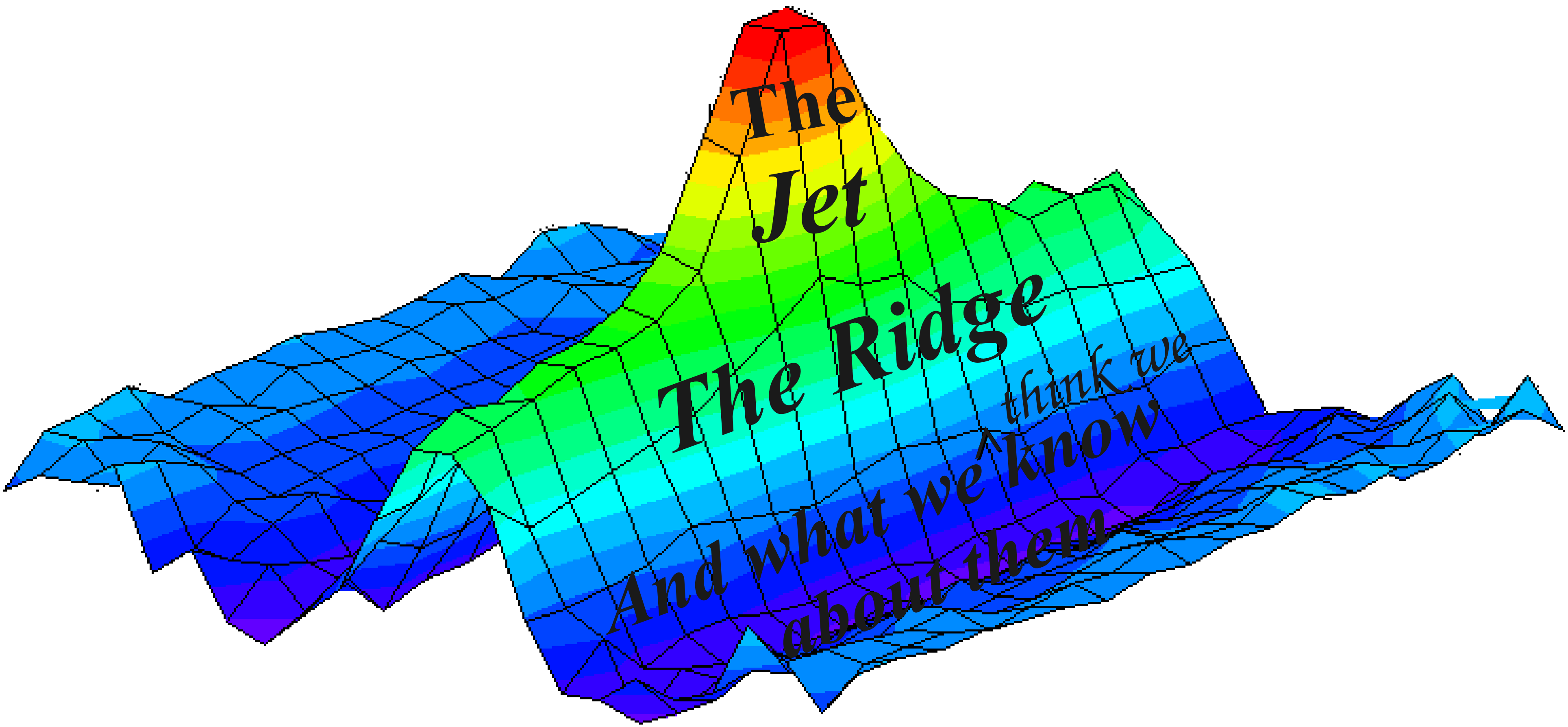
The Jet The Ridge And what we think we know about them



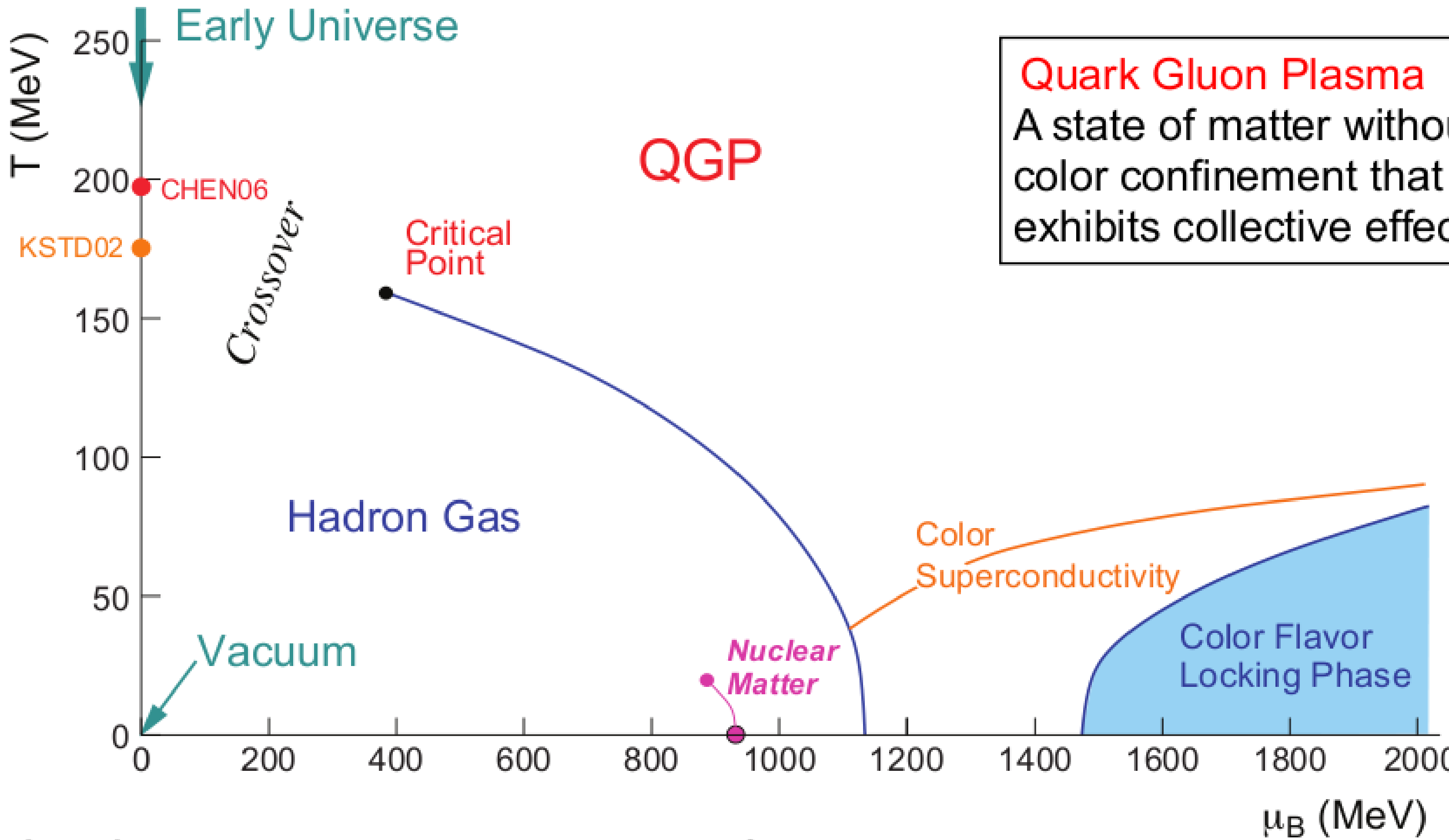
Christine Nattrass

Yale University

Outline

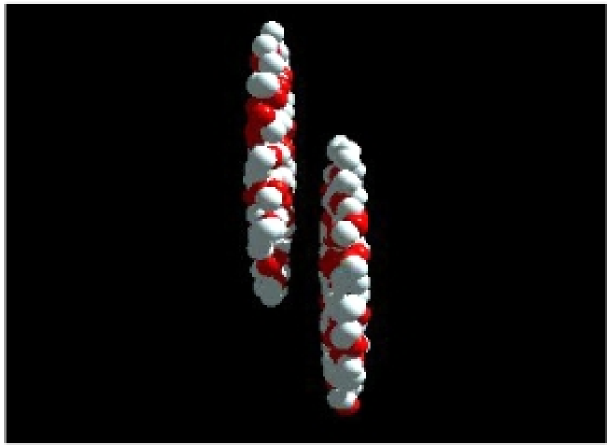
- Introduction to RHIC
- Introduction to the *Ridge*
- Central Au+Au $\sqrt{s_{NN}}$ = 200 GeV
- The *Jet* – energy, system, and particle type dependence
- The *Ridge* – energy, system, and particle type dependence
- Comparison to theories
- Conclusion

