STAR HIGH P_T

Oana Catu, Yale University,

for the STAR Collaboration

Motivation

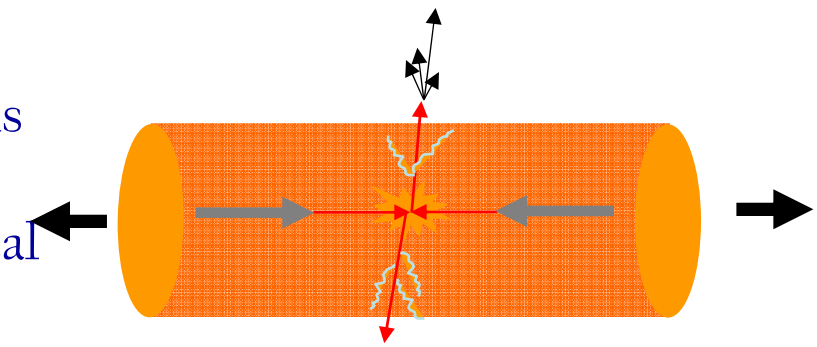
Use high-p_T particles and jets to *probe the hot medium*

measure medium properties

- Density, temperature, number of degrees of freedom
- Dynamical properties (e.g. viscosity)

• produced in the early stage of the collisions and interact with the produced medium

- can be calculated using pQCD – theoretical handle
- can be calibrated by reference measurements (p-p)



• Many interesting (sometimes surprising) experimental results already – promising topic

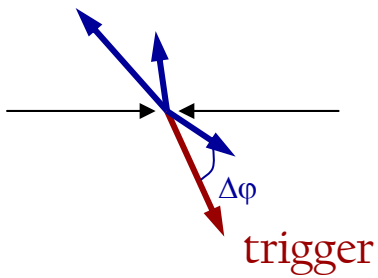
- Results stimulated new theoretical ideas – experiment driven area

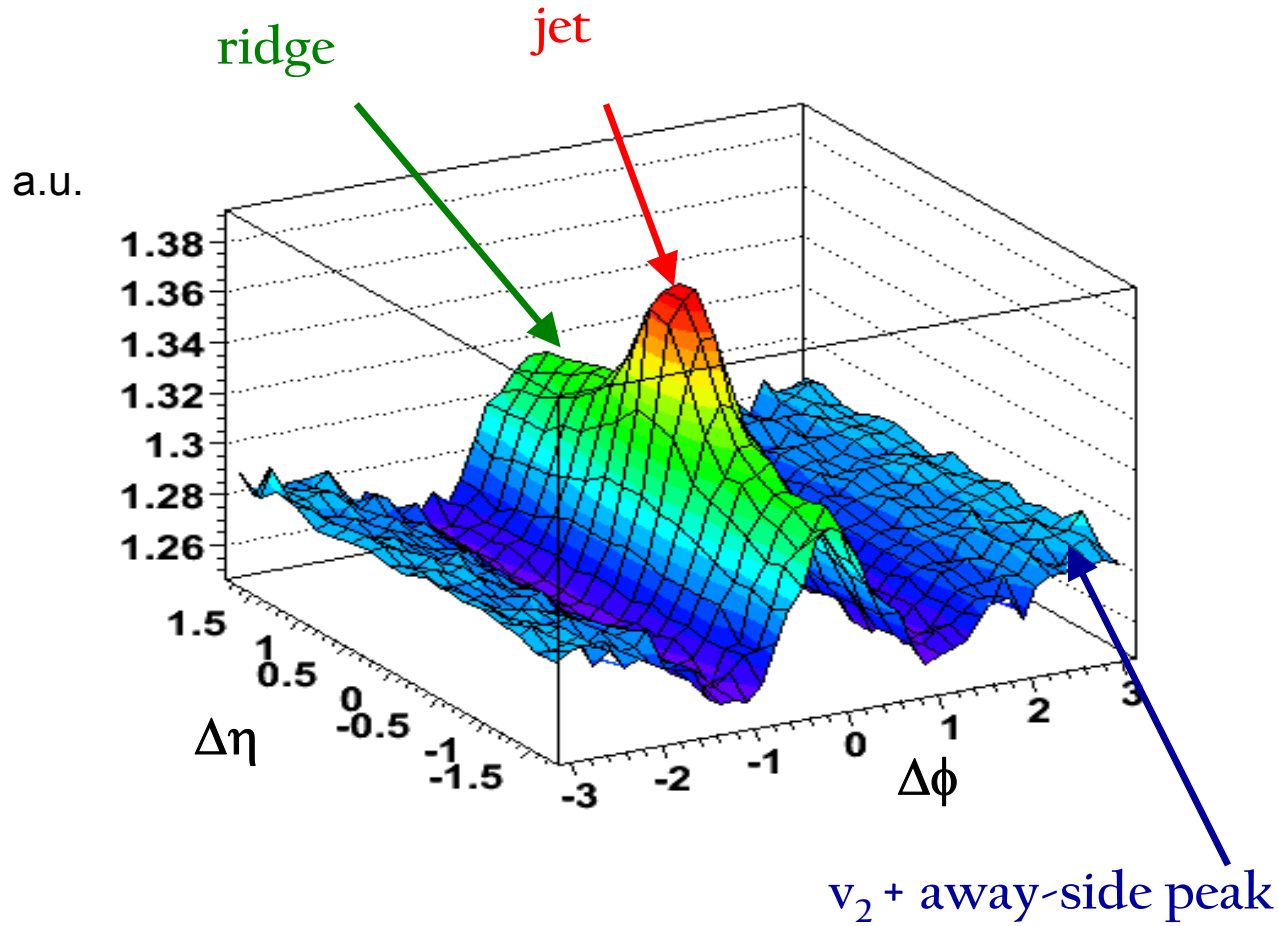
Outline

- **Hadron Correlations:**
  - Charged and identified
  - Near-side - Interaction of jet with bulk –"ridge"
    - Baryon/meson composition of jet, ridge
    - Dihadron fragmentation functions
  - Away-side
    - Suppression of dihadron fragmentation functions – determine the energy loss parameter
    - modification of shape at lower $p_{T\ assoc}$
    - Closer look using 3 particle correlations
    - new analysis pin-pointing di-jet axis
- **γ-h correlations in p+p** – Calibrated parton energy

Fragmentation and energy loss - near-side

Di-hadron correlations





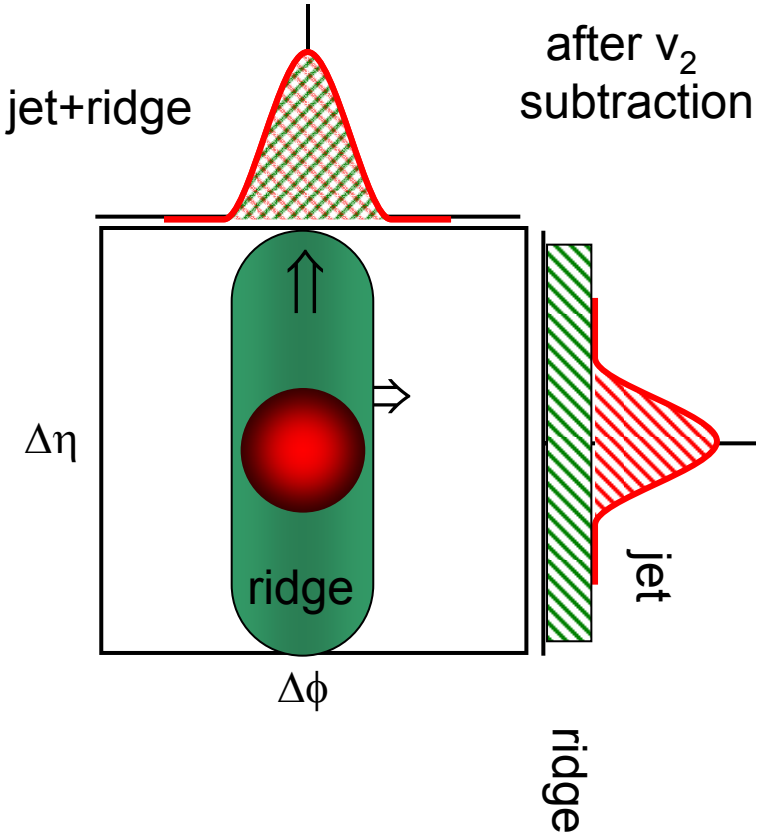
Au+Au central @ 200 GeV

p_T^{trig}=3-6 GeV/c,
1.5 GeV/c ‹p_T^{assoc}‹ p_T^{trig}

Au+Au: long-range Δη correlations at near side ("the ridge")

Lesson: The near-side jet does interact with the medium

Extracting the ridge and jet yields

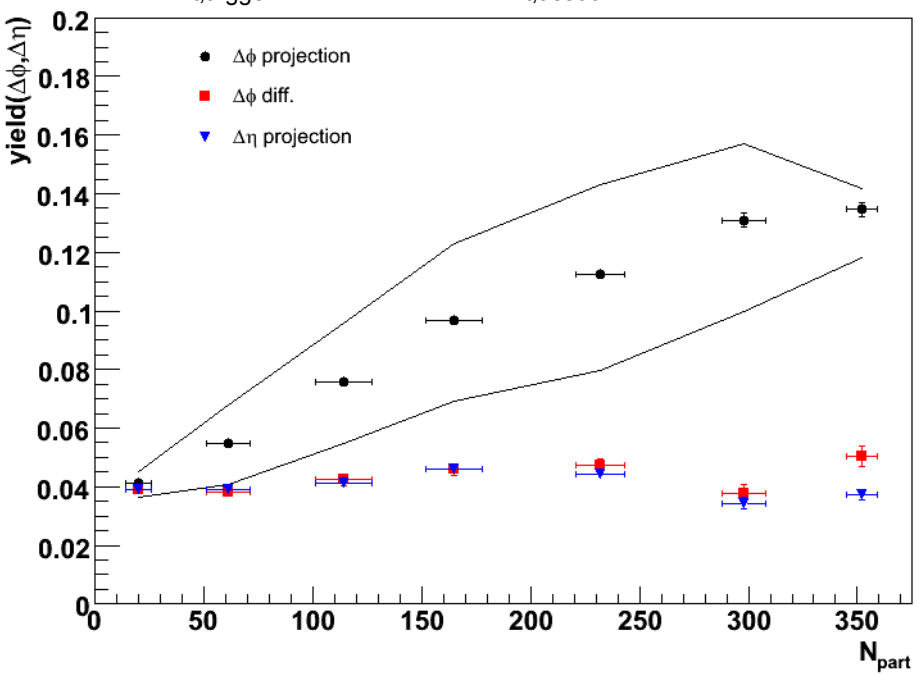


Near-side yield : $\Delta\phi$ (J+R) = $\Delta\phi$ (J) + $\Delta\phi$ (R)
Jet yield : $\Delta\phi$ (J) = $\Delta\phi$ ($|\Delta\eta| < 0.7$) - $\Delta\phi$ ($|\Delta\eta| > 0.7$)
Ridge yield : $\Delta\phi$ (R) = $\Delta\phi$ (J+R) - $\Delta\phi$(J)

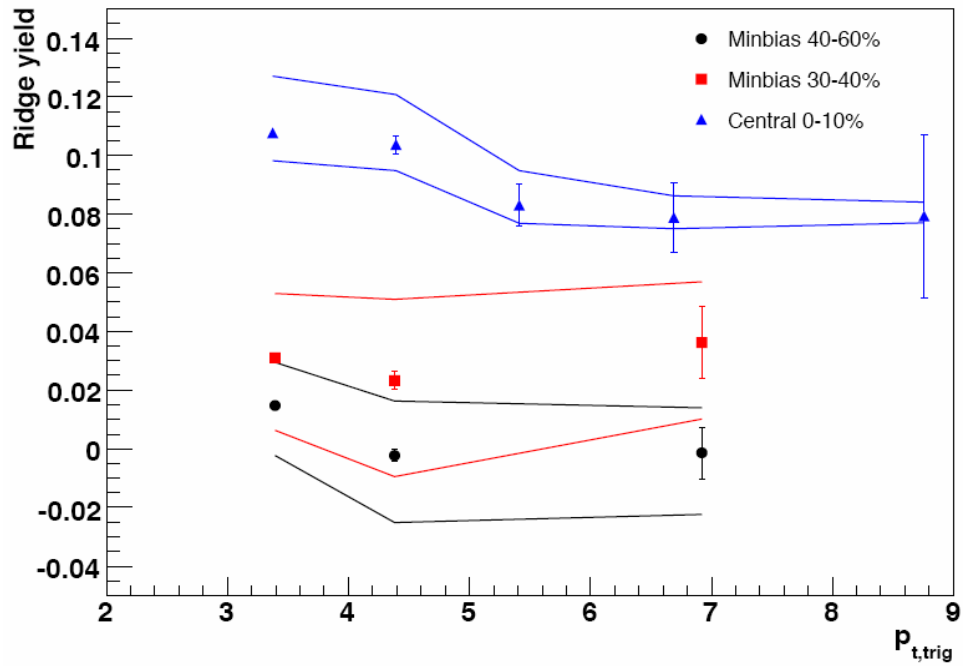
Centrality, $p_{T\ trigger}$ dependence of near-side yield

