Jets at RHIC

What have we learned from jet reconstruction and correlation measurements?

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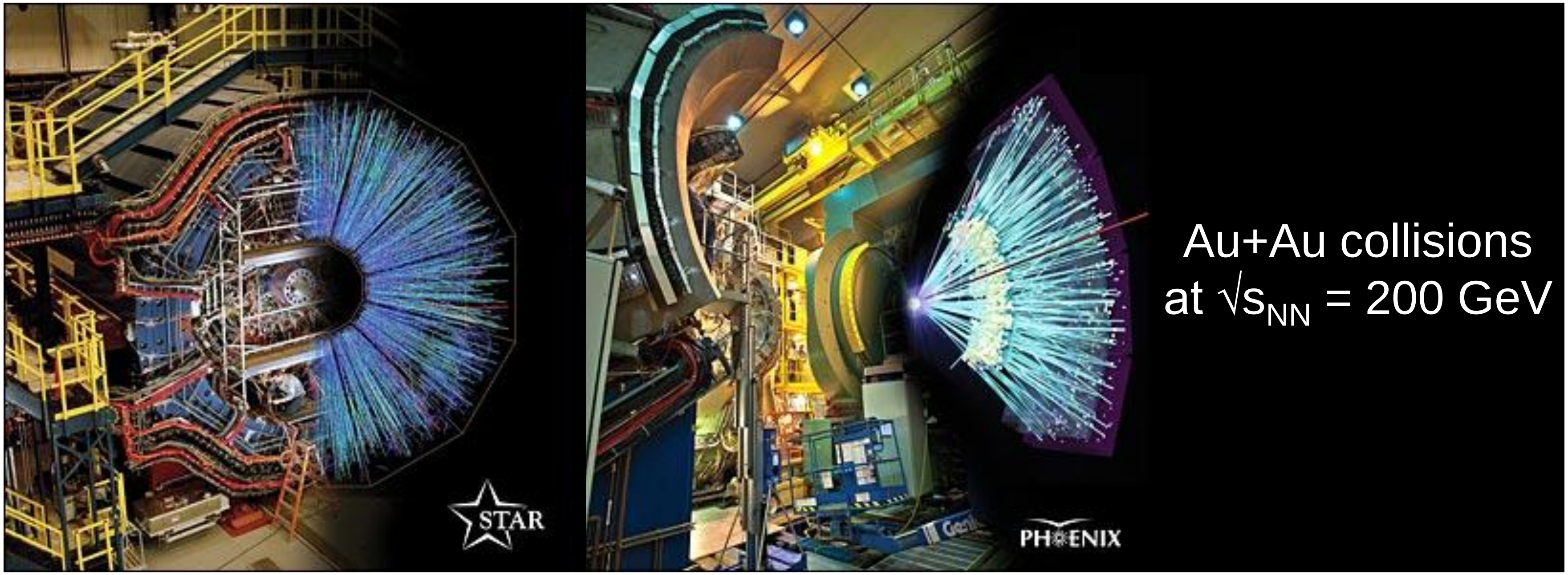
Jets at RHIC

- Hard-scattered partons fragment into collimated "jets" of hadrons
- By studying jets we can investigate interactions of the high-p_T partons with the Quark Gluon Plasma
- We look for…
  - Suppression of the number of jets (compared to p+p or p+A)
  - Modification of the p_T or angular distributions of jet fragments



High-p_T suppression

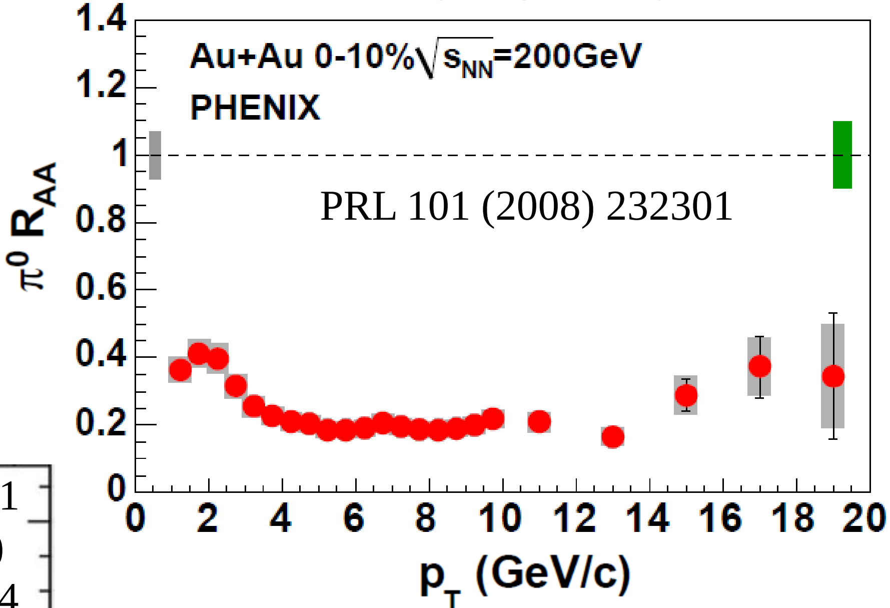
- Single-particle inclusive measurements

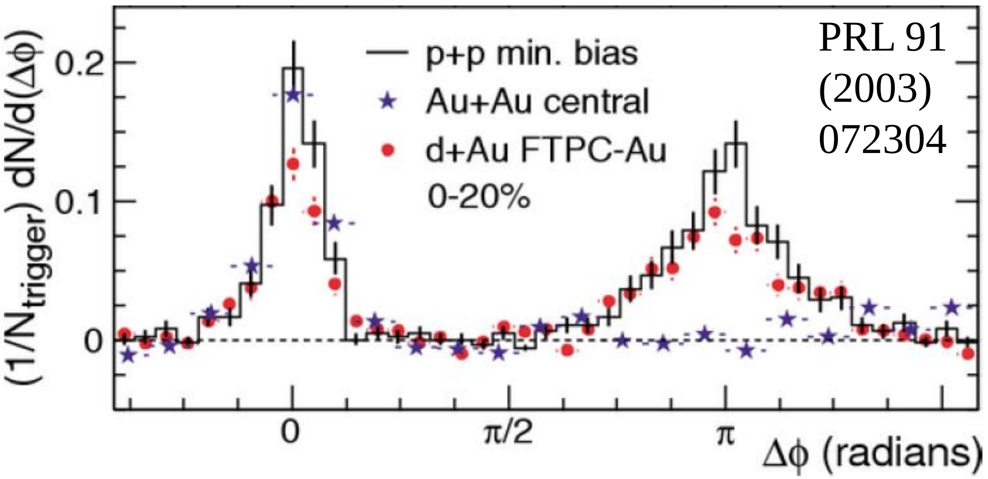
  → suppression of high-p_T hadrons in central Au+Au events

- Correlations w.r.t. high-p_T hadrons

  → suppression of particles associated with jet peak

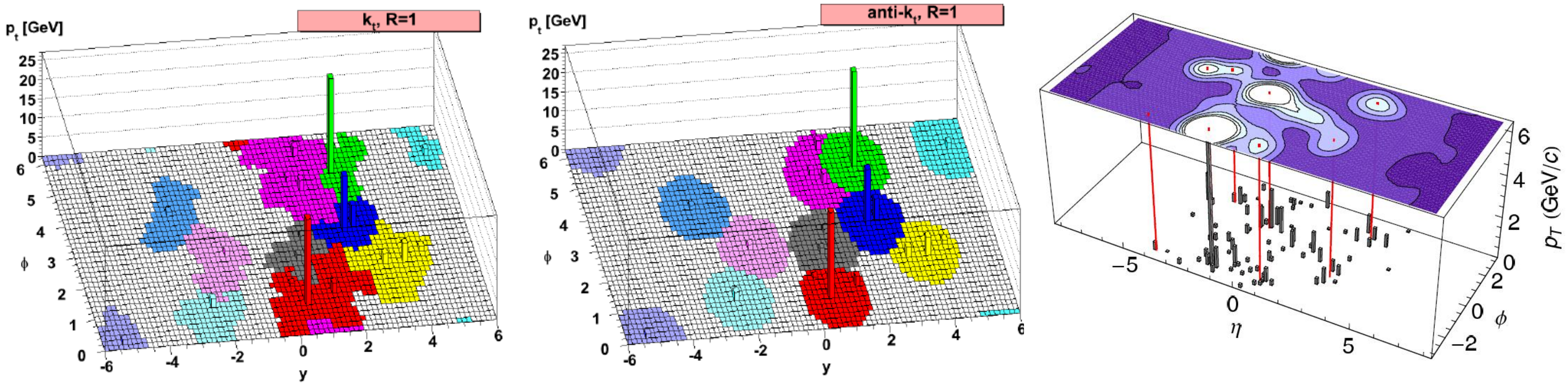
$$R_{AA}(p_T) = \frac{\sigma^{pp}_{\text{inel.}}}{\langle N_{\text{bin}} \rangle} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{pp}/dp_T d\eta}$$





Jet Reconstruction 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

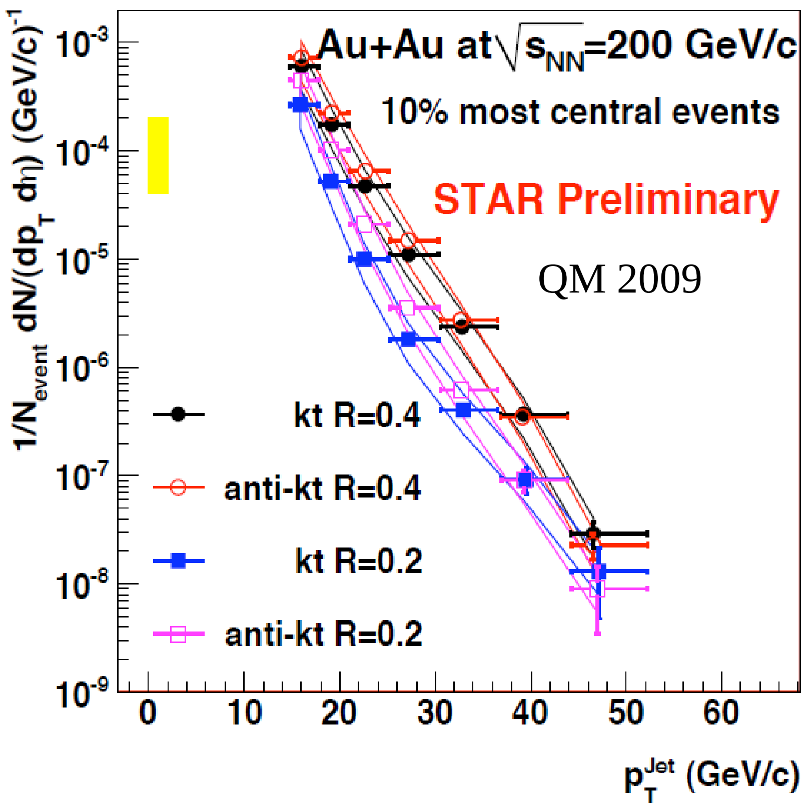


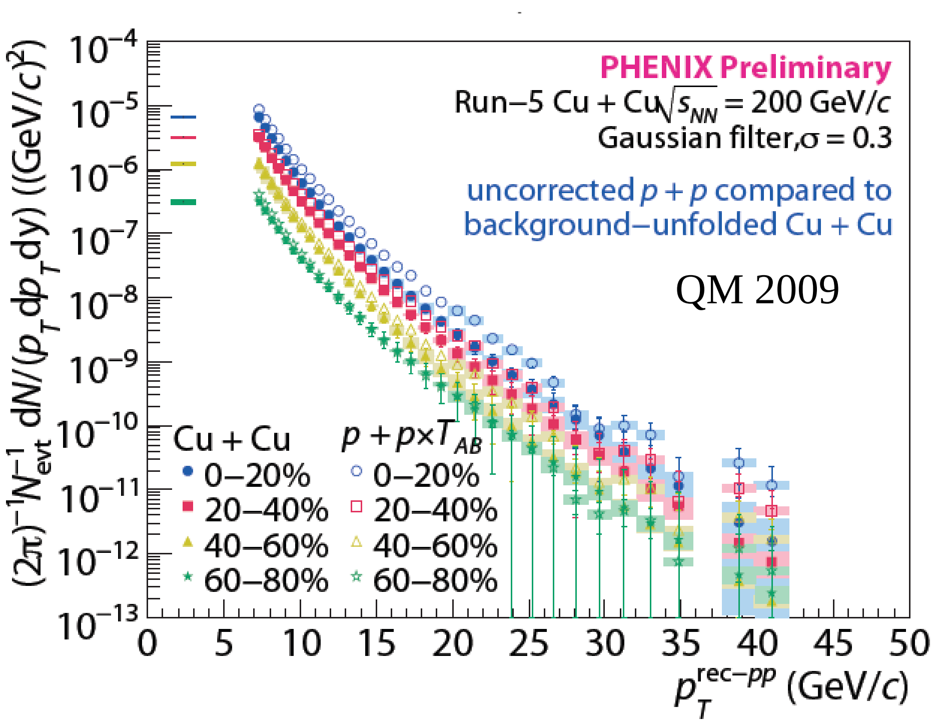
k_T & anti-k_T
JHEP04 (2008) 063

Gaussian filter
arXiv:0806.1499 [nucl-ex]

