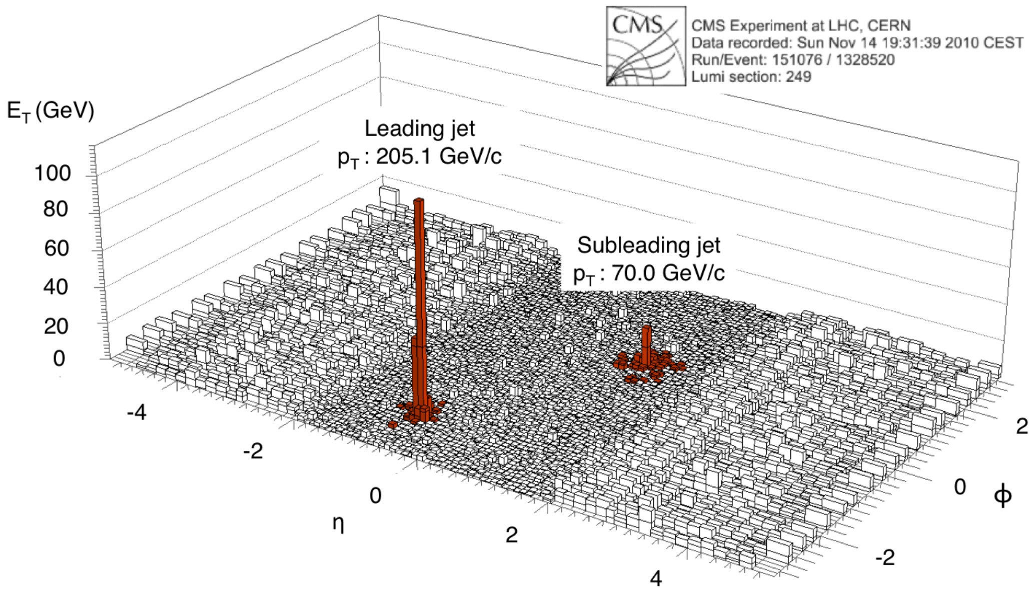
- TPC tracks only
- Year 2011 Au+Au $\sqrt{s_{NN}}$=200GeV

Solenoidal Tracker at RHIC (STAR)



full azimuthal coverage
pseudo-rapidity coverage: -1<η<1
TPC: low-momentum tracking (0.1 GeV/c)

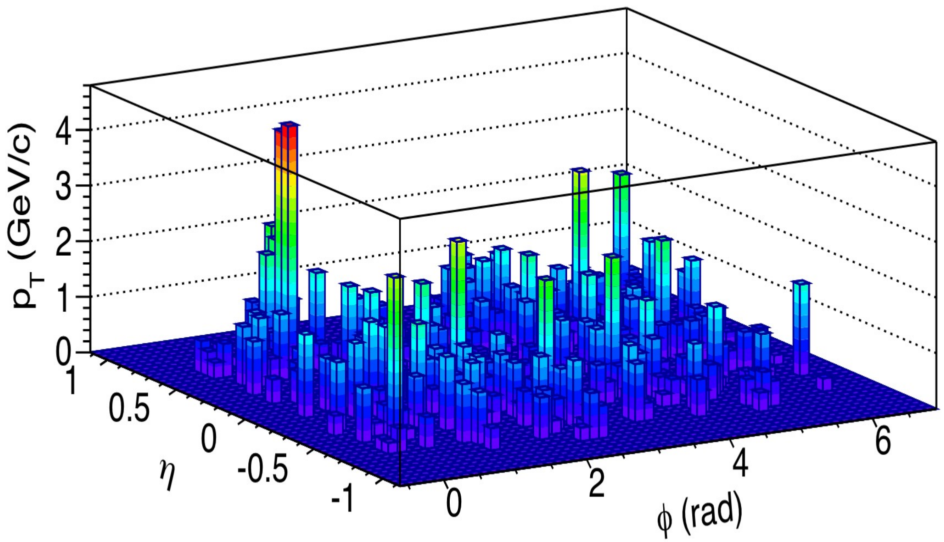
Jet Reconstruction in Heavy Ion Collisions



LHC:

- Jets dominate over the background

→ Clear jet identification (at high p_T)

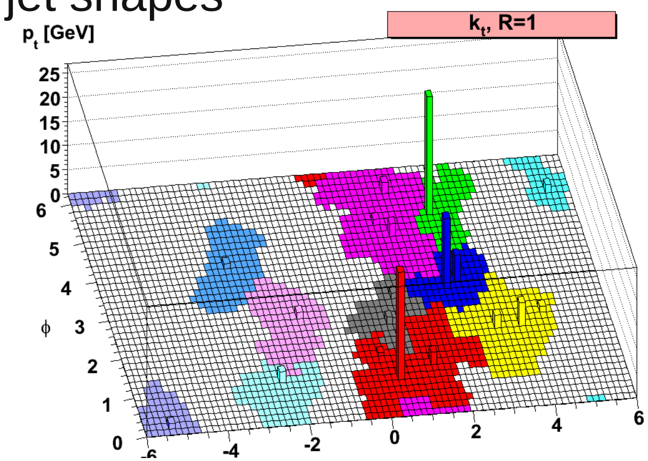


RHIC:

- **Background fluctuations comparable to signal** → Jet identification is extremely challenging task
- Signal identification on statistical basis

Jet Reconstruction Algorithms

- infrared and collinear safe reconstruction algorithms
  (FASTJET [Cacciari, Salam, Soyez : Eur.Phys. J. **C72** (2012) 1896])
- clustering algorithms:
  - k_T- starts clustering from low-p_T particles; irregular jet shapes
  - anti-k_T - starts clustering from high-p_T particles; cone-like jet shapes

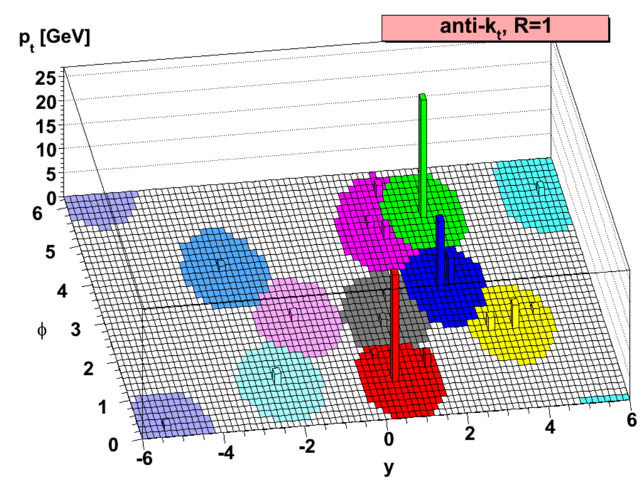


arXiv:0906.1598

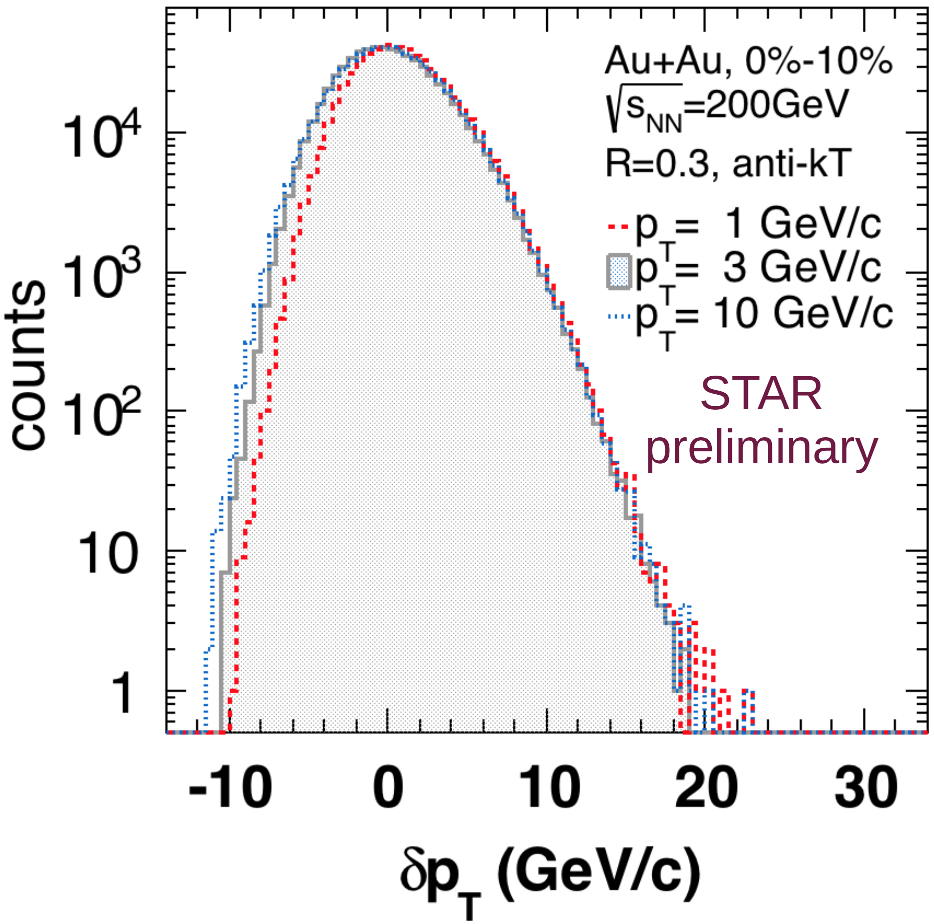
<u>key steps:</u>

- jet reconstruction: different resolution parameters *R*
- correction for background energy density $\rho = med\left\{\frac{p_{T,i}}{A_i}\right\}$ $\quad A_i$ ...jet area

$$\boxed{p_{T,reco} = p_T - A_{jet} \times \rho}$$



Background Fluctuations



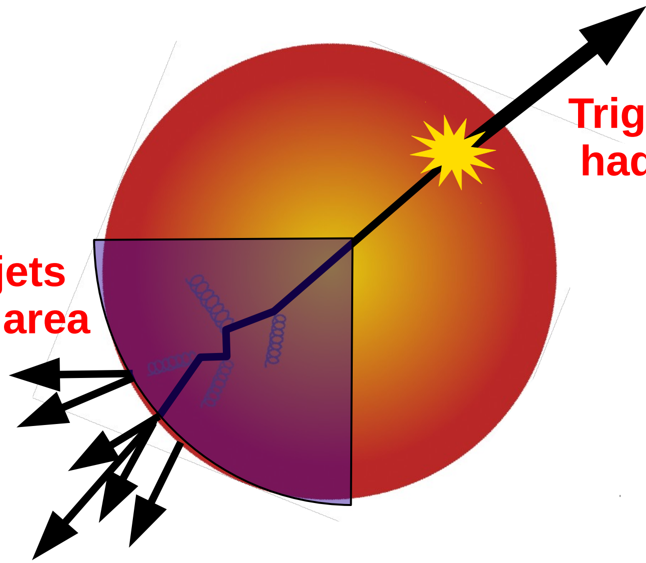
- Simulated jets embed into real events to determine effect of background fluctuations on jet momentum

$$\delta p_T = p_{T,reco} - p_{T,emb} = p_T - A_{jet} \times \rho - p_{T,emb}$$

- δp_T depends little on embedded particle momentum

- δp_T used to unfold the spectrum

Semi-inclusive Recoil Jets



Trigger: high-p_T hadron → selects hard event

Recoil side: use all jet candidates within +/- 45°

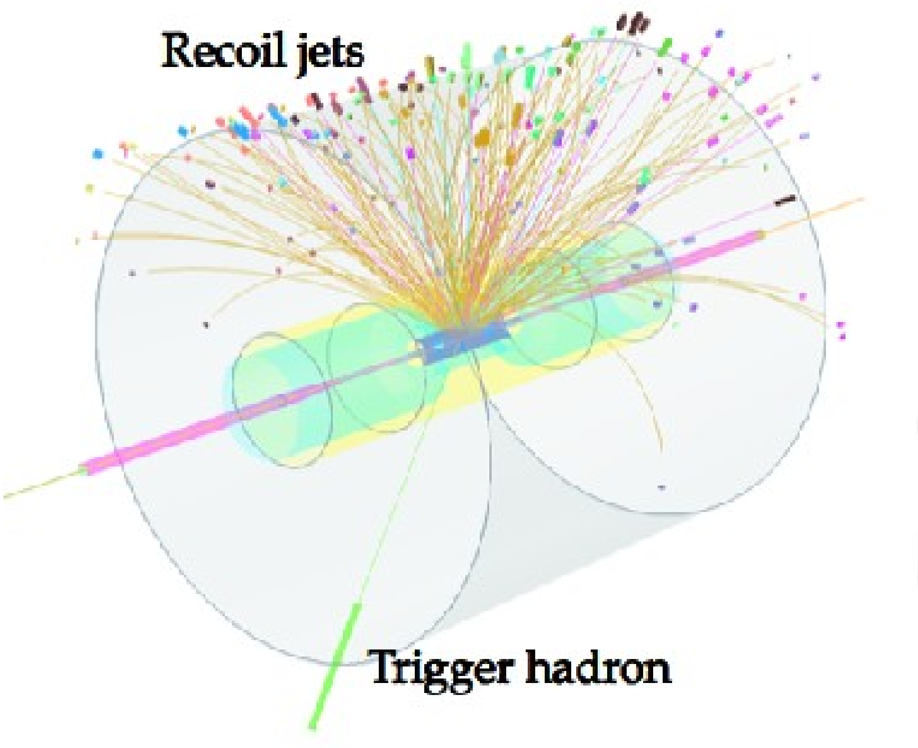
→ **no fragmentation bias**

Observable:
Recoil jets per trigger

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

Measured

Calculable in NLO pQCD



Semi-inclusive Recoil Jets

Analysis in STAR:

