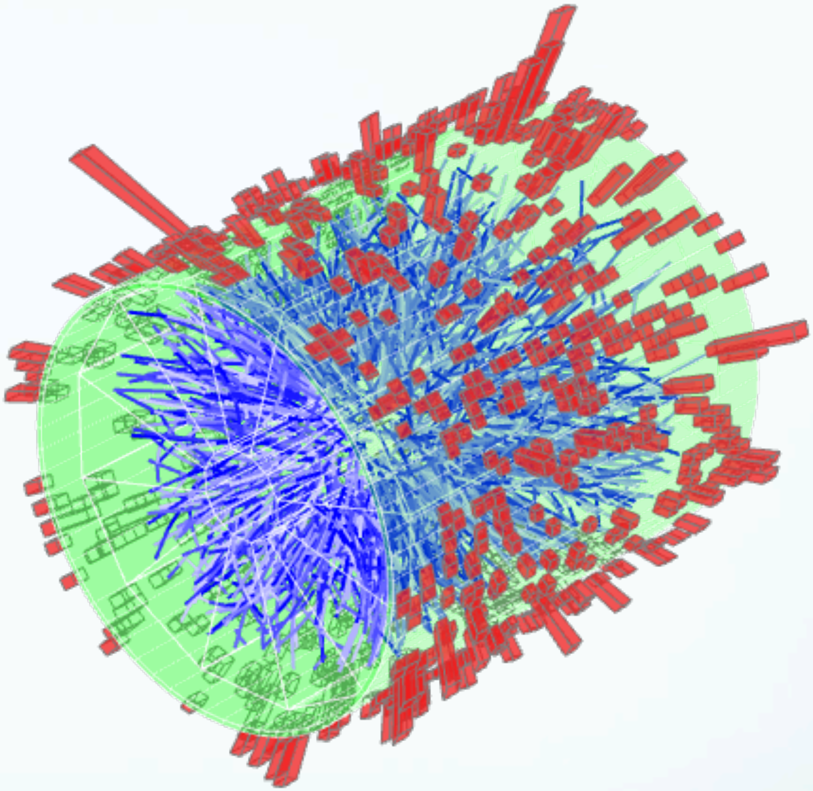
Gamma hadron and jet correlations with the STAR experiment

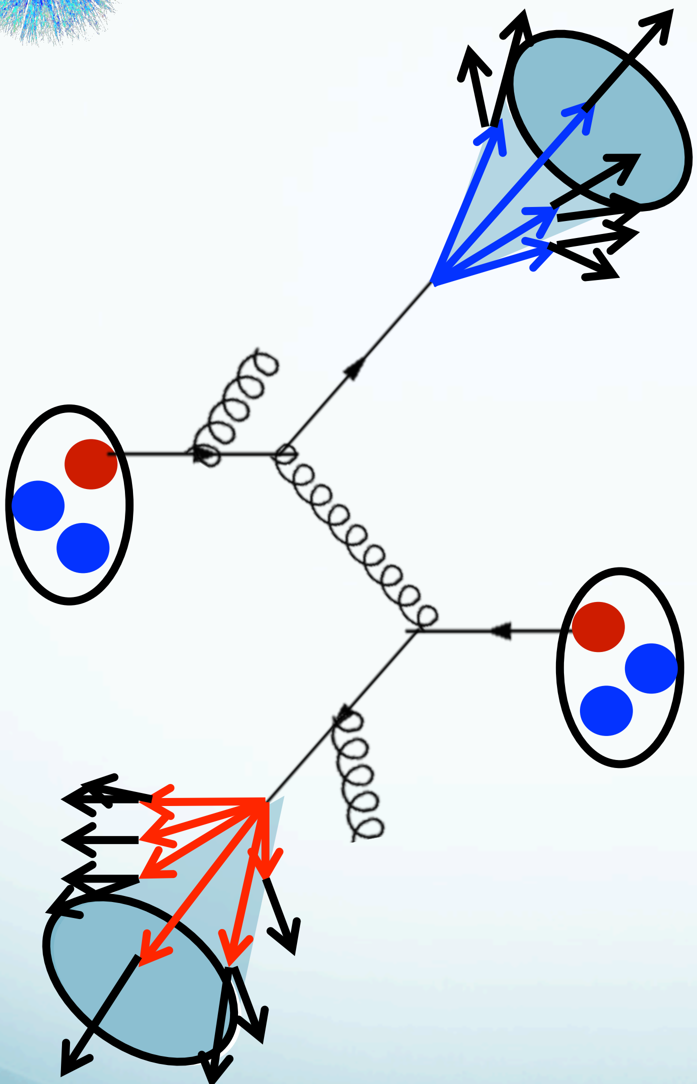
Rosi Reed
For the STAR Collaboration
Lehigh University

Outline

- Introduction
  - Jets and jet proxies
  - γ-jet and γ-h
- STAR detector
- γ_{rich}-$h^{\pm}$ and π^0-$h^{\pm}$ correlations
- Hadron-jet
- Conclusions



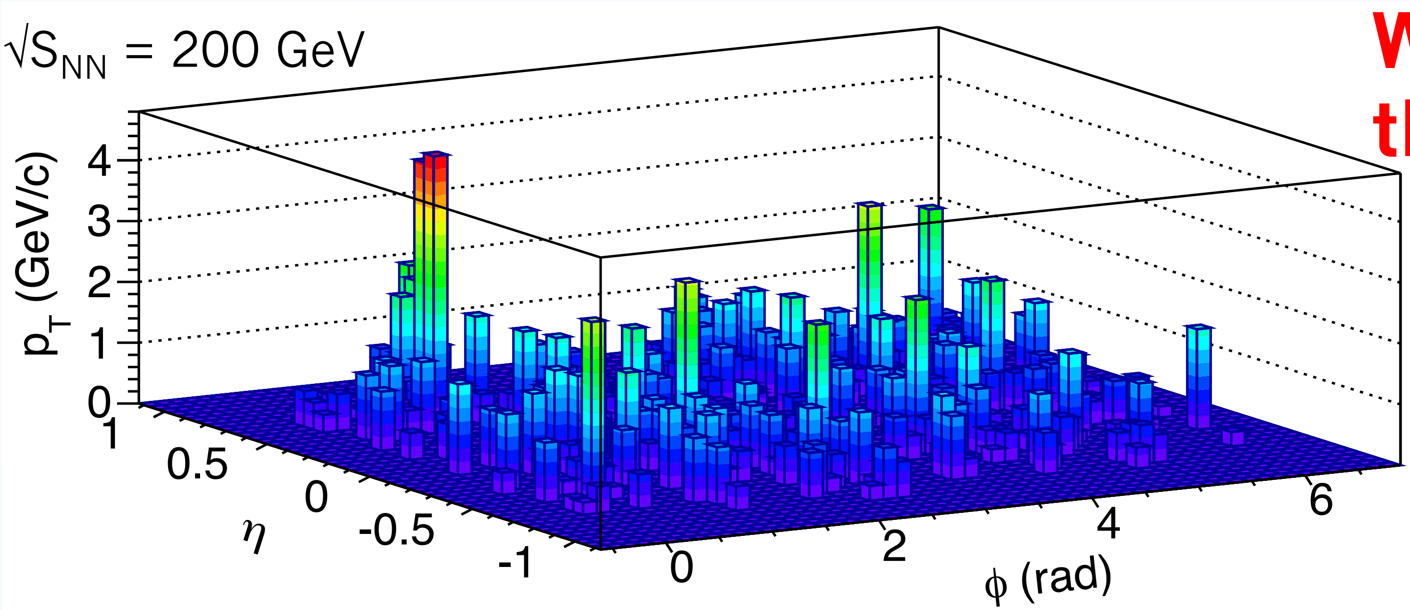
Jets in Heavy-Ion Collisions



There is no unambiguous definition of what a jet is!

- Colored partons undergo a hard scatter
  - Radiate soft gluons and quarks
  - Hadronize into a spray of particles
- Produced early prior to QGP formation
  - Interact and lose energy to the medium via radiation and collisions
- Expected to **reflect the kinematics and topology** of the hard scattered partons
  - Underlying background creates fake jets and smears the kinematics of "true" jets

Jets in Heavy-Ion Collisions
Complications: Background



Where are the jets?

0-10% central
STAR:
$\rho_{ch} \sim 29$ GeV
ALICE:
$\rho_{ch} \sim 130$ GeV

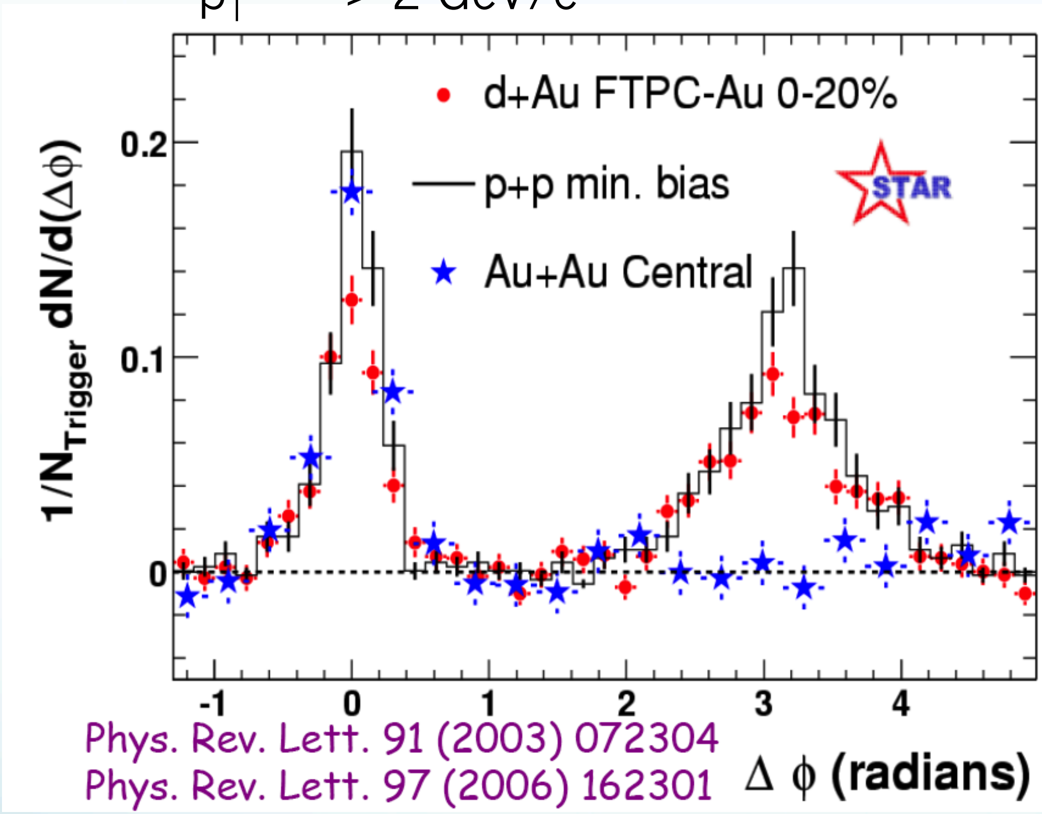
JHEP09(2015)170

- Unlike in pp collisions, the underlying event in AA collisions makes jet finding difficult
  - Fake jets → Jet finder clusters particles from bulk
  - Jet smearing → Background fluctuates underneath jet
- First "jet" results used high p_T hadrons as proxies

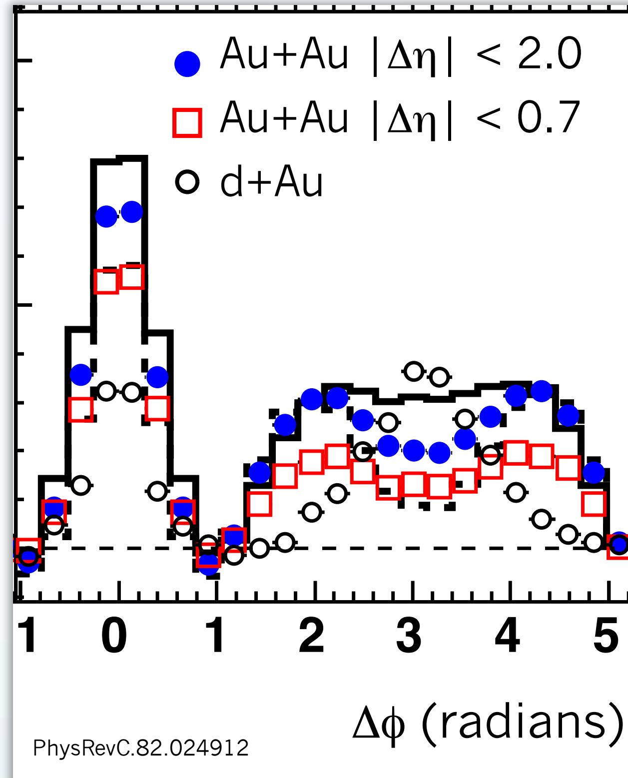
Di-hadron Correlations

A jet proxy

$4 < p_T^{trig} < 6$ GeV/c
$p_T^{assoc} > 2$ GeV/c



$4 < p_T^{trig} < 6$ GeV/c
$1 < p_T^{assoc} < 2.5$ GeV/c

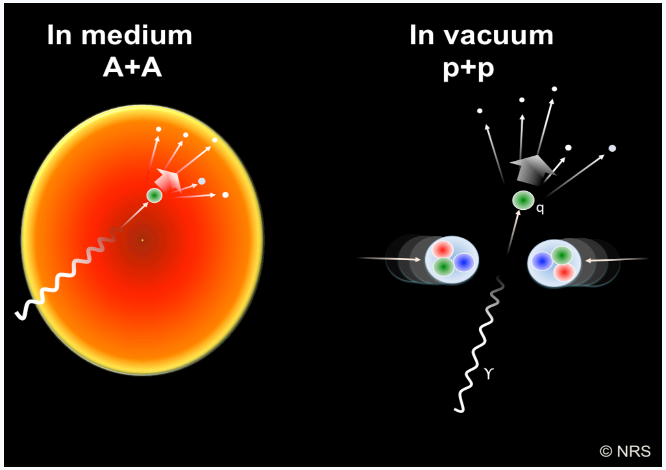


Strong modification of the recoil-jet indicated substantial partonic interaction with the QGP, d+Au results show not CNM

- Geometric "surface" bias
- What is the parton p_T and flavor?

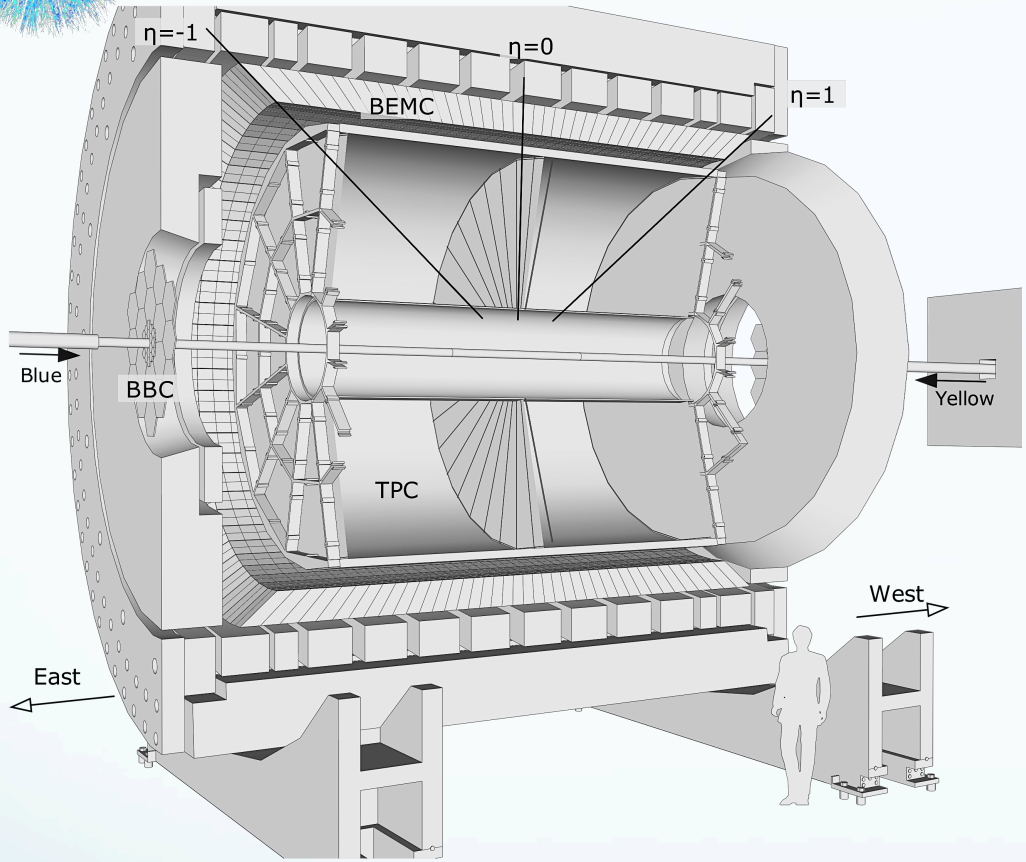
γ-jet: Golden Probe of the QGP

- Direct photon-jet analyses have many advantages
  - Photon is highly correlated with the parton kinematics
  - Process is dominated by Compton scattering ($qg \rightarrow q\gamma$)
    - Fixes flavor
  - Photon does not interact with the QGP
    - Reflects the initial parton kinematics
    - No geometric bias
    - Allows jet-medium tomography



- Disadvantages
  - Low cross-section
  - Still need to account for effect of underlying event
    - Common to all jet analyses
  - Use γ-$h^{\pm}$ as a jet proxy

STAR detector



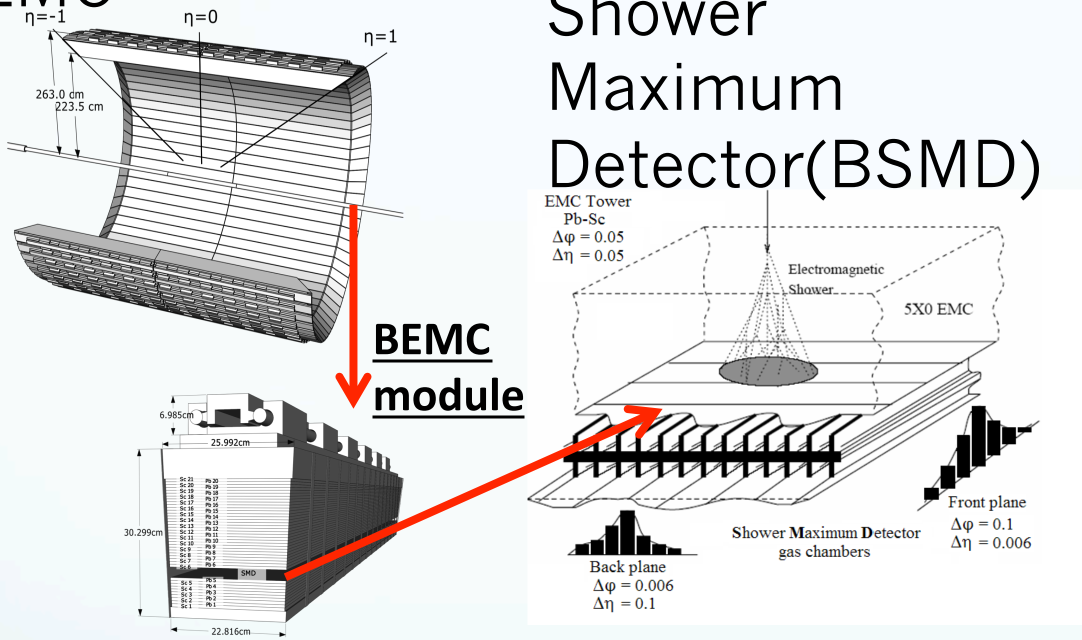
- Barrel Electromagnetic Calorimeter (BEMC) → measures EM clusters
  - High Tower Trigger
- Time Projection Chamber (TPC) → identifies charged hadron tracks
- Acceptance (BEMC + TPC):
  - 2π-azimuth
  - $|\eta| < 1.0$, both for BEMC and TPC
- Data sets:
  - Au+Au year-11: $\mathcal{L}_{int} = 2.8\ nb^{-1}$
  - pp year-9: $\mathcal{L}_{int} = 23\ pb^{-1}$

Transverse shower profile π^0/γ_{dir} discrimination

Main background comes from $\pi^0 \rightarrow \gamma\gamma$ decay

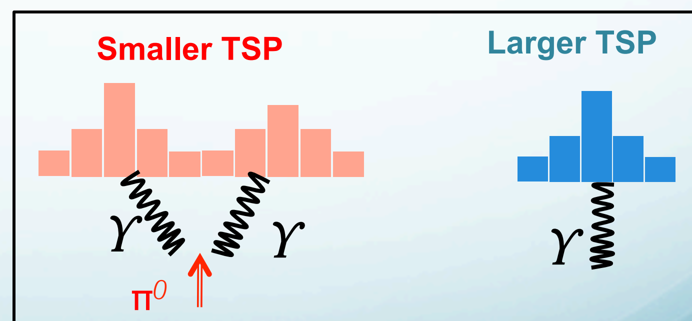
BEMC

Shower Maximum Detector(BSMD)



$$\mathbf{TSP} = \frac{\mathbf{E_{cluster}}}{\sum_i \mathbf{e_i r_i^{1.5}}}$$

$E_{cluster}$: Cluster energy
e_i: BSMD strip energy
r_i: distance between strip and cluster center

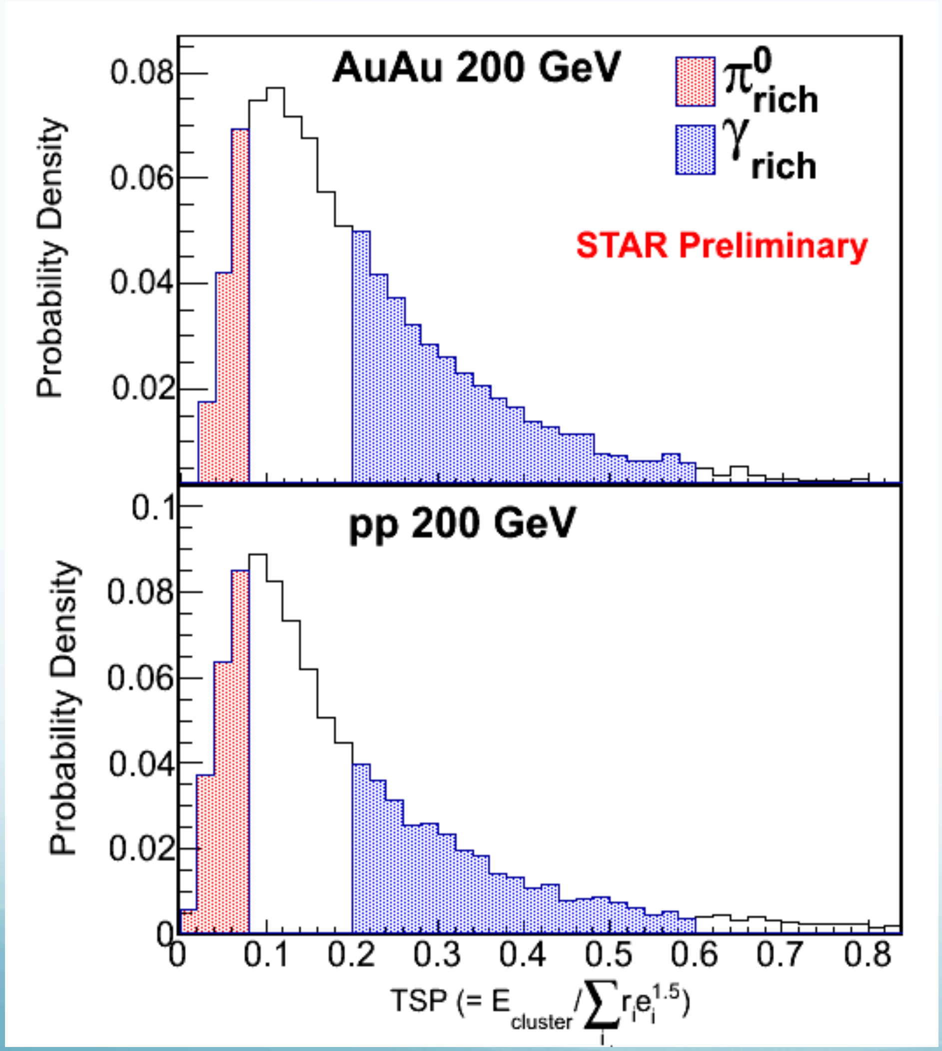


BSMD and BEMC tower used to determine Transverse Shower Profile (TSP)

- Nearly pure sample of π^0 (π^0_{rich})
- Sample with enhanced fraction of γ_{dir} (γ_{rich})

Transverse shower profile π^0/Υ_{dir} discrimination

Main background comes from $\pi^0 \rightarrow \gamma\gamma$ decay



$$\mathbf{TSP} = \frac{\mathbf{E_{cluster}}}{\sum_i \mathbf{e_i r_i^{1.5}}}$$

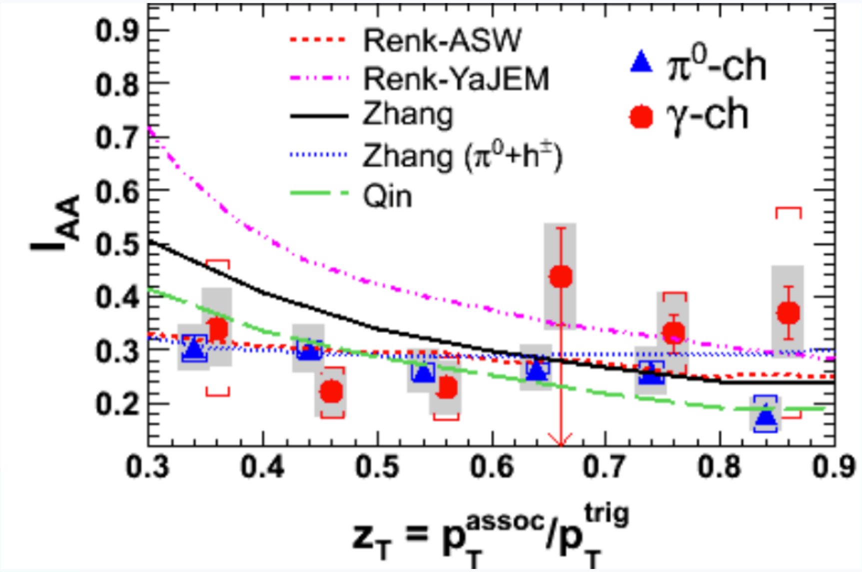
$E_{cluster}$: Cluster energy
e_i: BSMD strip energy
r_i: distance between strip and cluster center

Compare π^0_{rich} and γ_{rich} populations

- Path-length and color factor effects
- γ_{rich} away side should be less suppressed

I_{AA} vs z_T: Previous Results

(STAR Collab., PRC 82, 034909)



$8 < p_T^{trig} < 16\ GeV/c$

How much energy is lost and where is it recovered? Needed to extend measure to lower z_T