Jet Spectra at RHIC

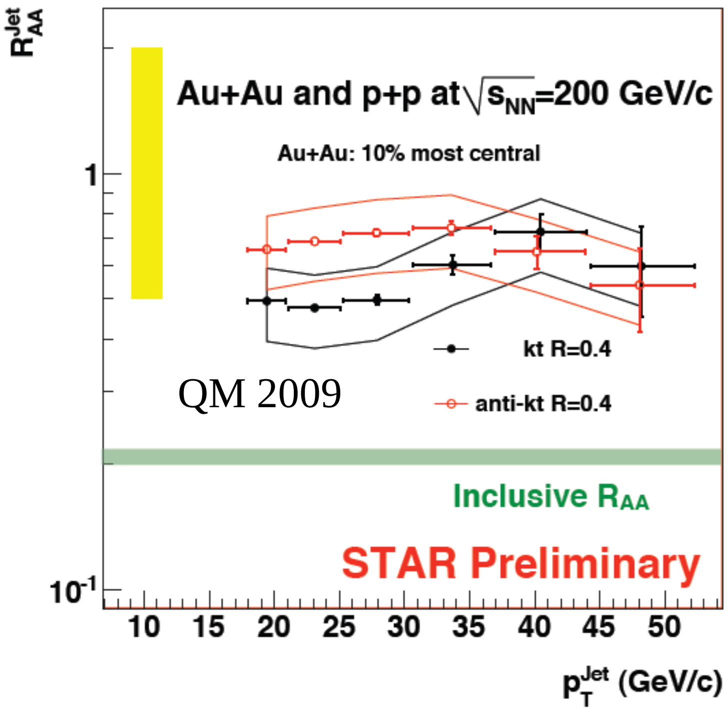
- For the first time → Full jet reconstruction in a heavy ion environment
- Different methods of jet reconstruction, background subtraction, fake-jet rejection

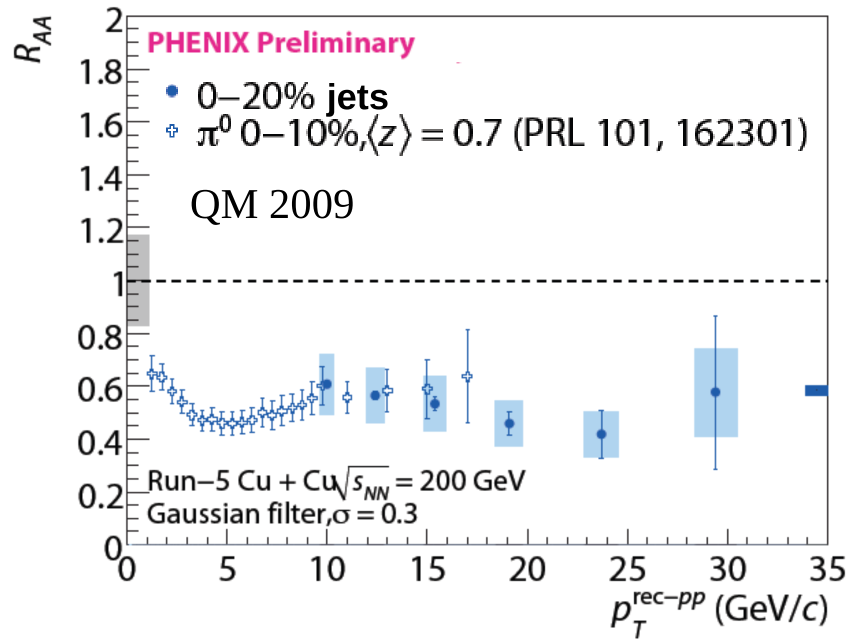




Jet R_{AA} at RHIC

- Reconstructed jets demonstrate suppression

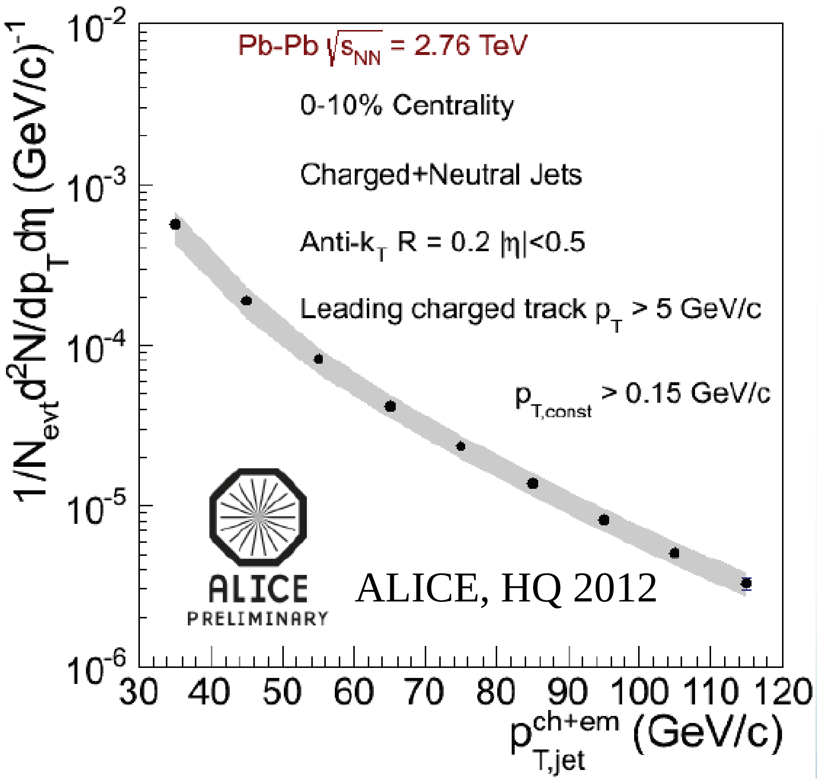


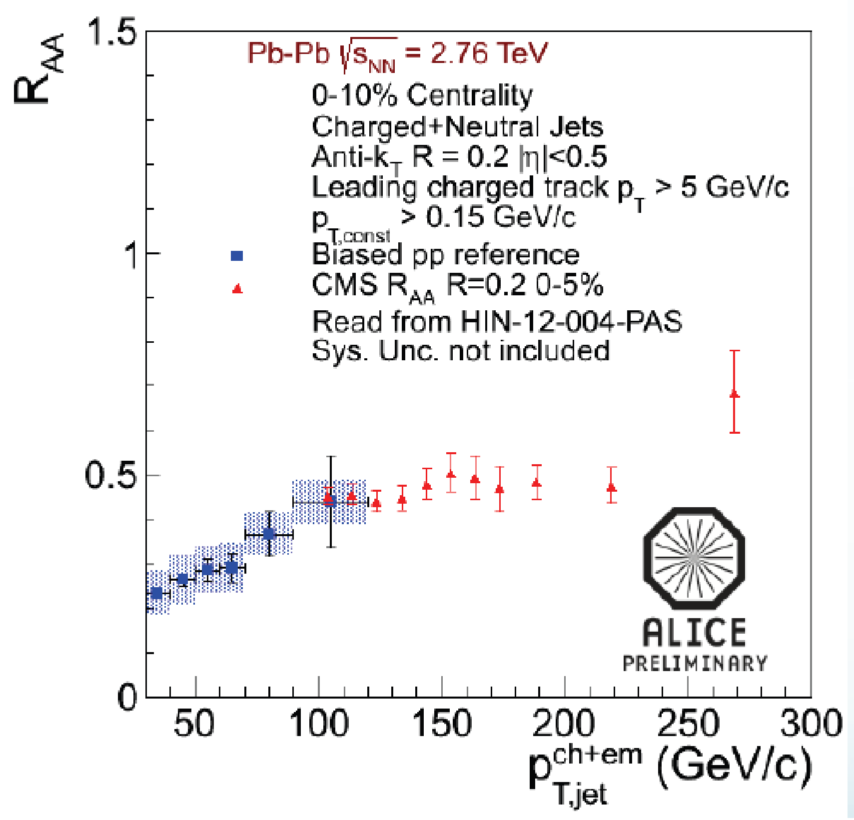


- Need to use similar techniques for direct comparison, further work is necessary to understand background fluctuations

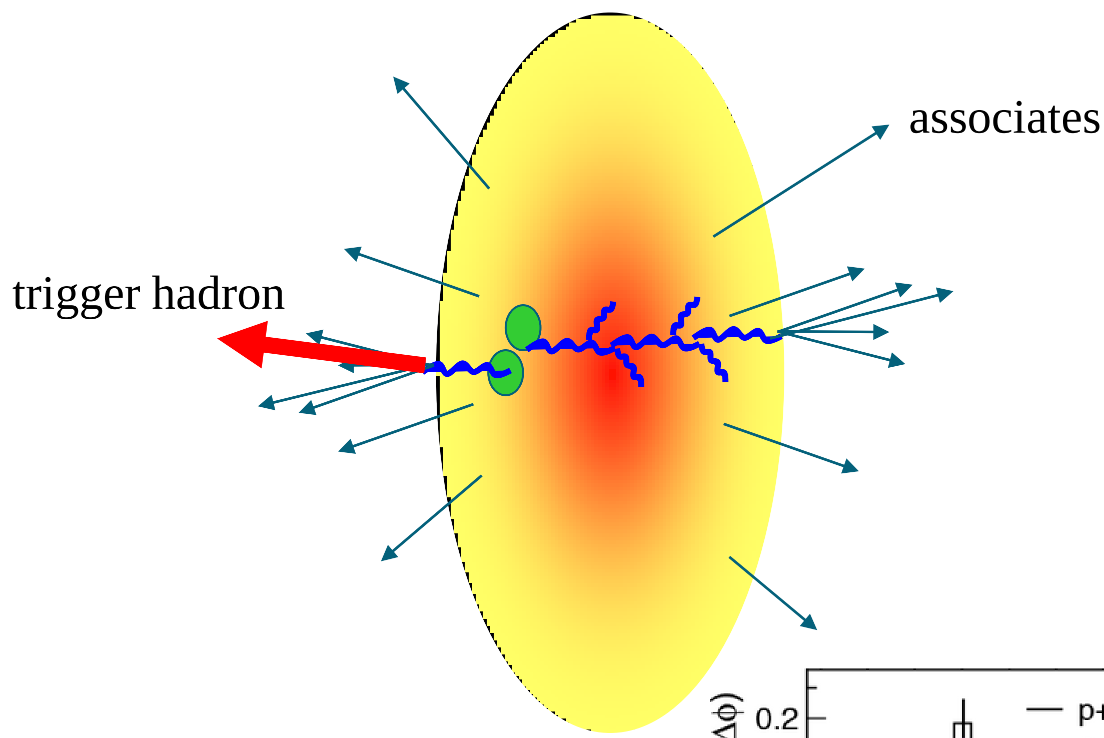
Jet Spectra at the LHC

- ALICE, CMS, and ATLAS have produced jet spectra for $30 < p_T^{jet} < 300$ GeV/*c*
- Jet R_{AA} shows suppression for wide range in jet p_T