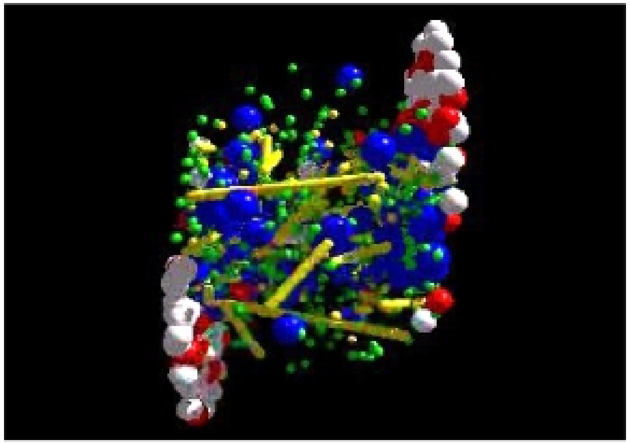
Phase diagram of nuclear matter

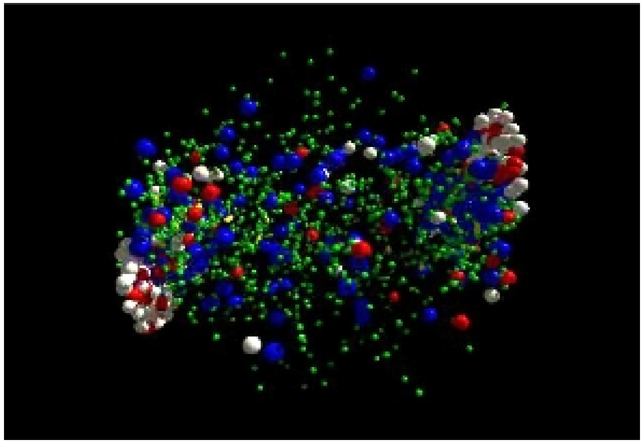


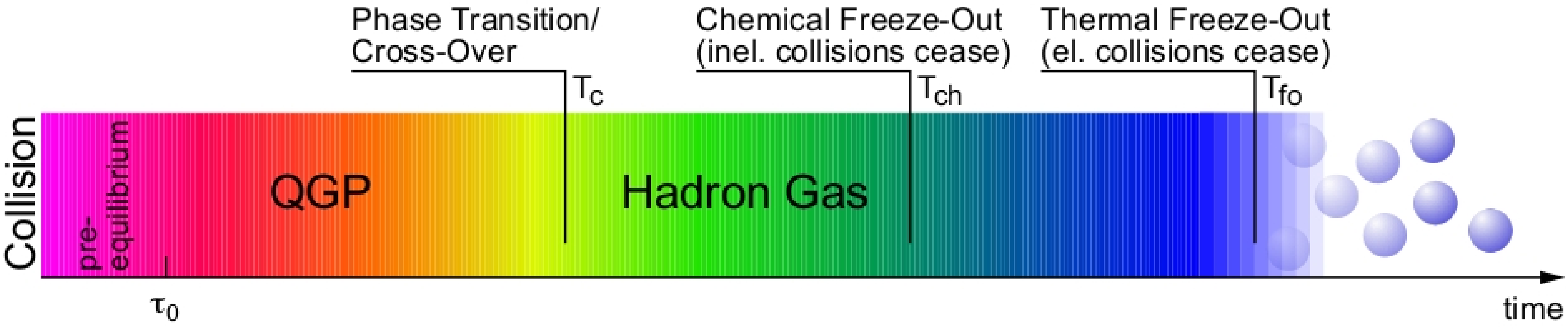
- Lattice says crossover at $\mu_B = 0$
- Some discussion on methods to extract T_C ($175 \leq T_C/MeV \leq 191$)
- Lattice suggest the transition becomes 1st order at μ_B above the critical point (2nd order at the CP)

The phase transition in the laboratory

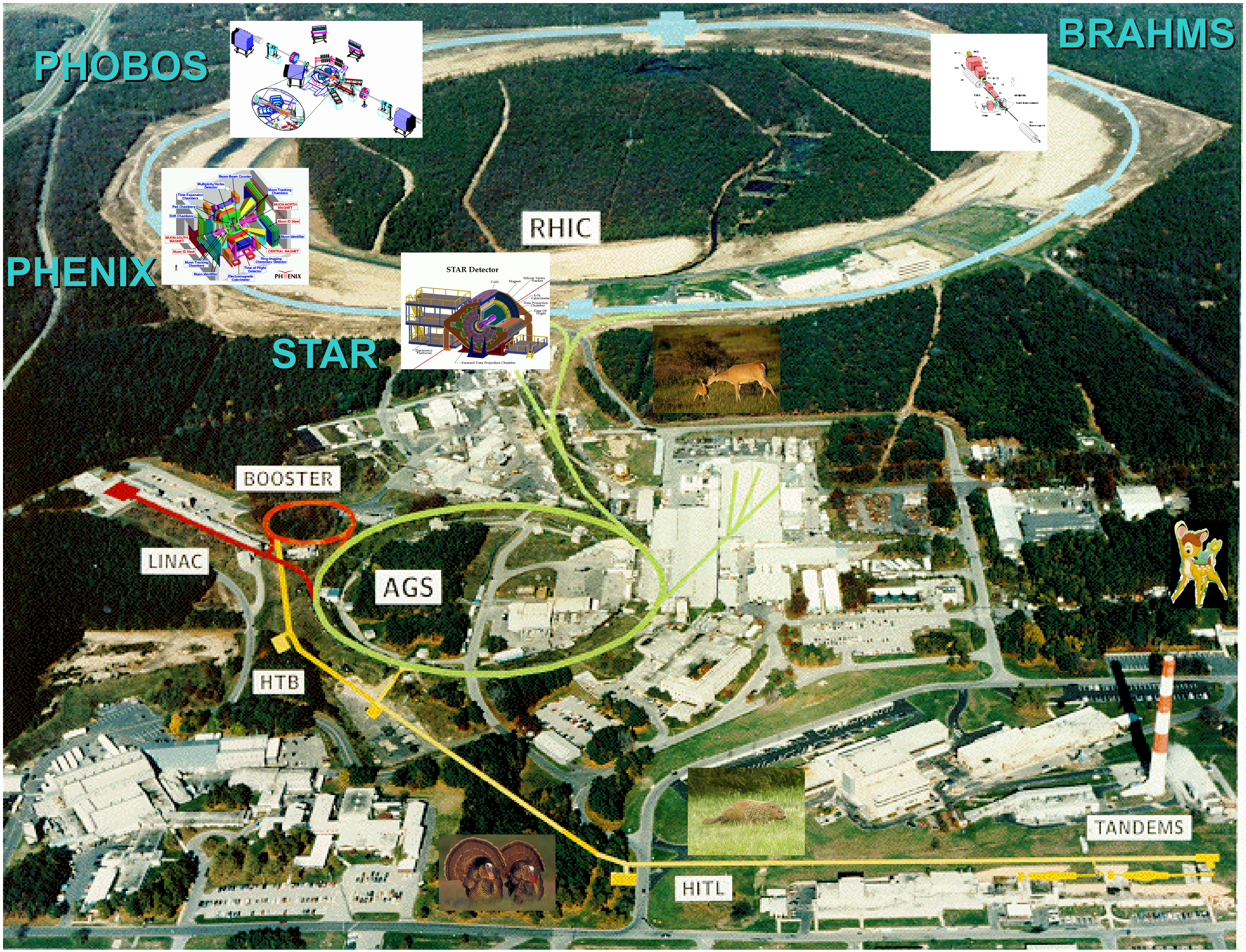








Relativistic Heavy Ion Collider



PHOBOS

- Coverage:

  With tracking:

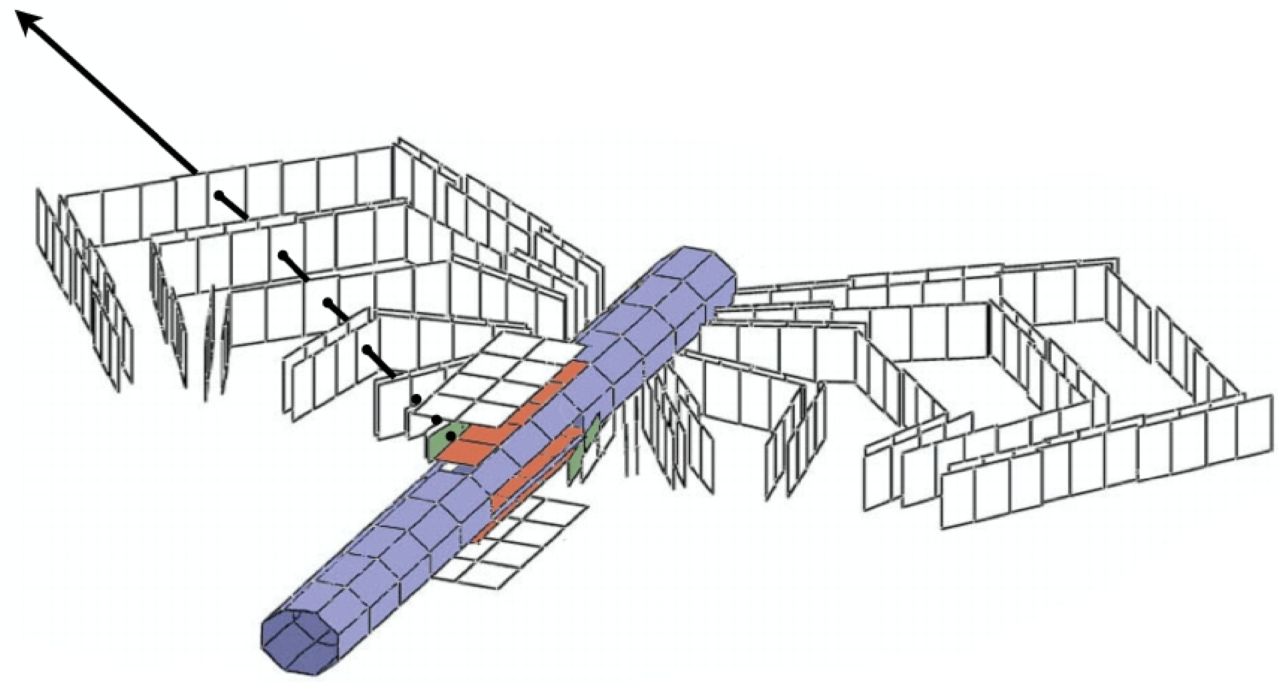
  $0<\phi<0.2$, x2

  $0<\eta<1.5$

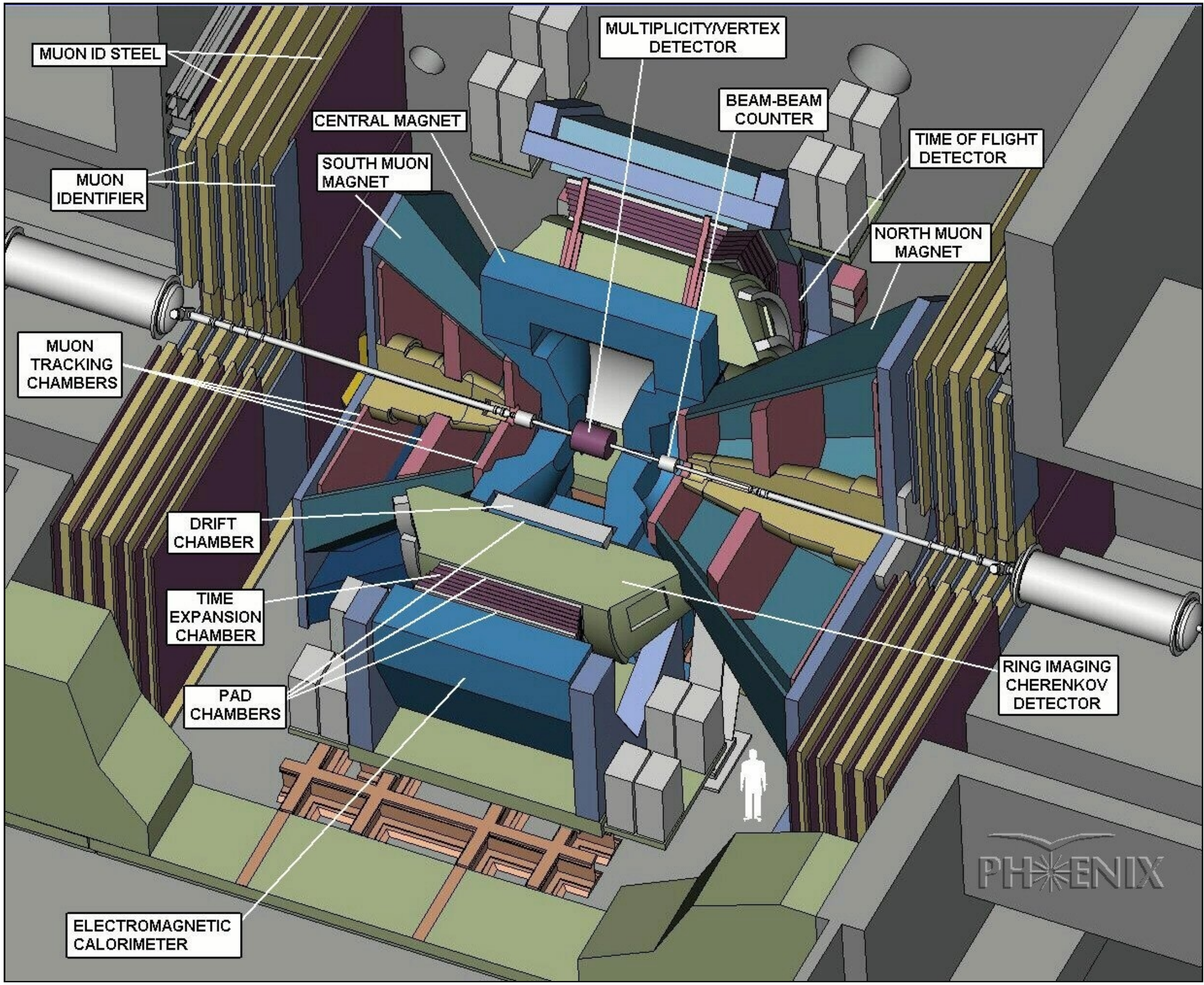
  Without tracking:

  $0<\phi<2\pi$

  $-3<\eta<3$



PHENIX



- Coverage:

  $0<\phi<\pi/2$, x2

  $-0.35<\eta<0.35$

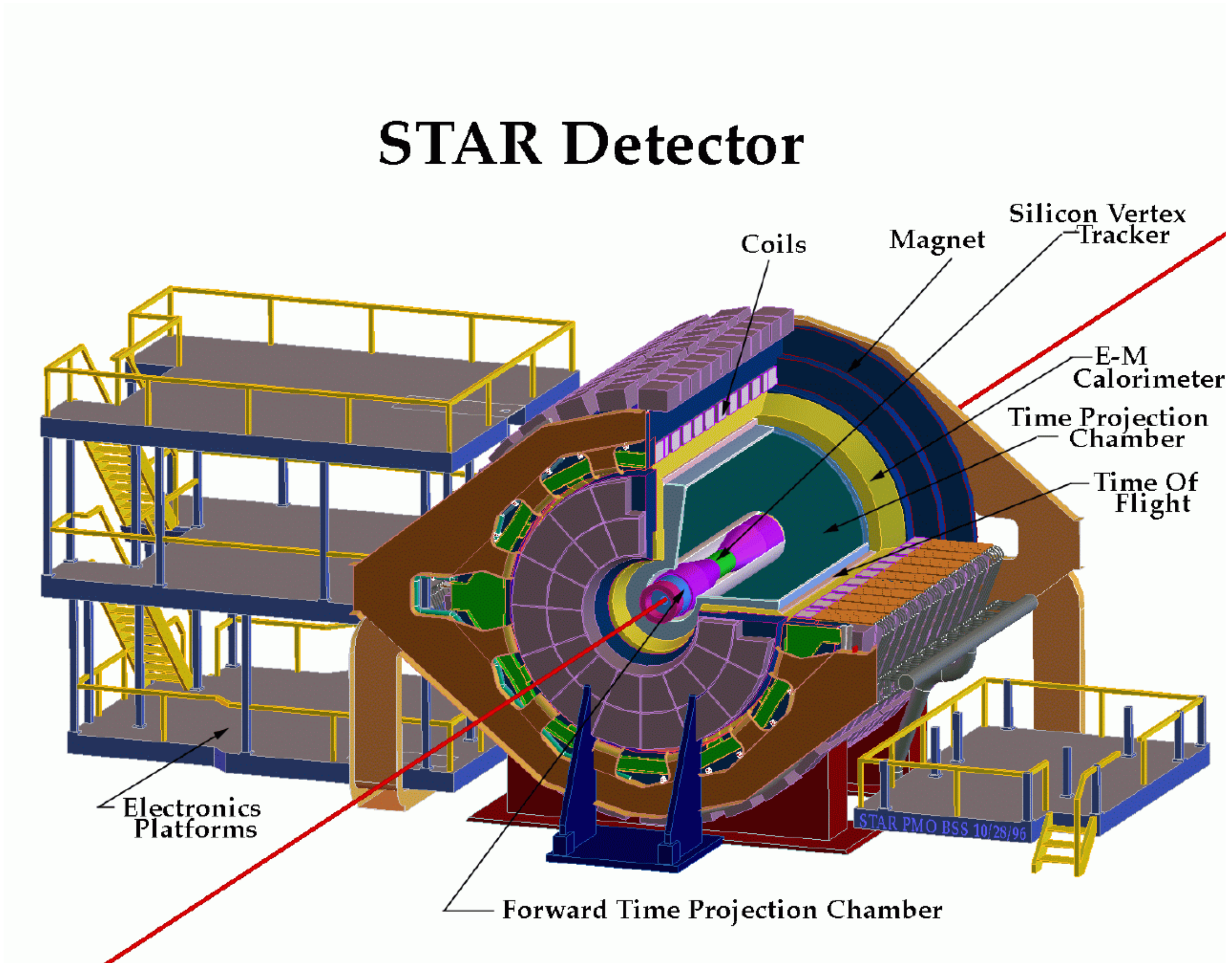
STAR

- Coverage:

  $0<\phi<2\pi$

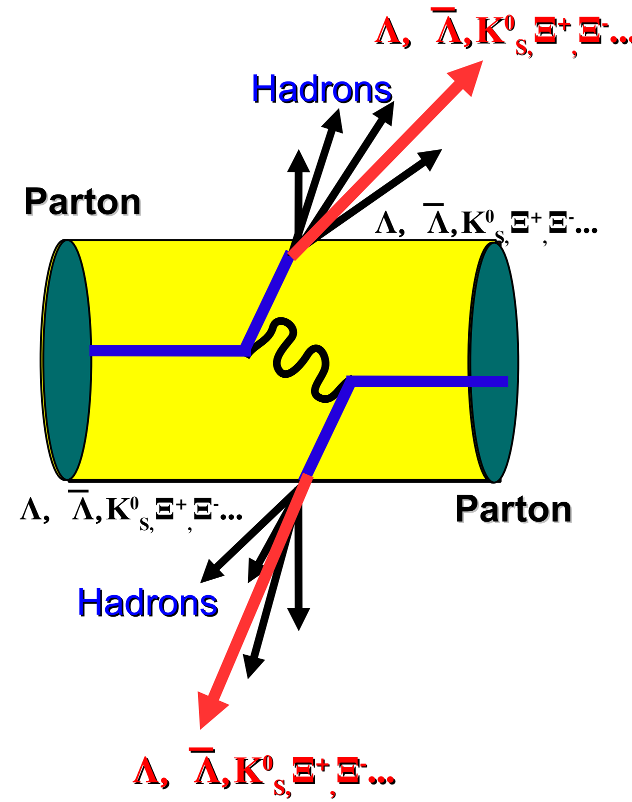
  $-1<\eta<1$

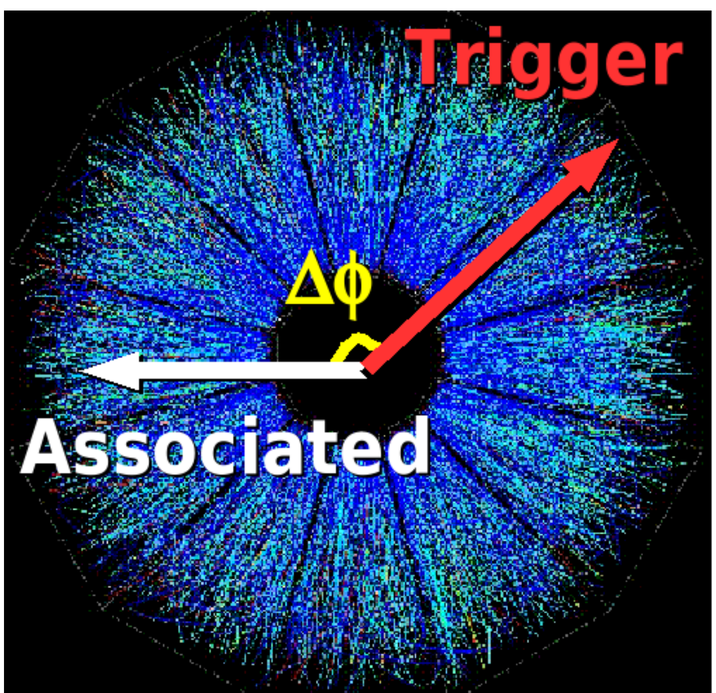
- Electromagnetic Calorimeter allows triggering



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 difficult to reconstruct
  - Study jets via correlations of particles in space





