Studies of Jets through Correlations in Heavy Ion Collisions at RHIC

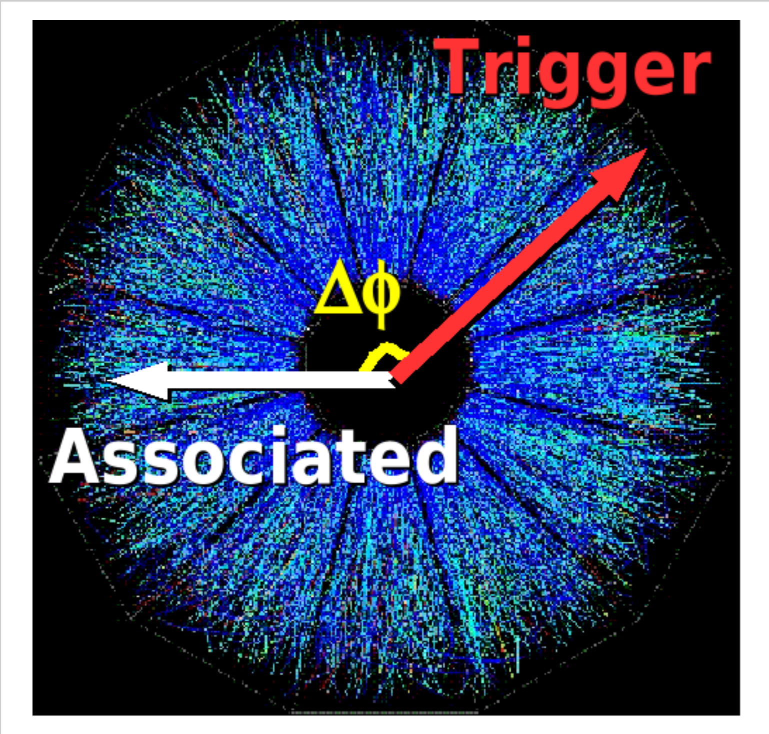
Christine Nattrass
Yale University

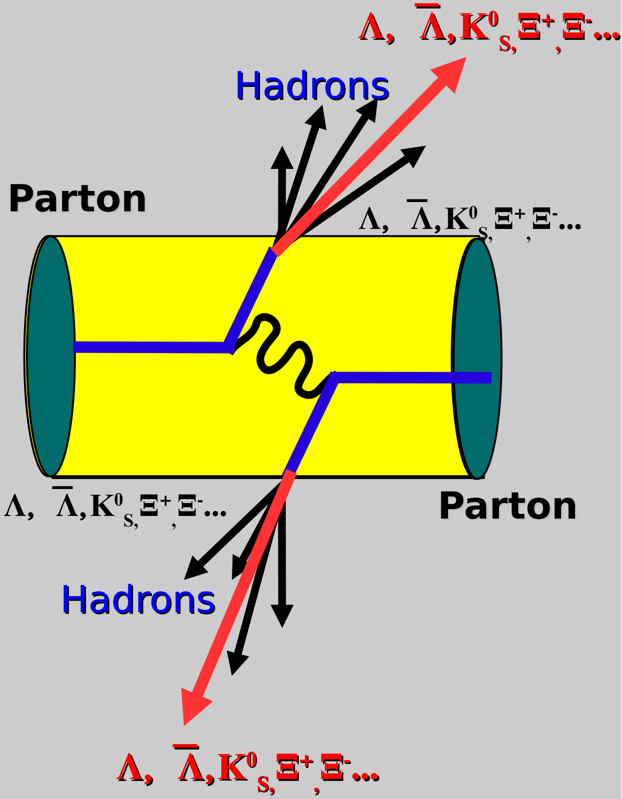
Introduction

- Why study jets in heavy ion collisions?
- The near-side
- The away-side
- Conclusions

Why study jets in heavy ion collisions?

- Hard parton scattering ⇒ back-to-back jets
  - Good (calibrated?) probe of the medium
- High multiplicity in A+A collisions
  - Individual jets cannot be reconstructed
  - Study jets via correlations of particles in space
    - •both azimuth and pseudorapidity





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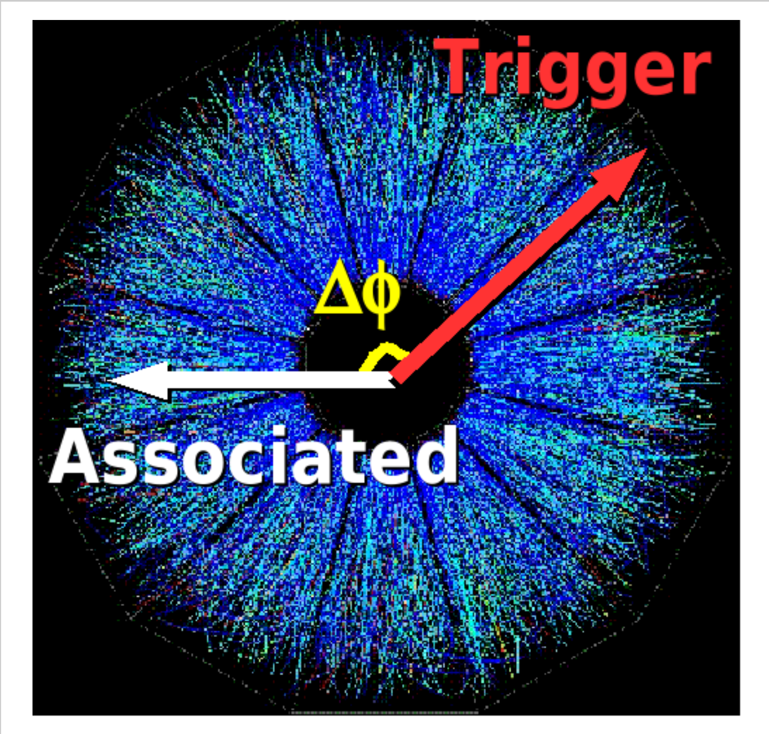

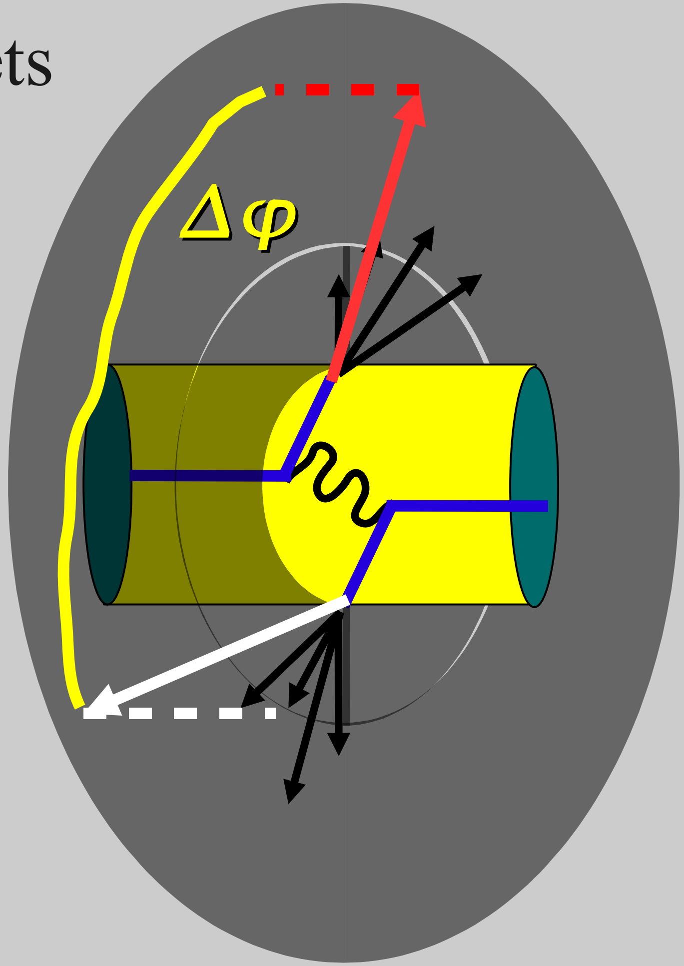

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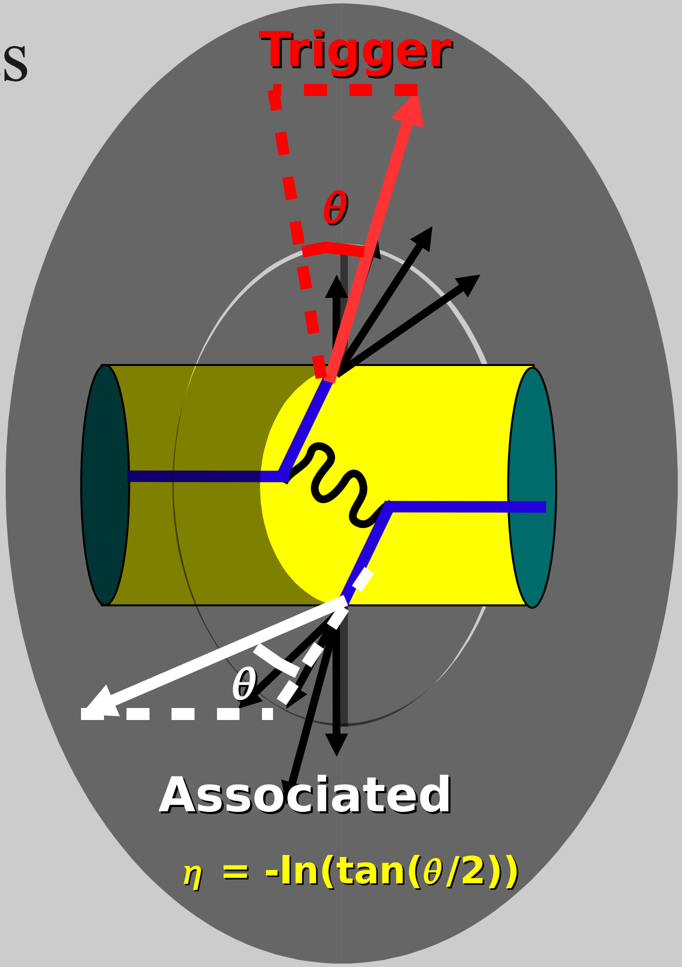
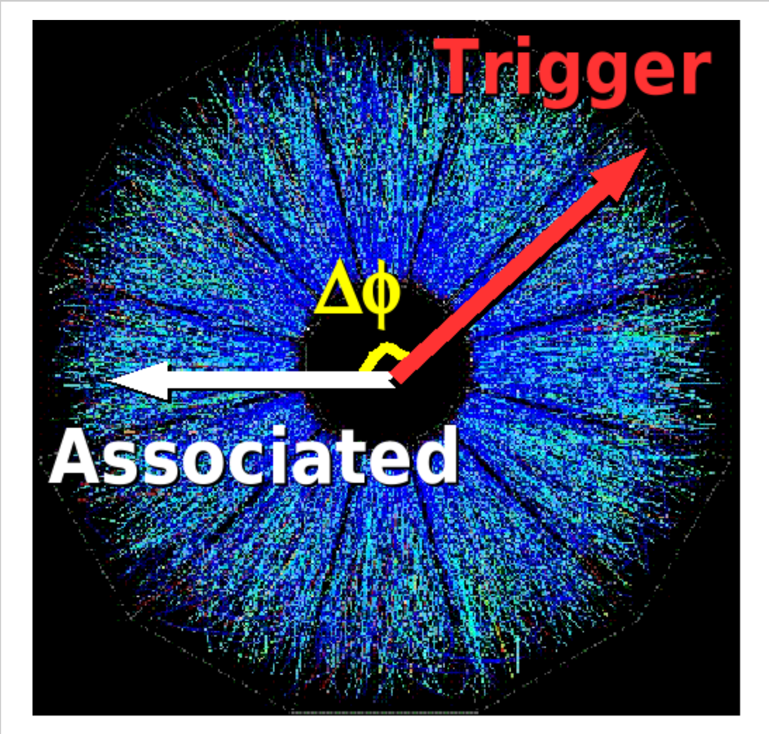
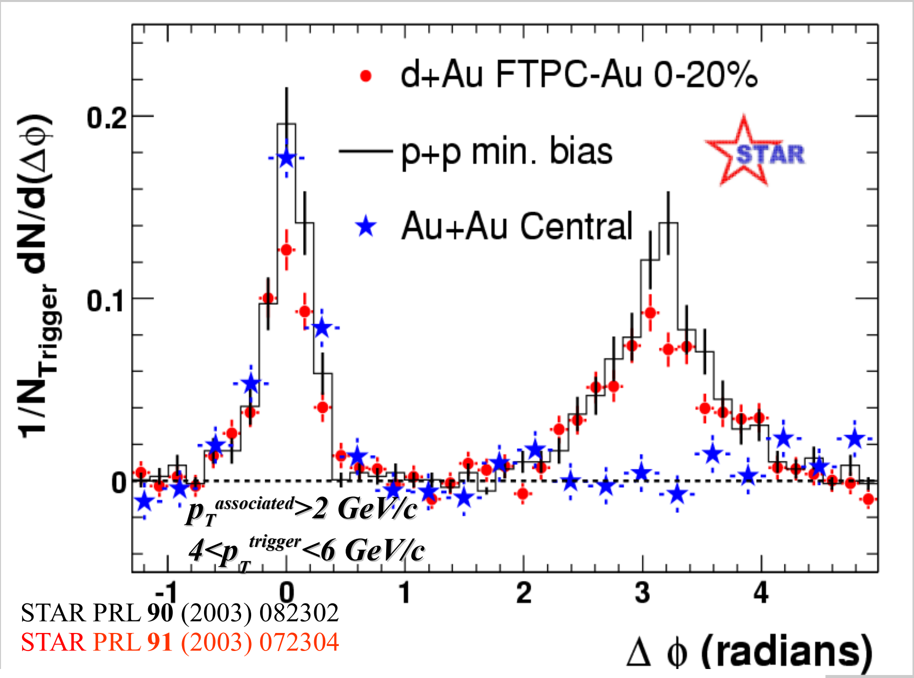
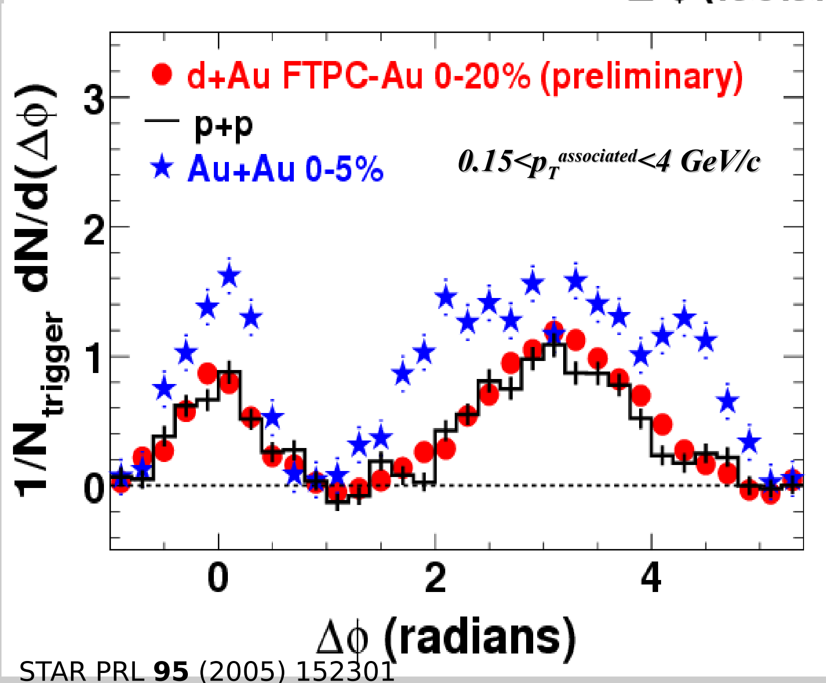




Motivation

- Initial studies showed suppression of away-side peak in A+A collisions
  - 2.0 GeV/c < $p_T^{associated}$
- Inclusive $p_T^{associated}$
  - reappearance of away-side
  - more complex structure than d+Au, p+p

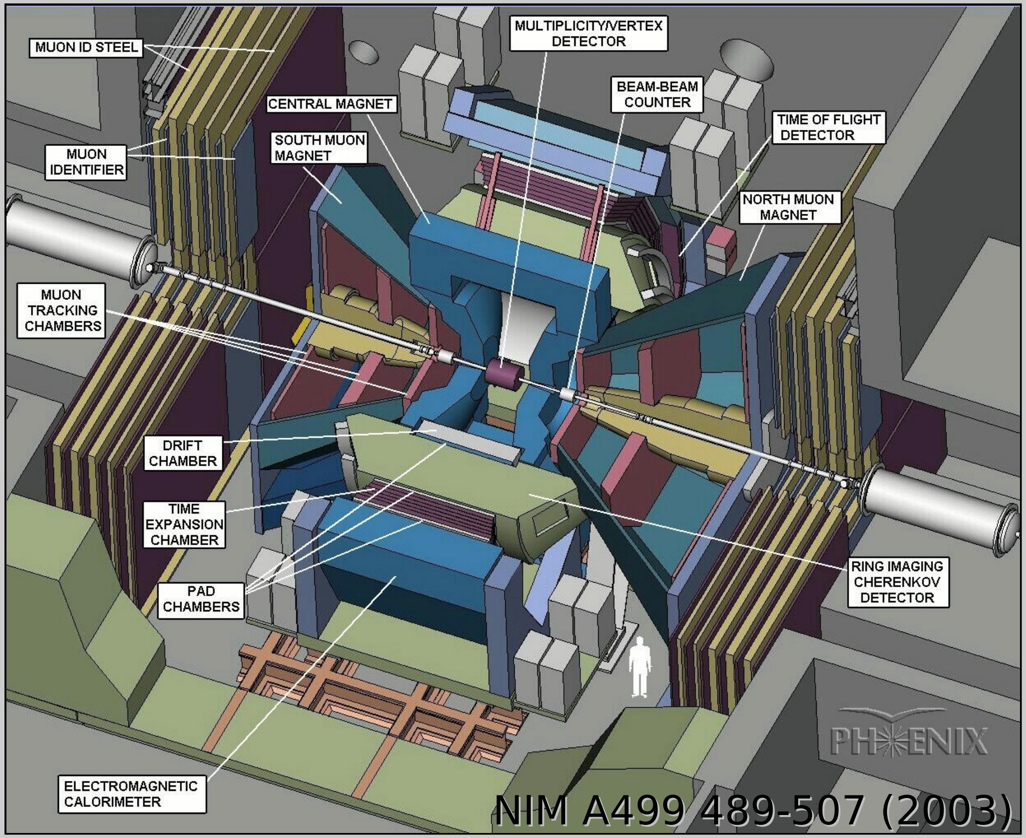


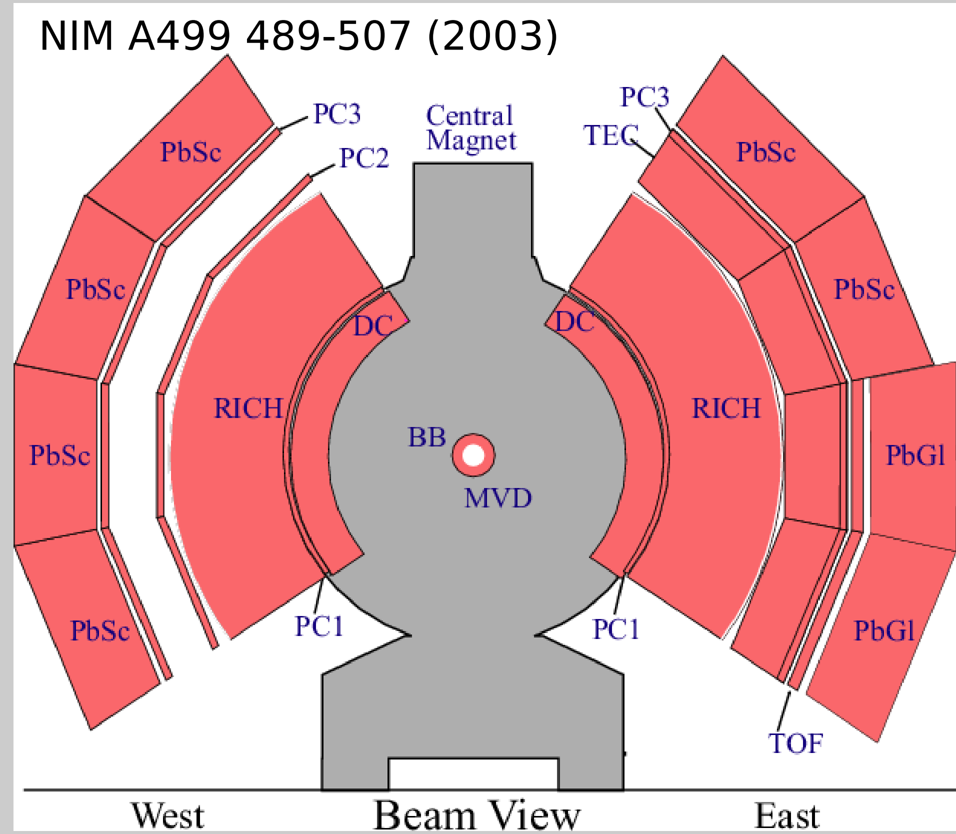


RHIC

- Luminosity $\sim 2 \cdot 10^{6}\ cm^{-2}s^{-1}$
- Can collide multiple species (Au+Au, Cu+Cu, d+Au, p+p...)
- Interaction diamond <20 cm long
- 56 bunches
- 10^{9} ions/bunch
- nominal 10 hour store time

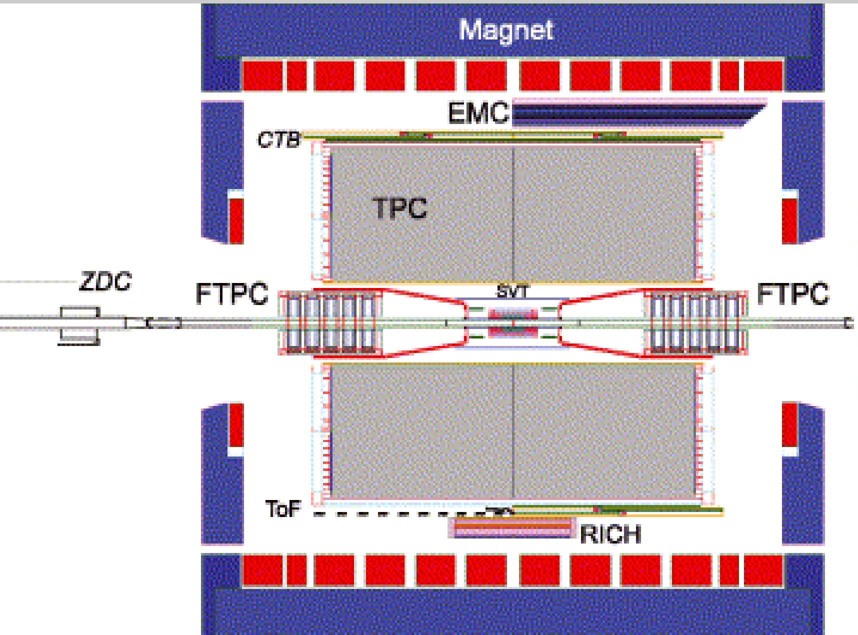
PHENIX



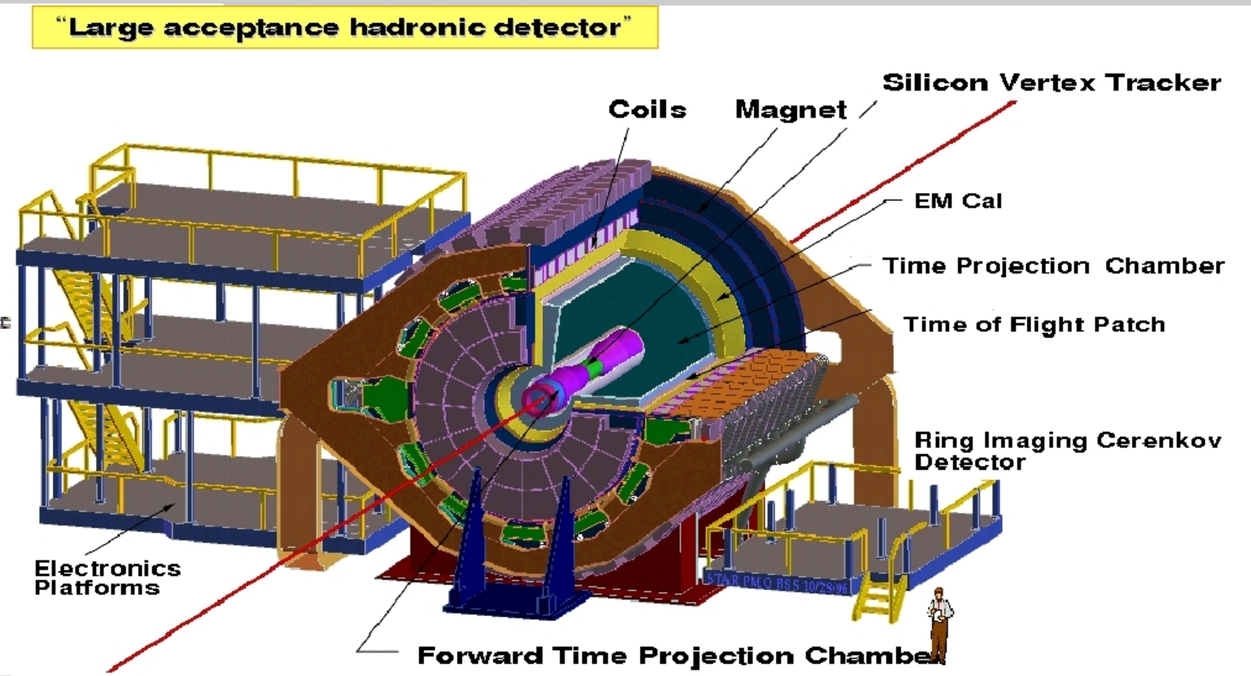


- Primary Detectors: Drift chambers, time expansion chambers, pad chambers, vertex detector
- Azimuthal coverage: Two sections of $0<\varphi<\pi/2$
- Pseudorapidity coverage: $-0.35<\eta<0.35$