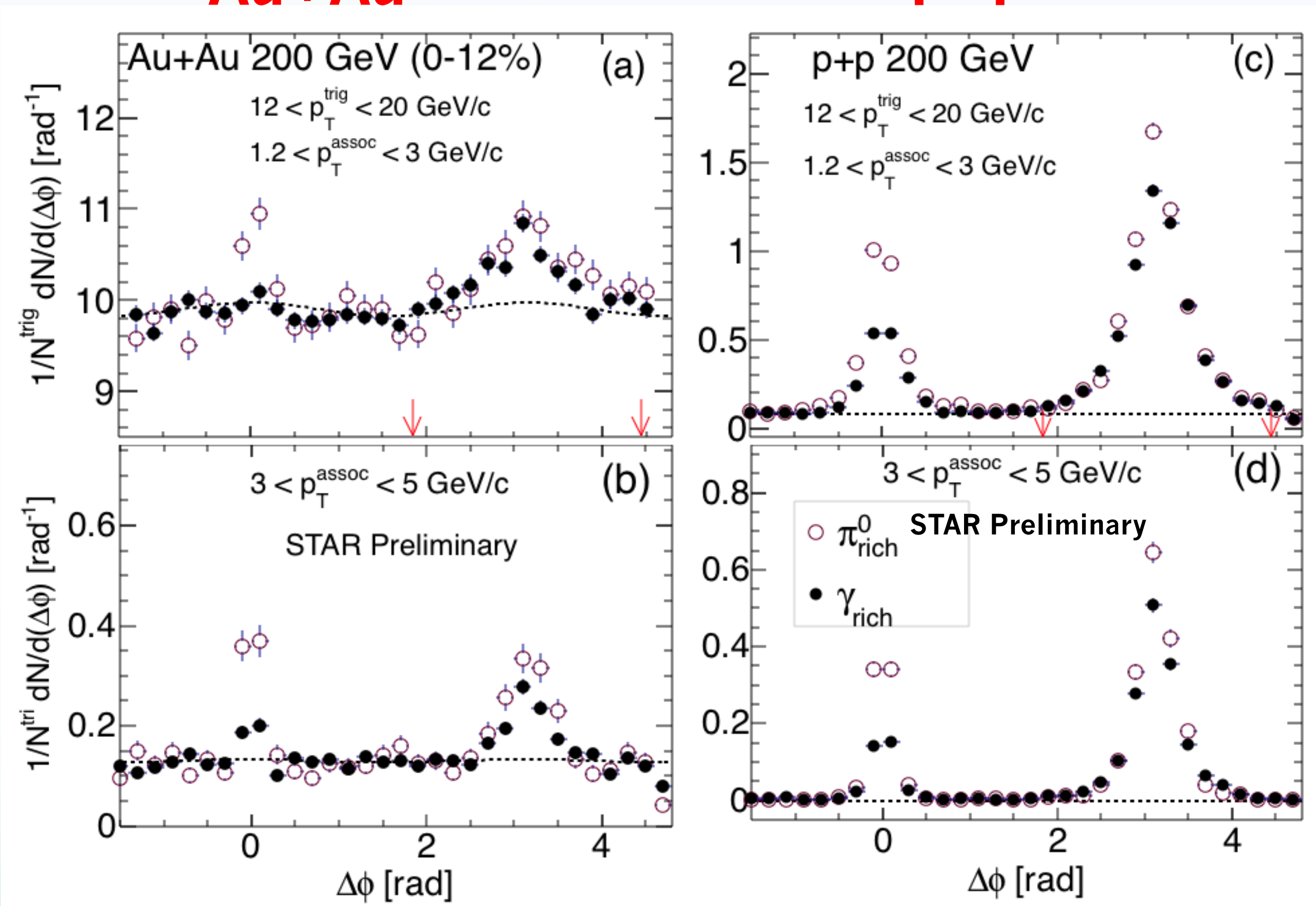
$$I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}} \qquad z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

$D(z_T)_{XX}$: per trigger away-side yield for X+X collisions

- I_{AA} showed similar level of suppression for both samples
- Jet fragmentation function is enhanced at low p_T
  - Effect should be seen in z_T

Raw Correlation functions

Au+Au **p+p**



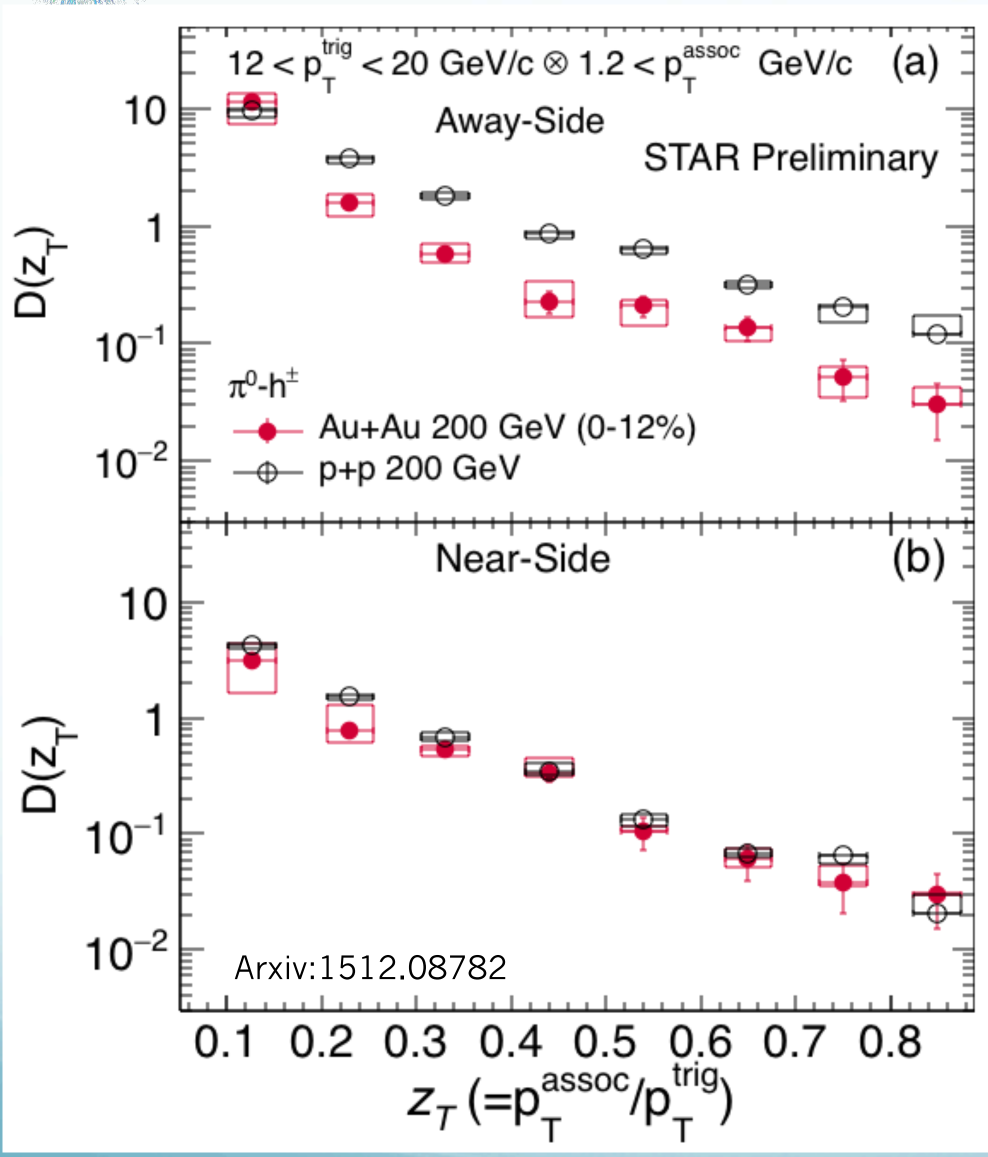
↓ Away-side integration window

background level

$|\eta| < 1.0$

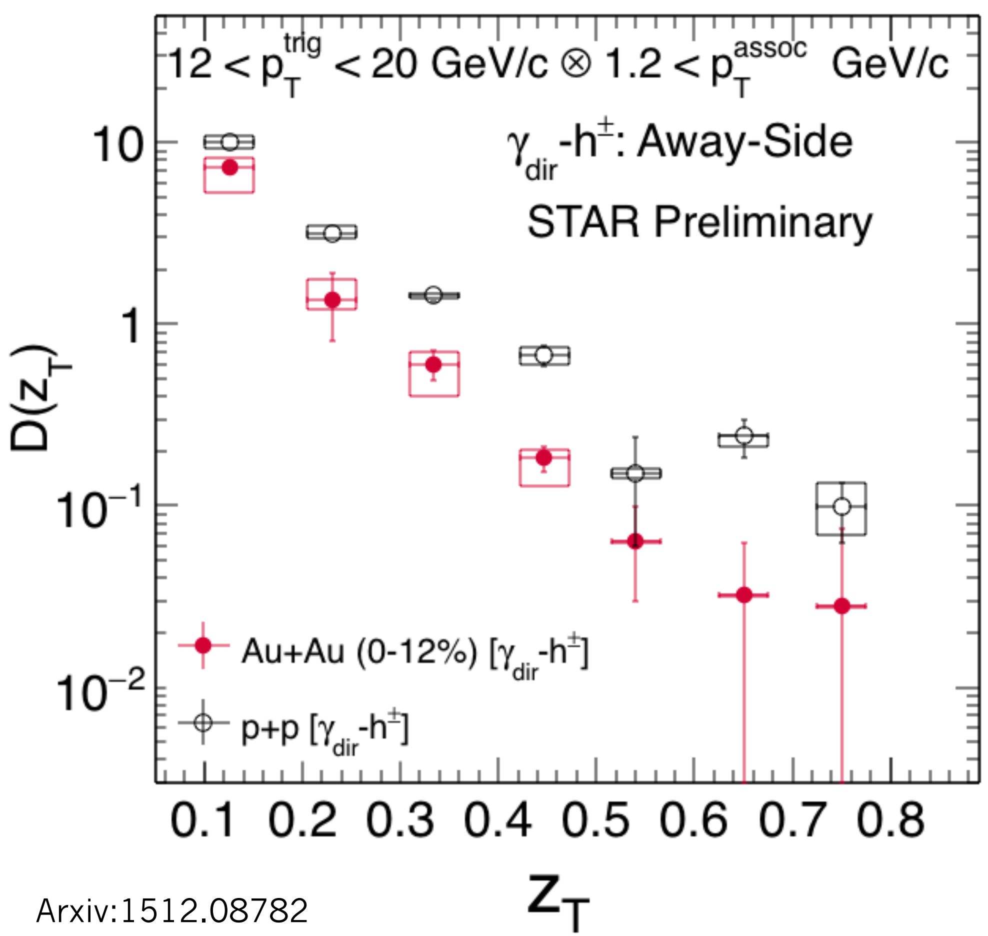
- Uncorrelated background is subtracted
- Δφ acceptance is corrected using the mixed events (modulated with elliptic flow for Au+Au collisions)

Yield associated with π^0



- Near-side $|\Delta\varphi| \leq 1.4$
- Away-side $|\Delta\varphi - \pi| \leq 1.4$
- **Away-side yields suppressed in central (0-12%) Au+Au collisions**
- Near-side shows no significant suppression
- Integrating near-side yields
  - ~85(±3)% energy fraction carried by π^0 over "charged jet energy" (π^0 + charged hadrons) in pp 200 GeV
    - γ carries nearly all, z_T is not precisely the same

Yield associated with γ



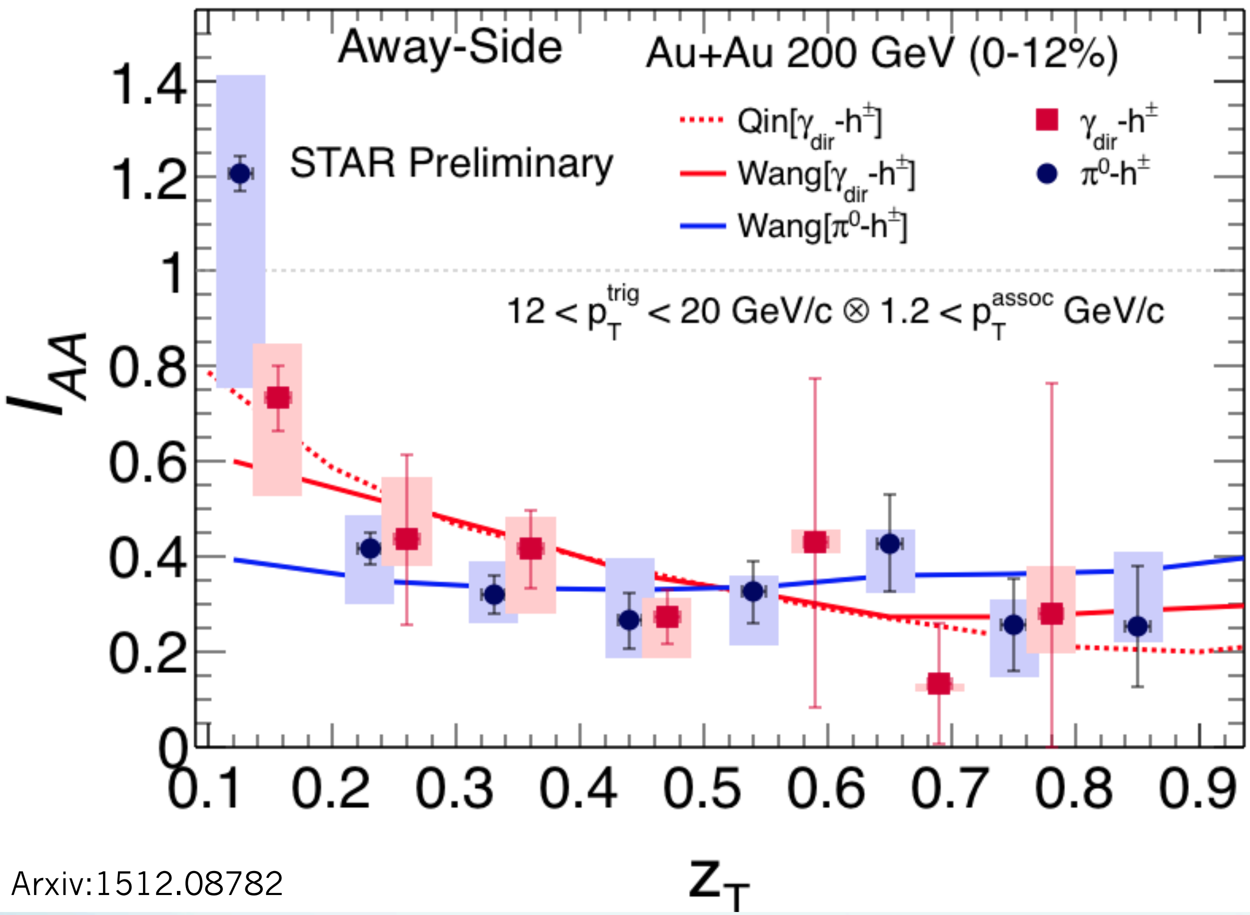
Arxiv:1512.08782

Away-side $|\Delta\varphi - \pi| \leq 1.4$

$$Y_{\gamma dir+h} = \frac{Y^a_{\gamma rich+h} - RY^a_{\pi 0+h}}{1\text{-R}}$$

- Y^a: away-side yield
- Y^n: near-side yield
- Normalized per trigger
- Purity of γ_{dir} vs γ_{rich} sample:
  - $1 - R = \frac{N_{\gamma dir}}{N_{\gamma rich}}$
- 1-R =
  - Central Au+Au ~70%
  - pp ~40%
- **Away-side yields suppressed in central (0-12%) Au+Au collisions**

I_{AA} of γ_{dir} and π^0



Arxiv:1512.08782

$$I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}}$$

$$z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

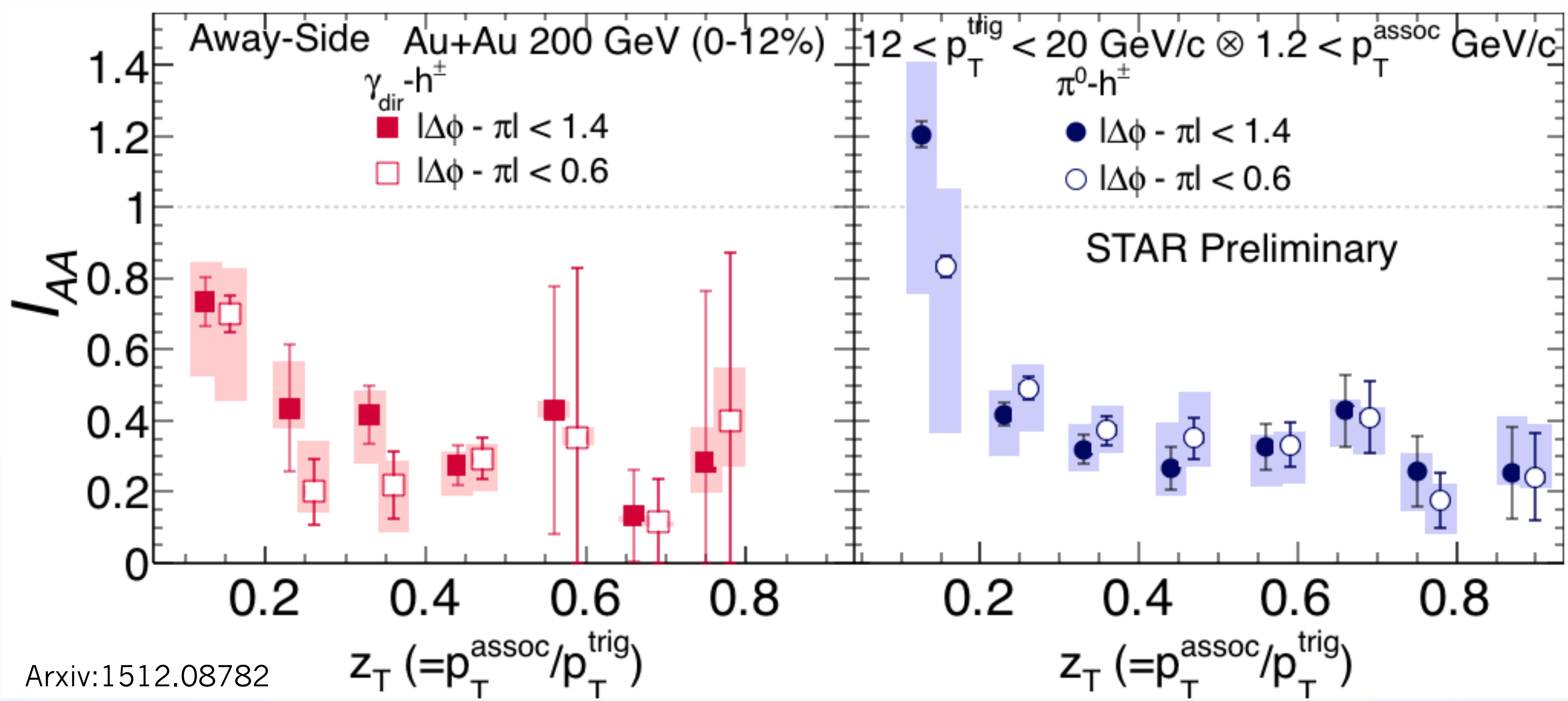
$I_{AA}^{\pi 0\text{-}h}$ and $I_{AA}^{\gamma dir\text{-}h}$ show similar strong suppression

- $I_{AA}^{\pi 0\text{-}h}$, $I_{AA}^{\gamma dir\text{-}h}$ less suppressed at $z_T<0.2$ than at high z_T
- Models don't include absorption and redistribution of lost energy in the medium

Qin: G.-Y Qin et al., PRC 80, 054909 (2009) (NLO pQCD + (3+1)hydro with jet-medium and fragmentation photon)

Wang: X. N. Wang et al., Phys. Rev. C 84, 034902 (2011) Phys. Rev. C 81, 064908 (2010) Phys. Rev. Lett. 103, 032302 (2009) (NLO pQCD + (3+1)hydro)

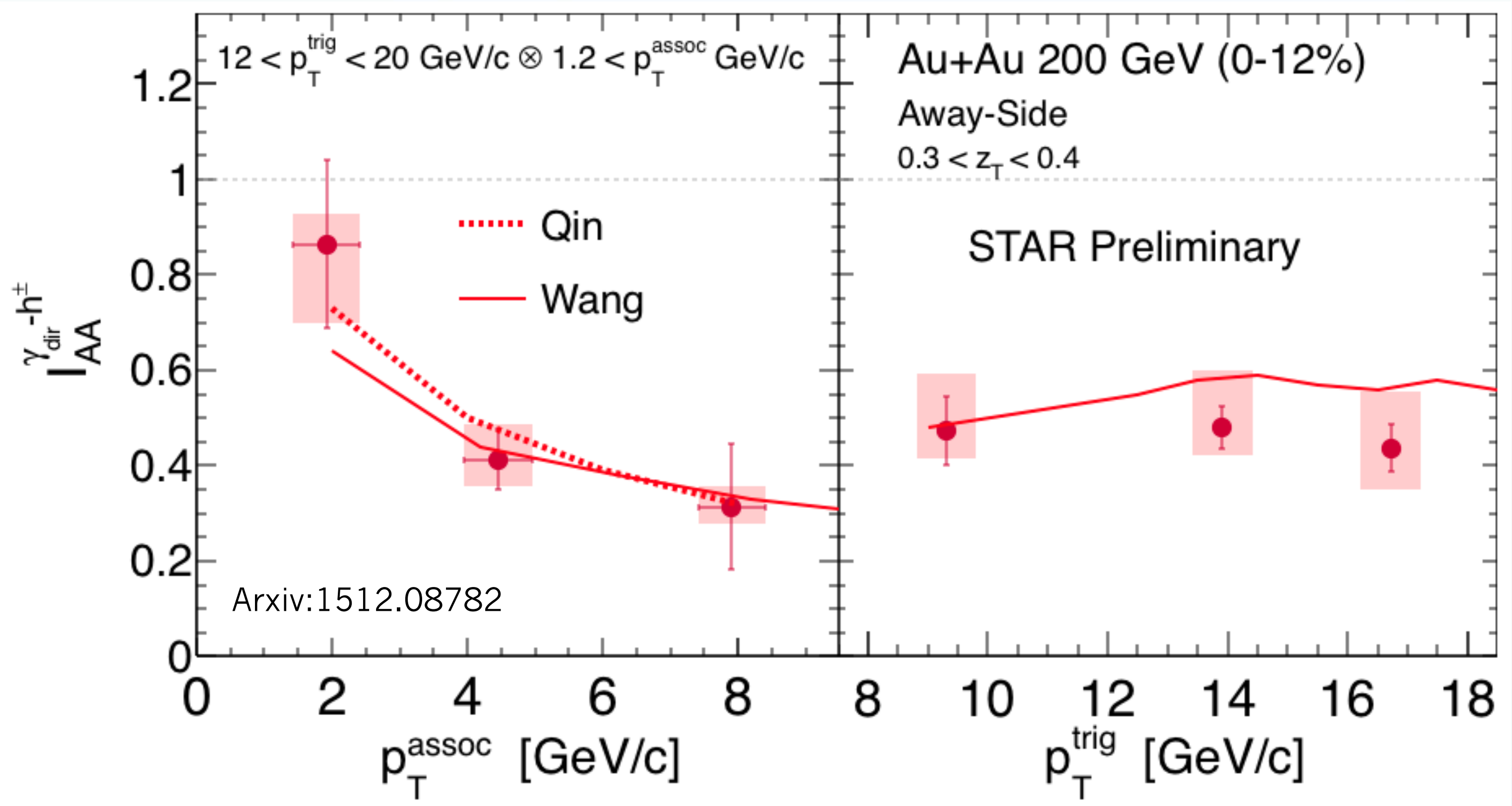
γ–h I_{AA} vs Integration window π^0–h



Arxiv:1512.08782

- Error bars are largely correlated
- **No significant dependence of suppression on integration window** is observed for Υ_{dir}-h$^{\pm}$ and π^0-h$^{\pm}$ I_{AA} results at high p_T^{Trig} ($12 < p_T^{Trig} < 20$ GeV/c)

I_{AA} vs p_T^{assoc} and p_T^{Trig}

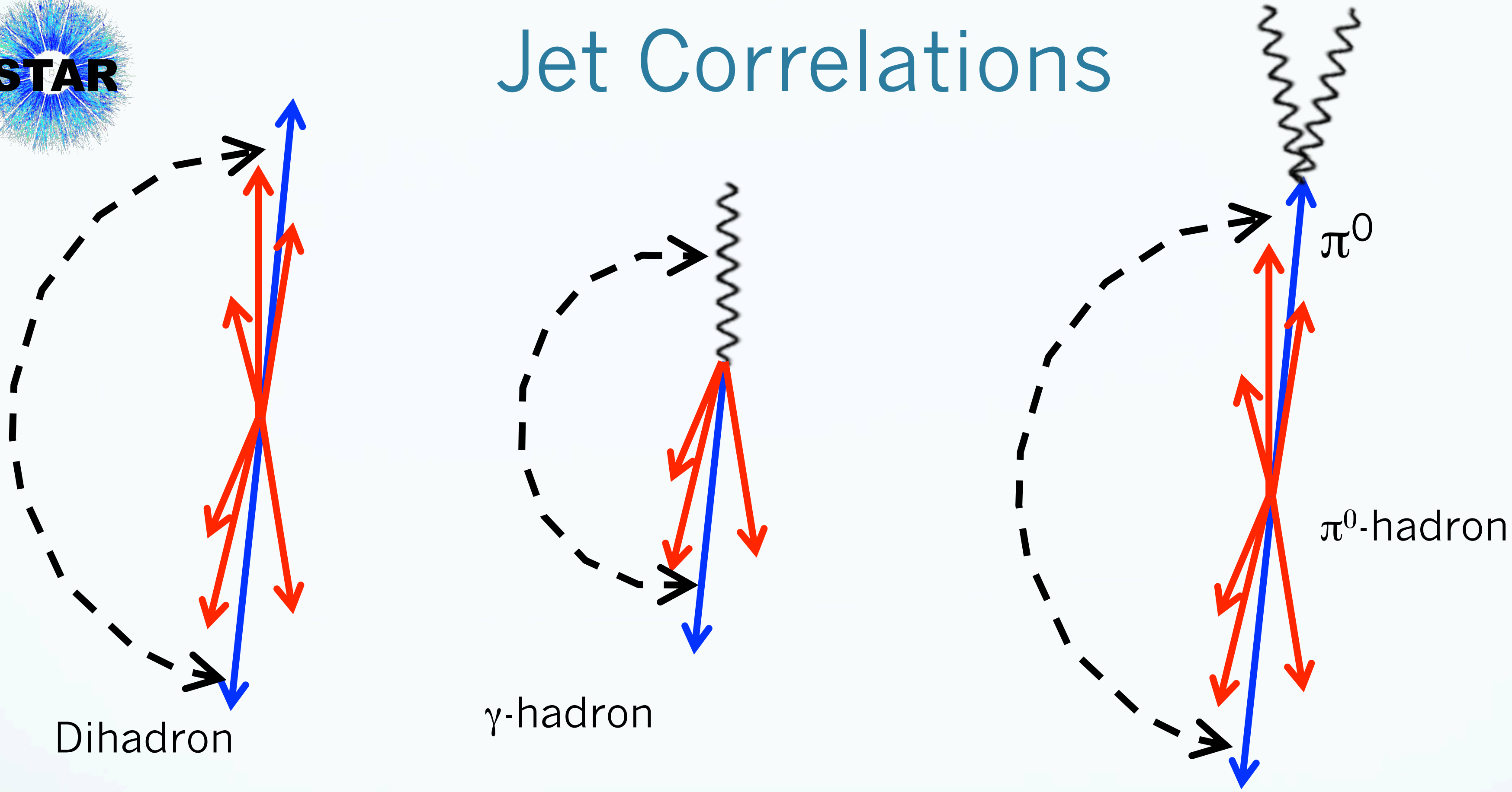


G.-Y Qin et al., PRC 80, 054909 (2009)