- both azimuth and pseudorapidity

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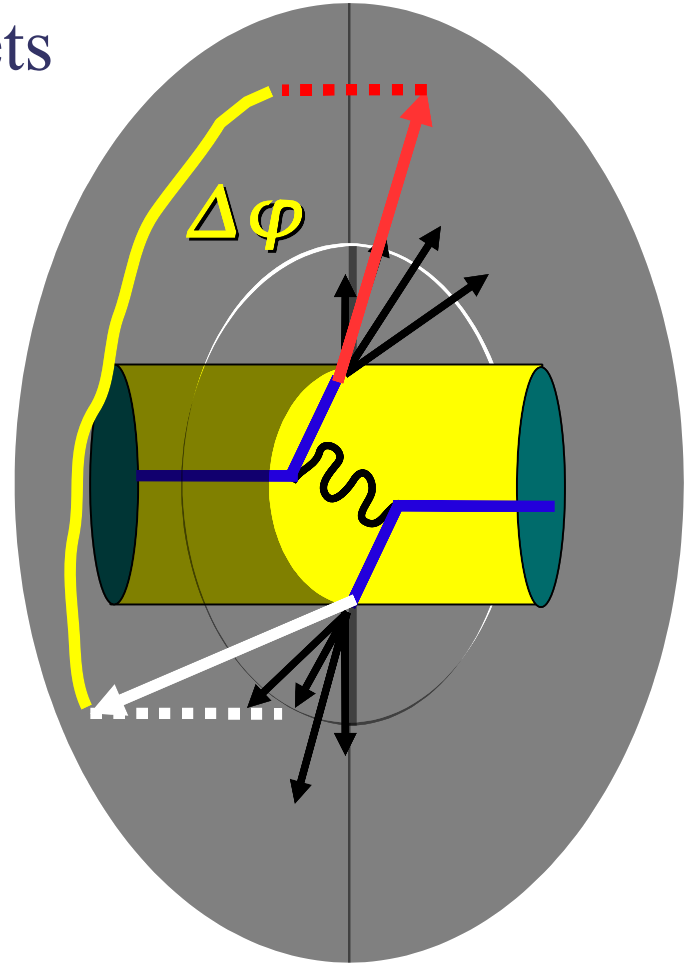

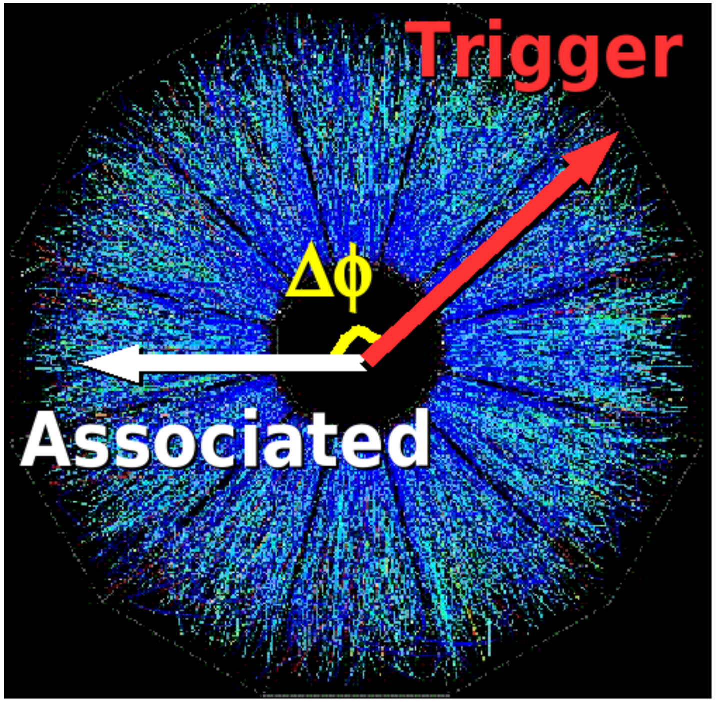

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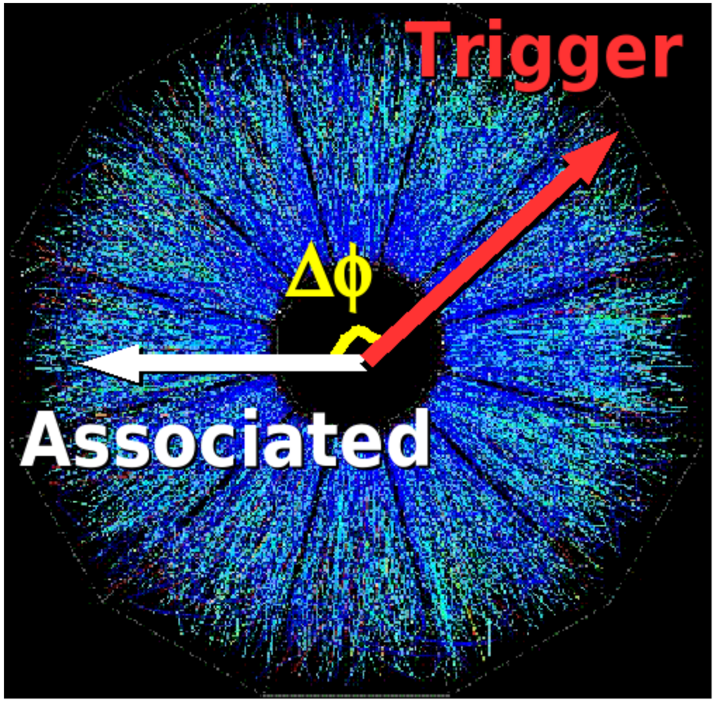
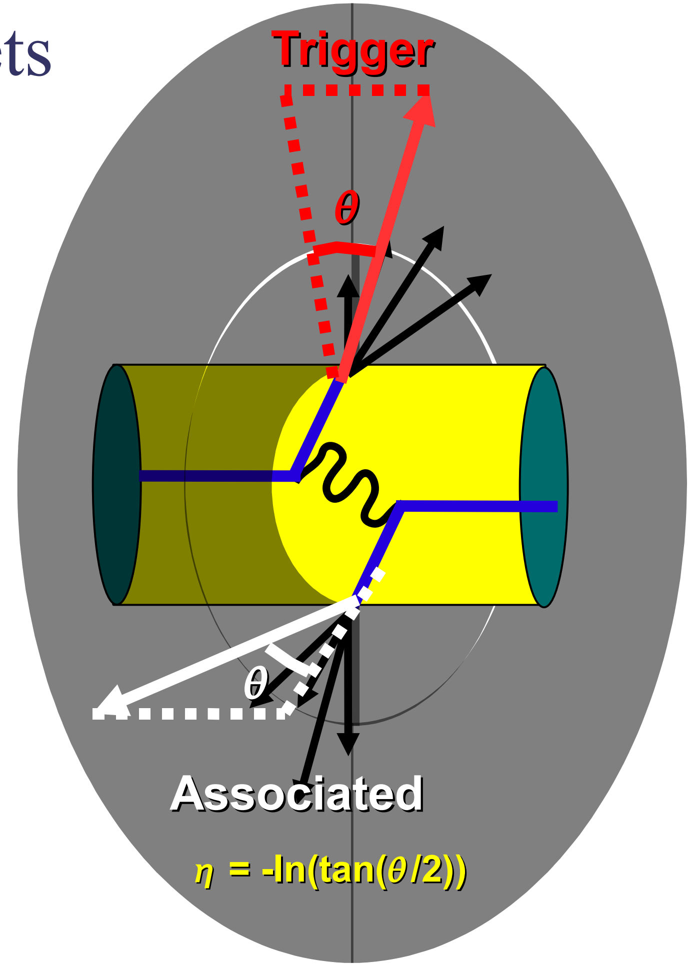