Au-Au at $\sqrt{s}$=200GeV

$3 < p_{t,trigger} < 4$ GeV and $p_{t,assoc.} > 2$ GeV



$p_{t,assoc.} > 2$ GeV

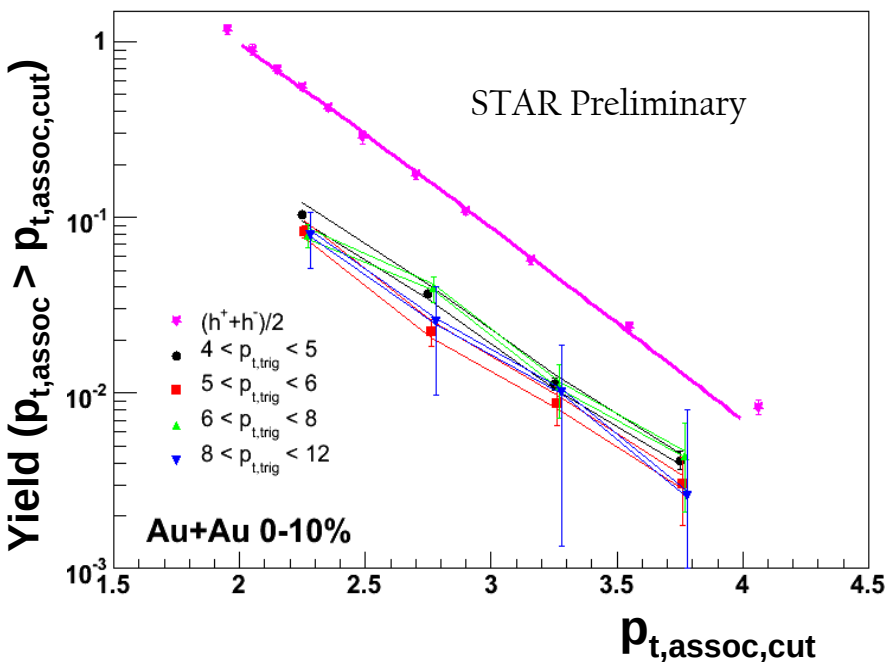


Ridge yield increases sharply with centrality
Jet yield independent of centrality

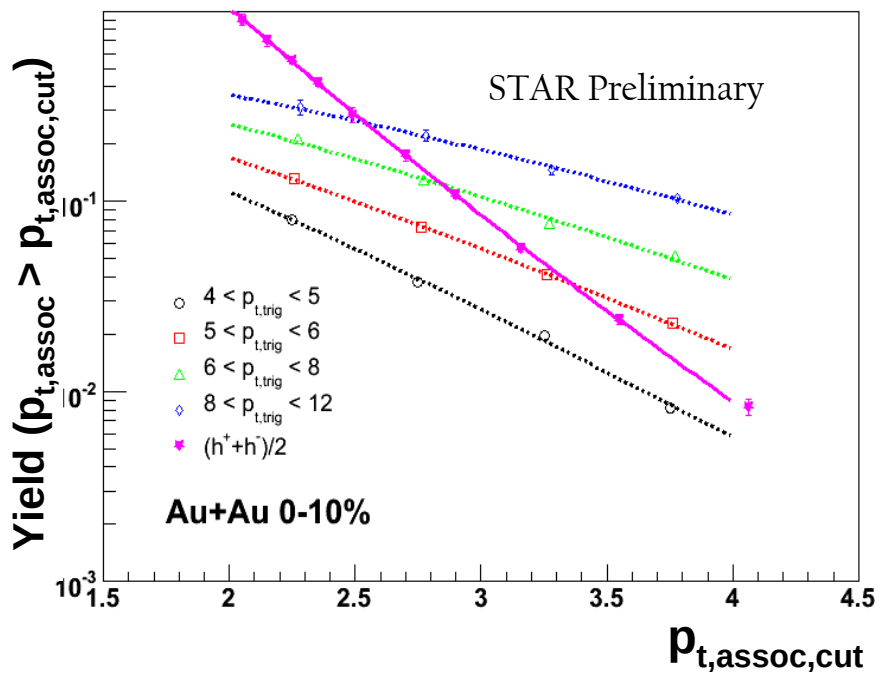
Ridge yield ~ constant as function of trigger p_T (slightly decreasing in central collisions)

Ridge and jet p_T- spectra

Ridge spectra



Jet spectra



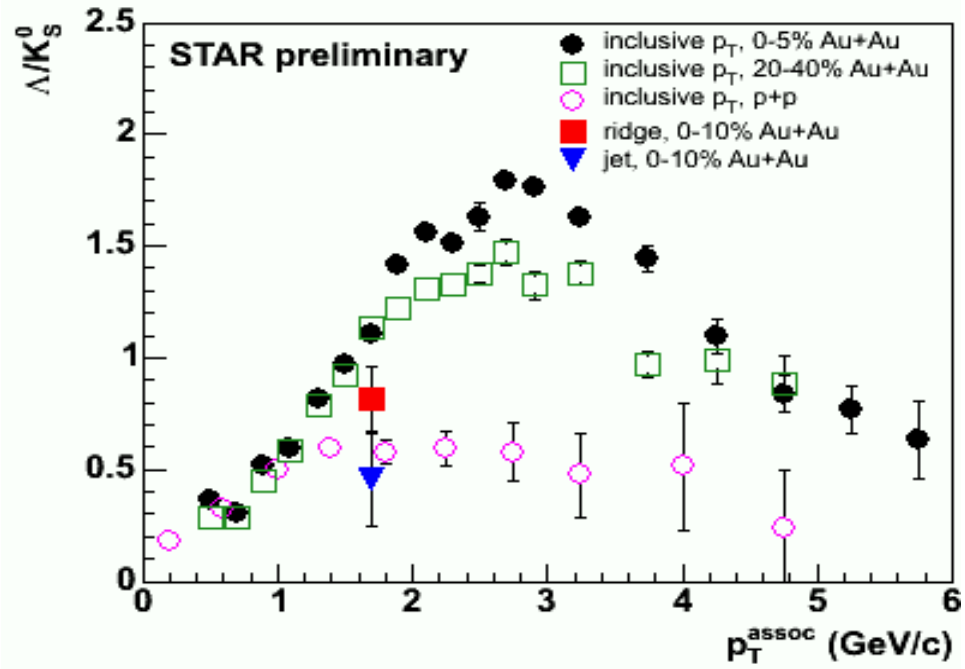
Ridge p_T-spectra are 'bulk-like'

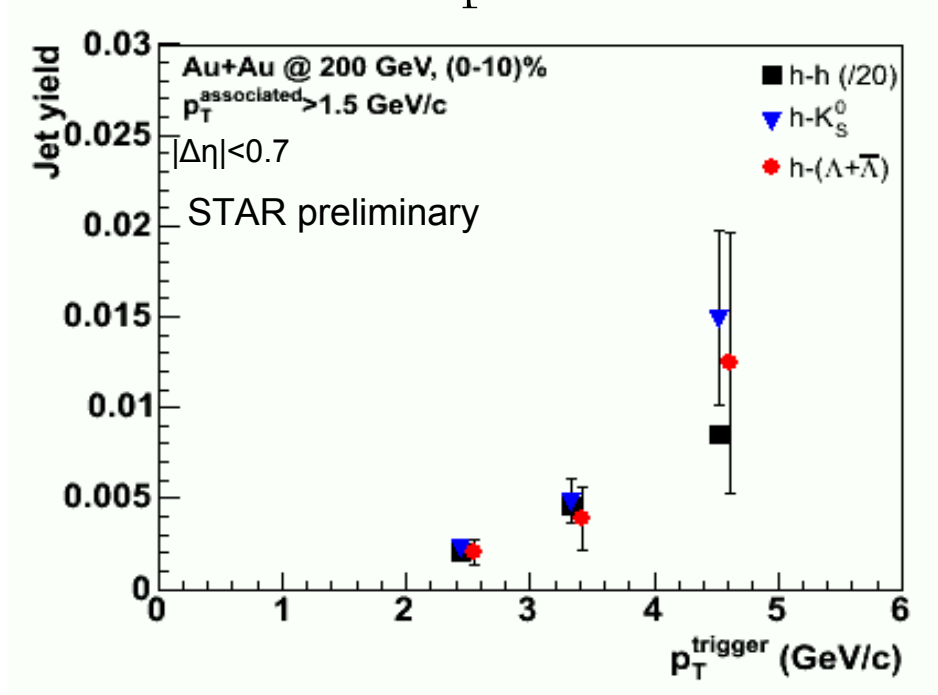
Jet spectra – much harder, harder for higher $p_{T\ trigger}$

Ridge spectra slopes - independent of $p_{T\ trigger}$

Particle composition of the ridge

By studying correlations with identified associated particles





Λ/K^0_S ratio:

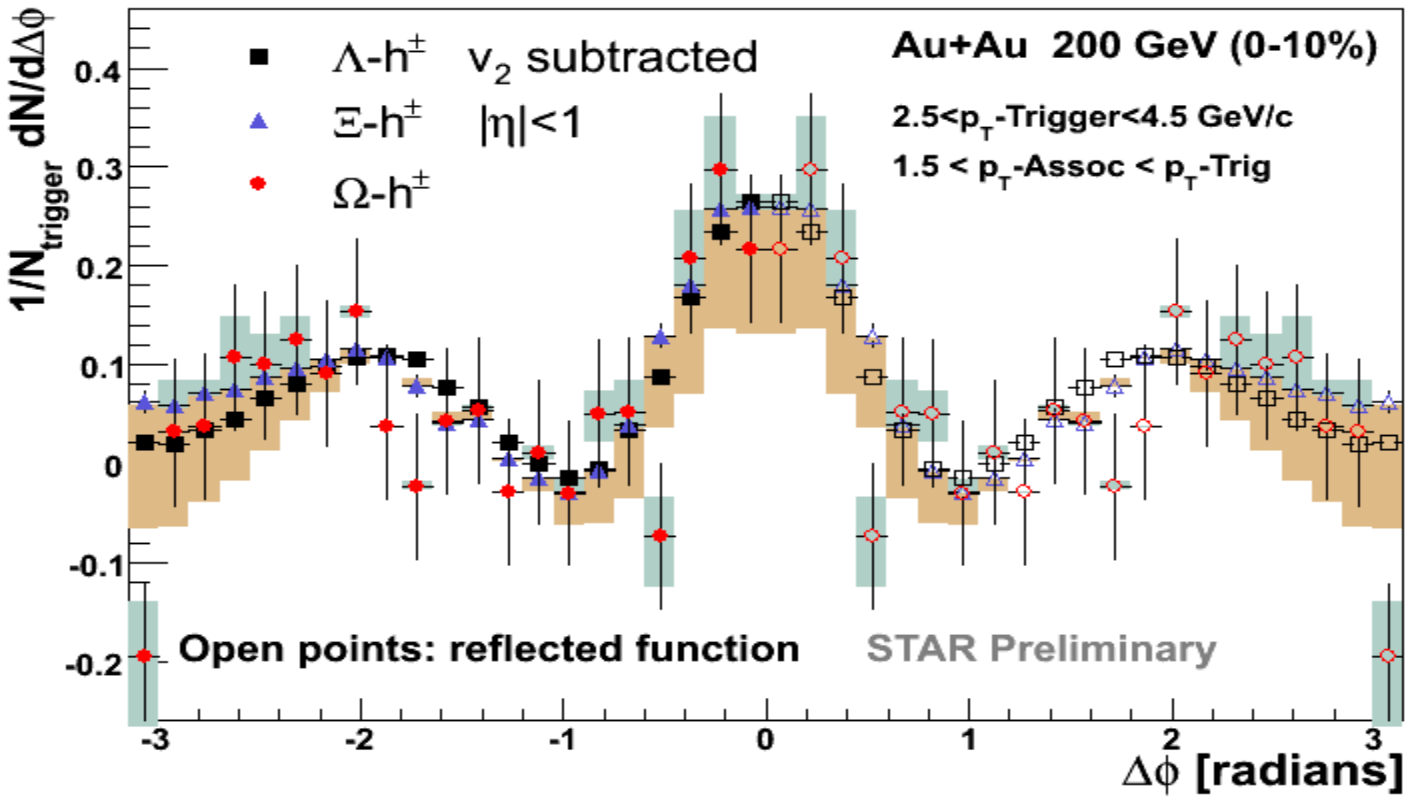
in the ridge: ~ 1.0 → similar to that from inclusive p_T spectra

in the jet: ~ 0.5 → consistent with p+p

Ridge – medium response

- several models on the market – need more quantitative predictions to pin down mechanism