X. N. Wang et al., Phys. Rev. C 84, 034902 (2011) Phys. Rev. C 81, 064908 (2010) Phys. Rev. Lett. 103, 032302 (2009)

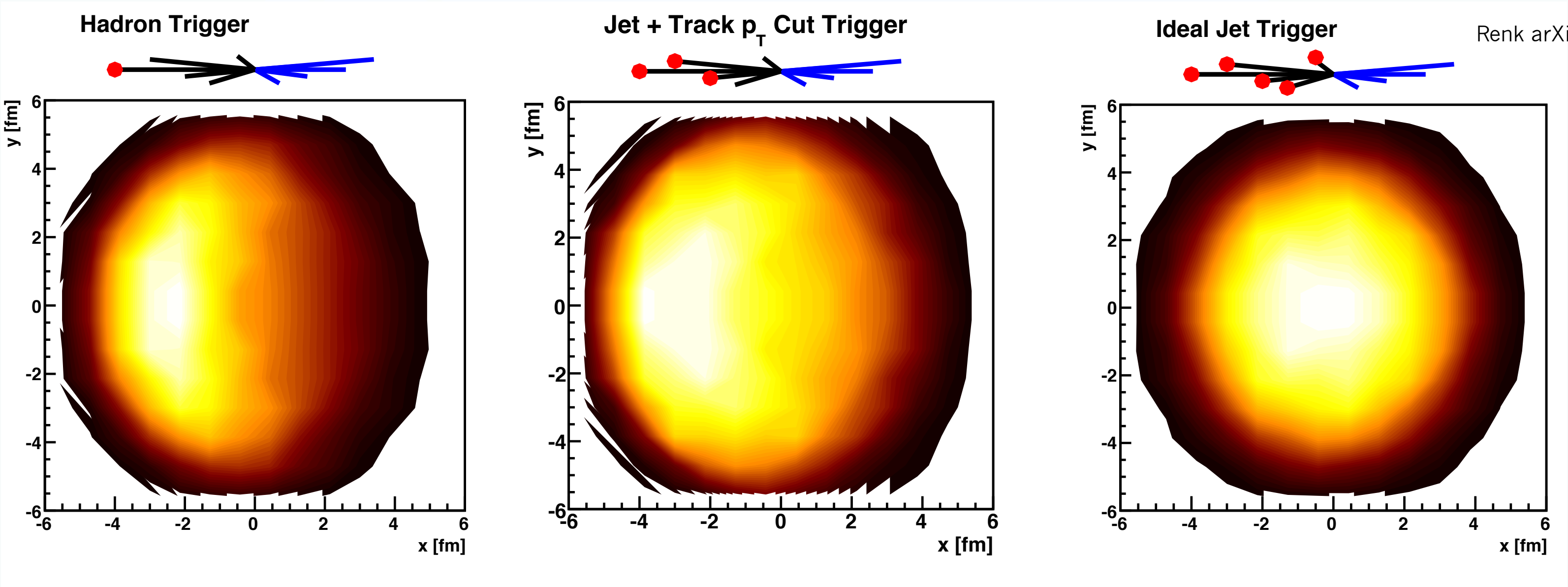
- Away-side suppression depends on p_T^{assoc}
- High-p_T suppression does not depend on direct photon trigger energy

Jet Correlations

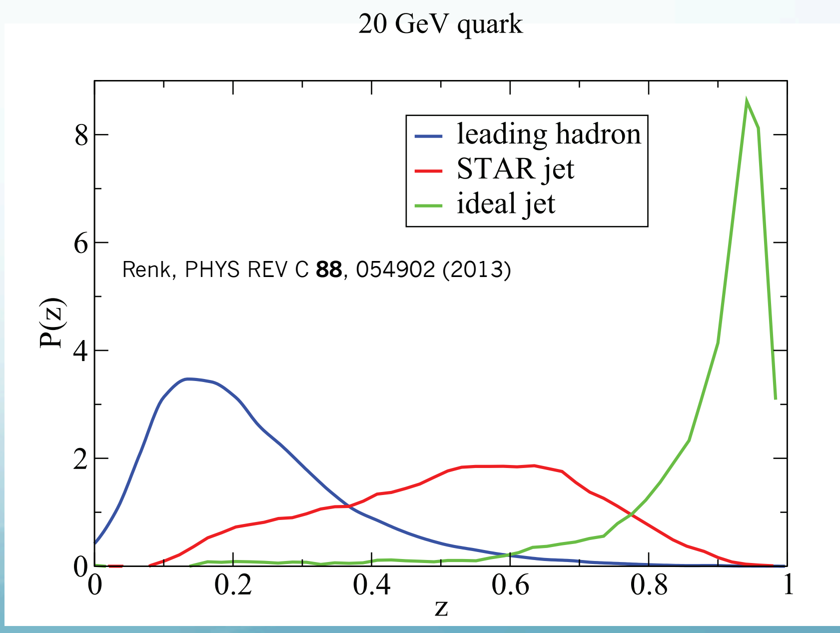


- Different biases→Jet Geometry Engineering
- Apply jet techniques developed at LHC/RHIC to RHIC jets!
  - Allows a measurement of the dijet or γ-jet energy imbalance
  - How much energy is still correlated with the initial parton? Need jet reconstruction!

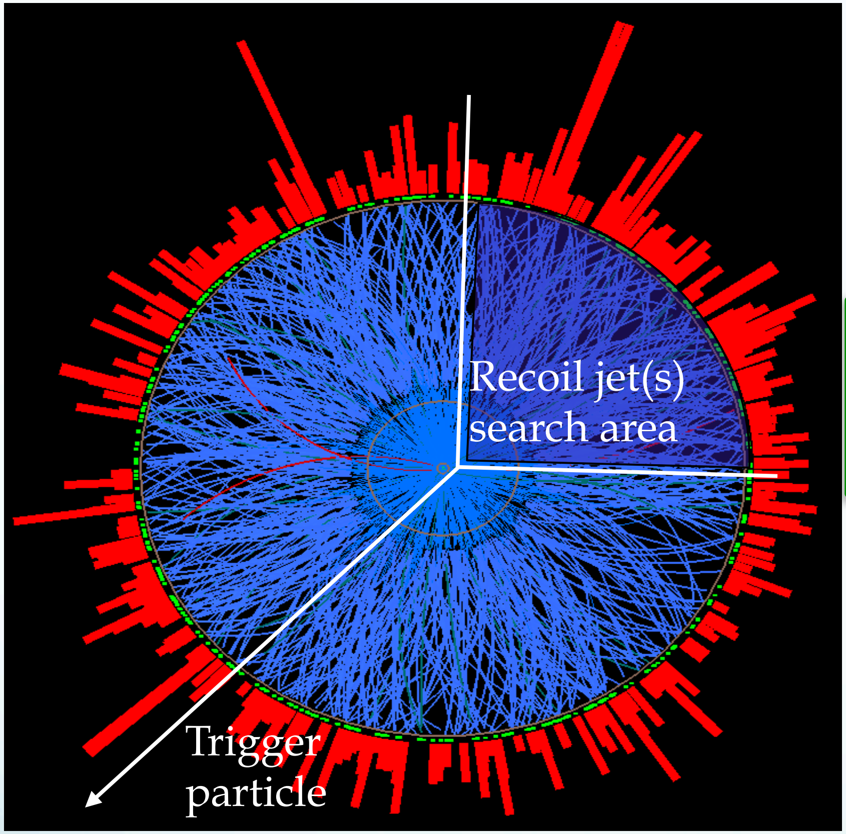
Reconstructed Jet Correlations



- **Biases for jets will be different than for π^0 or γ**
- Different biases→Jet Geometry Engineering
- New techniques and larger data samples allows jet-h+ h-jet correlations
- Probability density of $z = E_{obs}/E_{parton}$



h-Charged Jet correlations



Semi-inclusive yield of jets recoiling from a high p_T hadron trigger

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

Measured — Calculable in pQCD

Trigger on high p_T hadron → Selection of a high p_T process

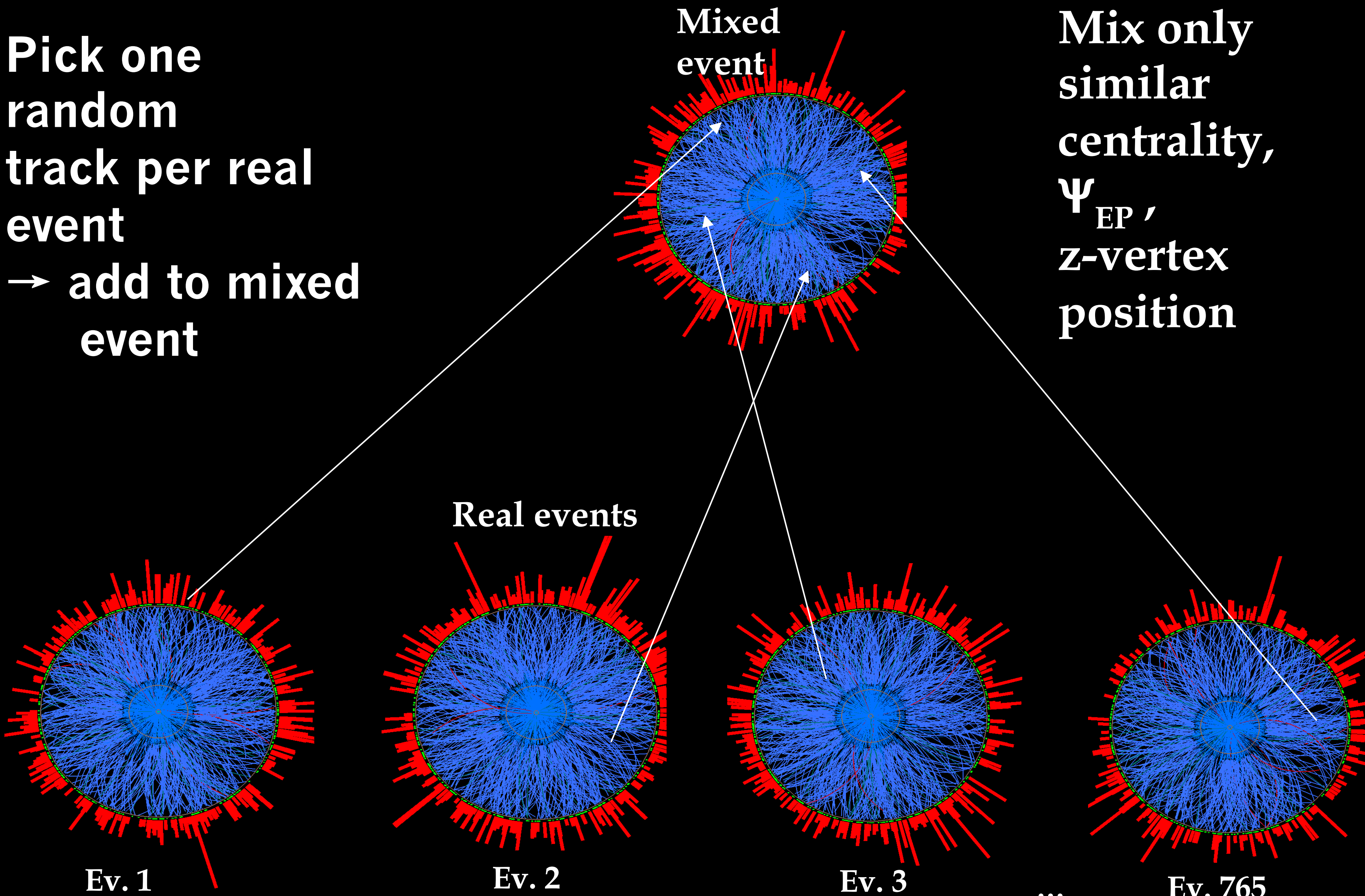
- Use all jet candidates on the other azimuthal hemisphere within +/- 45° → **no fragmentaion bias on recoil side**!

Combinatorial recoil jets? → Event mixing!

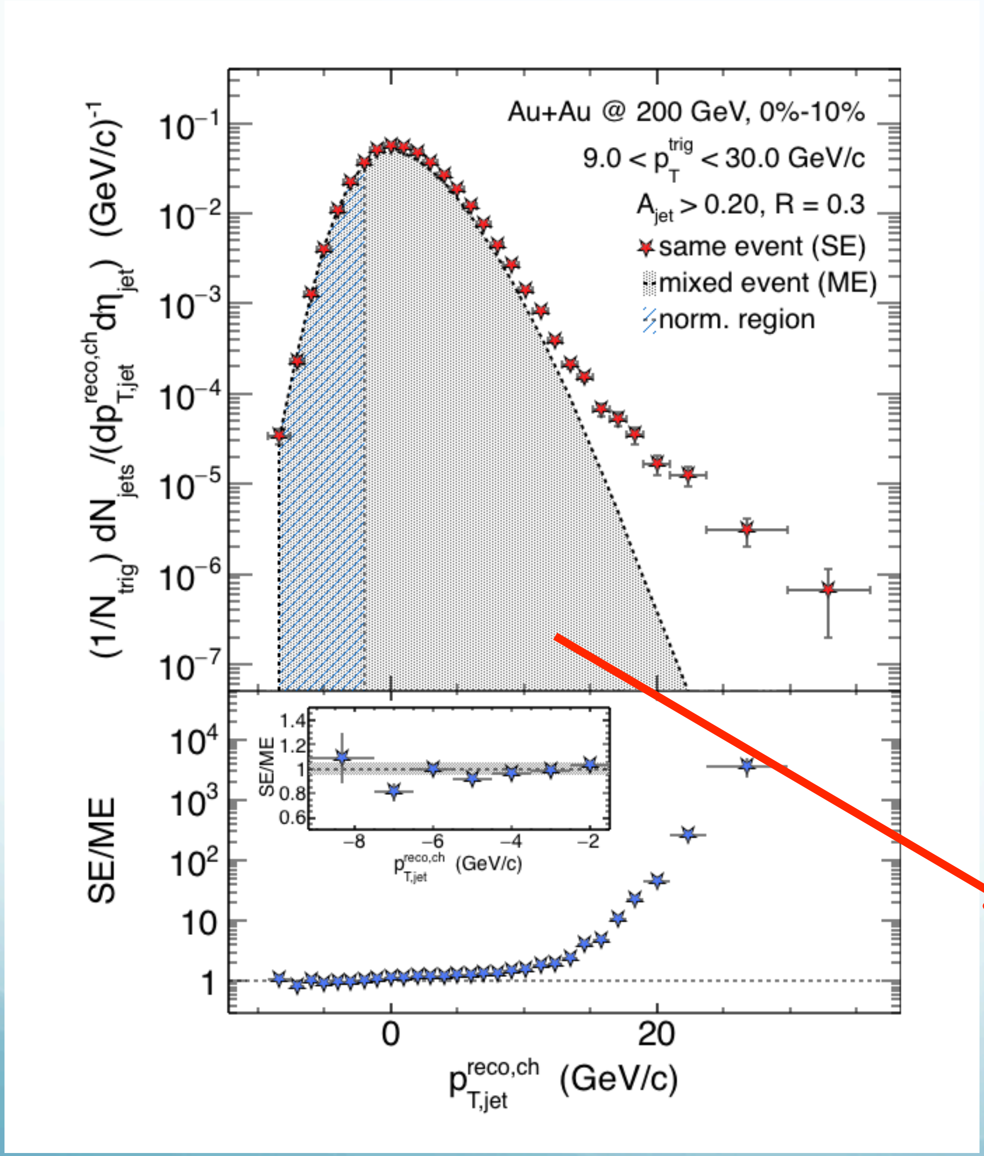
Mixed Event Generation for Jets

Pick one random track per real event
→ add to mixed event

Mix only similar centrality, Ψ_{EP}, z-vertex position



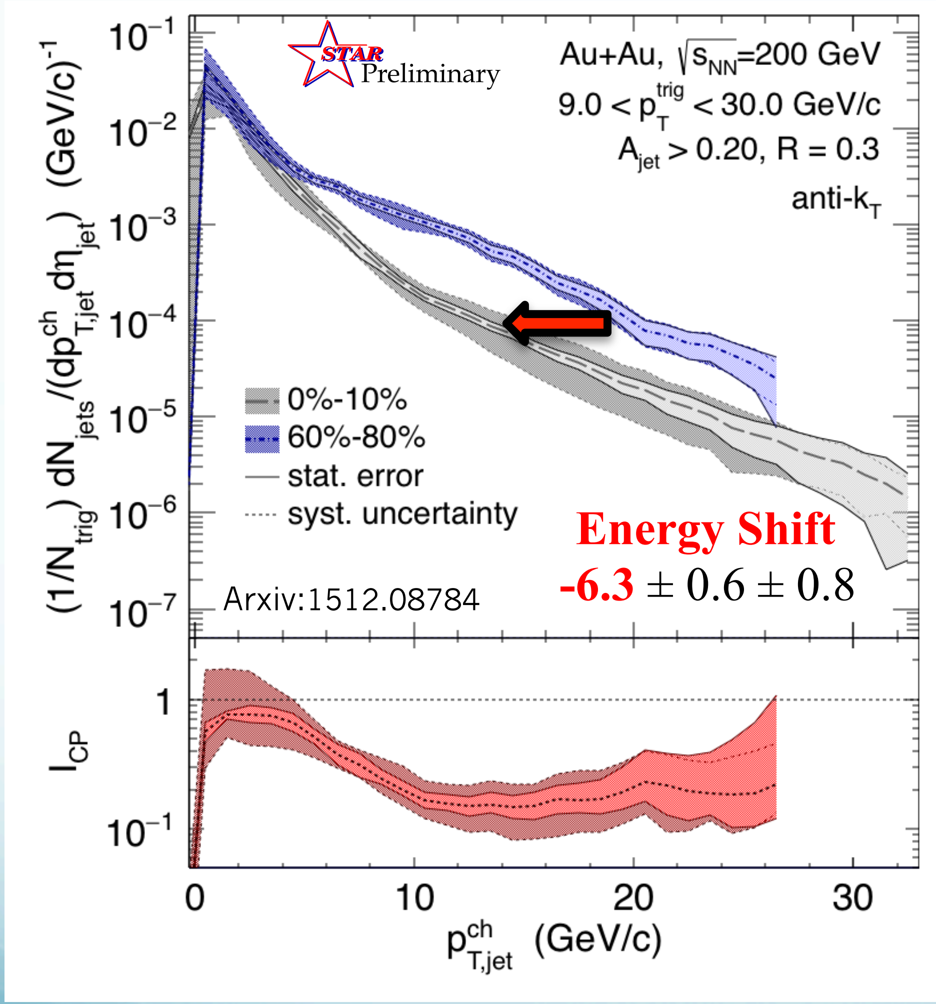
Charged Raw Recoil Jet Spectrum: Central



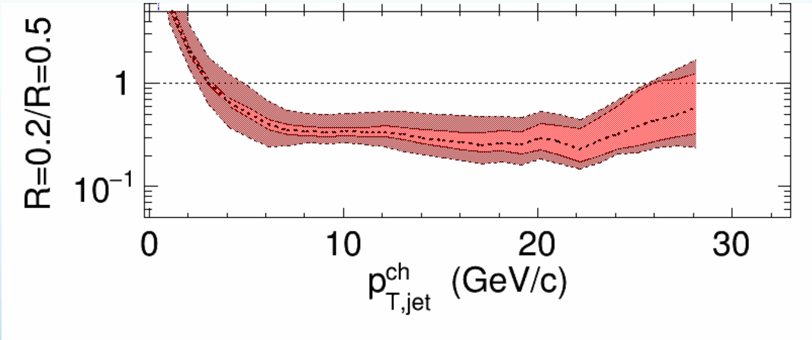
- Excellent description of low p_T SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at $p_T - \rho A > 10$ GeV/c

Combinatorial jet background → statistically described by mixed event technique

I_{CP} for h-jet correlations

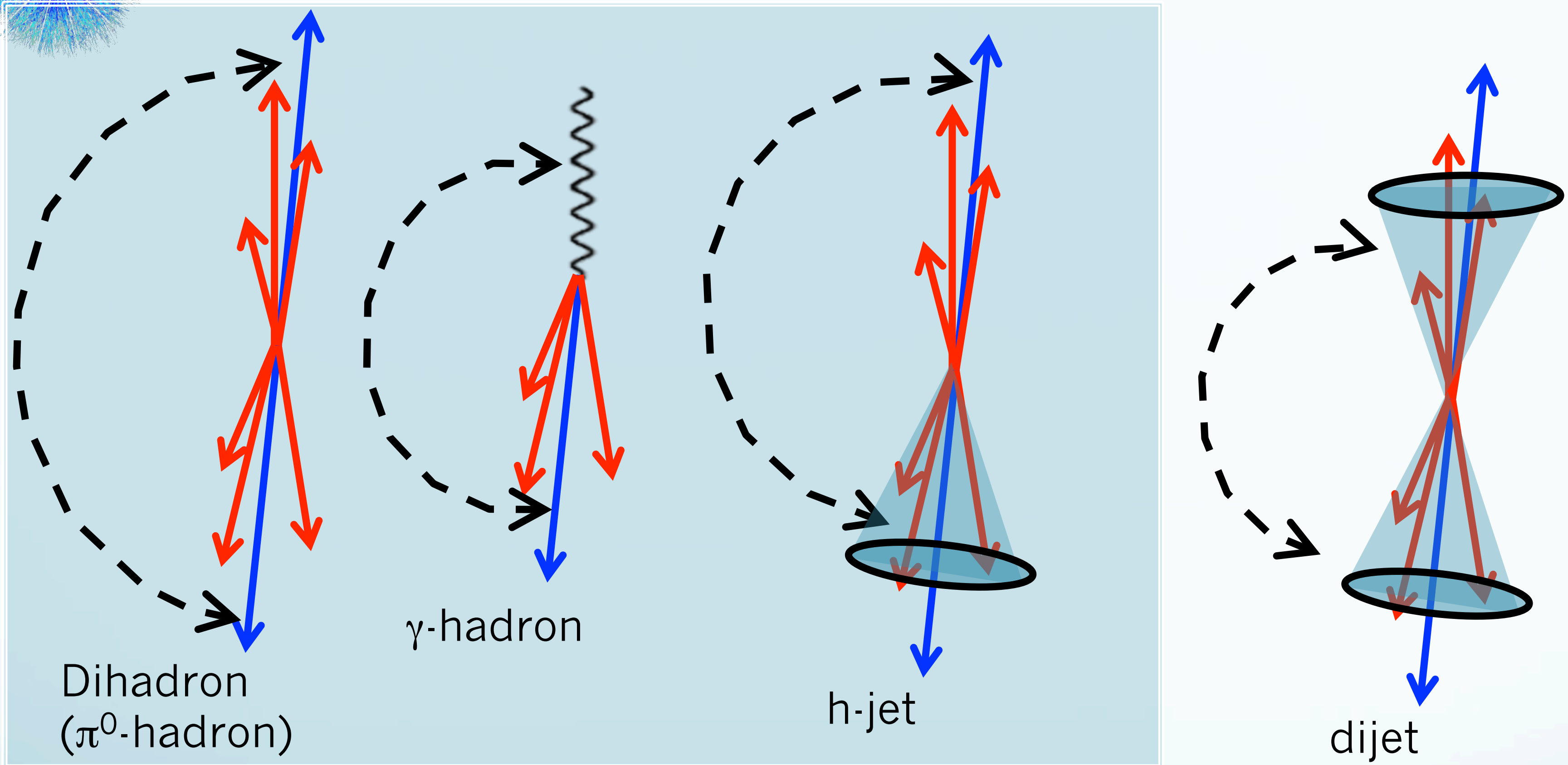


- Significant suppression (~0.2) at p_T > 10 GeV/c
  - γ-jet similar? (Geometry)
- Dijet Momentum Imbalance?
- Energy Shift
  - -6.3 (R=0.2) vs -3.8 (R=0.5)
- Ratio of cone size relatively flat for p_T > 10 GeV/c
- Compare RHIC and LHC → Need similar bias → Theory Calculation



Errors show combined systematics of unfolding and track reconstruction

Jets and Jet Correlations

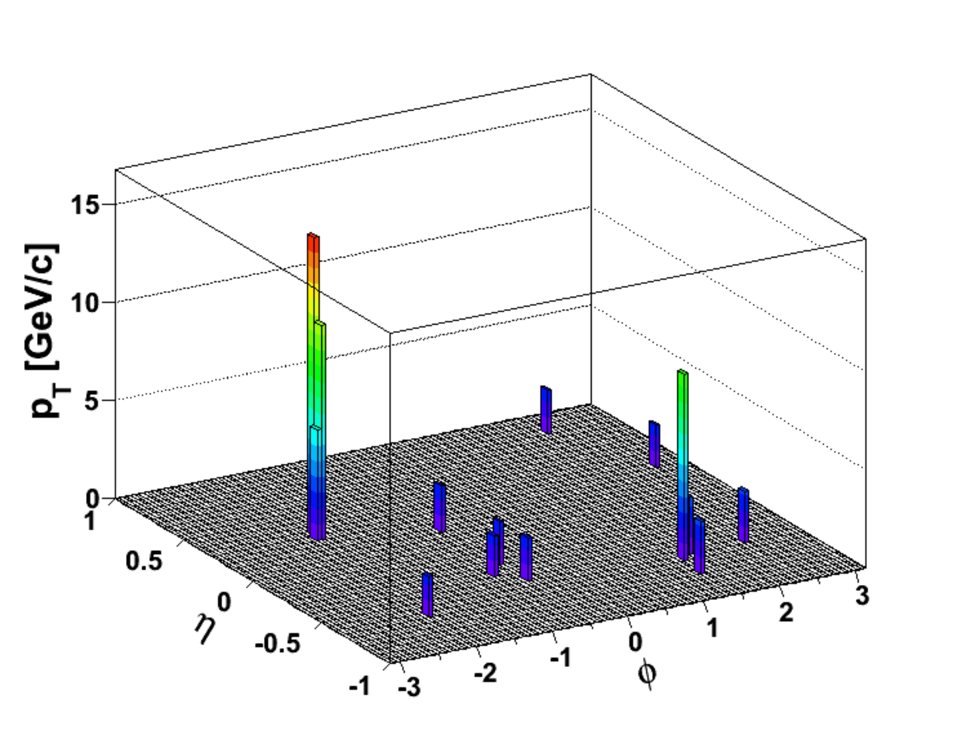


- Hadron triggered correlations do not allow a direct measure of the dijet momentum imbalance
- Experimentally we require a minimum p_T constituent cut
  - How does this effect the balance?