STAR



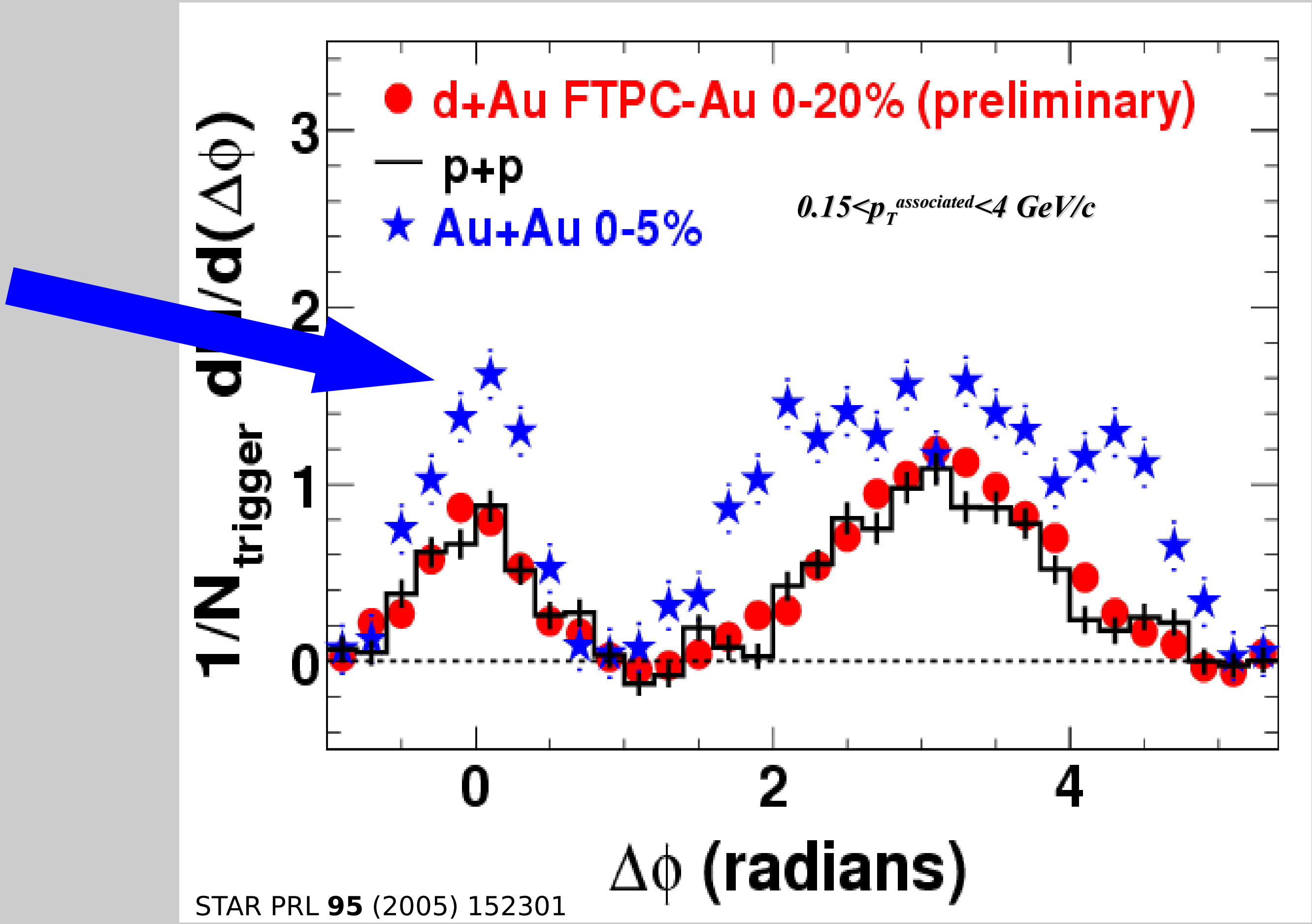
Nucl. Instrum. Meth. A 499 (2003) 624



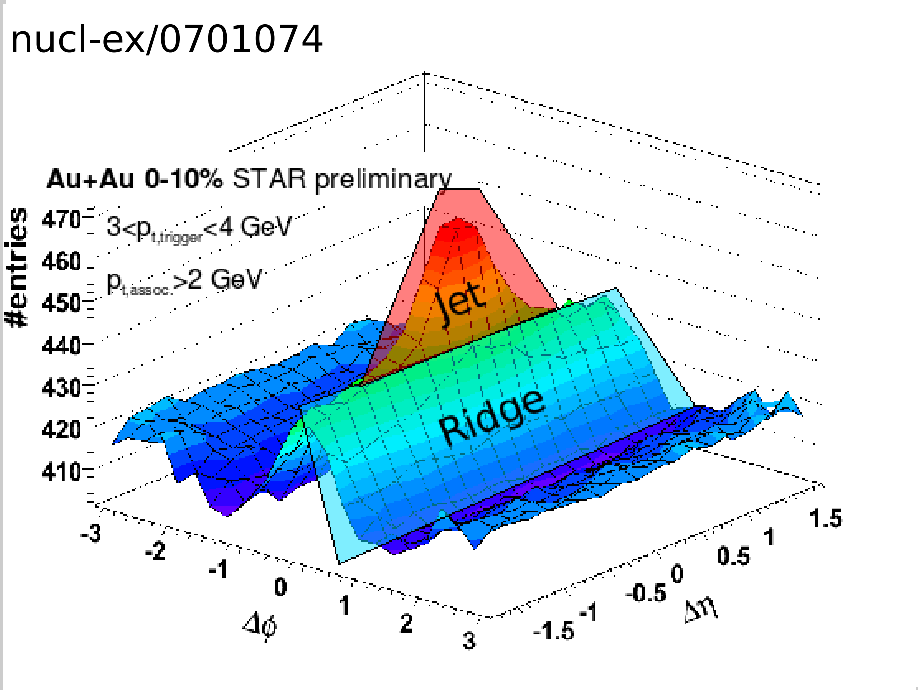
- Primary Detector: TPC
- Full azimuthal coverage: $0<\varphi<2\pi$
- Pseudorapidity coverage: $-1<\eta<1$

Near-side: Motivation

- Near-side shows modification
- Excess yield in Au+Au relative to p+p



Near-side: Motivation

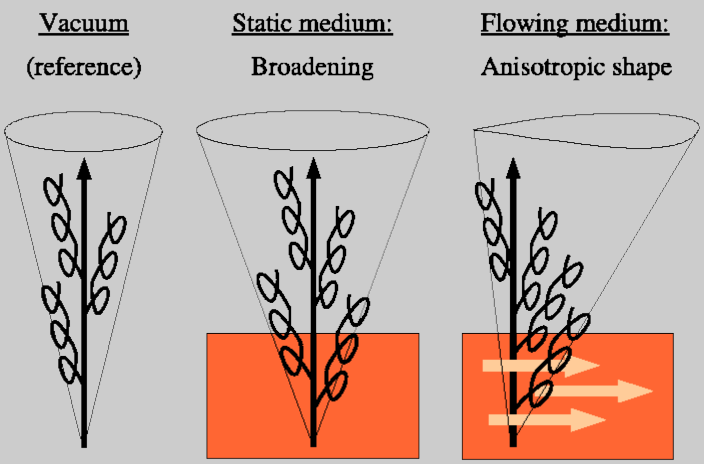


No v_2 subtraction – signal visible above v_2

- Long-range pseudorapidity ($\Delta\eta$) correlations observed by STAR in Au+Au at intermediate p_T
- Near side jet peak sits on plateau (*Ridge*)
  - Significant contribution to the near-side yield in central Au+Au

Near-side: Ridge production mechanisms

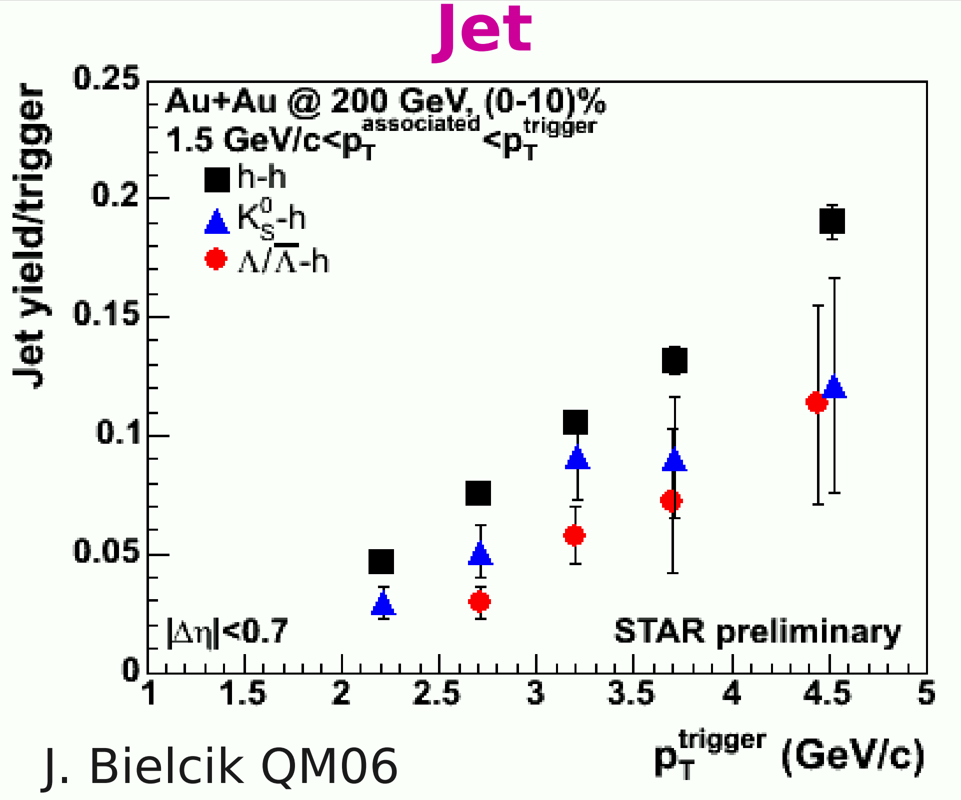
- Parton radiates energy before fragmenting and couples to the longitudinal flow
  - gluon bremsstrahlung of hard-scattered parton
  - parton shifted to lower p_T
  - radiated gluon contributes to broadening

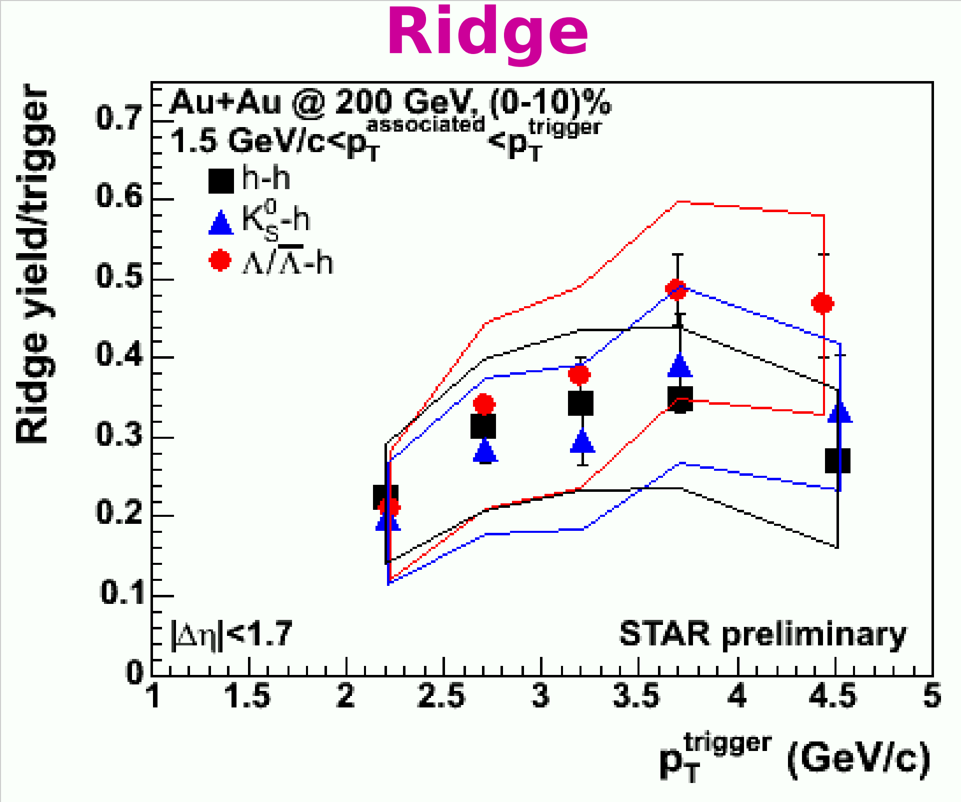


Armesto et al, PRL 93 (2004), nucl-ex/0405301

- Medium heating + parton recombination (Chiu & Hwa, Phys. Rev. C72:034903,2005)
  - Recombination of thermal partons only indirectly affected by hard scattering, not part of the jet
- Radial flow + trigger bias (Voloshin nucl-th/0312065, S. A. Voloshin, Nucl. Phys. A749,287 (2005))

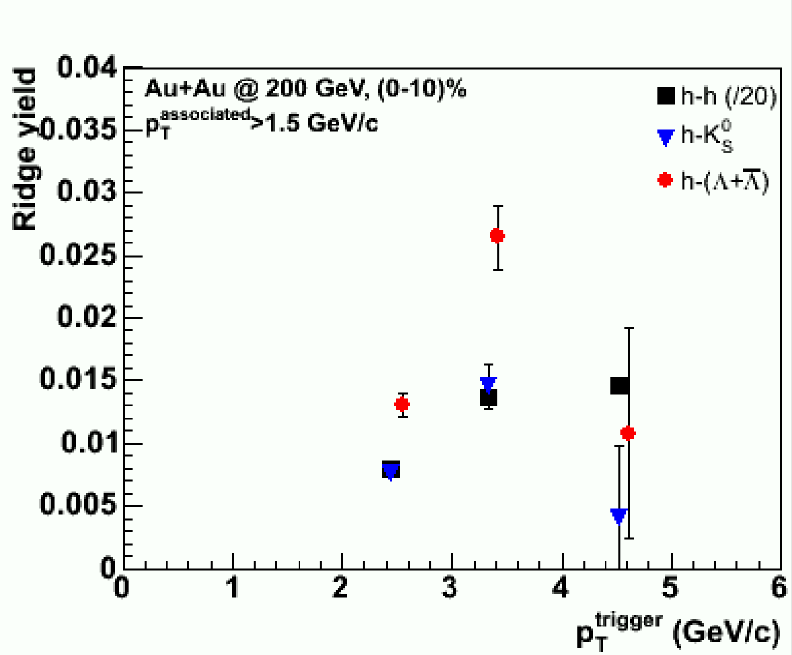
pT trigger dependence of Jet *and* Ridge



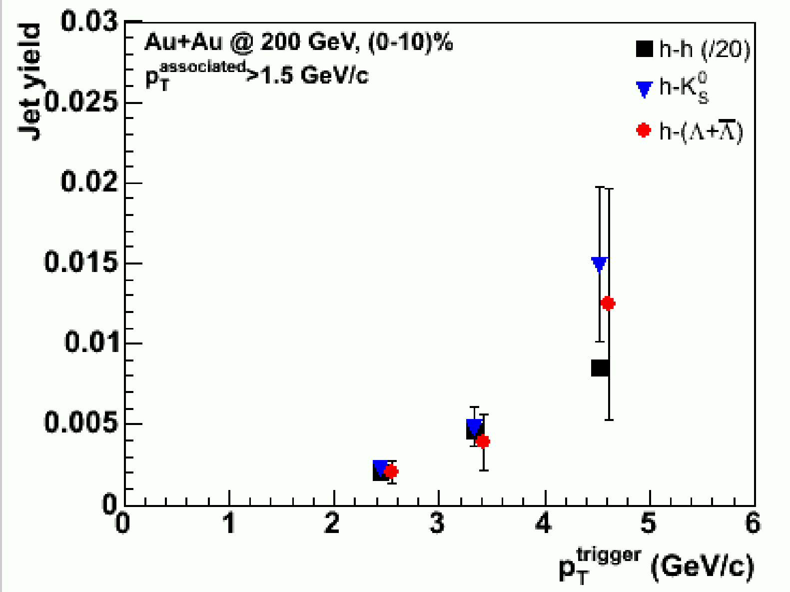


- *Jet* yield per trigger increases with $p_T^{trigger}$
- Expected because higher $p_T^{trigger}$ should be "jettier"
- *Ridge* yield decreases
- *Ridge* dominant in central Au+Au

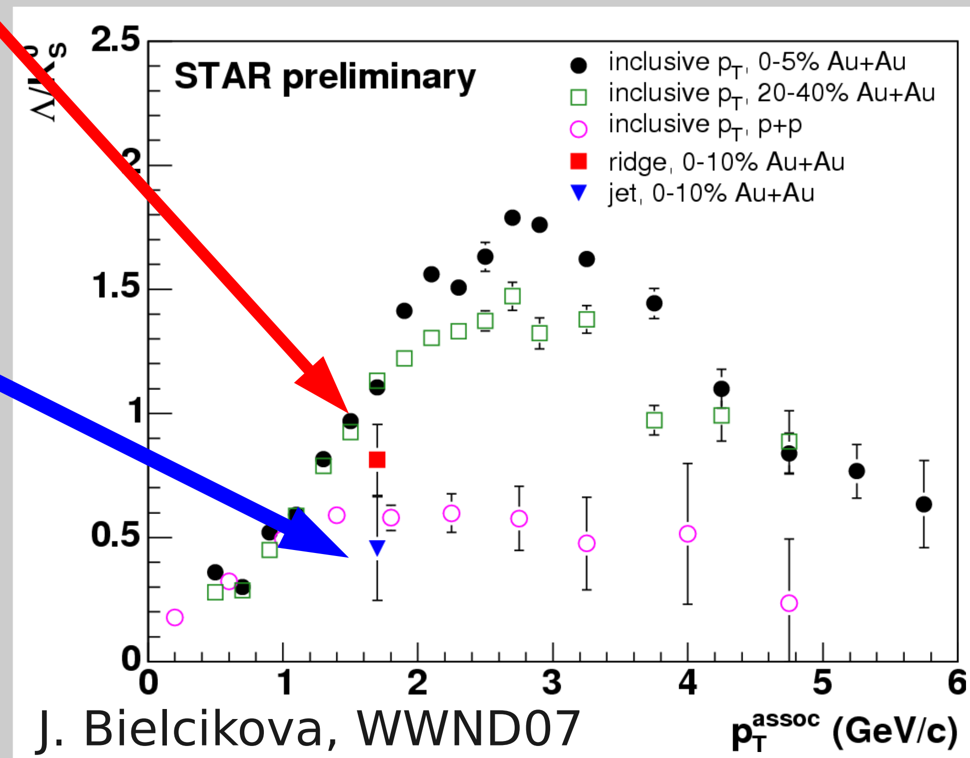
Near-side: particle dependence



J. Bielcikova, WWND07



- Identified particles show similar yield trends to unidentified
- Particle ratios in *Ridge* closer to bulk than those in the *Jet*

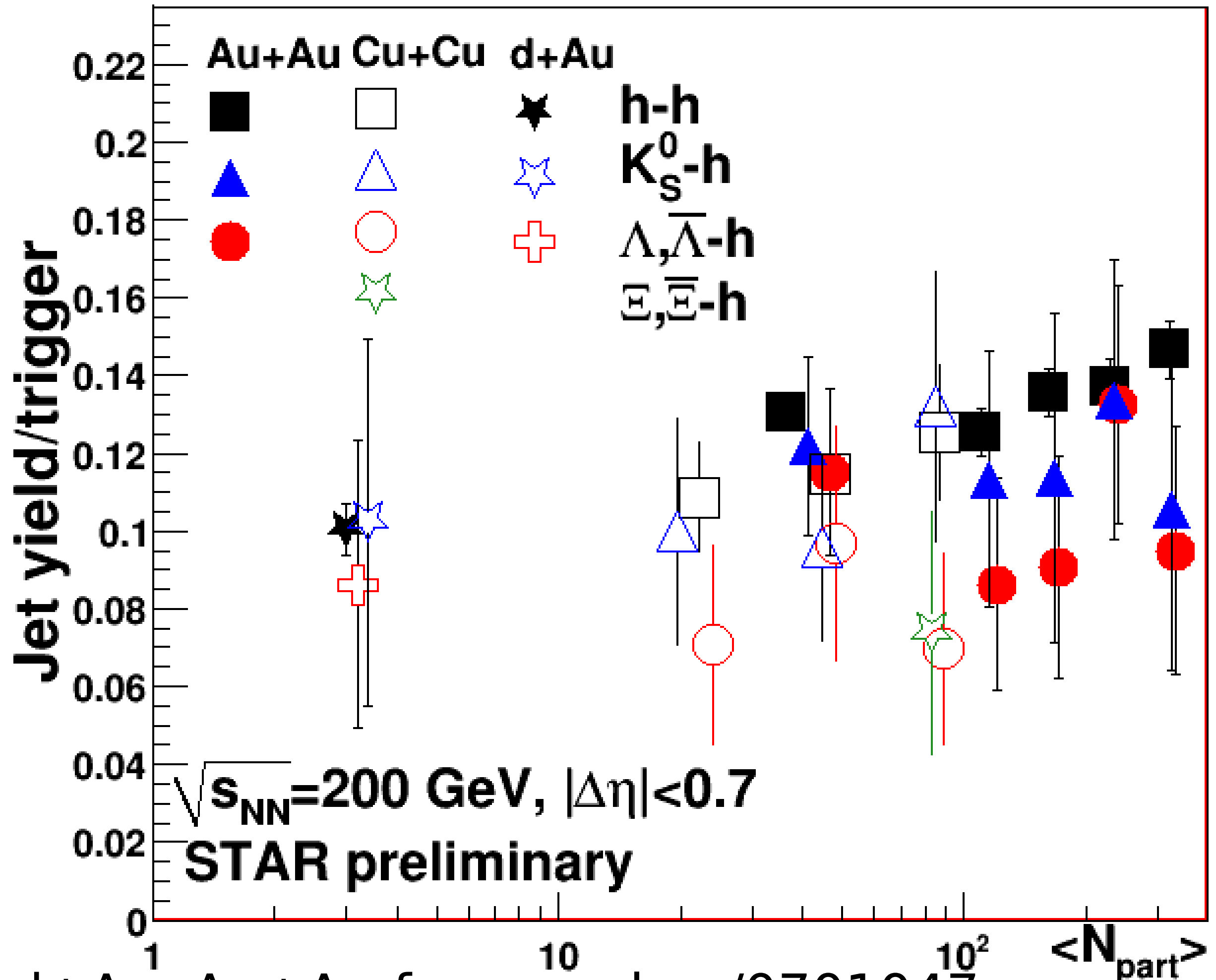


Near-side Yield vs N_{part} Cu+Cu vs Au+Au

Identified triggers:

- *Jet* yield
  - Nearly flat with N_{part} within errors across d+Au, Cu+Cu, Au+Au
  - No v_2 or background error due to method
  - No trigger dependence within errors
- *Ridge* yield
  - No *Ridge* within errors in d+Au
  - Rises with N_{part} in Cu+Cu and Au+Au
  - No trigger dependence within errors

3.0 GeV/c < $p_T^{trigger}$ 6.0 GeV/c; 1.5 GeV/c < $p_T^{associated}$ < $p_T^{trigger}$
C. Nattrass SQM07



d+Au, Au+Au from nucl-ex/0701047

Data points at same N_{part} offset for visibility
Jet yields: 10% error added to V^0 and h triggers to account for track merging, 15% to Ξ triggers