Λ,Ξ,Ω-h correlation



Near-side yield similar for Λ, Ξ, Ω triggered correlations

Initial expectation: Ω dominantly from TTT recombination, no associated yield

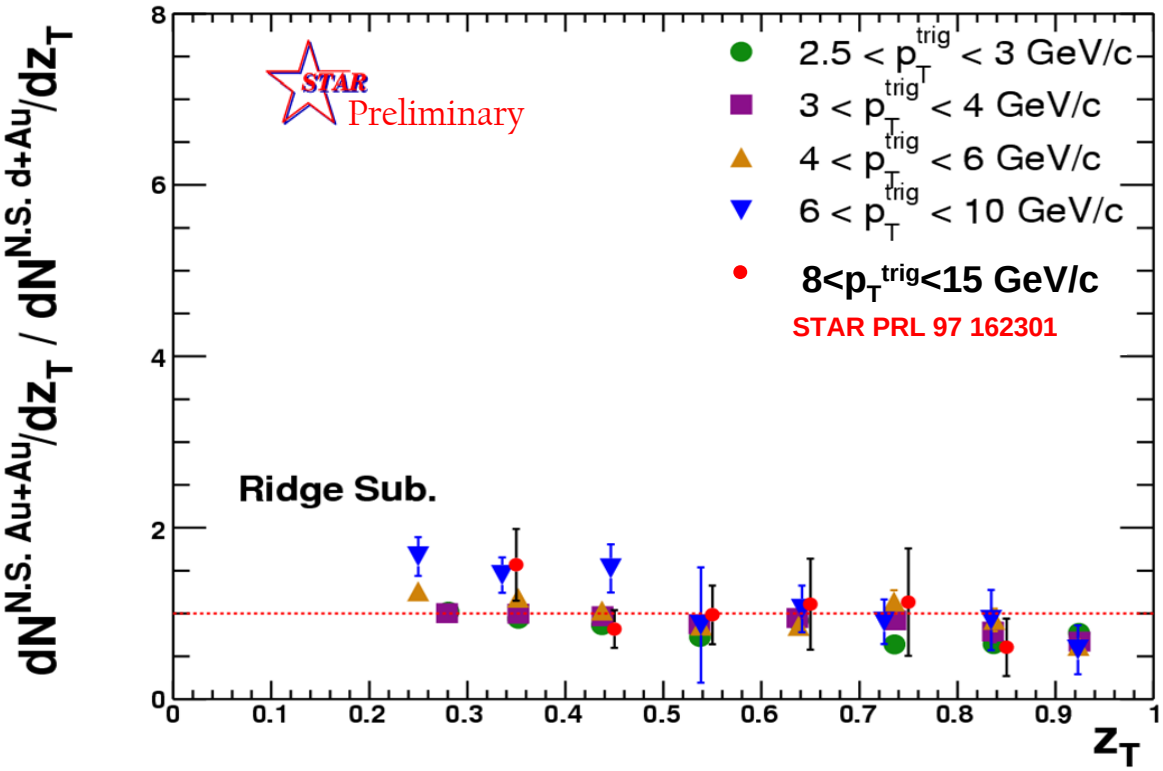
R. C. Hwa et al., nucl-th/0602024

Revisited (at QM06): possible large contribution from reheated medium

Experimental tests pending

Near-side z_T Distributions: "Jet"

- Measure hadron triggered fragmentation functions:
  - $D^{h1,h2}(z_T)$
  - $z_T = p_{T\,assoc}/p_{T\,trigger}$
- Ratio Au-Au/d-Au



$$D^{h_1 h_2}(z_T, p_T^{\rm trig}) = p_T^{\rm trig} \frac{d\sigma_{AA}^{h_1 h_2}/dp_T^{\rm trig} dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\rm trig}}$$

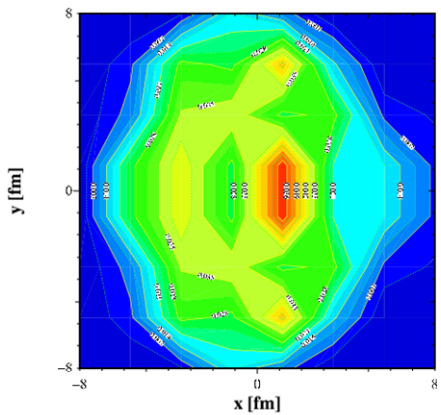
Near-side z_T distributions similar to dAu

no 50% dilution from thermal coalescence triggers?

R. Hwa, C.B. Yang - Phys.Rev. C70 (2004) 024905

Away-side suppression at high p_T

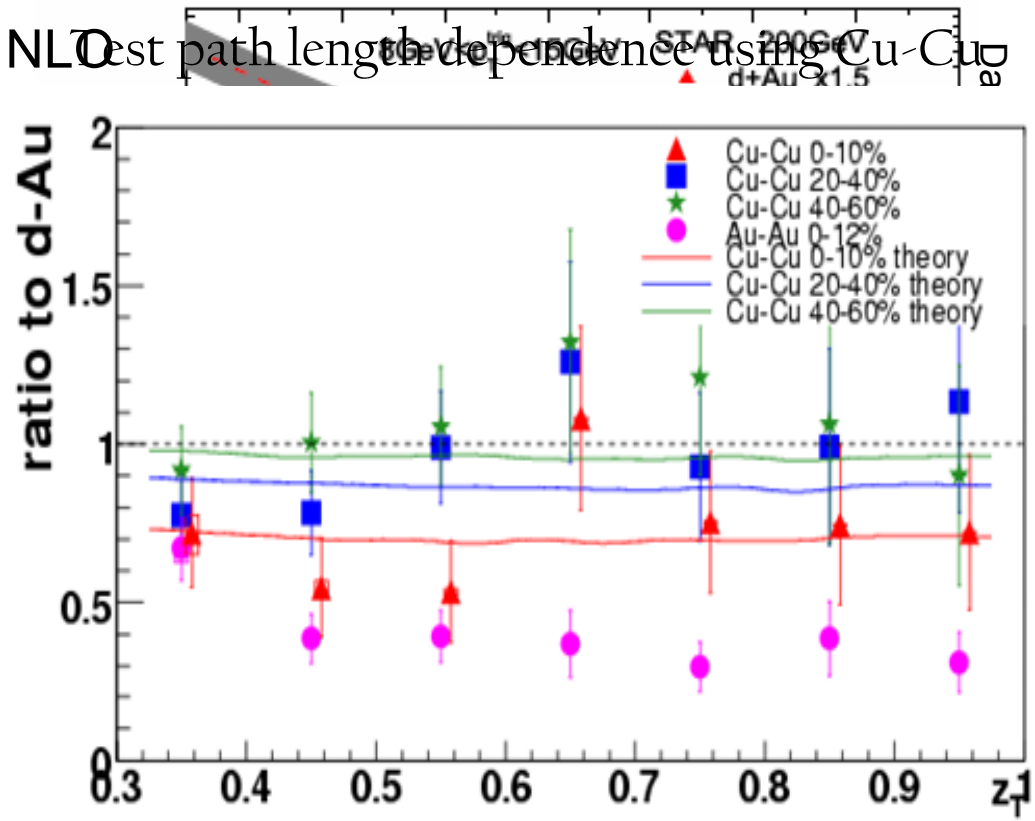
Emission points
Hydro profile



T. Renk and Eskola, hep-ph/0610059

Dihadron suppression: smaller surface bias, potentially better probe of the medium density

NLO test path length dependence using Cu-Cu



Theory: H. Zhang, J.F. Owens, E. Wang, X-N. Wang nucl-th/0701045

Extracted transport coefficient

$$q_0 \tau_0 \sim \hat{q} = 2.8 \pm 0.3 \text{ GeV}^2/\text{fm}$$

Input from other theory groups ?

Away-Side: shape modification

Away-side:

- Structures depend on p_T.
- becomes flatter with increasing p_T^{trig}
- yield increases

$1.3 < p_T^{assoc} < 1.8$ GeV/c

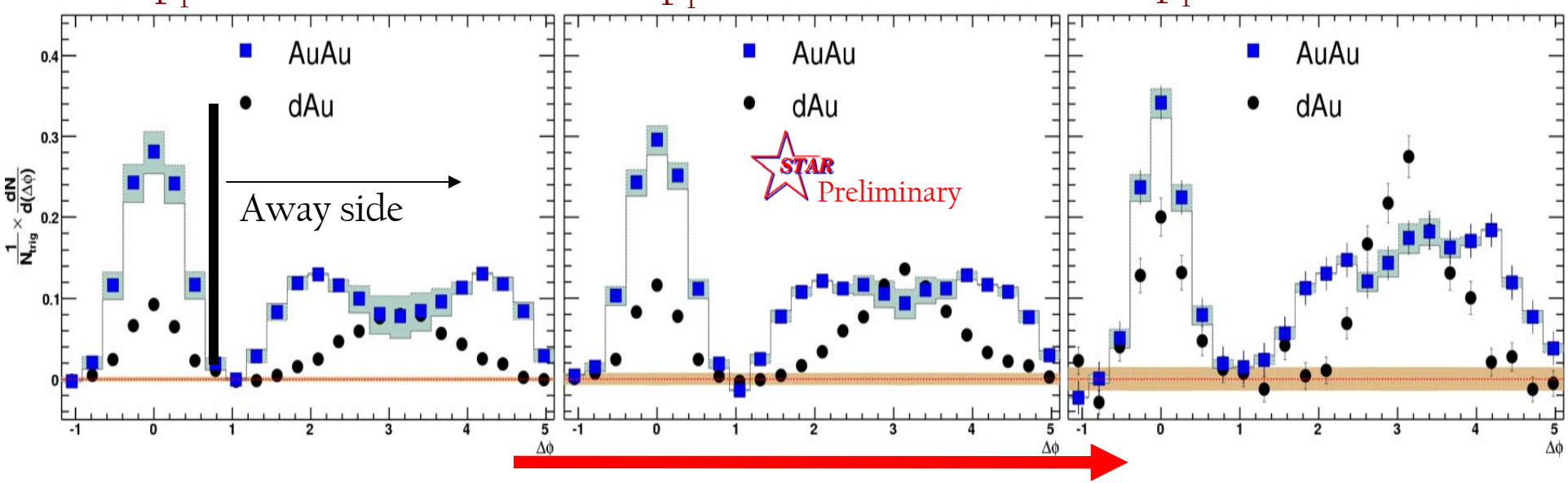
AuAu 0-12%

A central contribution "filling in" the dip at higher p_T^{trig} ?

$3.0 < p_T^{trig} < 4.0$ GeV/c

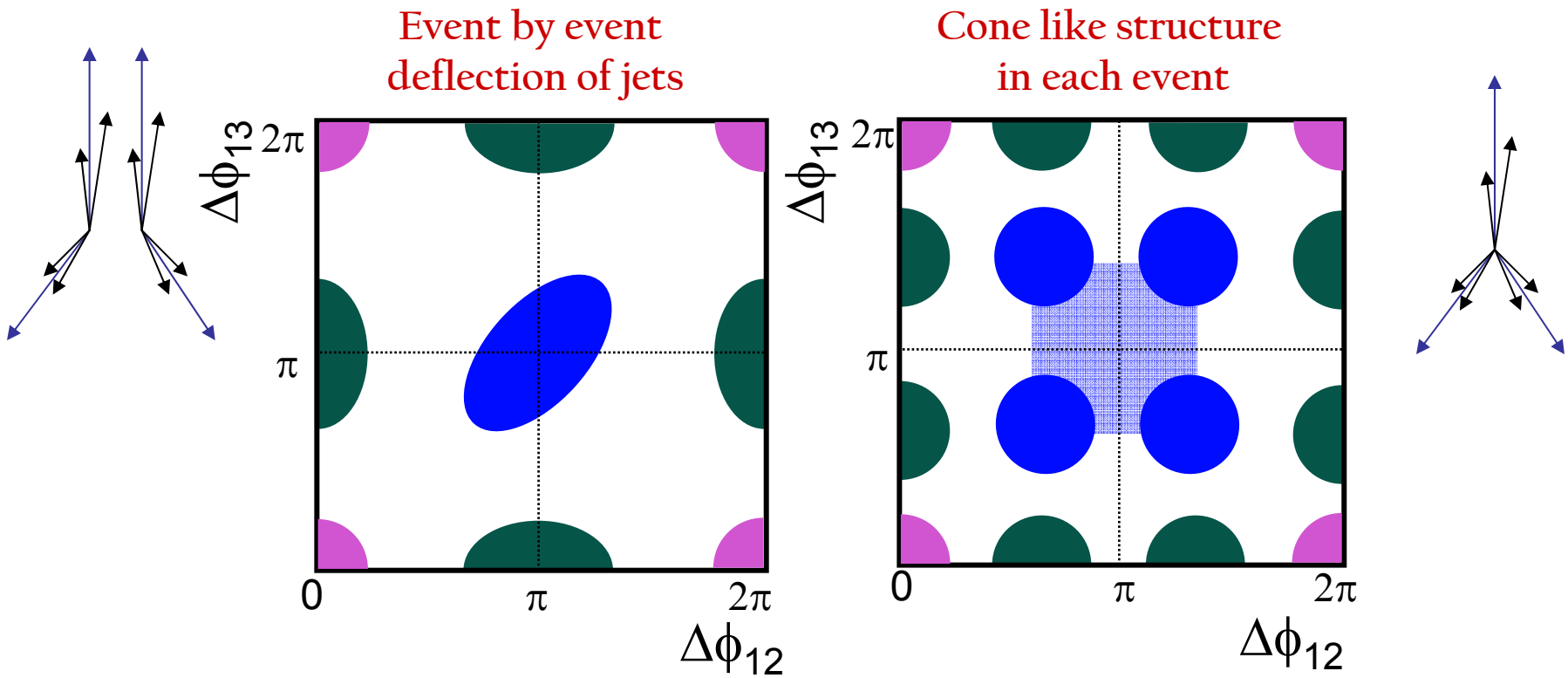
$4.0 < p_T^{trig} < 6.0$ GeV/c

$6.0 < p_T^{trig} < 10.0$ GeV/c



Oana Catu, Yale University

3-particle correlations



3-particle $\Delta\varphi$-$\Delta\varphi$ probes away-side structure:

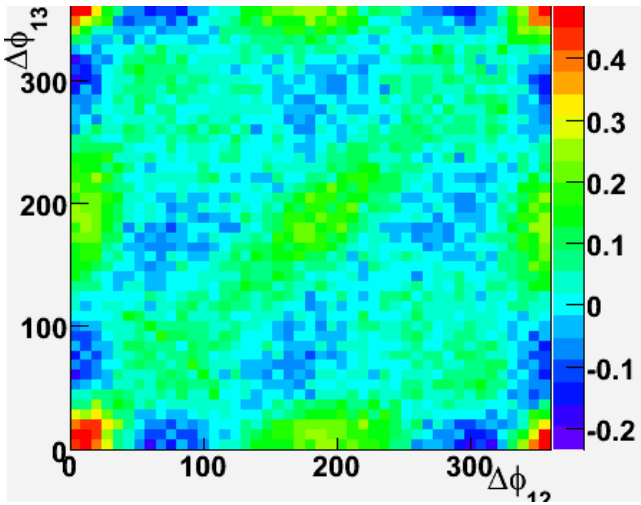
Distinguish event-by-event deflection vs
conical (Mercedes) emission pattern

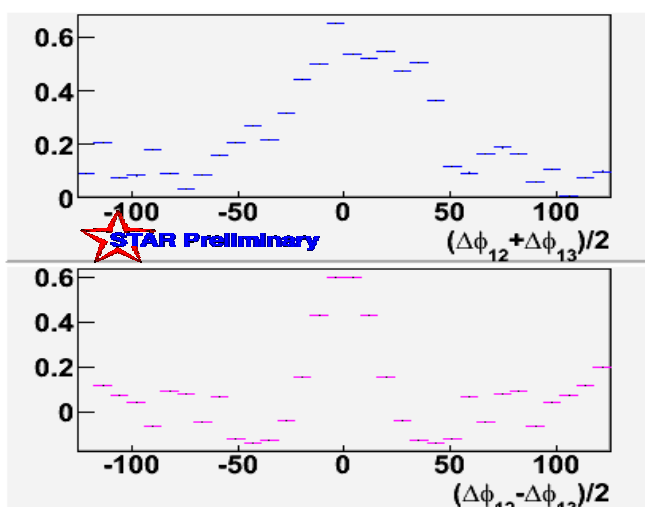
However: Large backgrounds, background shapes not simple

3-particle results

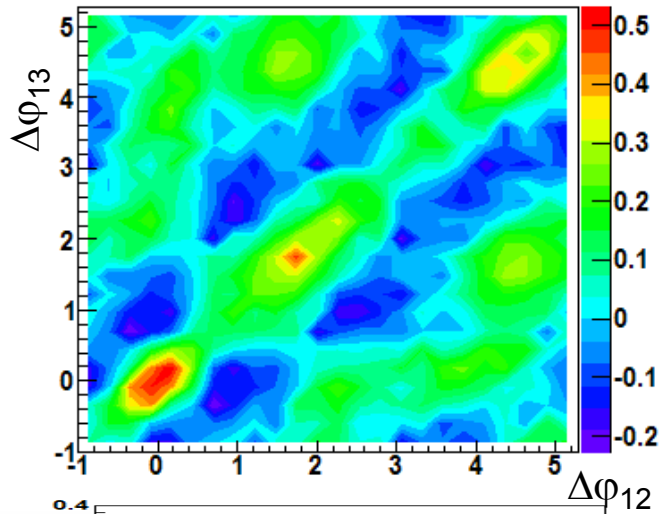
Used two approaches to extract the truly correlated 3-particles component

Cumulant analysis:
Model-independent
Non-zero 3-particle structure



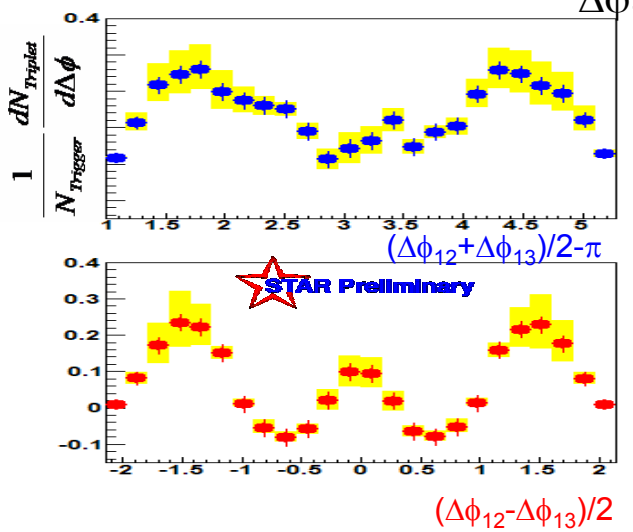


Jet+background analysis:
Model-dependent, more sensitive
Off-diagonal peaks consistent with conical emission



Au+Au 0-12%

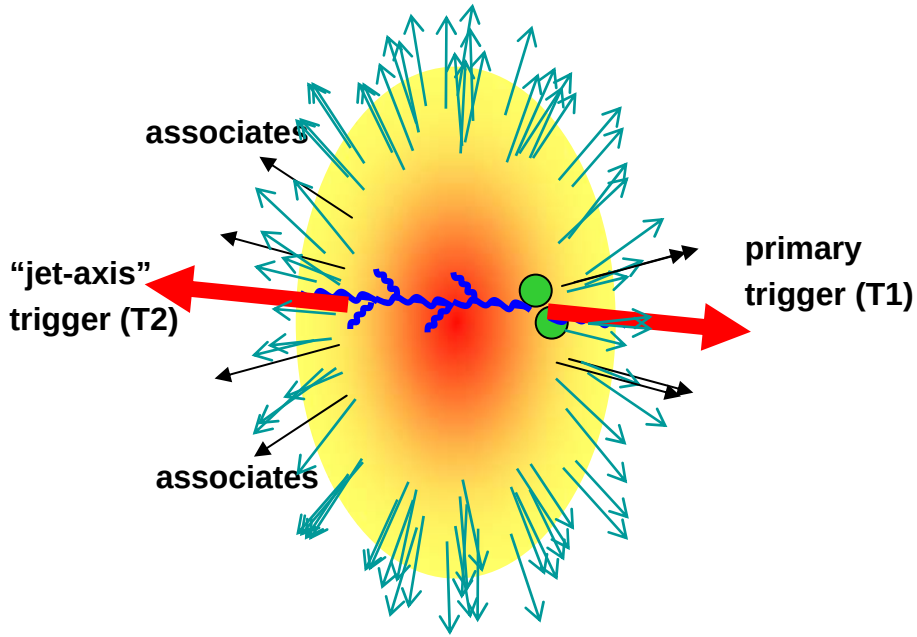
$3 < p_{T,trig} < 4$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c

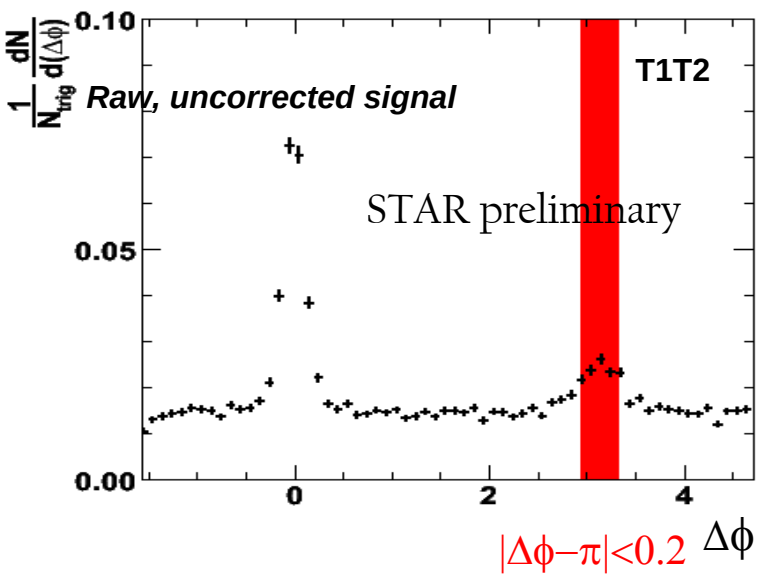


Need more clear understanding of the 3-particle structure

2+1 Correlations: Selecting di-jet events

- Aim of analysis – "pin" the jet axis
- Require that the 2 highest p_T particles are back-to-back in ϕ
- *Assume* this defines the jet-axis
- Correlate all particles with this axis



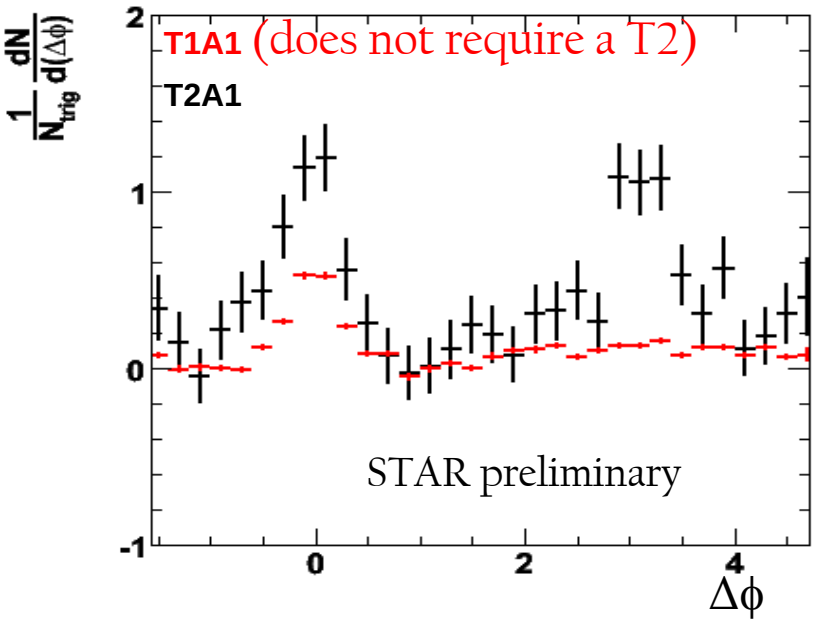


T1: p_T>5GeV/*c*

T2: p_T>4GeV/*c*

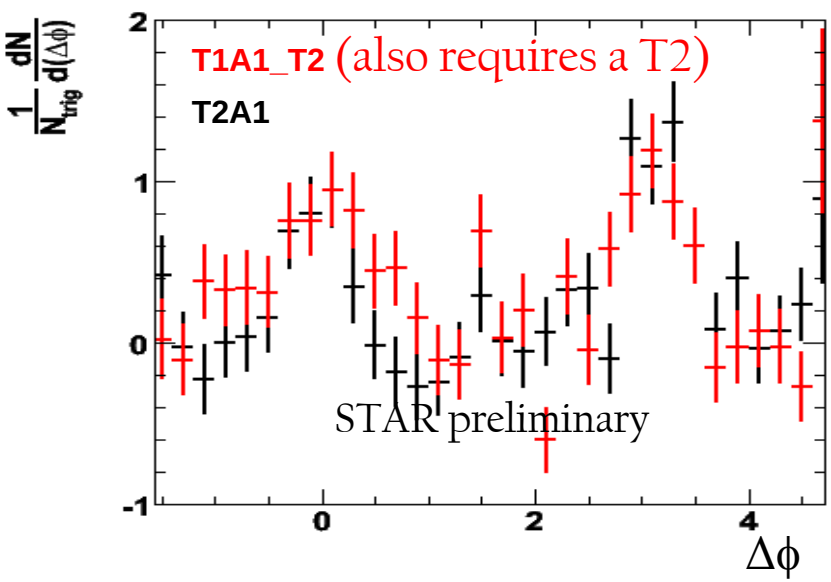
A: p_T>1.5GeV/*c*

2+1 Correlations - Results



Di-jet trigger - no modification on away-side

- Surface dominated?
  - No energy loss for di-jets?