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

ATLAS, PRL **105**, 252303
CMS, PRC **84**, 024906 (2011)

(Biased) Di-Jet Selection



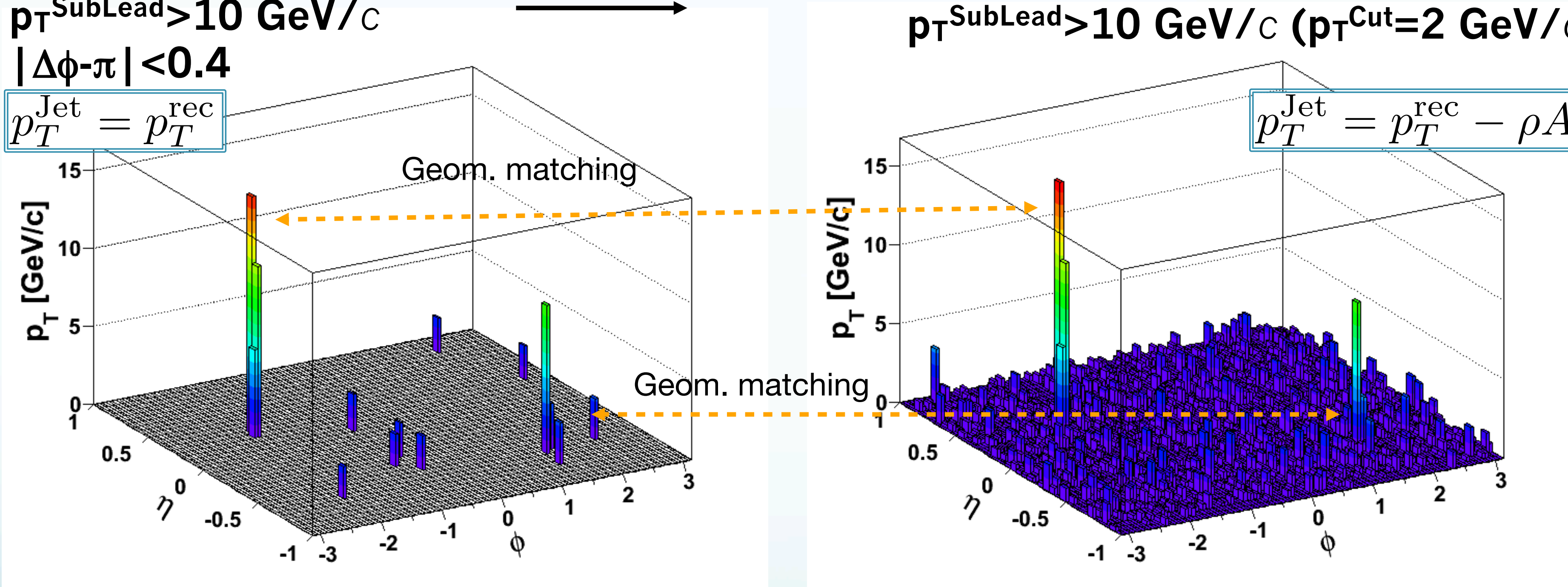
- Constituent p_T^{Cut} = 2 GeV/c
  - Reduce BG
  - Reduce combinatorial jets
- Di-jet Selection:
  - Jet p_T^{Lead}>20 GeV/c
  - Jet $p_T^{SubLead}$>10 GeV/c
  - $|\Delta\phi - \pi|<0.4$

Matched Di-jets w/o Constituent p_T Cut

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

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

p_T^{Cut}=0.2 GeV/c
p_T^{Lead}>20 GeV/c (p_T^{Cut}=2 GeV/c)
$p_T^{SubLead}$>10 GeV/c (p_T^{Cut}=2 GeV/c)

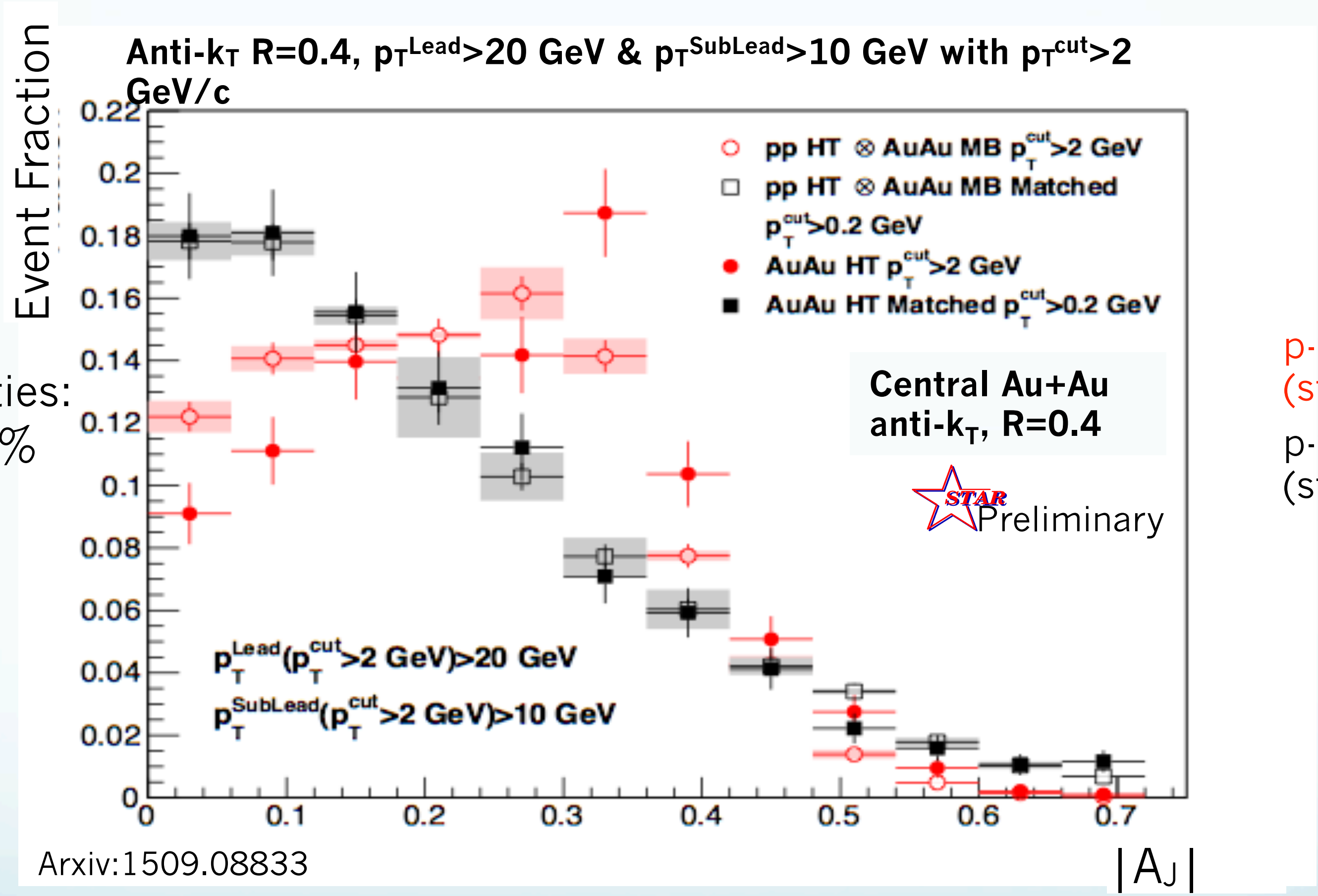


Keep this jet selection

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

Geom. matching: $\Delta R<0.4$

Di-Jet Imbalance A_J Central Au+Au, R=0.4



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

p-value < 10^{-4} (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)

STAR Statistics

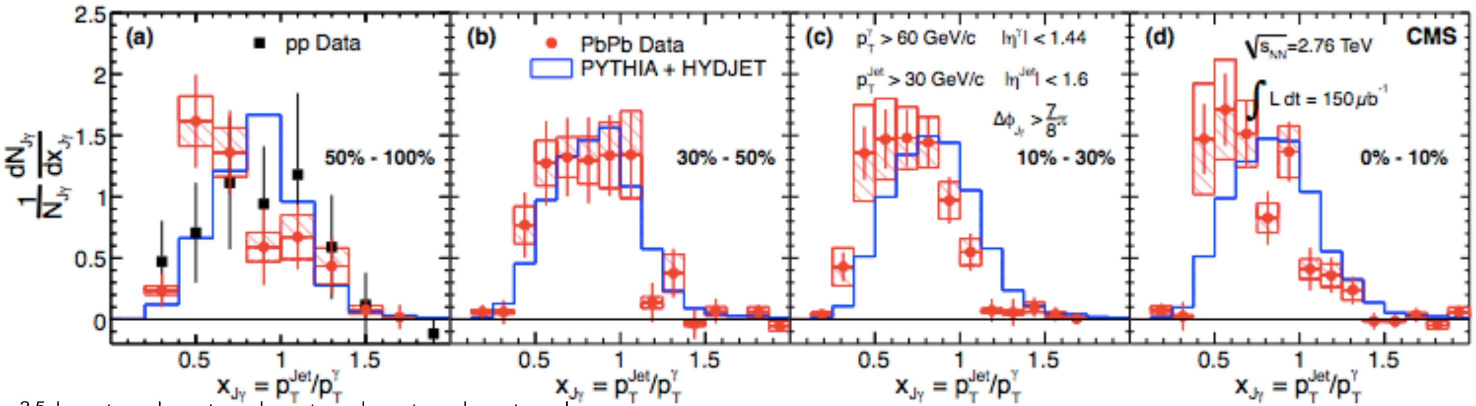
- Increased statistics recorded in 2011 will allow for γ_{rich}-jet correlations
  - Compare h-jet and γ_{rich}-jet
  - Path-length dependence
  - Energy loss

Year	Species	$\sqrt{s_{NN}}$	Integrated Luminosity
2006	pp	200 GeV	11 pb^{-1}
2007	Au+Au	200 GeV	535 μb^{-1}
2009	pp	200 GeV	23 pb^{-1}
2011	Au+Au	200 GeV	2.8 nb^{-1}
2014	Au+Au	200 GeV	43.9 nb^{-1}
2015	pp	200 GeV	382 pb^{-1}
2015	p+Au	200 GeV	1.27 pb^{-1}
2016	Au+Au	200 GeV	To be recorded

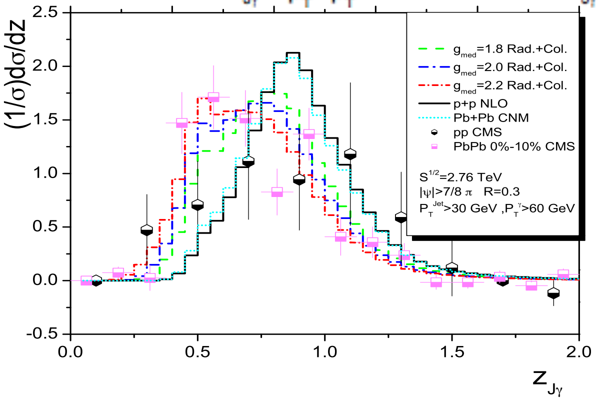
- Measuring the same observable at RHIC and the LHC with the same parton p_T and flavor will be key
  - Complementary to our understanding of QCD

Photon Jet Energy Fraction x_{Jg}

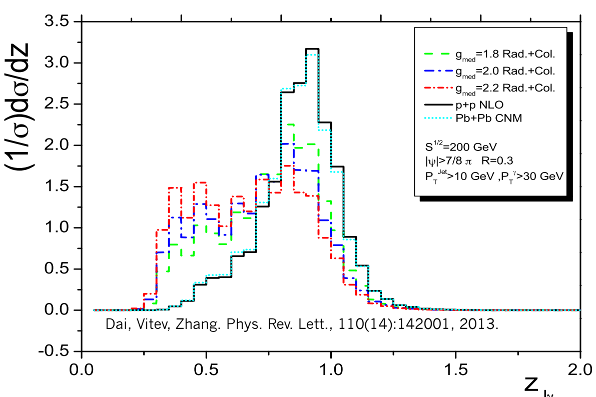
CMS: Phys. Lett., B718:773–794, 2013.



$$x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$



2.76 TeV



Dai, Vitev, Zhang. Phys. Rev. Lett., 110(14):142001, 2013.

200 GeV

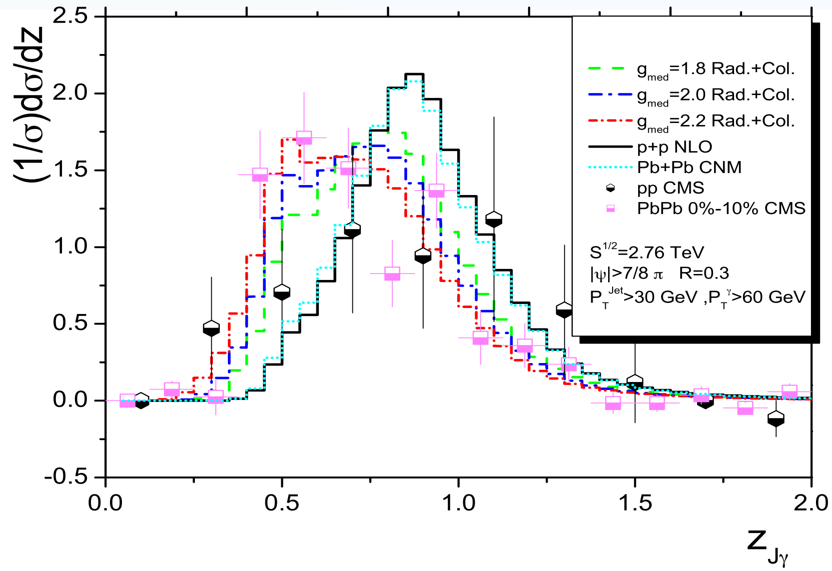
- The steeper falling RHIC cross-sections
  - Narrow $x_{J\gamma}$ distribution in pp
  - Larger broadening shift in $\langle x_{J\gamma} \rangle$ in A+A collisions
    - Less energy per jet is dissipated on average
- Order of magnitude increase in statistics make this feasible!

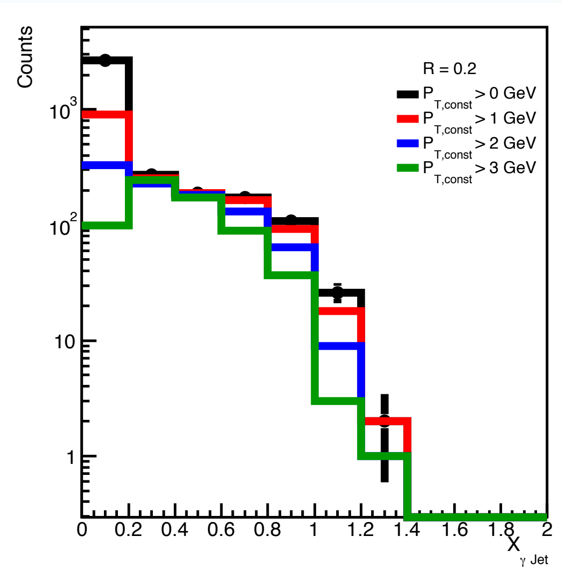
Conclusions

- Away-side hadrons of triggered γ_{dir} and π^0 show similar suppression
  - **Expected result of $I_{AA}\pi^0$-h < $I_{AA}\gamma_{dir}$-h isn't observed in 0.1 < z_T < 0.9 range, within uncertainties**
- Suppression at low z_T is less compared to high z_T
  - **Low p_T enhancement of jet fragmentation function**
- No direct photon trigger energy dependence of suppression is observed at high-p_T
- Clear away-side p_T^{assoc} dependence of suppression is observed for $I_{AA}\gamma_{dir}$-h
- I_{CP} of h-jet is ~0.2
  - **Energy shift is smaller for larger cone size**
- For biased dijets, the lost energy is recovered within R = 0.4, differs from LHC results
- Increased data will allow differential jet measurements at RHIC energies
  - Complementary with LHC results

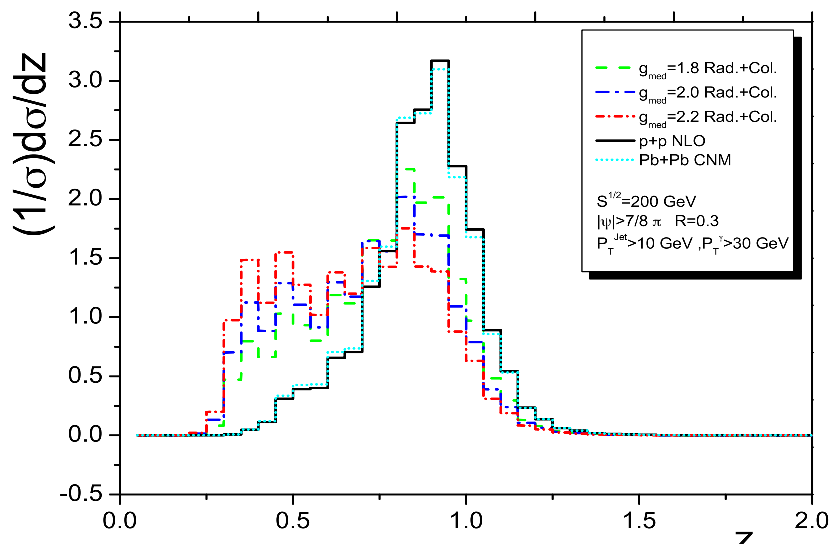
Back-Up

Photon Jet Energy Fraction x_{Jg}



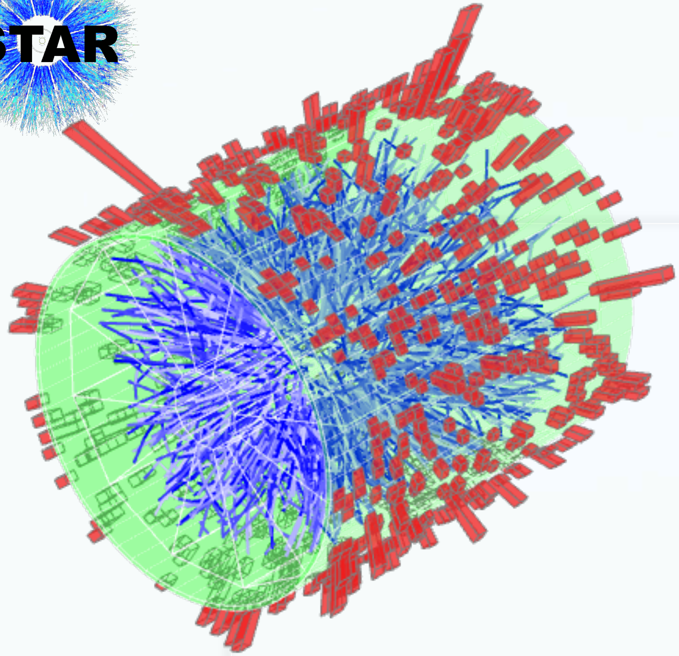


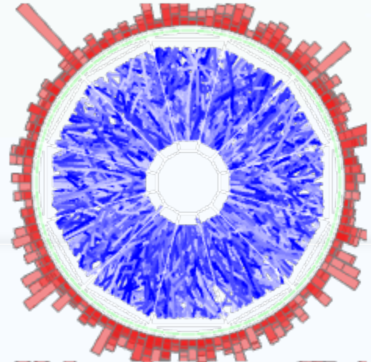
$$x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$

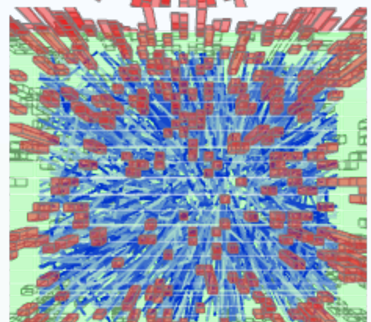


Dai, Vitev, Zhang. Phys. Rev. Lett., 110(14):142001, 2013.

- PYTHIA simulation shows expected statistics (no cut on lower pT jets) with new data







Kolja Kauder *for the STAR Collaboration*

July 02, 2015

Di-Jet Imbalance Measurements in Central Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV from STAR

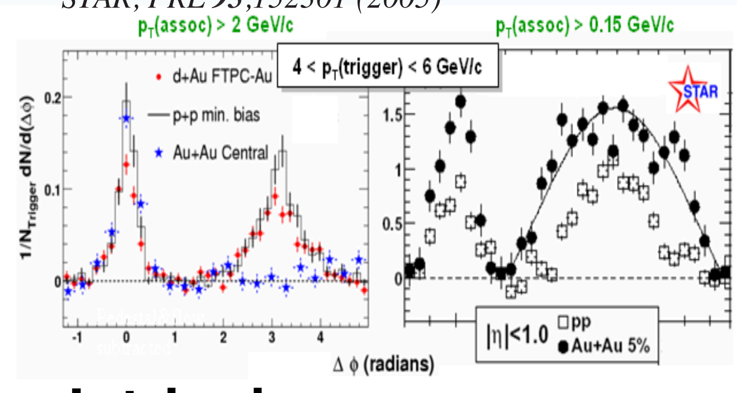
Overview

- Motivation
- Data Analysis
  - Data Selection and Jet Reconstruction
  - Method
- Results
- Summary

A Decade+ of Jet Quenching in STAR

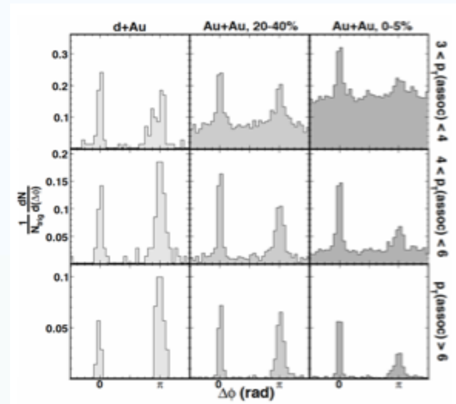
Di-hadron

*STAR, PRL **91**, 072304 (2003)*
*STAR, PRL **95**,152301 (2005)*



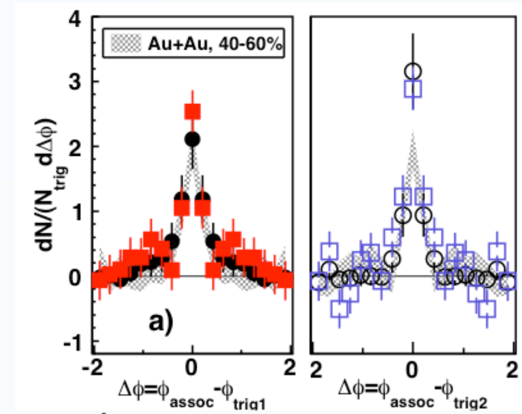
Di-Jets

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



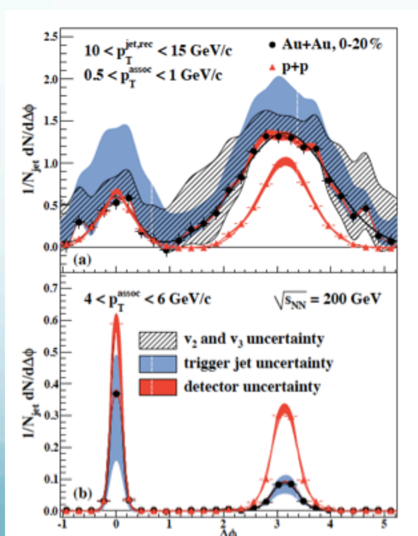
2+1

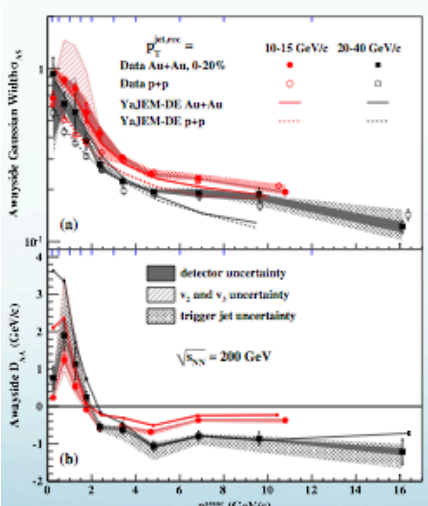
*STAR, PRC **83**, 061901 (2011)*



Jet-hadron

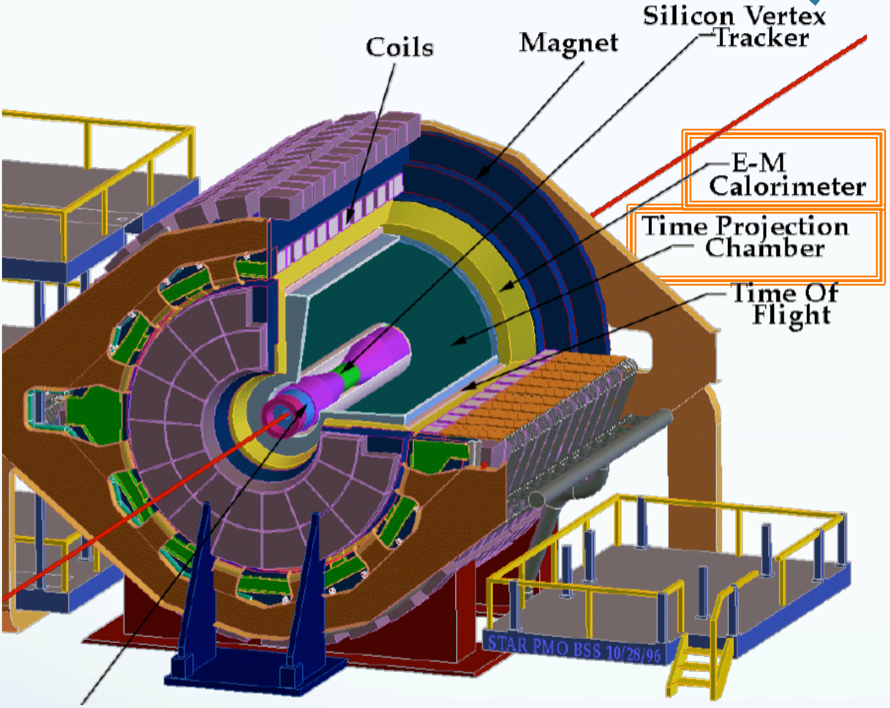
*STAR, PRL **112**, 122301 (2014)*





- *Ensemble-based*
  - hard trigger → small modification
  - Suppression at high p_T
  - Enhancement at low p_T
  - Broadening in Δφ
- Goal: jet-by-jet E-loss
  →**Di-jet Imbalance A_J**

The Solenoidal Tracker At RHIC (STAR)



- Tracking (charged) and EMC (neutral) in 2π (azimuth) × ±1 (η)
- High Tower (HT) trigger: E_T>5.5 GeV in one tower
- AuAu 2007: cut to 0-12% central
- *pp* from 2006: Embed into 0-12% central Au+Au
- Efficiency difference and systematic uncertainty assessed in embedded *pp*