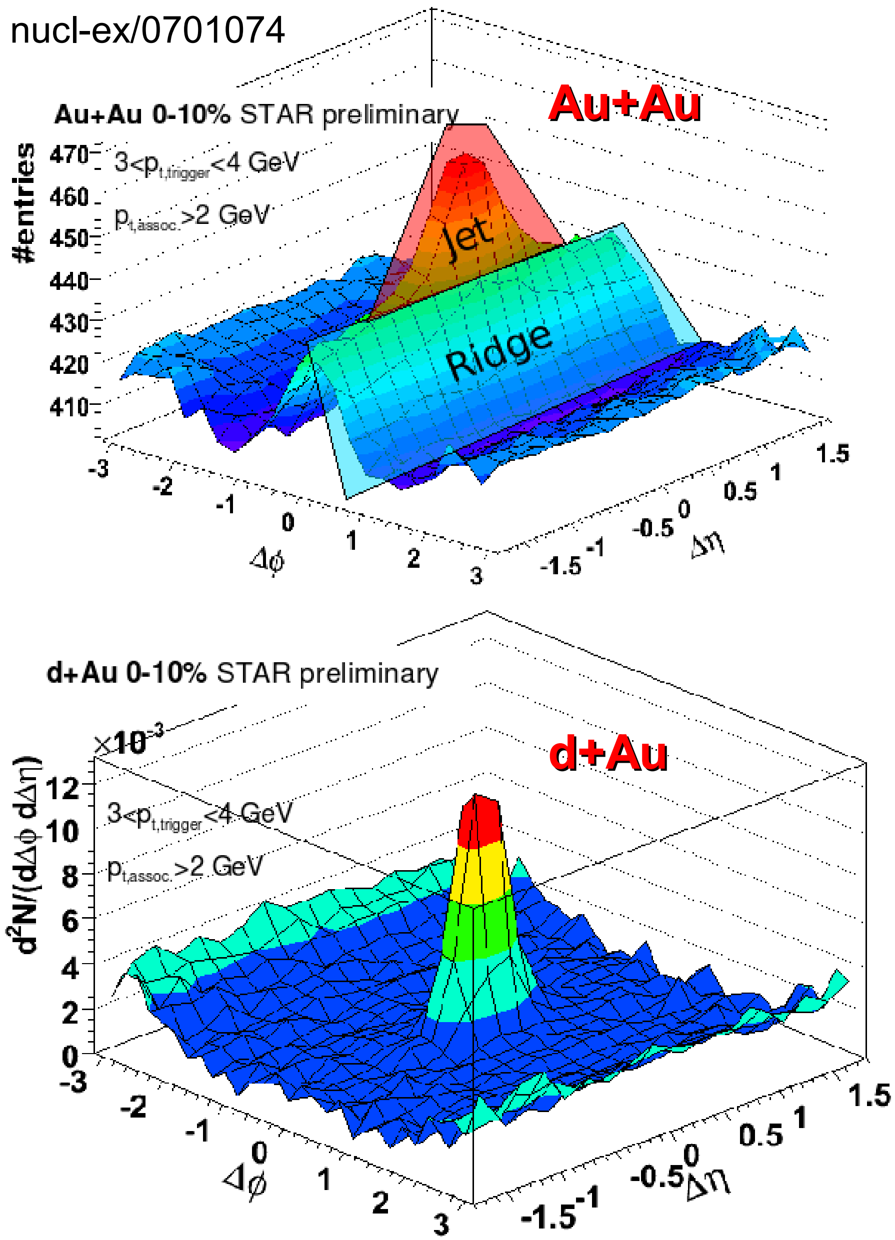
- both azimuth and pseudorapidity



Introduction to the Ridge

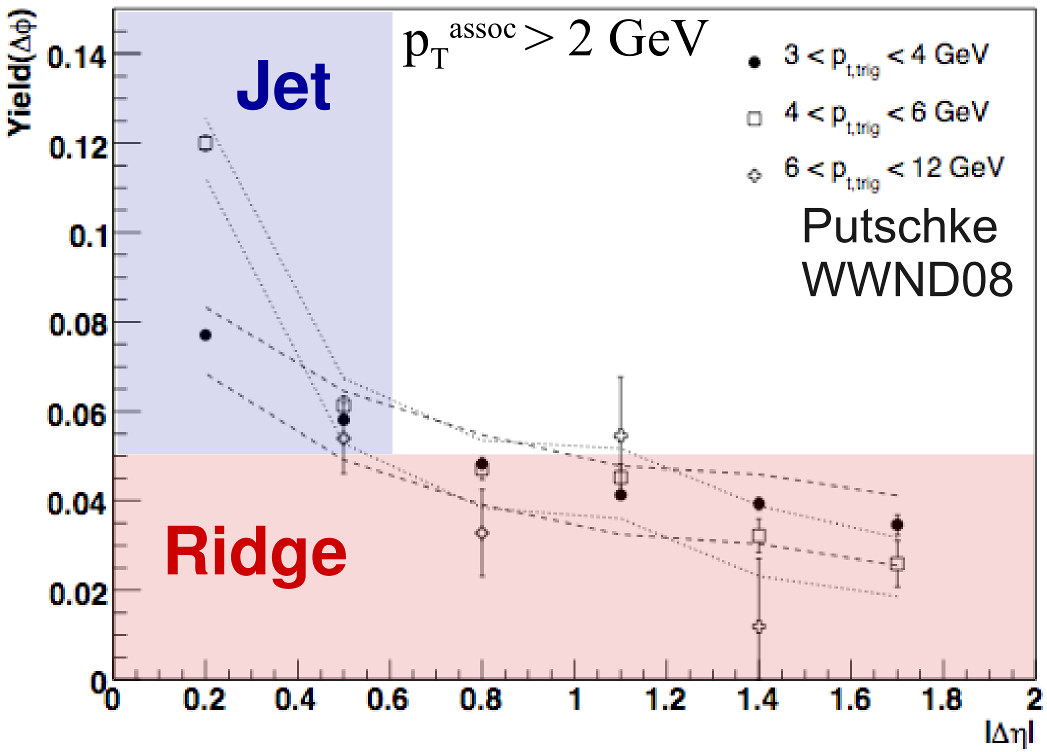
Motivation – Jet and Ridge

nucl-ex/0701074



- 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

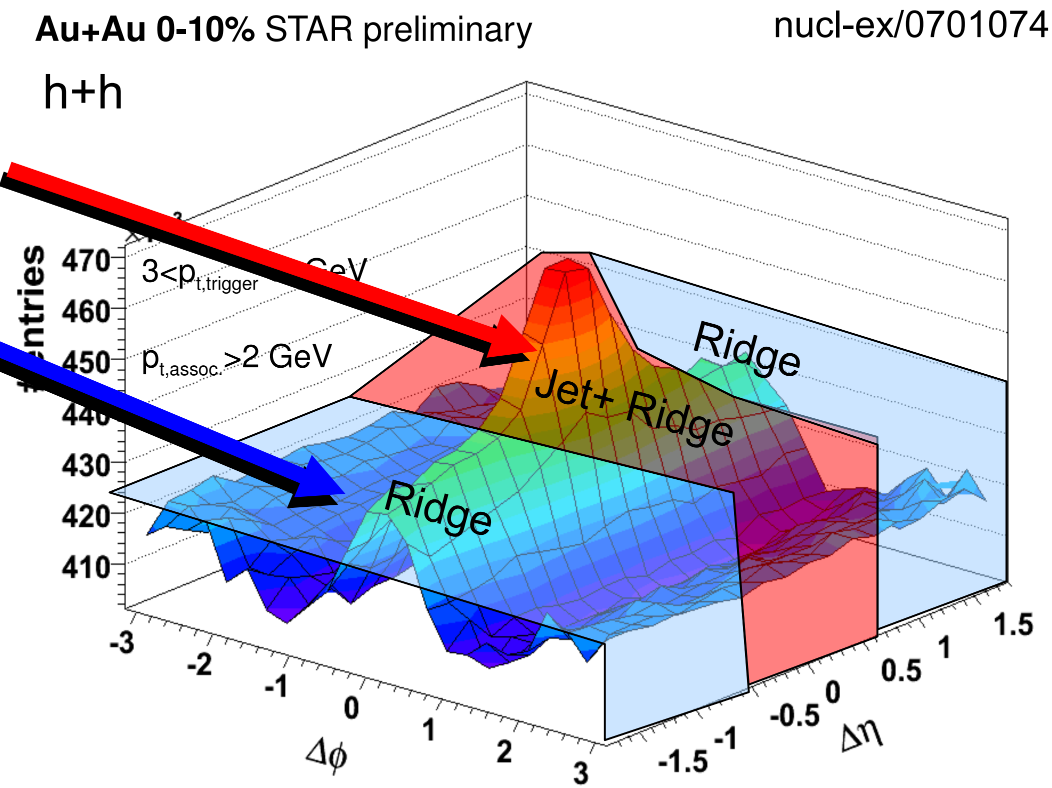
Extent of Ridge in Δη



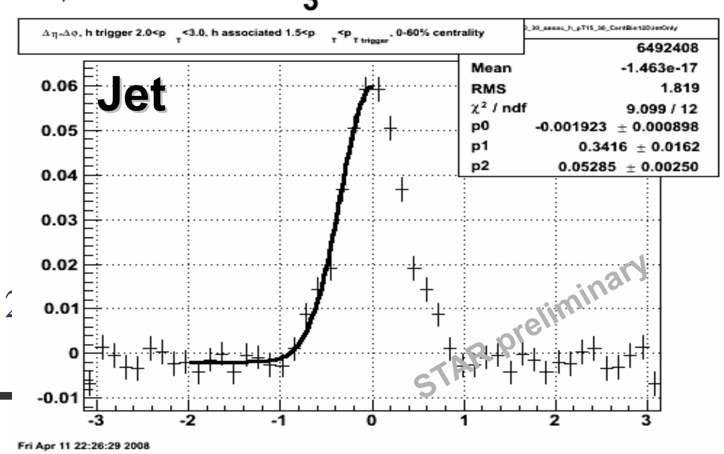
- *Ridge* yield approximately independent of $\Delta\eta$
- Jet increases with $p_T^{trigger}$

Method: Yield extraction

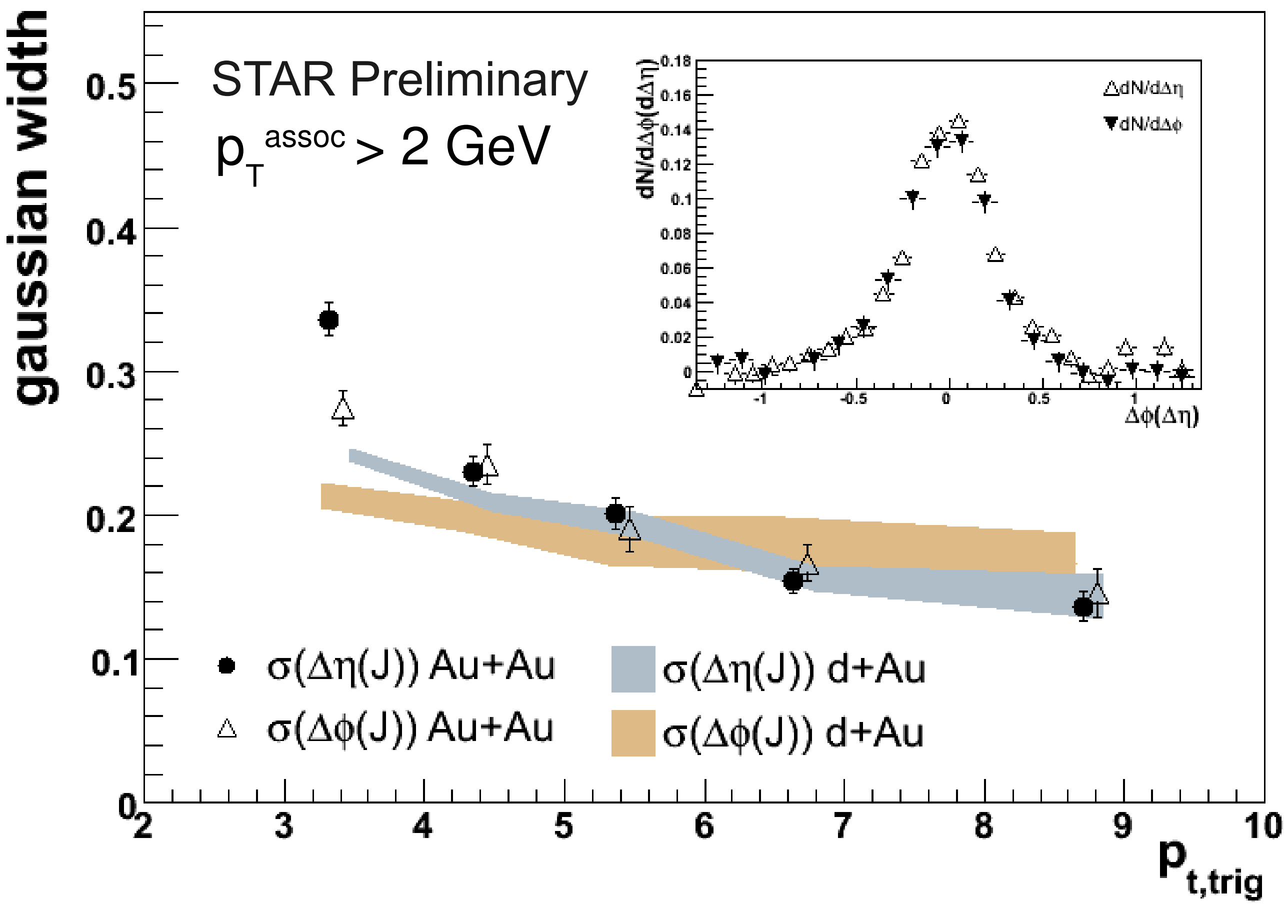
- *Ridge* previously observed to be independent in $\Delta\eta$ in Au+Au
- To determine relative contributions, find yields for near-side, take $\Delta\Phi$ projections in
  - $-0.75<\Delta\eta<0.75$ ***Jet + Ridge***
  - $0.75<|\Delta\eta|<1.75$ ***Ridge***
  - *Jet* = (*Jet+Ridge*) – *Ridge**.75/1.0
  - *Ridge* = yield from $-1.75<\Delta\eta<1.75$ – *Jet* yield