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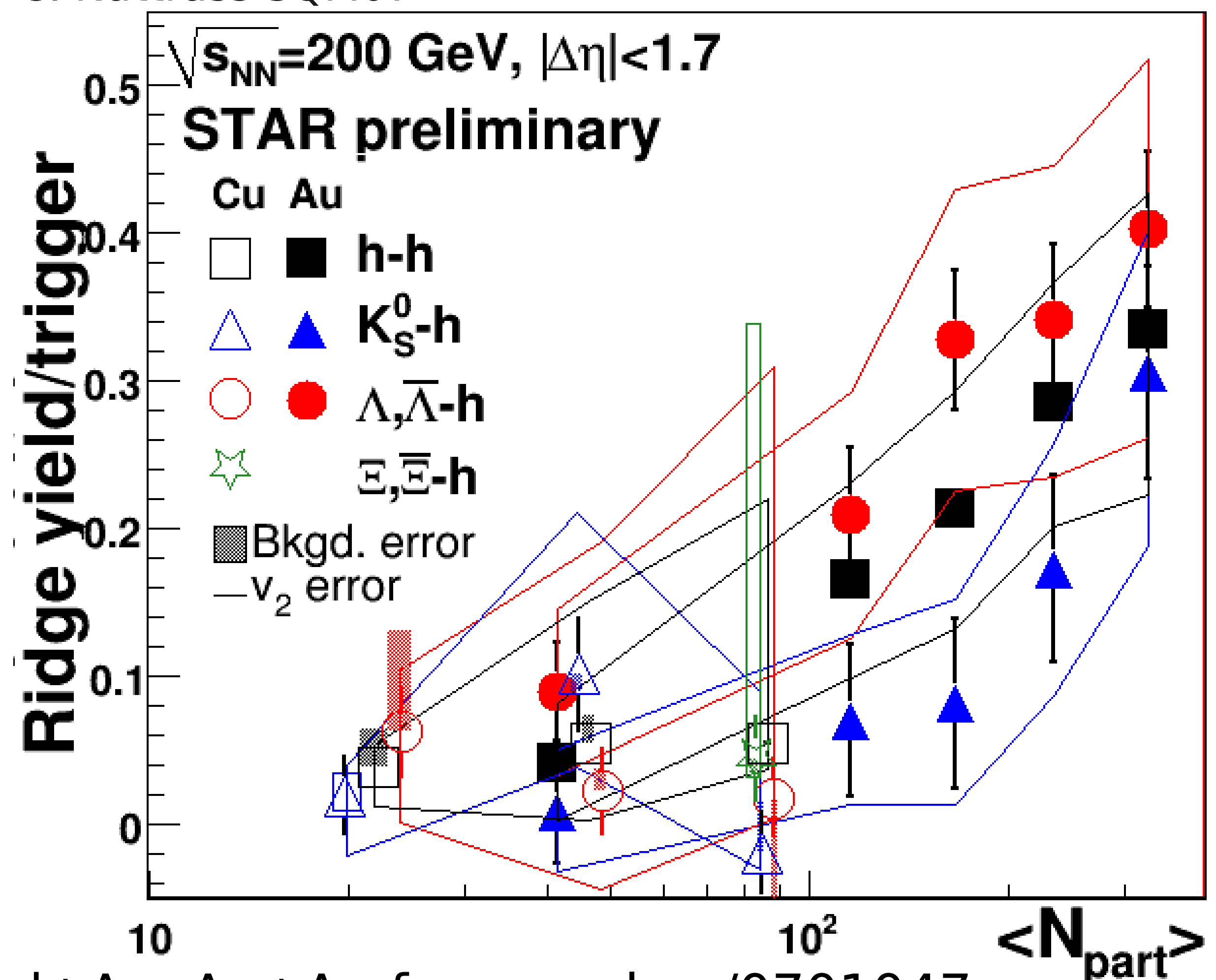

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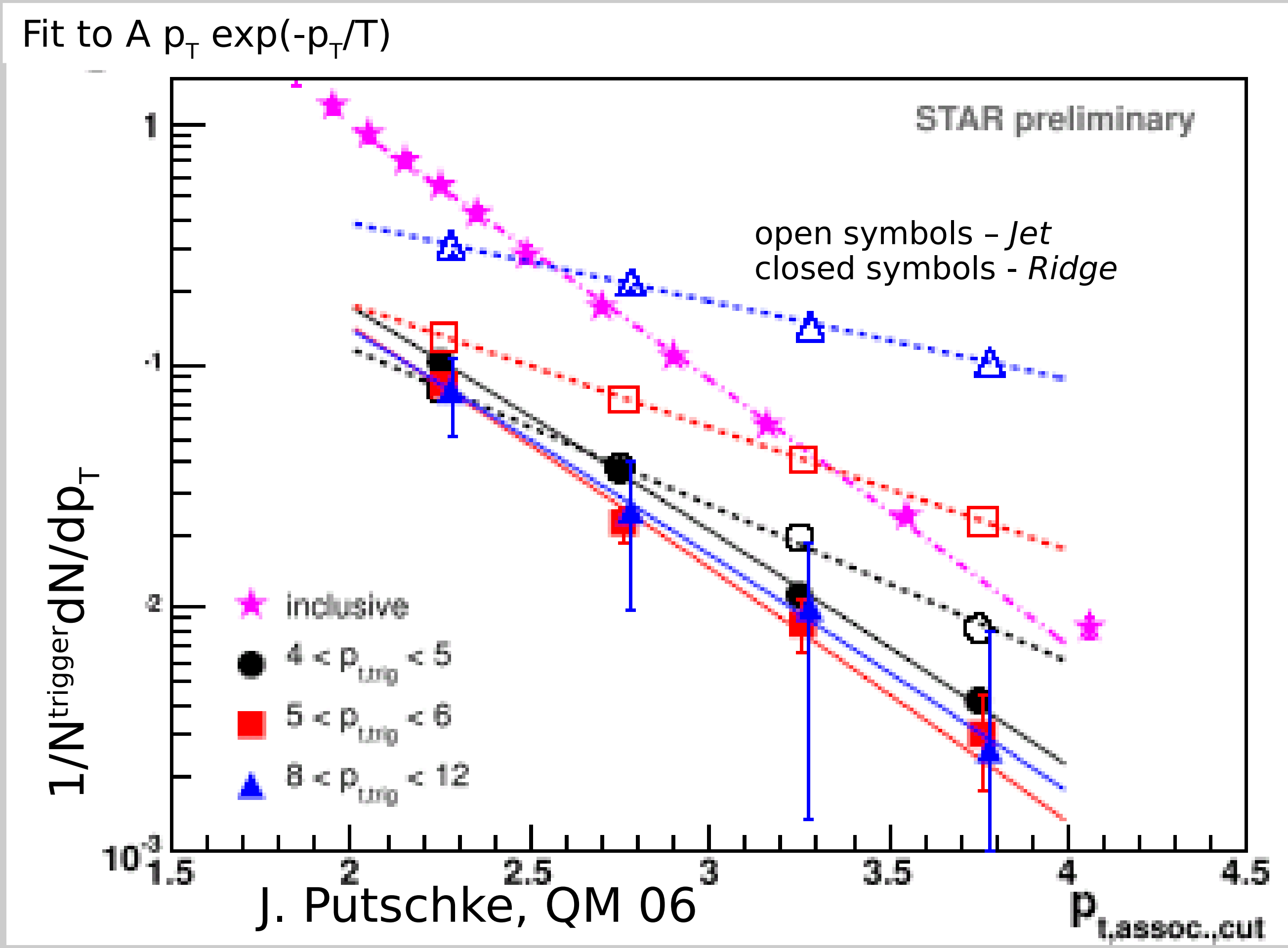
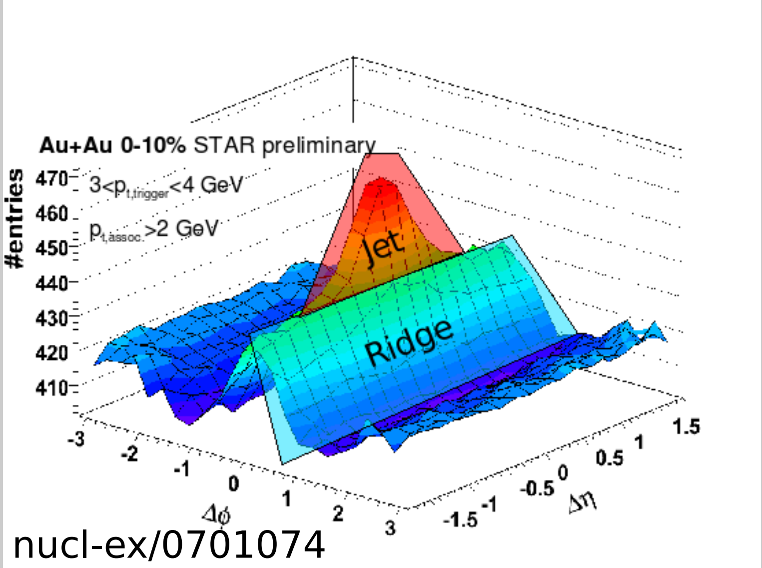
Near-side: Ridge



- Spectra of particles in *Jet* harder than those of particles in the *Ridge*
- Particles in *Ridge* similar to bulk

Near-side: Summary

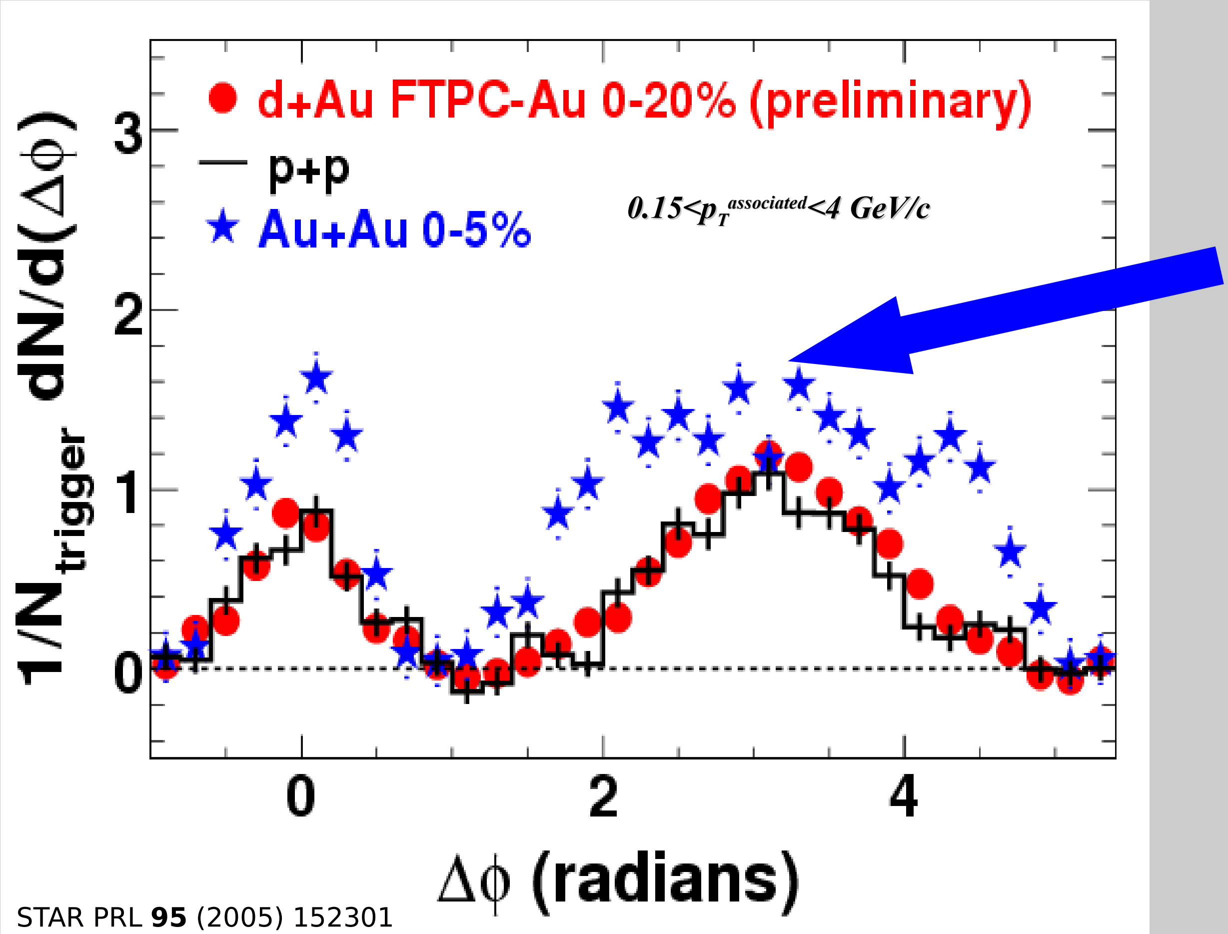
- Enhanced yield in Au+Au collisions relative to p+p
- Extra yield is in *Ridge*
- Particles in Ridge closer to those in the bulk than those in the Jet
  - Particle ratios
  - Spectra
- Consistent with N_{part} dependence on *Ridge* size



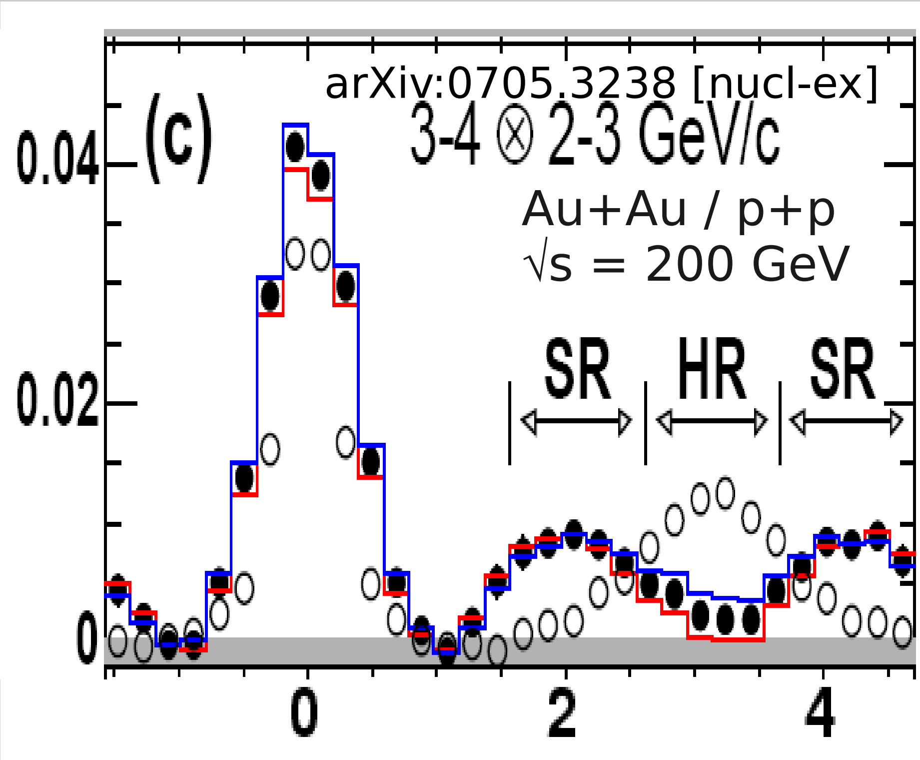
- Predictions which might distinguish mechanisms not quantitative enough to make detailed comparisons to theory

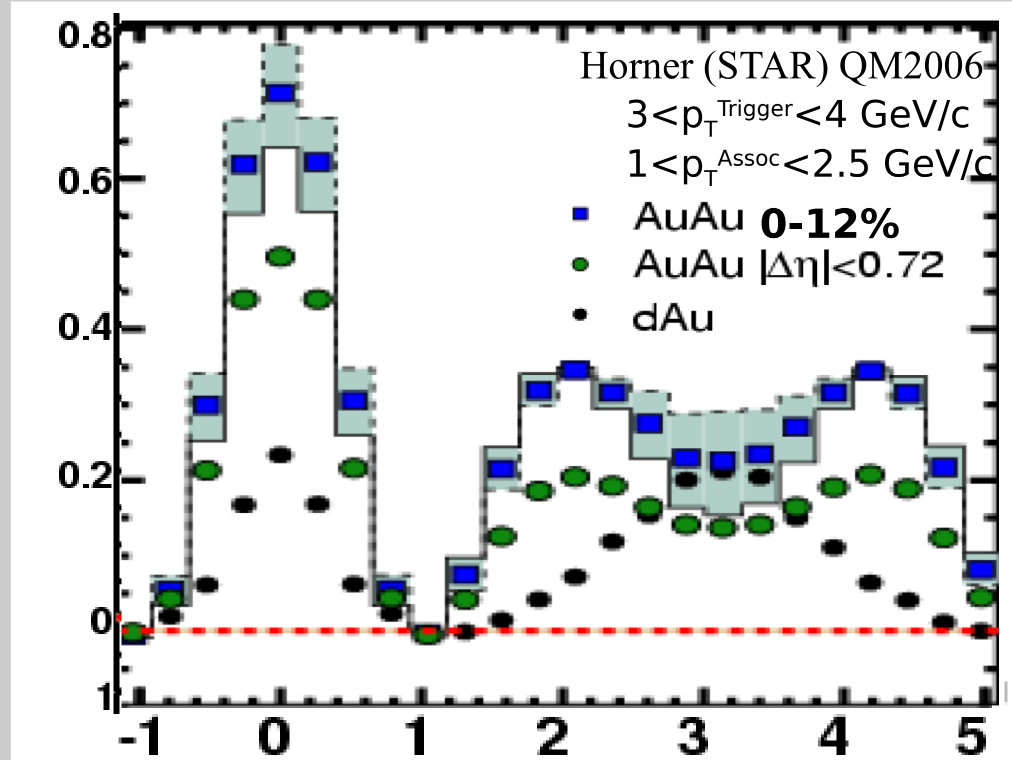
Away-side

- Shape change on away-side
- Excess yield at low p_T on away-side



Motivation: Away-side

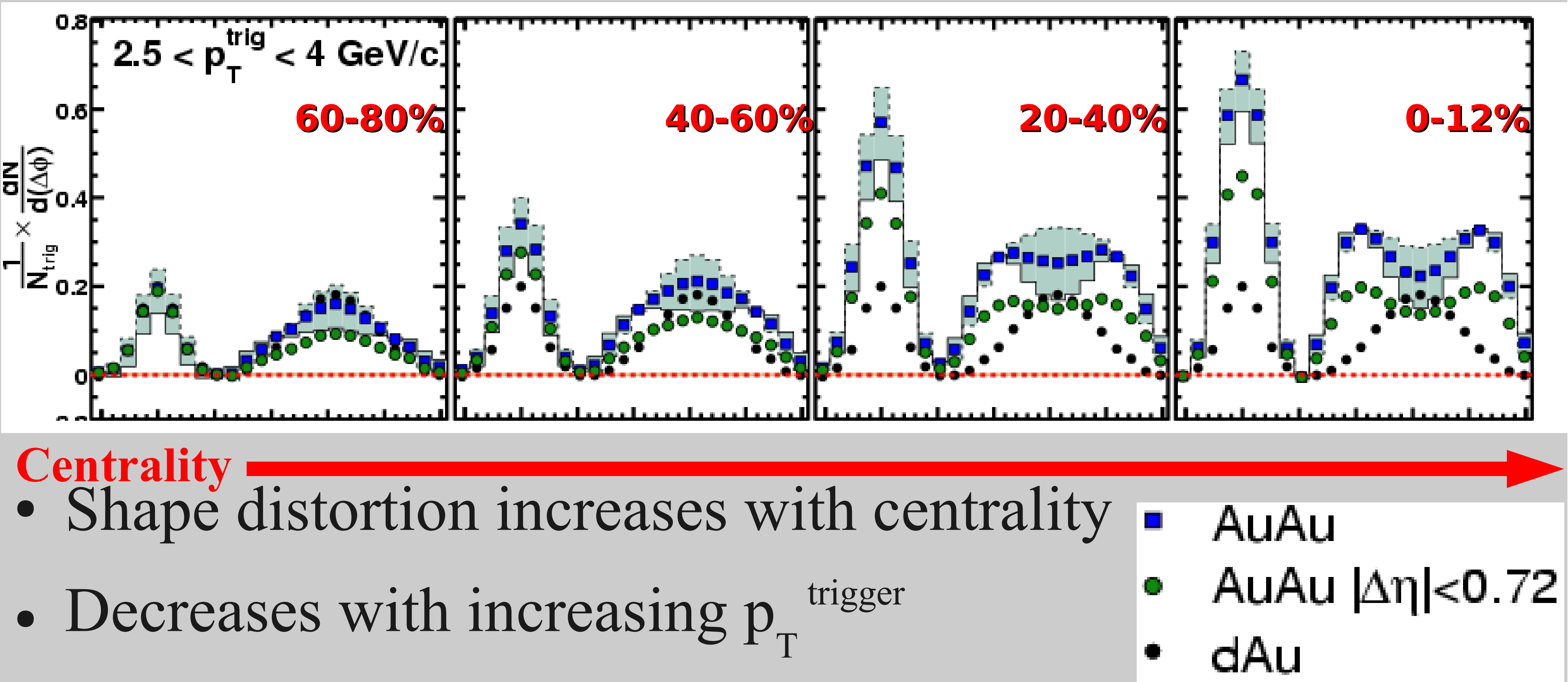




- STAR and PHENIX: qualitative agreement
- STAR: dependent on systematic errors
  - systematic errors from disagreement of different methods of measuring v_2
- PHENIX: claim smaller systematic errors
  - systematic errors from one v_2 measurement (reaction plane)

Away-side: Motivation

Or STAR results...



- Shape distortion increases with centrality
- Decreases with increasing $p_T^{trigger}$
- Degree of shape distortion dependent on v_2 subtraction
- Also see "punch through" of away-side at high $p_T^{associated}$

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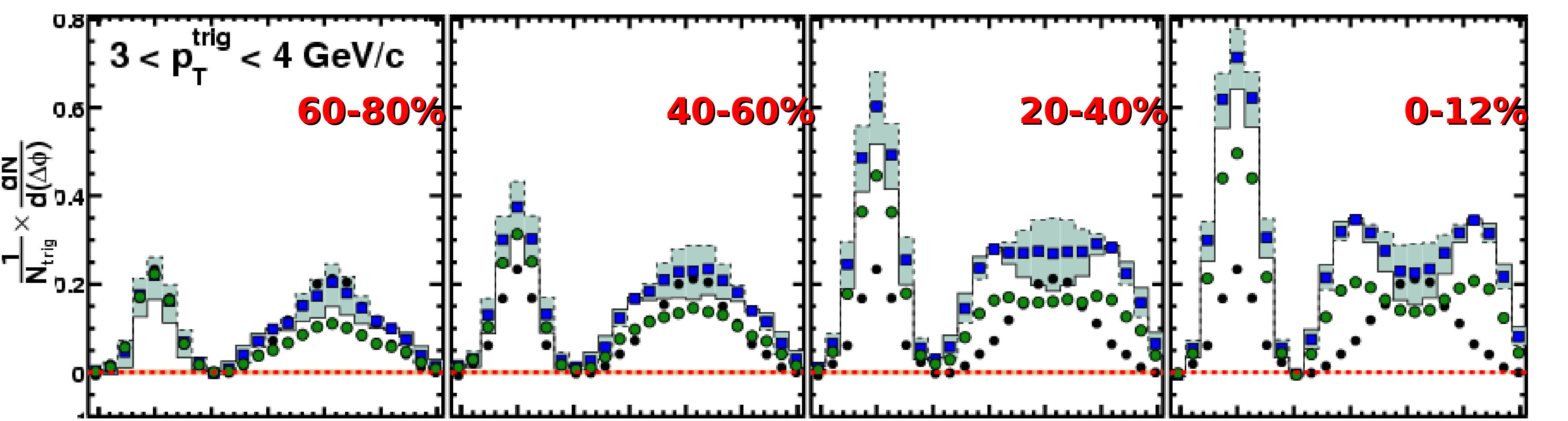

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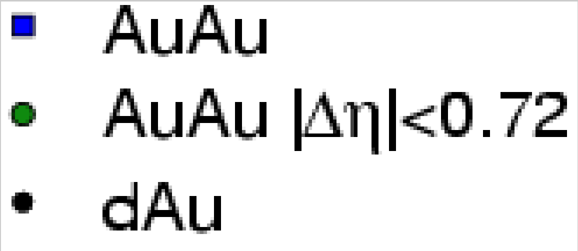