Correlation of associates with:

- T1 (also requires a T2)
- T2

Detailed shape of near- and away-side is the same

Towards γ-jet: (γ,π0)-h Δϕ Correlations

- High E_T Clusters - trigger particles

  $E_T^{trig} > E_T^{threshold1}$

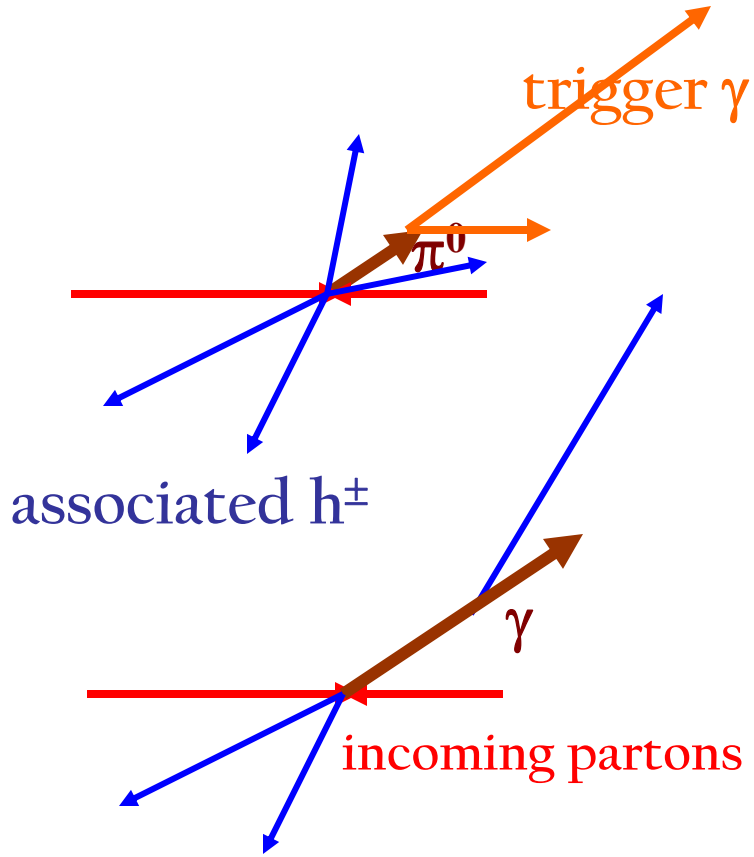
  (6.5-8.5GeV/c, 8.5-10.5 GeV/c ...)

- Associated tracks:

  $E_T^{trig} > p_T > p_T^{threshold2}$

  (> 1GeV/c)

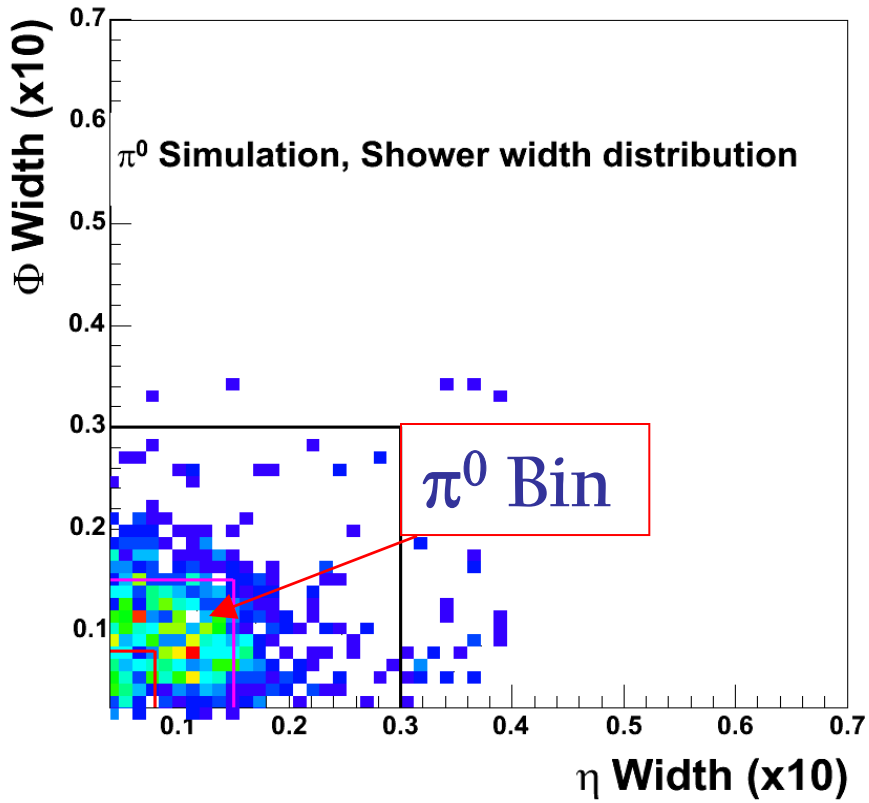
- 3x3 tower Charged-track-Veto for pure photon candidates

