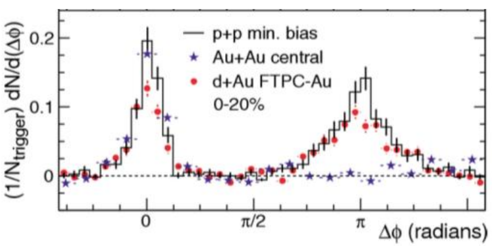
Jets at RHIC

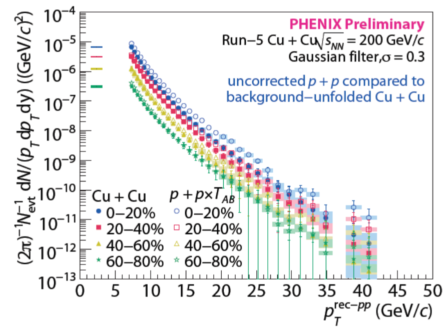
Where are we?
What have we learned?
What's next?

Alice Ohlson
Yale University

Jets at RHIC

Single-particle measurements: spectra & correlations

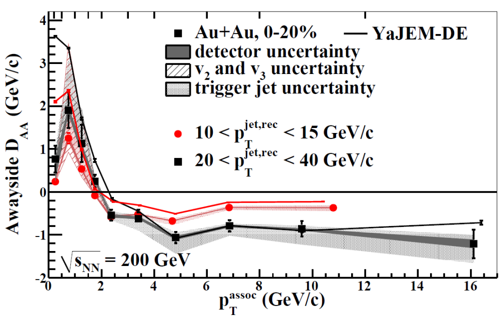




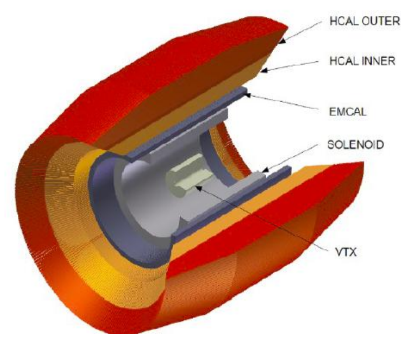
Reconstructed jet measurements: spectra & correlations

Comparison to LHC results

Understanding biases



Future of Jets at RHIC
Final Thoughts



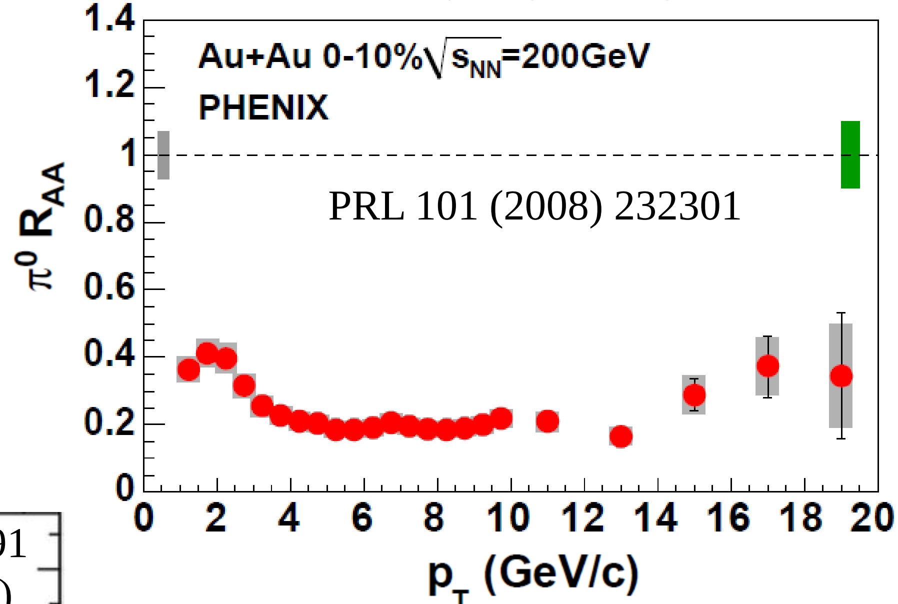
High-p_T suppression

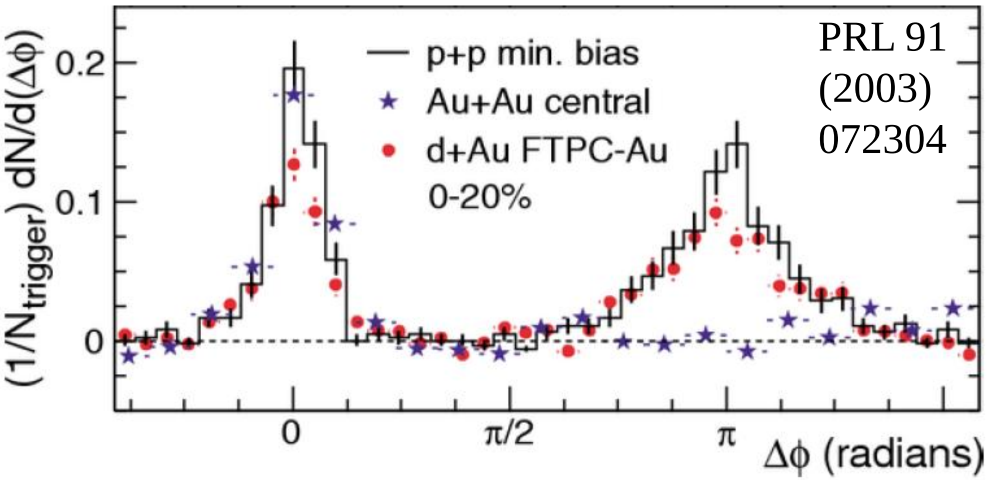
- Single-particle inclusive measurements

  → suppression of high-p_T hadrons in central Au+Au events
- Correlations w.r.t. high-p_T hadrons

  → suppression of particles associated with jet peak

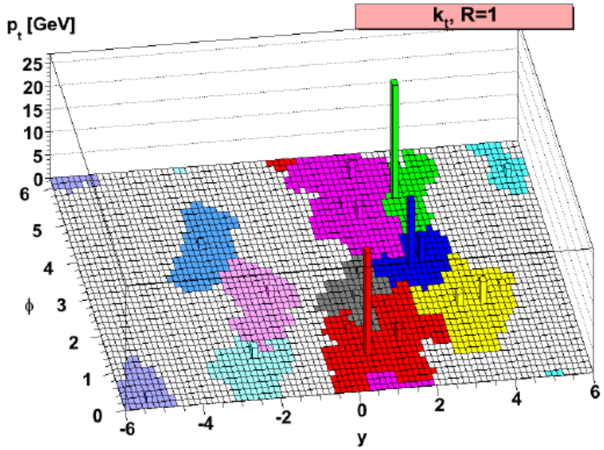
$$R_{AA}(p_T) = \frac{\sigma_{\mathrm{inel.}}^{pp}}{\langle N_{\mathrm{bin}} \rangle} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{pp}/dp_T d\eta}$$

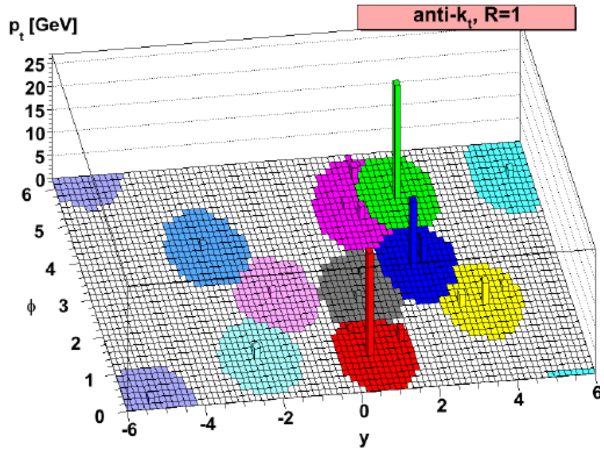




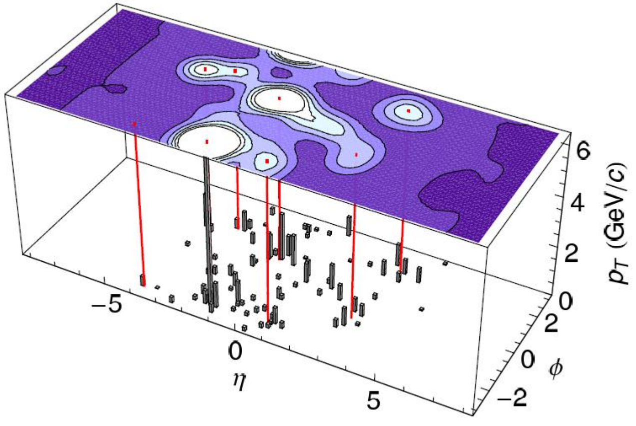
New Tools: Jet Reco. Algorithms

- The goal: Find clusters of particles, determine the direction and energy of the original parton
- Several options: k_T, anti-k_T, Gaussian filter, etc.
- Main challenge: subtracting the combinatoric heavy ion background, accounting for fluctuations