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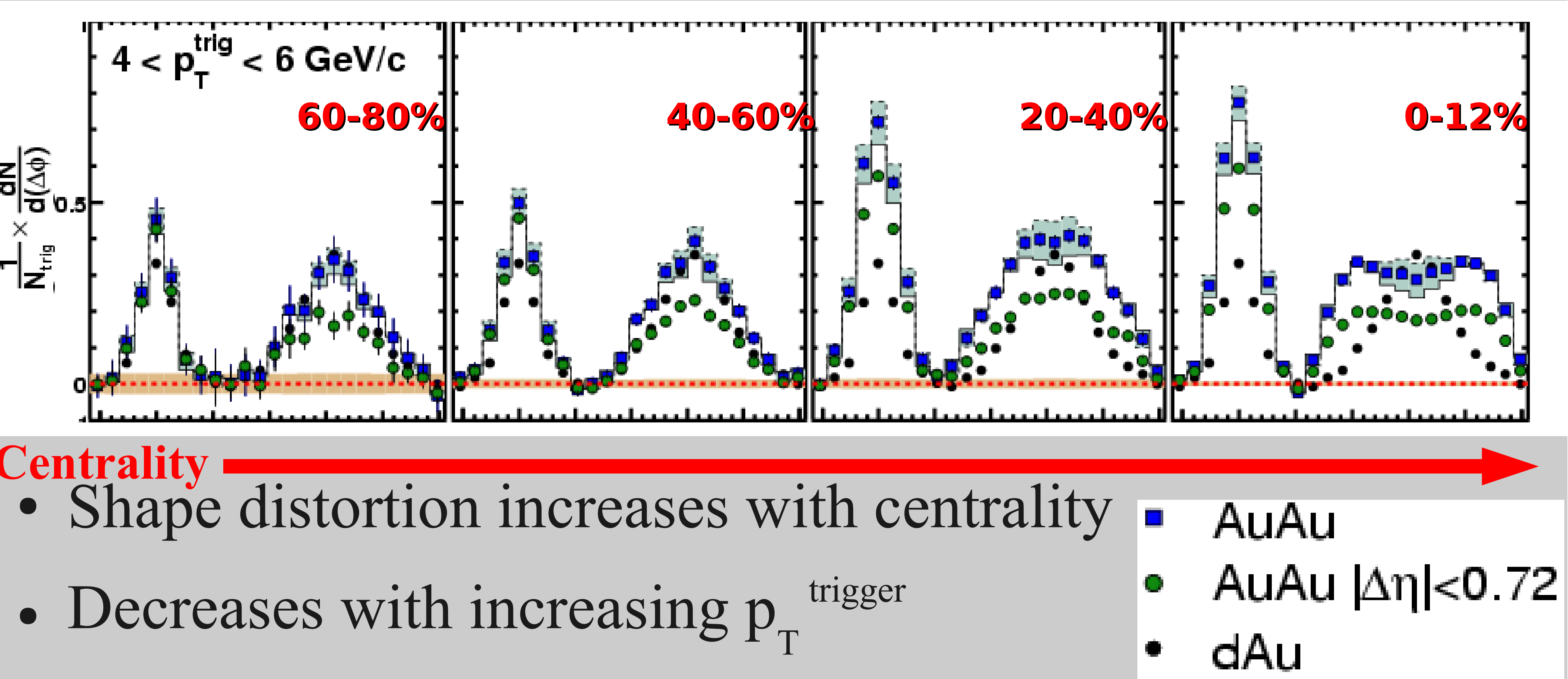

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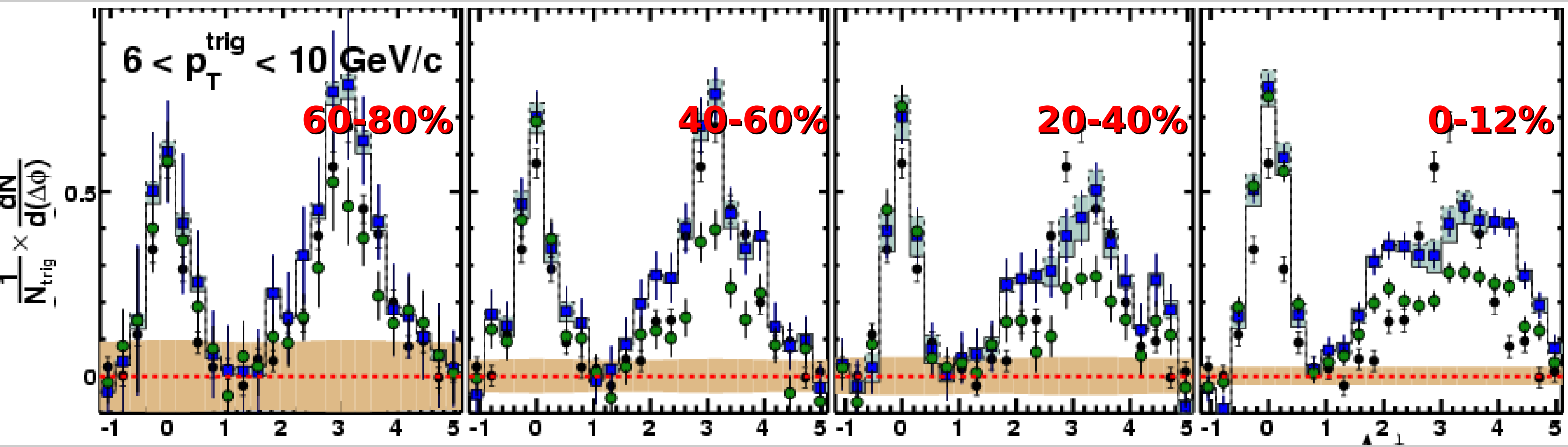

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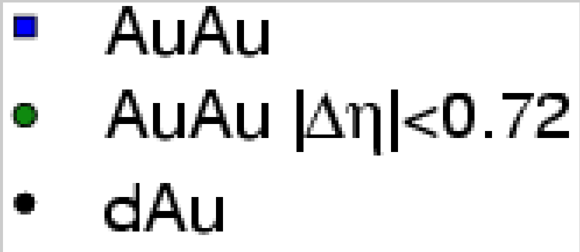


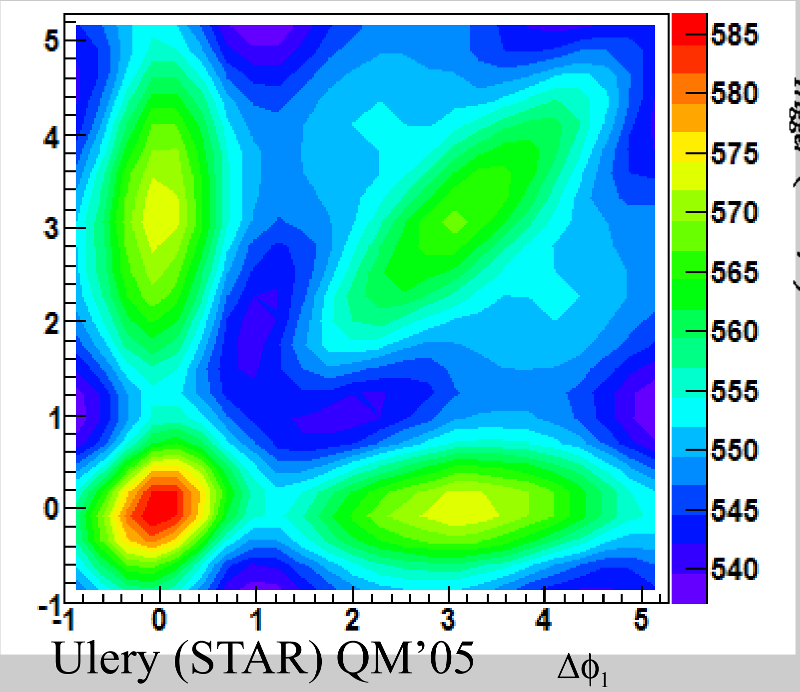
Away-side: Proposed models

- Where could this come from?
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stőcker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- 2-particle correlations give the same qualitative results for all models ➔ can't distinguish

3-particle correlations

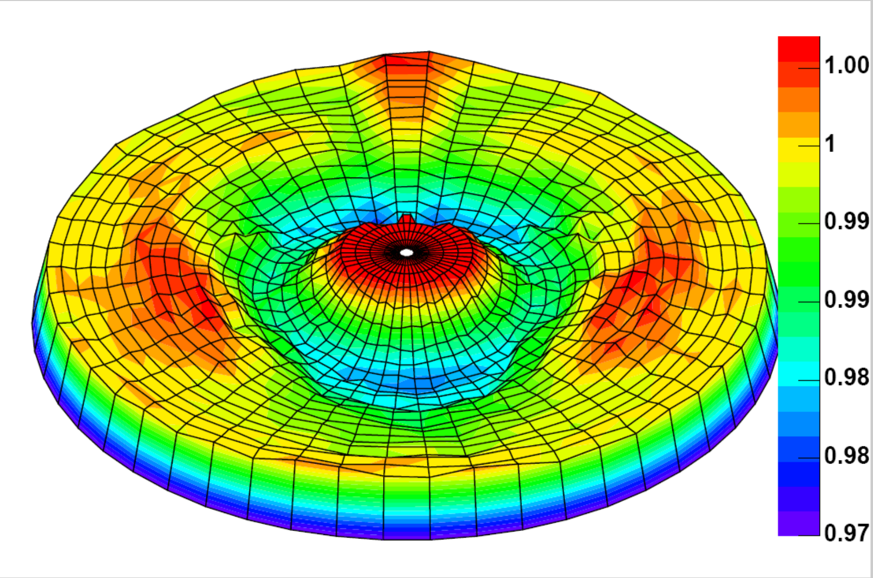
- Two different coordinate systems
- Different background subtractions
- Both assume 2 components (jet + flow background)

STAR
$\Delta\phi$-$\Delta\phi$ space ($\Delta\phi = \phi - \phi_{\text{Trigger}}$)



Ulery (STAR) QM'05

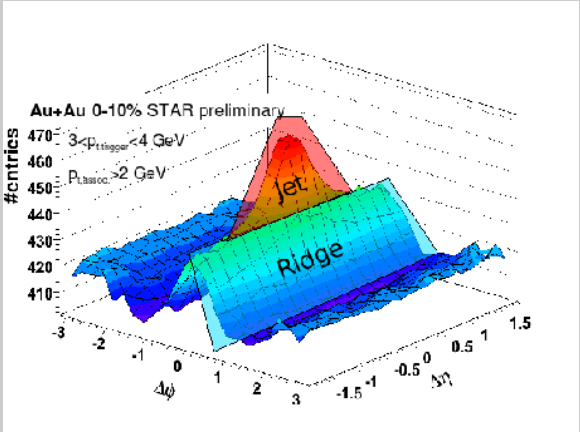
- PHENIX
- polar coordinates



Ajitanand (PHENIX) HP06, IWCF'06

Conclusions

- Jets have proven to be a powerful probe at RHIC
  - The near-side is modified
    - The Jet
      - Looks like vacuum fragmentation
    - The Ridge
      - Looks very similar to the bulk
  - Away-side is modified
- Many proposed models, more work to do



Wisdom from Goethe

Delacroix

Da steh' ich nun, ich armer Tor,

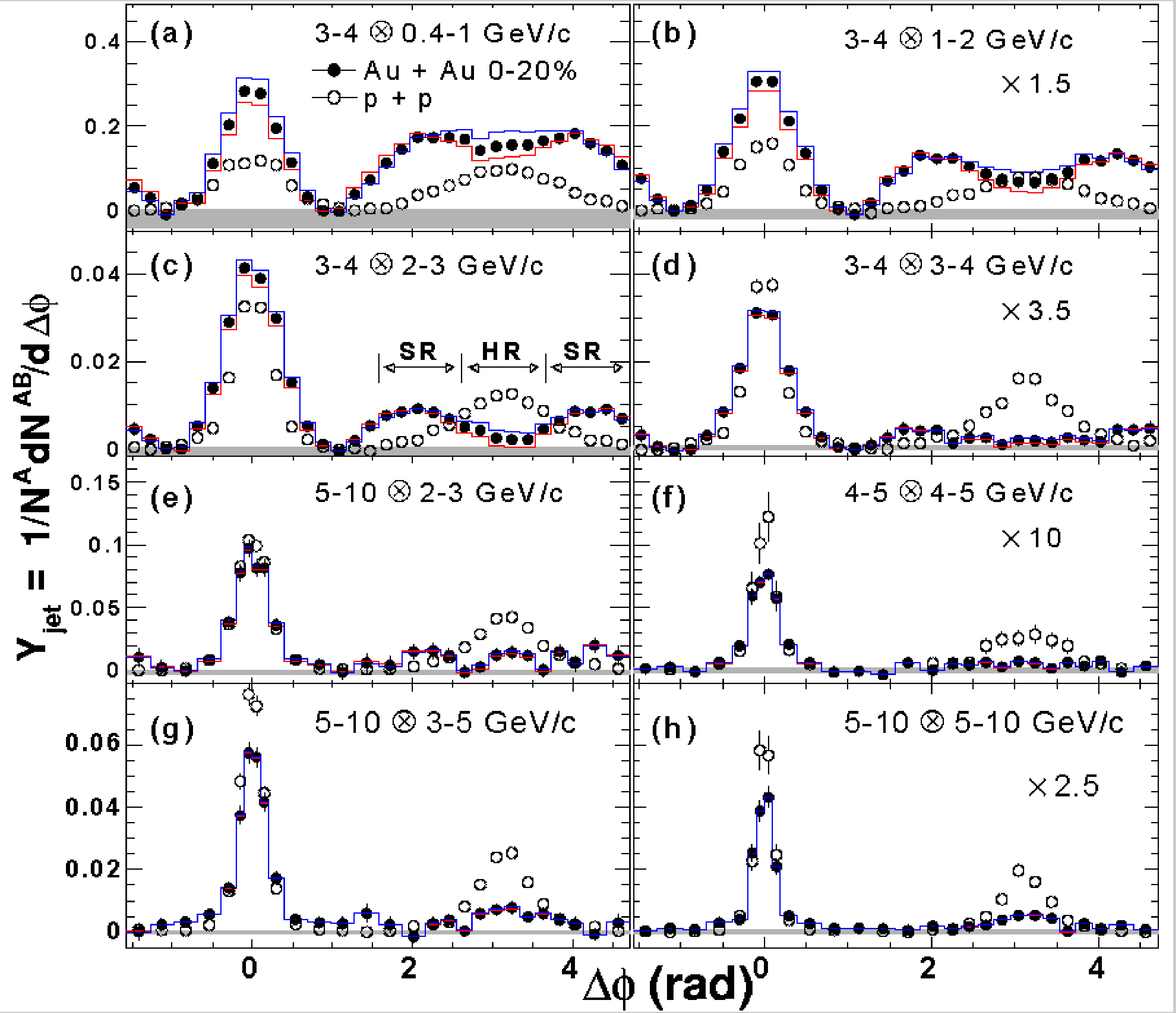
Und bin so klug als wie zuvor!

Faust I

Goethe

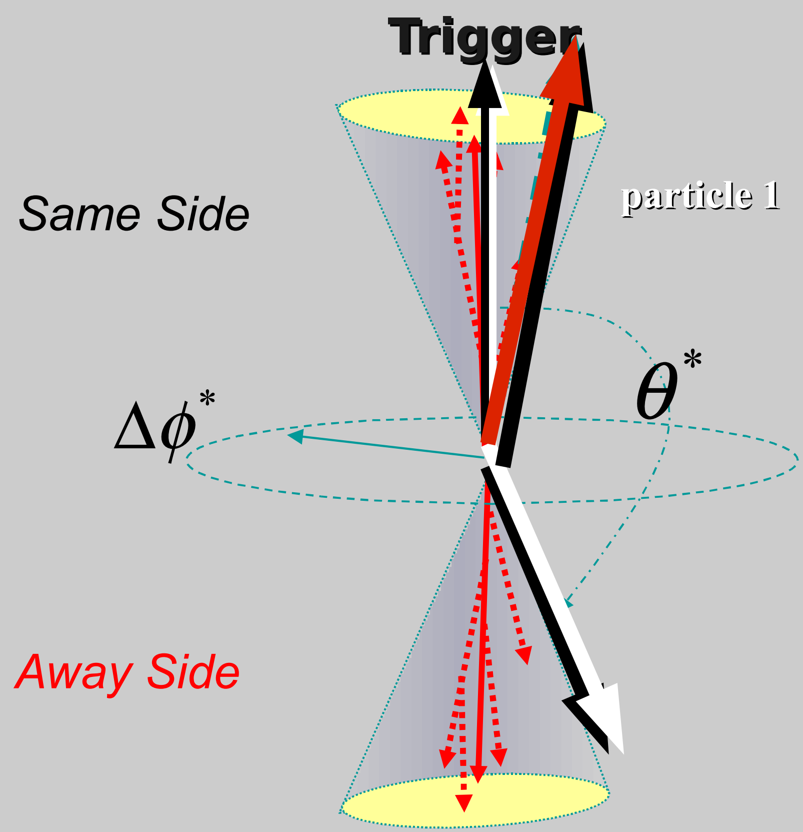
Away-side: Motivation

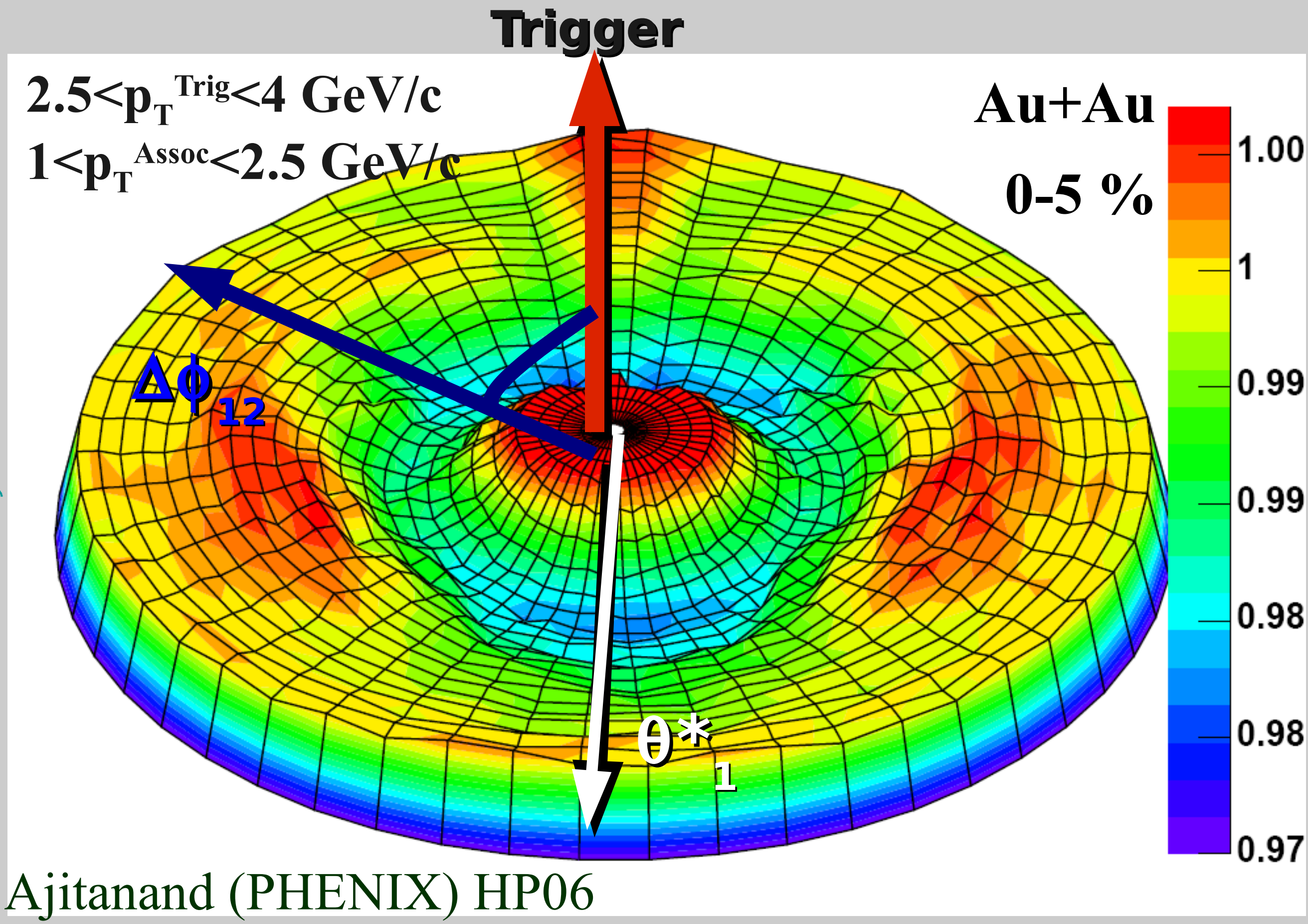
PHENIX
Au+Au & p+p
$\sqrt{s}$ = 200 GeV
arXiv:0705:3238



Whether we look at PHENIX results…

3-particle correlations: PHENIX





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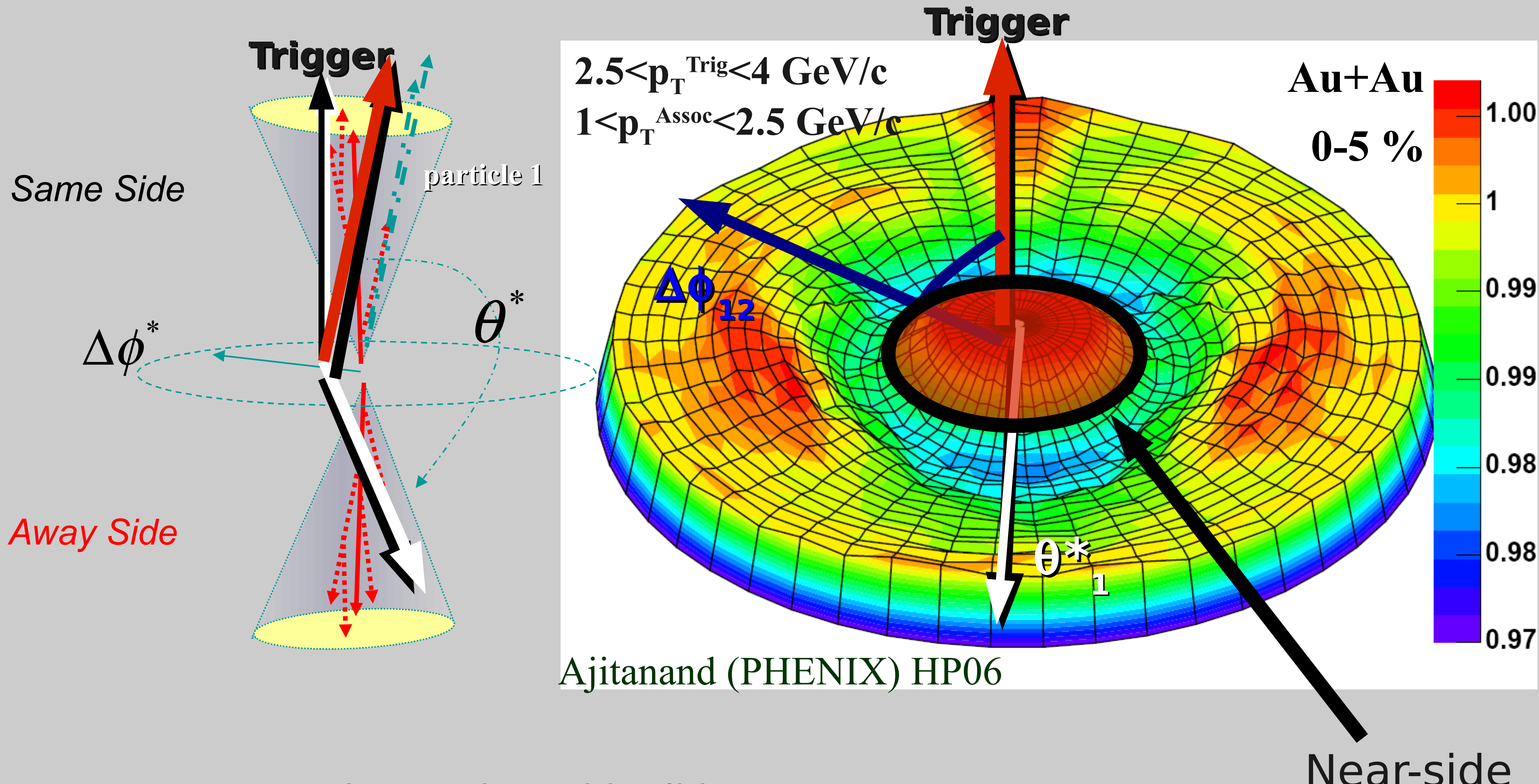
3-particle correlations: PHENIX



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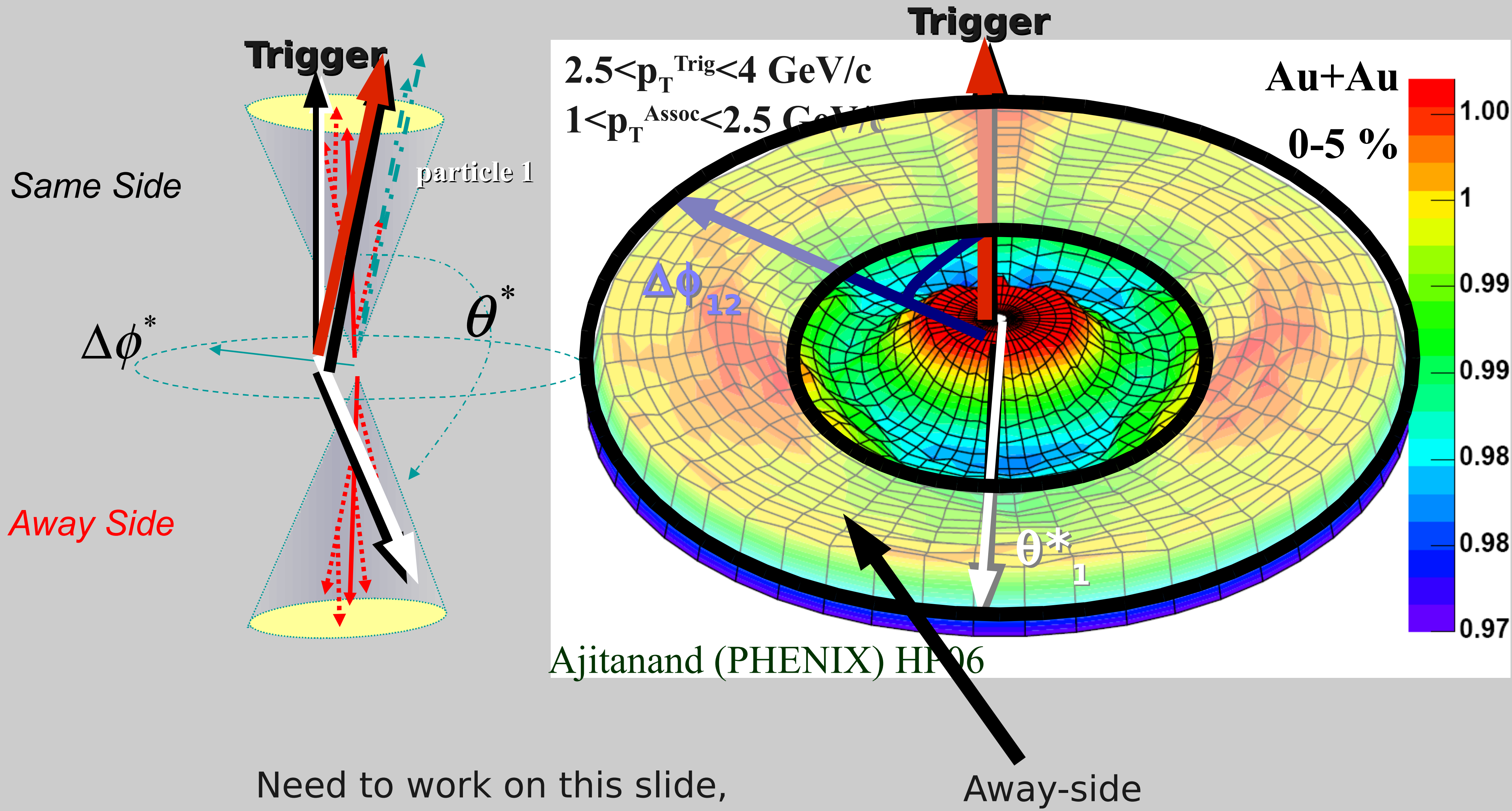