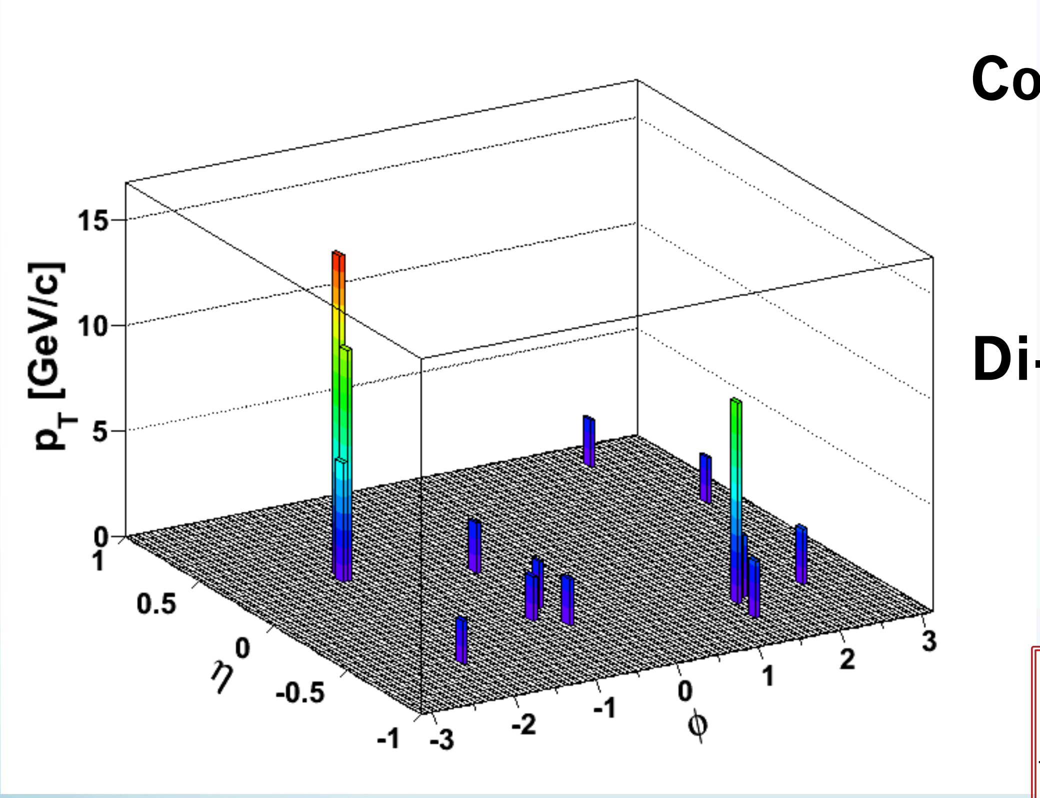
Jet-Finding:
FastJet3
M. Cacciari and G. Salam
Phys. Lett. B 641, 57 (2006)

- Anti-k_T, R=0.4 (0.2)
- Background: k_T, same R

$$p_T^{\mathrm{Jet}} = p_T^{\mathrm{rec}} - \rho A$$

(Biased) Di-Jet Selection

Constituent p_T^{Cut} = 0.2 GeV/*c*



Constituent p_T^{Cut} = 2 GeV/*c*

→ **Reduce BG**

→ **Reduce combinatorial jets**

Di-jet Selection:

Jet p_T^{Lead}>20 GeV/c

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

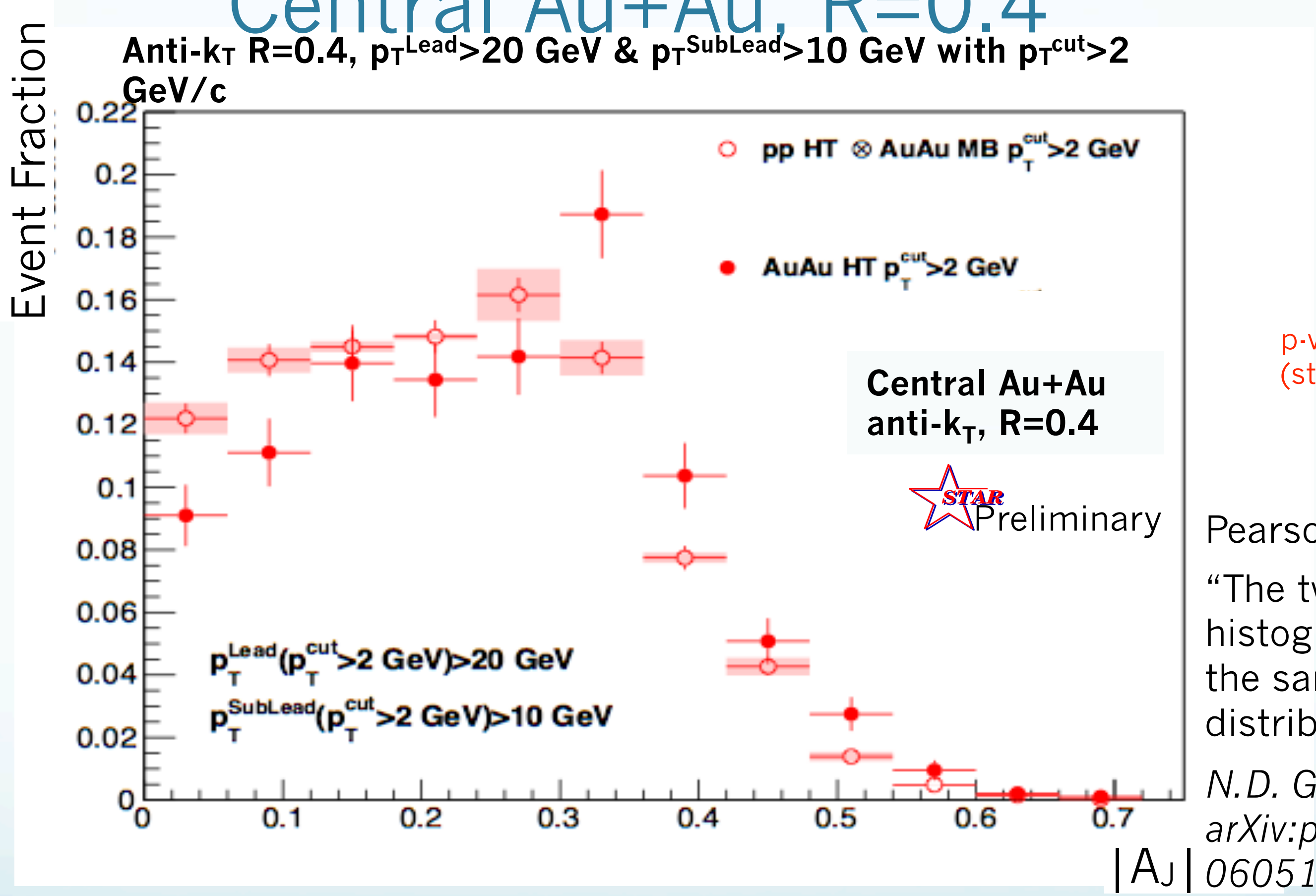
$|\Delta\phi-\pi|<0.4$

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

*ATLAS, PRL **105**, 252303*
*CMS, PRC **84**, 024906 (2011)*

Di-Jet Imbalance A_J
Central Au+Au, R=0.4

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



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

Pearson's χ^2-test of "The two histograms sample the same distribution"

N.D. Gagunashvili, arXiv:physics/0605123

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

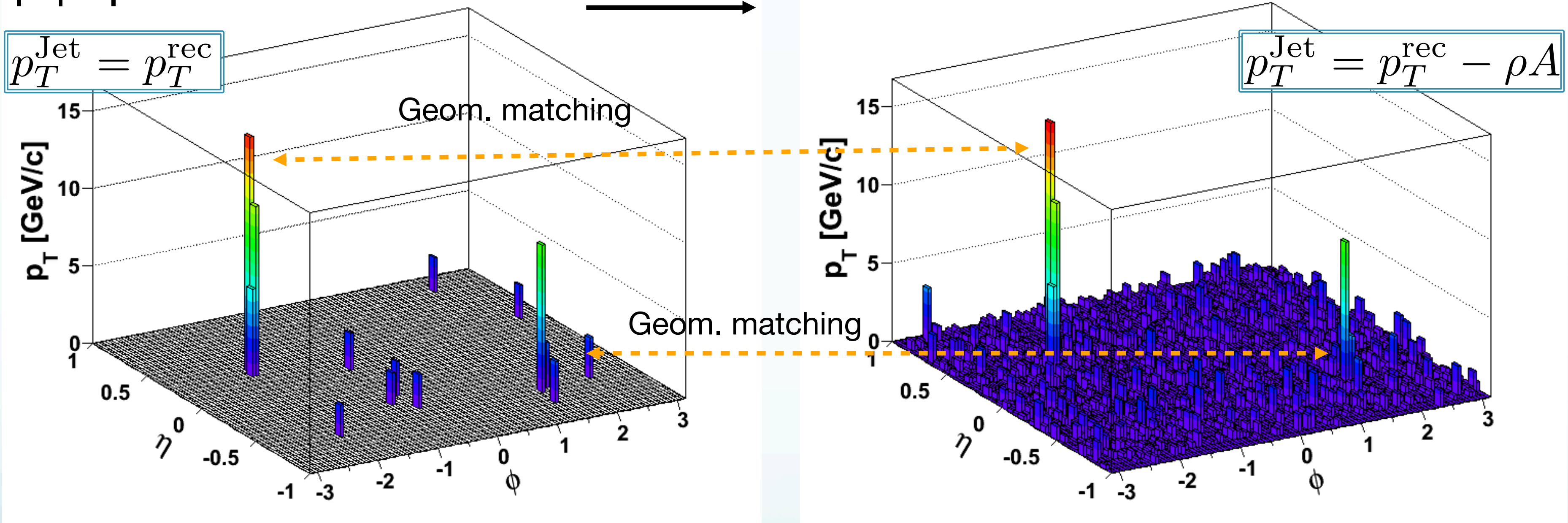
Can the balance be restored?

Matched Di-jets w/o Constituent p_T Cut

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

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

p_T^{Cut}=0.2 GeV/c
p_T^{Lead}>20 GeV/c (p_T^{Cut}=2 GeV/c)
$p_T^{SubLead}$>10 GeV/c (p_T^{Cut}=2 GeV/c)

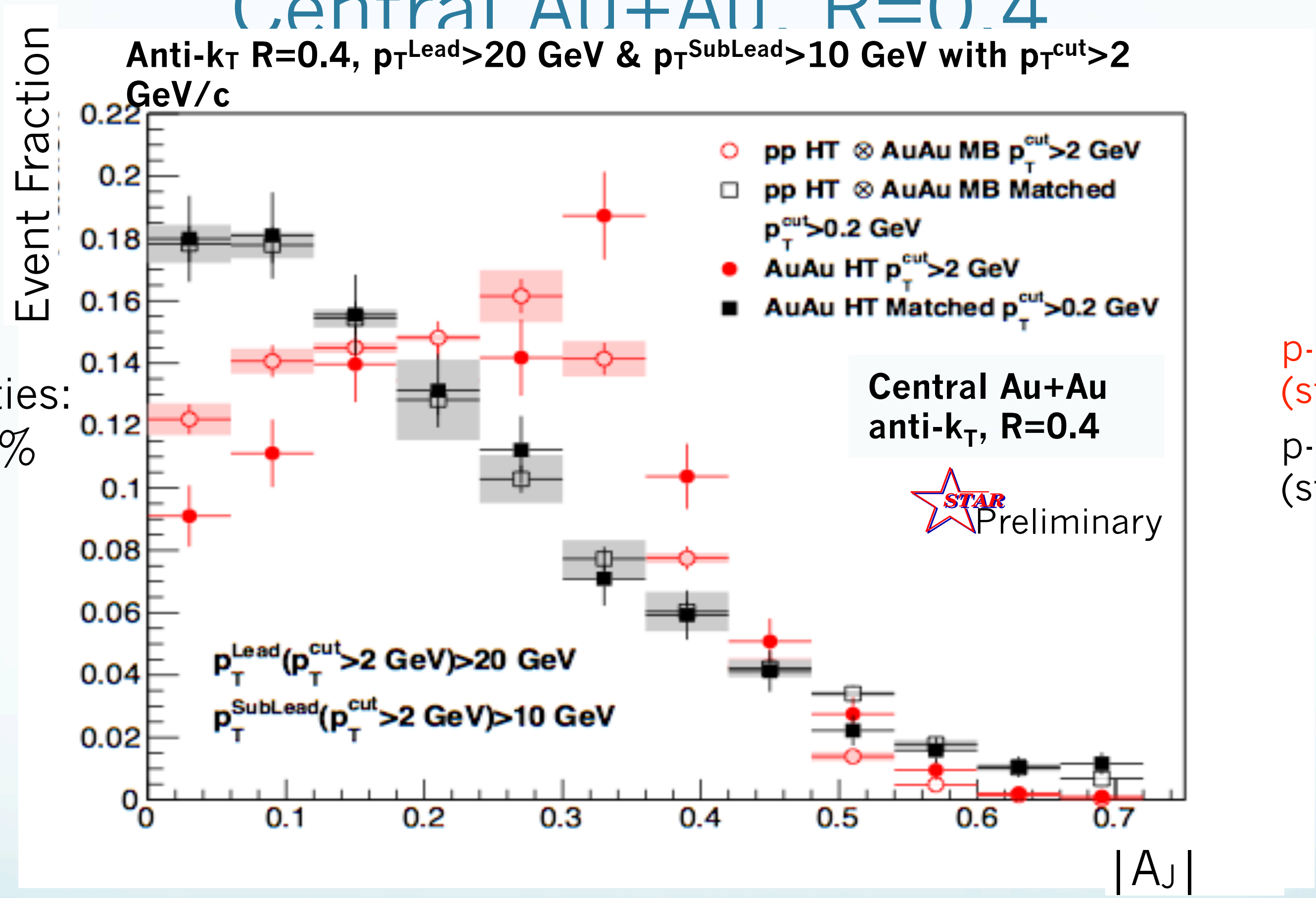


Keep this jet selection

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

Geom. matching: $\Delta R<0.4$

Di-Jet Imbalance A_J Central Au+Au, R=0.4



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

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

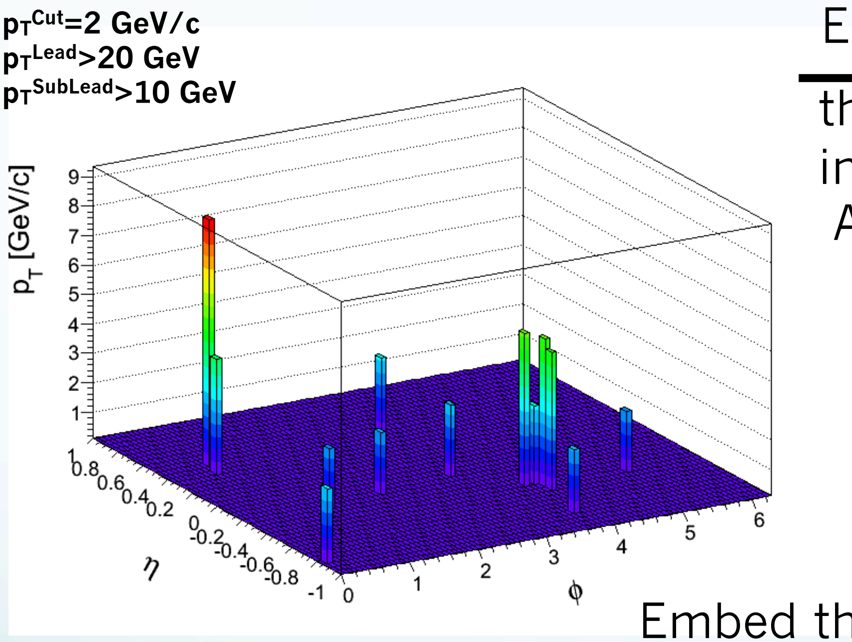
p-value = 0.8 (stat. error only)

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: Balance Restored by Uncorrelated BG?

Method 1: Random Cone (RC):

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



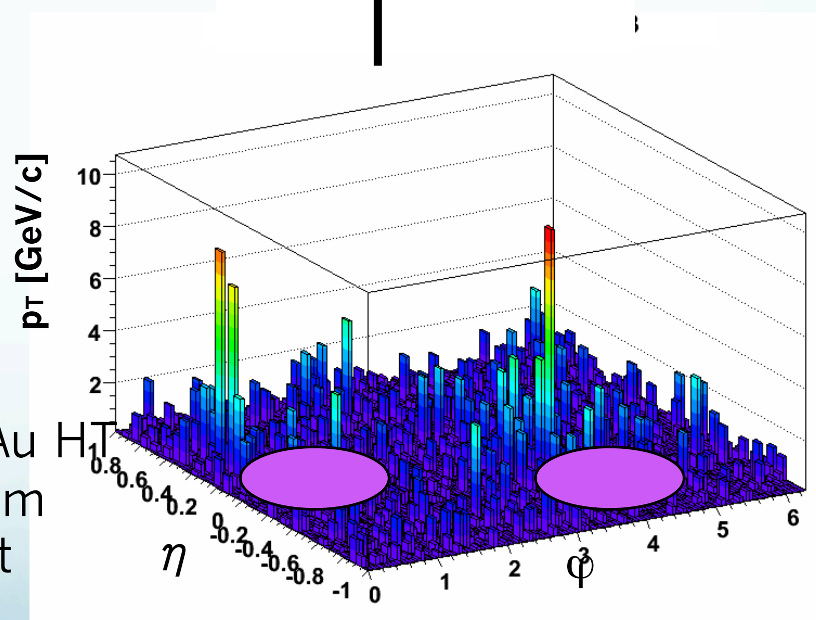
Embed randomly the 2 Jet vectors into a central Au+Au MB event

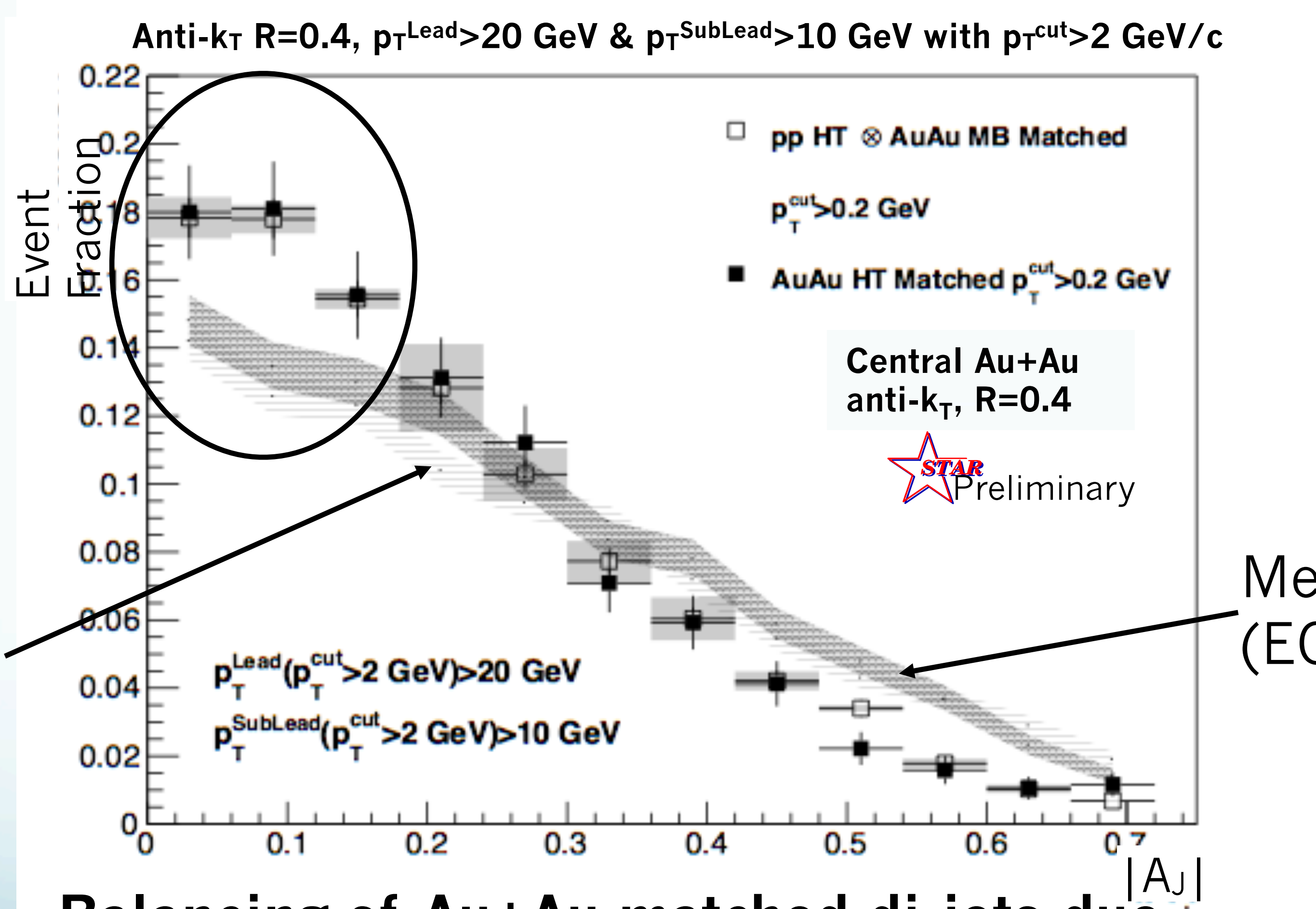
Calculate |A_J| with $p_T^{Cut}>0.2$ GeV/c using cone of R

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 a Au+Au HT event, 2R away from reconstructed di-jet pair in that event





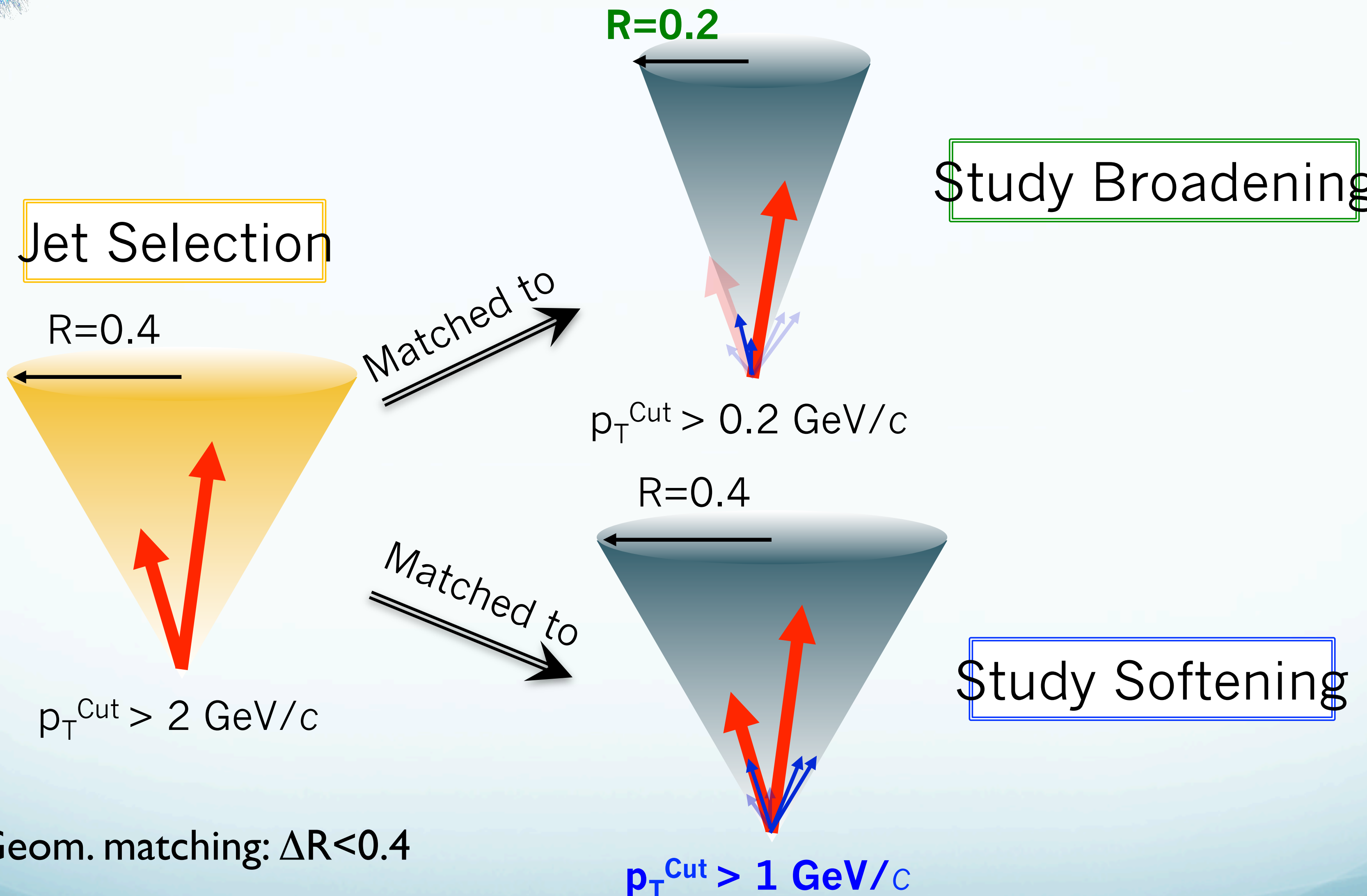
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