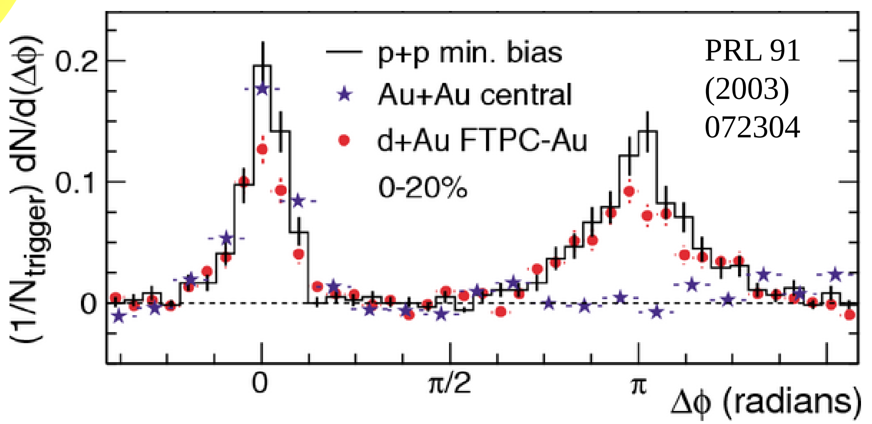




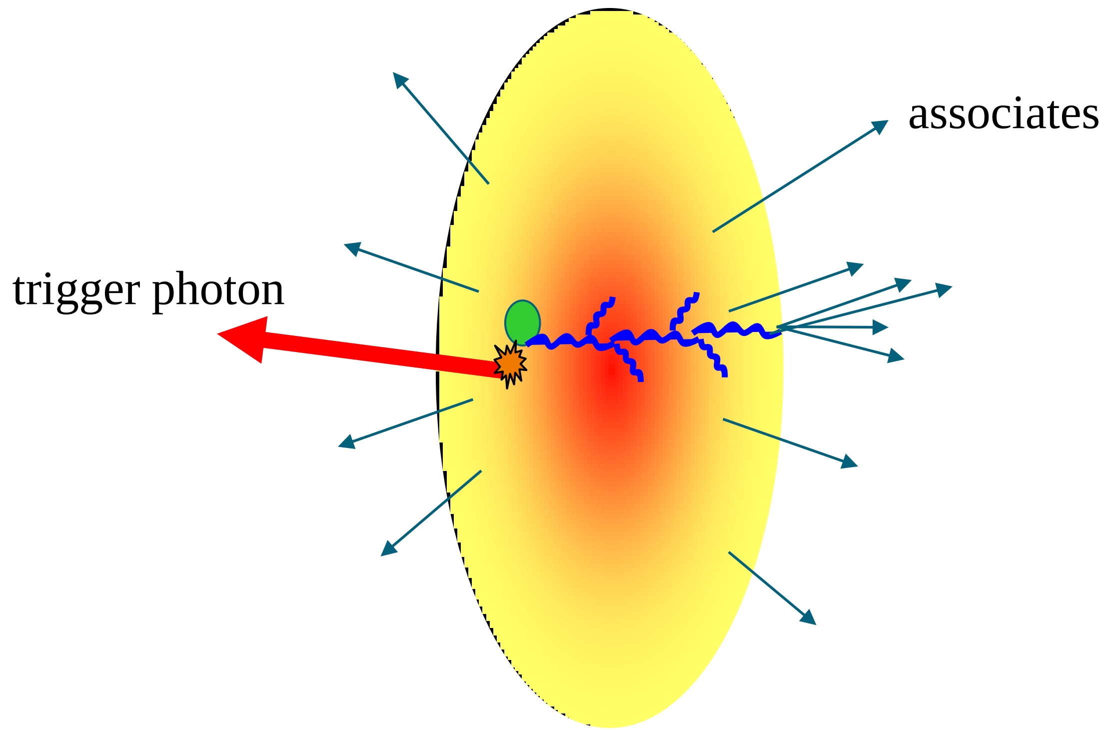
Dihadron Correlations



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



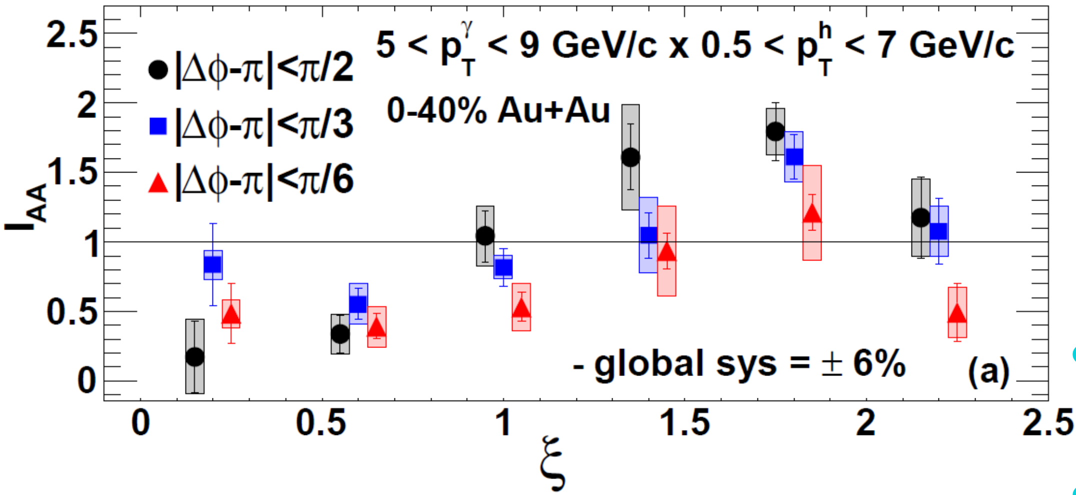
γ-hadron Correlations



- γ-jet pairs produced in q+g → q+γ
- Photons do not lose energy in the medium, therefore $p_T^{photon} \approx p_T^{parton}$

PHENIX, arXiv:1212.3323 [nucl-ex]
Accepted to PRL

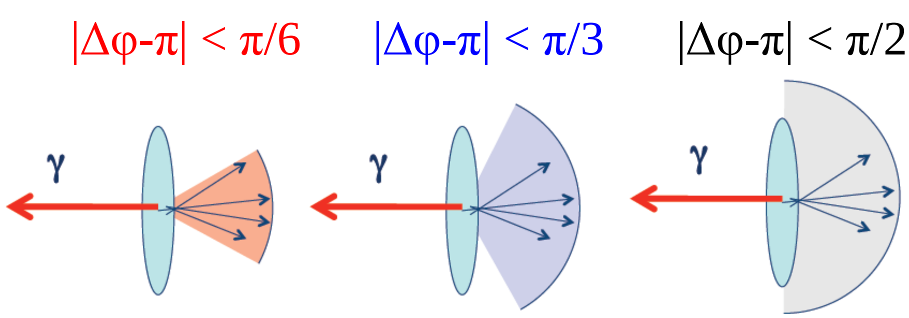
Awayside hadron yields



$$I_{AA} = \frac{\text{yield in Au+Au}}{\text{yield in p+p}}$$

$$\xi = \ln(1/z_T)$$
$$z_T = p_T^{hadron}/p_T^{photon}$$

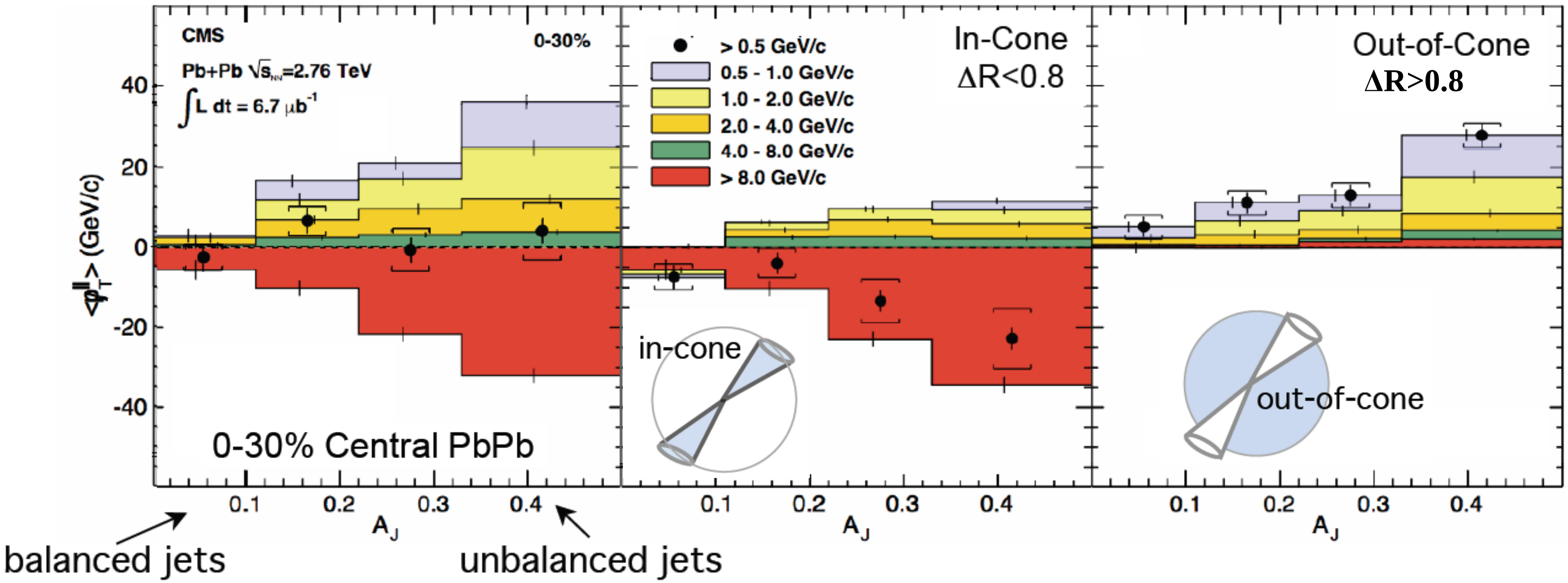
- Modified fragmentation function in Au+Au compared to p+p
- In narrow cone ($|\Delta\varphi-\pi| < \pi/6$): suppression ($I_{AA} < 1$) of high-$z_T$ hadrons, no corresponding enhancement at low z_T
- When integration region is expanded ($|\Delta\varphi-\pi| < \pi/2$), low-$z_T$ enhancement is observed



high z_T low z_T

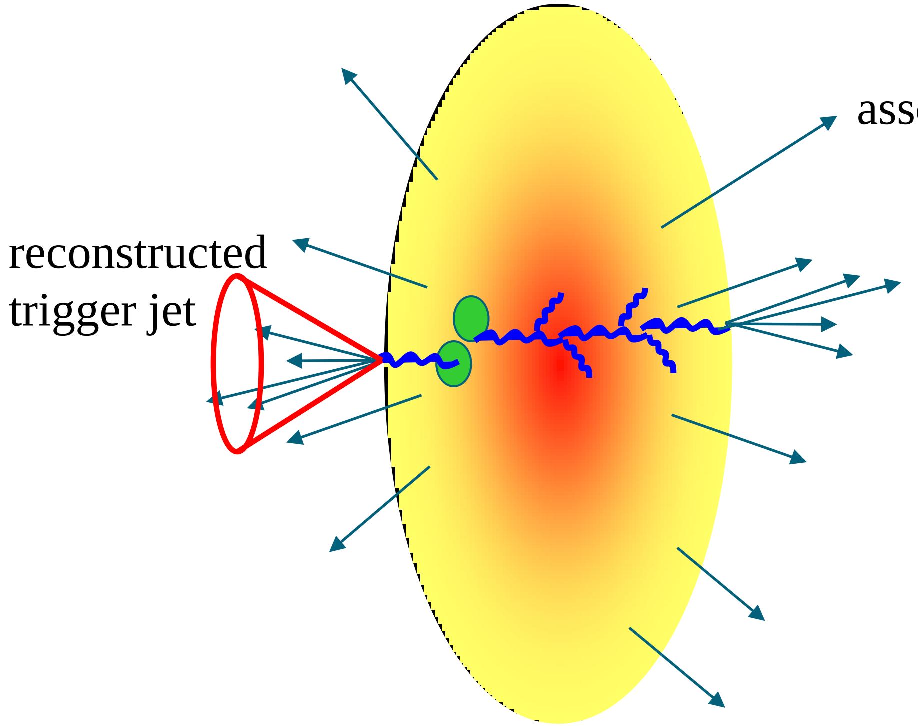
Jets at the LHC

- CMS result → Energy is distributed to very wide angles
  (ΔR > 0.8 ~ π/4)



- Similar conclusions for CMS A_J and PHENIX γ-jet measurements
- Where does the "missing" energy go?