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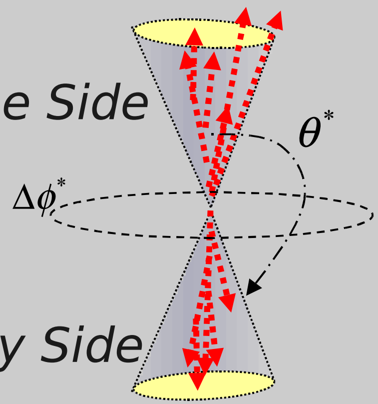
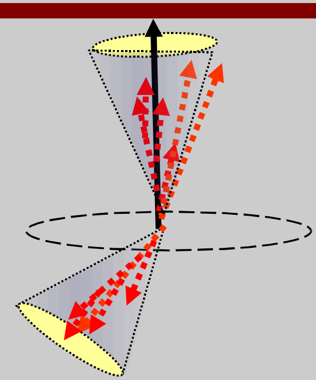
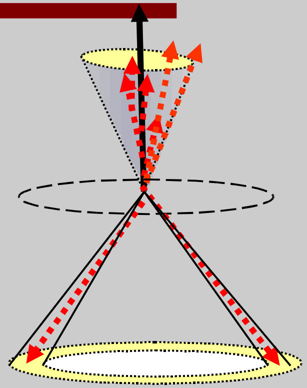
3-particle correlations: PHENIX

Same Side

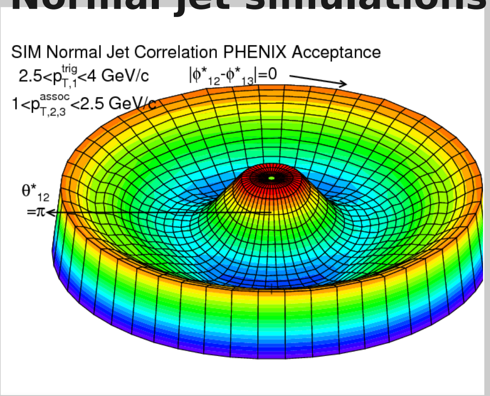


Away Side

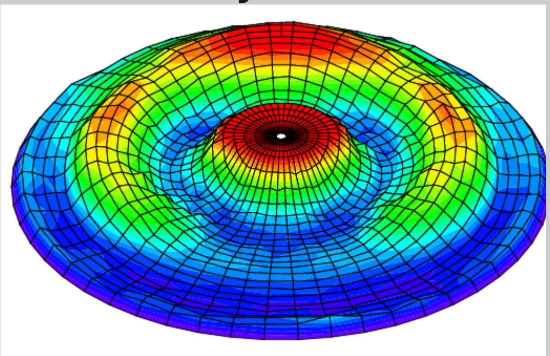




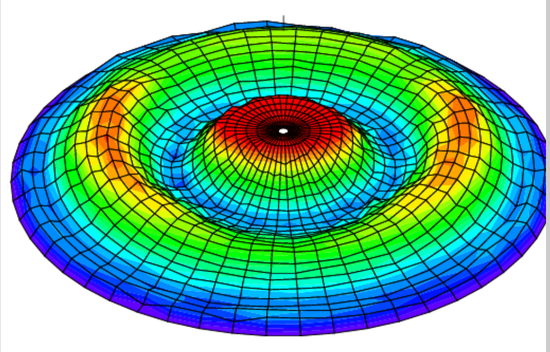
Normal jet simulations

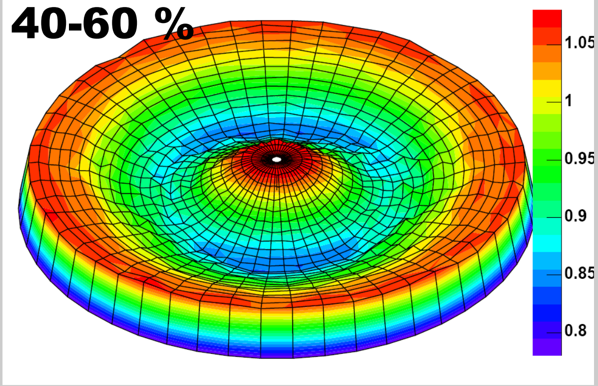


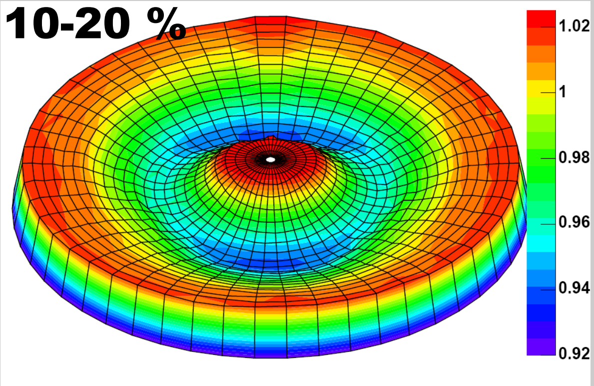
Deflected jet simulations

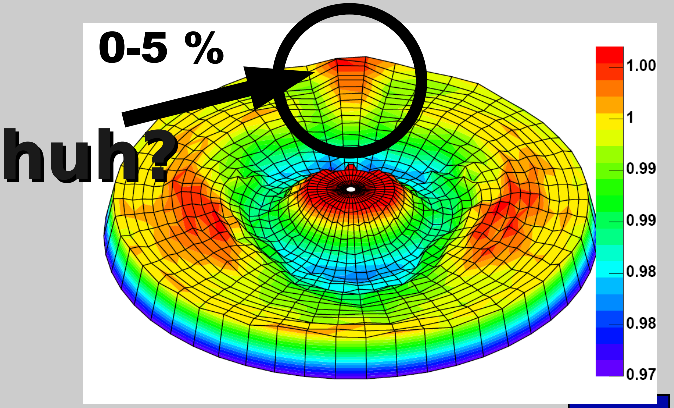


Mach Cone simulations









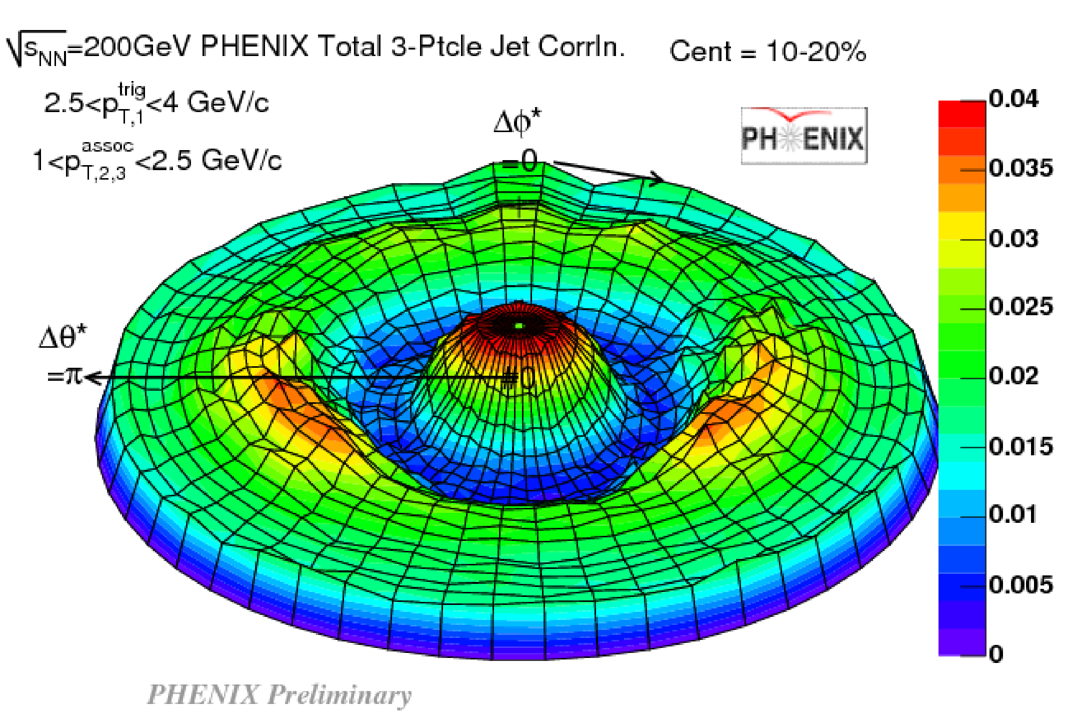
Hugo Pereira SQM 07

$2.5<p_T^{Trig}<4$ GeV/c $1<p_T^{Assoc}<2.5$ GeV/c

Ajitanand (PHENIX) HP06

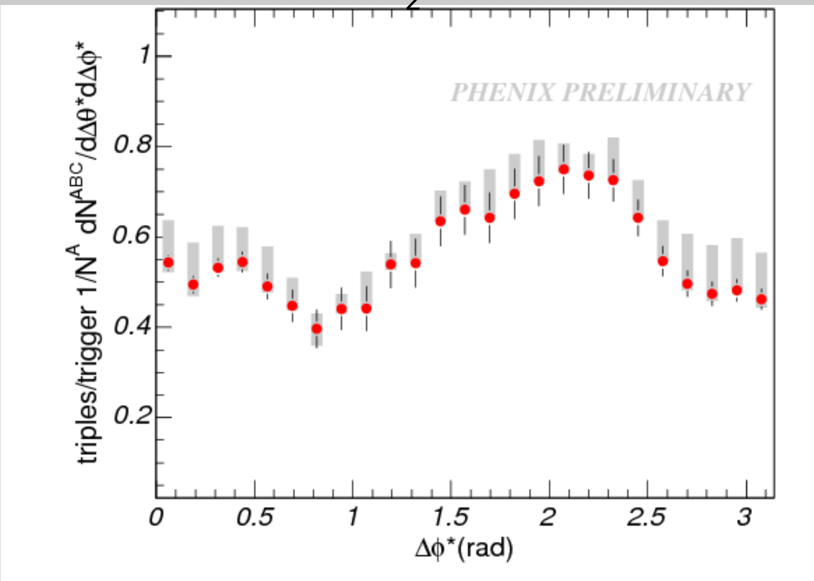
3-particle correlations: PHENIX

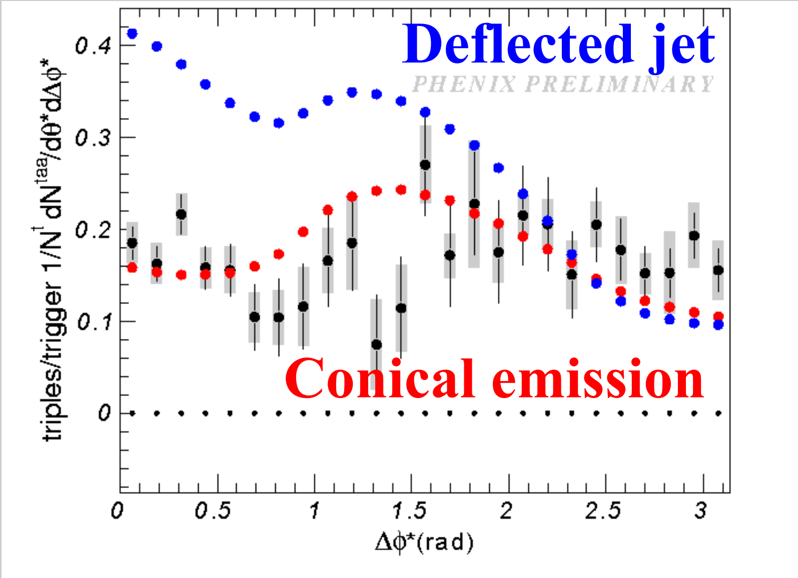
Ajitanand (PHENIX) HP06, IWCF'06



$\Delta\phi^*$ Projections

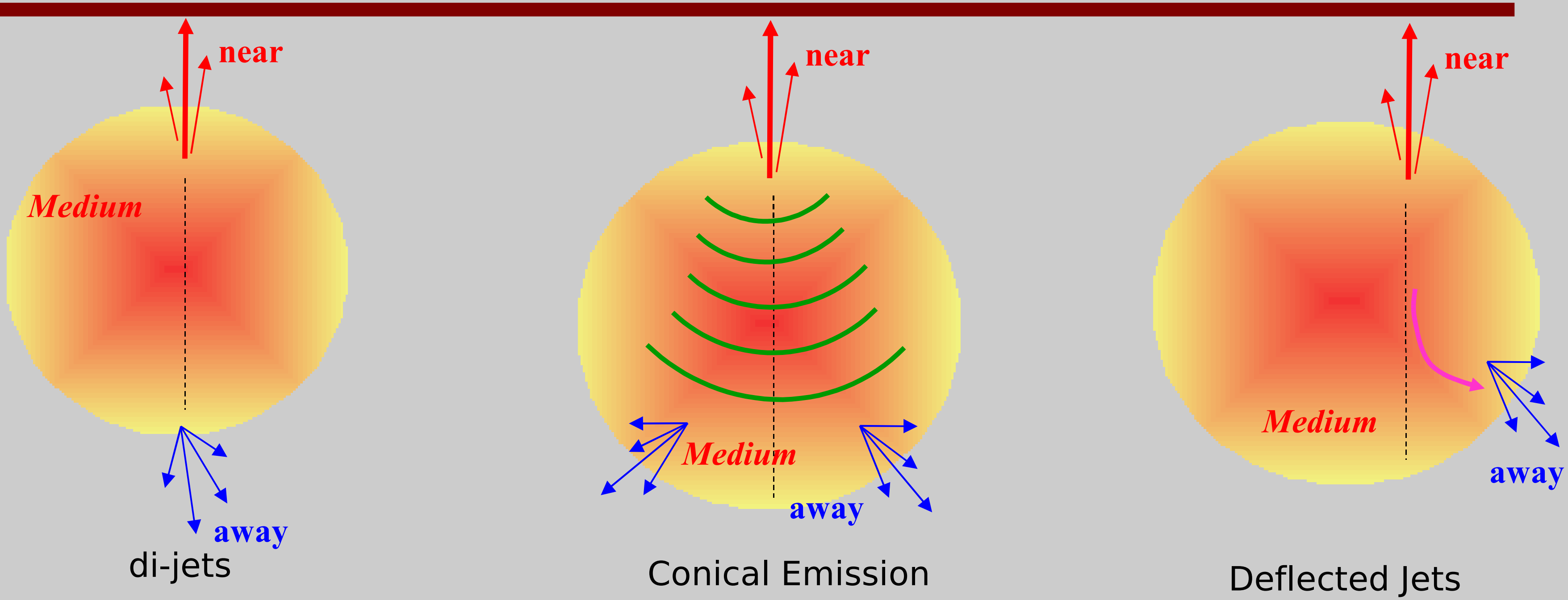
v_2 subtracted

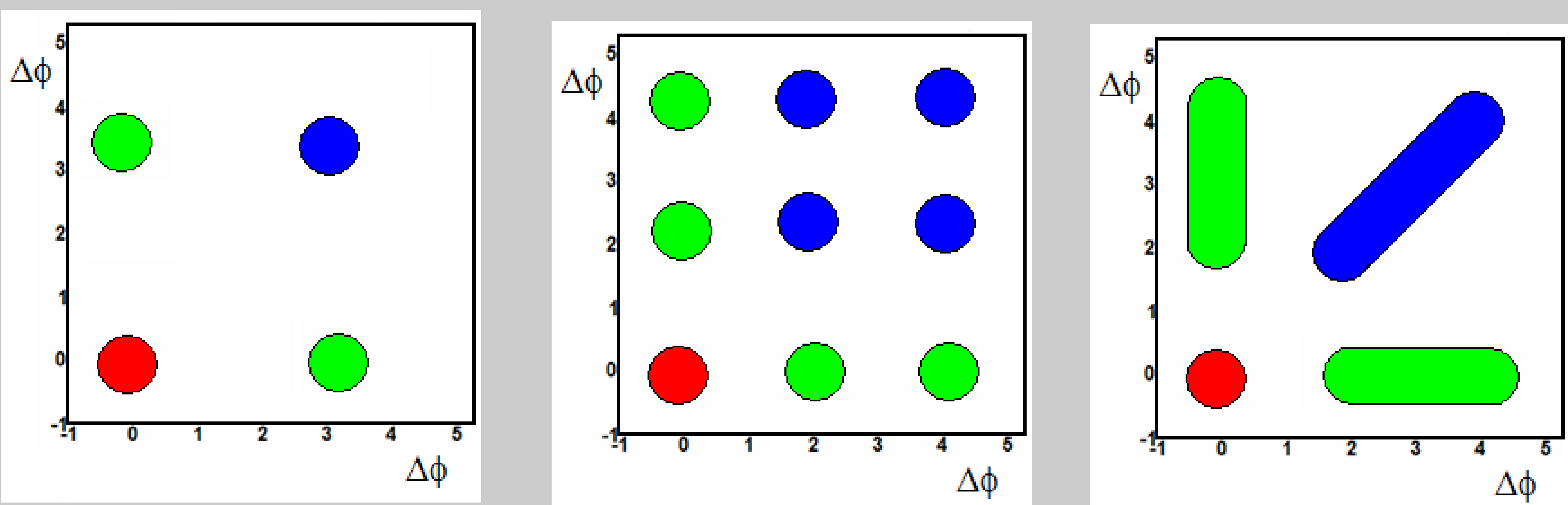




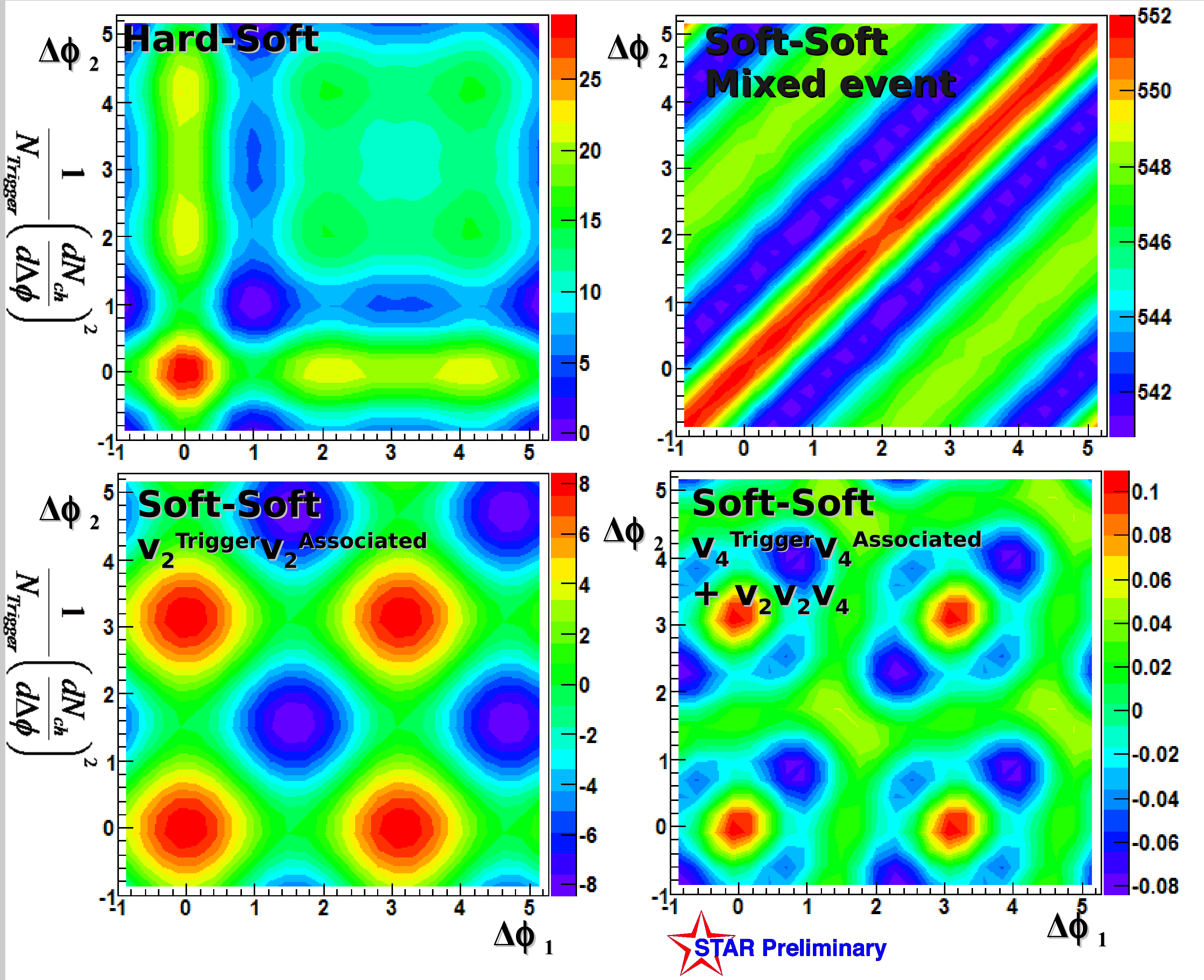
- Dependent on background subtraction
- Details of background subtraction not shown
- Central data not shown

3-particle correlations: STAR





3-particle correlations: STAR



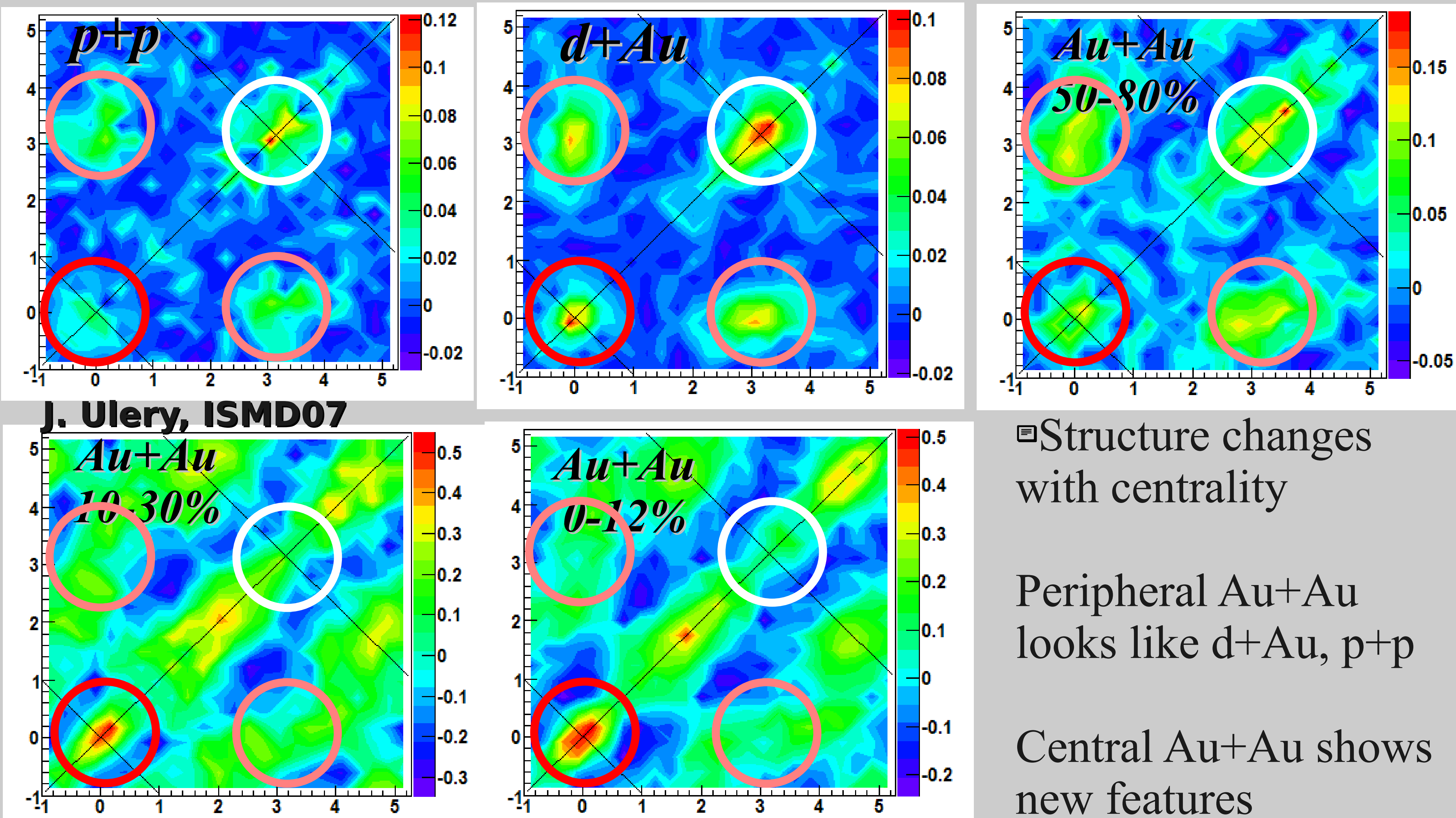
J. Ulery, ISMD07

Subtracting a complicated background...