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

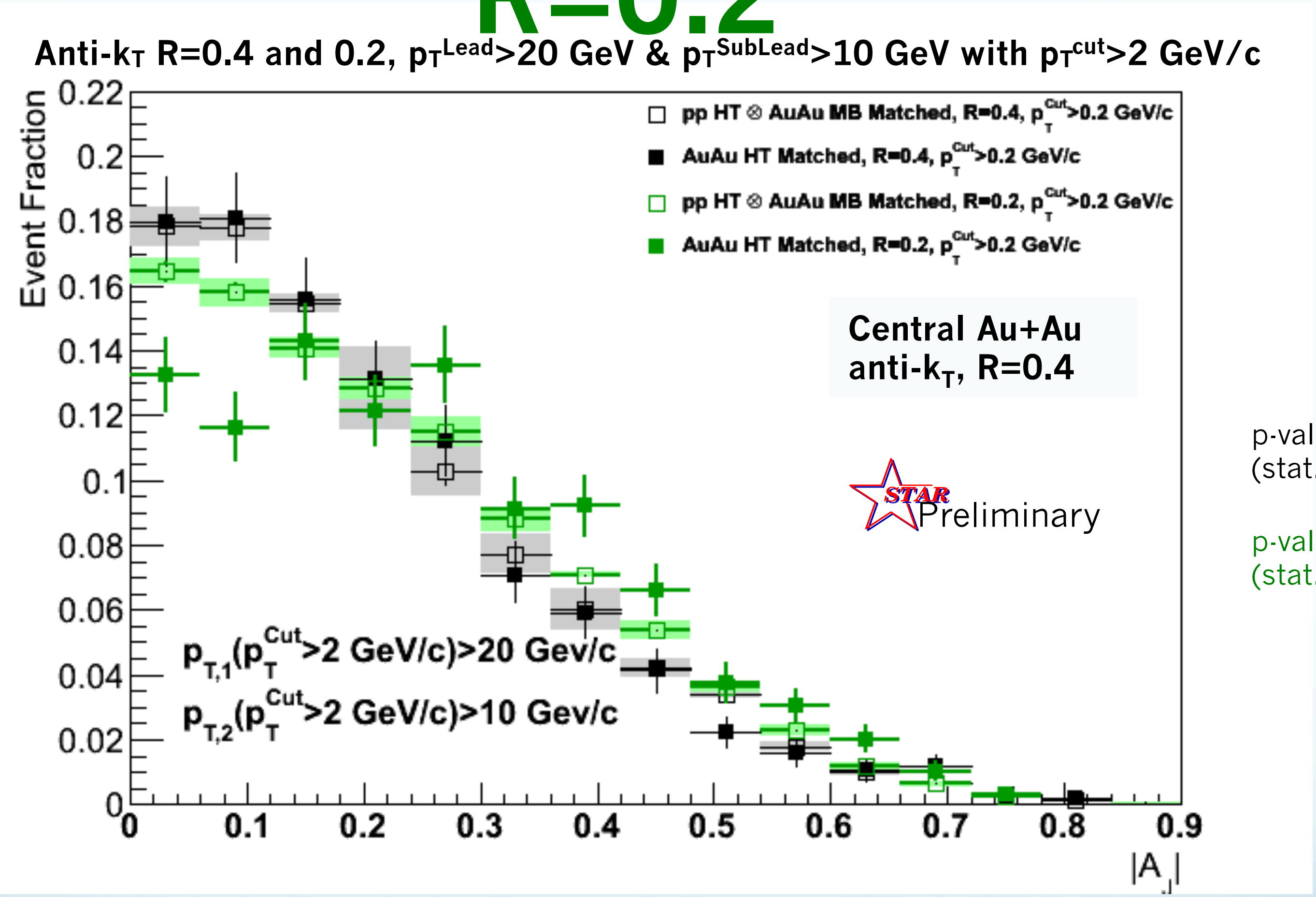
Differential Measurements



Geom. matching: $\Delta R<0.4$

Jet Broadening – Match to R=0.2

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

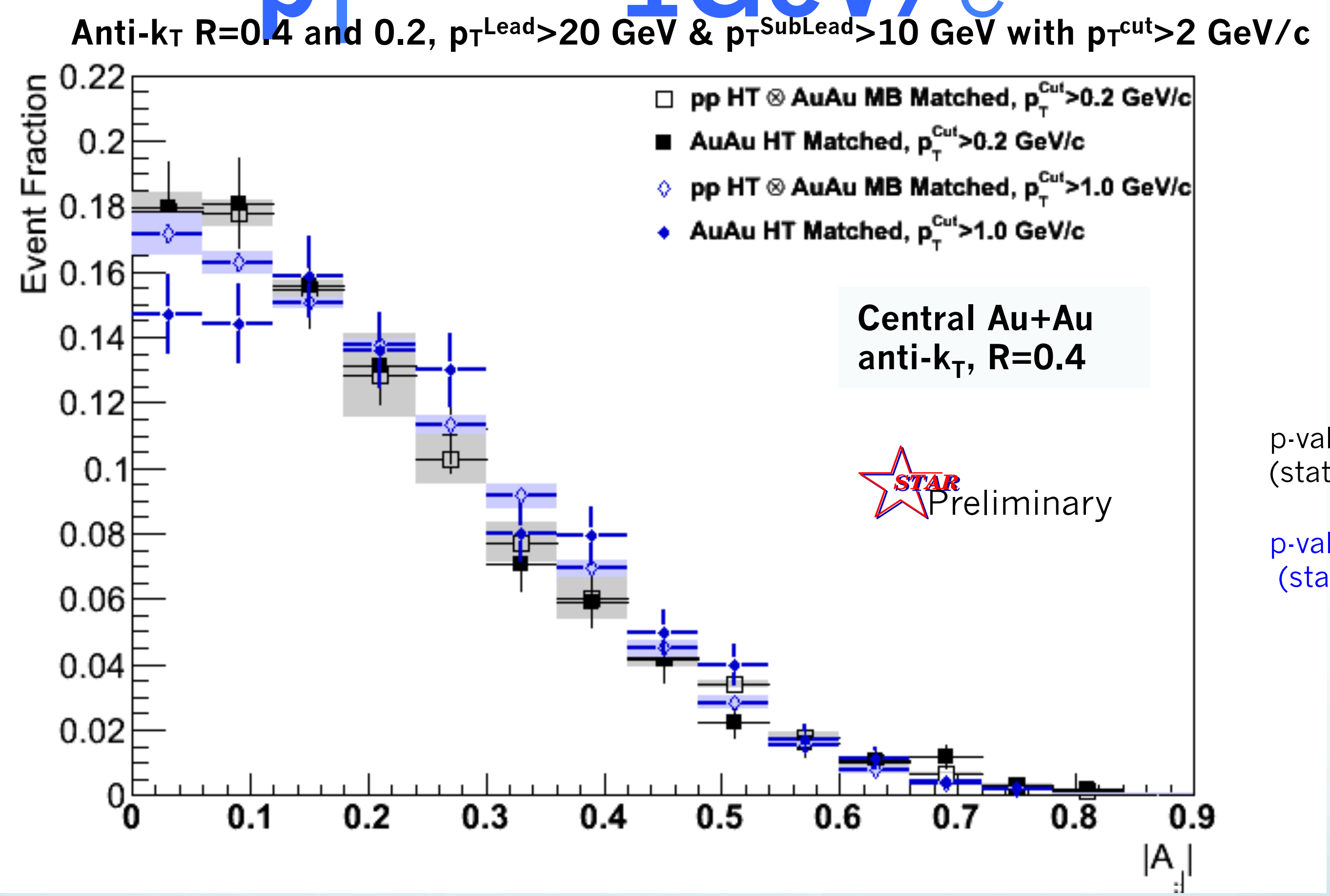


p-value = 0.8
(stat. error only)

p-value = 2×10^{-4}
(stat. error only)

For the same R=0.4, $p_{T,1}$>20, $p_{T,2}$>10 GeV Jets, balance can not be restored within R=0.2 → Broadening

Jet Softening – Match to $p_T^{Cut} = 1GeV/c$



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

p-value = 0.8 (stat. error only)

p-value =5-20% (stat. error only)

$p_T^{Cut} = 1GeV/c$ not sufficient to restore balance
→ signs of jet softening between 1 and 2 GeV/c

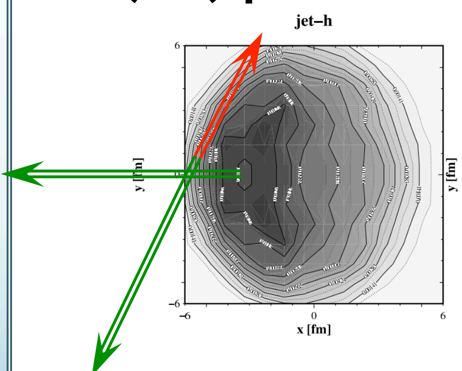
Discussion

For the first time: "Lost" energy of the dijets is recovered in a jet of R=0.4
for $p_T^{Cut} = 0.2$ GeV/c

Interpretation:

(Constituent) $p_T^{Cut} = 2$ GeV/c
+ High Tower
+ (Jet) $p_T^{Lead} > 20$ GeV/c

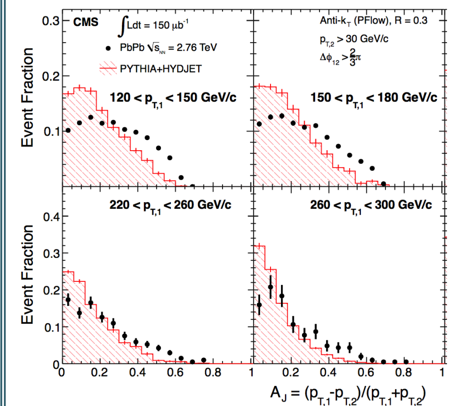
Bias



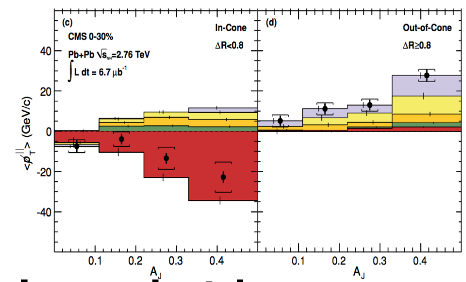
STAR:
$p_T^{lead} > 15$ GeV/c
$p_T^{cut} > 2$ GeV/c
T. Renk, PRC 87, 024905 (2013)

+ (Recoil) $p_T^{SubLead} > 10$ GeV/c
→ Path Length Control

Contrast to LHC:

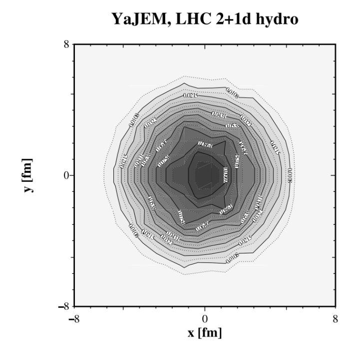


CMS, PRC 84, 024906 (2011)



Large imbalance, balanced at large angles

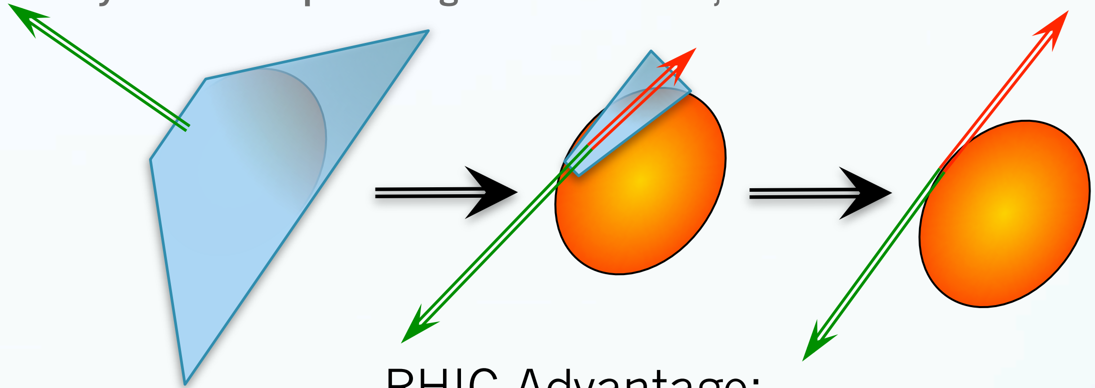
LHC:
A_J Dijet Trigger
T. Renk, PRC 85, 064908 (2012)



- "Unbiased" di-jet selection
  → longer path lengths
  & Larger energy loss at early times
  → more diffusion in medium

Unique Opportunity for Jet Geometry Engineering at RHIC

- $p_T^{SubLead}$ & Constituent p_T → **systematically** dial in the **path length** of the recoil jet

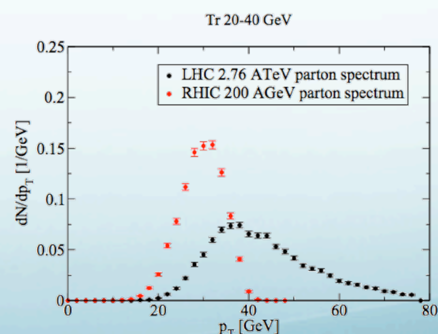


- Dijet Imbalance = Recoil E-loss?
- Found a **"sweet spot"**
  Lost energy seems to be
  contained within R=0.4

RHIC Advantage:
Steeply falling spectrum
→ Good correlation between jet and original energy

- **Matching:** *Differentially* study
  - Broadening – *jet-by-jet*
  - Softening – *jet-by-jet*

- Future:
  Statistics × 7
  →Fragmentation function and radial profile of in-medium jet energy loss



$R=0.4, p_T^{Cut}>2$ GeV/c
T. Renk, PRC 87, 024905 (2013)

Summary

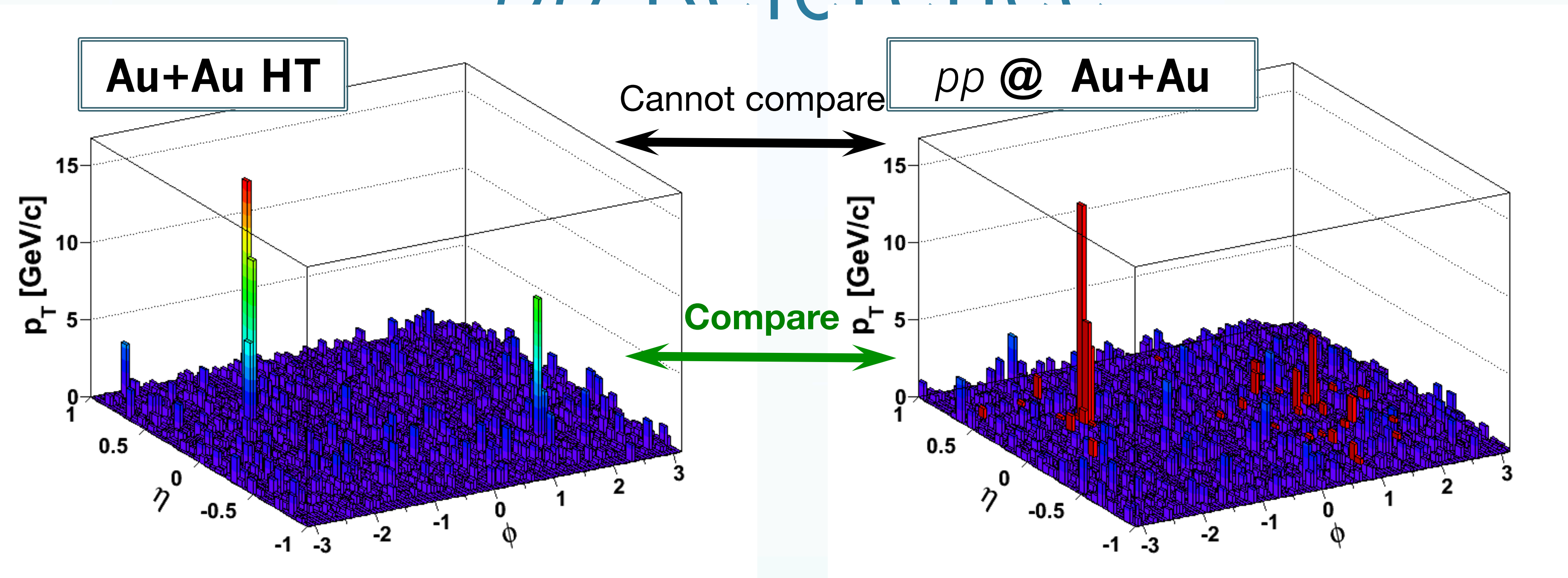
- Jet reconstruction of leading and recoil jet
  → Energy loss *jet-by-jet* instead of ensemble-based

- A_J: Define a subset of imbalanced di-jets in Au+Au, that can be restored to *pp* balance
  - "Lost" energy seems **contained within R=0.4 and low p_T**
  - Imbalance remains for smaller cone or higher constituent cutoff

  → Observed **Broadening** and **Softening** *jet-by-jet*

Backup

pp Reference

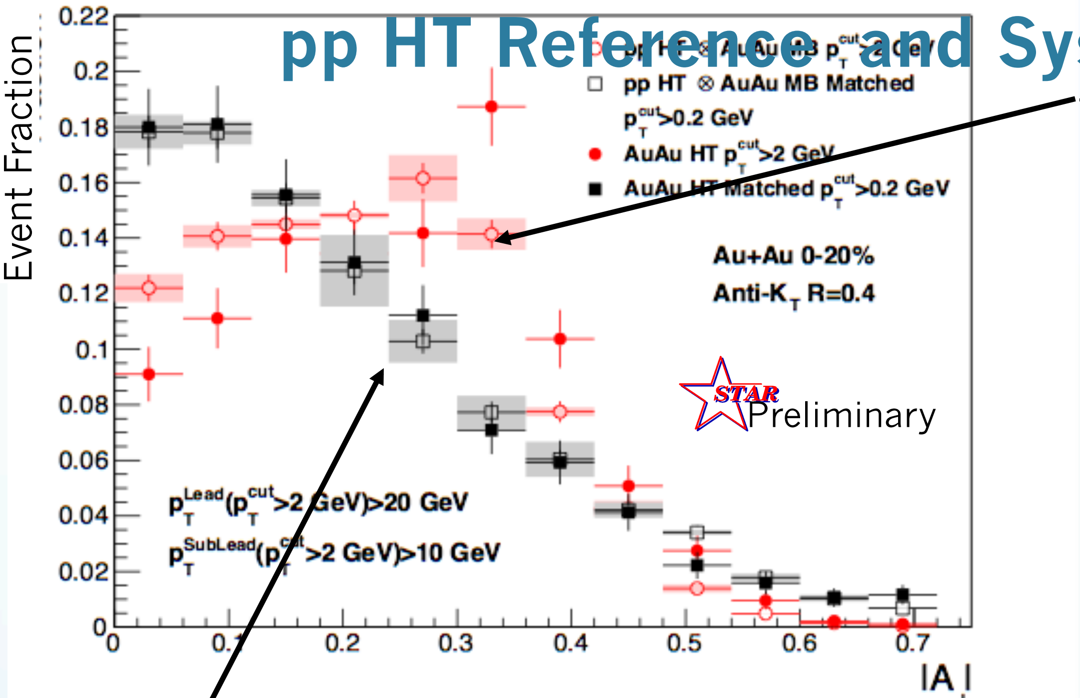


No correction to particle level. To compare on equal footing:

- Embed full pp events into (unbiased) central events

Tower and efficiency uncertainty studied in *pp*

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

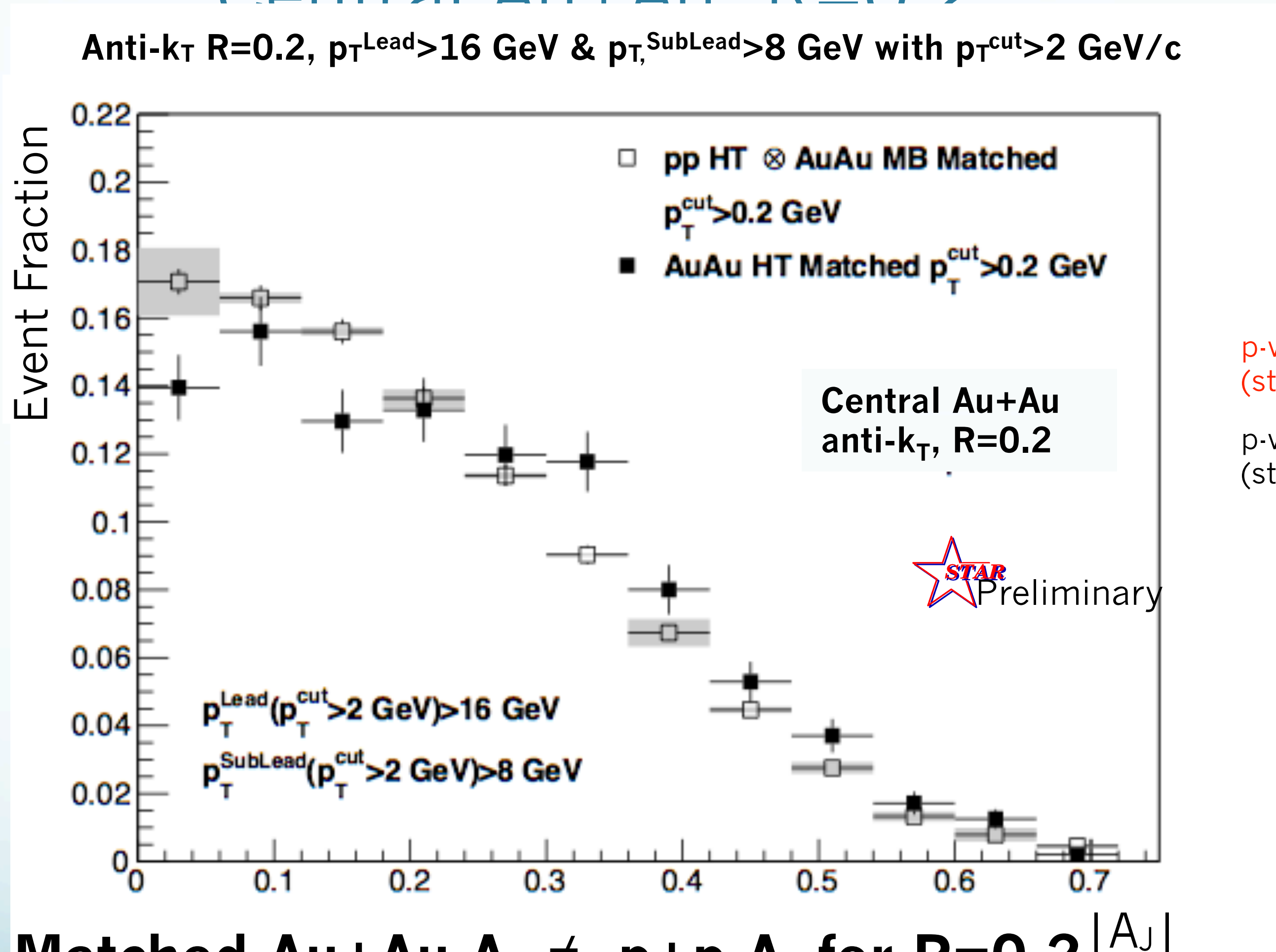
*STAR, PRL **112**, 122301 (2014)*

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

Di-Jet Imbalance A_J
Central Au+Au, R=0.2

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

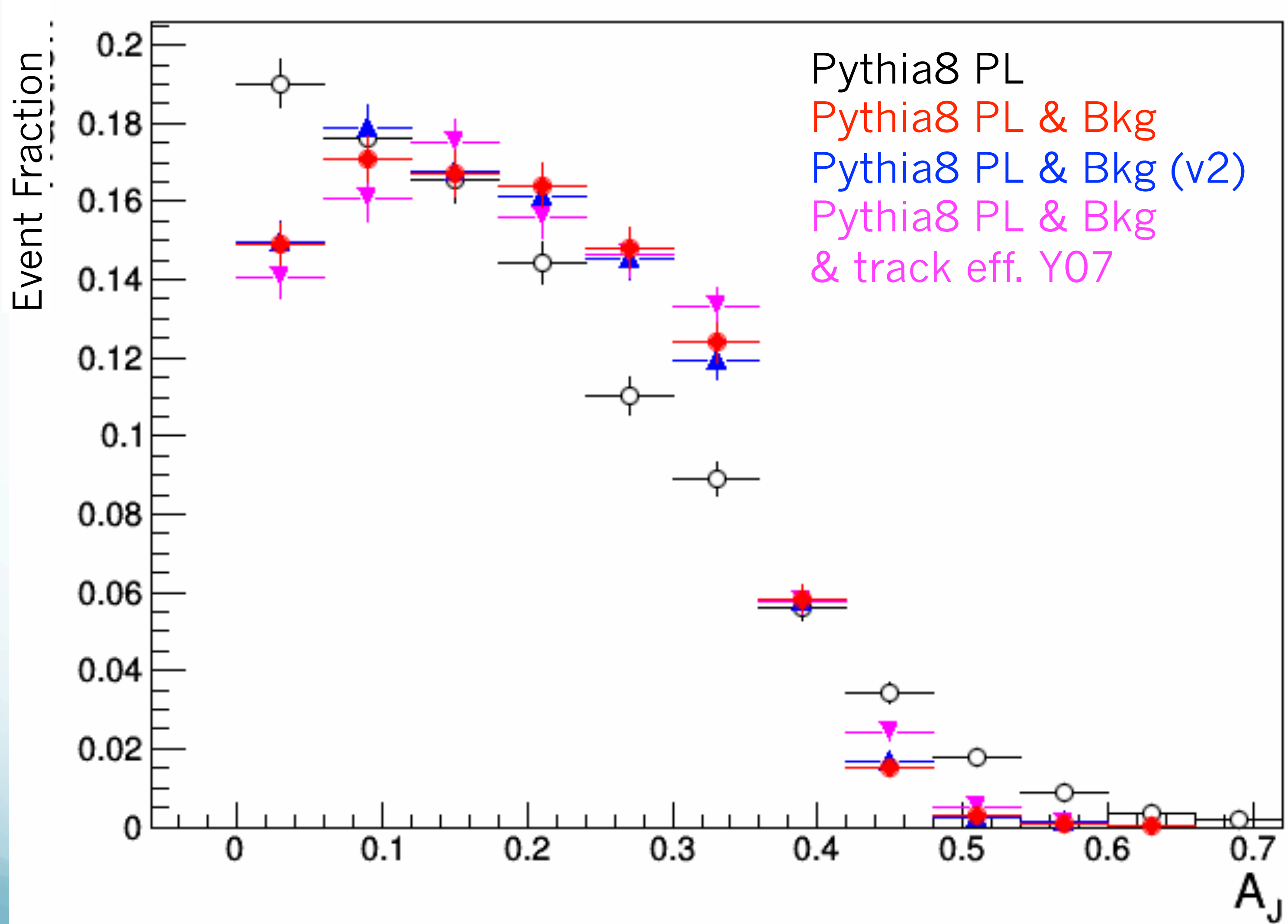


p-value < 10^{-10}
(stat. error only)

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

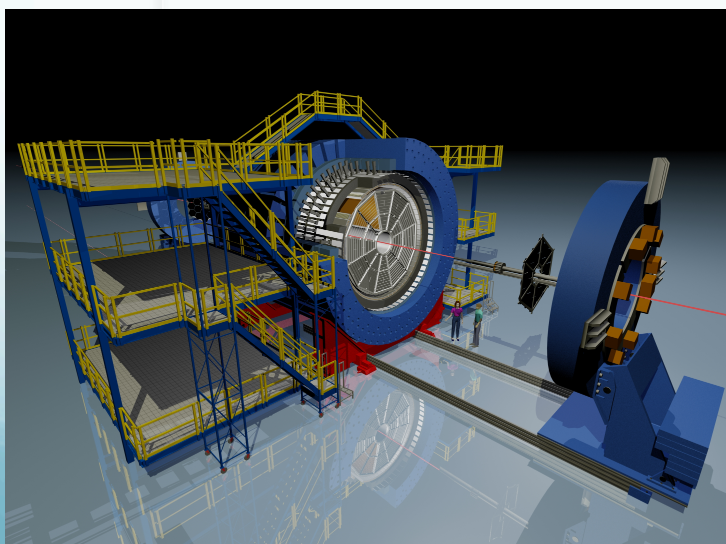
Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

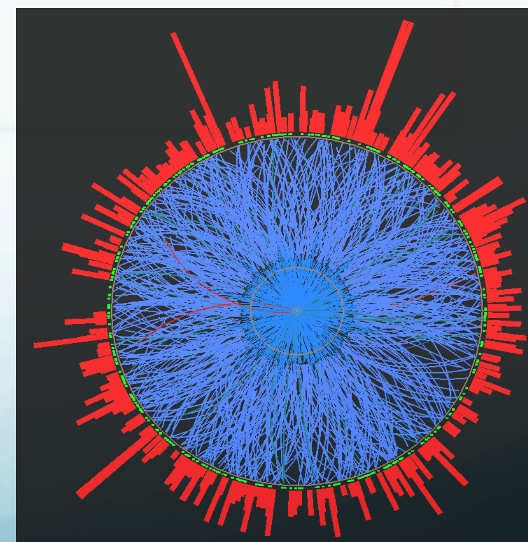
PYTHIA8 Particle Level (PL) and Toy Bkg. Model



Semi-inclusive charged je measurements in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV