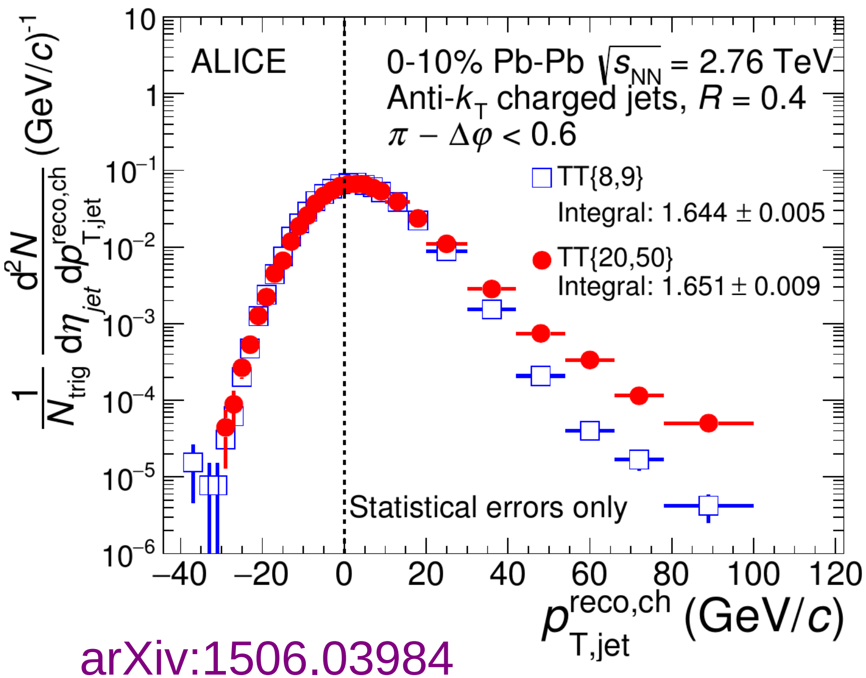
- Recoil jet azimuth: $|\Delta\varphi-\pi|<\pi/4$
- No rejection of jet candidates on jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)
- **Background subtraction:**

  Mixed event technique

ALICE:

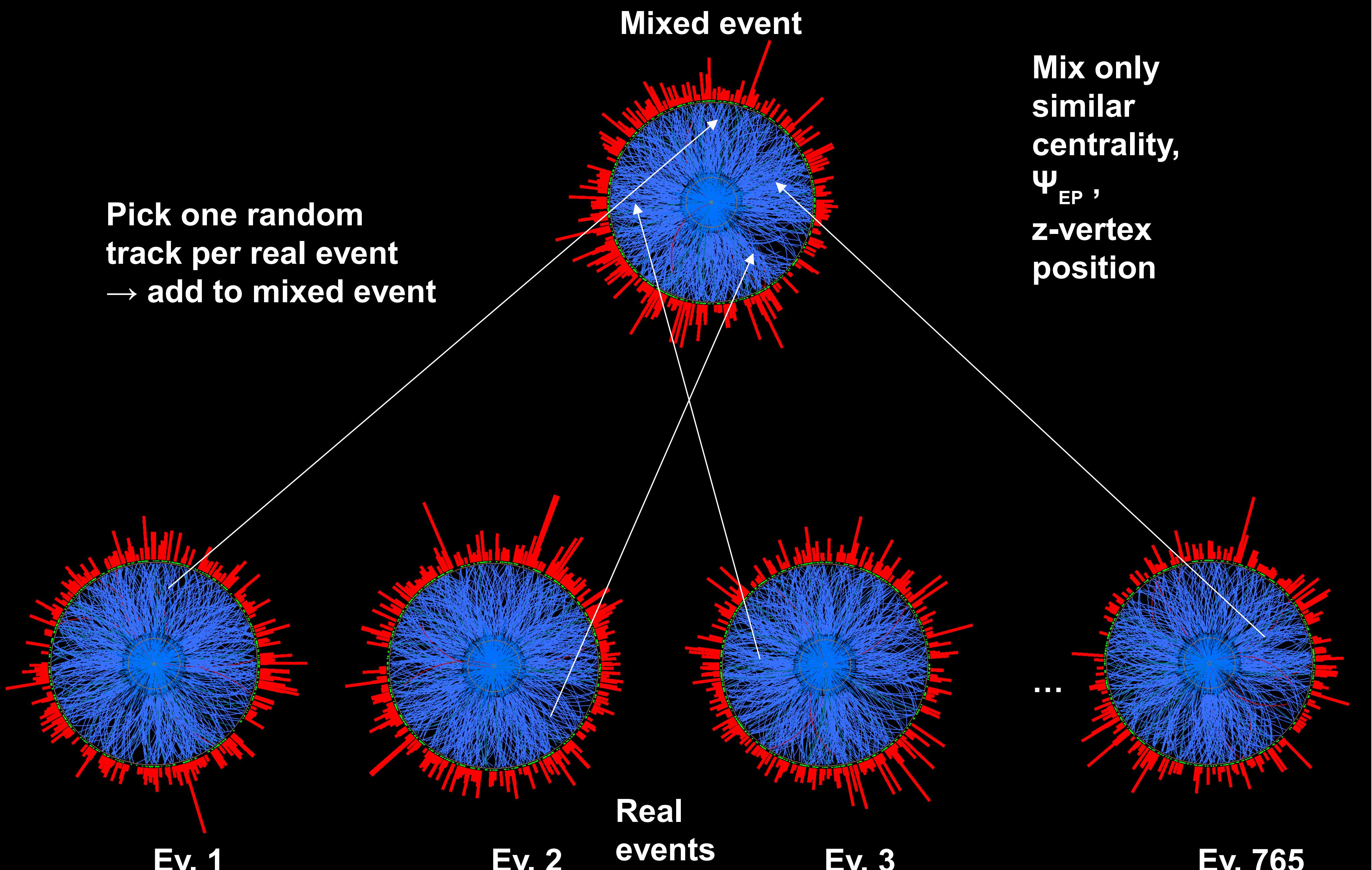
- **Background subtraction: two different trigger track (TT) p_T ranges**

Δ_{recoil}=TT_{signal}-$TT_{reference}$

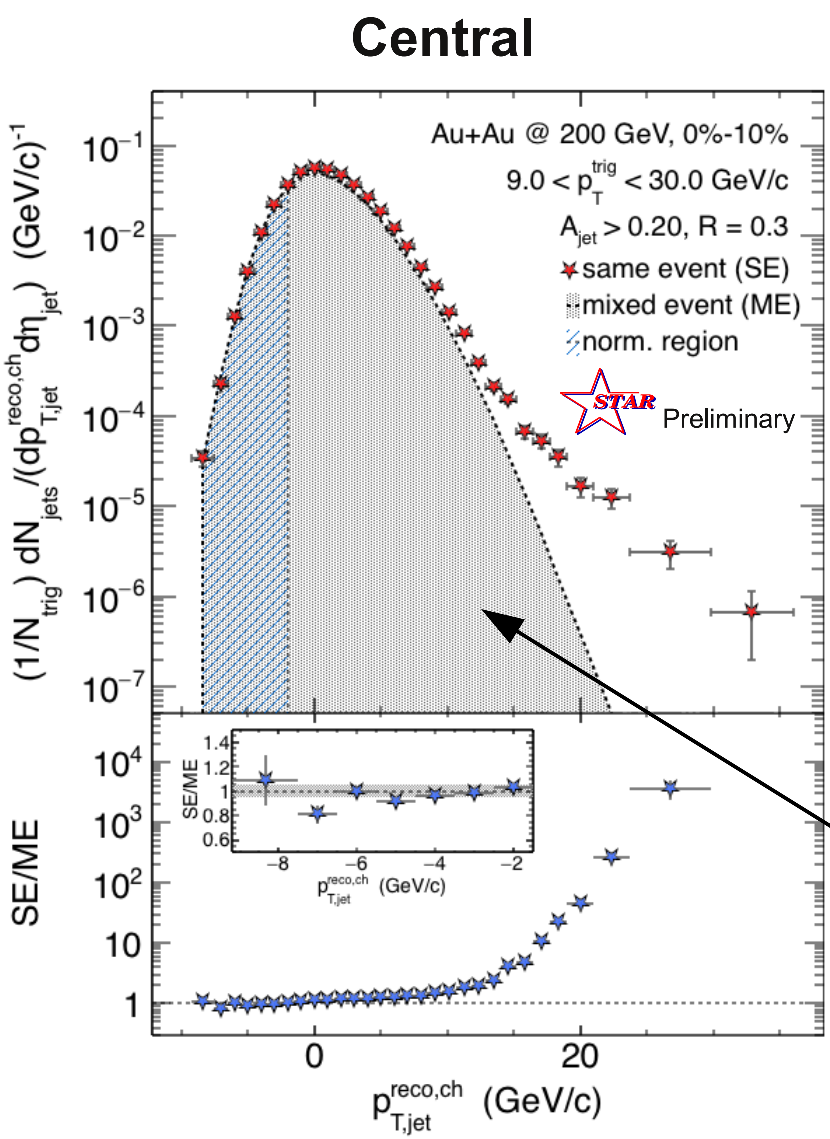


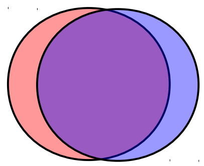
arXiv:1506.03984

Mixed Event Generation for Jets



Raw Charged Recoil Jet Spectrum: Central

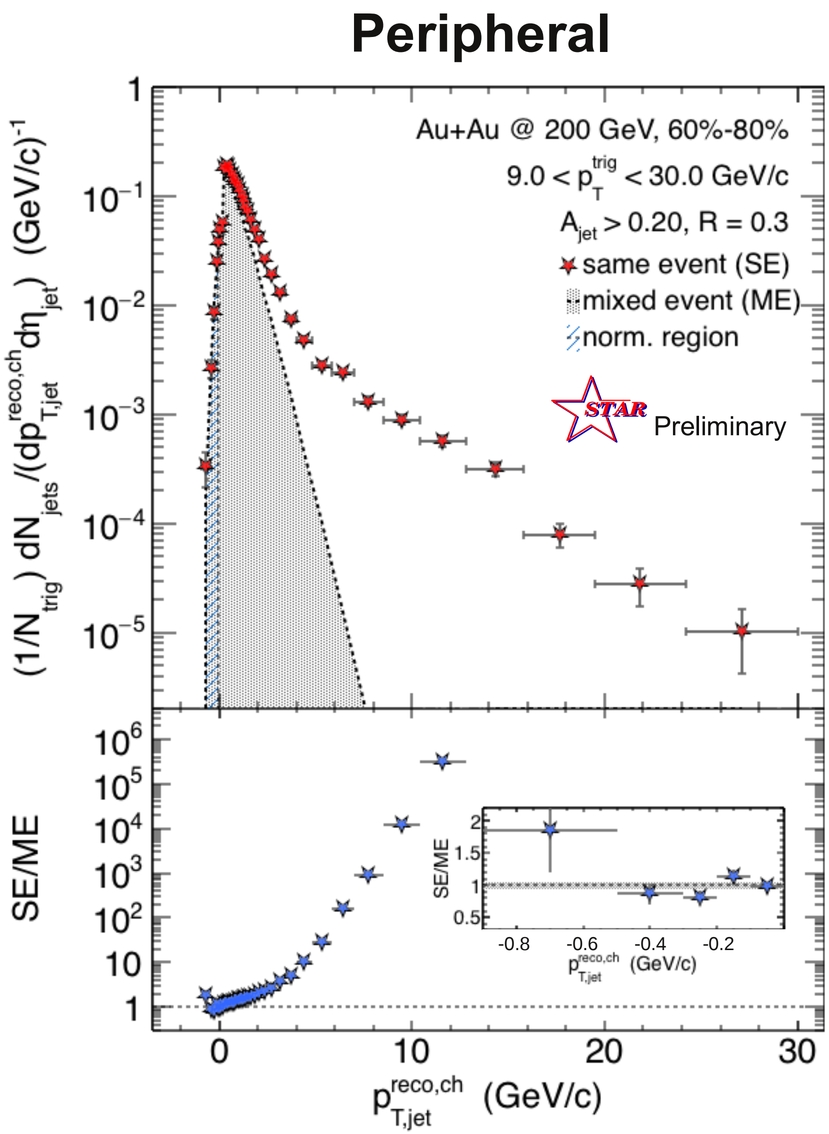


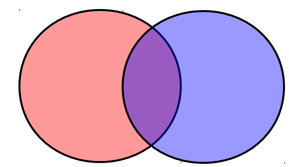


- Excellent description of low p_T SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at p_T^{reco}=p_T-ρA > 10 GeV/c