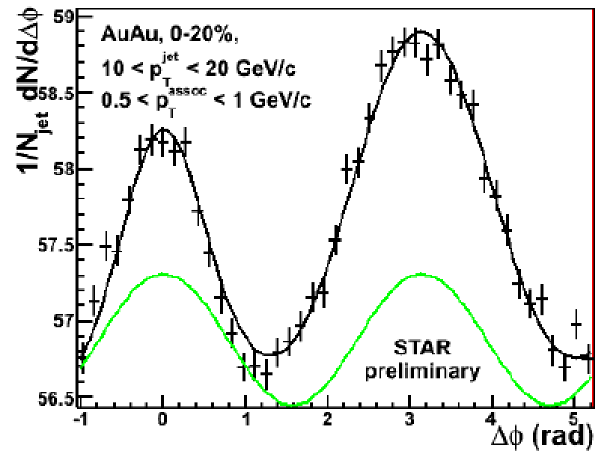
Jet-hadron Correlations

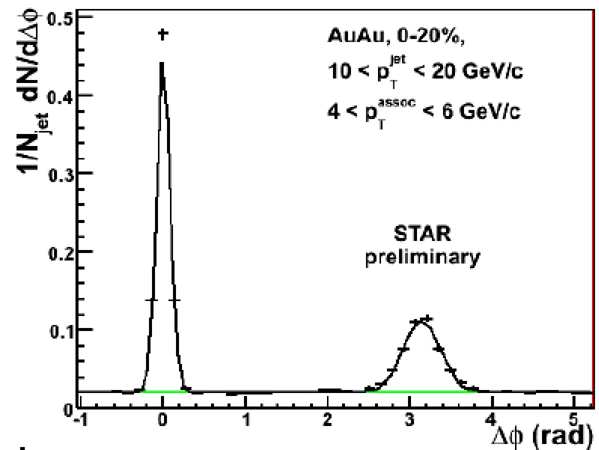


- Jet-hadron correlations have increased kinematic reach compared to dihadron correlations, allow for more precise determination of parent parton energy

Jet-hadron Correlations

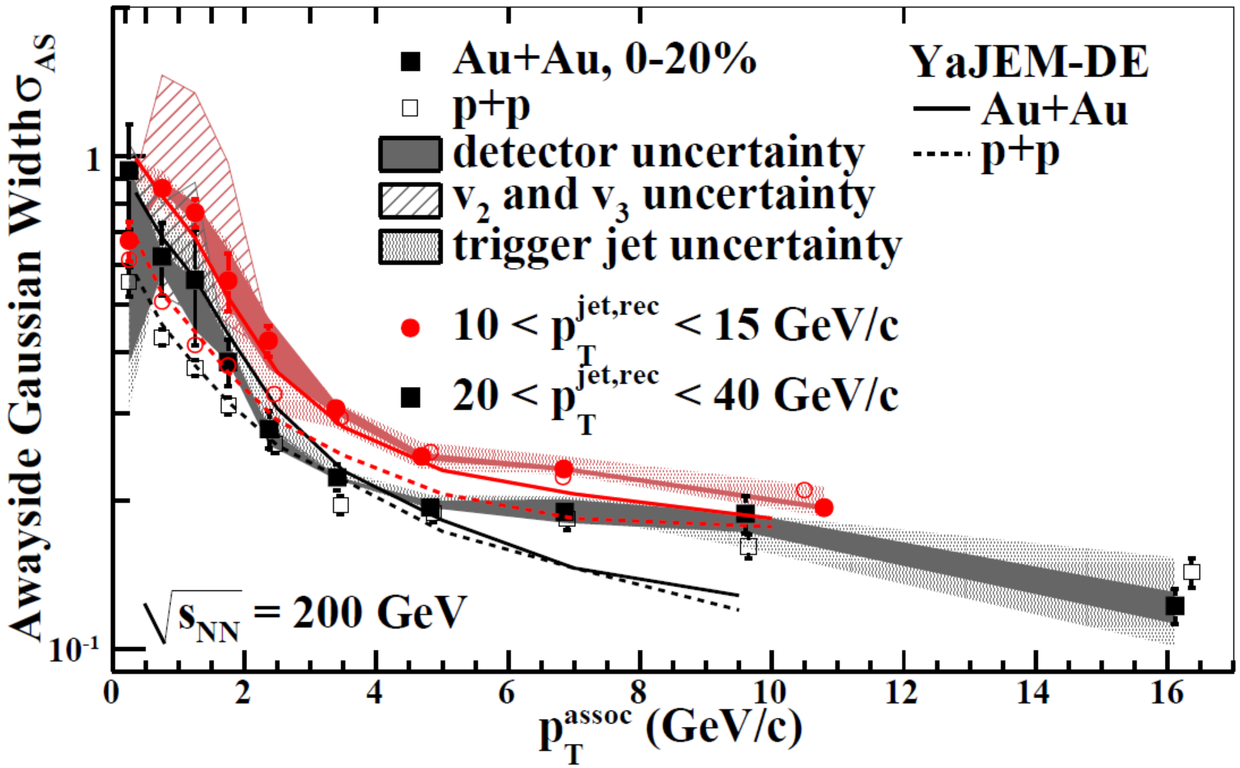
- Intentionally impose a bias towards unmodified trigger jets! (surface bias?)
  - E_T > 6 GeV in a single BEMC tower (Δφ x Δη = 0.05 x 0.05)
  - Anti-k_T (R = 0.4) using tracks/towers with p_T > 2 GeV/*c*
- HT trigger requirement and constituent p_T cut
  - Reduce effects of background fluctuations
  - 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



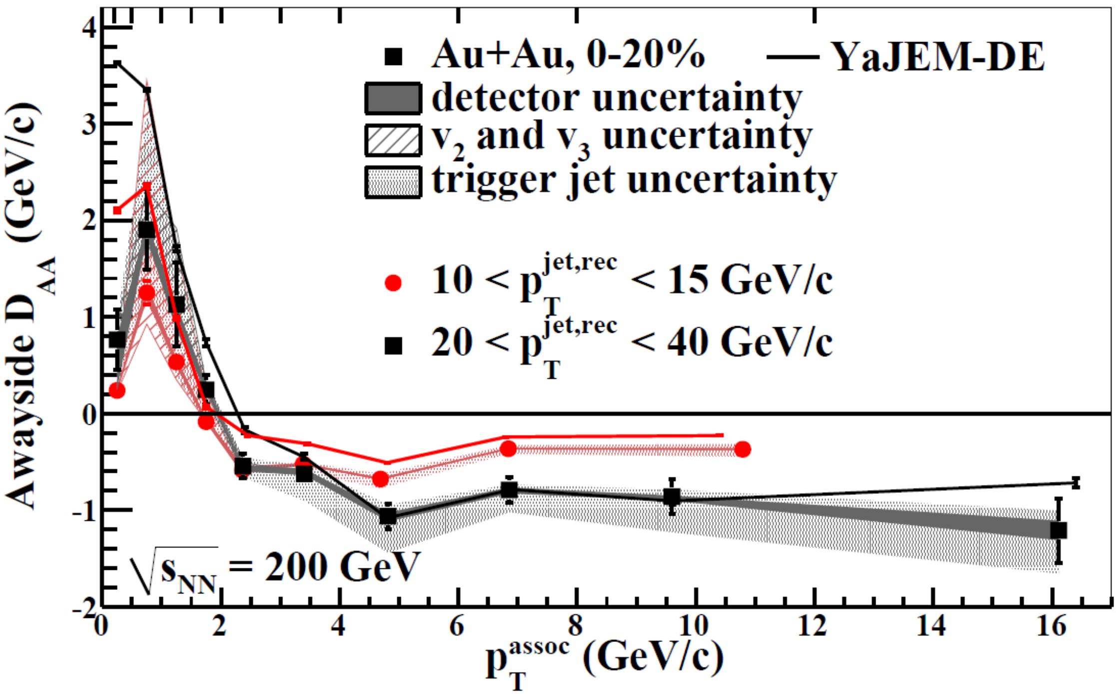
- Awayside widths suggest jet broadening to large angles at low-p_T (but highly-dependent on assumed v_3 modulation)
- Further information is needed about v_2^{jet}, v_3^{jet} (possible correlation of jets with reaction plane / participant planes)…

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

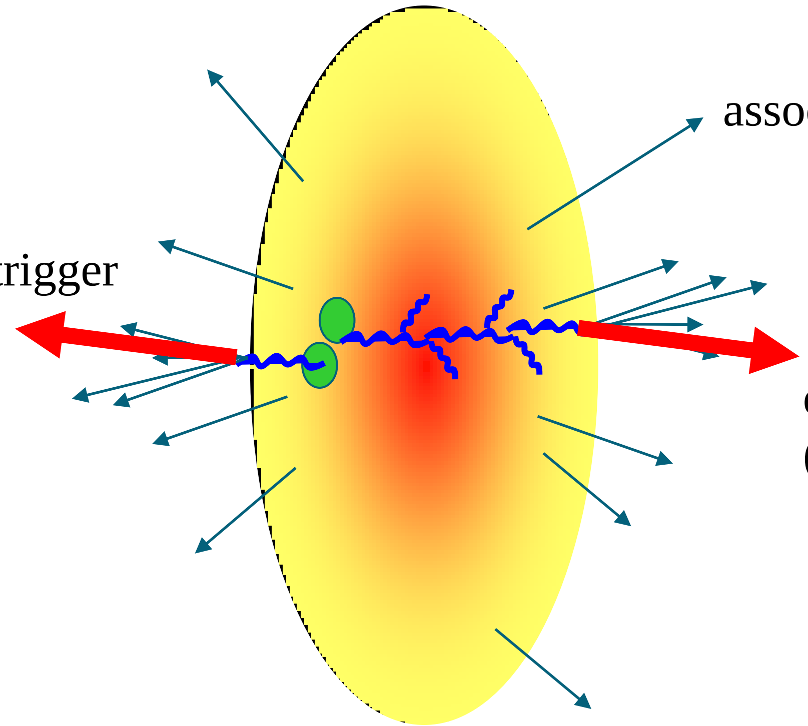
- Suppression of high-p_T associated hadron yield is in large part balanced by low-p_T enhancement.

From Qualitative Consistency to Quantitative Conclusions

- Need to assess biases in measurements at RHIC and the LHC…
  - Dihadron correlations: high-p_T hadron → hard fragmentation
  - γ-hadron correlations: no geometrical bias?
  - Jet-hadron correlations: HT trigger and high-p_T constituent cut → hard fragmentation
  - CMS A_J: Two reconstructed jets with high energy
- Need to do the same measurements at each experiment
  - A_J at RHIC
  - Jet-hadron correlations at LHC

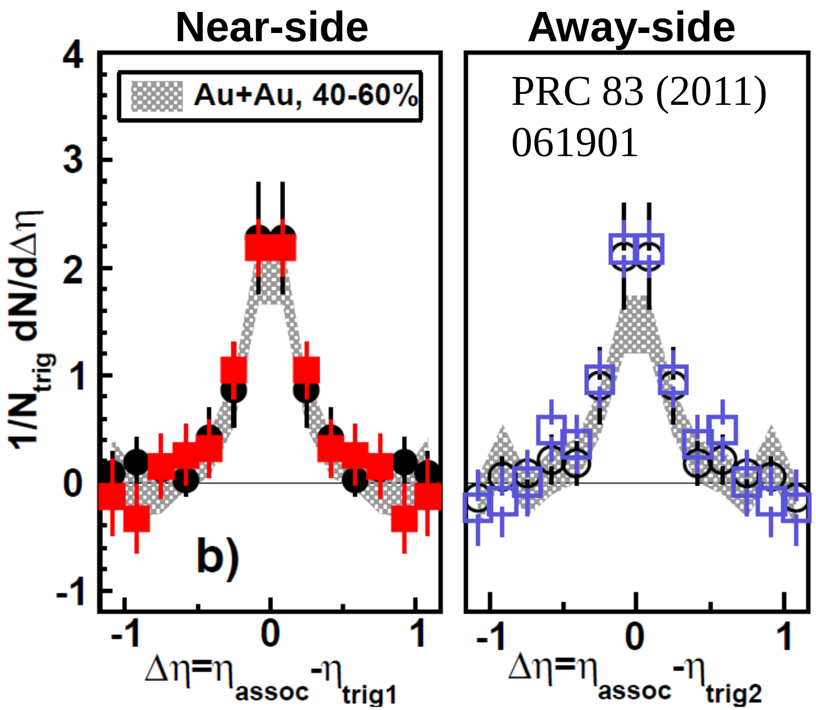
2+1 Correlations

- Select events containing pairs of back-to-back high-p_T hadrons (likely due to dijet production)