- Flow contributions to *Jet* cancel
  - v_2 independent of η for $|\eta|<1$
    - Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 1



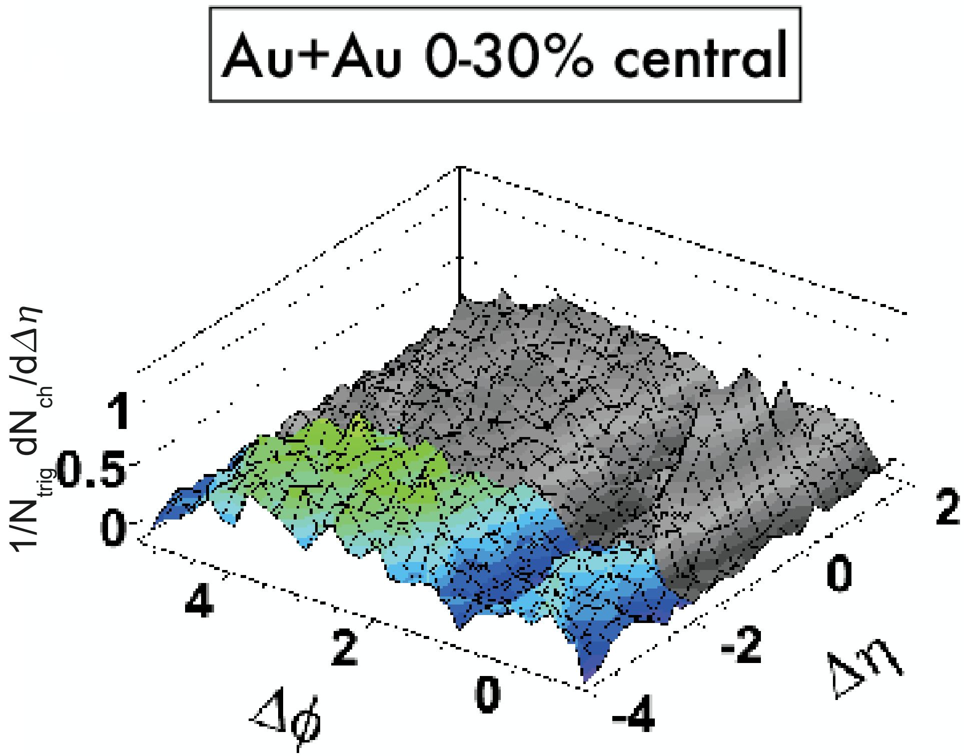
Jet-like peak width in central Au+Au



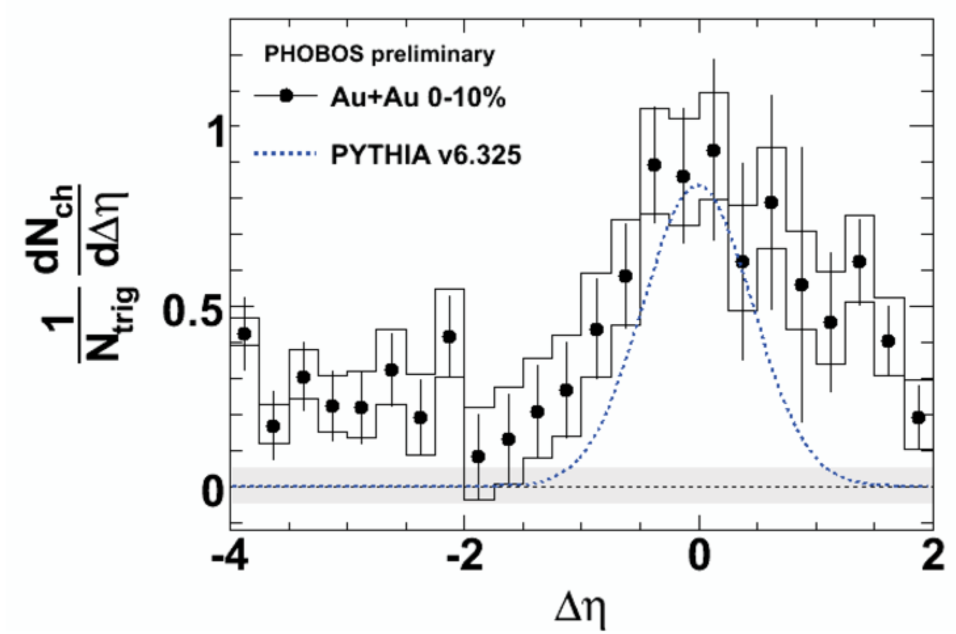
Putschke
WWND08

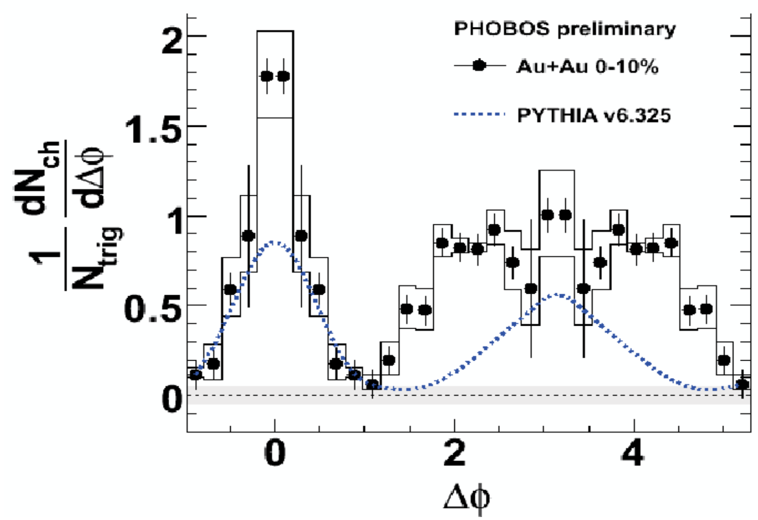
- *Jet* peak symmetric in Δη and Δφ for $p_T^{trigger} > 4$ GeV and comparable to d+Au
- *Jet* peak asymmetric in Δη for $p_T^{trigger} < 4$ GeV and significantly broader than d+Au