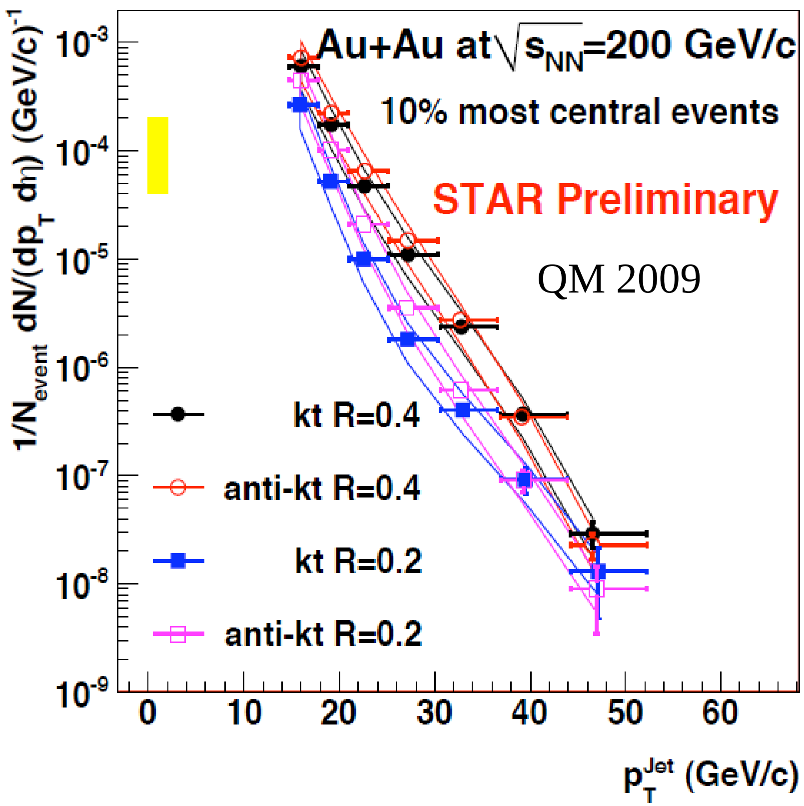
k_T & anti-k_T
JHEP04 (2008) 063

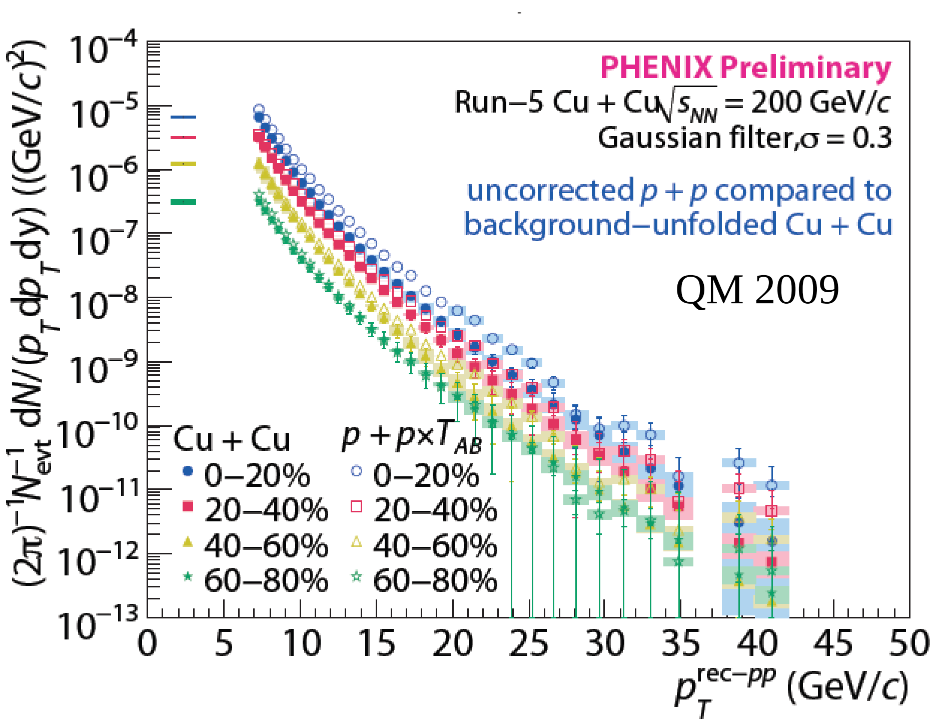


Gaussian filter
arXiv:0806.1499 [nucl-ex]

Jet Spectra at RHIC

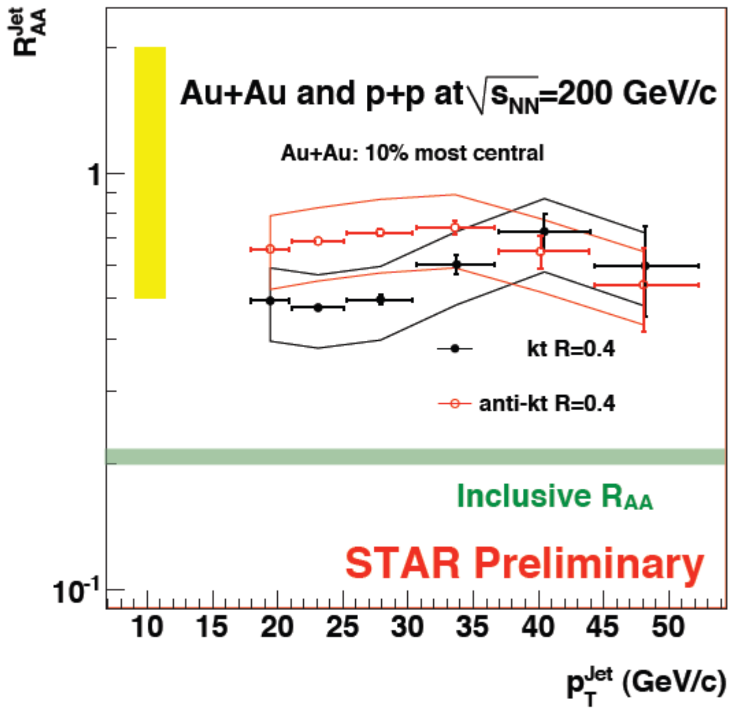
- For the first time → Full jet reconstruction in a heavy ion environment
- Different methods of jet reconstruction, background subtraction, fake-jet rejection

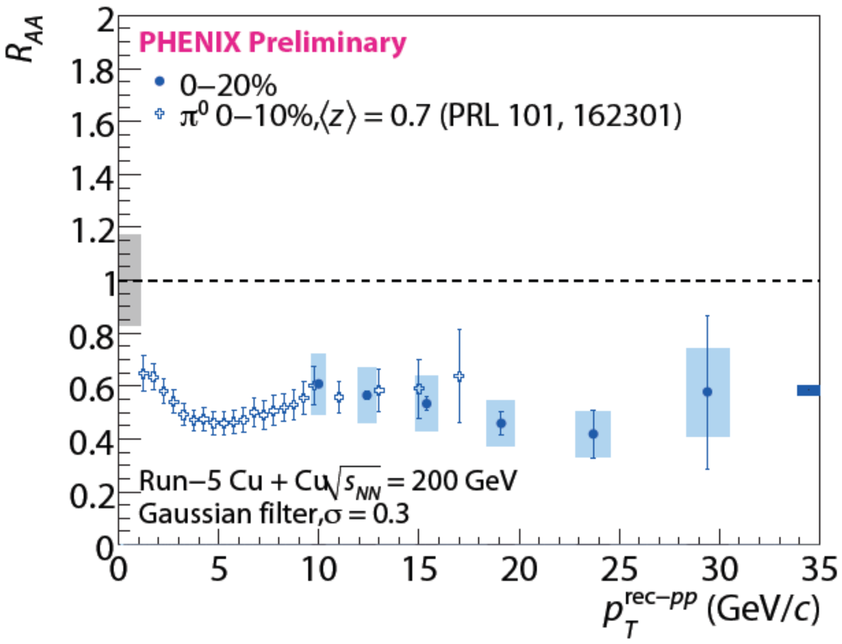




Jet R_{AA} at RHIC

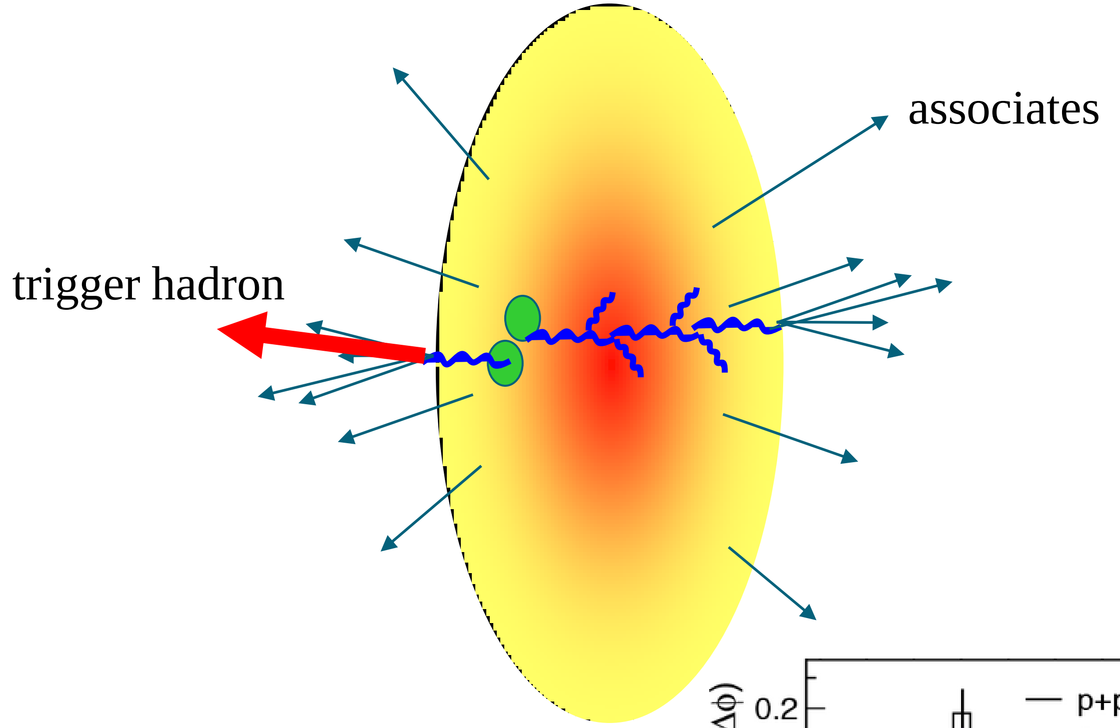
- Reconstructed jets demonstrate suppression
  STAR: in Au+Au jets less suppressed than single hadrons
  PHENIX: in Cu+Cu jets show similar suppression to hadrons



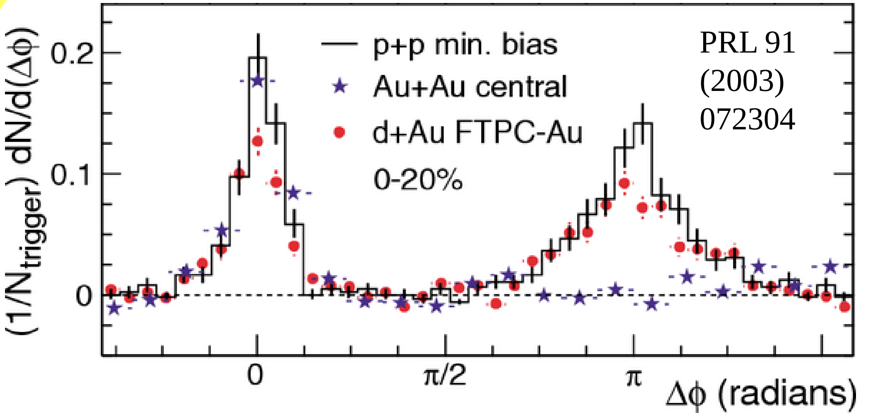


- Need to use similar techniques for direct comparison, further work is necessary to understand background fluctuations