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

Symmetric Triggers

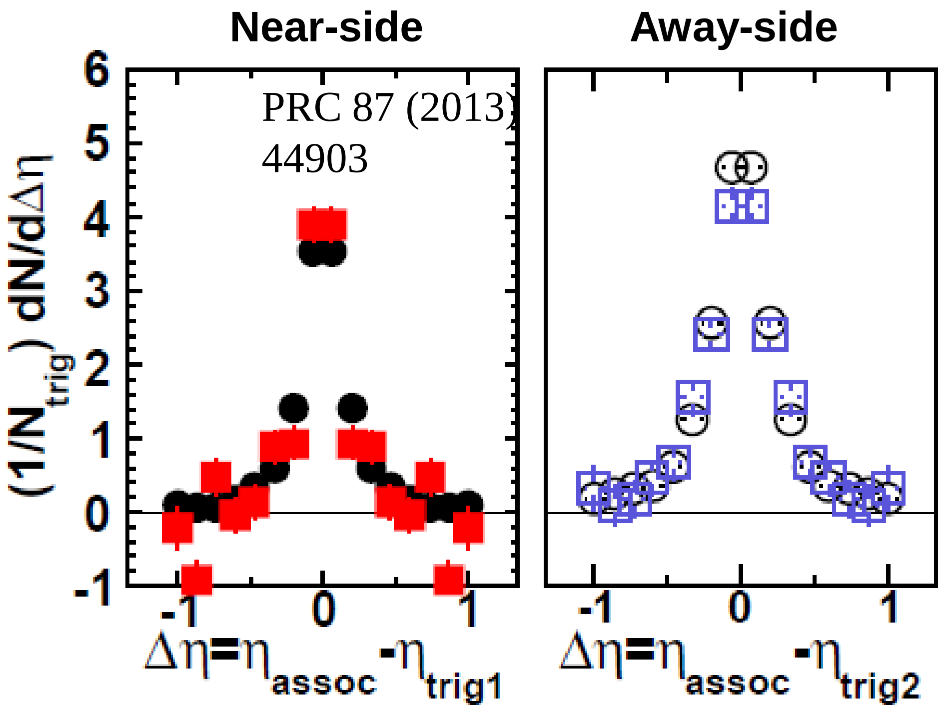


Au+Au
d+Au

$5 < p_T^{trig1} < 10$ 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

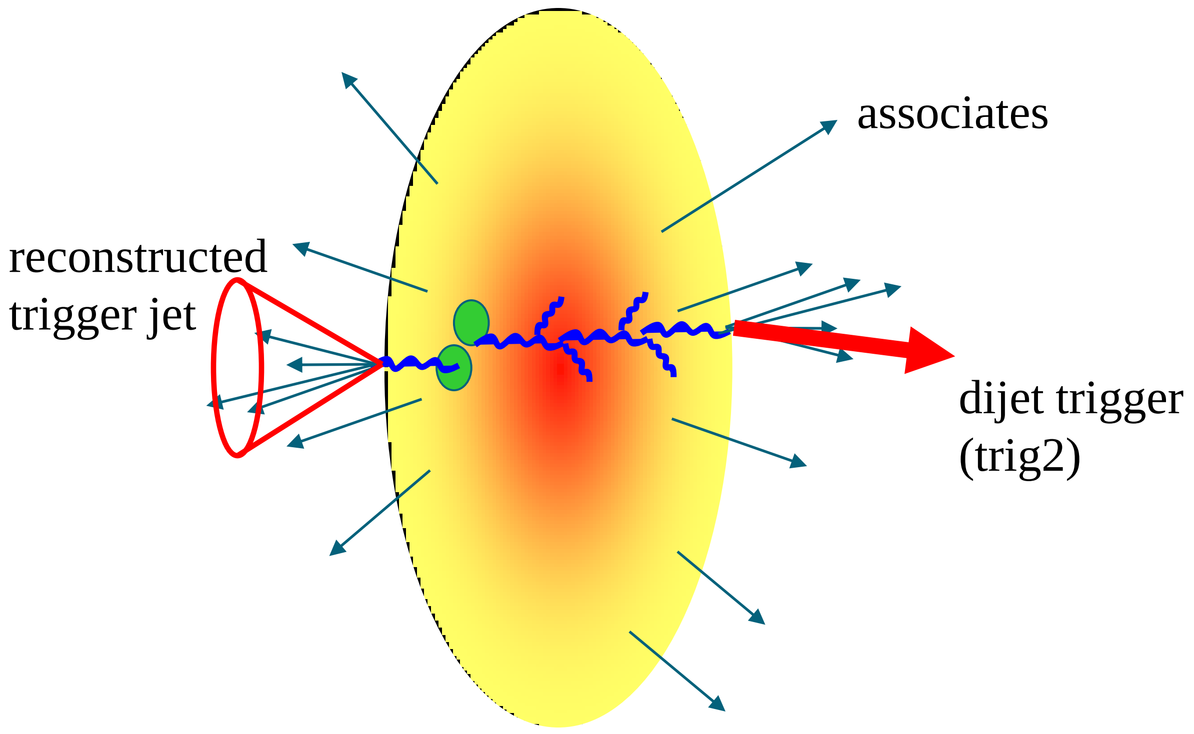


Au+Au
d+Au

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

- Still no large 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



- Require a high-p_T hadron ~180° away from reconstructed trigger jet

Jet-Hadron and 2+1 Correlations

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

$|\varphi_{jet} - \varphi_{trig2}| > \pi - 0.2$

STAR, WWND 2011

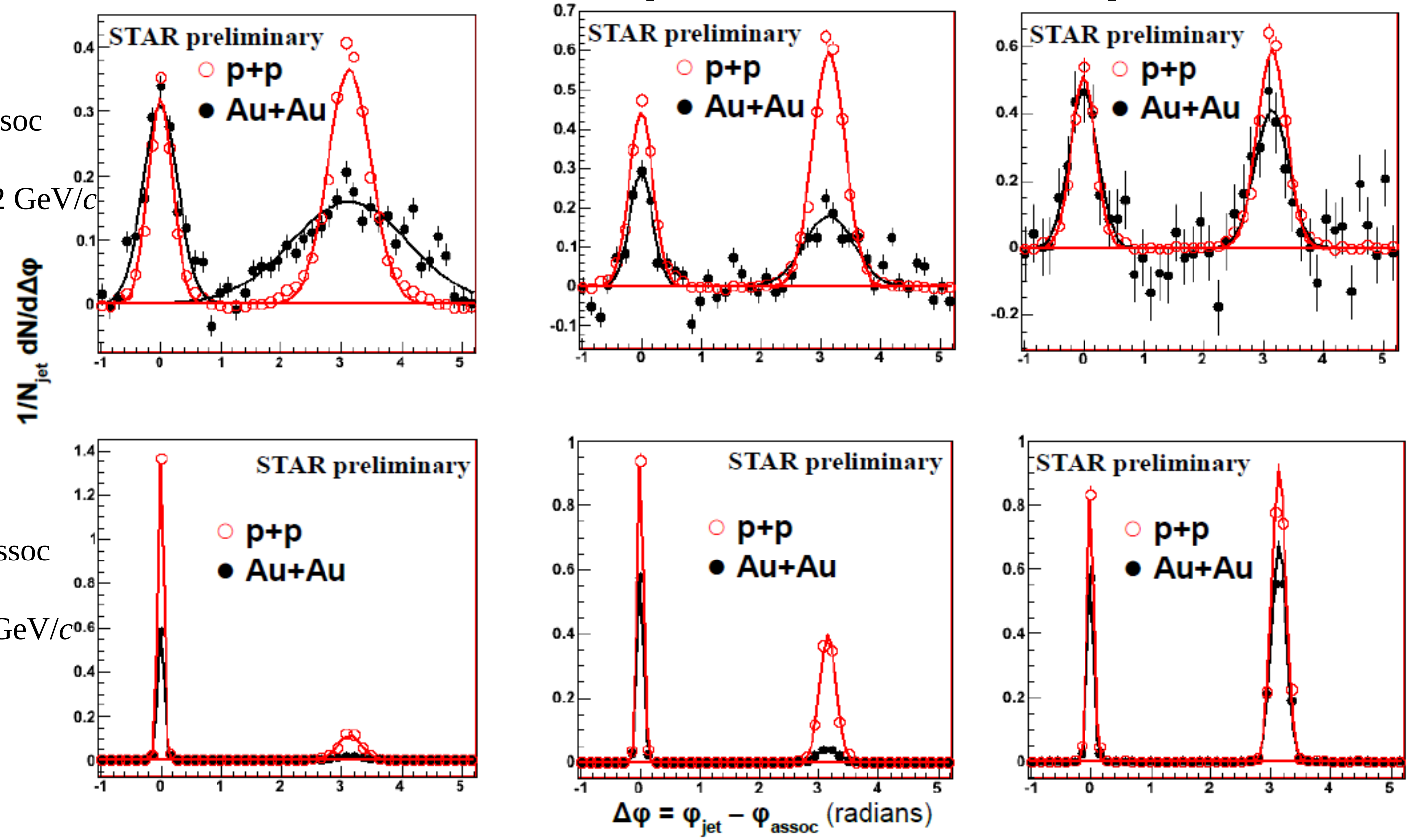
no trig2 requirement | $p_T^{trig2} > 2$ GeV/c | $p_T^{trig2} > 4$ GeV/c

Low p_T^{assoc}

$1.5 < p_T^{assoc} < 2$ GeV/c

High p_T^{assoc}

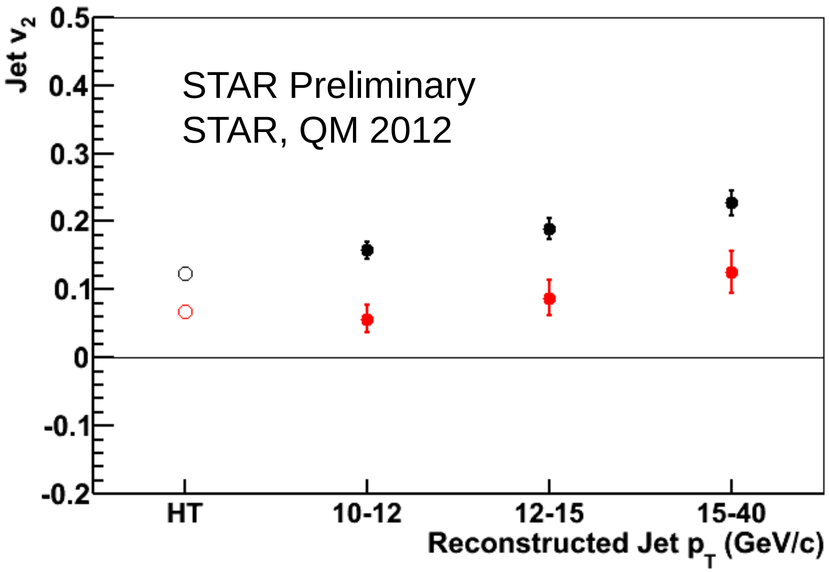
$6 < p_T^{assoc} < 8$ GeV/c



- Select unmodified jets with $p_T^{hadron} > 4$ GeV/c requirement.

Jet v_2 at STAR

- Correlation between jet axis and event plane



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

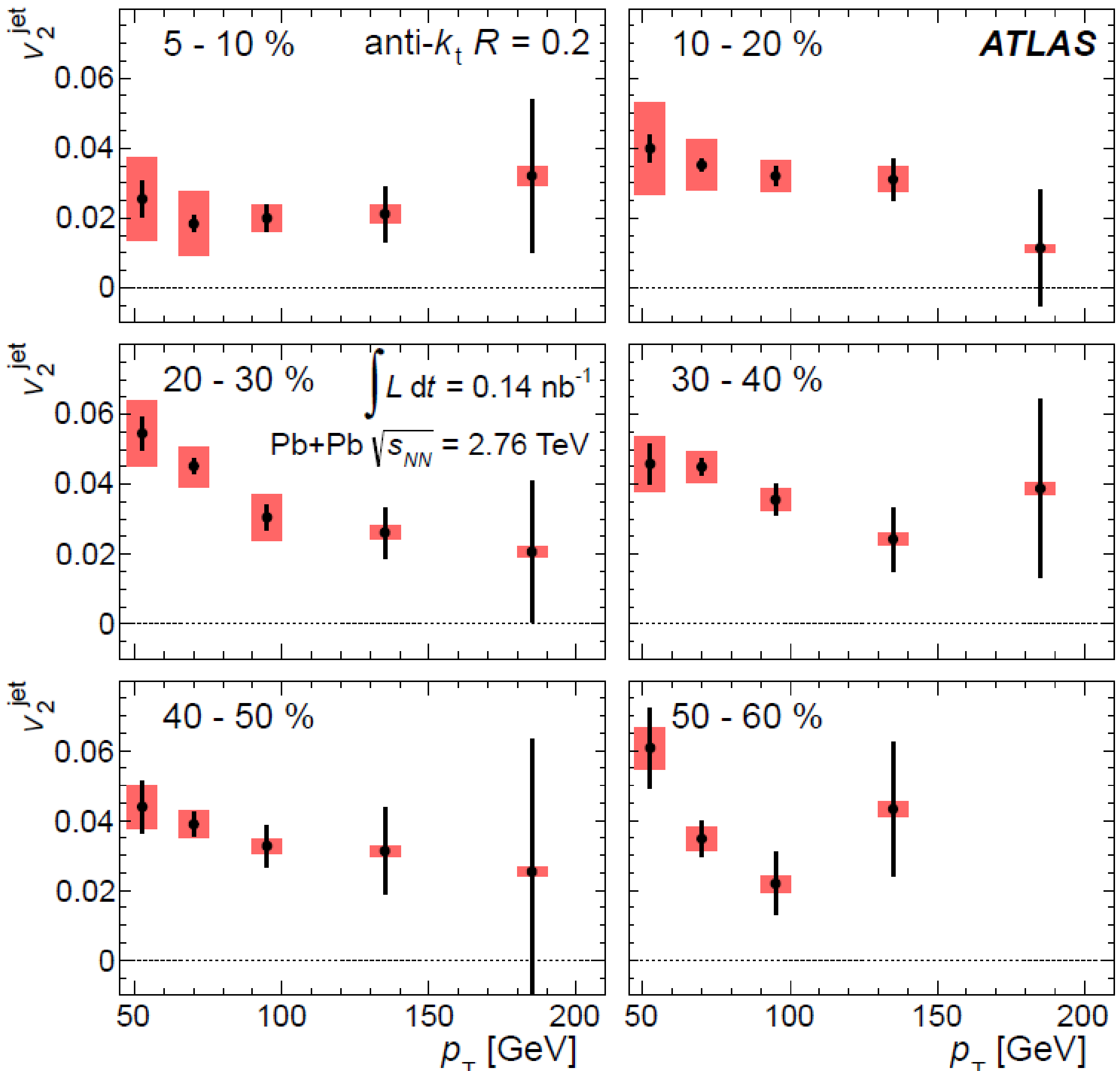
Jet Definition:
HT trigger E_T > 5.5 GeV
constituent p_T^{cut} = 2 GeV/*c*
$|\eta_{jet}| < 0.6$

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 → bias towards unmodified jets largely driven by HT requirement