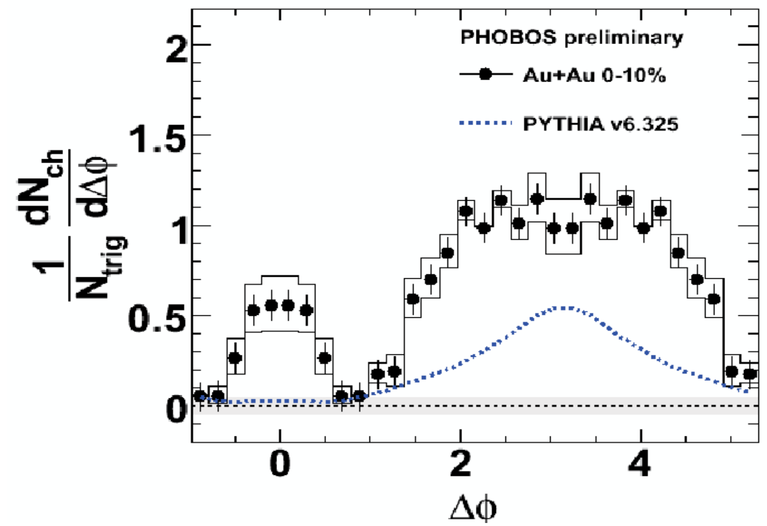
Extent of Ridge in Δη



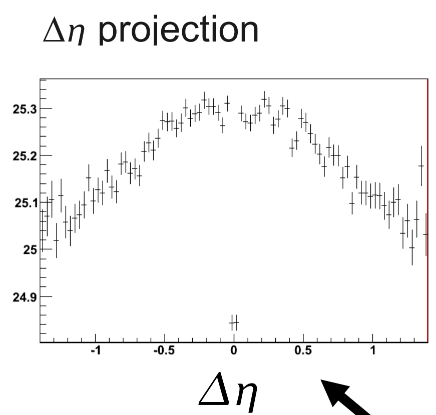
Wenger QM08

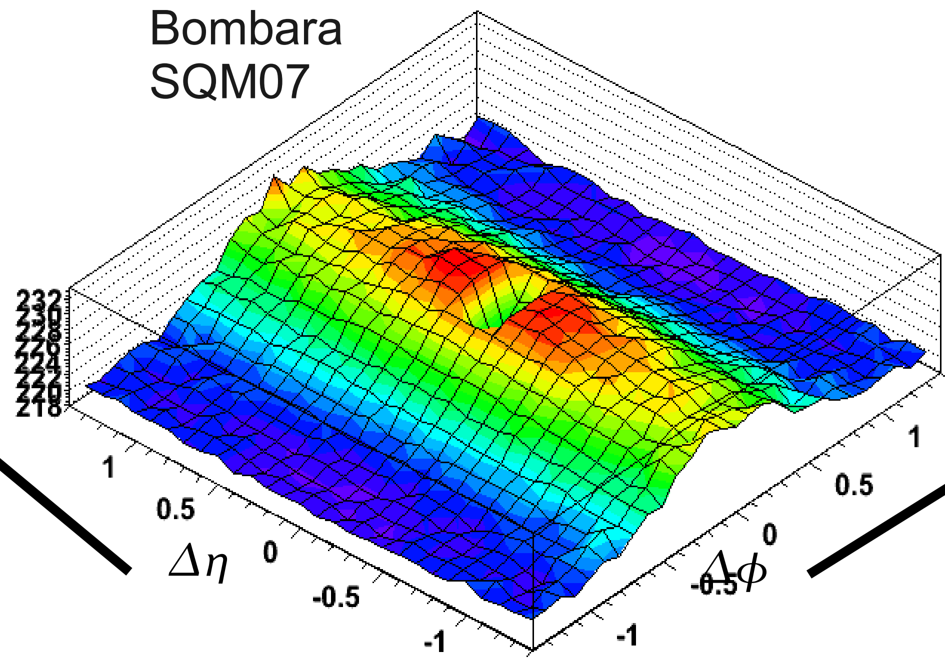


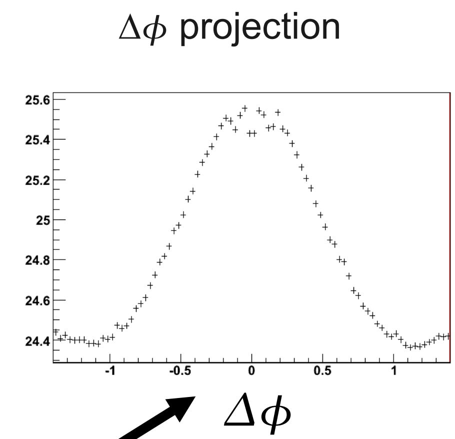




Track merging





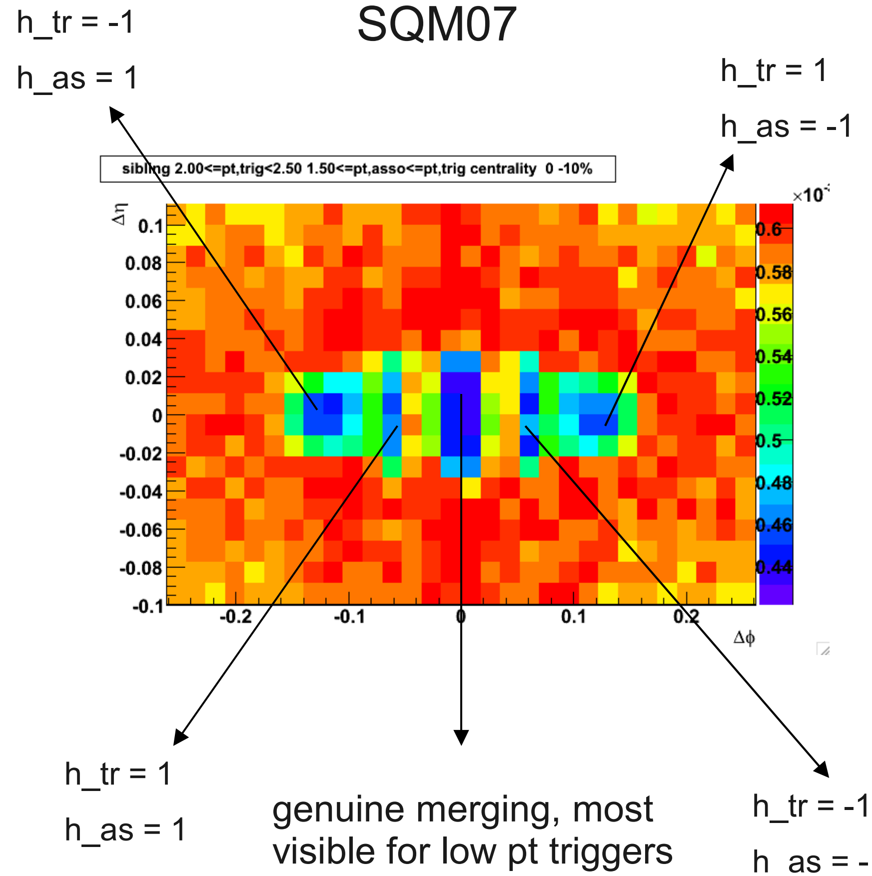


- Intrinsic limits in two-track resolution → loss of tracks at small $\Delta\phi$, $\Delta\eta$
  - Crossing of tracks, true merging of tracks
- Particle type dependent: affects reconstructed vertices (K^0_S, Λ, Ξ) more
- Dependent on p_T: affects lower $p_T^{trigger}$, p_T^{assoc} more
- With *Ridge*/*Jet* separation method affects *Jet* only

Track merging correction

- Calculate number of merged hits in a track pair from track geometry
- If the fraction of merged hits is greater than 10%, throw out the pair
- Do this for real and mixed event pairs
- Bin by helicity of trigger and associated and reflect the points from unaffected helicity bins to recover dip

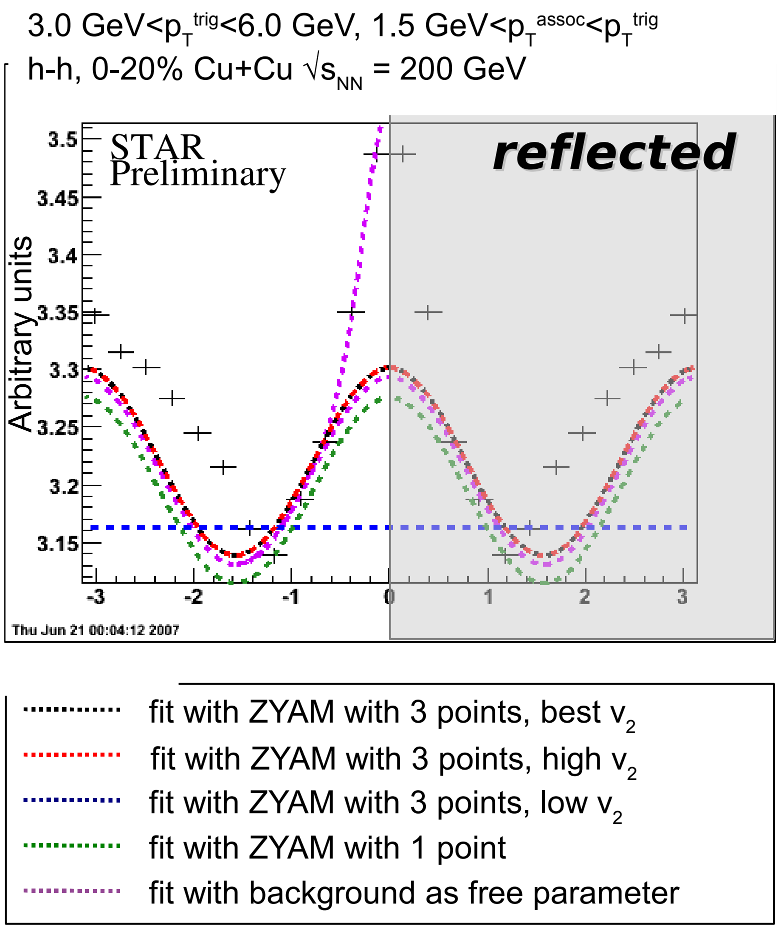
Bombara
SQM07



h_tr - helicity of trigger

h_as - helicity of associated

Determination of yields and errors



- Background:
  $B(1+2\, v_2^{trig}\, v_2^{assoc}\, \cos(2\Delta\Phi))$
- Different fit methods for determination of B
  - *Z*ero *Y*ield *A*t *M*inimum (ZYAM)
    - 1 point, 3 points
  - B as Free parameter (used as best guess)
- v_2 error
  - v_2 measurements in Cu+Cu in progress
    - Upper bound for v_2 measured
      - $v_2 \approx$ 10-15% depending on p_T, centrality
    - Estimate for lower bound, near 0
  - **Λ, $\bar{\Lambda}$, K^0_S, Ξ^+, Ξ^-...** v_2: large statistical errors
    - Assume quark scaling of h v_2 in Cu+Cu

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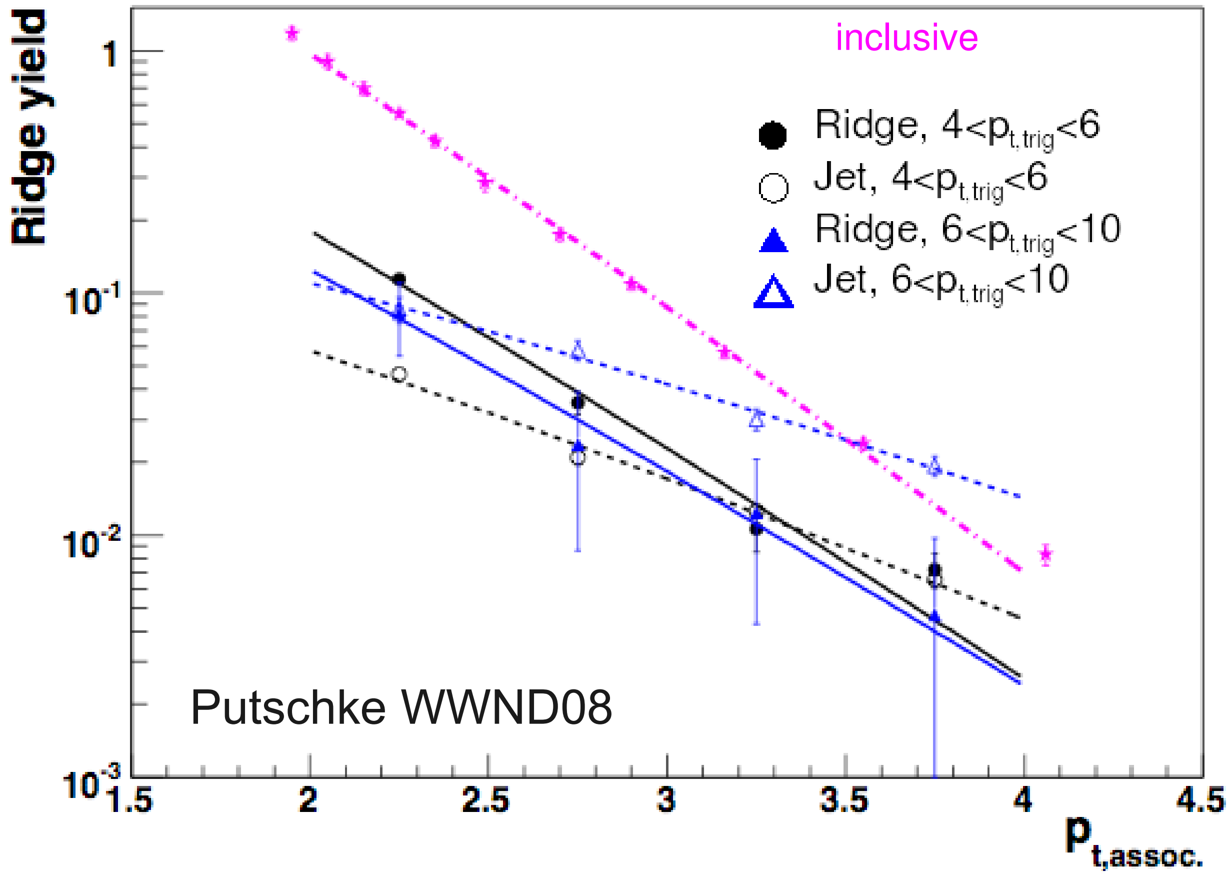
Caveats and assumptions