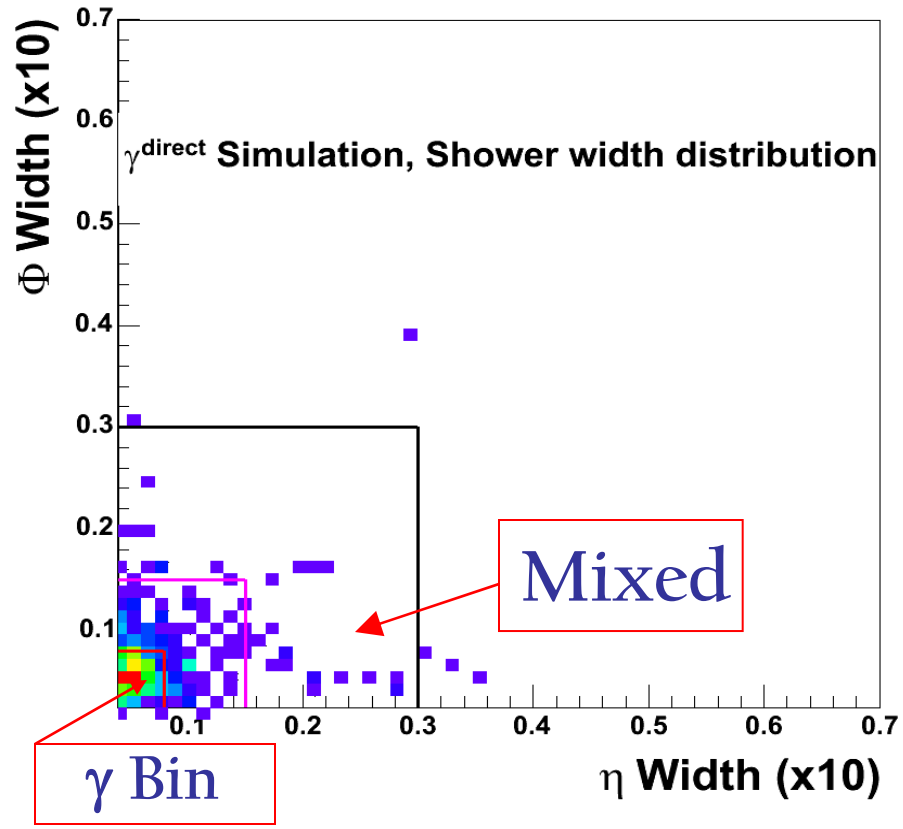


Selection of photon-rich samples

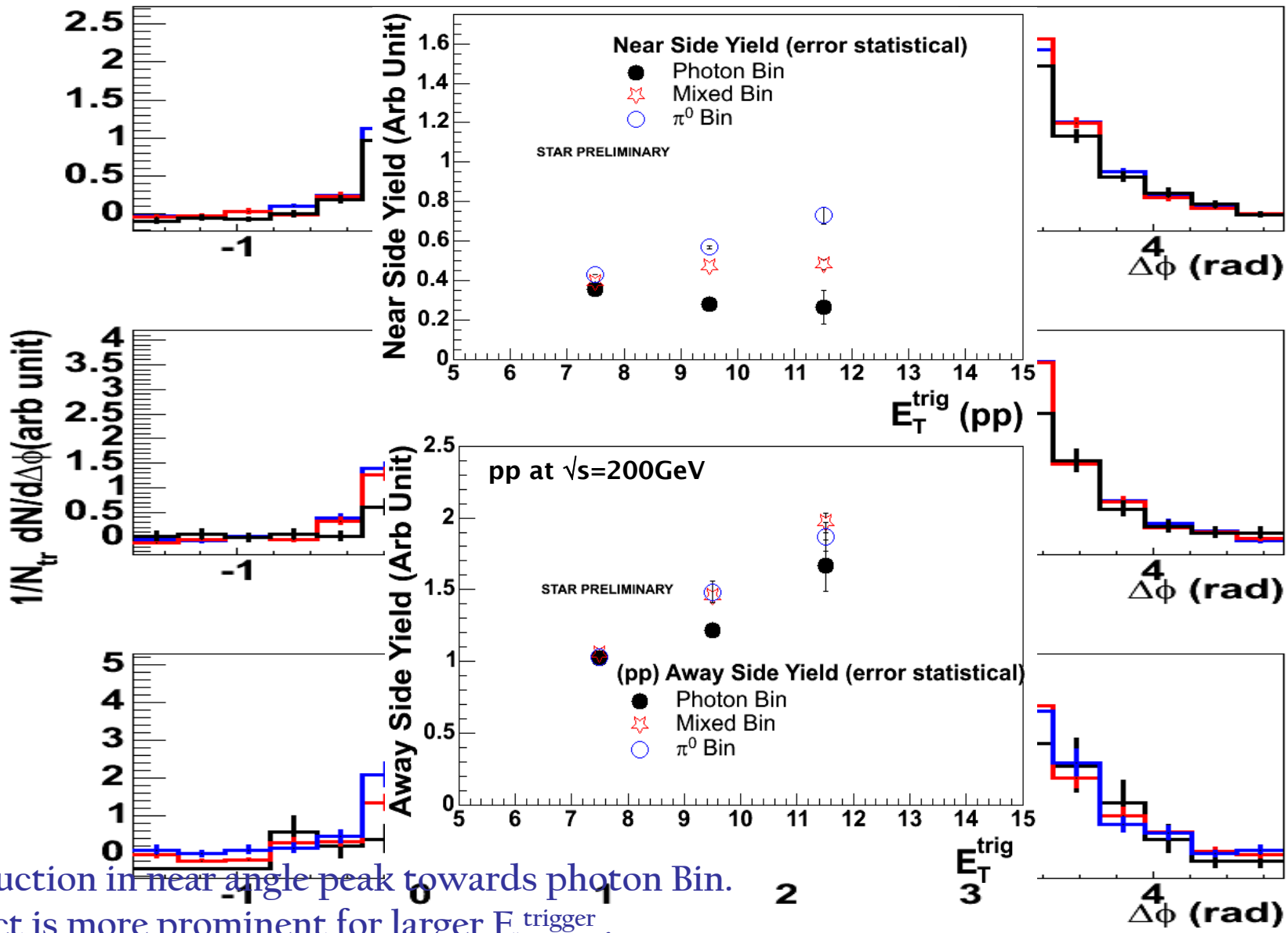
2D shower shape analysis

2D Selection regions varied to get optimum results





(γ,π0)-h Δϕ Correlations – p-p collisions

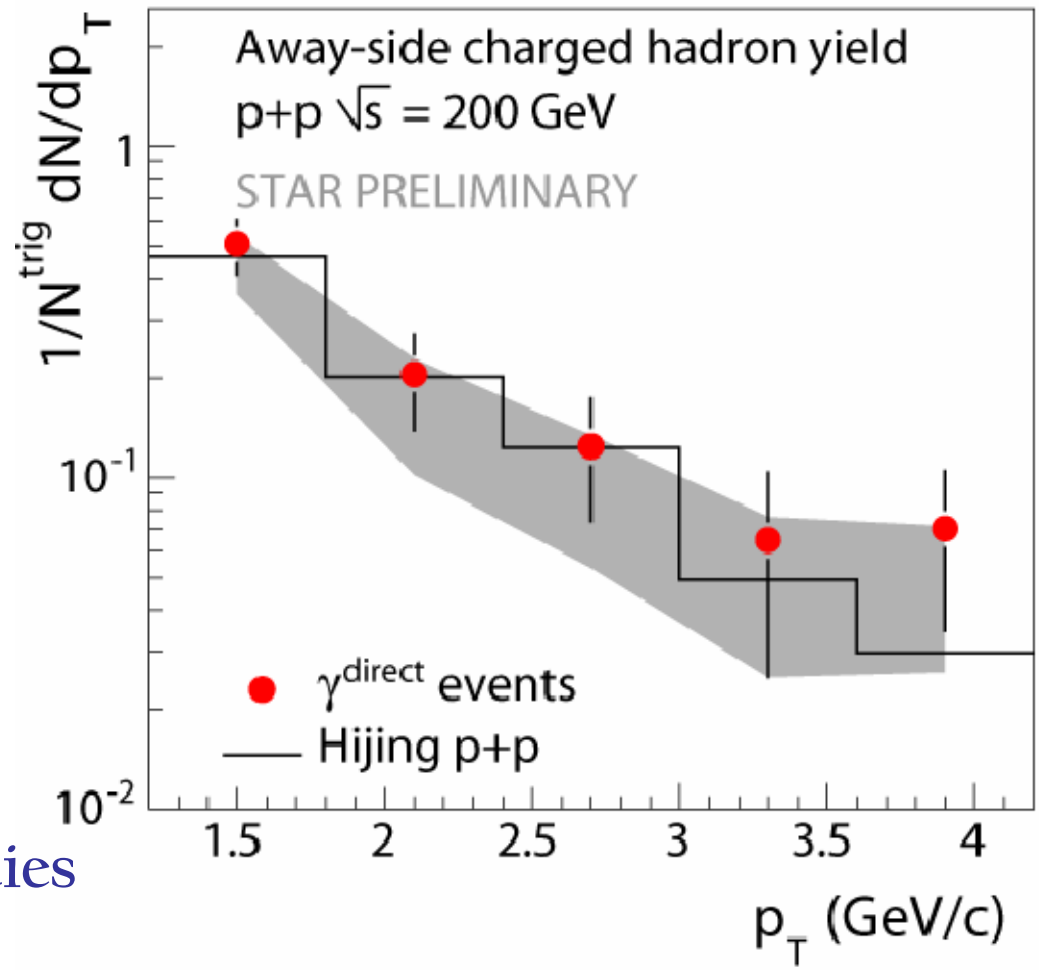


- Reduction in near angle peak towards photon Bin.
- Effect is more prominent for larger $E_t^{trigger}$.
- Away-side yield is slightly reduced.

Spectra for γ-tagged Events

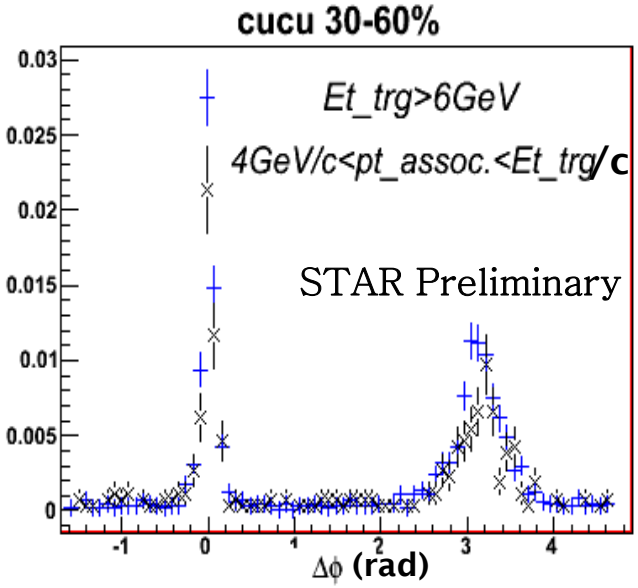
Use γ-enriched sample and subtracting the fraction of the π^0 contribution : Extract the away-side p_T spectra for photon-tagged events

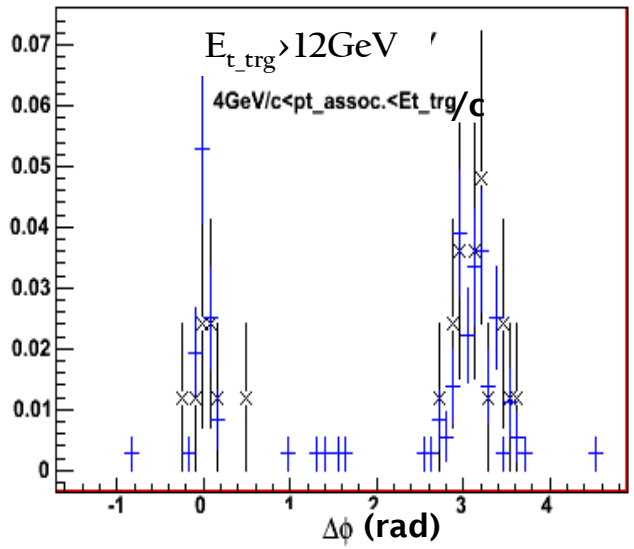
Matches charged hadron spectra in direct photon events from HIJING.



Promising for future γ-jet studies in heavy ions with increased statistics

(γ,π0)- Δϕ Correlations in heavy ions

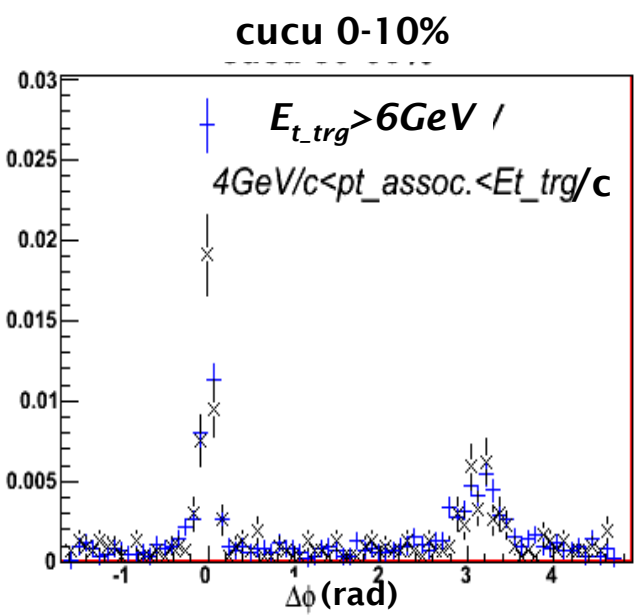


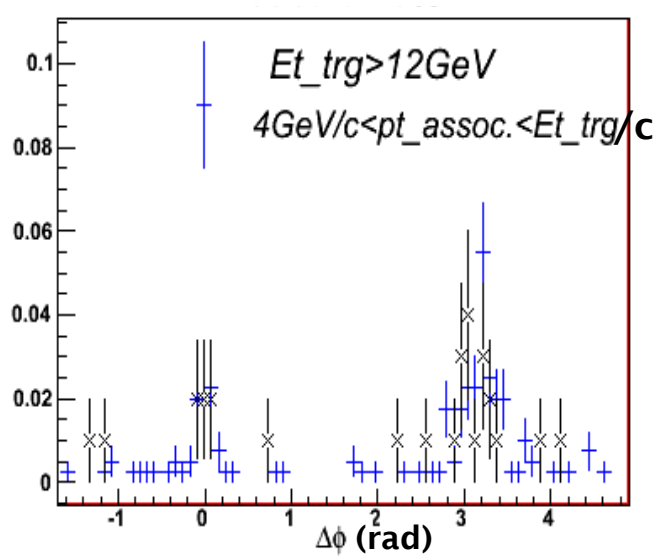


Y axis: $1/N_{trg}\, dN/d(\Delta\Phi)$

Blue - π^0 bin

Black - γ bin





- Similar Away-side for π^0 and γ
- Reduction in the near-side for γ compared to π^0.
- Reduction is more noticeable at higher E_{T_trig} and also at higher centrality bins.

Summary

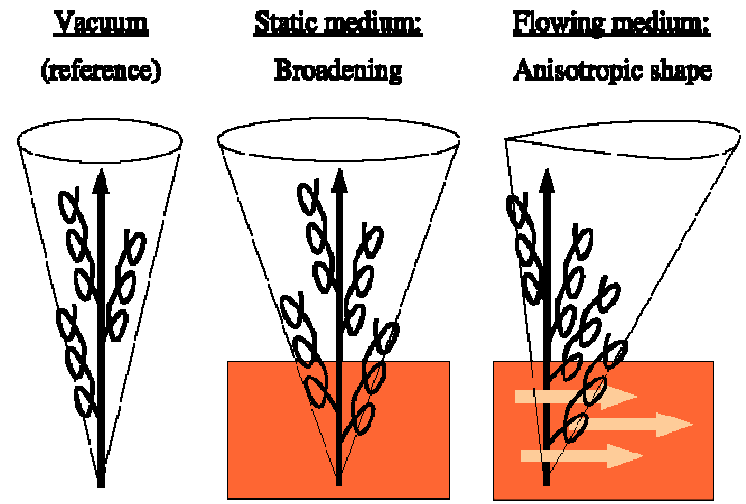
Hadron correlations:

- **Near Side**: Broadening along $\Delta\eta$. ("Jet"+"Ridge")
  - "ridge" – bulk-like spectra, baryon/meson ratio
  - after subtraction of long range $\Delta\eta$, $D(z_T)$ similar to d-Au.
- **Away side:**
  - Suppression of dihadron fragmentation function – extract energy loss parameter using NLO calculations
  - Shape modification - contribution to $\Delta\Phi=\pi$ increases with higher p_T^{trig}, fills dip
  - 3-particle correlations showing promise for a more detailed look
- **γ - hadron correlations** analysis in p-p -> reference, analysis in place to look into heavy ion collisions when enough data available
- A wealth of results for different system sizes – helped stimulate new theoretical ideas
- Ready for more!

What is the ridge?

Proposed explanations so far:

- Radiated gluons, broadened by
  - Longitudinal flow, Armesto et al, PRL 93 (2004)
  - QCD magnetic fields, Majumder et al, hep-ph/0611035
  - Anisotropic plasma, P. Romantschke, PRC,75014901 (2007)



Armesto et al, nucl-ex/0405301

- Medium heating + recombination
  Chiu & Hwa, PRC72, 034903

- Radial flow + trigger bias
  S. Voloshin, nucl-th/0312065, Nucl. Phys. A749, 287

All models in qualitative agreement ⇒ quantitative calculations needed !

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

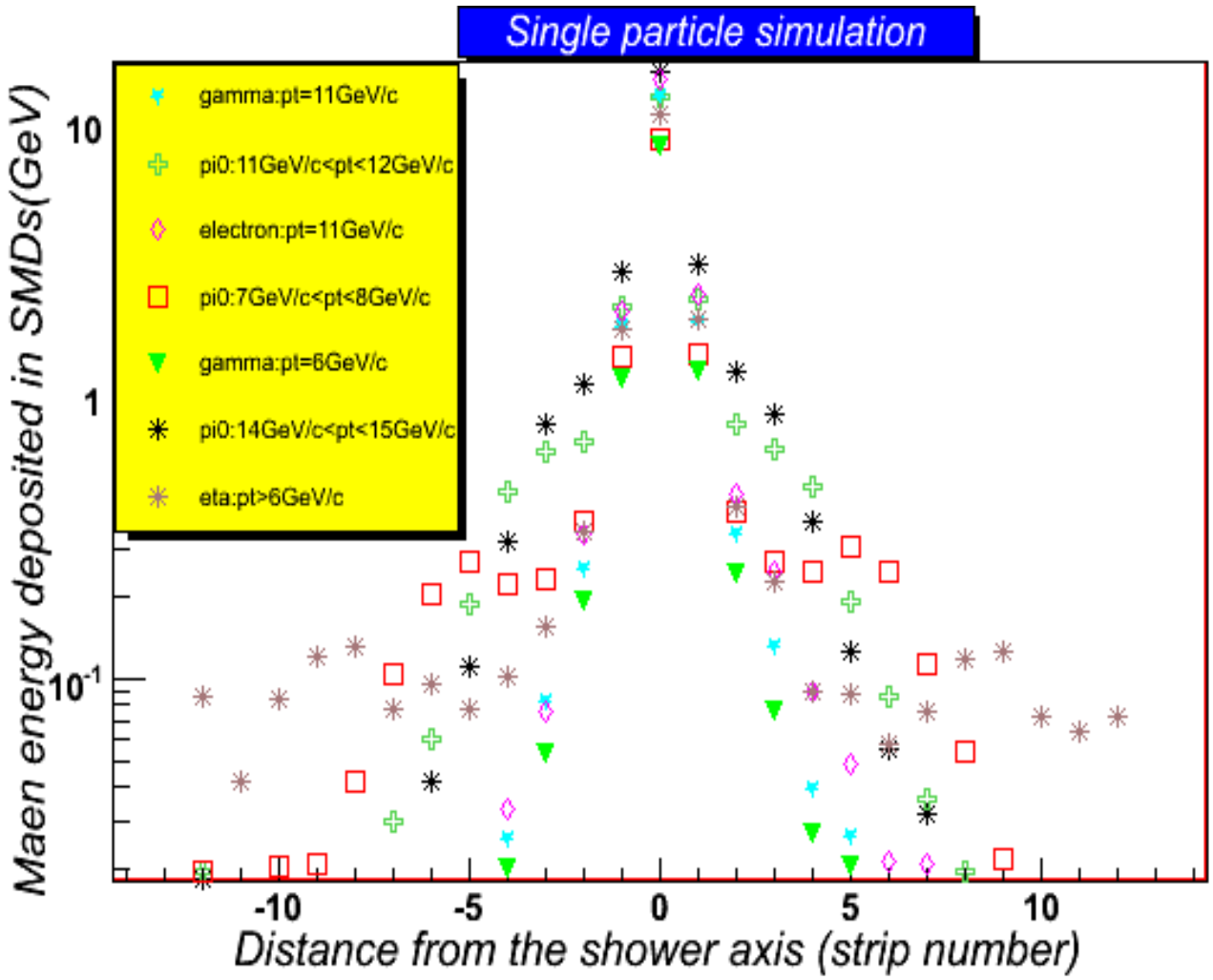
1) Cumulant technique:

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

2) Jet+Flow Subtraction Model:

$$\hat{J}_3(\Delta\varphi_{12}, \Delta\varphi_{13}) = J_3(\Delta\varphi_{12}, \Delta\varphi_{13}) - \hat{J}_2(\Delta\varphi_{12}) B_2(\Delta\varphi_{13}) - \hat{J}_2(\Delta\varphi_{13}) B_2(\Delta\varphi_{12}) - B_3(\Delta\varphi_{12}, \Delta\varphi_{13})$$

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



- Clear structure for the two showers in η and π^0 at moderate energy.
- π^0 shower at high energy is still wider than the single photon shower.
- Clear sensitivity to the halo region.

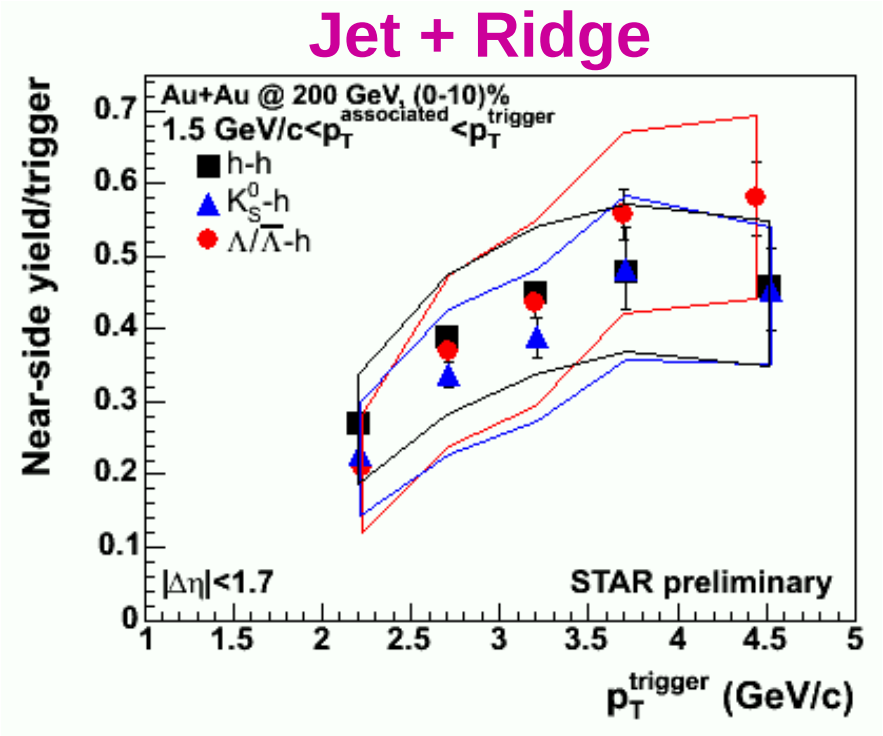
- Could be used to distinguish π^0/γ

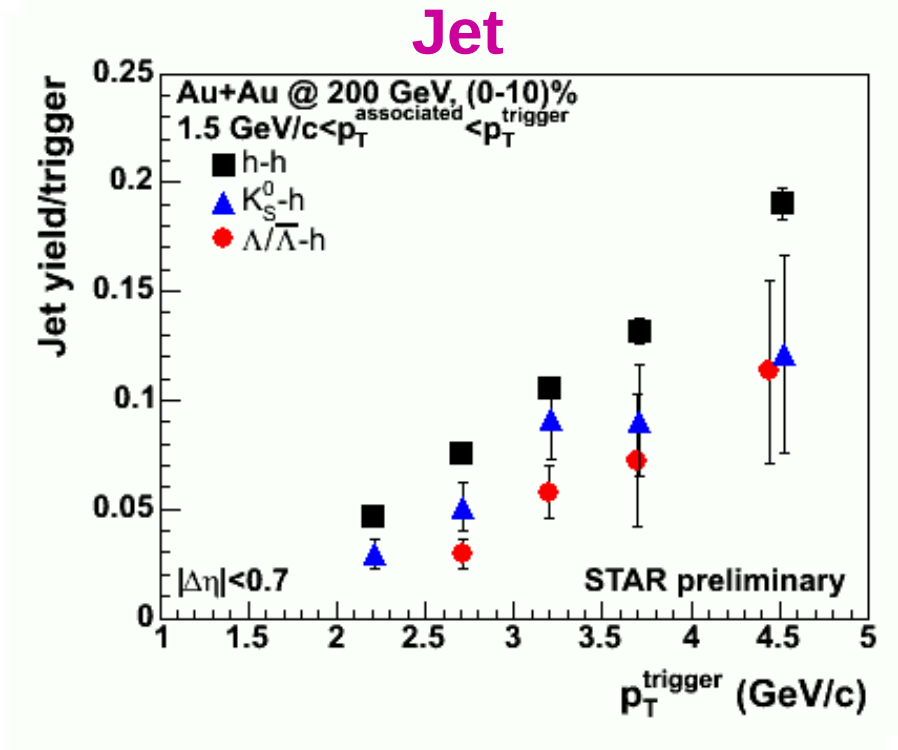
Extraction of away-side charged particle p_t spectra for "photon-tagged" events for pp collisions ($E_{t,trig}$: 8.5 – 10.5 GeV/c)

Method:

- Evaluate π^0 fraction (f) from reduction in near side yield in "photon bin" compared to " π^0 bin"
- Take away-side p_T spectra for π^0 bin and scale down by f
- Subtract away-side pt spectra for "scaled π^0 bin" from "photon-bin" and make a (1-f) scaling.
- Compare with Hijing for extracted spectra from π^0 and photon bins.

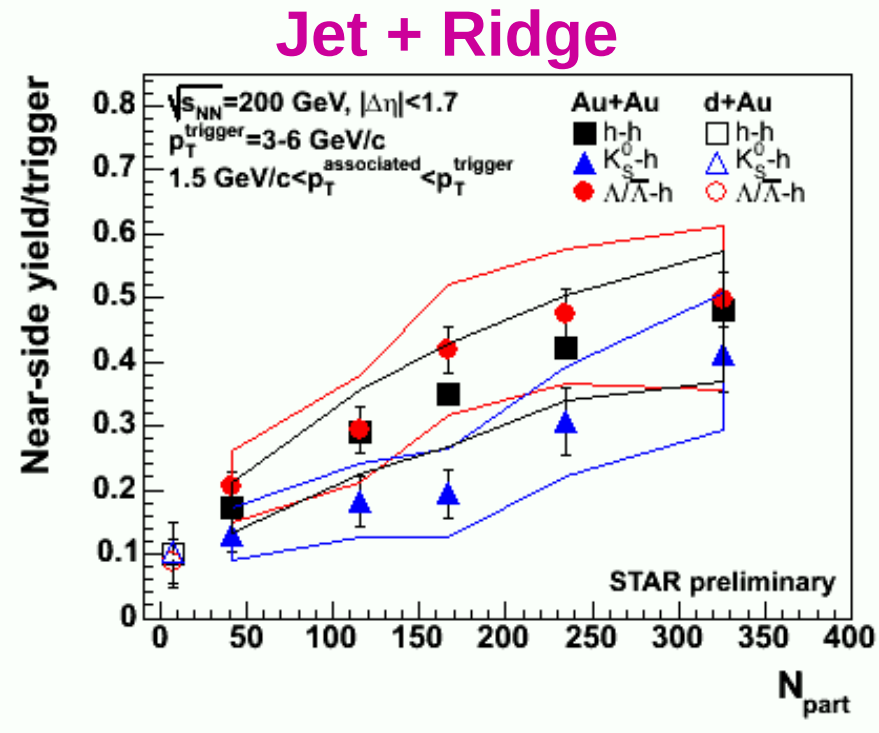
$p_T^{trigger}$ dependence of jet and ridge yields

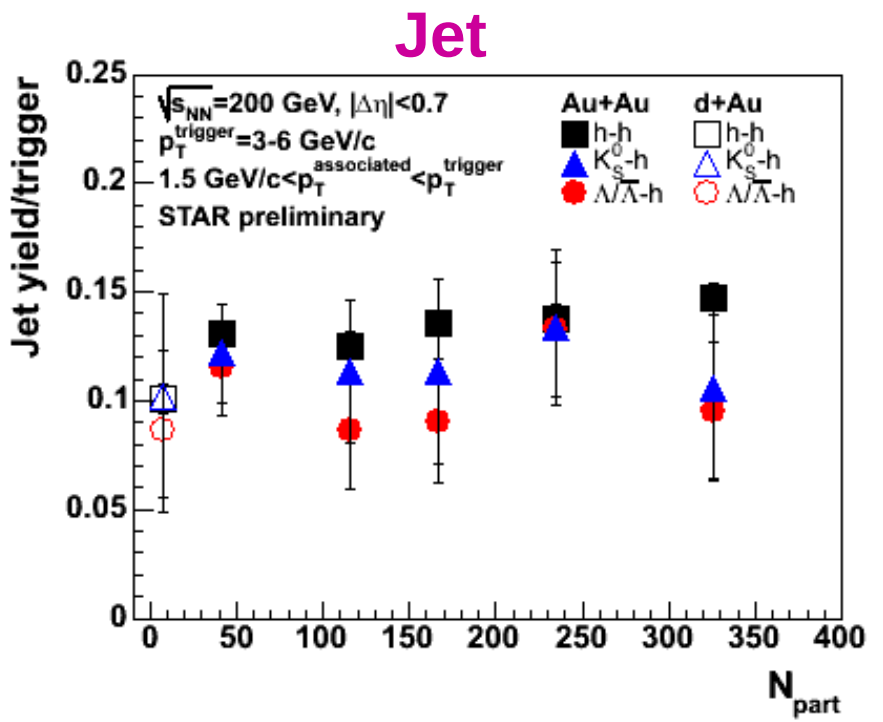




- both unidentified and identified (neutral strange) hadrons
- near-side associated yield is ridge dominated at intermediate p_T
- jet yield:
  - increases steeply with $p_{T\ trigger}$
  - jet/ridge ratio increases with $p_{T\ trigger}$

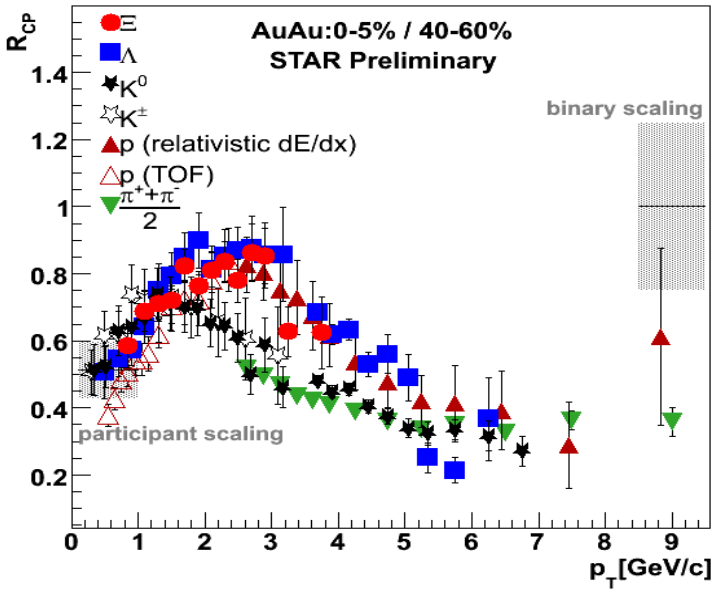
Centrality dependence of near-side yield