ATLAS, arXiv:1306.6469 [hep-ex]
Submitted to PRL

Jet v_2 at ATLAS

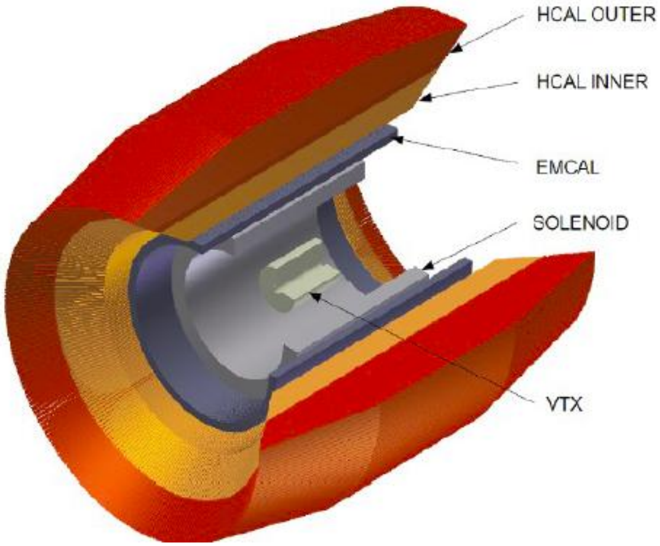


- Jet v_2 measured for $45 < p_T^{jet} < 210$ GeV/c, R = 0.2
- Also observed $v_2^{jet} > 0$
- Different kinematic range and biases than STAR measurement

  → different trend with p_T^{jet}

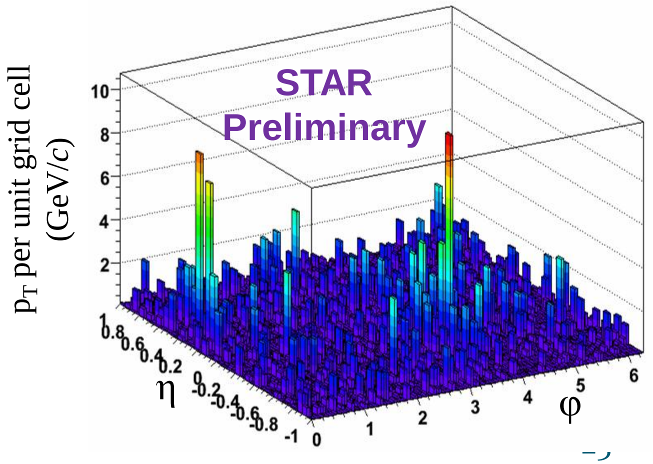
RHIC/LHC Complementarity

- RHIC + LHC can cover a huge kinematic range of jets…
  - ~5-10 GeV γ-jets in PHENIX
  - ~10-40 GeV reconstructed jets in STAR
  - ~30-100 GeV jets in ALICE
  - ~50-350 GeV jets in CMS/ATLAS
- 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 → jets beyond 50 GeV
- sPHENIX upgrade will allow additional reach



Conclusions & Final Thoughts

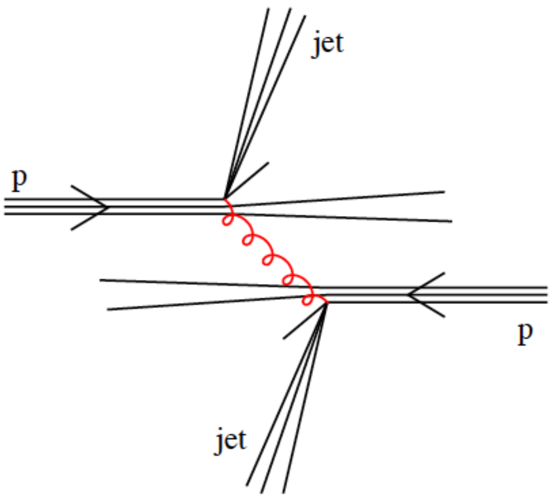
- Complementary analyses demonstrate jet quenching at RHIC & LHC
  - Softening and broadening of jets which traverse the medium in heavy ion collisions compared to p+p collisions
- It is necessary to understand biases present in analyses
  - At RHIC energies, a p_T > 4 GeV/*c* hadron requirement selects 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

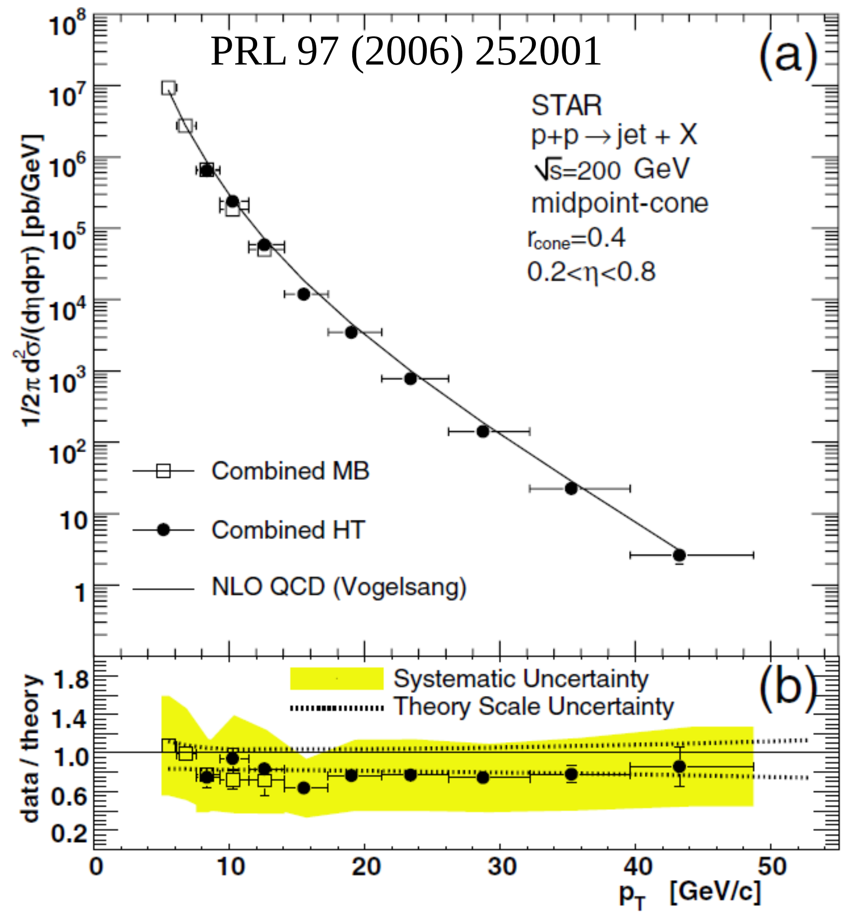
Jets

- 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

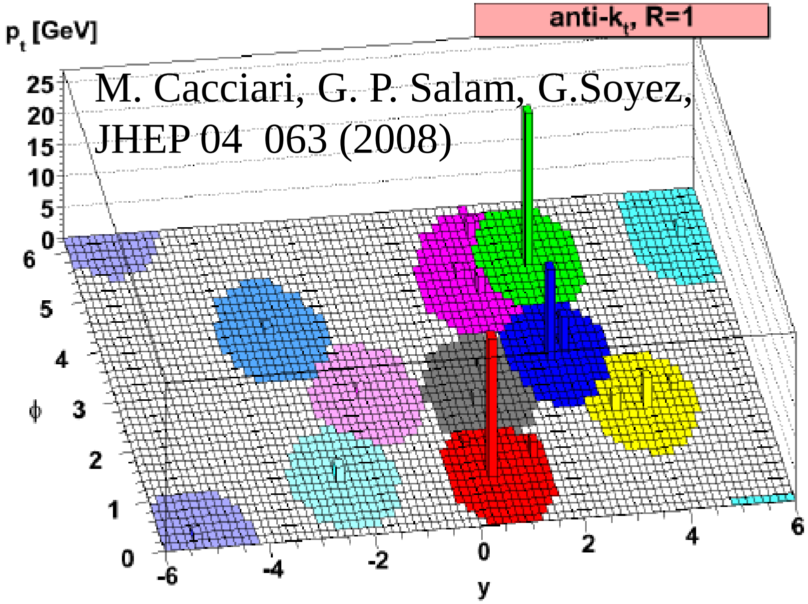


Jet Reconstruction

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

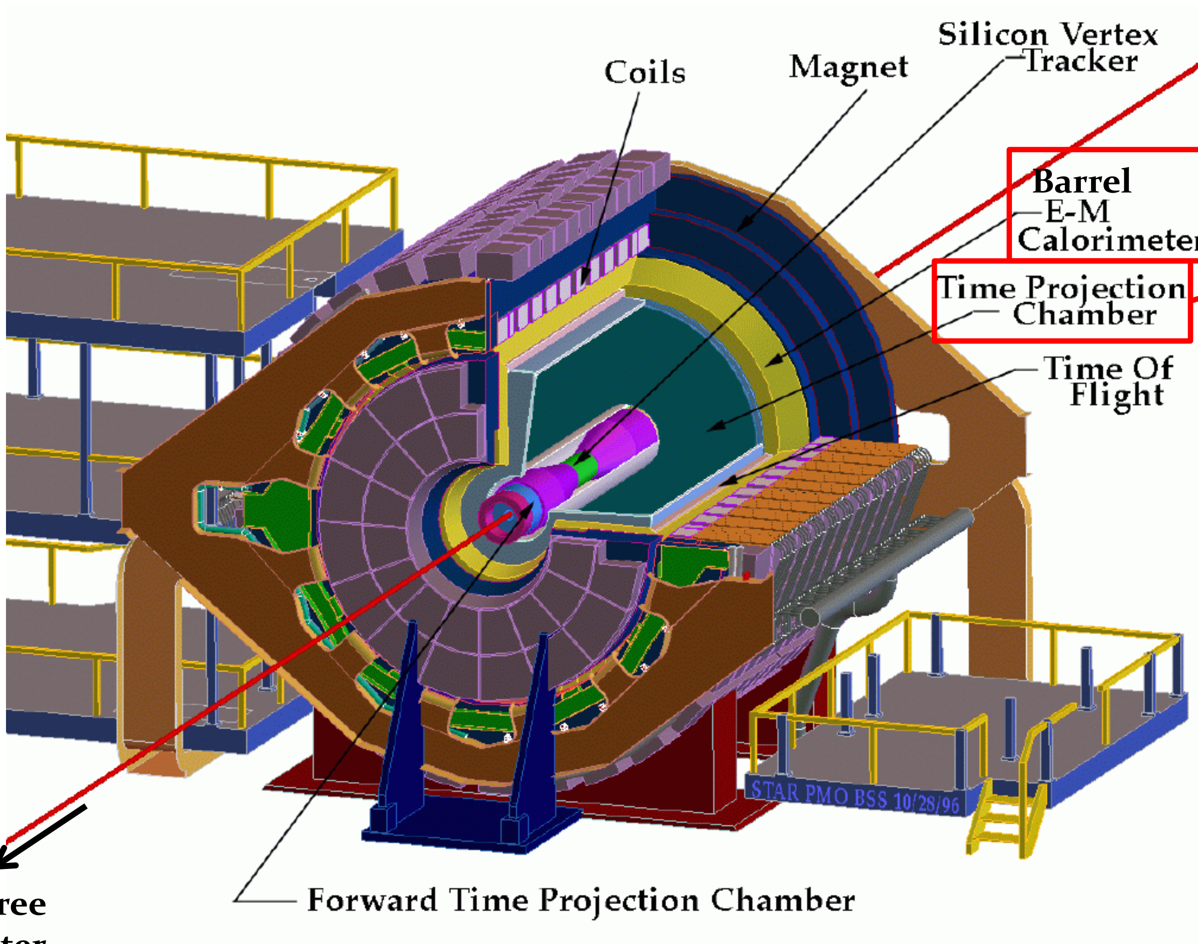
$$d_{ij} = \min(1/p_{Ti}^2, 1/p_{Tj}^2)((\Delta y)_{ij}^2+(\Delta\varphi)_{ij}^2)/R^2$$

  - 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



M. Cacciari, G. P. Salam, G.Soyez, JHEP 04 063 (2008)

STAR (Solenoidal Tracker at RHIC)