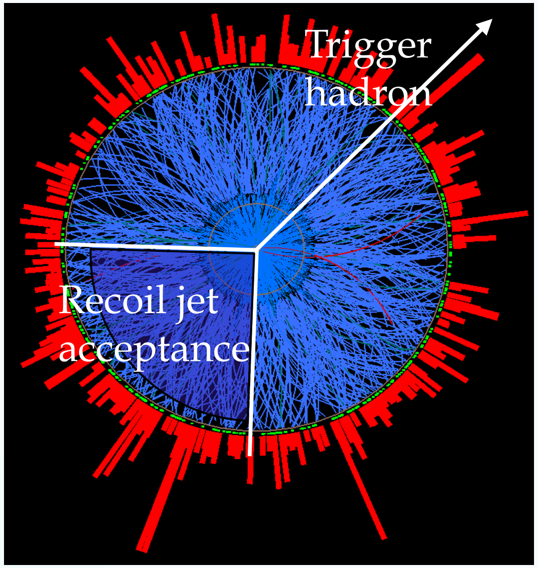
Peter Jacobs
Lawrence Berkeley National Laboratory
for the STAR Collaboration





correlation

Trigger-normalized yield of jets recoiling from a high p_T hadron trigger



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

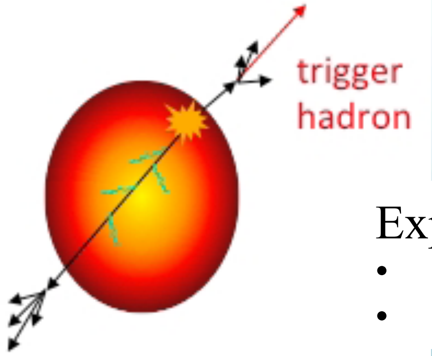
Measured — Calculable in pQCD

Semi-inclusive: event selection only requires trigger hadron

- experimentally clean; trigger bias theoretically calculable

Count all recoil jet candidates:

- uncorrelated background corrected at level of ensemble-averaged distributions
- jet selection does not impose fragmentation bias



Expected geometric bias: surface, not tangential

- Large path length for recoil
- Model studies: T. Renk, PRC74, 024903; H. Zhang et al., PRL98 212301;…

Analysis details

Dataset

Year 2011 data: Au+Au, $\sqrt{s_{NN}}$=200 GeV

Minbias trigger; 500M events after cuts

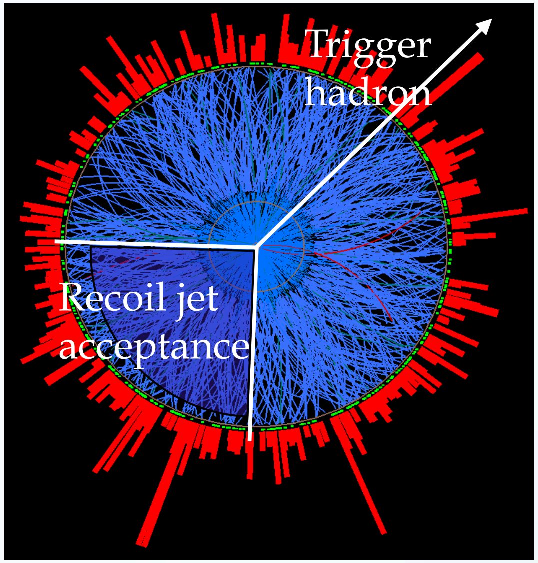
- Offline centrality selection 0-10%, 60-80% (mid-rapidity raw multiplicity)

Charged jet reconstruction

Charged tracks: $0.2 < p_T^{track} < 30$ GeV/c

Algorithm: anti-k_T, R=0.2, 0.3, 0.4, 0.5

- Jet centroid: $|\eta^{jet}| < 1.0 - R$
- Recoil jet centroid acceptance: $[\pi - \pi/4, \pi + \pi/4]$



Hadron trigger

Charged particle, $9 < p_T < 30$ GeV/c

- Inclusive selection: choose one trigger particle without regard to rest of event ➔ trigger may not be highest p_T track

Uncorrelated background measured via mixed events (new method)

Correction for background fluctuations and instrumental effects

- Event-wise pedestal shift ρ*A (Fastjet prescription)
- Unfolding of ensemble averaged distribution

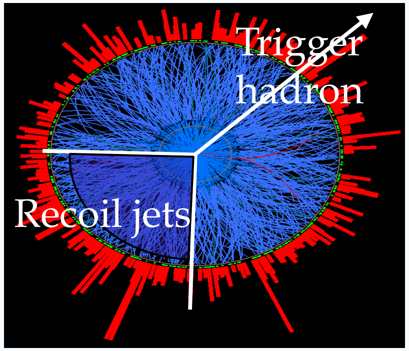
} Procedures are coupled

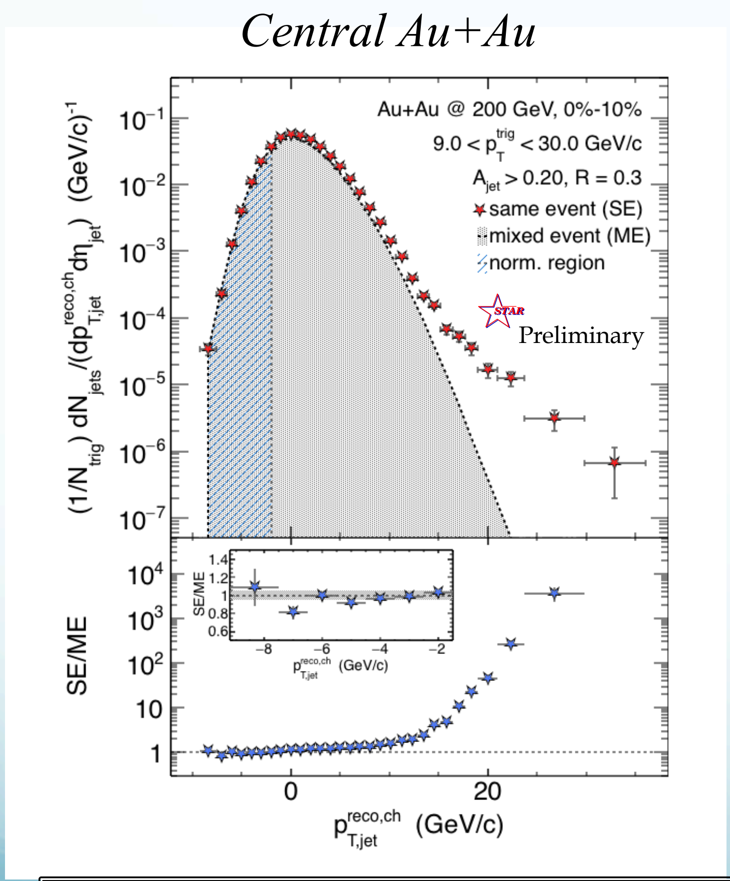
Corrected $p_T^{jet} > 0$

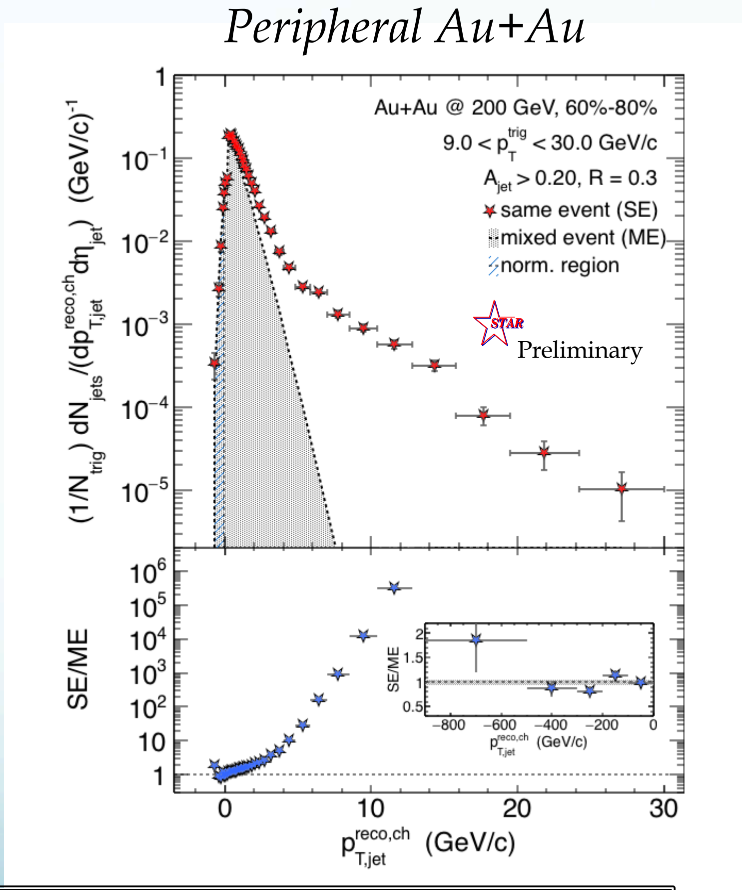
Recoil jet spectrum

$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A$$

ρ = estimated background energy density

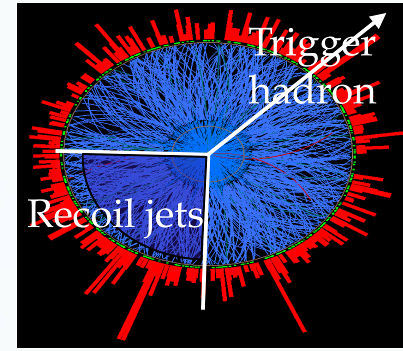




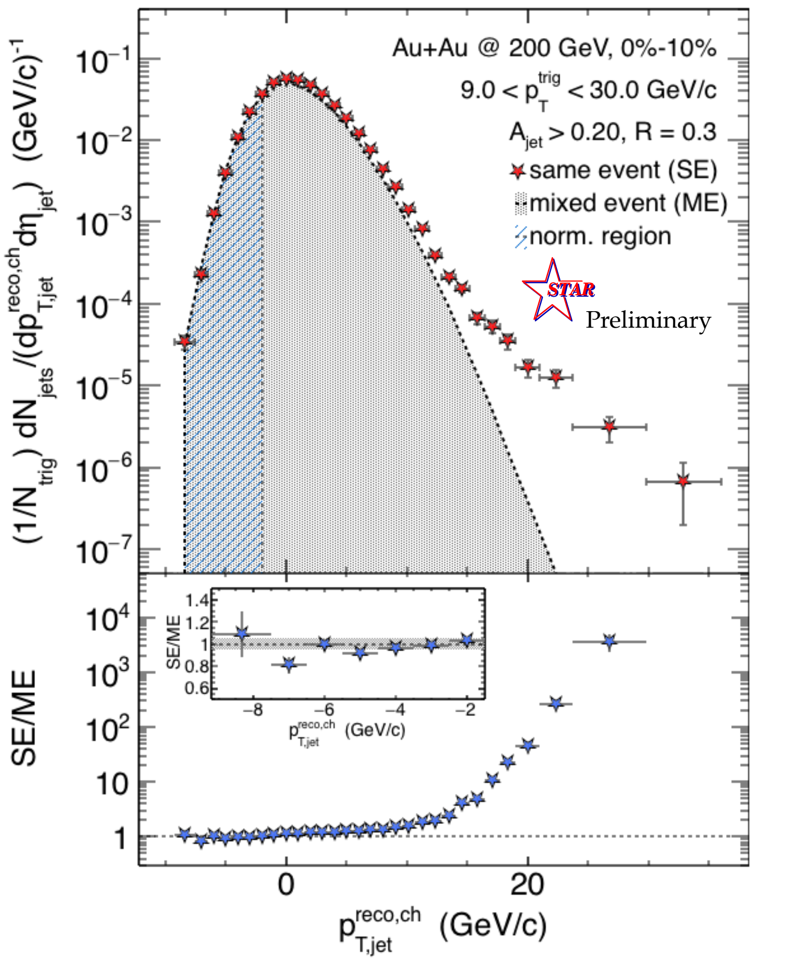


Mixed event distribution is good description of combinatorial jet background

vs LHC



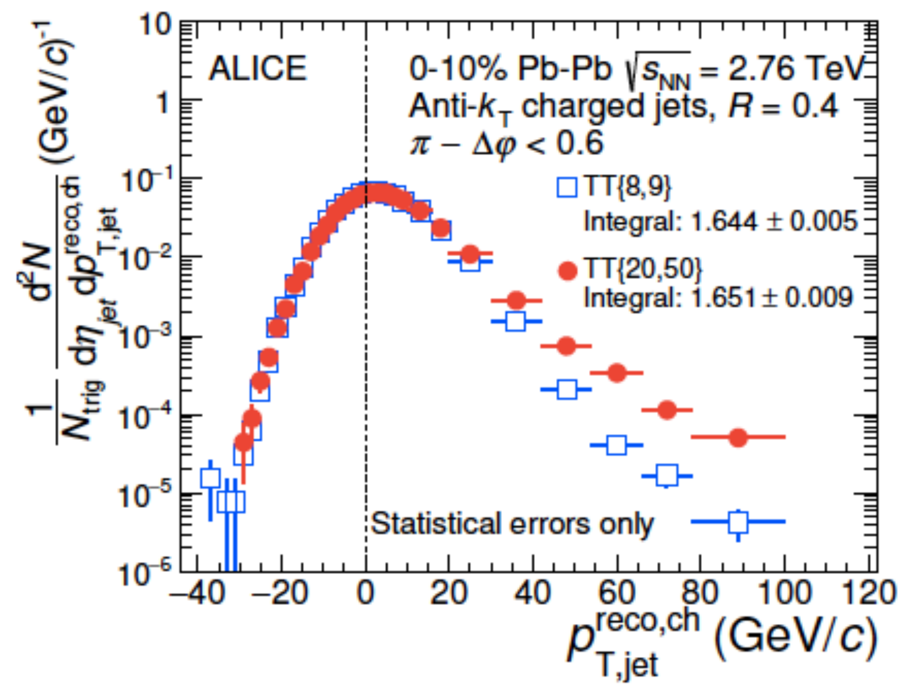
Central Au+Au, $\sqrt{s_{NN}}$=200 GeV



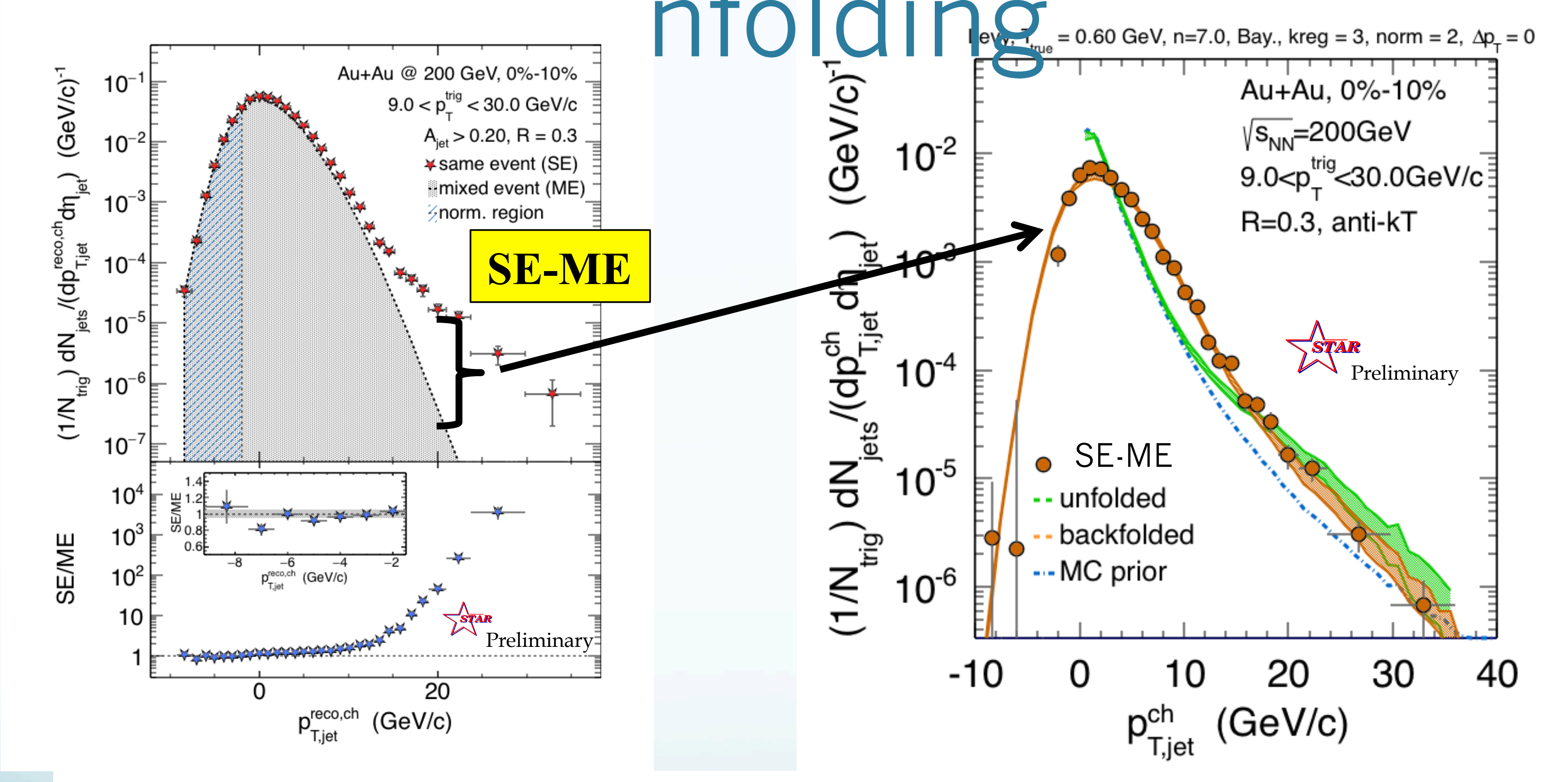
Closely related ALICE measurement

arXiv:1506.03984

Central Pb+Pb, $\sqrt{s_{NN}}$=2.76 TeV



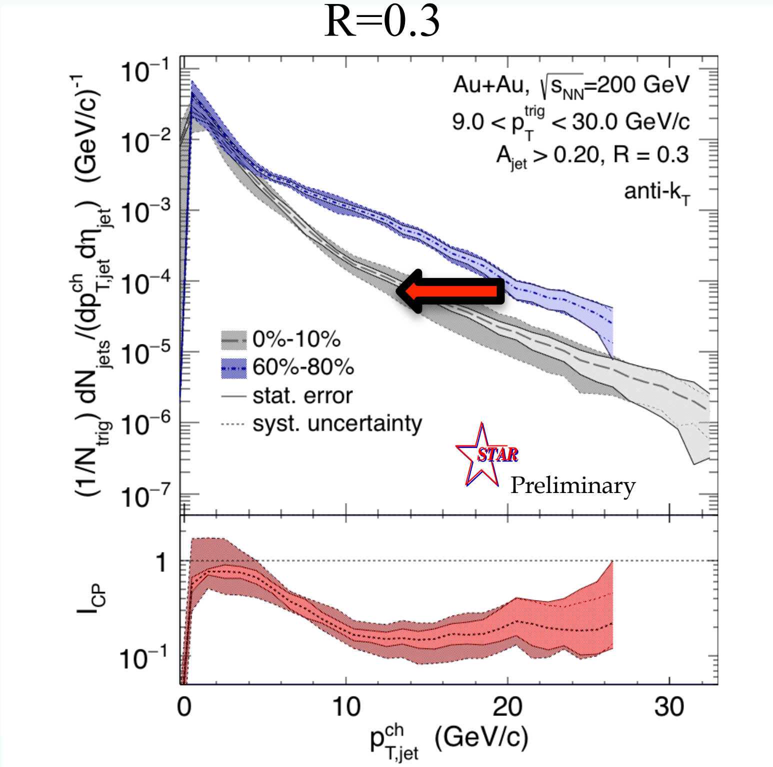
Correction of p_T-scale via unfolding

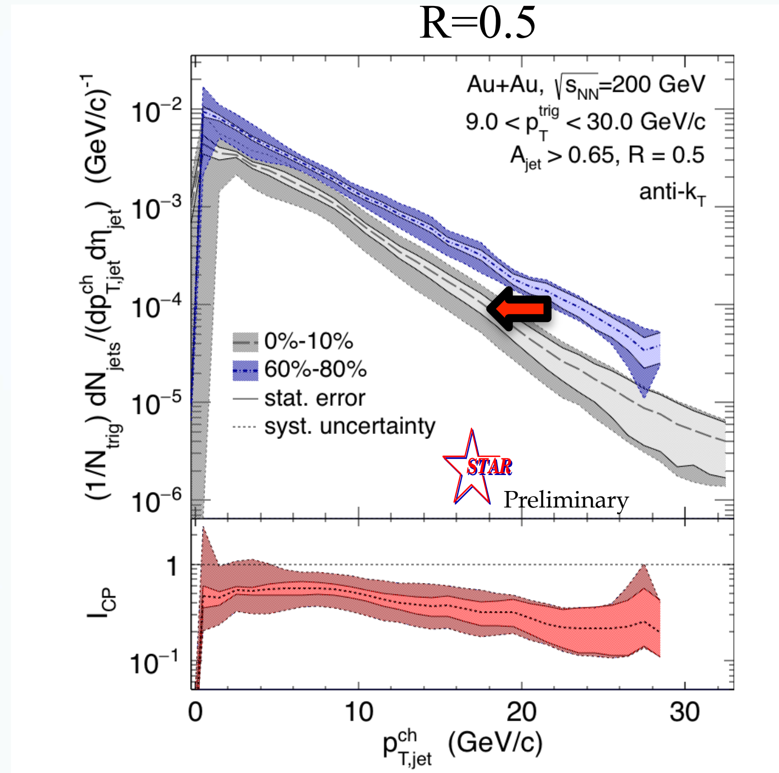


Unfolding generates large off-diagonal covariance ➔ corrected distribution is unbinned

- Unfolding algorithms: SVD, Bayesian
- Systematic variations: prior, regularization, tracking efficiency, ME normalization, bkgd fluctuation distribution
- Consistency check: χ^2 of backfolding

Recoil yield suppression





Calculate spectrum shift
- requires distributions ~ exponential, ratio ~ flat

Spectrum Shift Periph/pp → Central

	$p^{ch}_{T,jet}$ range [GeV]	Shift R=0.3 [GeV]	Shift R=0.5 [GeV]
Au+Au @ 200 GeV	[10,20]	**-6.3** ± 0.6 ± 0.8	**-3.8** ± 0.5 ± 1.8
Pb+Pb @ 2.76 TeV *ALICE arXiv:1506.03984*	[60,100]		**-8** ± 2

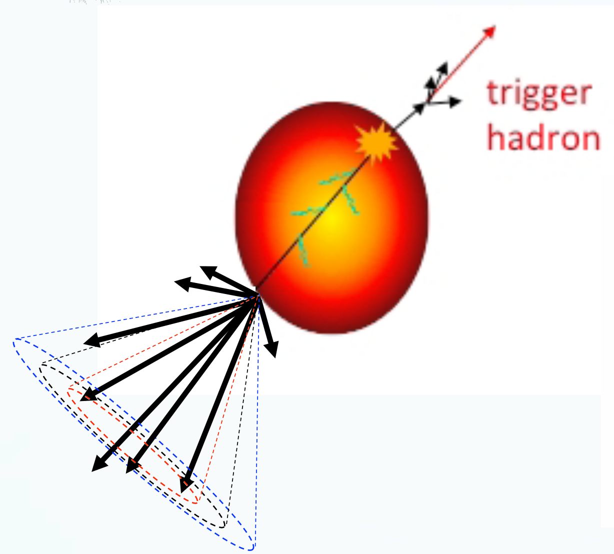
RHIC: smaller shift for larger R

R=0.5: smaller shift at RHIC than LHC

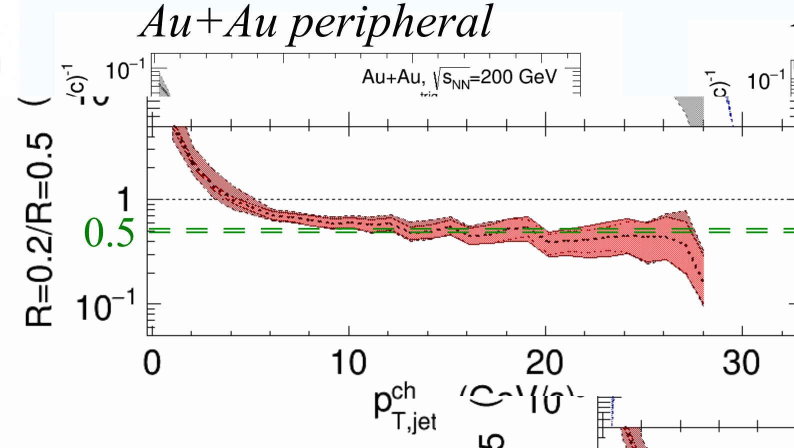
Out-of-cone energy transport ?
- comparison requires similar trigger bias → theory calculation

vs. R

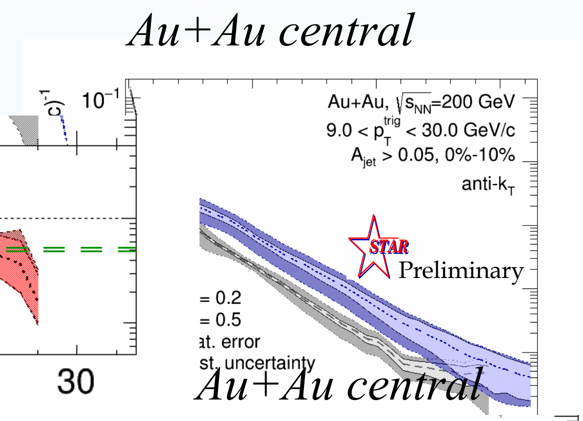
Redistribution of jet energy transverse to jet axis

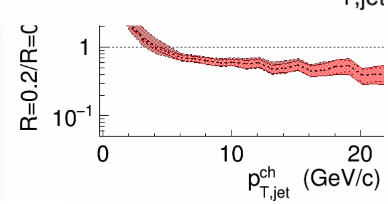


Au+Au peripheral

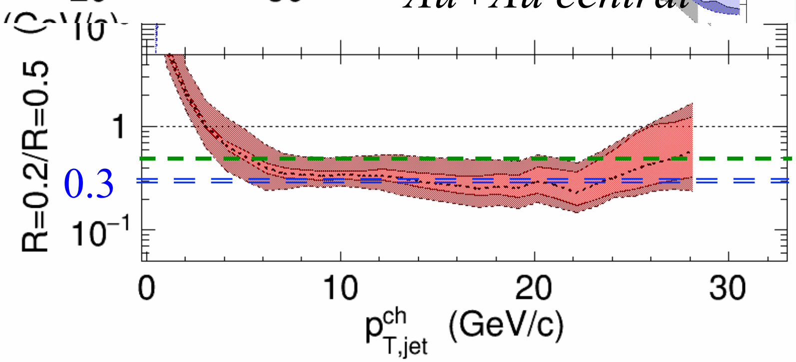


Au+Au central

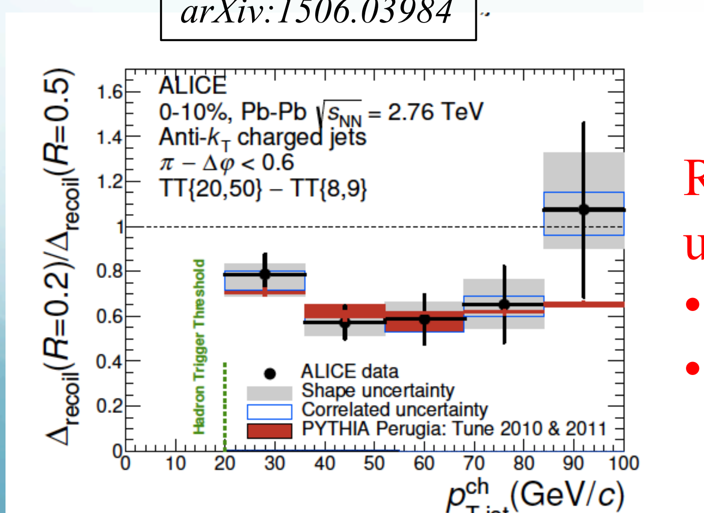




Au+Au central



arXiv:1506.03984



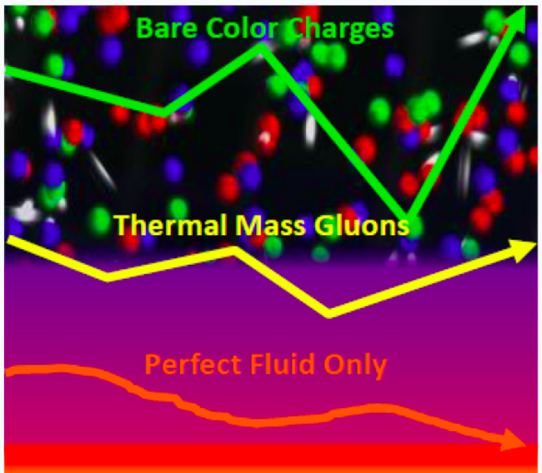
Ratios for peripheral and central are consistent within uncertainties

- compatible with some broadening within R<0.5
- future measurement (higher stats): reduce uncert.