Still assuming ZYAM...

$v4 = 1.15\ v_2^2$

3-particle Correlations: STAR Results



- Structure changes with centrality

Peripheral Au+Au looks like d+Au, p+p

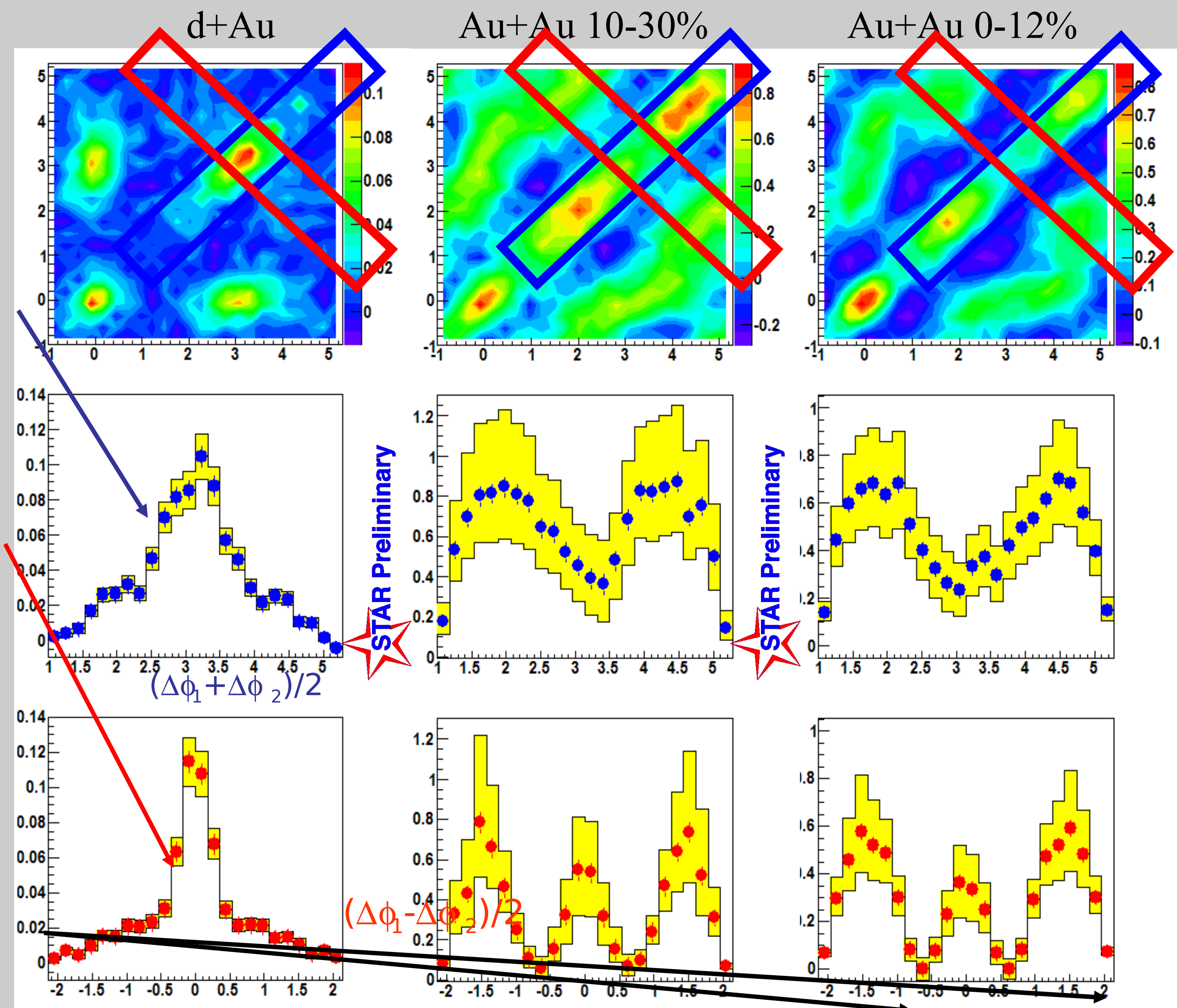
Central Au+Au shows new features

Near-Near   Near-Away   Away-Away

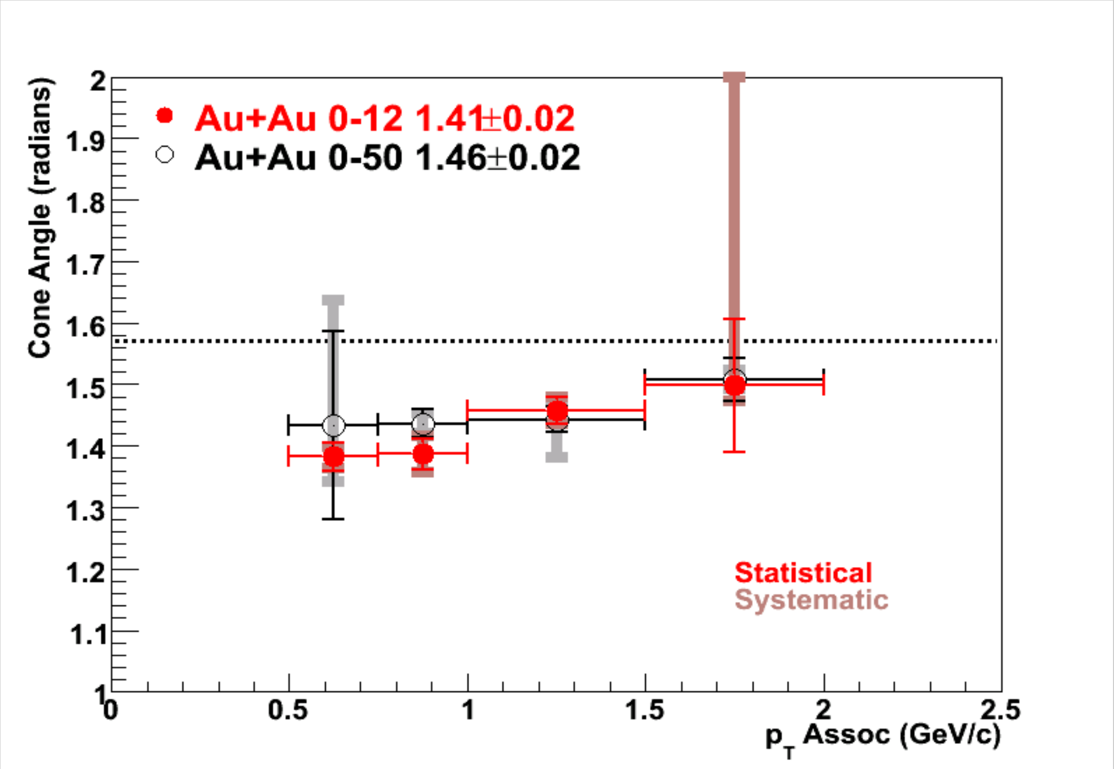
$1 < p_T^{associated} < 2$ GeV/c, $3 < p_T^{trigger} < 4$ GeV/c

3-particle Correlations: STAR Results

- On-diagonal and off-diagonal projections.
- Yellow bands are systematic errors.
- Significant off-diagonal peaks.

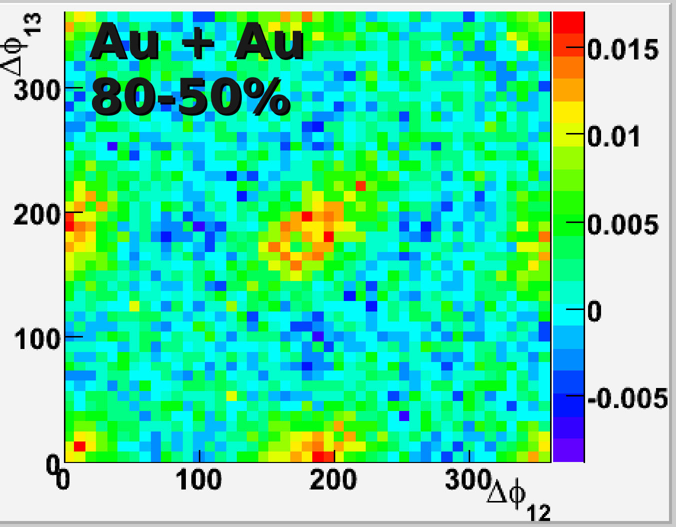


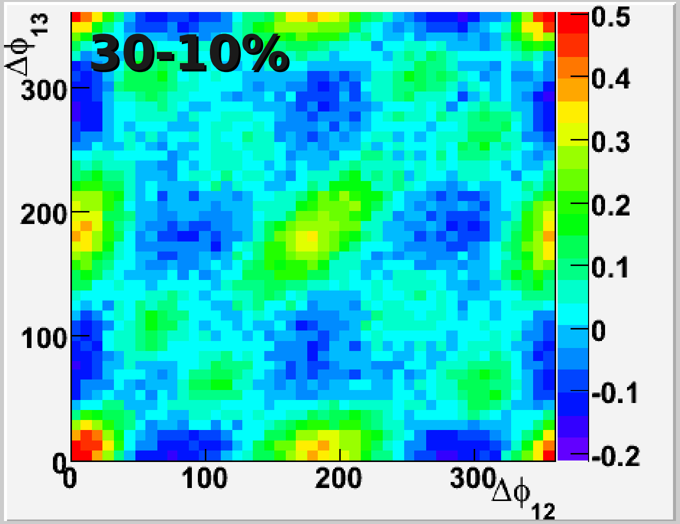
3-particle Correlations: STAR Results

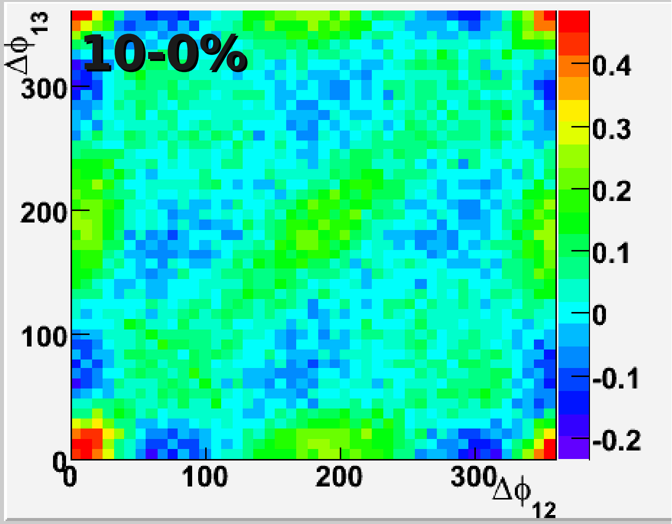


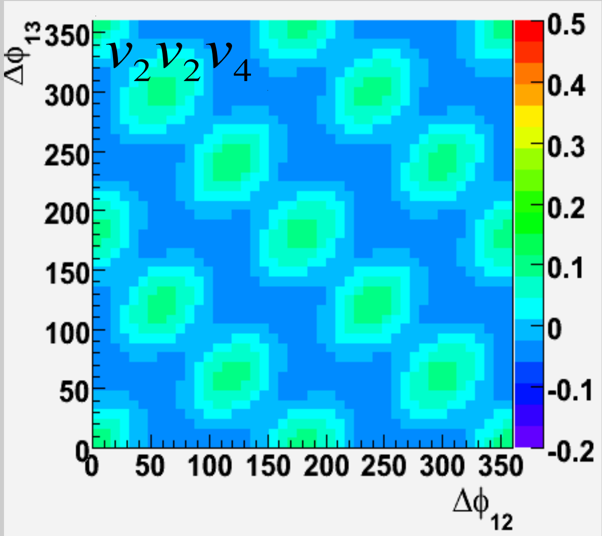
- Attempts at extracting emission angle
- No apparent p_T dependence
- No apparent centrality dependence

3-particle Correlations: STAR Cumulant







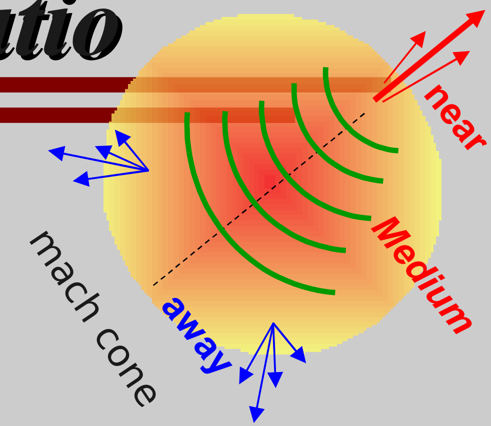


- Clear mathematical definition
- Difficult to interpret
- Favors modification but the type of modification is unclear

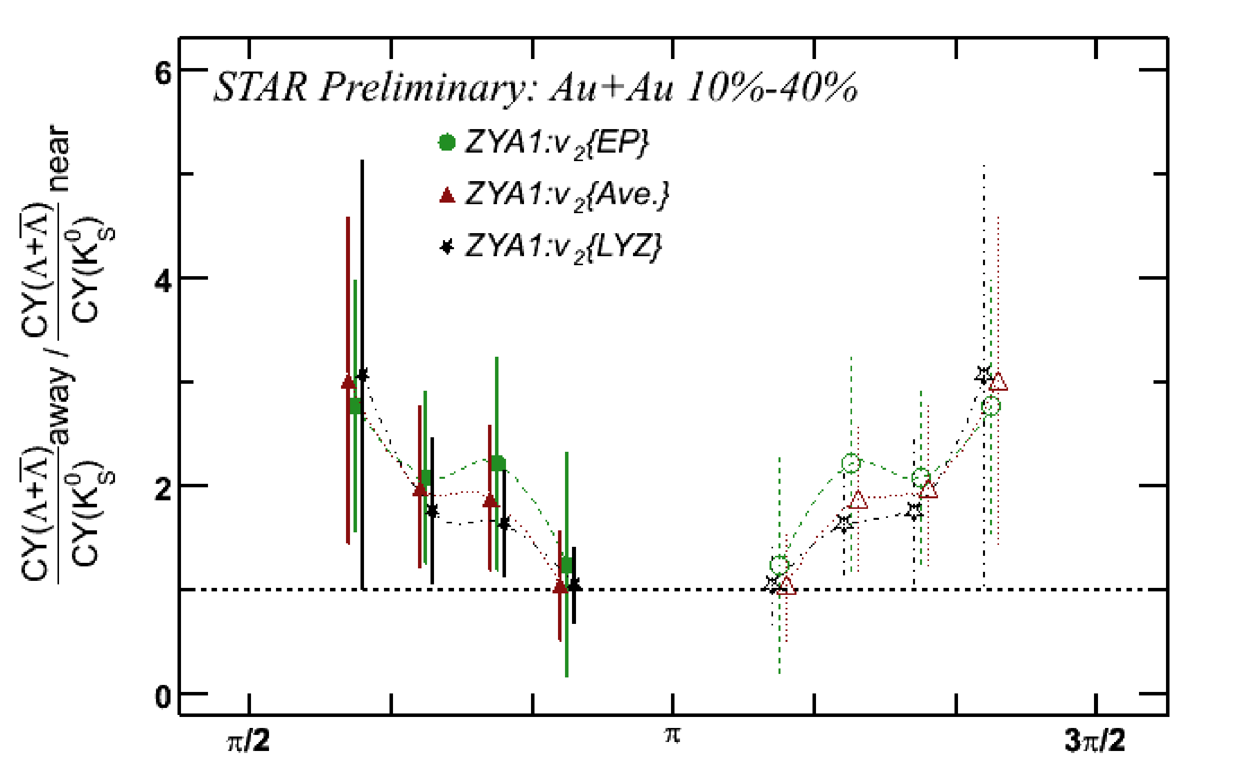
3-particle Correlations: Summary

- Both STAR and PHENIX standard analyses slightly favor conical emission
    - STAR data slightly favors Mach cone over Cerenkov radiation
    - Both analyses dependent on validity of
        - ZYAM
        - 2 component picture
- Similar STAR analysis which does not support conical emission but has unclear interpretation

Another method - Baryon/Meson Ratio



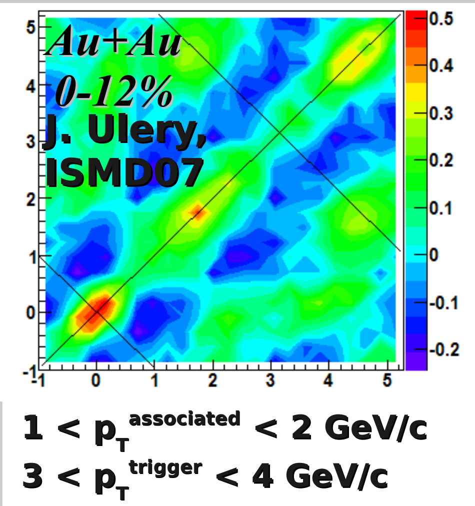
- If there is a Mach cone, angle should depend on mass
- Error bars are still too large to conclude
- However, at least systematic errors for K^0_S and Λ are correlated

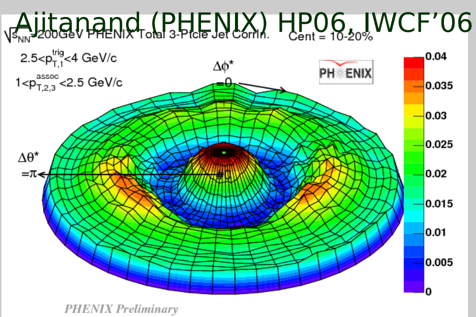


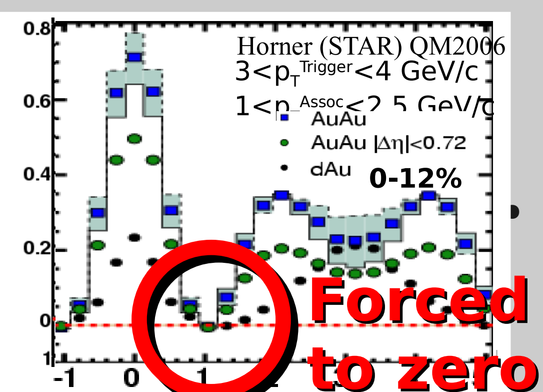
J. Xuo SQM07

- Disadvantages:
  - Current error bars prevent any conclusions
- Advantages:
  - STAR year 7 data allow 4x statistics
  - New method (Brooke Haag, QM08 poster) may allow even higher stats/higher p_T
  - systematic errors due to v_2 at least move together

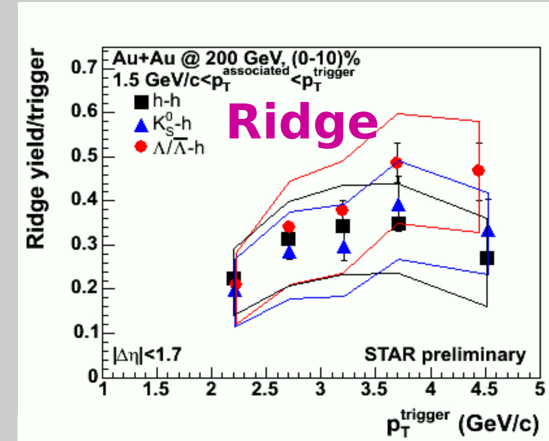
Summary

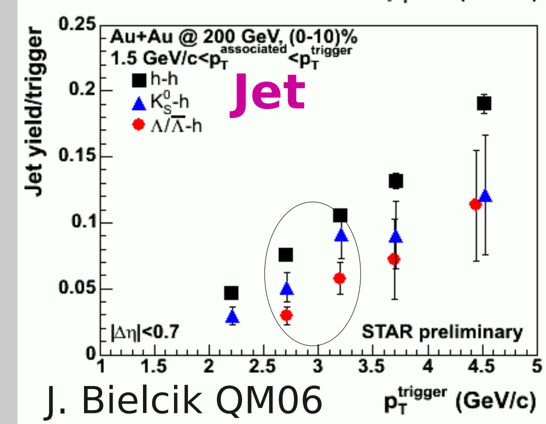


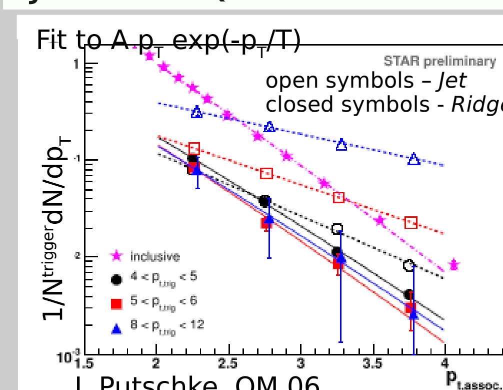




- Studies showing shape changes on away-side
  - Signal/Background > 1/20
  - Systematic errors due to v_2 large because background is large
  - 1 GeV/c $<p_T^{associated}$
    - Ridge yield significant on Near-side
    - ➔ ZYAM assumption could lead to significant errors
- We don't understand the near-side yet
  - 2.5 GeV/c trigger (PHENIX) isn't very "jetty"
  - 3.0 GeV/c (STAR) is only slightly better
  - 1 GeV/c $<p_T^{associated}$ - on near-side, Ridge dominates. Does this affect the away-side?
- How do we know that the production mechanisms for the Ridge and the shape changes on the away-side are distinct?