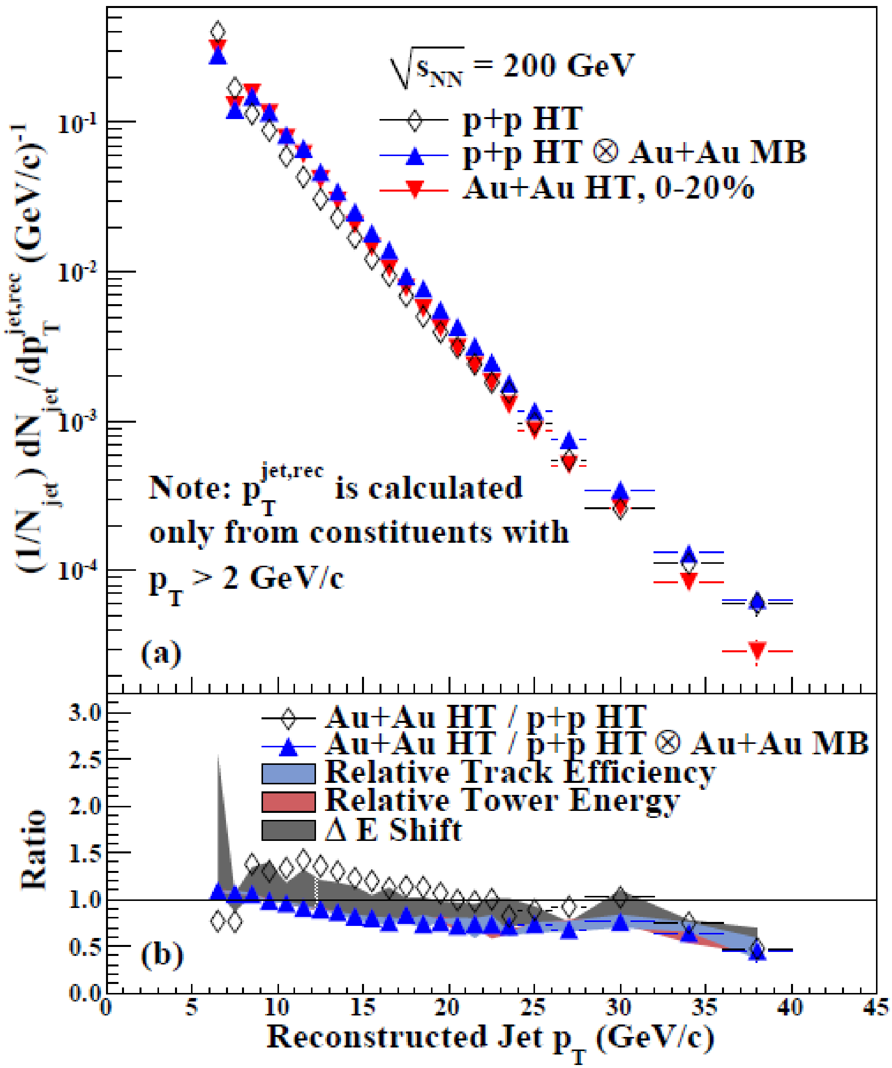
Zero Degree Calorimeter

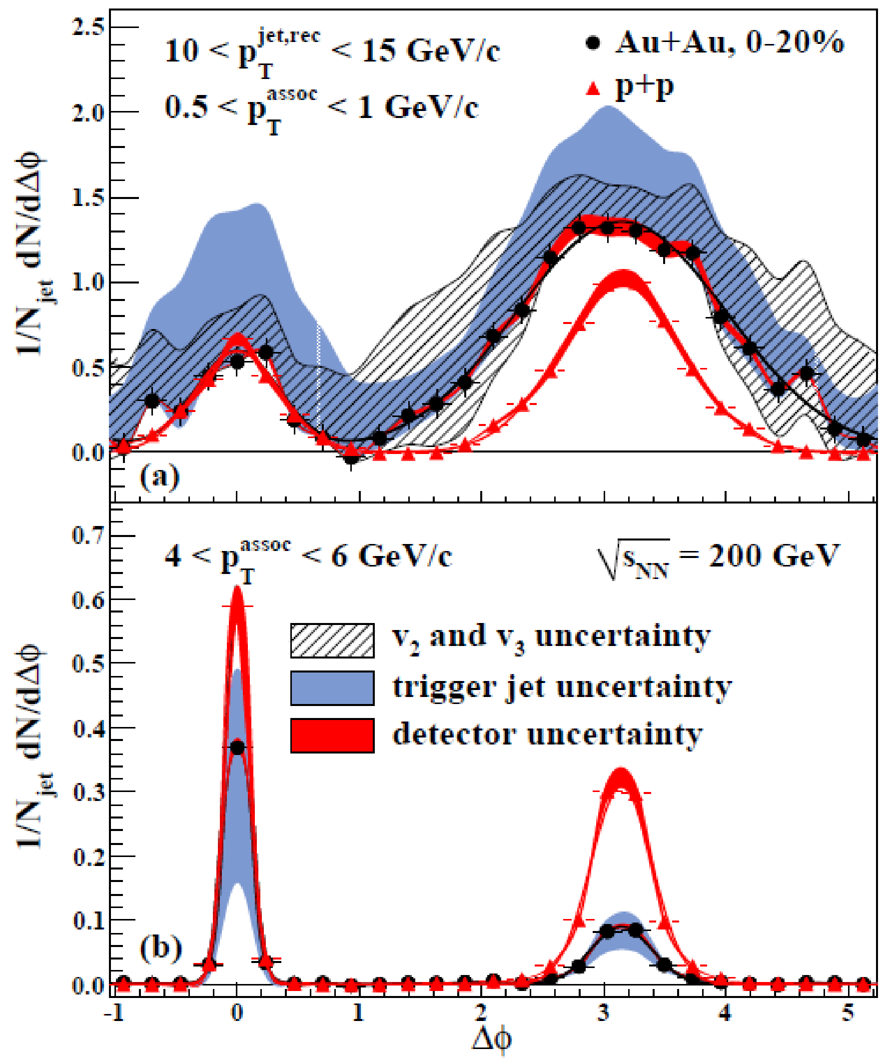
neutral energy detection

charged particle tracking & PID

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

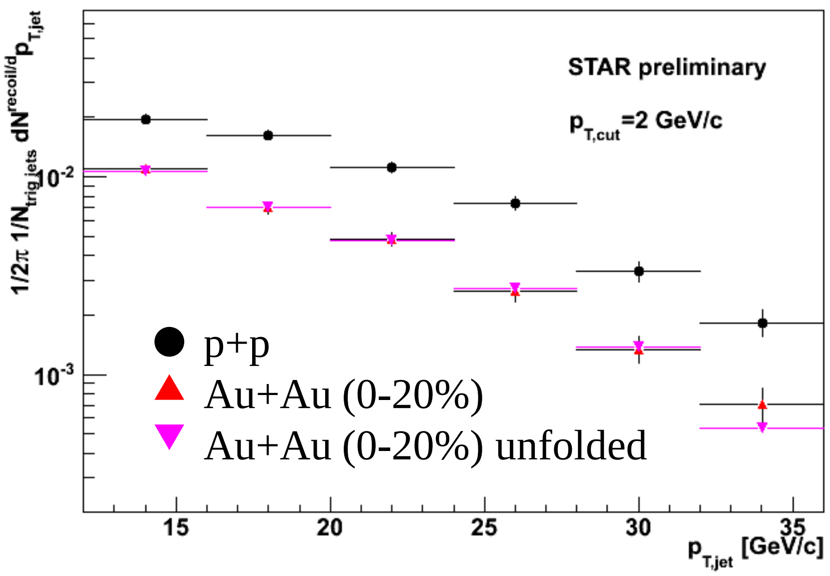
Jet-Hadron correlations





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



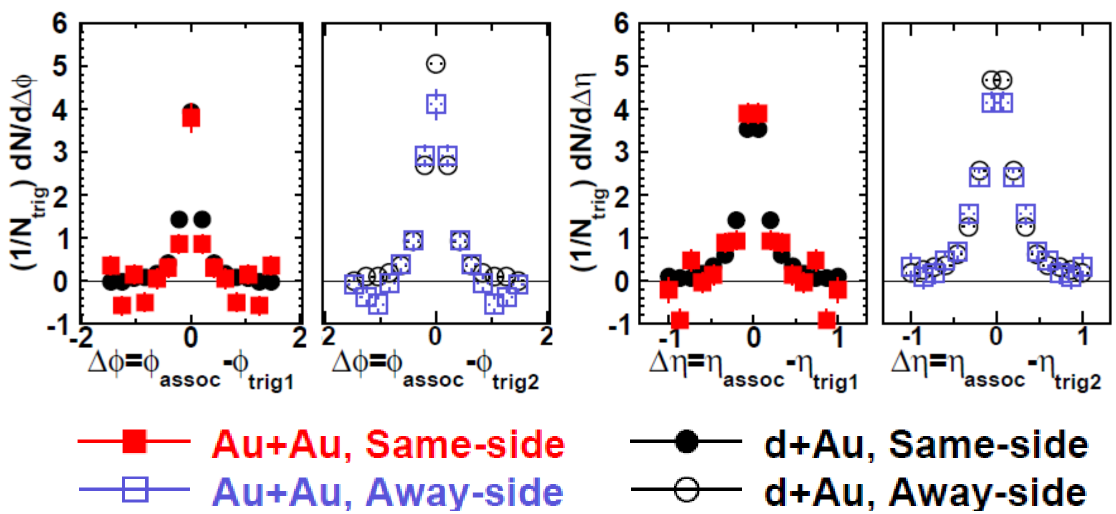
Trigger Jet:
R = 0.4
$p_{T,cut} = 2$ GeV/c
$p_T^{jet} > 20$ GeV/c

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

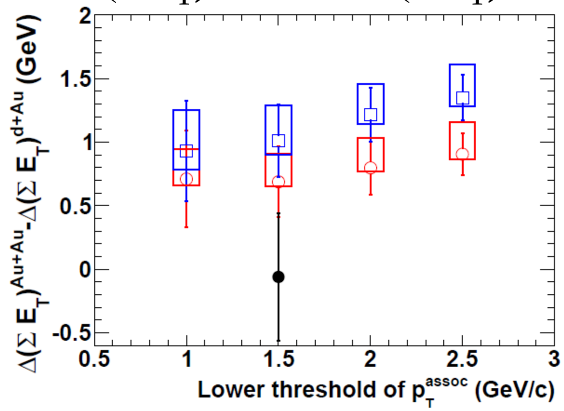
- Suppression of recoil jet in Au+Au
- Due to softening and/or broadening outside of jet cone
- Consistency between correlations and inclusive measurements.

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

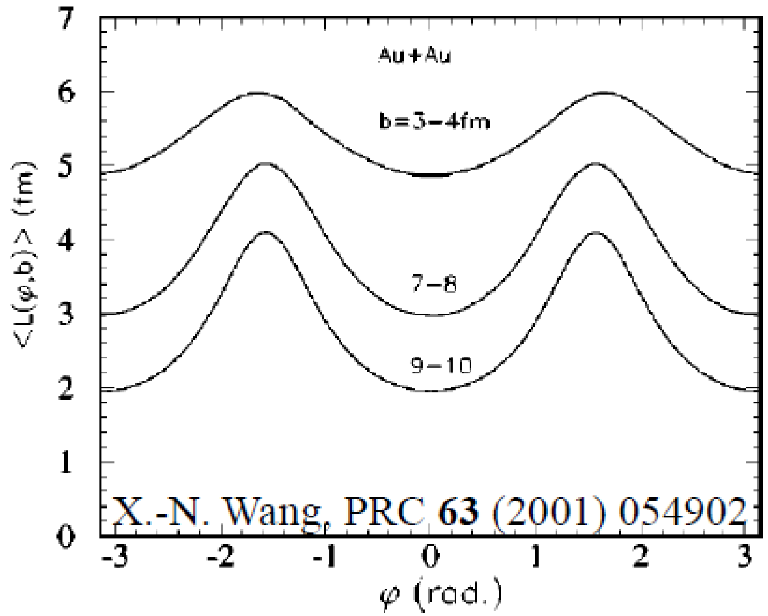
- Dijet imbalance indicates slight softening of awayside peak
- Still no significant shape difference between near- and away-sides, or between Au+Au and d+Au.
- Compare/contrast to dihadron and jet-hadron results.

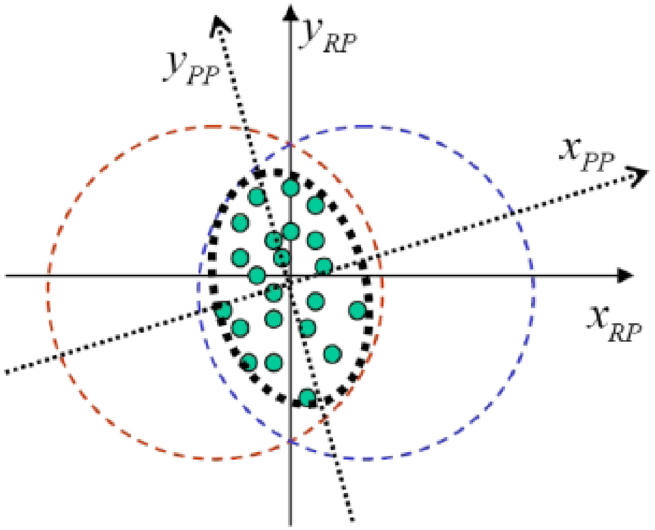
What is jet v_2?

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.