LHC: similar picture in overlapping p_T range

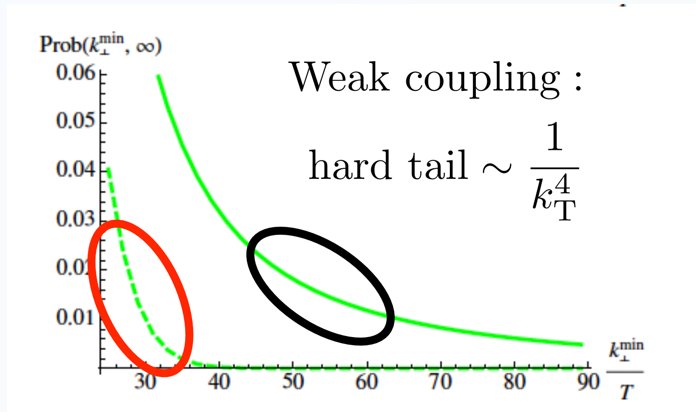
Secondary scattering off the QGP

Discrete scattering centers or effectively continuous medium?

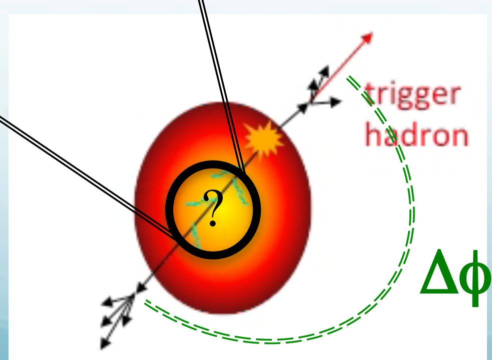


d'Eramo et al, arXiv:1211.1922

Distribution of momentum transfer k_T



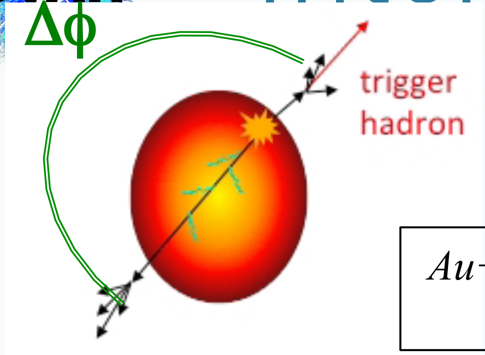
Strong coupling:
Gaussian distribution



Conjecture for weak coupling: $\Delta\phi$ distribution dominated by single hard Molière scattering at "sufficiently large" $\Delta\phi$

- vacuum QCD effects fall off more rapidly
- "sufficiently large" not yet known

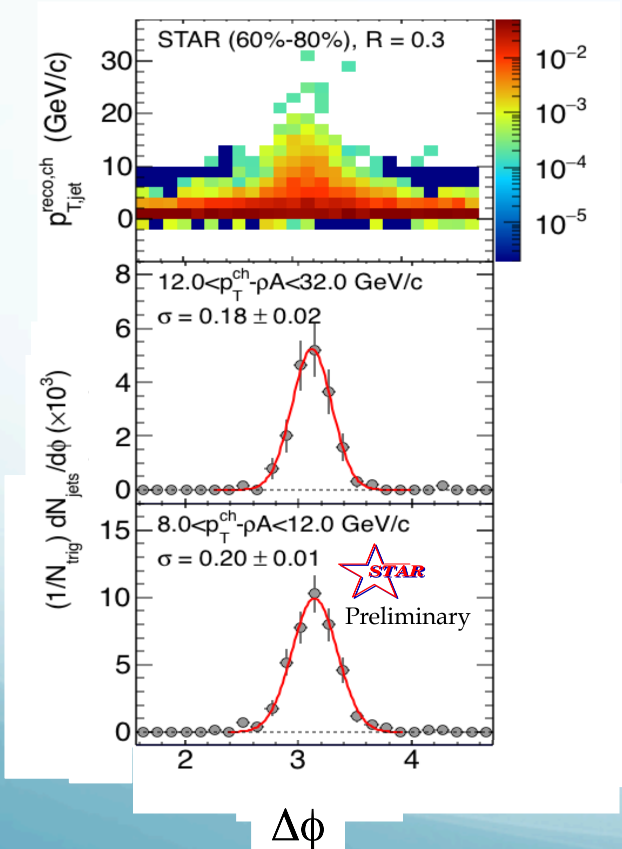
Inter-jet broadening: data



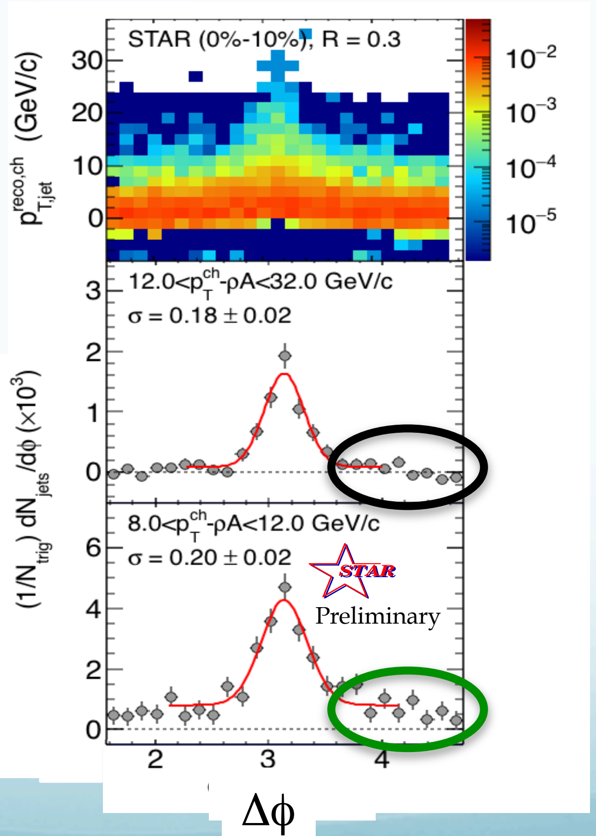
Quantitative search requires absolute normalization
➔ semi-inclusive distribution

Au+Au $\sqrt{s_{NN}}$=200 GeV
p_T^{trig}>9 GeV/c

peripheral



central



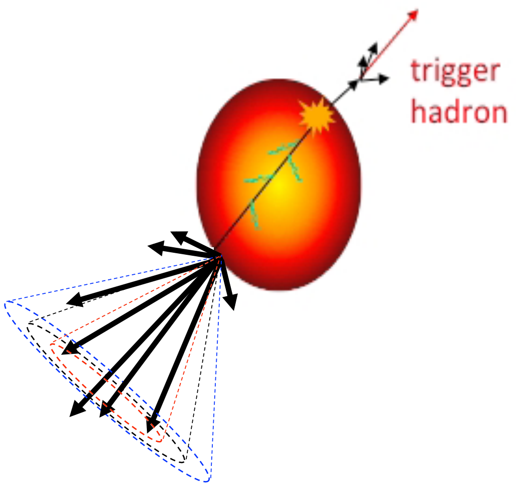
Consistent with zero at current precision

Low energies: hint of finite yield at large Δϕ yield at but not fully corrected for uncorrelated background

QCD calculation in progress (d'Eramo): will indicate integrated luminosity needed for significant measurement

Summary and Outlook

Semi-inclusive h+jet correlations:
- jet measurements with large R over full p_T range at RHIC
- comparable to similar ALICE measurement



Recoil yield is suppressed
Suggests less out-of-cone energy transport for
- large R
- central A+A collisions
- central AA @ RHIC vs. LHC

Intra-jet broadening:
- compatible with some broadening within R<0.5

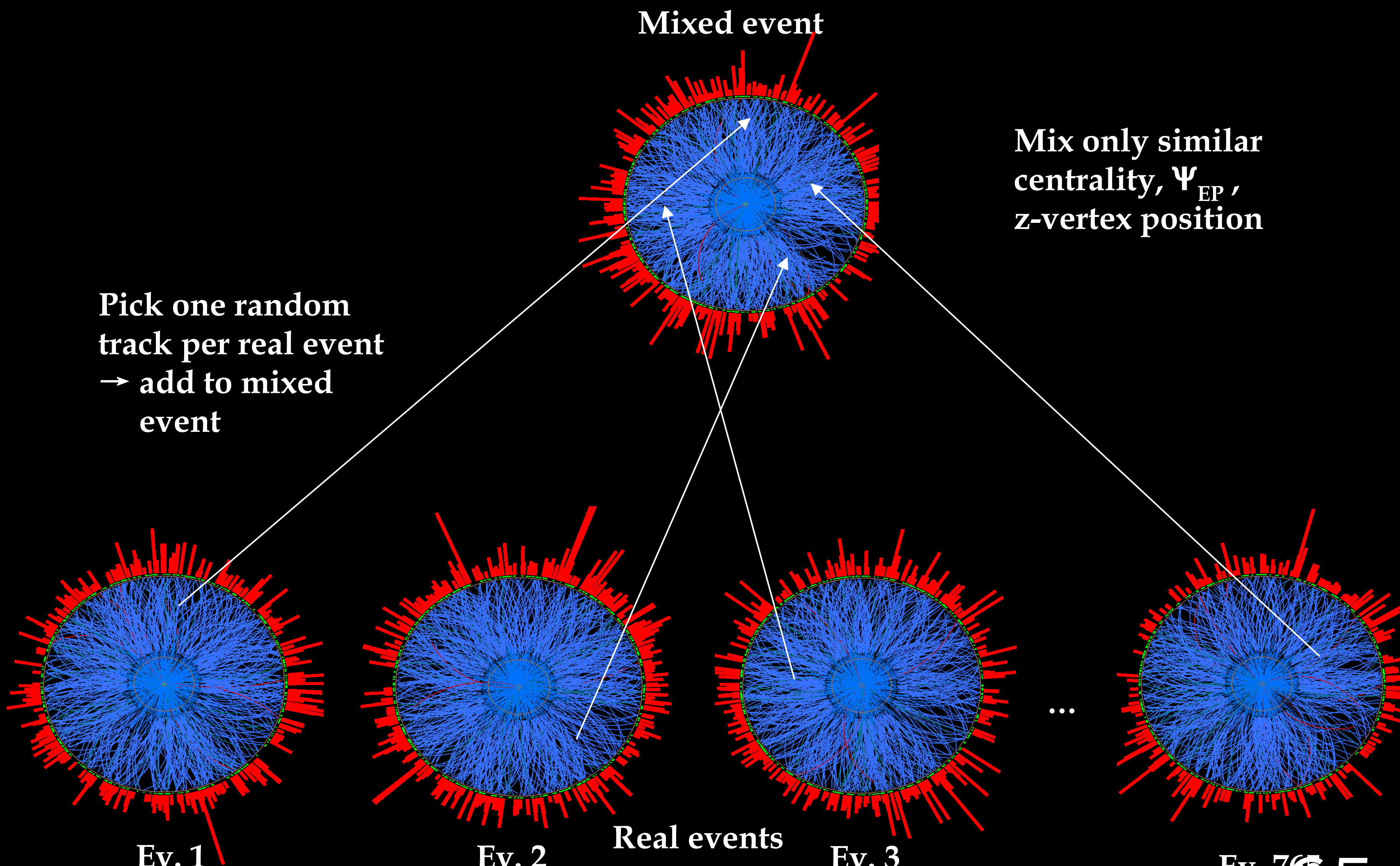
Large-angle scattering: probe quasi-particle degrees of freedom in QGP
- proof of principle; low energy jets are crucial
- QCD calculation in progress ➔ future measurements at RHIC and LHC

Next step: extend to fully measured jets with BEMC (higher int lumi in Year 14 data)
- reduced systematic uncertainties for all observables

Theory calculations needed to assess biases, compare RHIC/LHC

Backup slides

Uncorrelated Background: Mixed Events

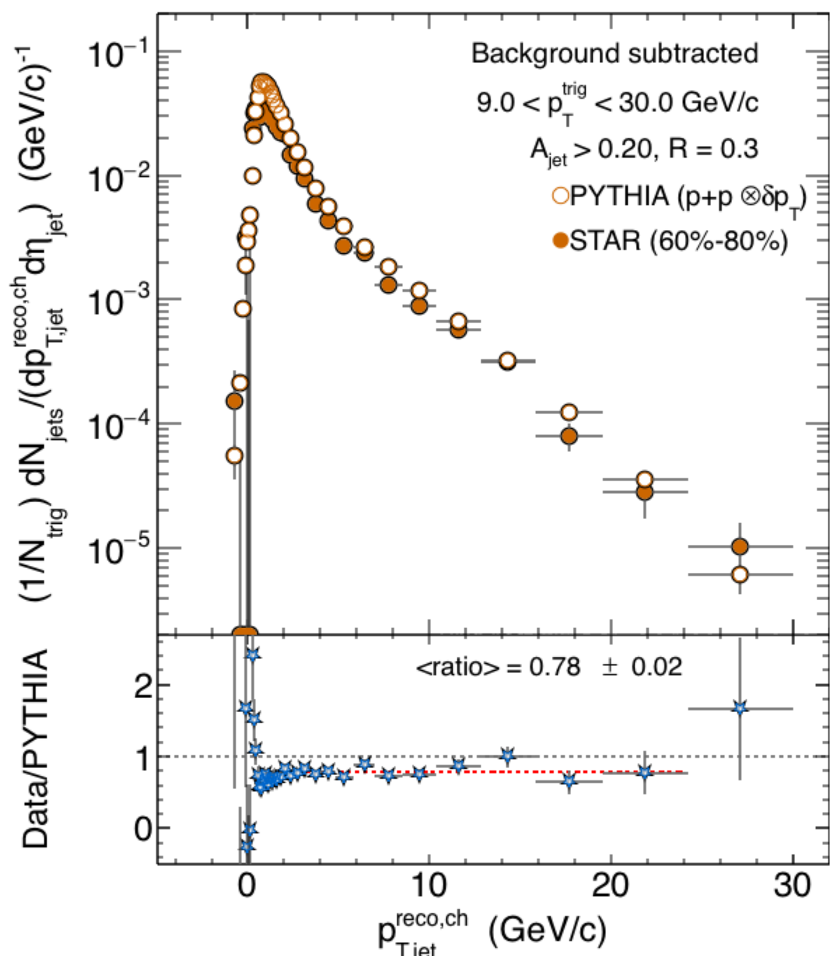


Mix only similar centrality, Ψ_{EP}, z-vertex position

Pick one random track per real event → add to mixed event

Spectra: STAR Au+Au 60-80 and PYTHIA pp

Peripheral 60-80%

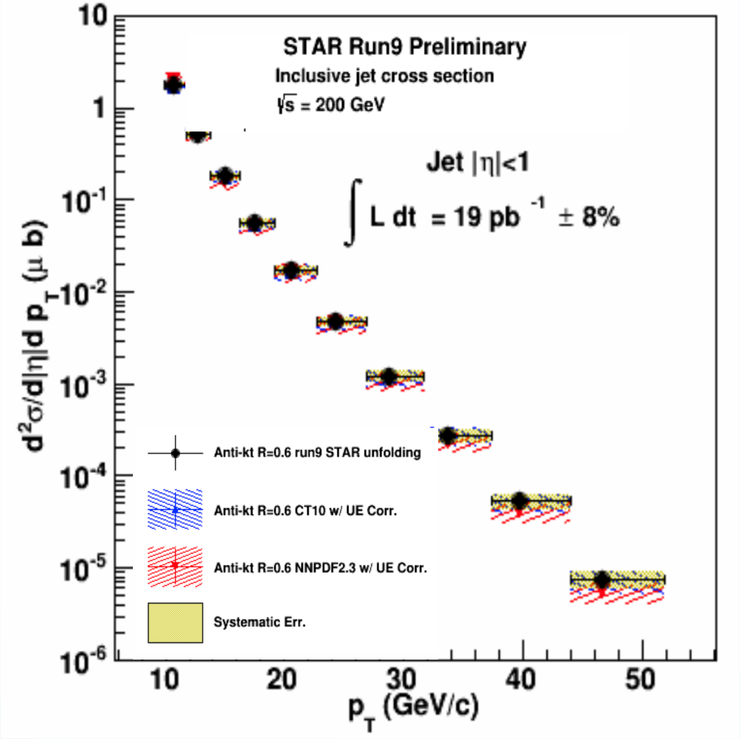


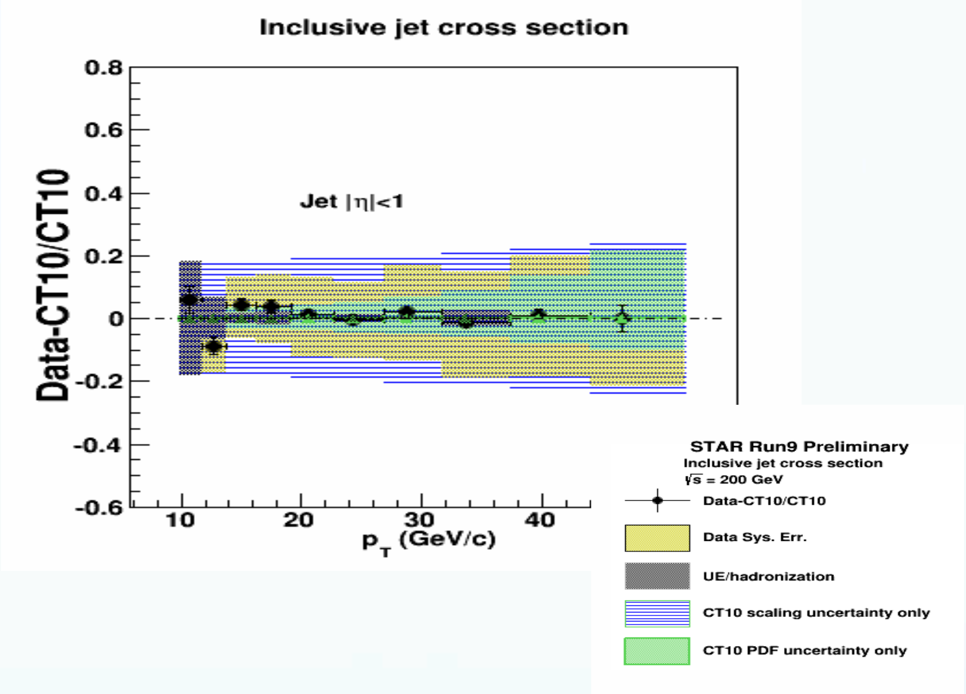
Smeared PYTHIA: convolute recoil jet spectrum from p+p@200 GeV with distribution of background fluctuations

Compare Au+Au 60-80% with smeared PYTHIA

Both shape and yield in good agreement

Jets in STAR: inclusive jet cross section in p+p collisions at √s=200 GeV



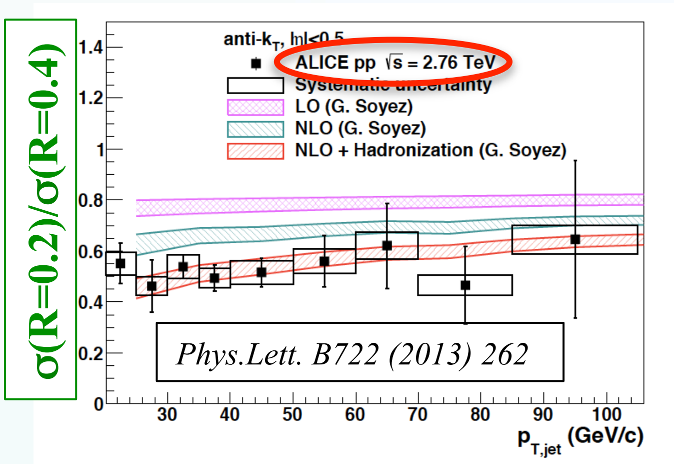


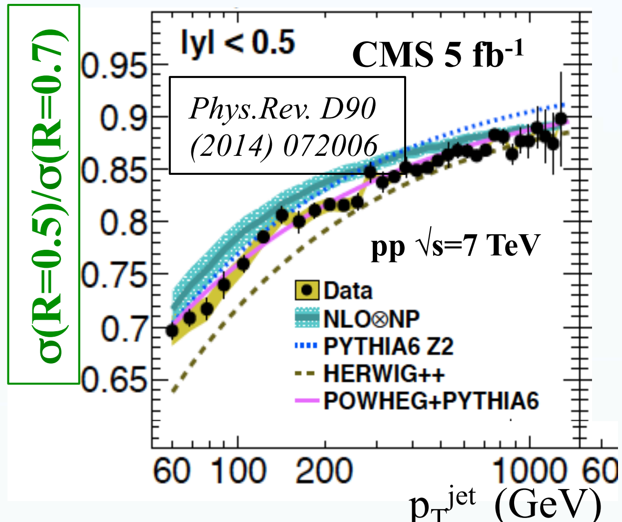
- Good and improvable systematic uncertainties over broad kinematic range
- Good agreement with NLO pQCD

Jets in heavy ion collisions: instrument is in place, need the right algorithms

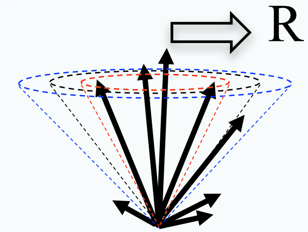
(semi-)inclusive ratios at different R

Inclusive jets, pp √s= 2.76, 7 TeV





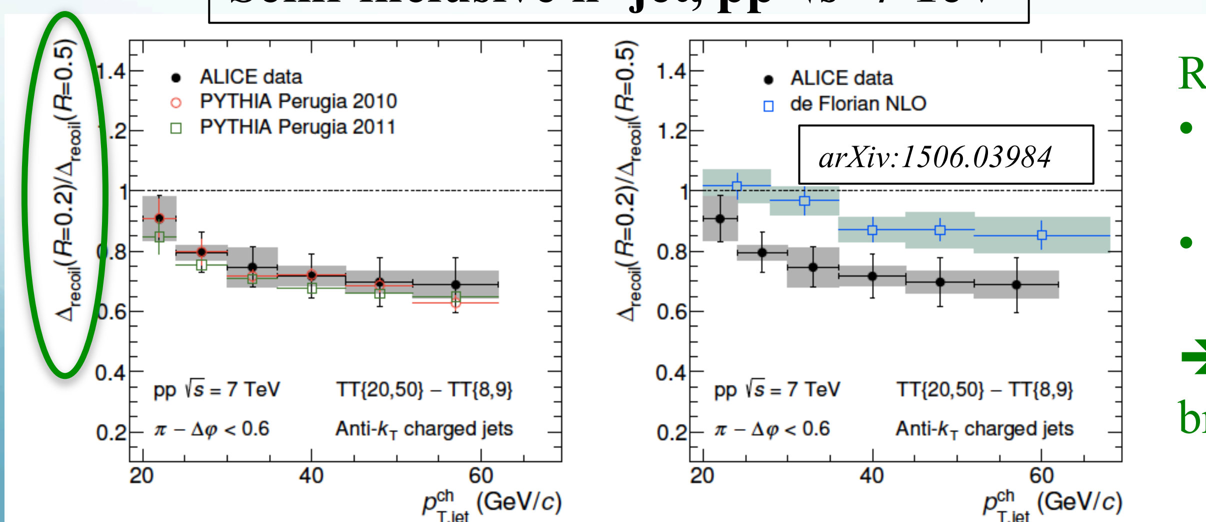
Jets with different R sensitive to different components of shower



Calculable perturbatively:

- require (N)NLO + non-pert. corrections
- MC models ~OK

Semi-inclusive h+jet, pp √s=7 TeV



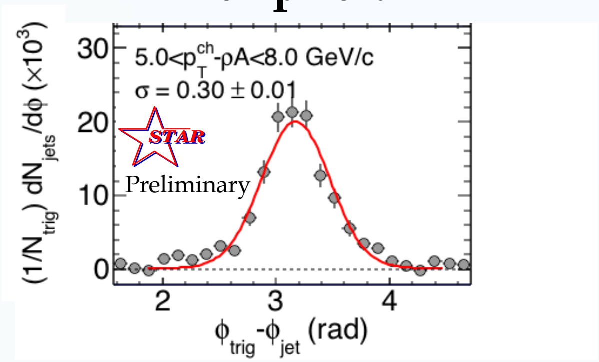
Ratios in vacuum

- sensitive to transverse jet structure
- rigorous data/theory comparison

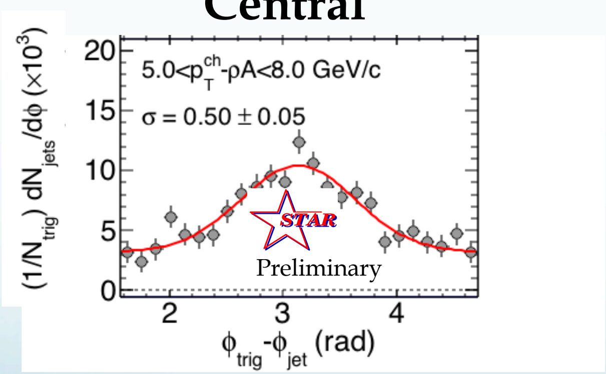
➔ Now use to measure intra-jet broadening due to quenching

QGP: low p_T^{jet}

Peripheral



Central



- Significant difference at $5 < p_T\text{-}\rho A < 8$ GeV/c
  → Flow?
  → Φ dependent normalization needed?
  → Background from multiple interactions?
  → More studies needed!