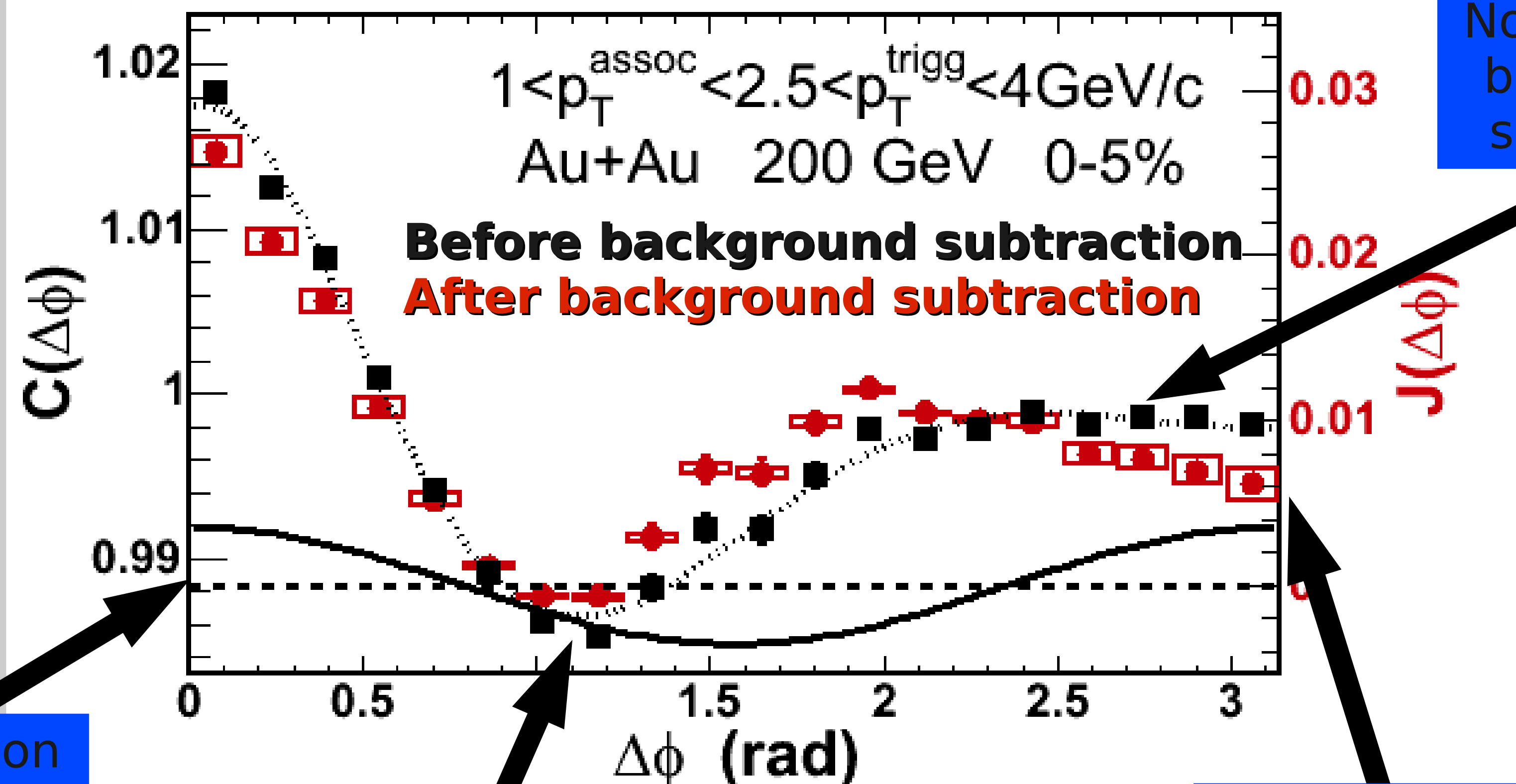
Outlook

- Higher p_T on 3-particle correlations?
  - Really need higher $p_T^{associated}$, $p_T^{trigger}$ to understand results
  - More data not yet analyzed
  - Detector upgrades which would allow more data in a run
  - Advances in triggering
- Need to understand the near-side
  - More data helps in particle ratios
  - More particles?
- Jet reconstruction in heavy ion collisions?
  - Some progress
  - Would allow reconstruction of near-side

Backup slides

Reminder: Background Subtraction

Phys.Rev.Lett.98:232302,2007



No dip before background subtraction

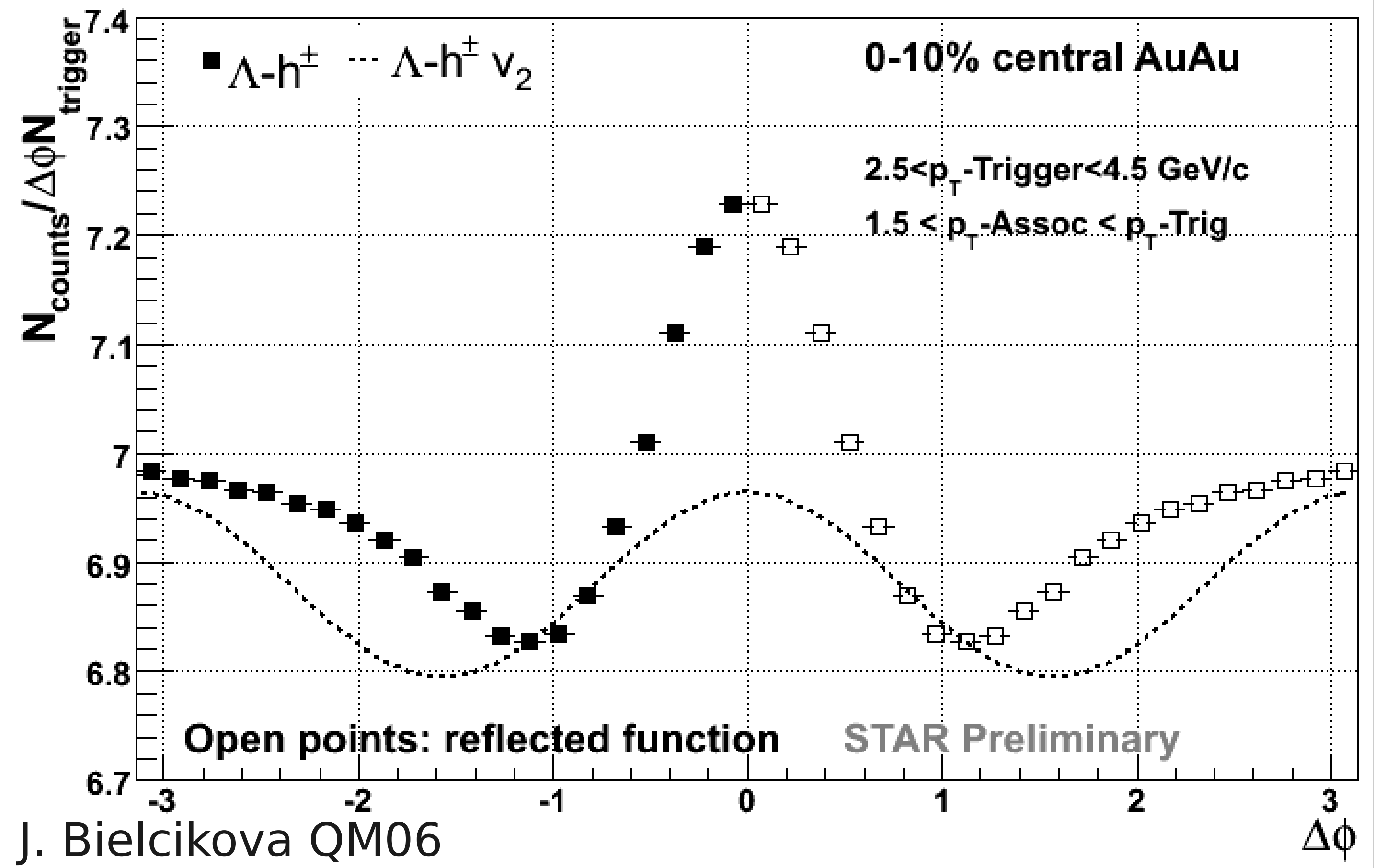
Signal sits on top of large background

Assumption that there is no yield at minimum

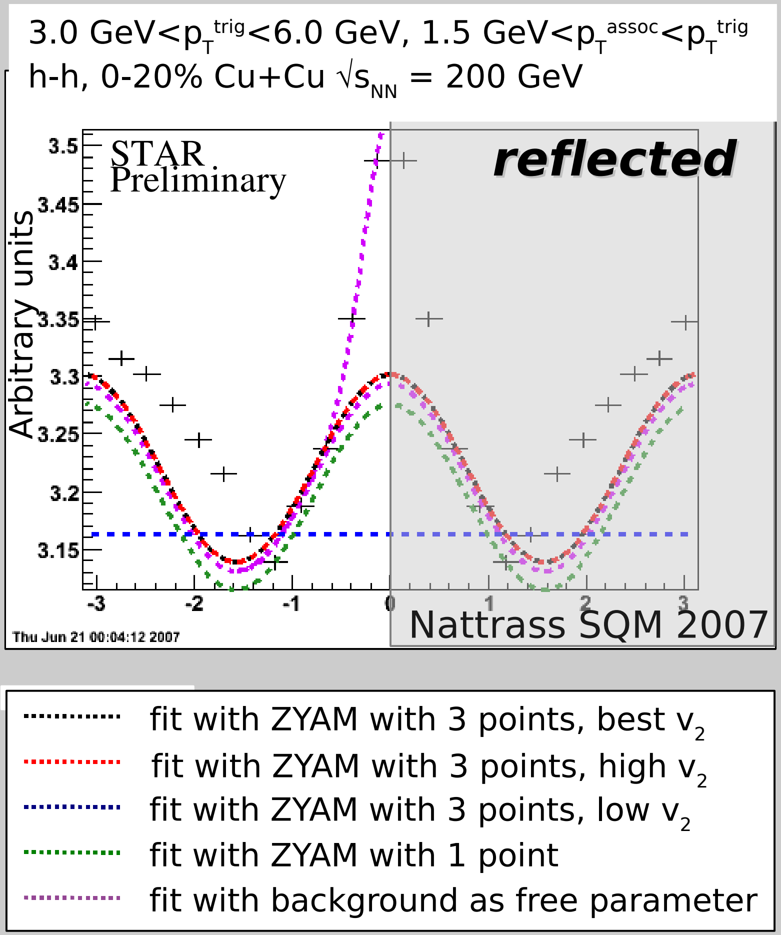
Dip appears after background subtraction

A caveat...

- Large background subtraction...
  - Signal/Background ≈ 0.05
    - Depends on kinematic region
    - Signal/Background higher at higher p_T



Determination of yields and errors



- Background:
  $B(1+2\, v_2^{trig}\, v_2^{assoc} \cos(2\Delta\Phi))$
  v_2 – elliptic flow
- Different fit methods for determination of B
  - Assume there is no yield correlated with the jet at some point
  - *Z*ero *Y*ield *A*t *M*inimum (ZYAM)
  - *Z*ero *Y*ield *A*t *1* (ZYA1)
- v_2 error -> systematic error on correlations *assuming ZYAM is correct*

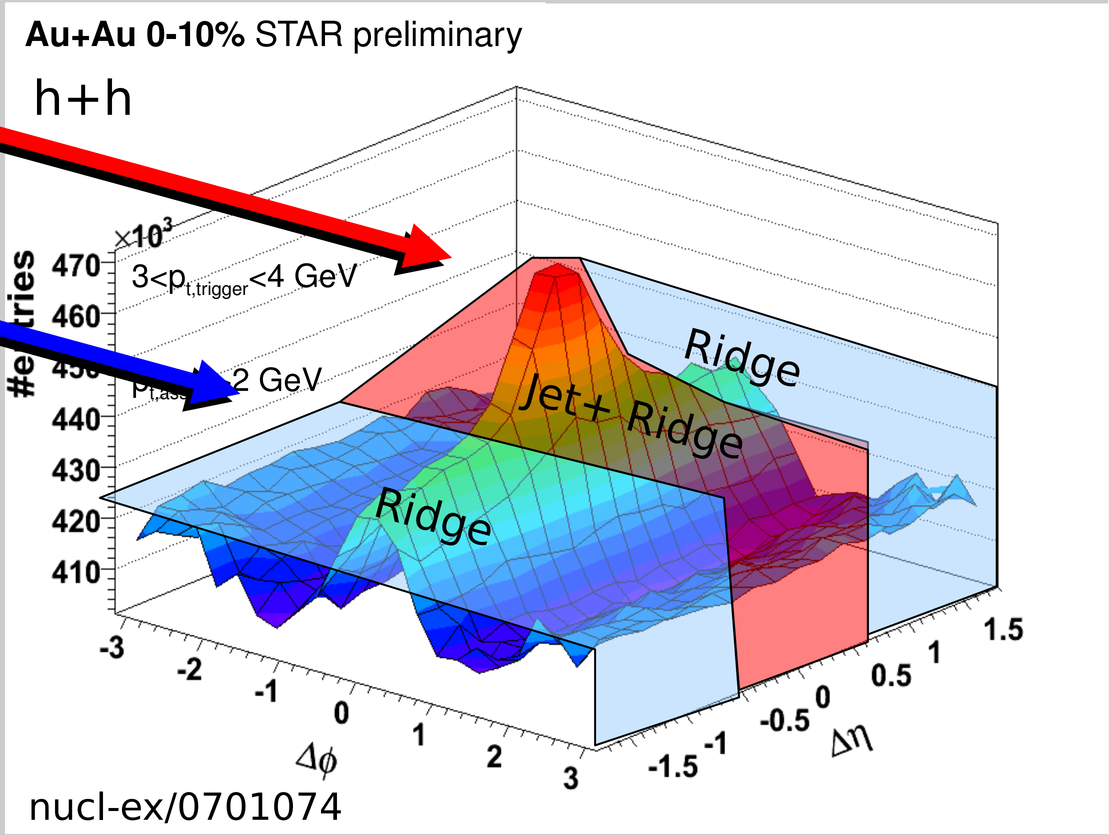
Assumptions in background subtraction

- The only background is elliptic flow
- Elliptic flow is independent of jets and therefore the correlations can be separated into two *independent* components
- There is a point in azimuth where none of the correlations are due to jets

Any conclusions are heavily dependent on the validity of these assumptions!

Near-side: Method

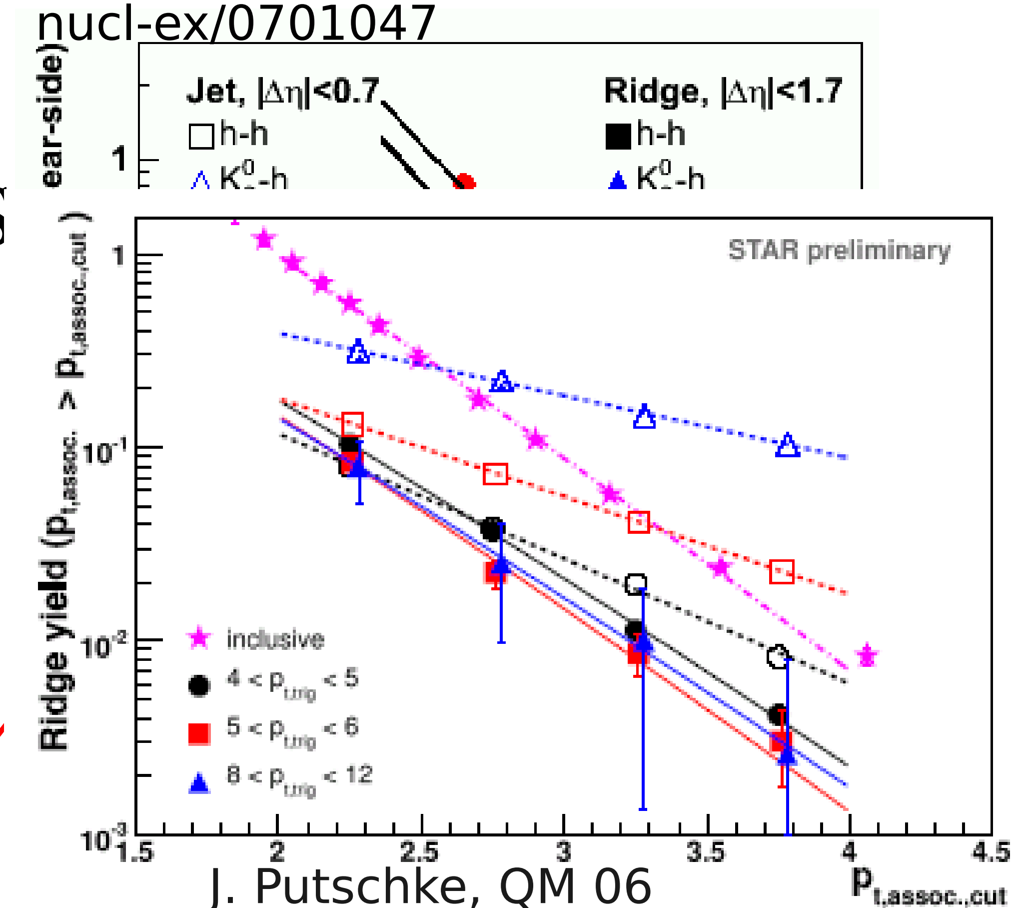
- *Ridge* previously observed to be flat in $\Delta\eta$ in Au+Au
- To determine relative contributions, find yields for near-side, take $\Delta\Phi$ projections in
  - $-0.75<\Delta\eta<0.75$ ***Jet + Ridge***
  - $0.75<|\Delta\eta|<1.75$ ***Ridge***
  - *Jet* = (*Jet*+*Ridge*) – *Ridge**.75/1.75
  - *Ridge* = yield from $-1.75<\Delta\eta<1.75$ – *Jet* yield

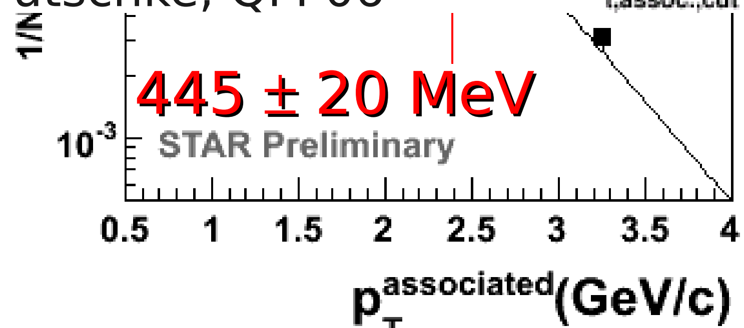


- Flow contributions to jet cancel
  - v_2 flat with η for $|\eta|<1$
    - Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 122303 (2005)

p_T-distribution of associated particles

- Ridge spectra similar to the bulk
  - Cu+Cu measurements probably not possible
- Jet spectra are slightly harder
  - Cu+Cu T within error of Au+Au
  - Cu+Cu fit only to h-h





Trigger particle	T(ridge) MeV	T (jet) MeV
$h^{+/-}$	438 ± 4 (stat.)	478 ± 8
K^0_S	406 ± 20 (stat.)	530 ± 61
Λ	416 ± 11 (stat.)	445 ± 49

Fit to A exp($-p_T$/T)

Nattrass SQM 2007

Two Analysis Techniques

Measure 1-, 2-, and 3-Particle Densities

$$\rho_1(\varphi_i) \equiv \frac{d^2N}{d\varphi_i} \qquad \rho_2(\Delta\varphi_{ij}) \equiv \frac{d^2N}{d\Delta\varphi_{ij}} \qquad \rho_3(\Delta\varphi_{ij},\Delta\varphi_{ik}) \equiv \frac{d^3N}{d\Delta\varphi_{ij}\,d\Delta\varphi_{ik}}$$

3-particle densities = superpositions of ***truly*** correlated 3-particles, and combinatorial components.
We use ***two approaches*** to extract the truly correlated 3-particles component

- Cumulant technique:

$$C_3(\Delta\varphi_{12},\Delta\varphi_{13}) = \rho_3(\Delta\varphi_{12},\Delta\varphi_{13}) - \rho_2(\Delta\varphi_{12})\rho_1(3) - \rho_2(\Delta\varphi_{13})\rho_1(2)$$
$$-\rho_2(\Delta\varphi_{13}-\Delta\varphi_{12})\rho_1(1) + 2\rho_1(1)\rho_1(2)\rho_1(3)$$

- Jet+Flow Subtraction Model:

$$\hat{J}_3(\Delta\varphi_{12},\Delta\varphi_{13}) = \vartheta_3(\Delta\varphi_{12},\Delta\varphi_{13}) - \vartheta_2(\Delta\varphi_{12})B_2(\Delta\varphi_{13})$$
$$-\vartheta_2(\Delta\varphi_{13})B_2(\Delta\varphi_{12}) - B_3(\Delta\varphi_{12},\Delta\varphi_{13})$$

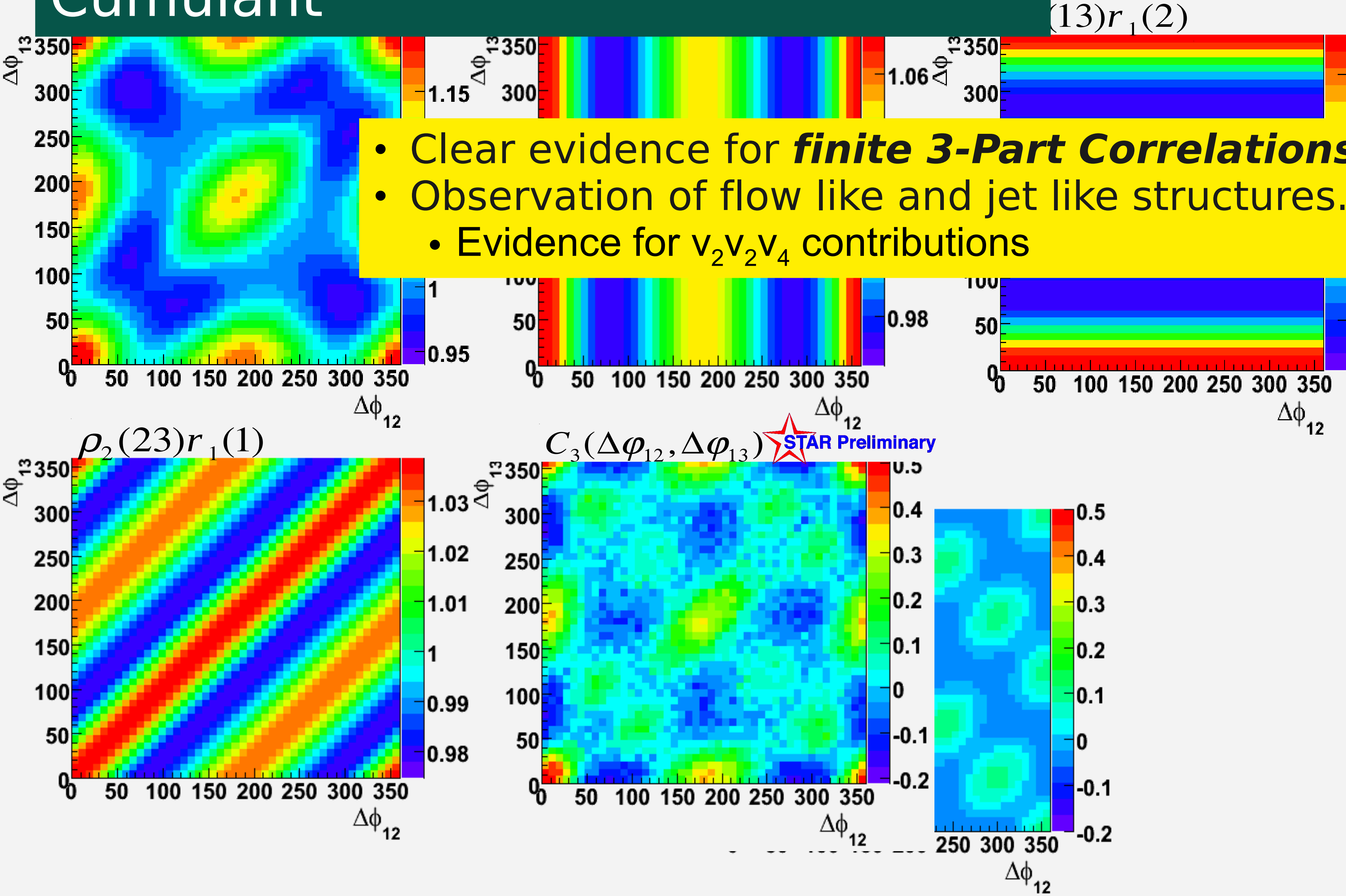
	Cumulant technique	Jet+Flow Subtraction Model
PROs	Simple Definition Model Independent.	Intuitive in concept Simple interpretation in principle.
CONs	Not positive definite Interpretation perhaps difficult.	Model Dependent v_2 and normalization factors systematics

See poster 36 by C. Pruneau & nucl-ex/0608002

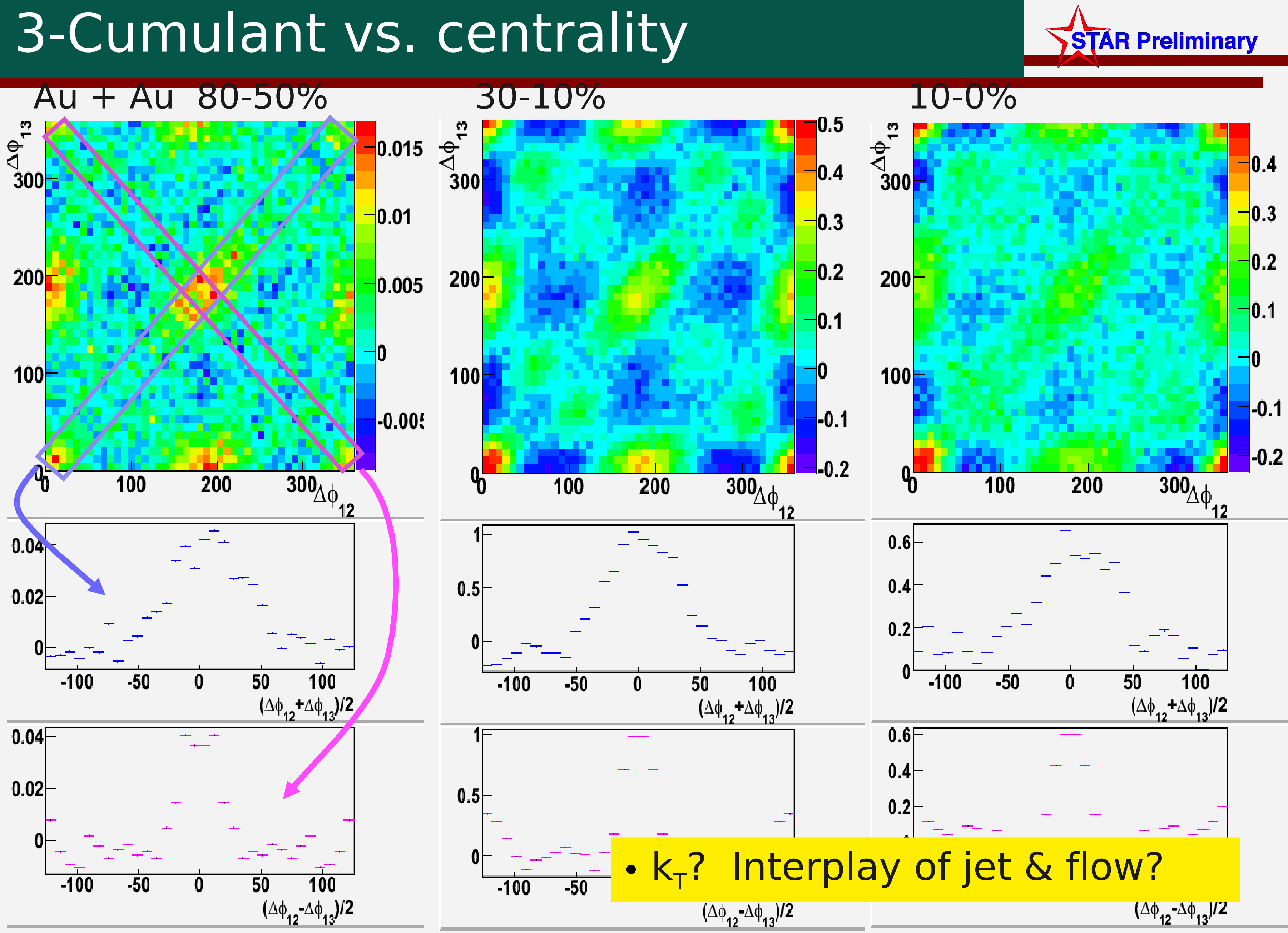
See poster 44 by J. Ulery & nucl-ex/0609017/0609016