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

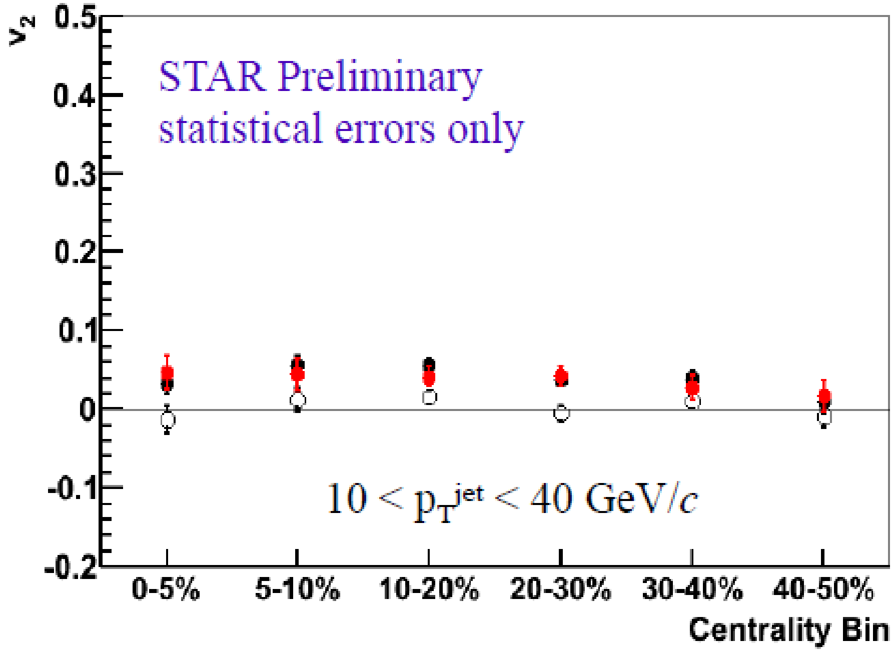
Artificial Sources of Anisotropy

- **Background Fluctuations and the Jet Energy Scale**
  Background particles (with $p_T > 2$ GeV/c) with significant v_2 are more likely to be clustered into the jet cone in-plane versus out-of-plane
  → more low-p_T jets reconstructed with a higher p_T
  → increased number of in-plane jets in a fixed reconstructed jet p_T range

- **Biased Event Plane**
  Jet fragments included in event plane calculation
  → event plane pulled towards jet

Background Fluctuations

- Embed p+p HT jets isotropically into Au+Au minimum bias events
- Reconstruct p_T of p+p jet before and after embedding
- Correlate reconstructed jet axis with event plane of Au+Au event
- Calculate jet v_2 for a given range in jet p_T

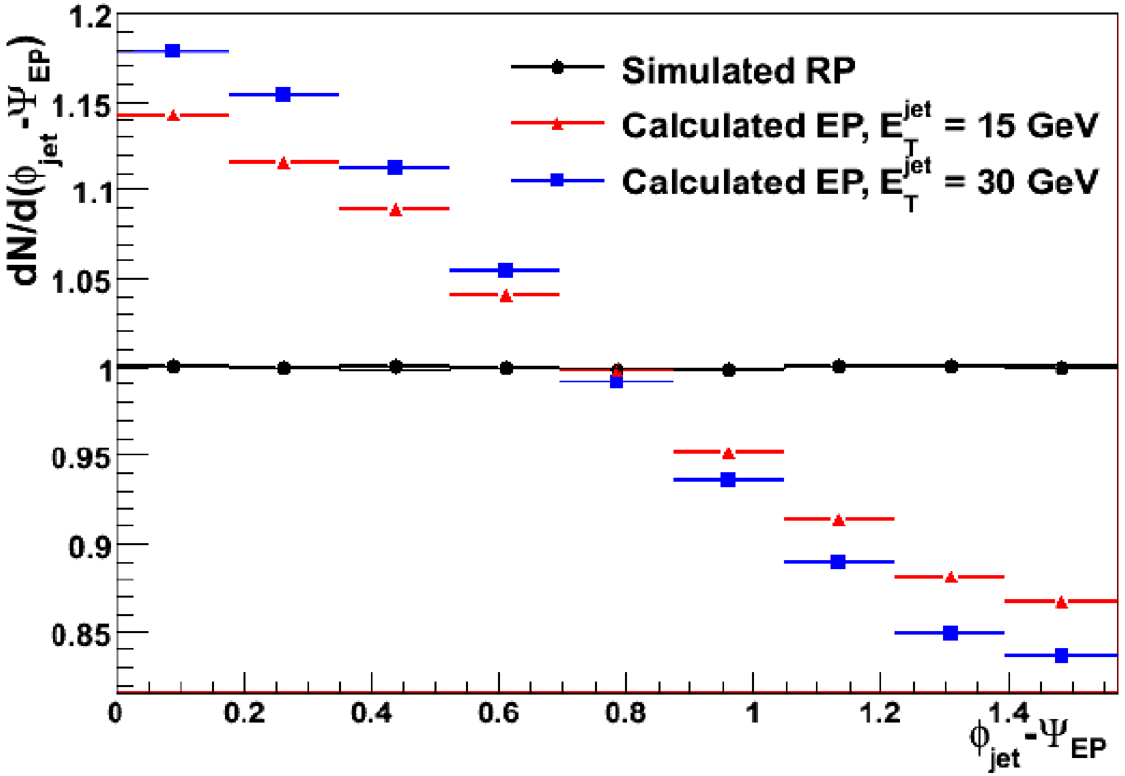


Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- ○ jet p_T calculated before embedding
- ● jet p_T calculated after embedding
- ● difference

- Artificial jet v_2 caused by background fluctuations is ~ 4%
- Subtract from measured jet v_2 values.

Jet - Event Plane bias

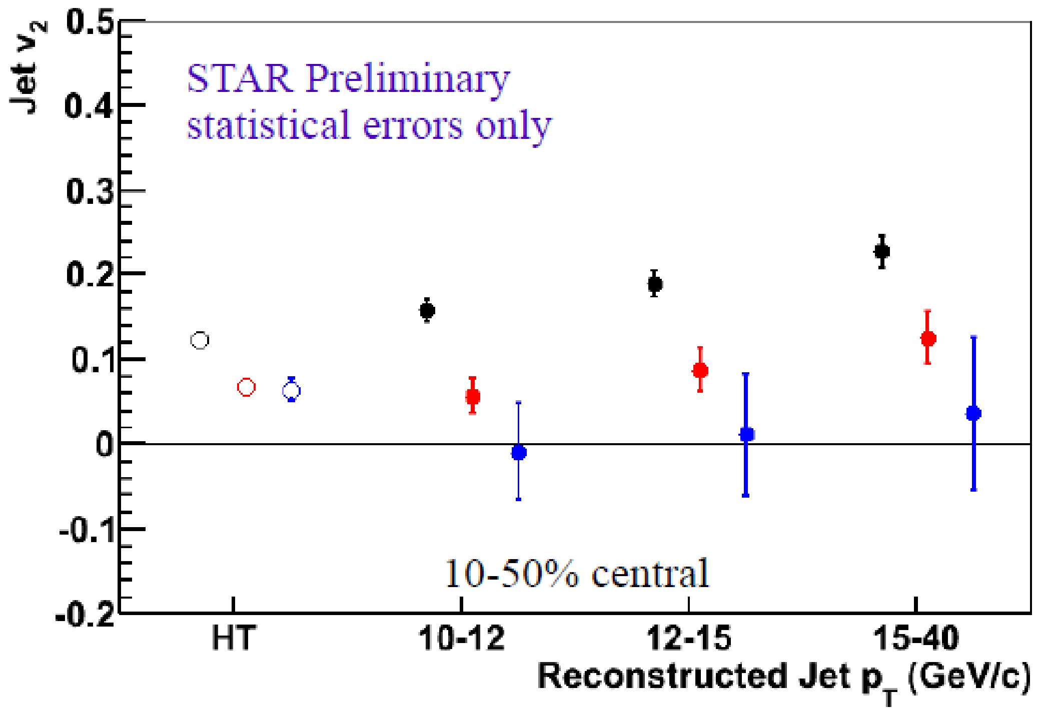


Simulation:
PYTHIA jets embedded in thermal background

- Calculating the event plane at mid-rapidity leads to significant jet – event plane bias!

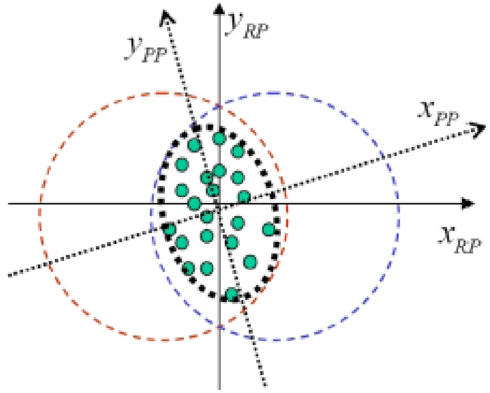
- Need to determine event plane at forward rapidities to measure jet v_2 at mid-rapidity...

Jet v_2 vs. Reconstructed Jet p_T



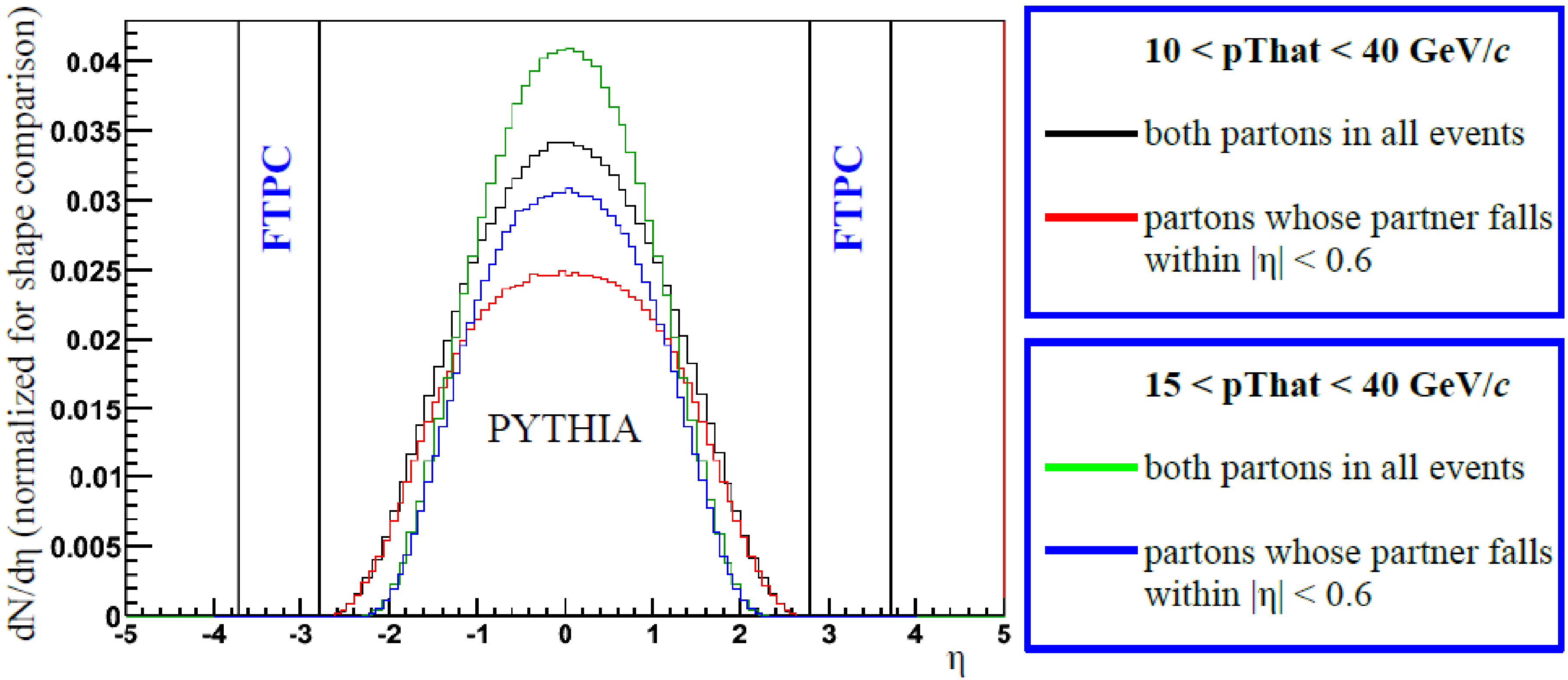
Jet Definition:
HT trigger E_T > 5.5 GeV
constituent p_T^{cut} = 2 GeV/c

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



- Jet v_2{FTPC} increases slightly with jet p_T
- Jet v_2{FTPC} > Jet v_2{ZDC-SMD}
  → In single-particle v_2 measurements, this difference is attributed to flow in participant plane vs. reaction plane, v_2(PP) > v_2(RP)
  → Jet energy loss sensitive to geometry in participant frame?

Does the recoil jet hit the FTPC?



- For pThat > 10 GeV/*c*, in 2M events, < 10 partons point towards the η region covered by the FTPC
- For pThat > 15 GeV/*c*, in 2M events, 0 partons point towards the η region covered by the FTPC