Combinatorial jet background statistically described by mixed event technique

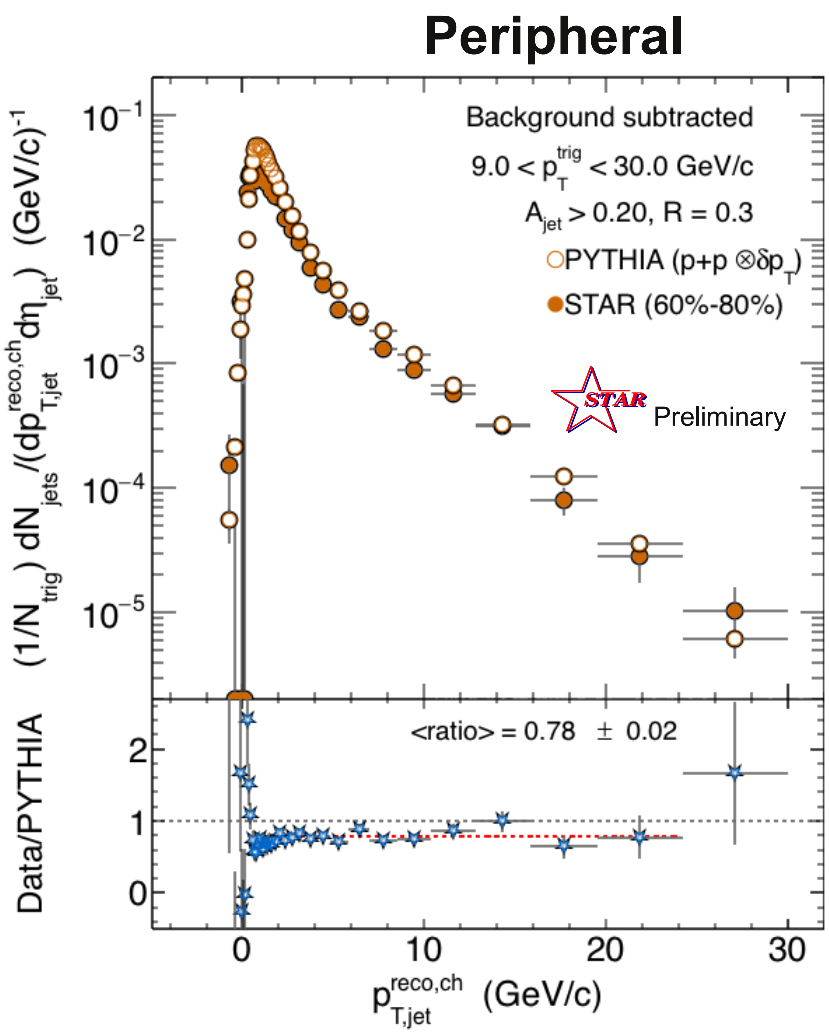
Raw Charged Recoil Jet Spectrum: Reference

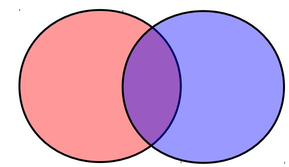




- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c

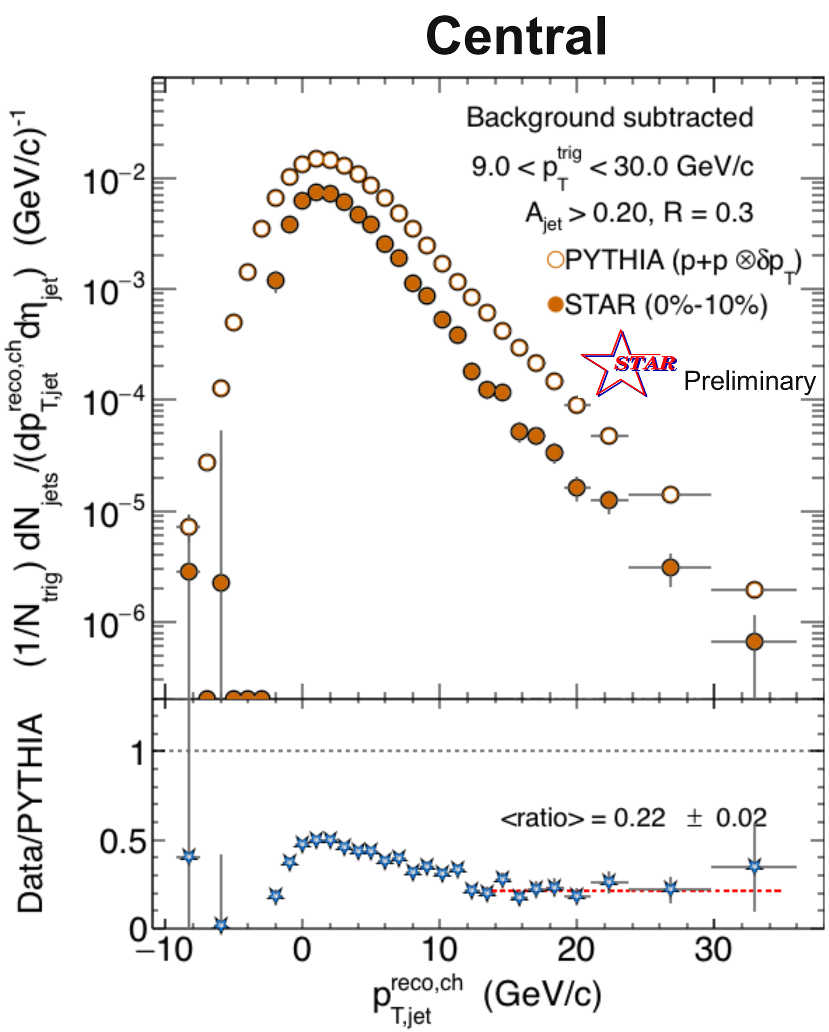
Reference vs. PYTHIA

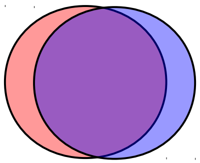




- Background-subtracted spectrum in 60%-80% Au+Au in comparison with smeared PYTHIA
- PYTHIA shape in good agreement with 60%-80% data
- small suppression in yield (data/PYTHIA)

Recoil Jet Energy Loss



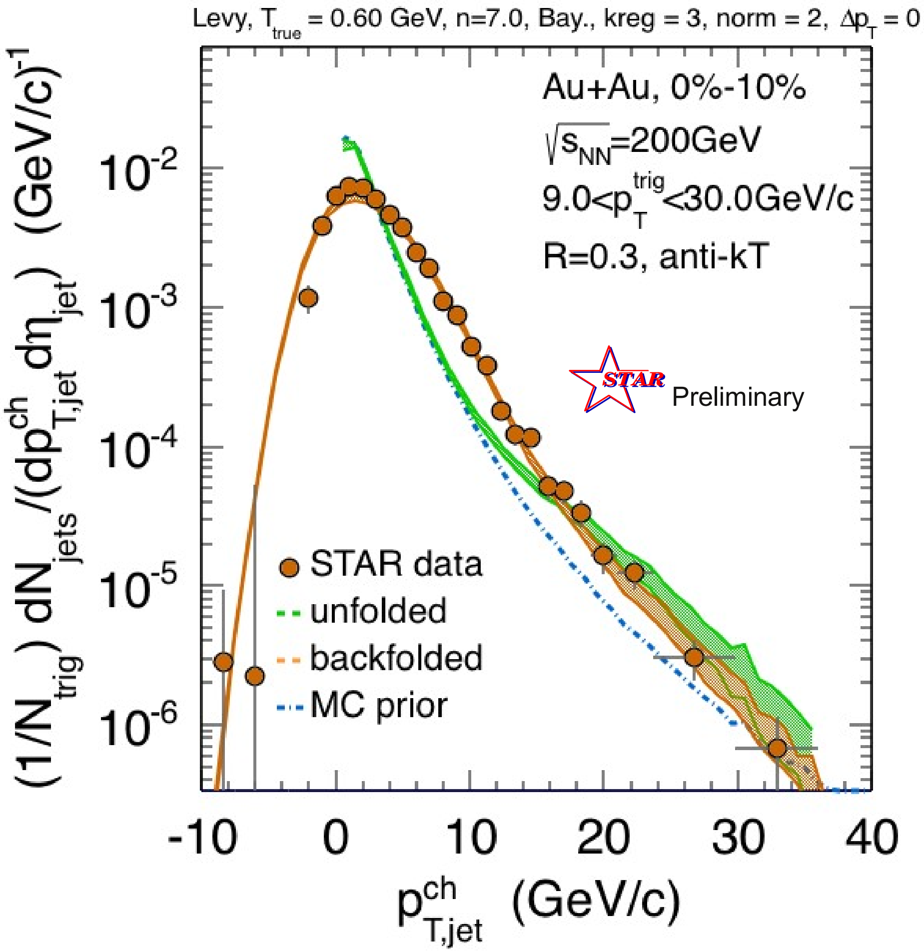


- Significant suppression (central/smeared PYTHIA) over whole p_T range
  → energy loss

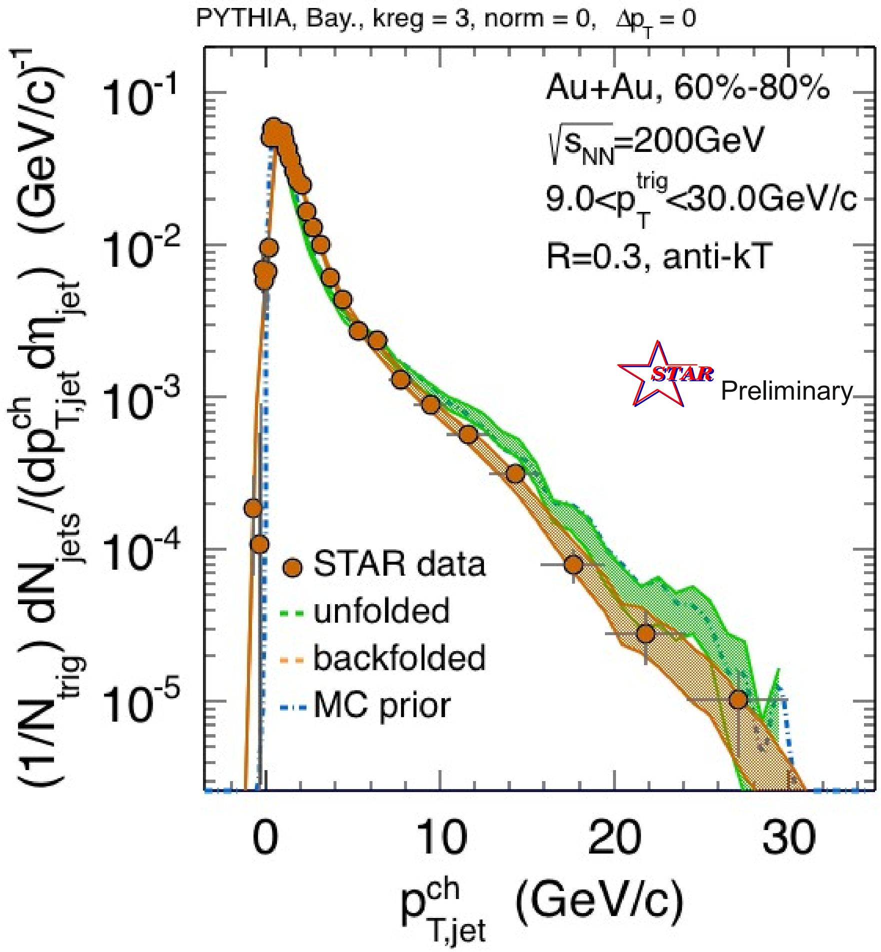
- Very similar shape over 4 orders of magnitude