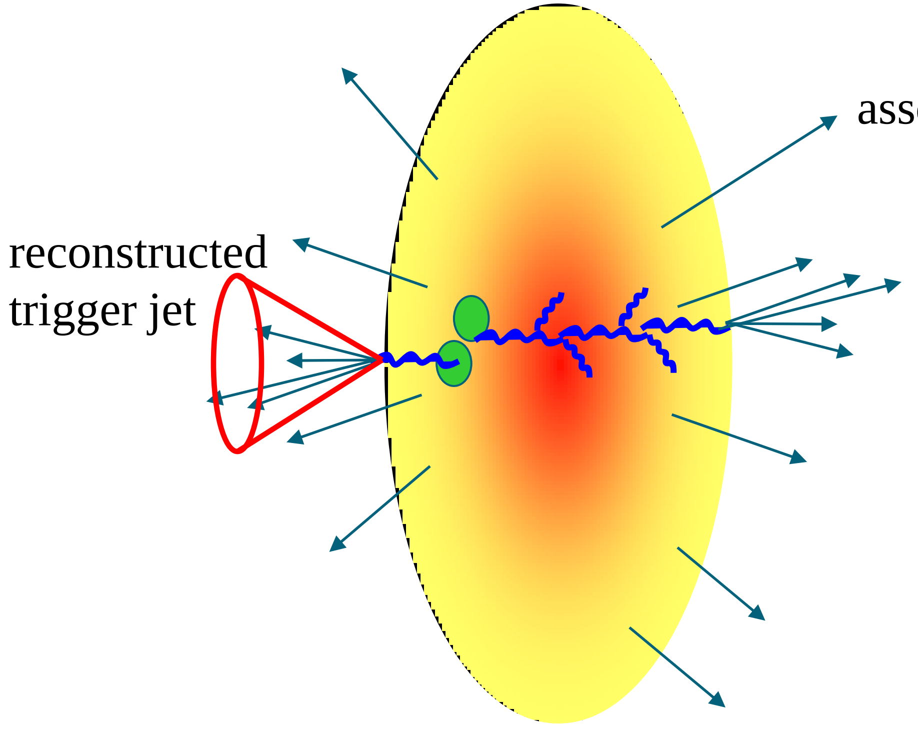
Dihadron Correlations



- Investigate correlations of all "associated" particles with a "trigger"



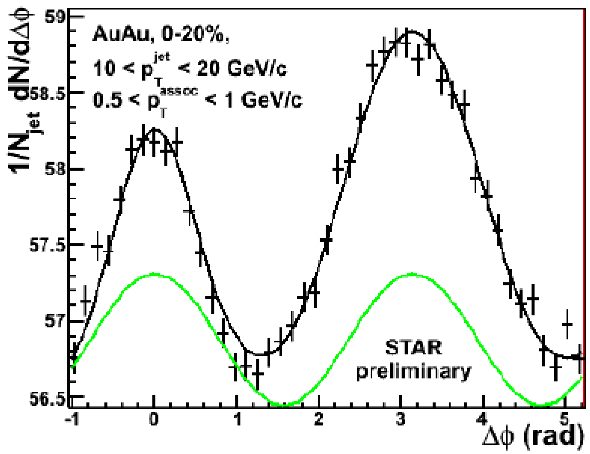
Jet-hadron Correlations

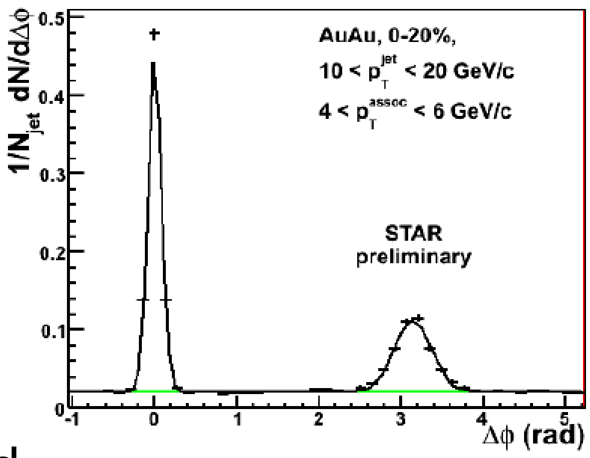


- Jet-hadron correlations have increased kinematic reach compared to dihadron correlations, allow for more precise determination of parent parton energy

Jet-hadron Correlations

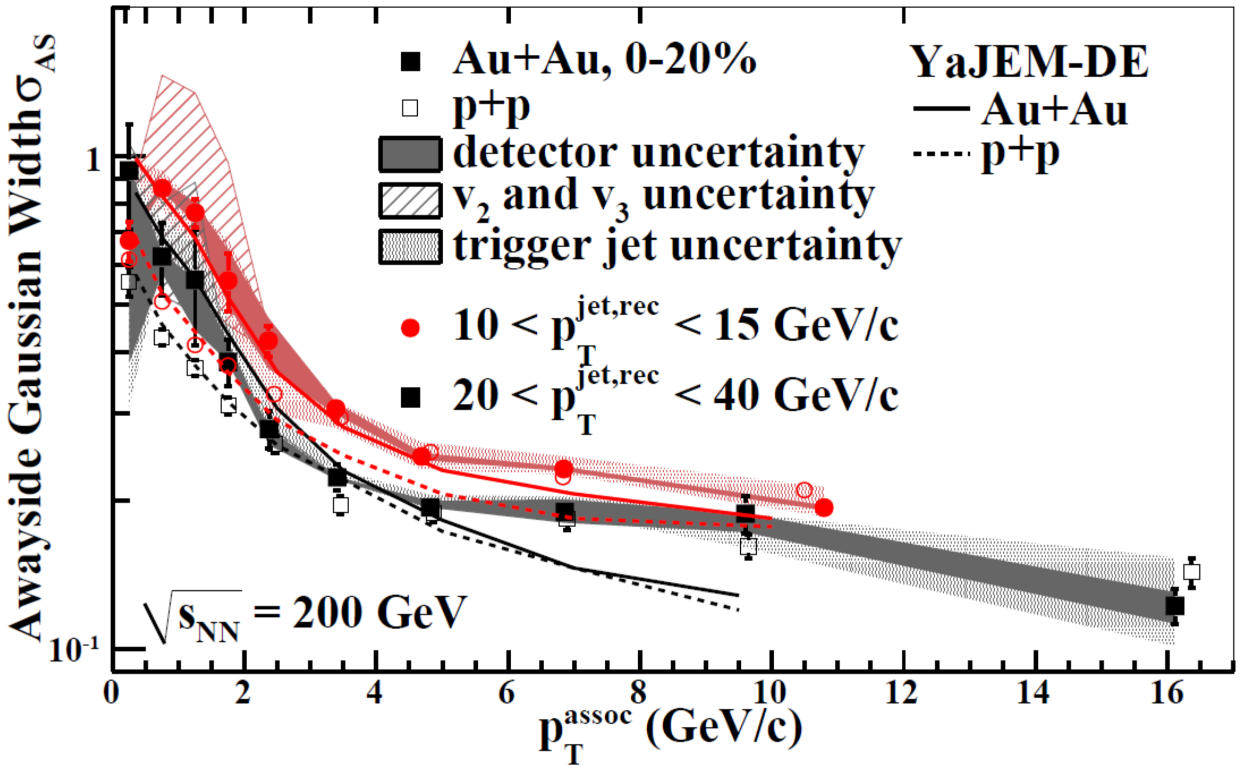
- Intentionally impose a bias towards unmodified trigger jets!
  - E_T > 6 GeV in a single BEMC tower
    ($\Delta\varphi$ x $\Delta\eta$ = 0.05 x 0.05)
  - Anti-k_T (R = 0.4) using tracks/towers with p_T > 2 GeV/*c*
- HT trigger requirement and constituent p_T cut
  - Reduce effects of background fluctuations
  - Comparison to p+p is more straightforward
- Trigger (nearside) jet population is highly-biased
  - Used to assign uncertainties to shape of background (v_2 and v_3) and trigger jet energy scale
- Recoil (awayside) jet fragmentation is unbiased





STAR, arXiv:1302.6184 [nucl-ex]
Submitted to PRL

Awayside Gaussian Widths



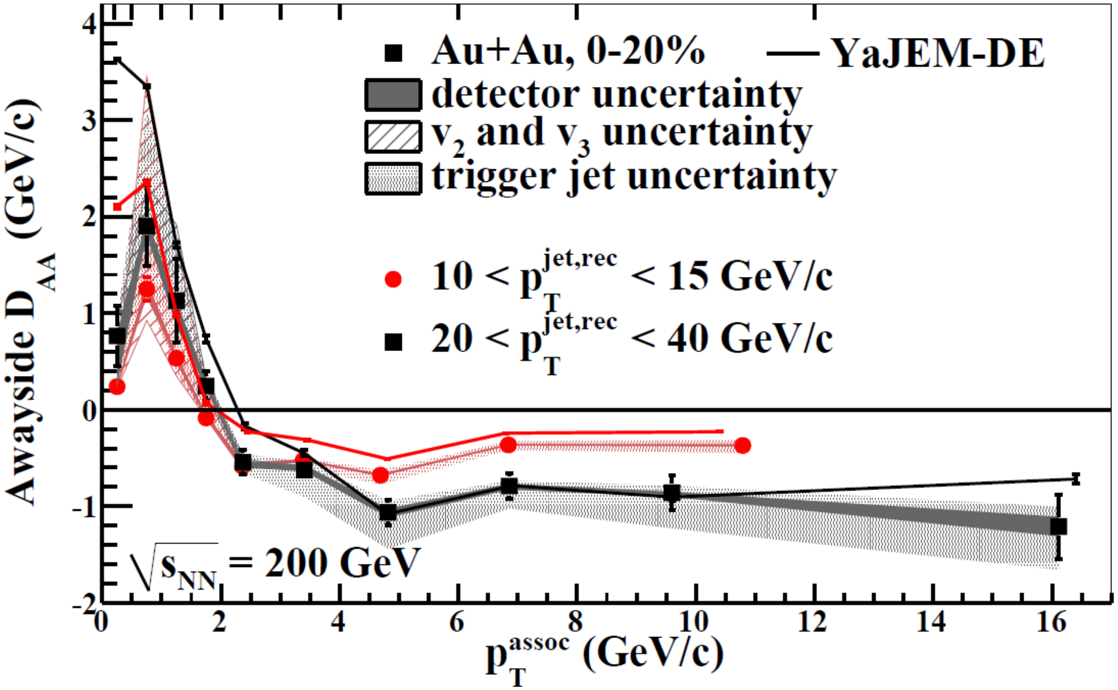
Awayside widths suggest jet broadening, but they are highly-dependent on v_3 modulation.
Further information is needed about v_2^{jet}, v_3^{jet} (possible correlation of jets with reaction plane / participant planes)…