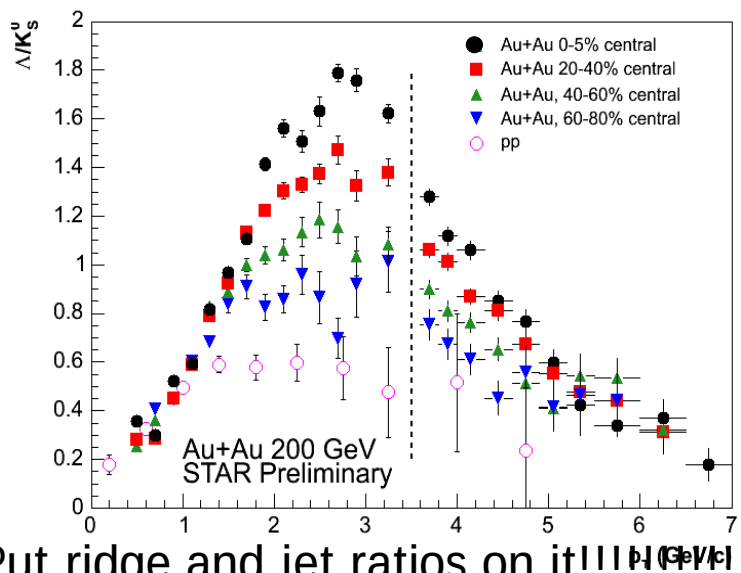




- steep increase of near-side yield with centrality in Au+Au
- ratio of yields in central Au+Au/d+Au ~ 4-5
  - -> "ridge" yield increases with centrality
  - -> "jet" yield is independent of centrality and agrees with d+Au

Baryon/meson anomaly at intermediate p_T





R_{CP}:

- intermediate p_T :
  baryon/meson splitting independent of strangeness content
- high p_T (p_T > 5 GeV/c) :
  all particles have similar R_{CP} and appear to show similar suppression

- large enhancement of baryon/meson ratio in central Au+Au relative to p+p collisions
  - reaches maximum at p_T~3 GeV/c

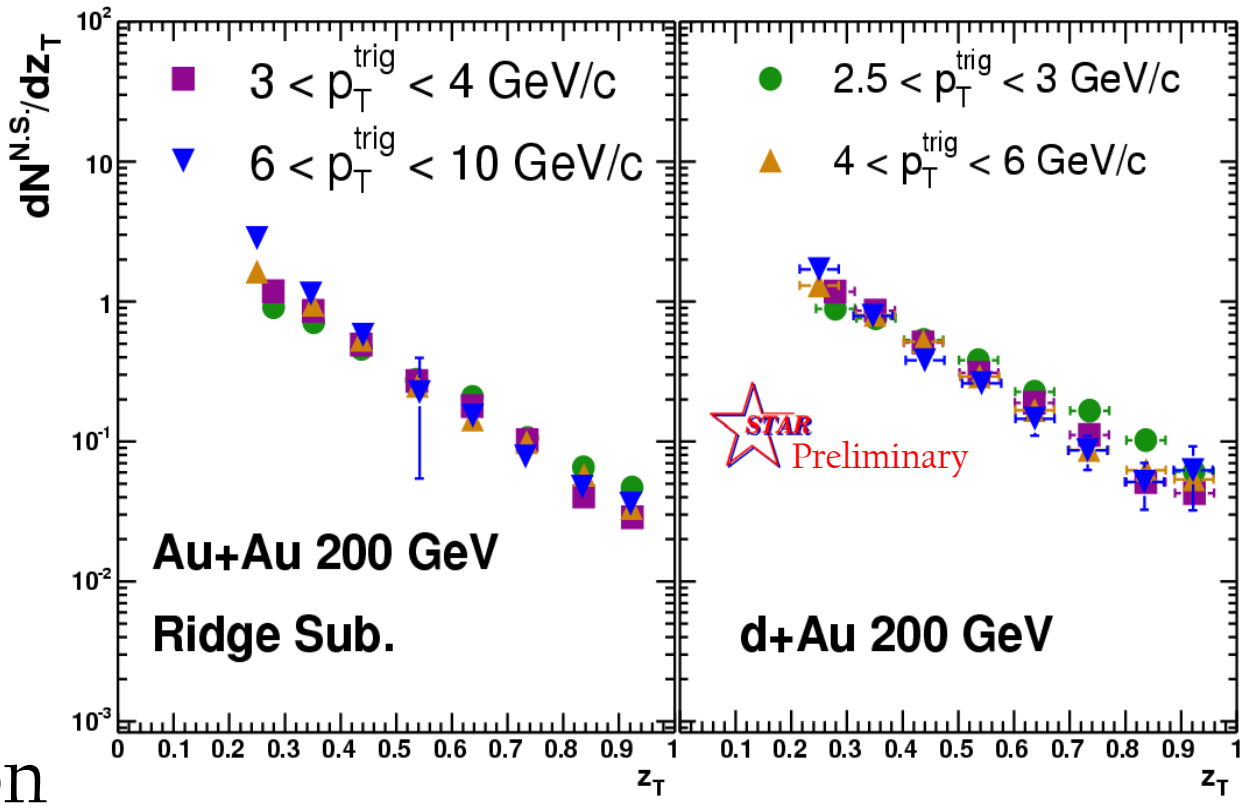
⇩

- jet fragmentation is not a dominant source of particle production

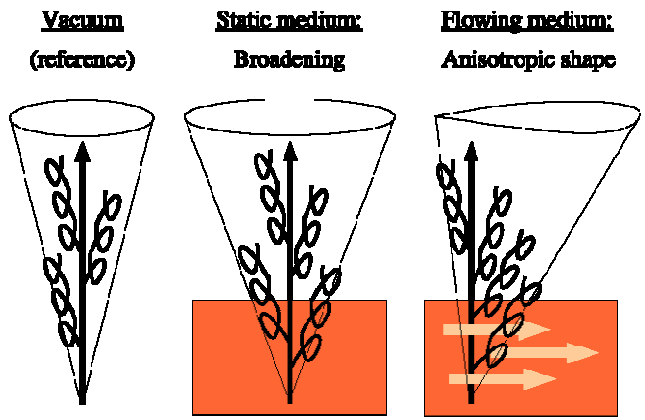
Put ridge and jet ratios on it!!!

Near-side z_T Distributions: "Jet"

- Measure hadron triggered fragmentation functions:
  - $D^{h1,h2}(z_T)$
  - $z_T = p_T^{assoc}/p_T^{trig}$
- Similarity between *AuAu* and *dAu* after ridge subtraction



What is the origin of the ridge ?



1) Parton radiation coupling to longitudinal flow - Armesto et al, PRL 93 (2004)

Longitudinal broadening of quenched jets in turbulent color - A. Majumder, B. Mueller, S.A.Bass, hep-ph/0611135

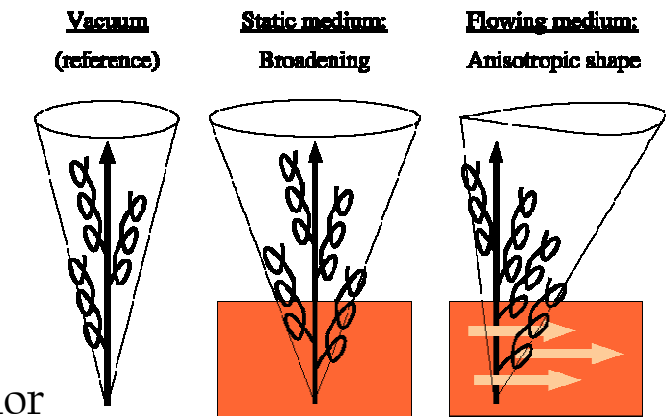
2) Medium heating + parton recombination

Chiu & Hwa Phys. Rev. C72:034903,2005

3) Radial flow + trigger bias

S.Voloshin, nucl-th/0312065, Nucl. Phys. A749, 287 (2005)

What is the origin of the ridge ?



1) Parton radiation and its coupling to the longitudinal flow Armesto et al, PRL 93 (2004)

- gluon bremsstrahlung of hard-scattered parton
  → parton is shifted to lower p_T
- radiated gluon contributes to broadening

Longitudinal broadening of quenched jets in turbulent color fields - A. Majumder, B. Mueller, S.A.Bass, hep-ph/0611135

plasma instabilities in expanding medium → broadening of jet cone

2) Medium heating + parton recombination

Chiu & Hwa Phys. Rev. C72:034903,2005

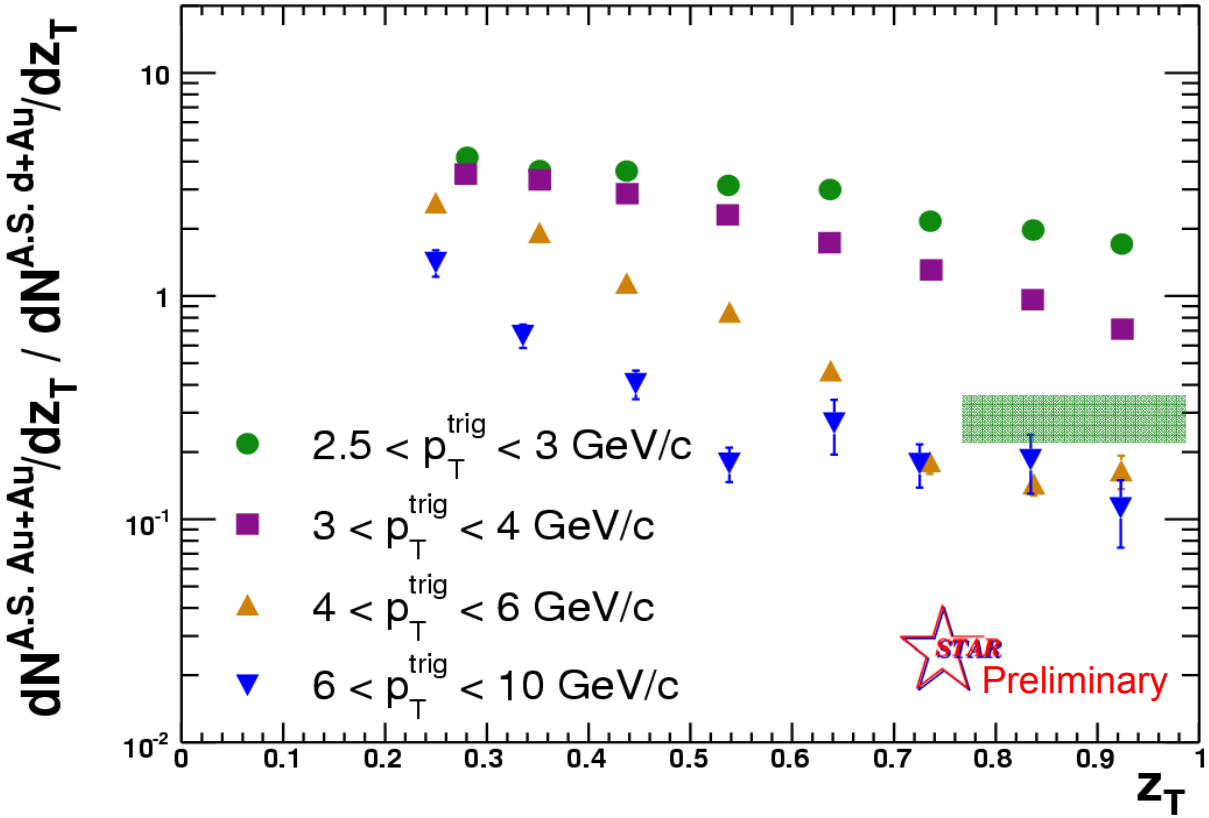
- hard parton passing through the medium → enhanced thermal parton distribution (ΔT=15 MeV) → recombination of thermal partons forms a pedestal (ridge)
- enhanced baryon/meson ratio

3) Radial flow + trigger bias

S.Voloshin, nucl-th/0312065, Nucl. Phys. A749, 287 (2005)

Away-side: z_T Distributions

- High z_T for hard triggers shows suppression (~0.2)
- Larger yields seen at low z_T or low p_T^{trig}
  - bulk response
- Deviation from suppression depends on p_T^{trig}



$2.5 < p_T^{trig} < 4.0$ GeV/c never reaches the 0.25 ± 0.06 I_{AA} away-side suppression for $p_T^{trig} > 8$ GeV/c (STAR PRL 97, 162301)