Unfolding Examples

Central (Levy prior example)



Peripheral (PYTHIA prior example)



- SVD and Bayesian unfolding used
- Systematic variation of: Prior → {Levy function (T, n), PYTHIA}, regularization parameter, +/-5% efficiency variation, ME normalization, δp_T distribution (single particle embedding, PYTHIA jet embedding)
- Check based on backfolding χ^2

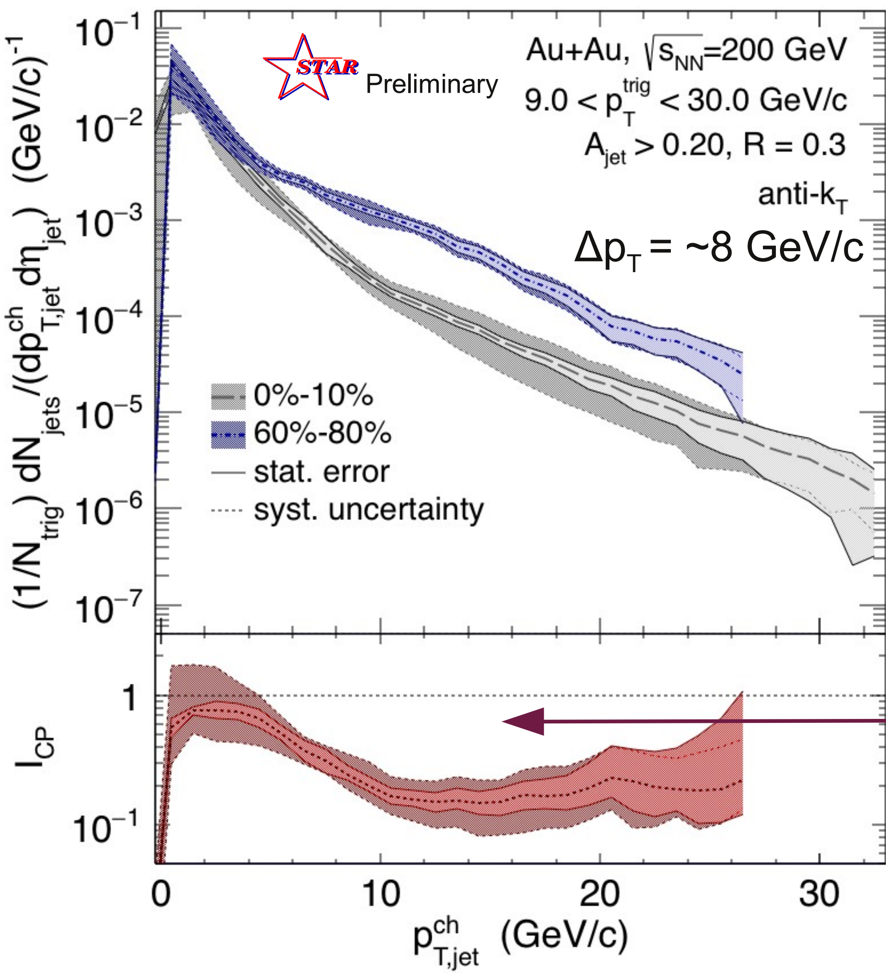
Comparison Central-Peripheral: I_{CP}

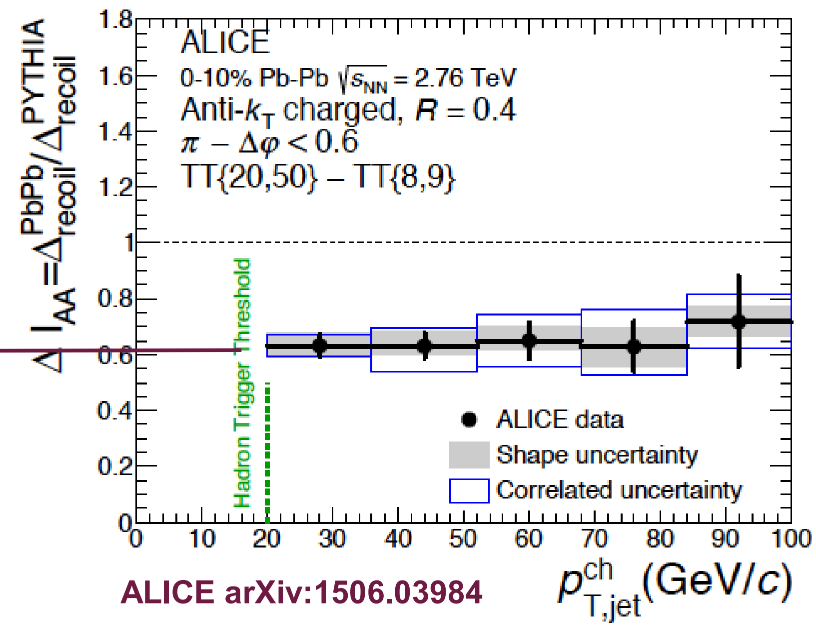
- Significant suppression (~0.2) at p_T > 10 GeV/c

- I_{CP} close to 1 at low p_T

- Larger suppression wrt LHC energies
  - but: different trigger range, back-ground subtraction, $\Delta\varphi$ cut,...

- Similar shift in Δp_T (-8+/-2 GeV/c for ALICE)





ALICE arXiv:1506.03984

- Errors show combined systematics of unfolding and track reconstruction

Summary

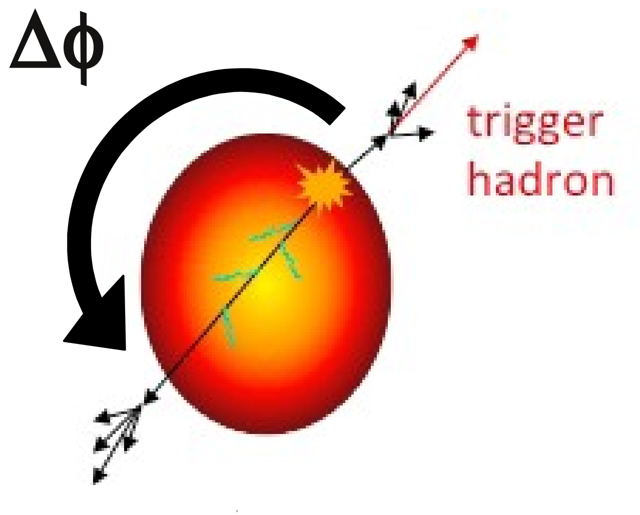
- First measurement of hadron triggered recoil jet spectra at RHIC
- New mixed event technique can reproduce combinatorial jet background
- Low p_T jets accessible, and no bias on recoil jet side
- Direct comparison to pQCD calculations possible
- Suppression (~0.2) is larger compared to LHC energies

Outlook

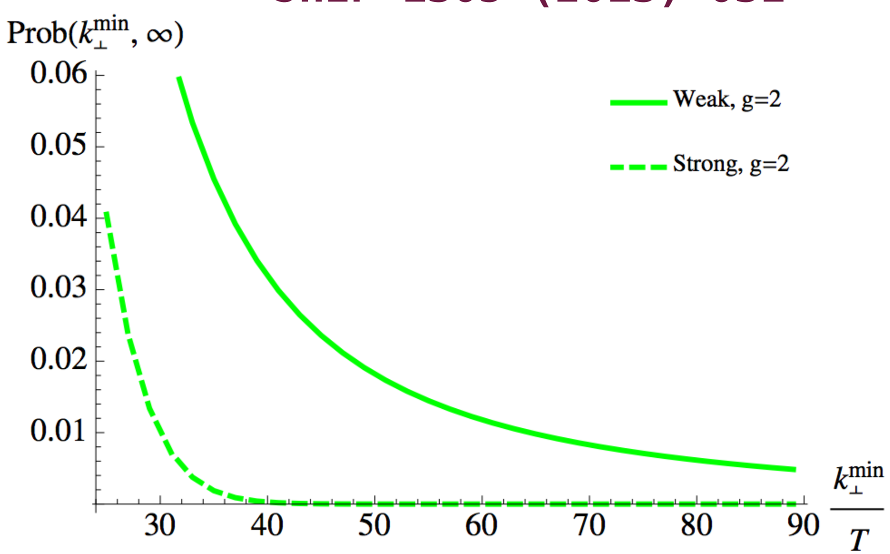
- Full jet reconstruction @ 200 GeV+ more statistics soon
- Low energy (Au+Au @ 62.4 GeV) jet reconstruction

BACKUP

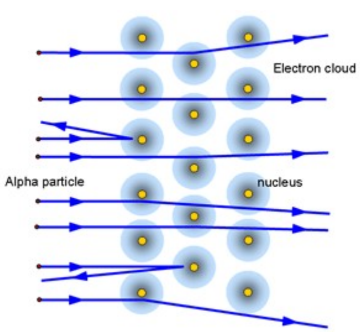
Large Angle Scattering off the QGP?



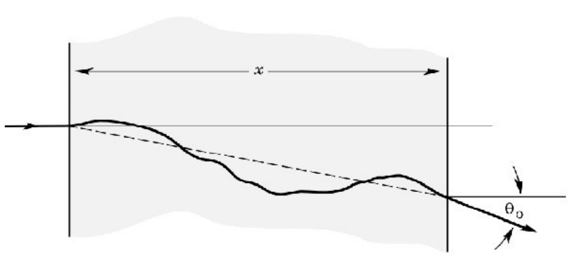
JHEP 1305 (2013) 031



Discrete scattering centers or effectively continuous medium?



“Weak”



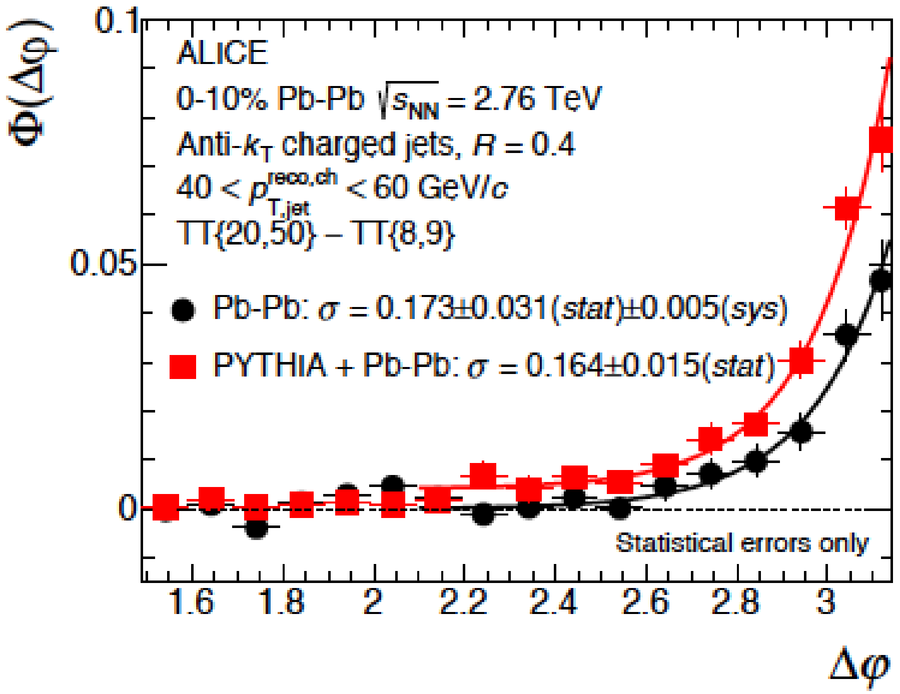
“Strong”