STAR, arXiv:1302.6184 [nucl-ex]
Submitted to PRL

Awayside Energy Balance

$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

$$\Delta B = \sum_{p_T^{assoc}\ \mathrm{bins}} D_{AA}(p_T^{assoc})$$



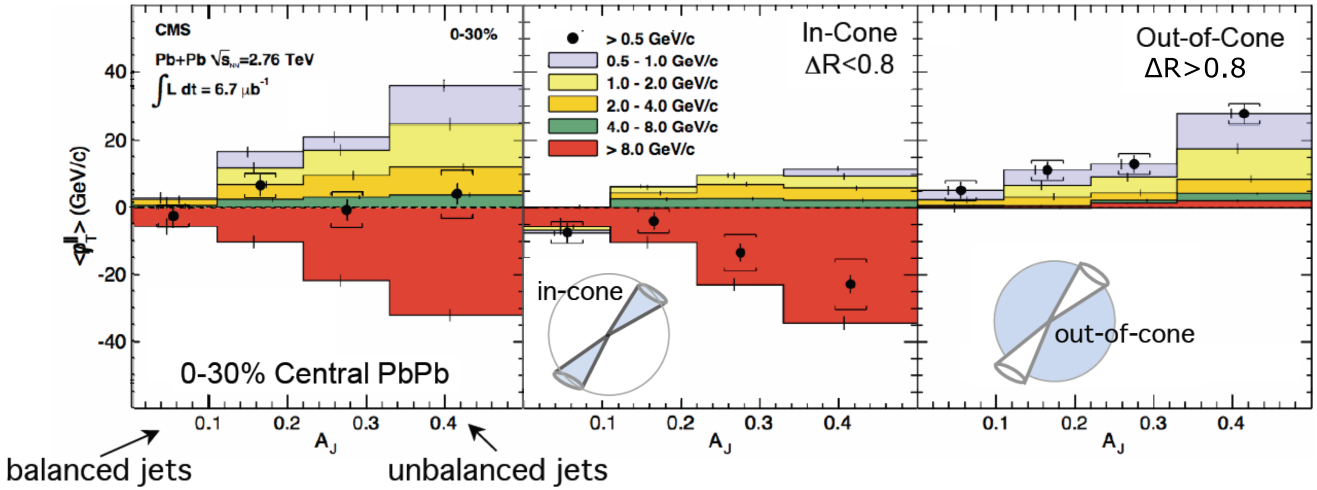
$p_T^{jet,rec}$ (GeV/c)	ΔB (GeV/c)			
10-15	-0.6 ± 0.2	$^{+0.2}_{-0.2}$	$^{+3.7}_{-0.5}$	$^{+2.3}_{-0.0}$
15-20	-1.8 ± 0.3	$^{+0.3}_{-0.3}$	$^{+1.0}_{-0.0}$	$^{+1.9}_{-0.0}$
20-40	-1.0 ± 0.8	$^{+0.1}_{-0.8}$	$^{+1.2}_{-0.1}$	$^{+0.3}_{-0.0}$

Uncertainties due to:
detector effects
v_2 and v_3
jet energy scale

Suppression of high-p_T associated hadron yield is in large part balanced by low-p_T enhancement.

Jets at the LHC

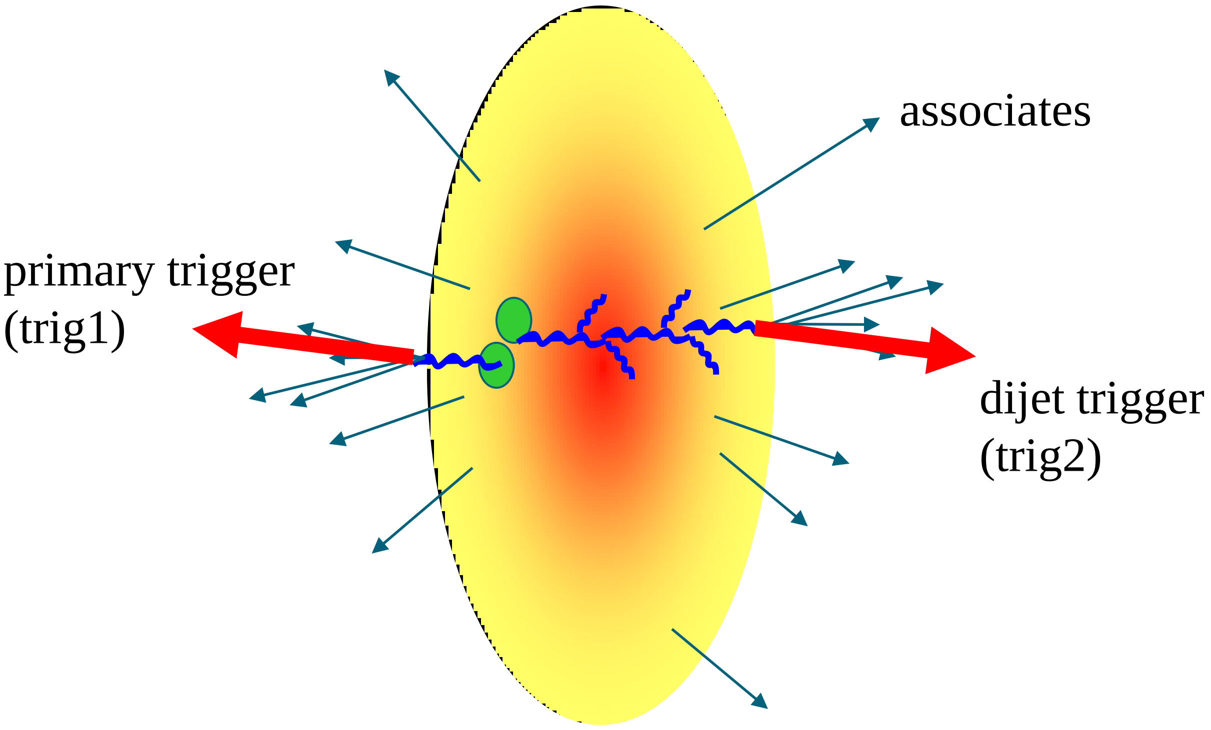
- RHIC result → Energy is recovered from low-p_T hadrons, still correlated with jet axis, although broadened
- CMS result → Energy is distributed to very wide angles ($\Delta R > 0.8$)



- Are we seeing a qualitative difference between jet quenching at RHIC and LHC energies?
- Need to do similar measurements at both… A_J at RHIC, jet-hadron correlations at LHC
- Need to understand biases at both experiments…

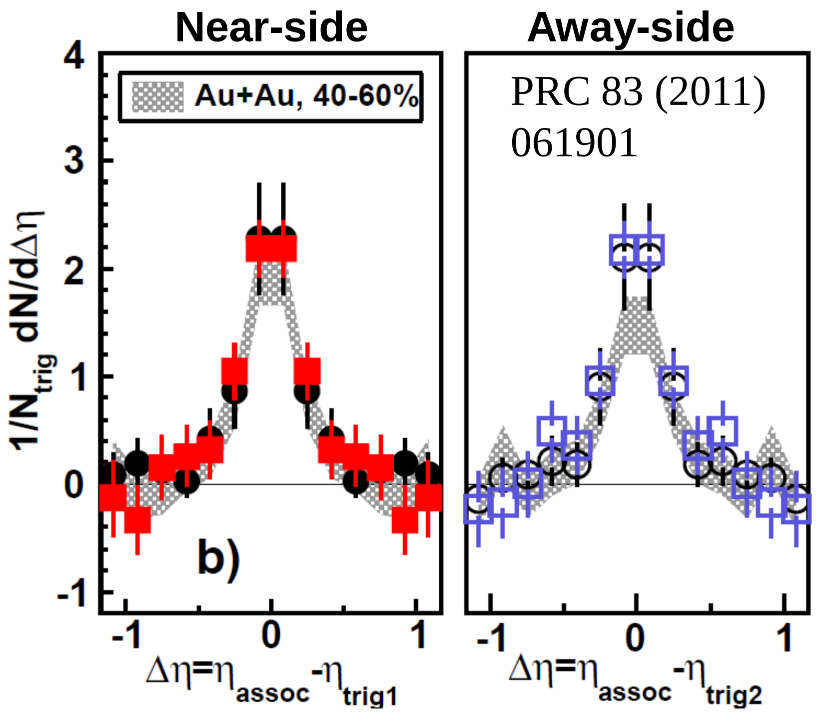
2+1 Correlations

- Require high-p_T "dijet trigger" hadron opposite trigger



- Investigate distributions of associated hadrons with respect to both trigger hadrons

Symmetric Triggers

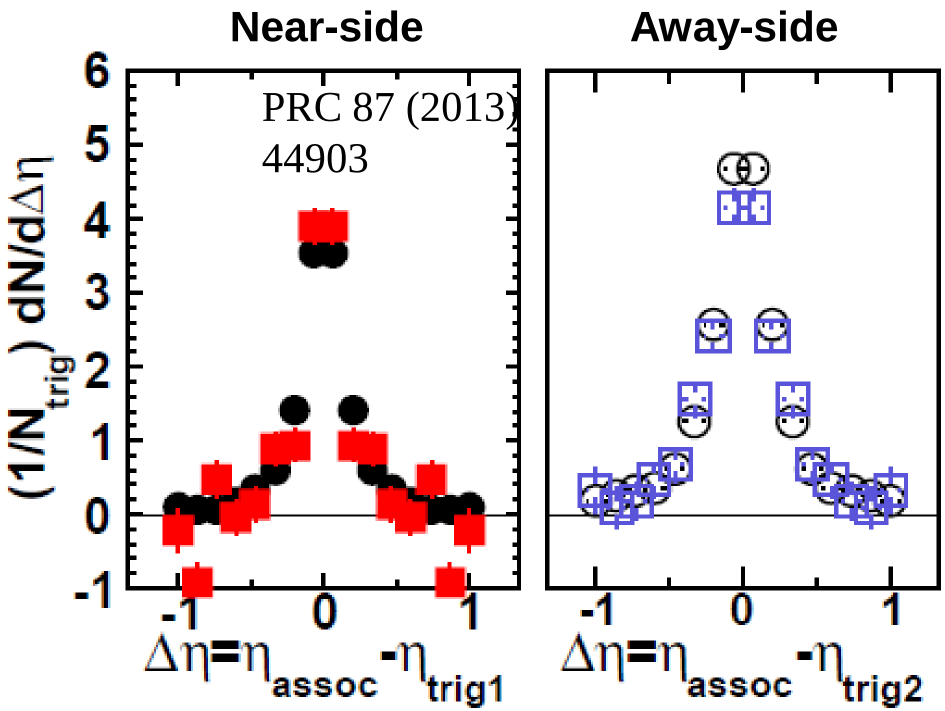


Au+Au
d+Au

$5 < p_T^{trig1} < 10$ GeV/c
$4 < p_T^{trig2} < p_T^{trig1}$
1.5 GeV/$c < p_T^{assoc} < p_T^{trig1}$

- No significant difference between Au+Au and d+Au
- No significant difference between near-side and away-side.
- Are we sampling surface-biased/unmodified dijets? Or dijets in which both jets lose similar amounts of energy?