Measurement of 3-Particle Cumulant

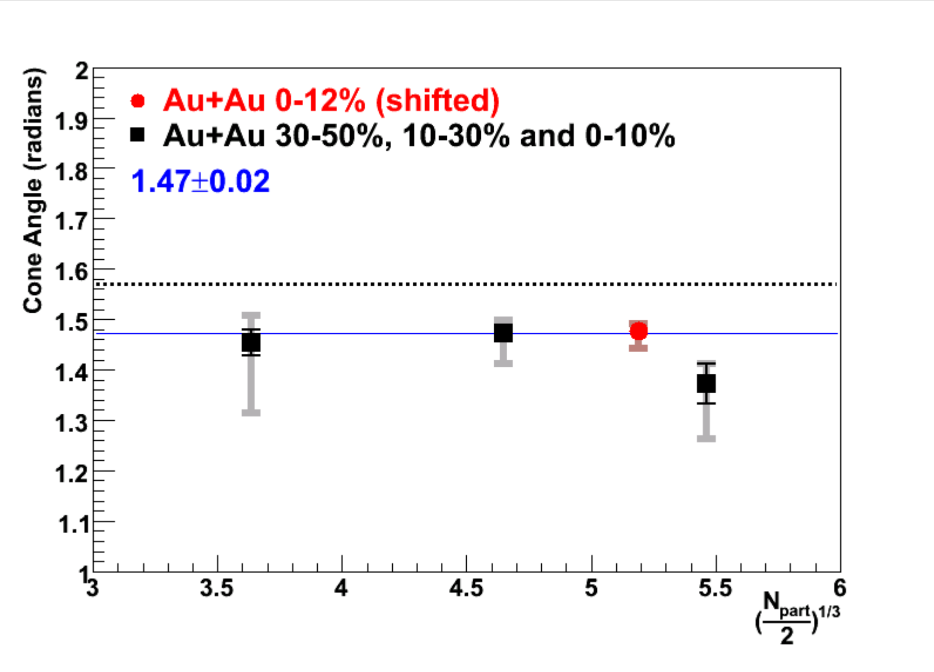
- Clear evidence for ***finite 3-Part Correlations***
- Observation of flow like and jet like structures.
  - Evidence for $v_2 v_2 v_4$ contributions



3-Cumulant vs. centrality



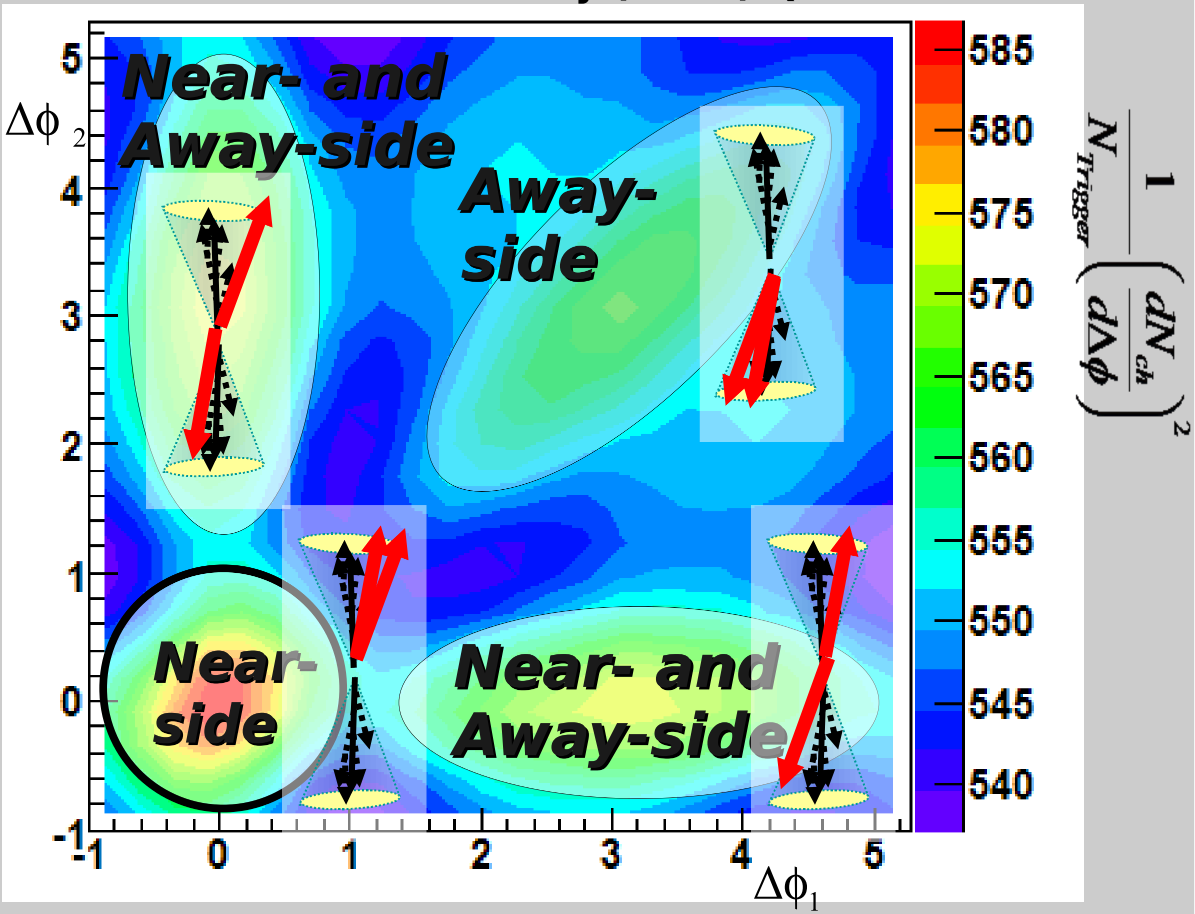
• k_T? Interplay of jet & flow?


Au+Au 0-12% (shifted)
Au+Au 30-50%, 10-30% and 0-10%
1.47±0.02
Cone Angle (radians)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
3
3.5
4
4.5
5
5.5
6
$(\frac{N_{part}}{2})^{1/3}$

3-particle correlations: STAR

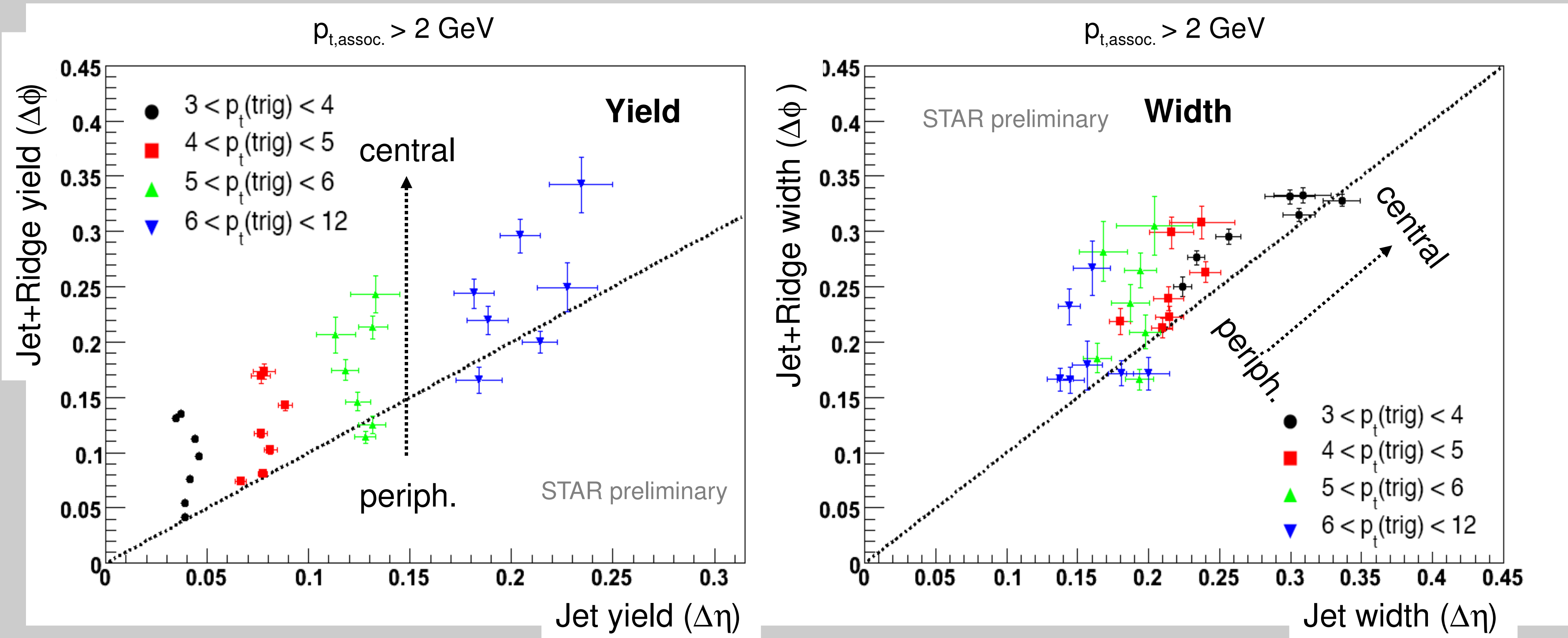
- Trigger particle $3<p_T<4$ GeV/c with pairs of associated particle $1<p_T<2$ GeV/c..
- Complicated background...
  - Raw signal contains (Jet+Bkgd) ⊗ (Jet+Bkgd).
  - To obtain Jet ⊗ Jet we must subtract Bkgd ⊗ Bkgd and Jet ⊗ Bkgd (and Bkgd ⊗ Jet.)

Ulery (STAR) QM05



Jet and Jet+Ridge yields & widths

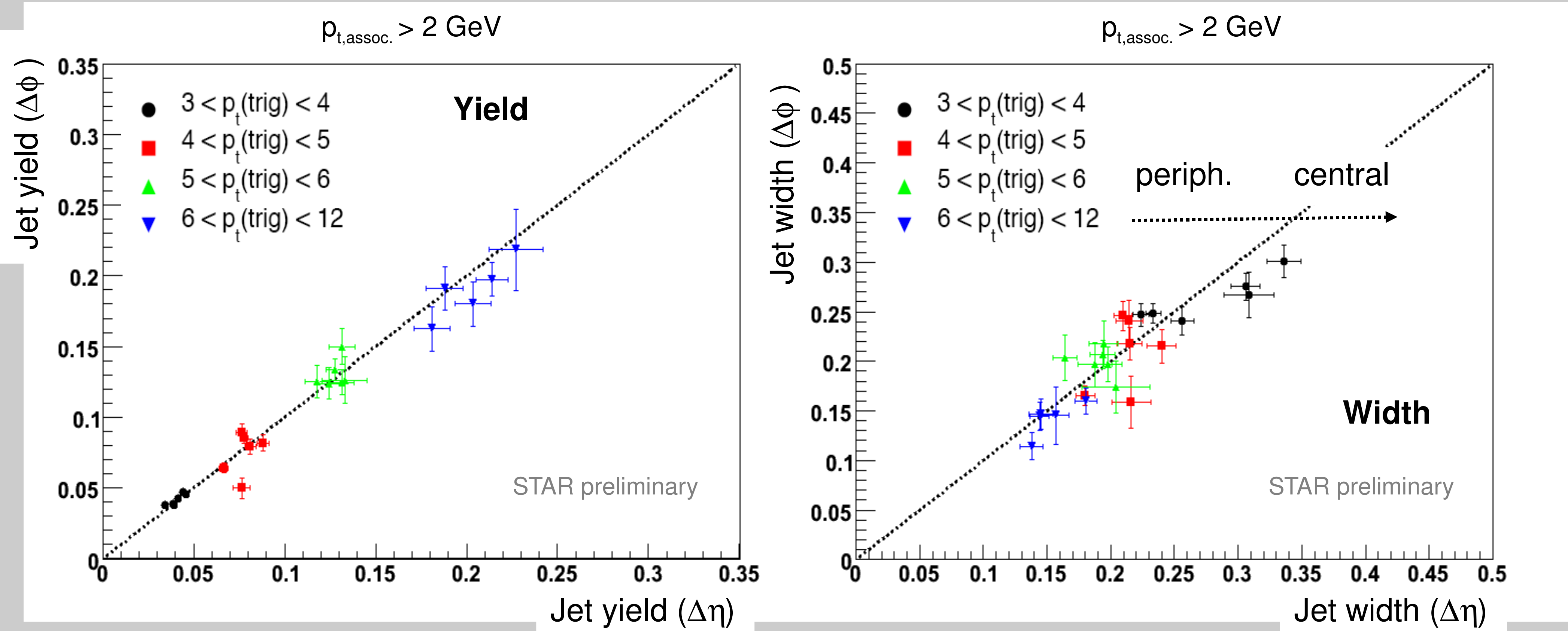
Correlate Jet ($\Delta\eta$(J)) and Jet+Ridge ($\Delta\phi$ (J+R)) widths & yields via centrality



- Jet+Ridge yield increasing with centrality
- Jet+Ridge shape asymmetric in $\Delta\eta$ and $\Delta\phi$

Jet yields & widths: $\Delta\eta$ vs. $\Delta\phi$

Correlate Jet ($\Delta\eta$(J)) and Jet ($\Delta\phi$ (J)) widths and yields via centrality

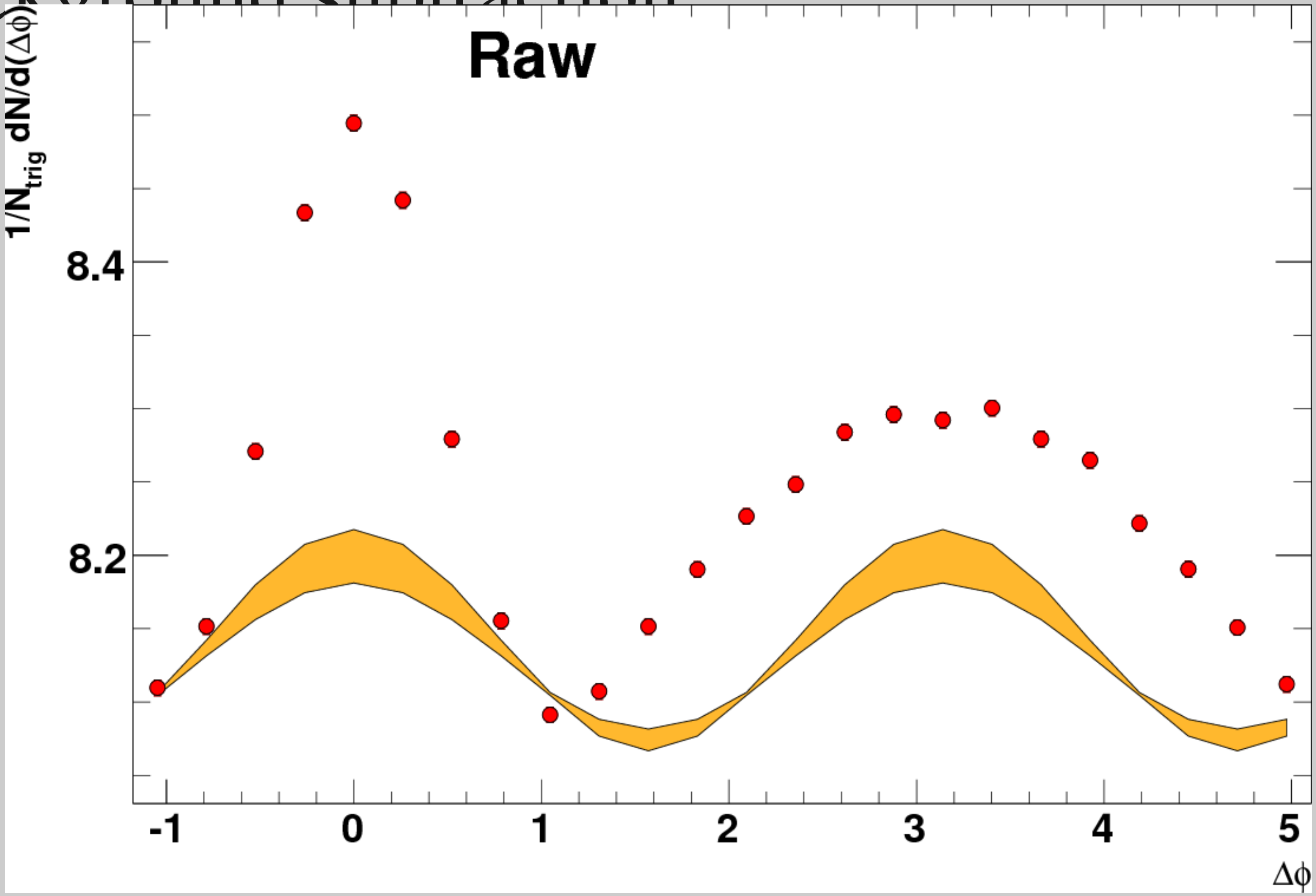


- Jet yield ~ symmetric in $\Delta\eta\times\Delta\phi$
- Jet shape ~ symmetric in $\Delta\eta\times\Delta\phi$ for $p_{t,trig}$ > 4 GeV

(asymmetric in $\Delta\eta$ for $p_{t,trig}$ < 4 GeV)

A caveat...

- Large background subtraction

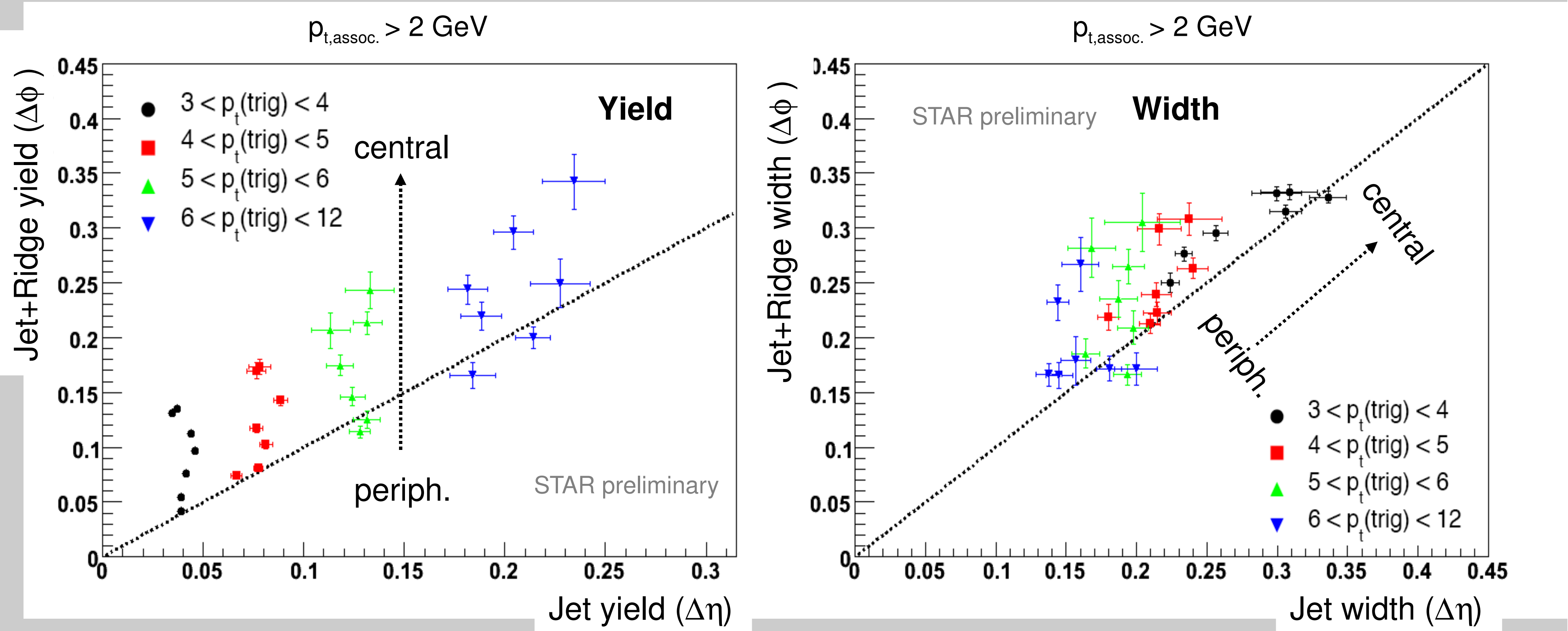


3-particle correlations: STAR background

- Add page(s) w/ equations

Jet and Jet+Ridge yields & widths

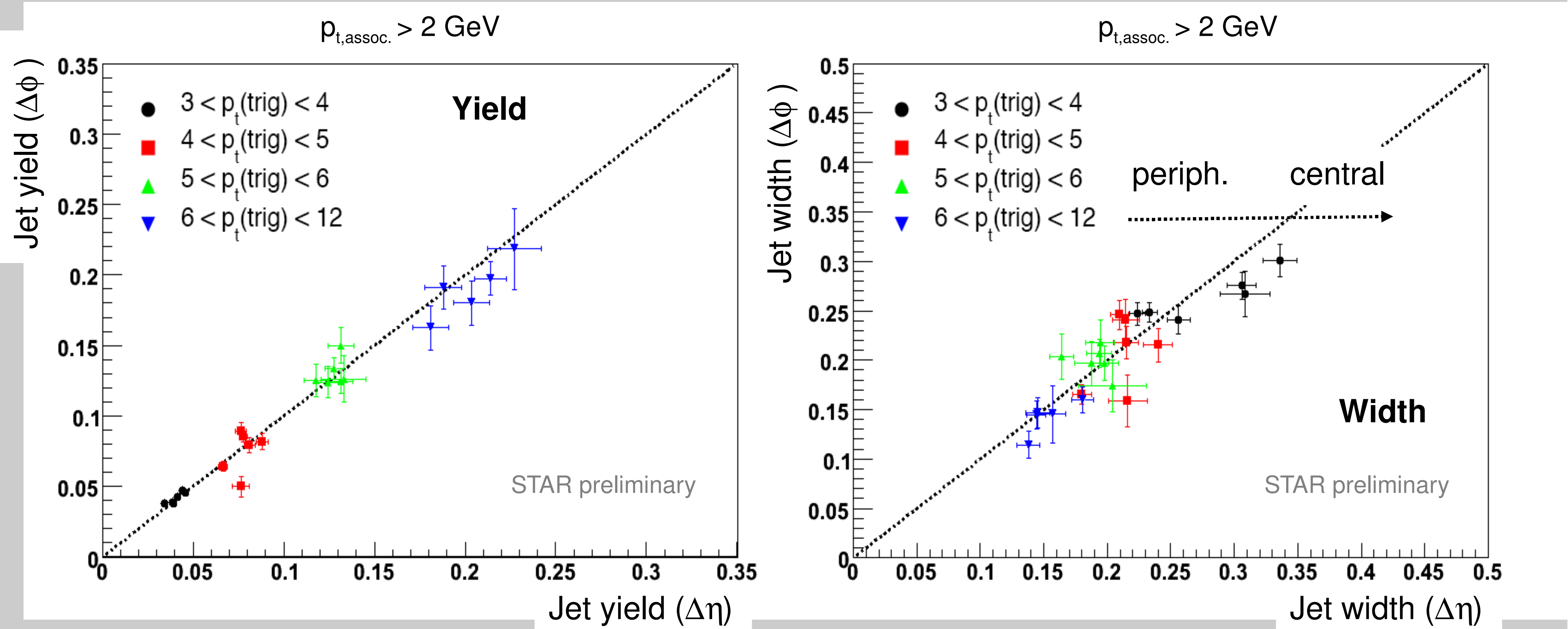
Correlate Jet (Δη(J)) and Jet+Ridge (Δϕ (J+R)) widths & yields via centrality



- Jet+Ridge yield increasing with centrality
- Jet+Ridge shape asymmetric in Δη and Δϕ

Jet yields & widths: Δη vs. Δφ

Correlate Jet (Δη(J)) and Jet (Δφ (J)) widths and yields via centrality



- Jet yield ~ symmetric in Δη× Δφ
- Jet shape ~ symmetric in Δη× Δφ for $p_{t,trig}$ > 4 GeV

(asymmetric in Δη for $p_{t,trig}$ < 4 GeV)

Away-side: Motivation

- See shape change in 2-D correlations
- apparent peak at dphi != pi
- already see strong dependence on the background subtraction
- Qualitatively STAR and PHENIX see the same thing
- shape change as you go peripheral -> central
- quantitatively STAR and PHENIX disagree dramatically on size of systematic errors

3-particle correlations

- Two different approaches to measurement w/ different ways of plotting data
- Similar qualitative results – weak support for conical emission
- Statistical errors - can be reduced
- Systematic errors – can they be reduced?