Scattering probability can give us important information about coupling

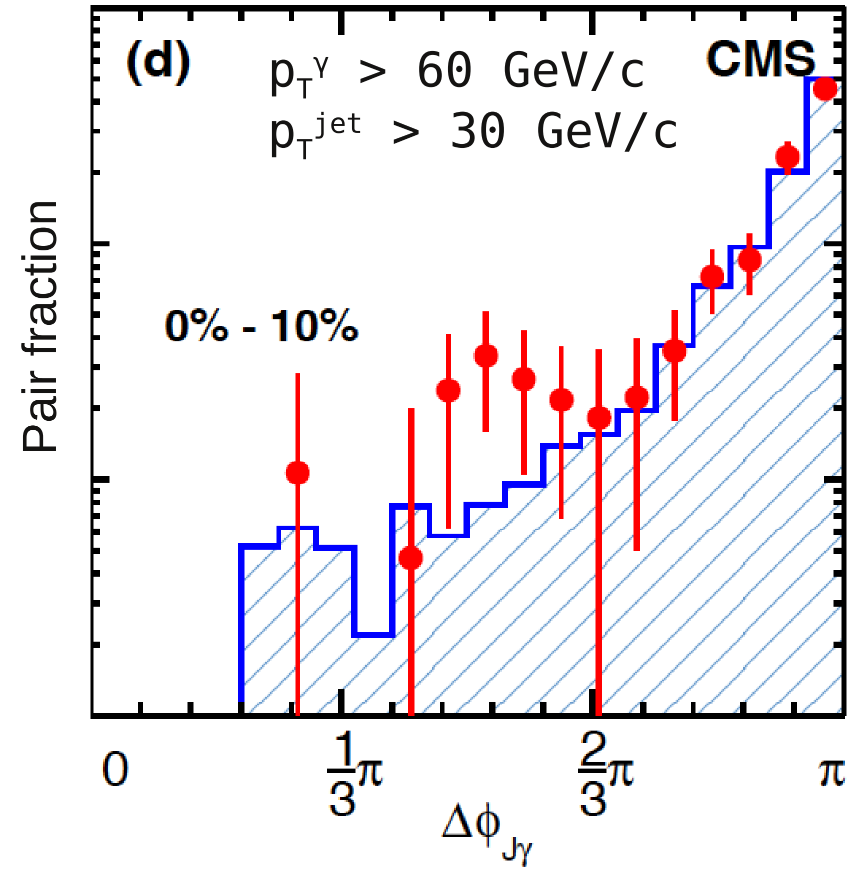
- strongly/weakly coupled QGP
- quasiparticles?

Large Angle Scattering at LHC

arXiv:1506.03984 [nucl-ex]

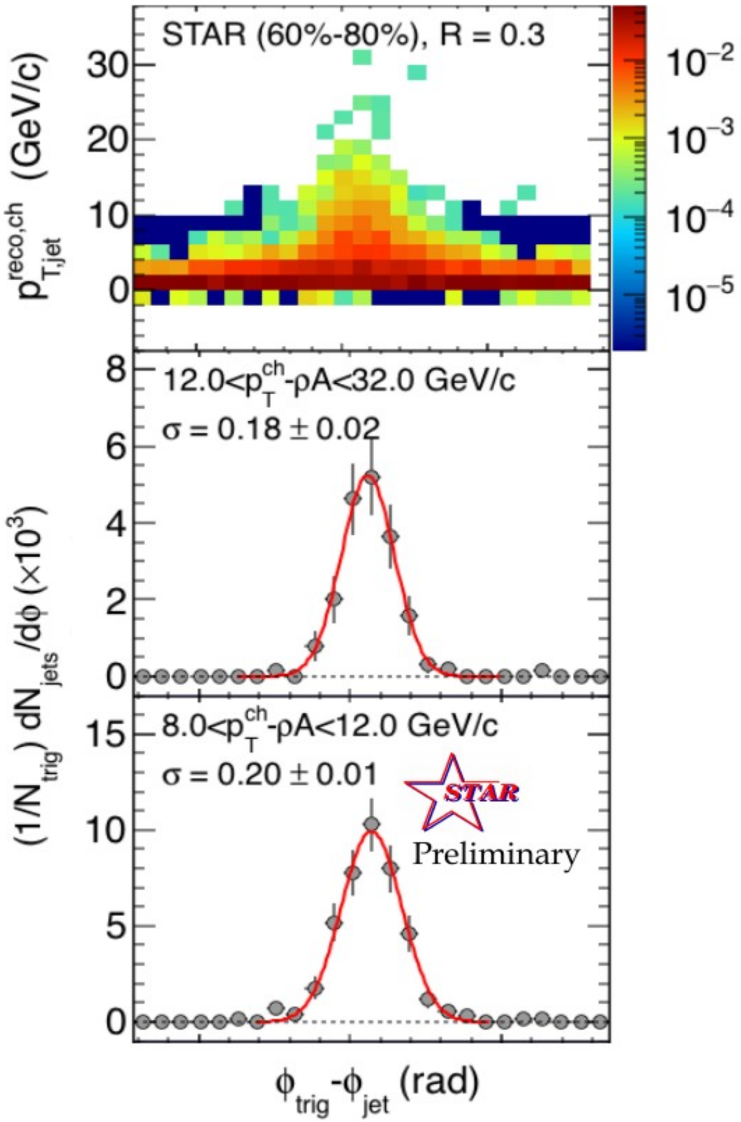


Phys.Lett. B718 (2013) 773-794



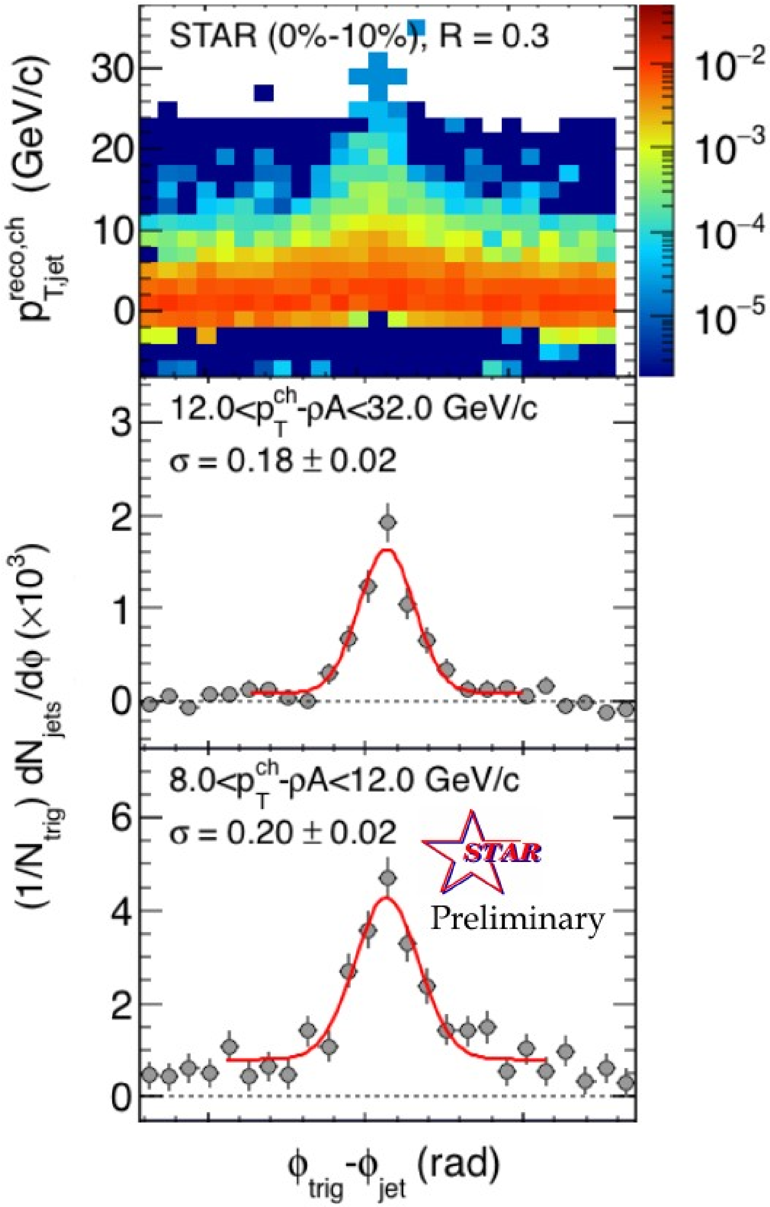
- No additional broadening observed in Pb+Pb compared to p+p so far

ΔΦ, 60%-80%, R = 0.3



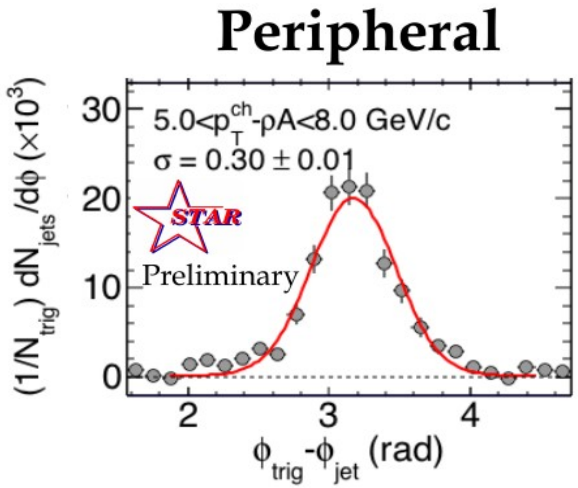
- $\Delta\phi = \phi_{trig} - \phi_{jet}$
- Projections for different recoil jet p_T
- Gaussian + 0th order polynomial
- Fit results do not depend on ME normalization
- Almost no pedestal for 60%-80%

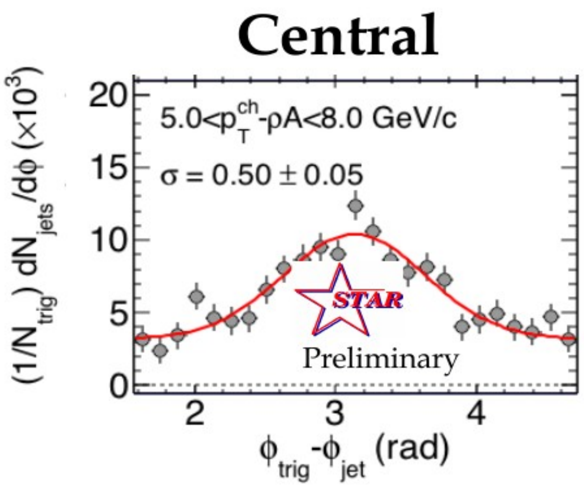
ΔΦ, 0%-10%, R = 0.3



- $\Delta\phi = \phi_{trig} - \phi_{jet}$
- Projections for different recoil jet p_T
- Gaussian + 0th order polynomial
- Fit results do not depend on ME normalization
- Some pedestal for 0%-10%