Asymmetric Triggers



Au+Au
d+Au

$10 < E_T^{trig1} < 15$ GeV (in BEMC)
$4 < p_T^{trig2} < 10$ GeV/c (in TPC)
$1 < p_T^{assoc} < 10$ GeV/c

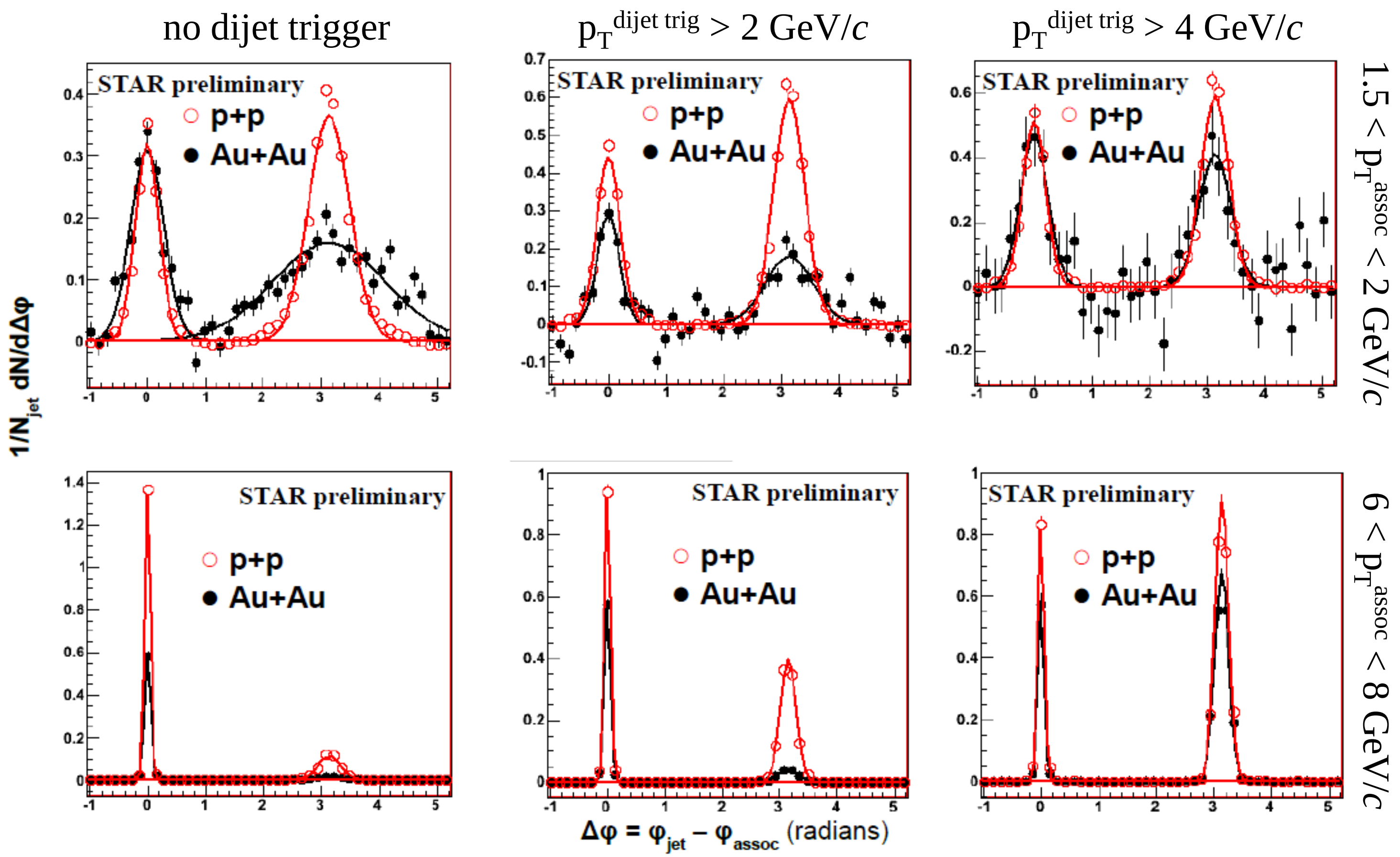
- Still no significant shape difference between near- and away-sides, or between Au+Au and d+Au.
- Energy imbalance indicates slight softening of awayside peak
- Compare/contrast to dihadron and jet-hadron results.

Jet-Hadron and 2+1 Correlations

$10 < p_T^{jet} < 20$ GeV/c

$|\varphi_{jet} - \varphi_{dijet\ trig}| > \pi - 0.2$

STAR, WWND 2011

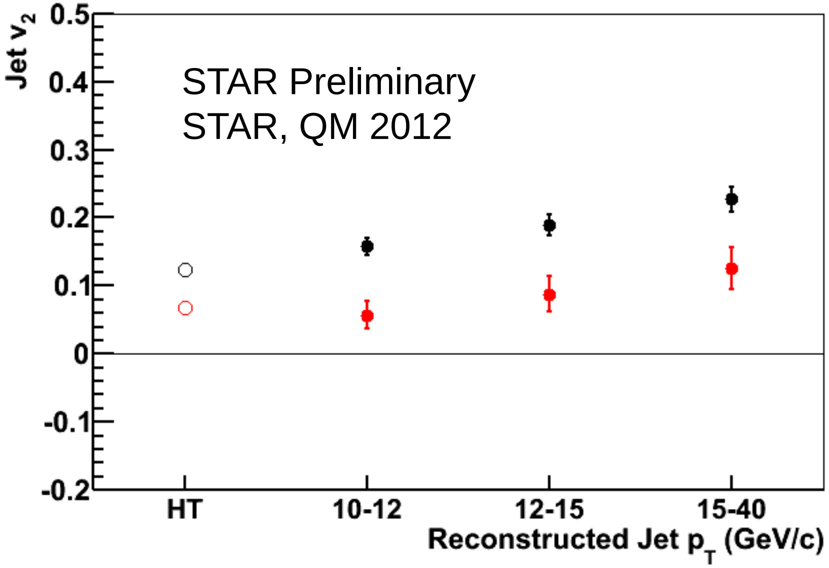


Select unmodified jets with $p_T^{dijet\ trig} > 4$ GeV/c requirement.

Jet v_2 at STAR

- Correlation between jet axis and event plane

$$v_2^{\text{jet}} = \frac{\left\langle \cos\left(2(\Psi_{\text{jet}} - \Psi_{\text{EP}})\right)\right\rangle}{R}$$

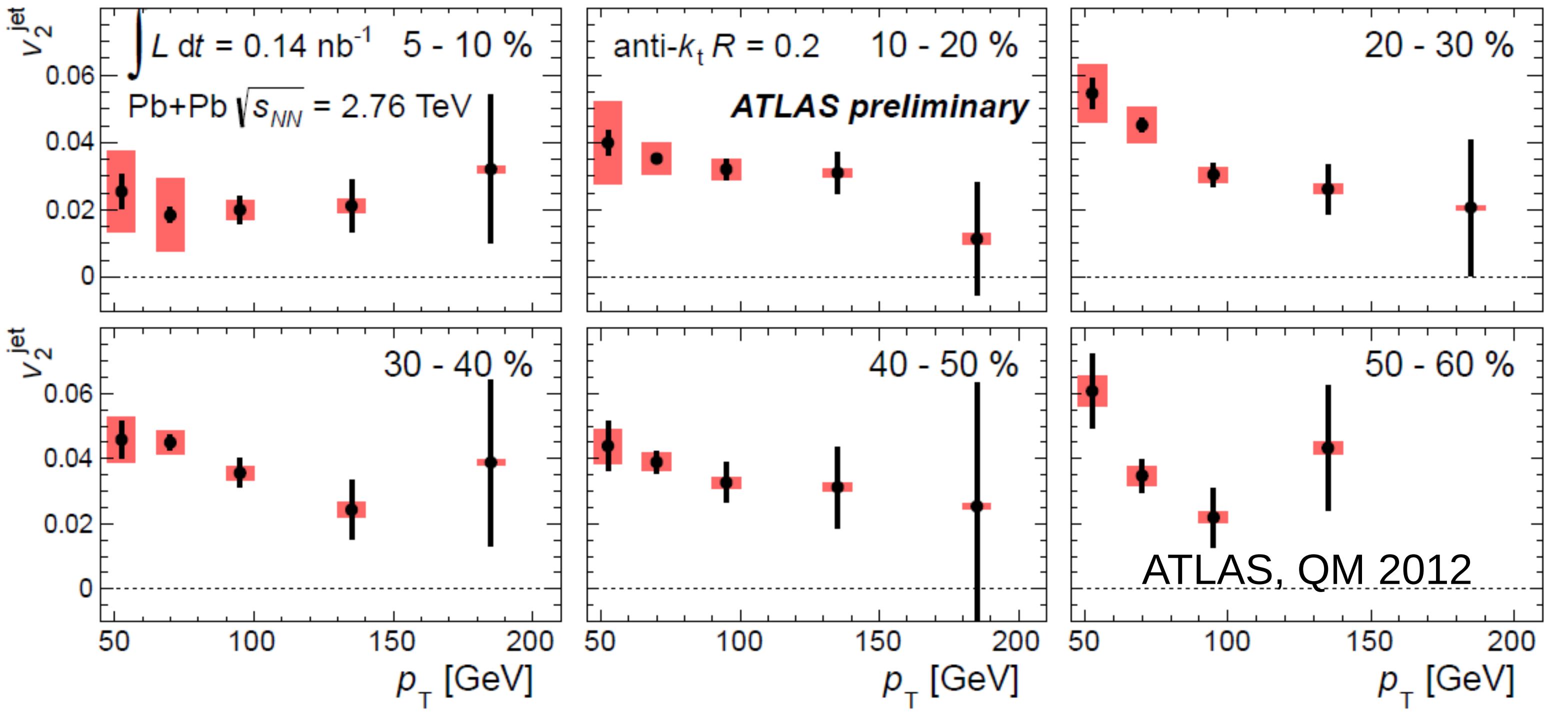


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/*c*
$|\eta_{jet}| < 0.6$

v_2\{TPC EP\} ($|\eta| < 1$)
v_2\{TPC EP\} ($2.8 < |\eta| < 3.7$)