ΔΦ, at low p_T

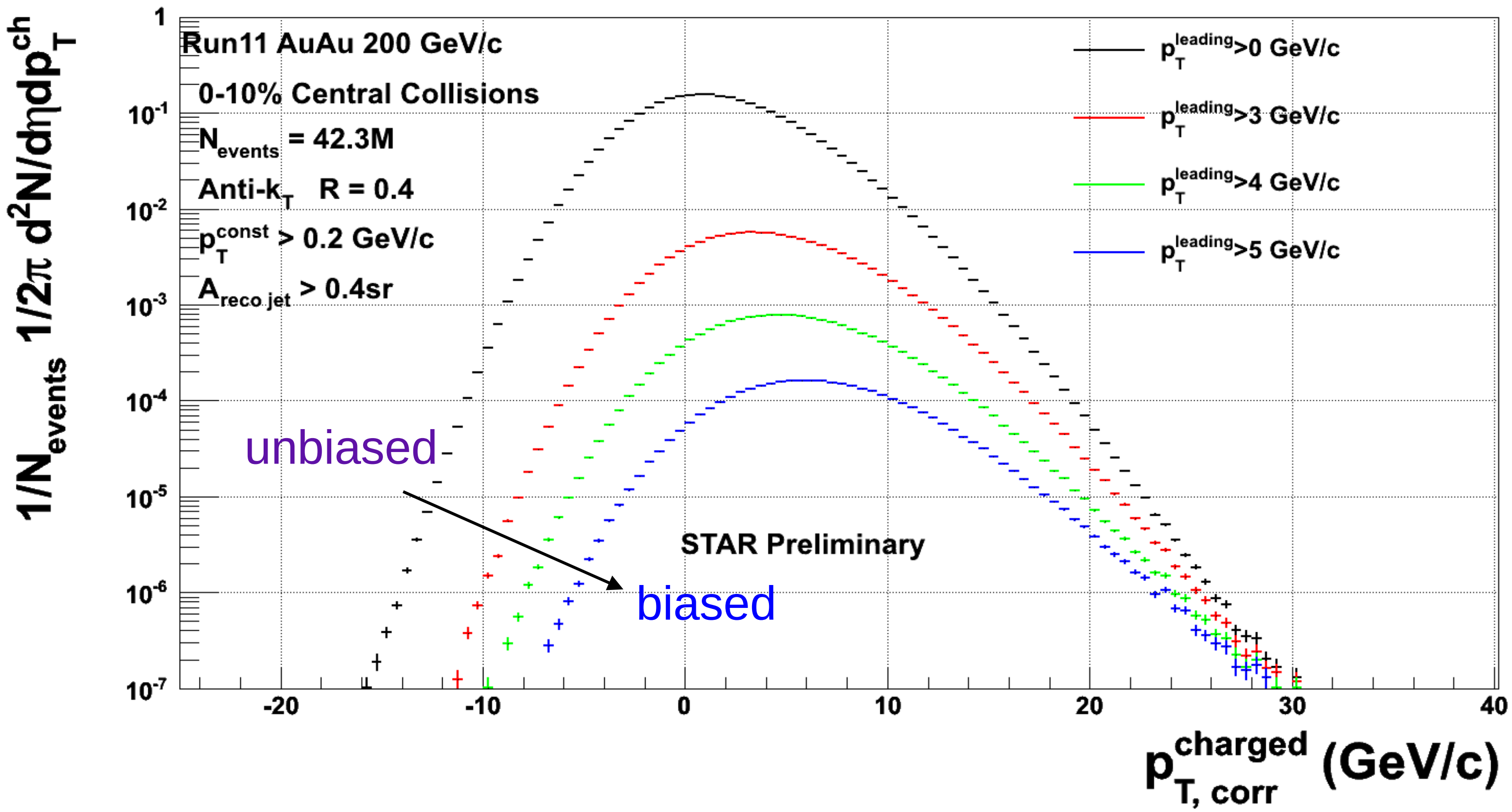


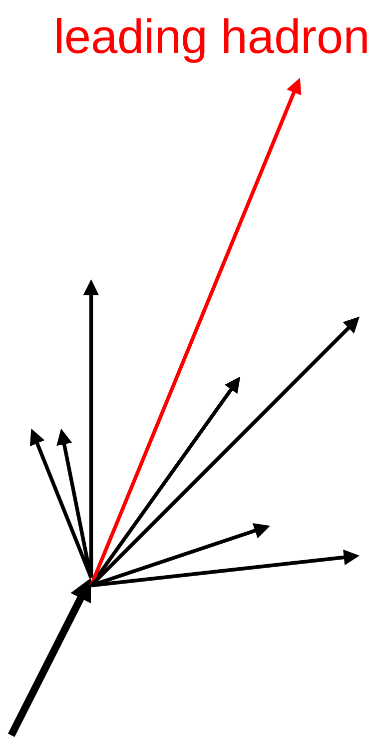


- Significant difference at 5 < p_T-ρA < 8 GeV/c
  - → Flow?
  - → Φ dependent normalization needed?
  - → Background from multiple interactions?
  - → More studies needed!

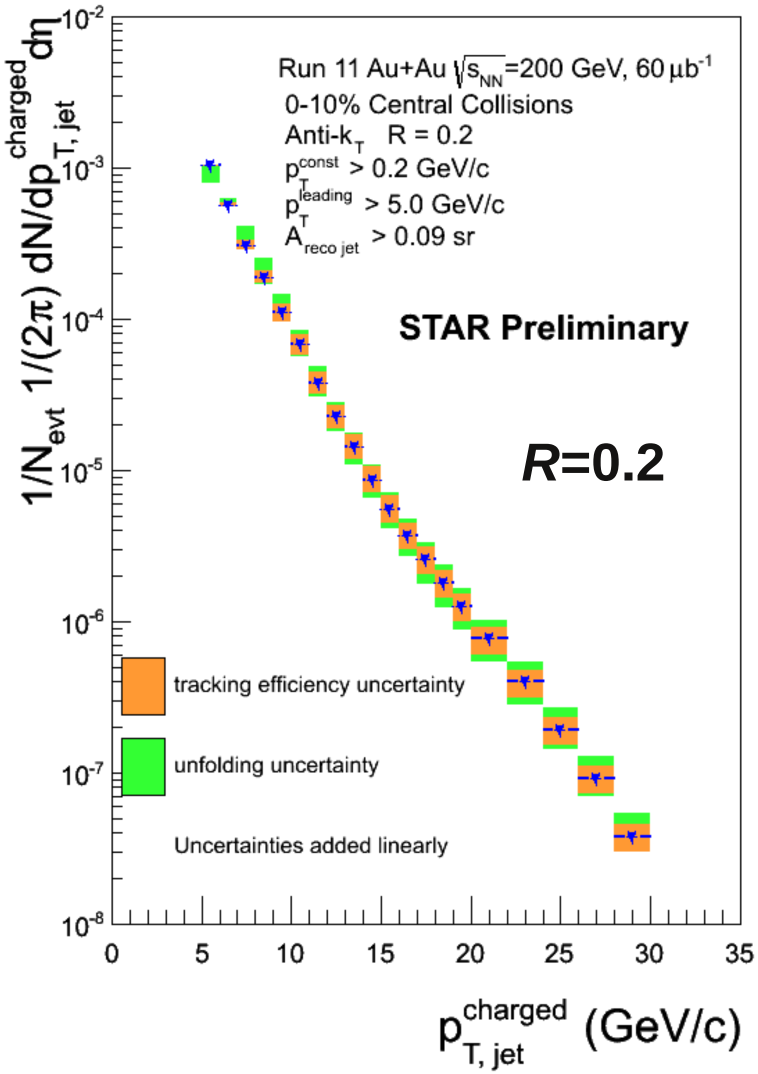
Inclusive Jet Measurement

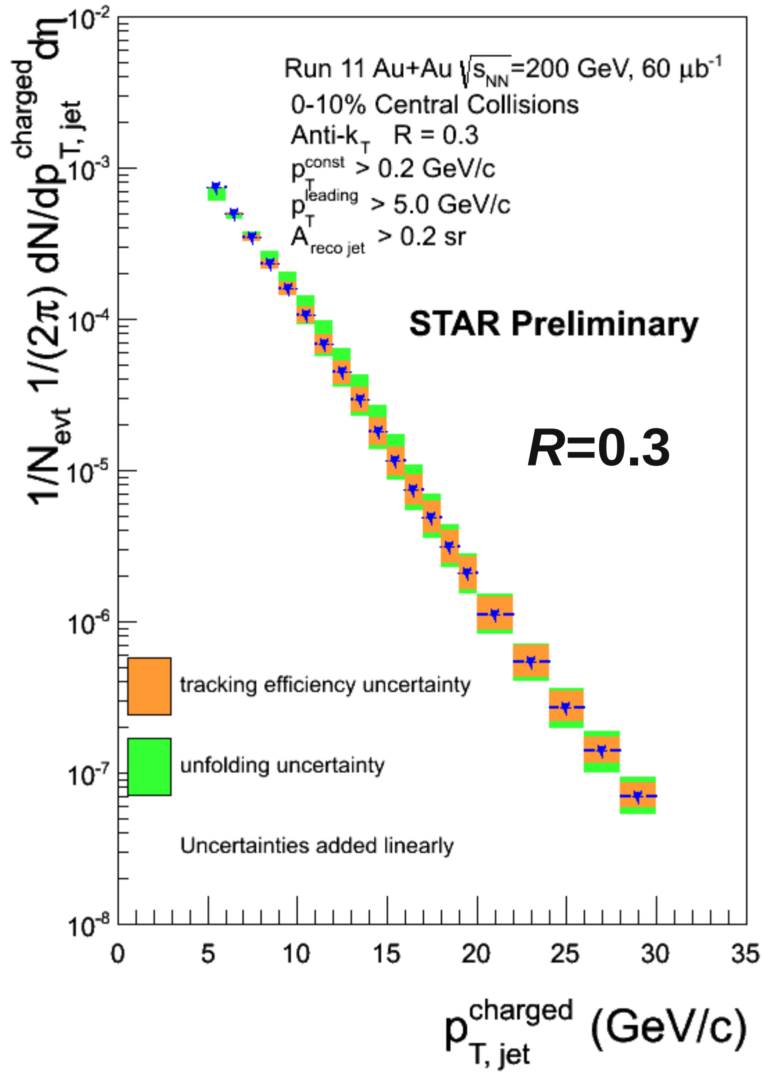
- combinatorial background reduced by a cut on leading hadron p_T
  [G. de Barros et al, Nucl. Phys. A910:314-318, 2013]
- induces bias (however jet can still contain many soft constituents)