- Jet v_2\{FTPC EP\} is non-zero
  → more jets reconstructed in-plane than out-of-plane
  → evidence of pathlength-dependence of parton energy loss
- Jet $v_2 \approx$ HT v_2 →surface bias largely driven by HT requirement

Jet v_2 at ATLAS

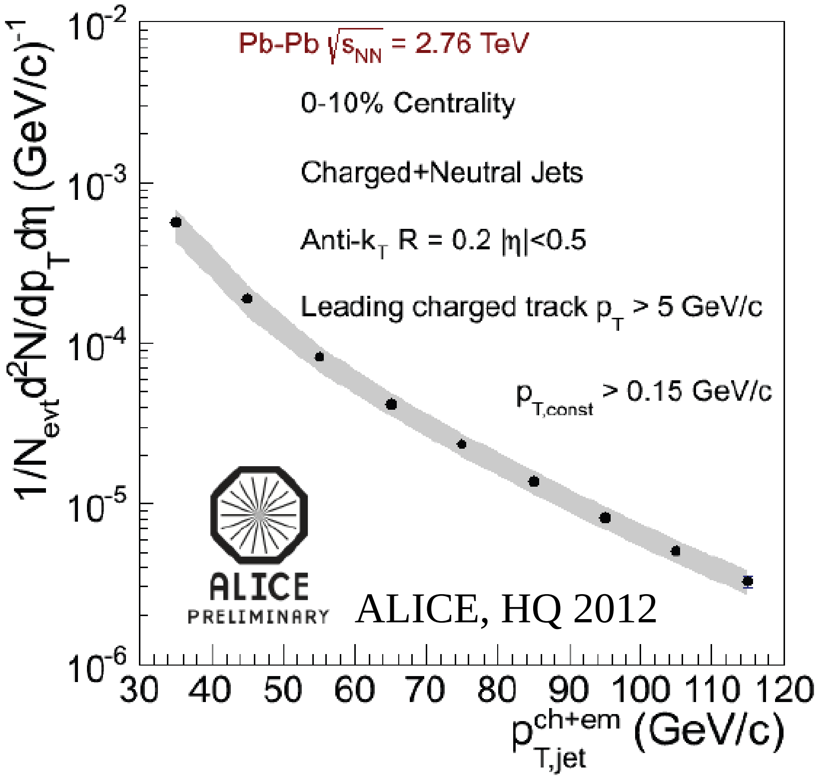


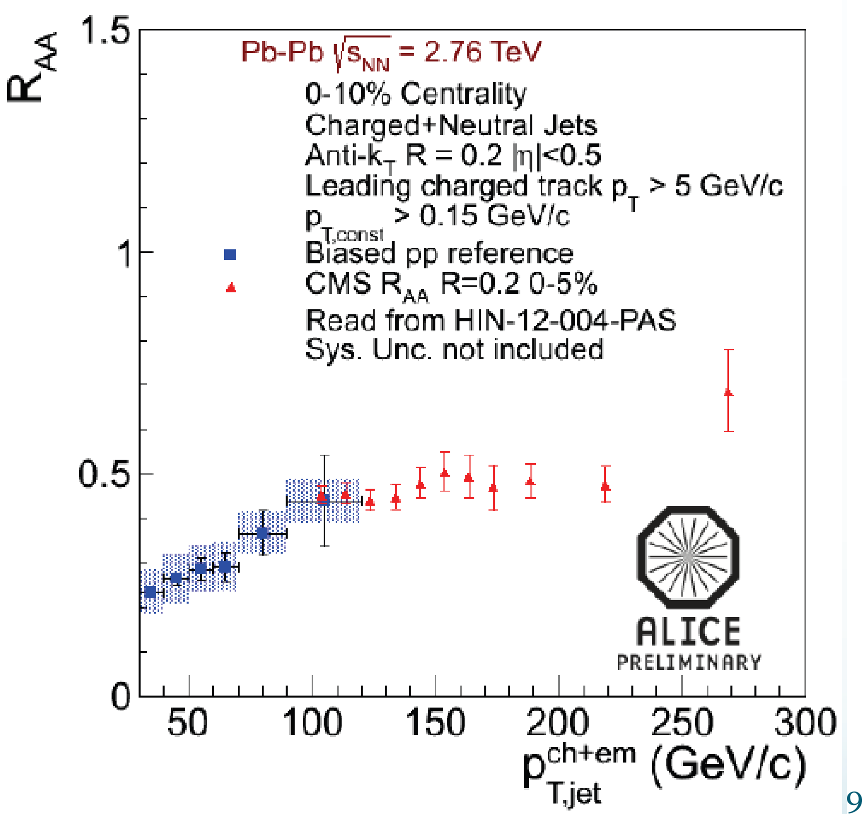
- Jet v_2 measured for $45 < p_T^{jet} < 210$ GeV/c, R = 0.2
- Also observed $v_2^{jet} > 0$
- Different kinematic range and biases than STAR measurement
  $\rightarrow$ different trend with p_T^{jet}

Jet Spectra at the LHC

- ALICE, CMS, and ATLAS have produced jet spectra for 30 < p_T^{jet} < 300 GeV/*c*

  → with different methods, constituent cuts, biases, etc.
- Jet R_{AA} shows suppression ~0.5 for wide range in jet p_T





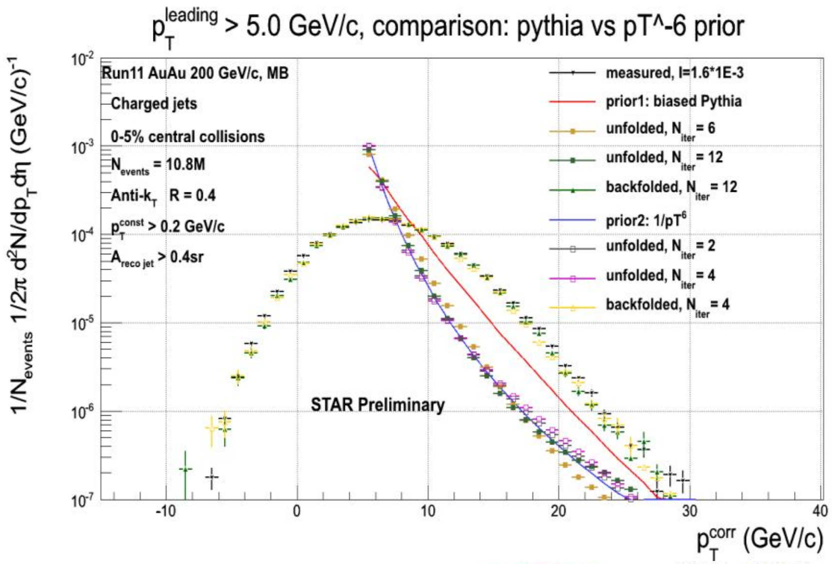
Future of Jets at RHIC

- STAR is working to improve their jet p_T spectrum measurement

  → Recent advancements in understanding the details of jet reconstruction

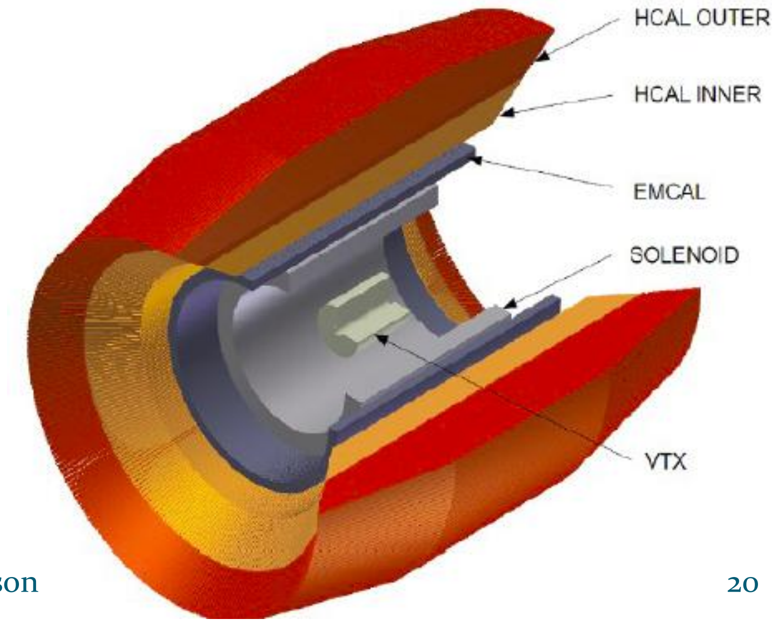
  → Similar methods as ALICE for direct comparison

  → A new high-statistics dataset



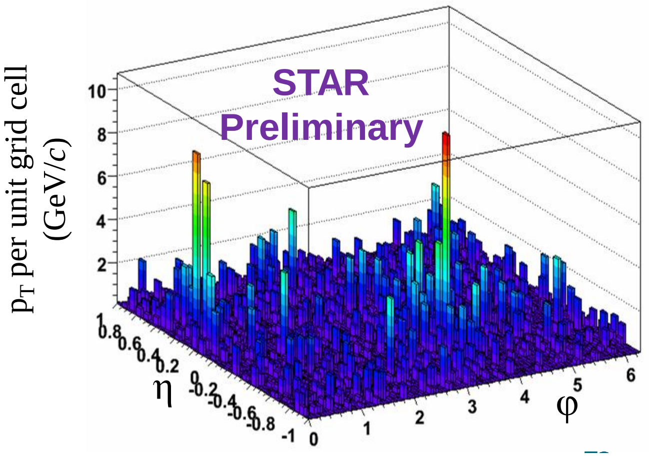
- sPHENIX project

  → See J. Frantz's talk, next



Conclusions & Final Thoughts

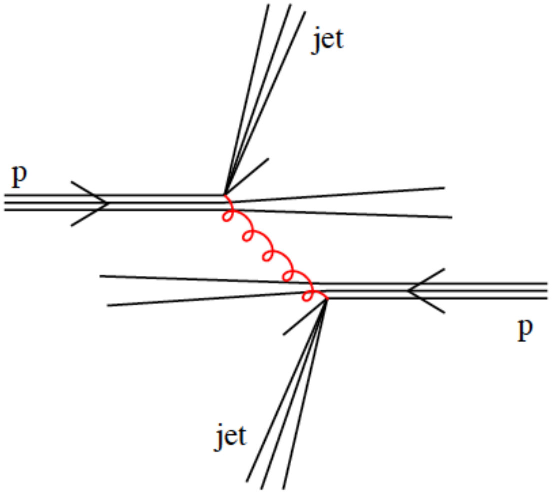
- Complementary analyses demonstrate jet quenching at RHIC
  - Softening and broadening of jets which traverse the medium in heavy ion collisions compared to p+p collisions
  - Are these results consistent with LHC measurements?
- It is necessary to understand biases present in analyses
  - At RHIC energies, a $p_T > 4$ GeV/*c* track selects mostly unmodified jets
  - What about at LHC energies?
- Necessary to do similar measurements with similar techniques among RHIC experiments and at the LHC
- Complementarity between RHIC and LHC measurements provide information about parton energy loss over a wide kinematic range



Backup

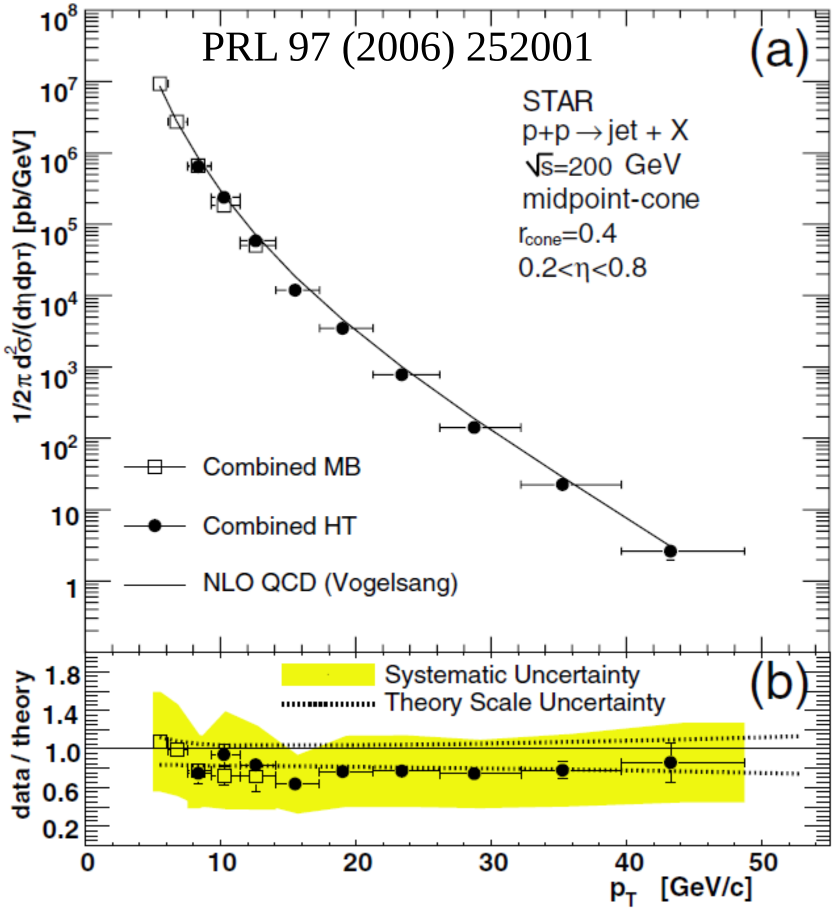
Jets

- Hard-scatterings occur in the early stages of the collision
- Recoiling partons fragment into clusters of hadrons, known as “jets.”



- Use jets as probes of the medium.

- Jets in p+p are well-described by pQCD

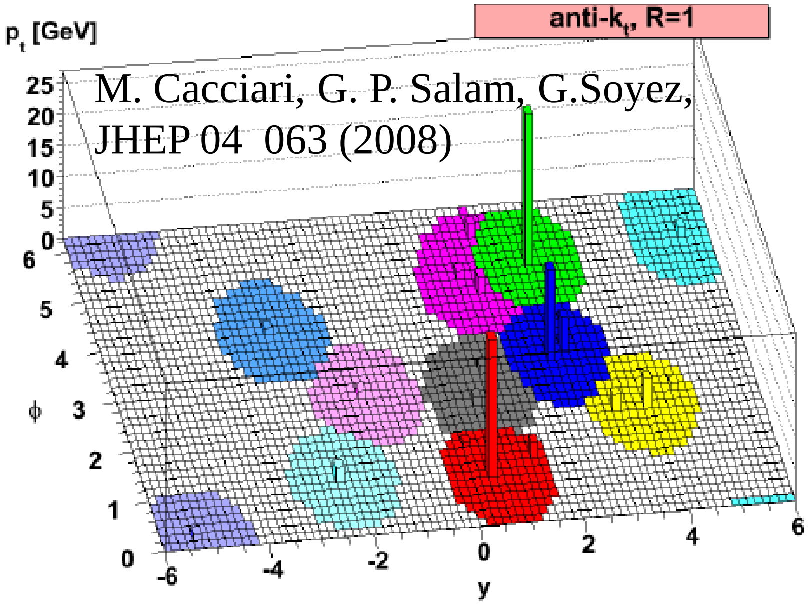


Jet Reconstruction

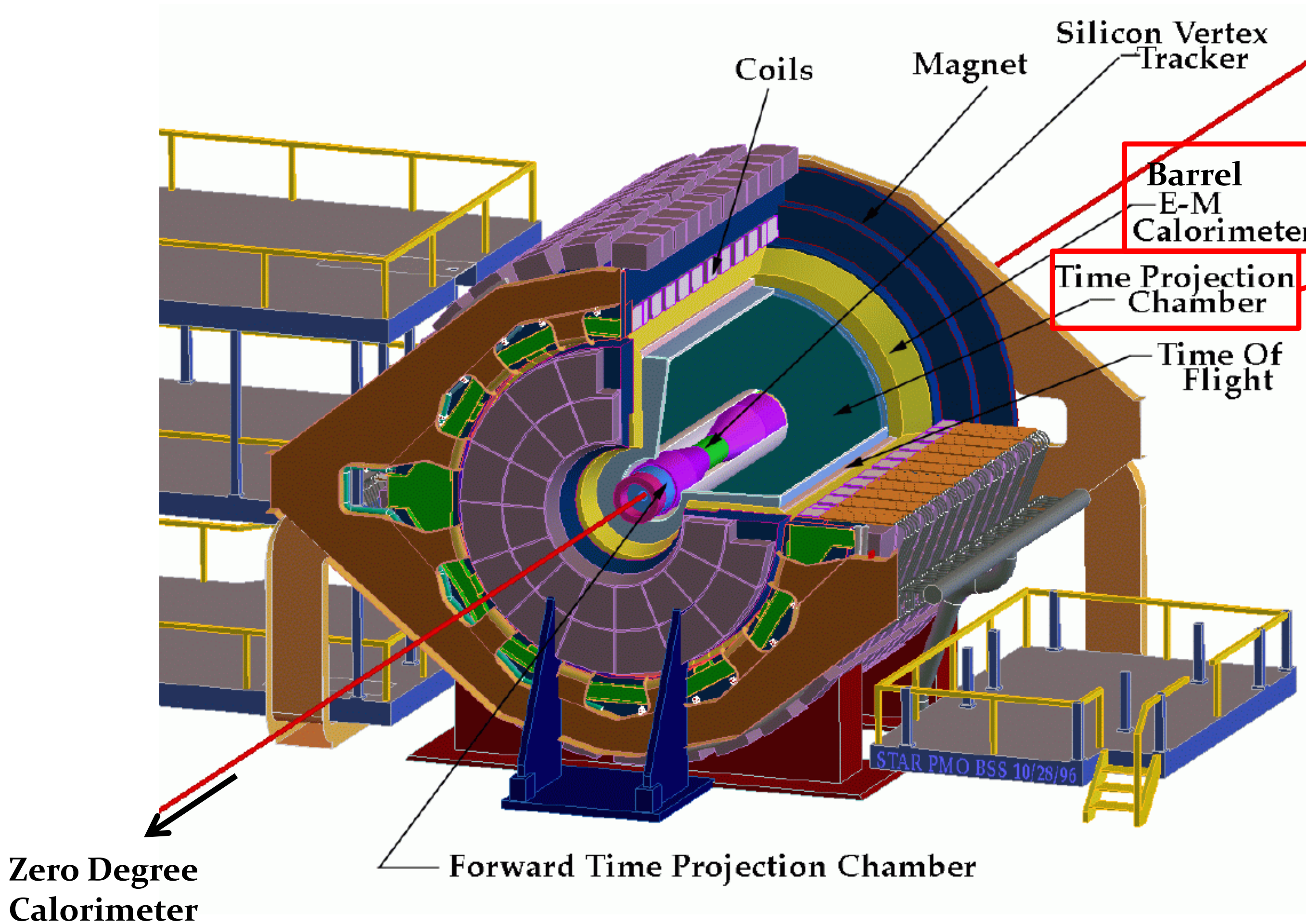
- Anti-k_T algorithm – sequential recombination [PLB 641 (2006) 57]
  - Start with high-p_T particles
  - For each pair of particles (*i*,*j*), calculate

$$d_{ij} = \min(1/p_{Ti}^2, 1/p_{Tj}^2)((\Delta y)_{ij}^2+(\Delta \varphi)_{ij}^2)/R^2$$

  - If $d_{ij} < 1/p_{Ti}^2$, merge the particles, else call particle *i* a jet
  - Repeat until all particles are clustered
  - R is resolution parameter
    → characteristic jet radius



STAR (Solenoidal Tracker at RHIC)