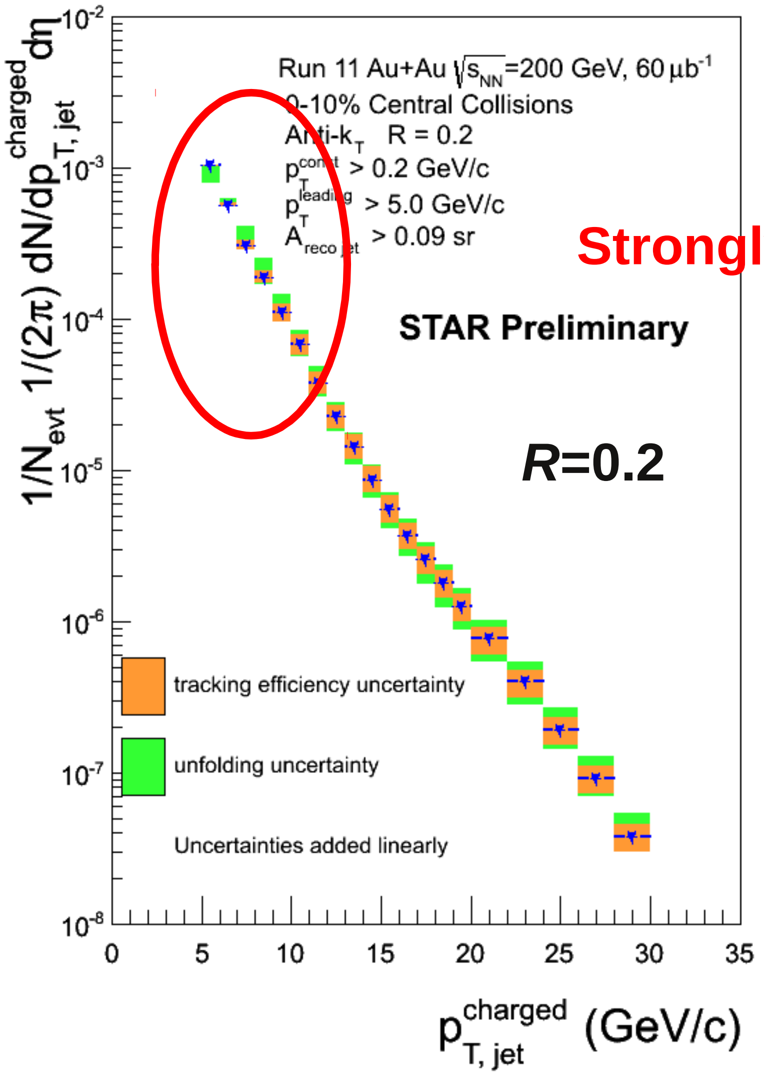
Inclusive Charged Jet Spectra



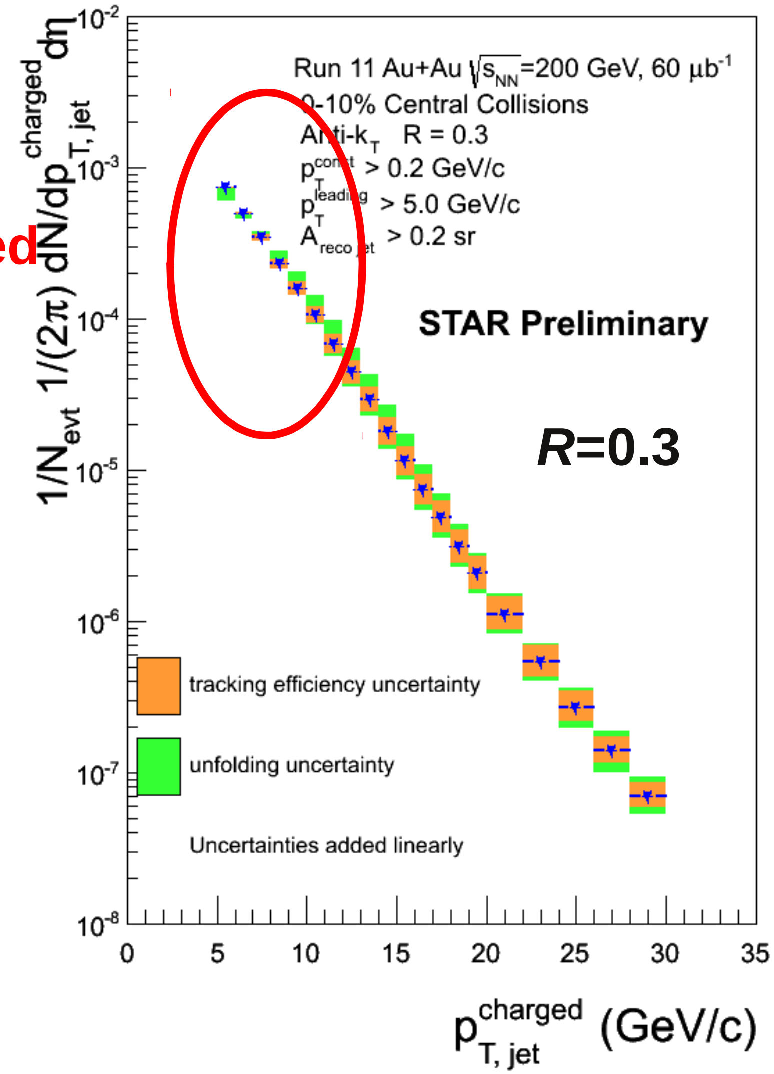


- Measured spectra corrected via Bayesian unfolding
- Jet energy scale resolution: roughly 5% (mainly due to track. eff. uncertainty)
- R_{AA}: Work in progress: further systematic uncertainties, pp baseline improvement

Inclusive Charged Jet Spectra



Strongly biased



- Measured spectra corrected via Bayesian unfolding
- Jet energy scale resolution: roughly 5% (mainly due to track. eff. uncertainty)
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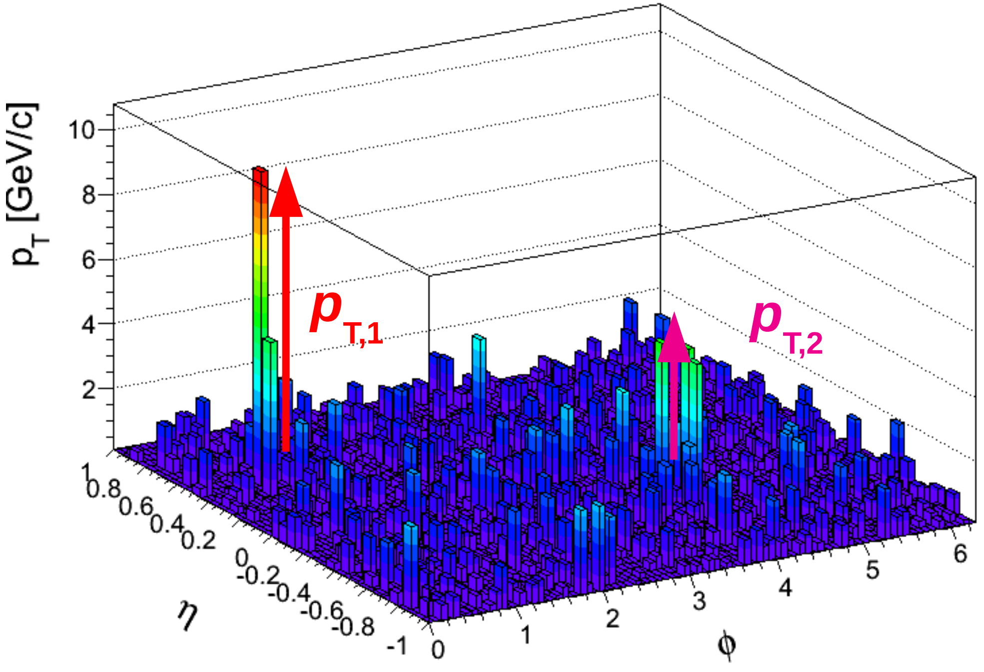
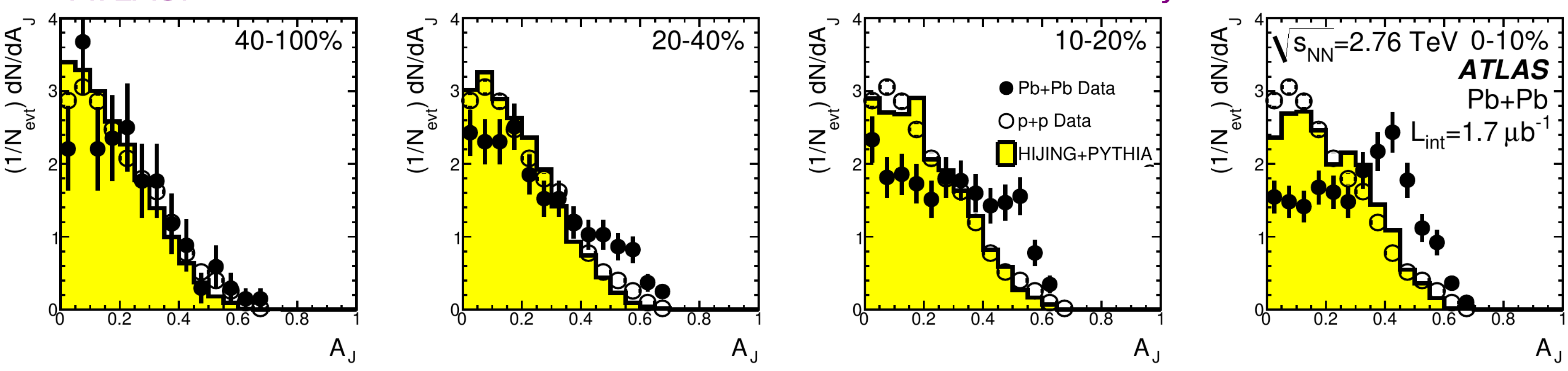
Jet Imbalance A_J Measurements

$$\boxed{A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}}$$

- di-jet momentum asymmetry
- signal of medium-induced jet modification

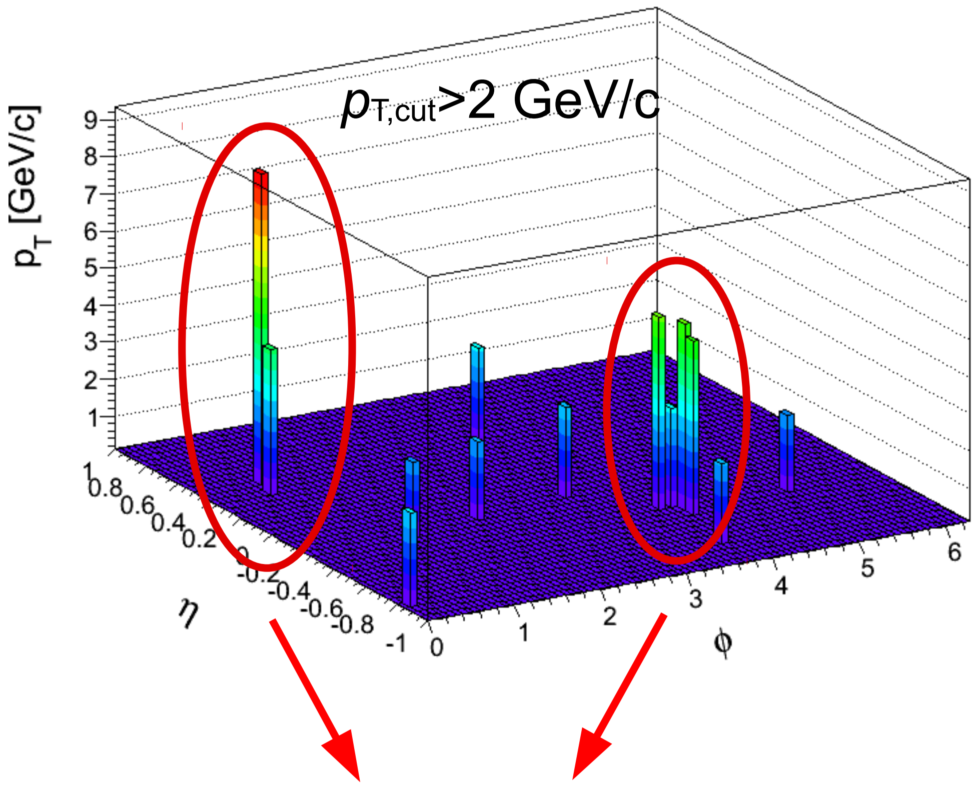


ATLAS: Phys. Rev. Lett. 105 252303



A_J Calculation in STAR

p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$\Delta\Phi_{Lead,SubLead} > 2/3\ \pi$



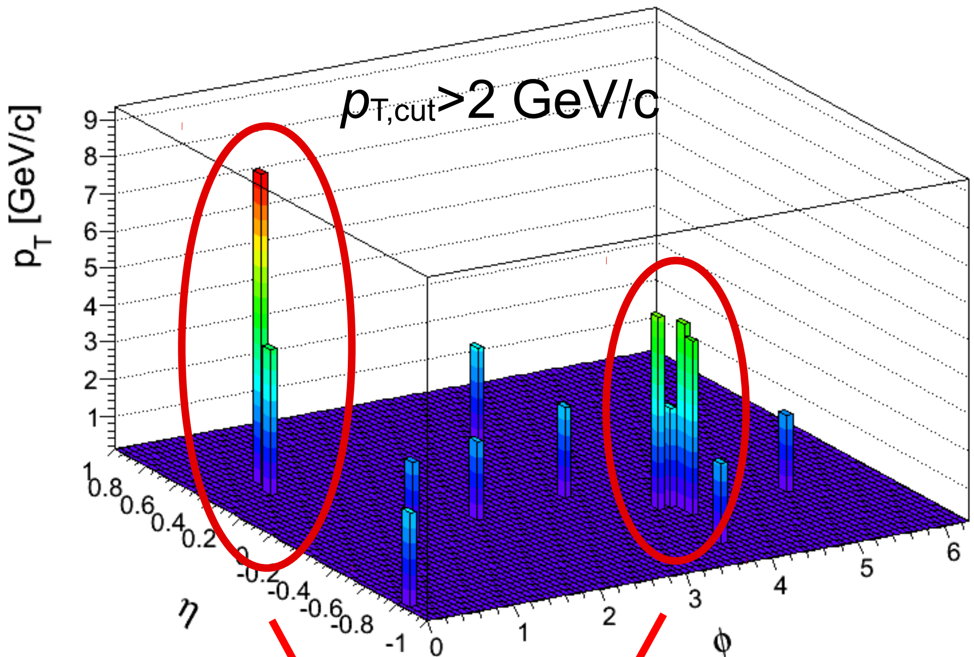
Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

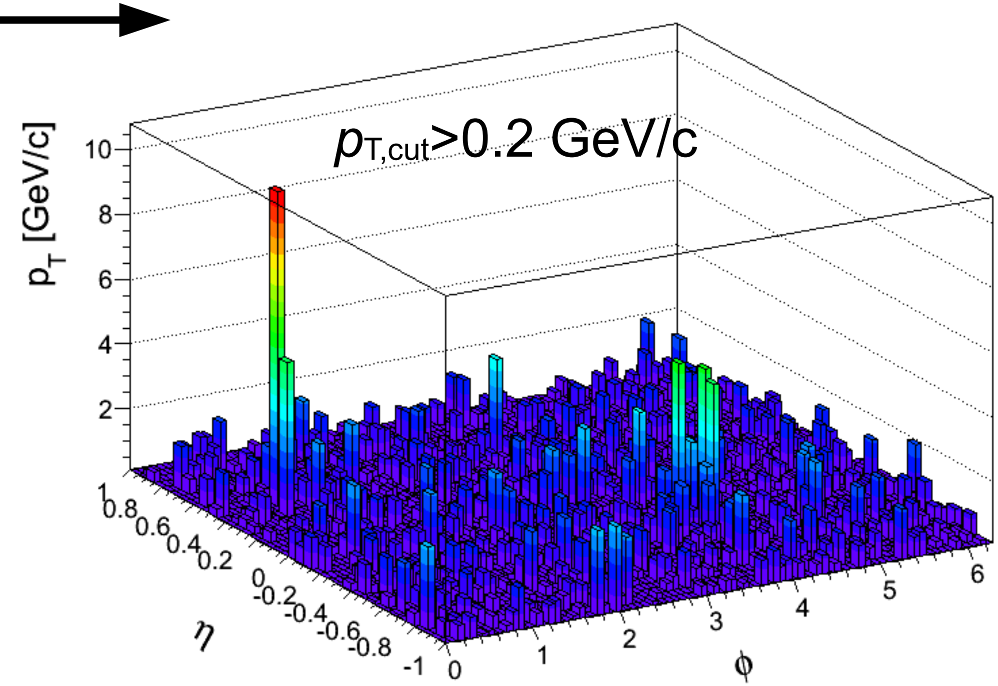
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad p_T = p_T^{rec} - \rho \times A$$