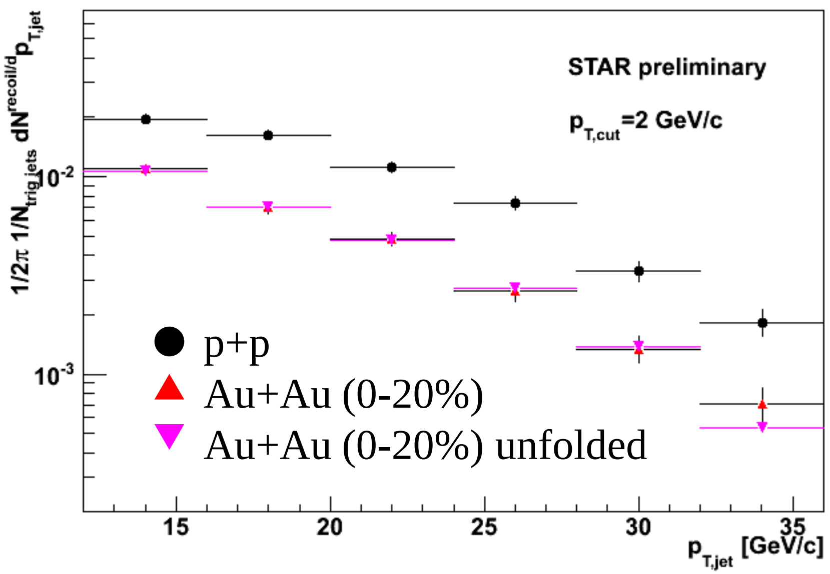
neutral energy detection

charged particle tracking & PID

$0 < \varphi < 2\pi$
$|\eta| < 1$

Dijet Coincidence Rate

- Similar trigger jet population in Au+Au and p+p due to p_T cut and HT trigger requirements
- Compare recoil jet spectrum in Au+Au and p+p



Trigger Jet:
R = 0.4
$p_{T,cut}$ = 2 GeV/c
p_T^{jet} > 20 GeV/c

Recoil Jet:
R = 0.4
$p_{T,cut}$ = 2 GeV/c

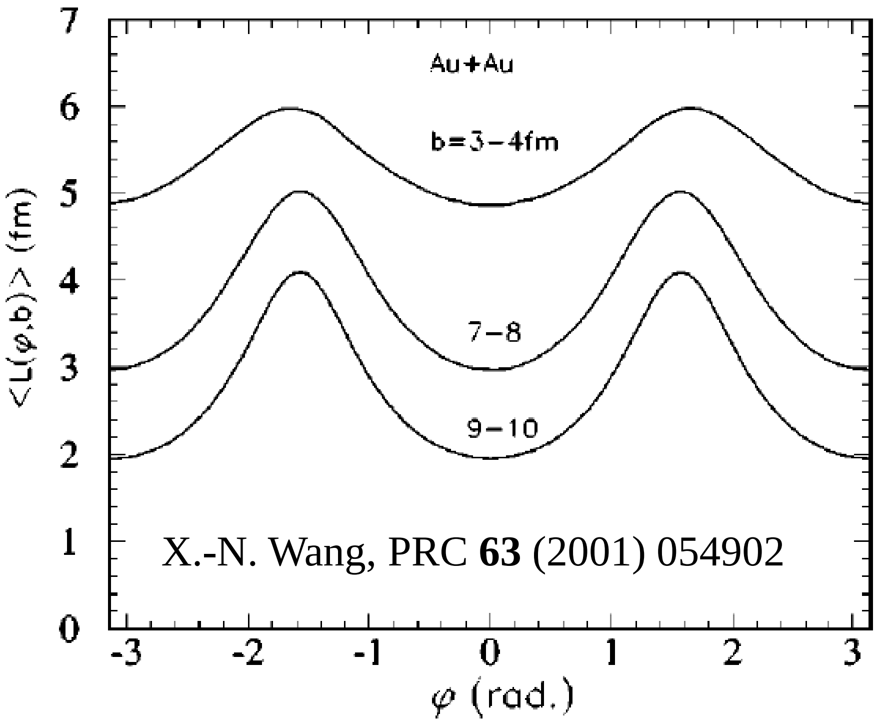
- Suppression of recoil jet in Au+Au
- Due to softening and/or broadening outside of jet cone
- Consistency between correlations and inclusive measurements.

Pathlength-dependent energy loss

In-medium pathlength depends on orientation to reaction plane

Pathlength-dependent jet quenching →

Energy/number of reconstructed jets may depend on orientation to reaction plane

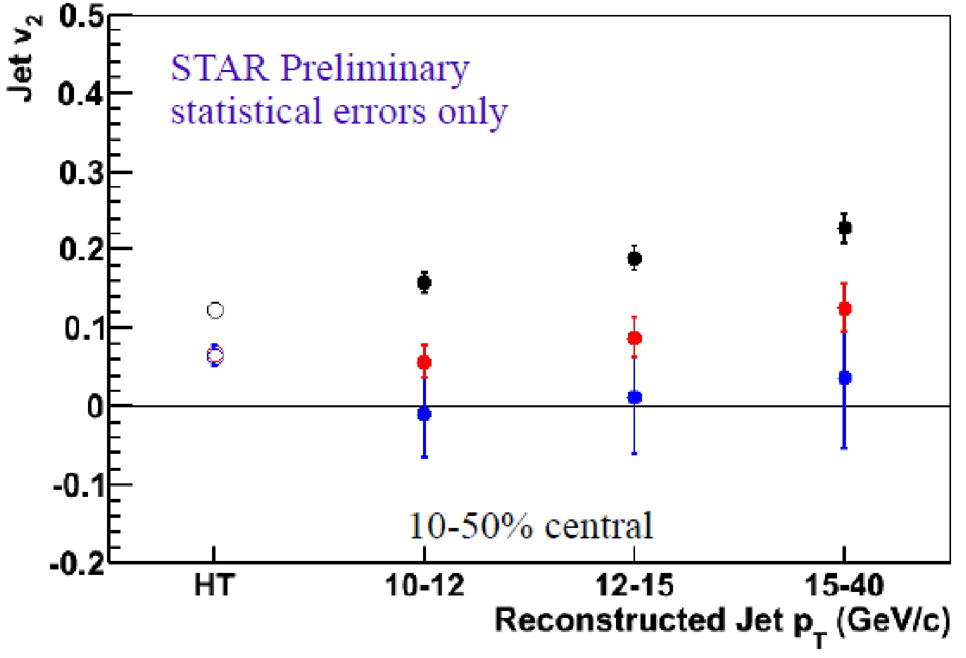


$$v_2^{jet} = \frac{\left\langle \cos\left(2(\Psi_{jet} - \Psi_{EP})\right)\right\rangle}{R}$$

- "Jet v_2" → correlation between reconstructed jets and the reaction plane (or 2nd-order participant plane)
- "Jet v_2" ≠ "Jet flow"

Jet v_2

- Jet axis restricted to $|\eta| < 0.6$
- Event plane reconstructed in TPC ($|\eta| < 1$), FTPC ($2.8 < |\eta| < 3.7$), and ZDC-SMD ($|\eta| > 6.3$)



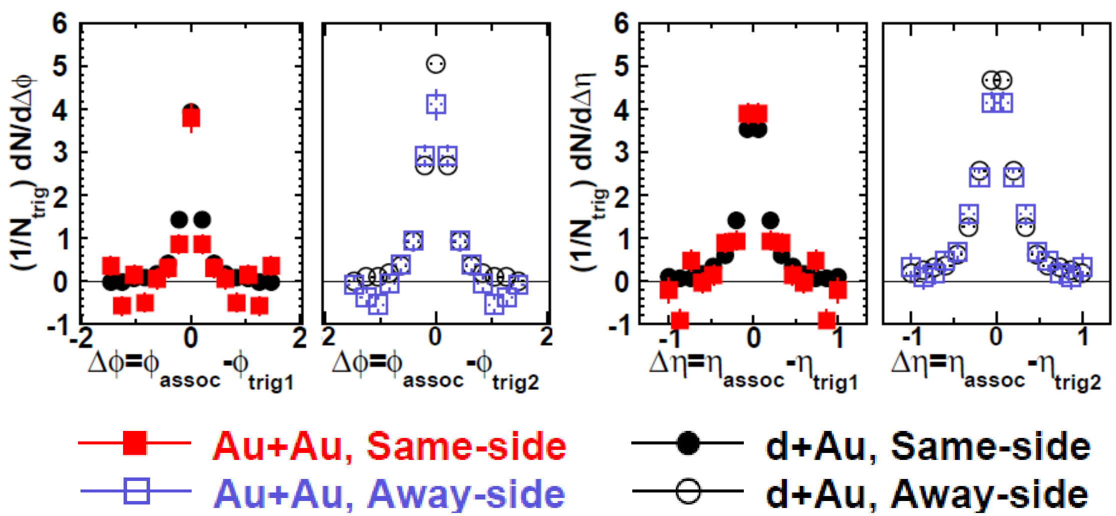
Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- Jet v_2{TPC EP}
- Jet v_2{FTPC EP}
- Jet v_2{ZDC-SMD EP}

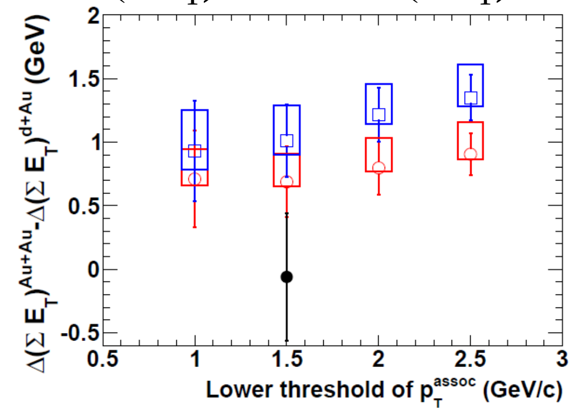
PRC 87 (2013) 44903

Asymmetric Triggers

$10 < E_T^{trig1} < 15$ GeV (in BEMC)
$4 < p_T^{trig2} < 10$ GeV/c (in TPC)
$1 < p_T^{assoc} < 10$ GeV/c



Relative dijet imbalance
$\Delta(\Sigma E_T)^{Au+Au} - \Delta(\Sigma E_T)^{d+Au}$



$8 < E_T^{trig1} < 10$ GeV
$10 < E_T^{trig1} < 15$ GeV

- Dijet imbalance indicates slight softening of awayside peak
- Still no significant shape difference between near- and away-sides, or between Au+Au and d+Au.
- Compare/contrast to dihadron and jet-hadron results.