A_J Calculation in STAR

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

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



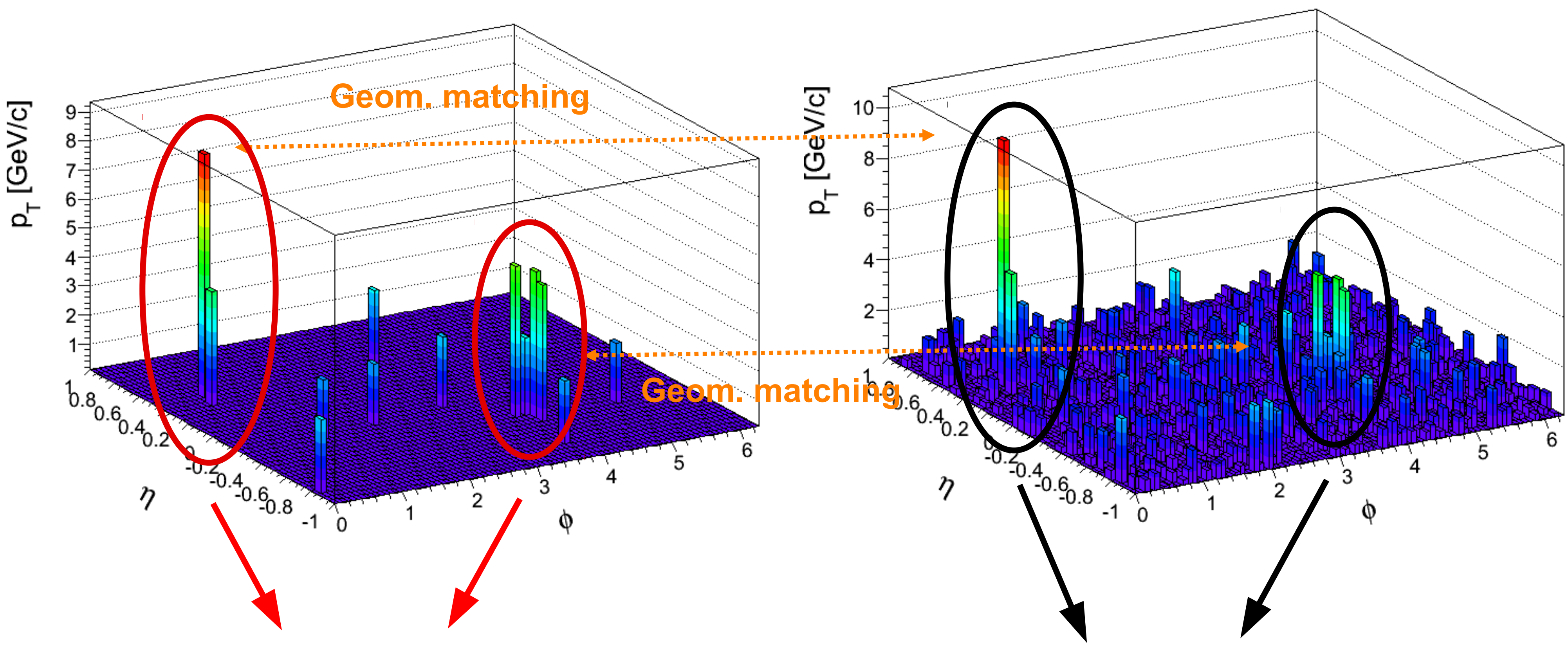


Calculate A_J with constituent
HIGH $p_{T,cut}$>2 GeV/c

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

A_J Calculation in STAR

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

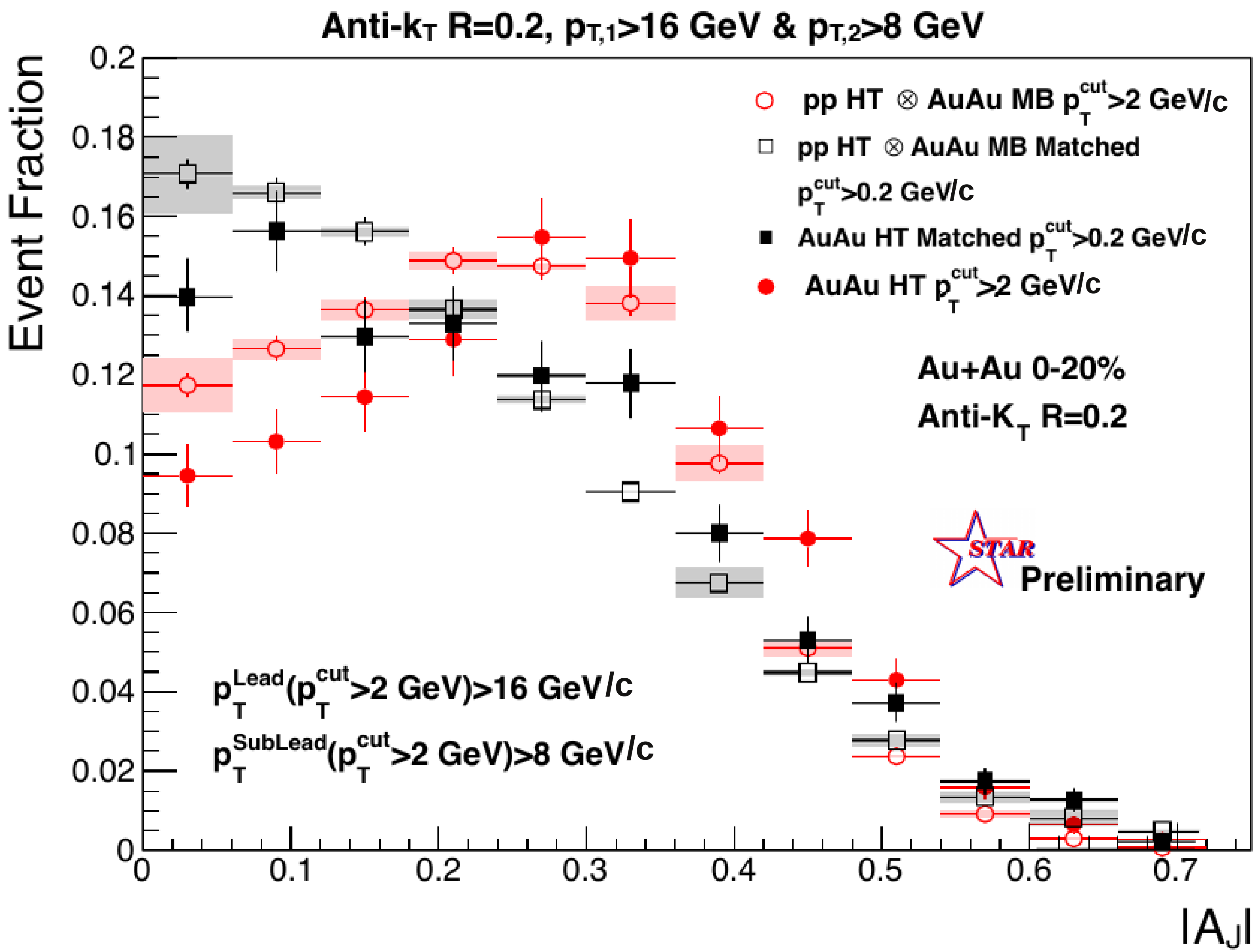


Calculate A_J with constituent **HIGH $p_{T,cut}$>2 GeV/c**

Calculate "matched" A_J with constituent **LOW $p_{T,cut}$>0.2 GeV/c**

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

A_J: R=0.2

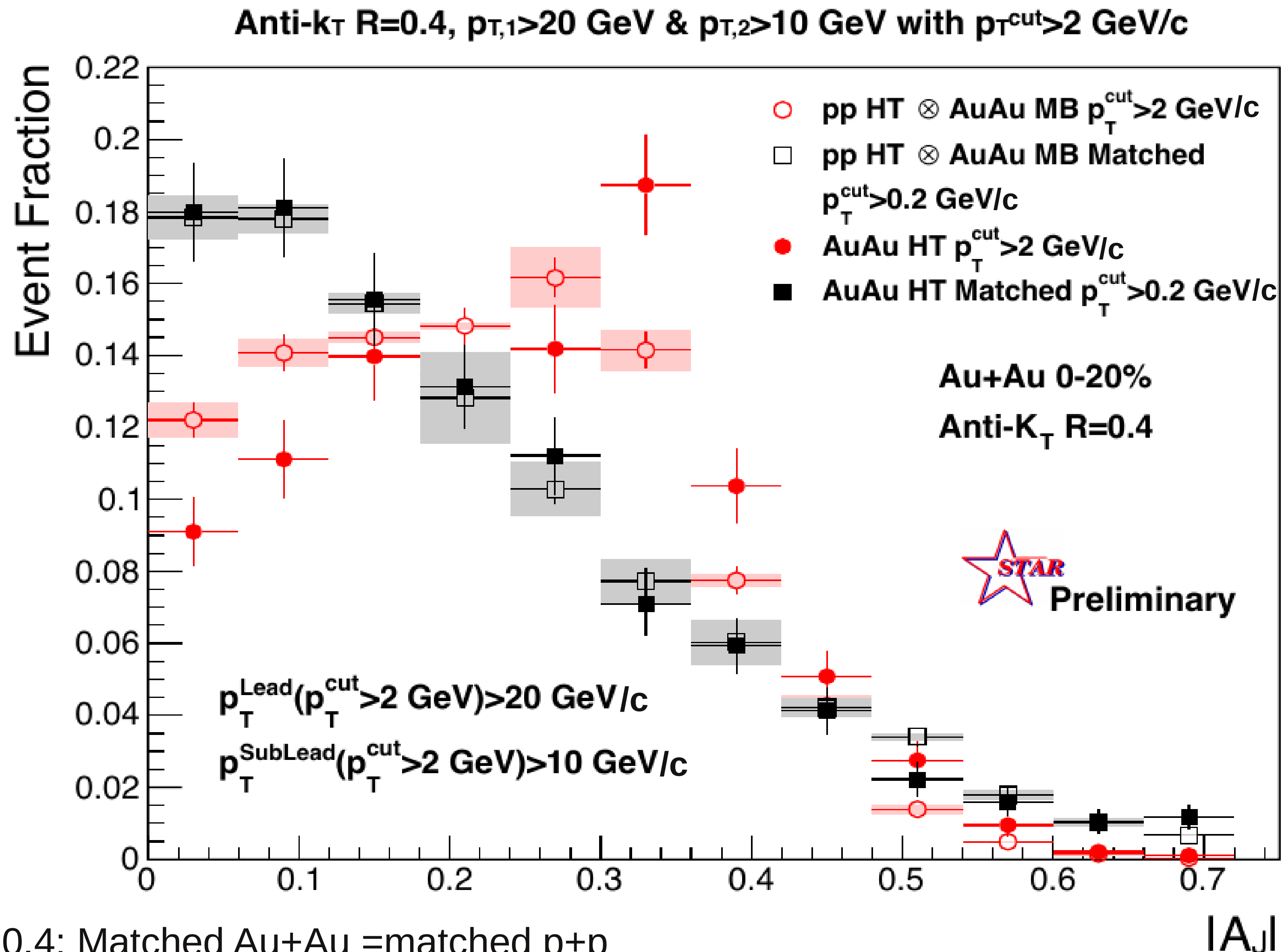


p-value<10^{-10}
(stat. error only)

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

R=0.2: Matched Au+Au ≠ matched p+p

A_J: R=0.4



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

p-value~0.8
(stat. error only)

R=0.4: Matched Au+Au =matched p+p

=>Energy recovered for R=0.4 with low p_T particles