- *Jet*: track merging
  - Correction CPU intensive, in progress
  - 5% in central Au+Au for $p_T^{trigger} \sim 3$ GeV/c, $p_T^{assoc} \sim 1.5$ GeV/c for h-h
  - Increases for lower $p_T^{trigger}$, p_T^{assoc}, identified particles
- *Ridge*: ZYAM
- *Jet* and *Ridge*: assumption that *Ridge* is independent of $\Delta\eta$
  - If not, may overestimate *Jet*

Au+Au collisions at $\sqrt{s}_{NN} = 200$ GeV

Jet is like p+p, Ridge is like bulk



- Spectra of particles associated with *Ridge* similar to inclusive
- Spectra of particles associated with *Jet* harder

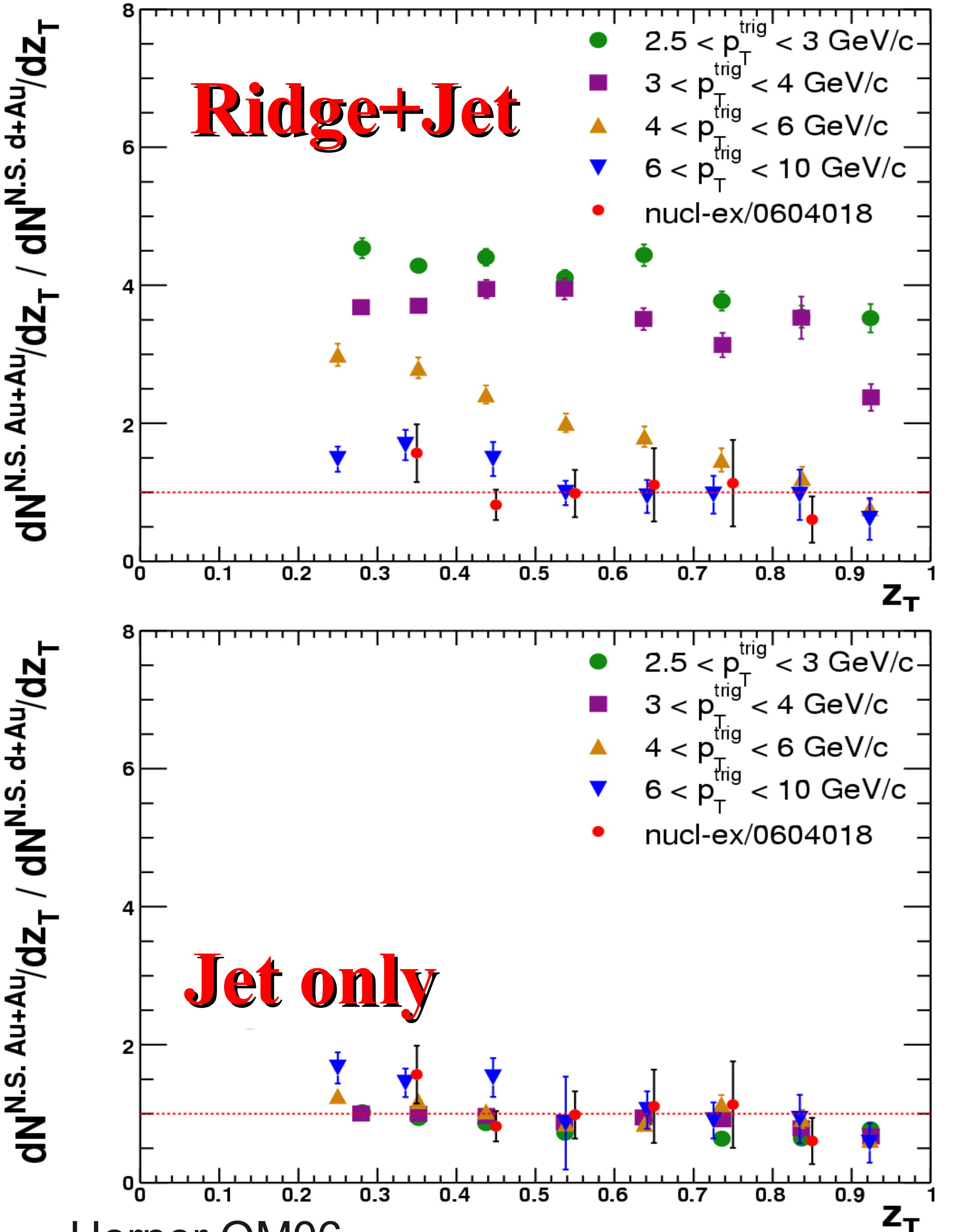
Fragmentation functions

- Measure hadron triggered fragmentation functions:

  $D^{h1,h2}(z_T)$

  $z_T = p_T^{assoc}/p_T^{trigger}$

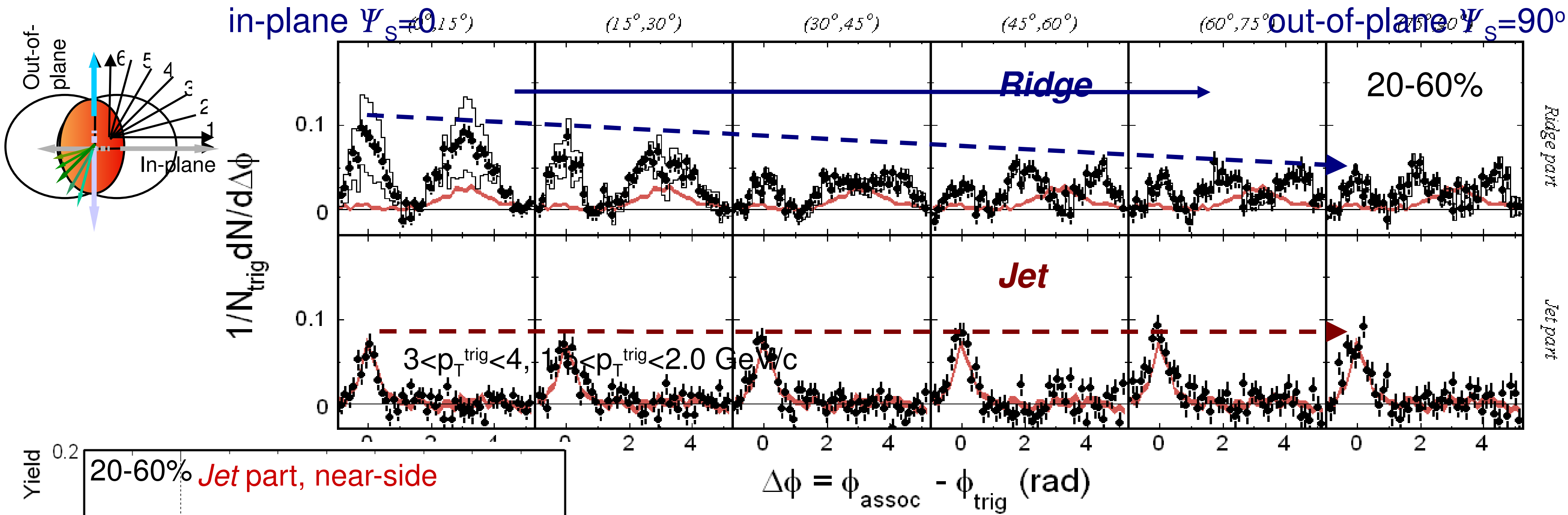
- *Jet+Ridge*: $D^{h1,h2}(z_T)$ different for d+Au, Au+Au
- *Jet* only: $D^{h1,h2}(z_T)$ within errors for d+Au, Au+Au

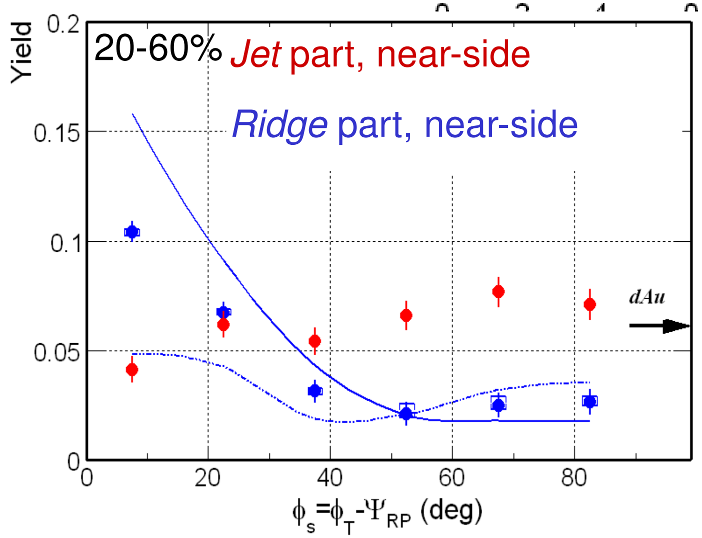


Horner QM06

Jet/Ridge w.r.t. reaction plane

Feng QM08





- *Ridge* yield decreases with φ_S. Smaller ridge yield at larger φ_S
- *Jet* yield approx. independent of φ_S and comparable with d+Au

Jet yield independent of $\varphi_{S,}$ consistent with vacuum fragmentation after energy loss and lost energy deposited in ridge, if medium is "black" out-of-plane and more "gray" in-plane for surviving jets.

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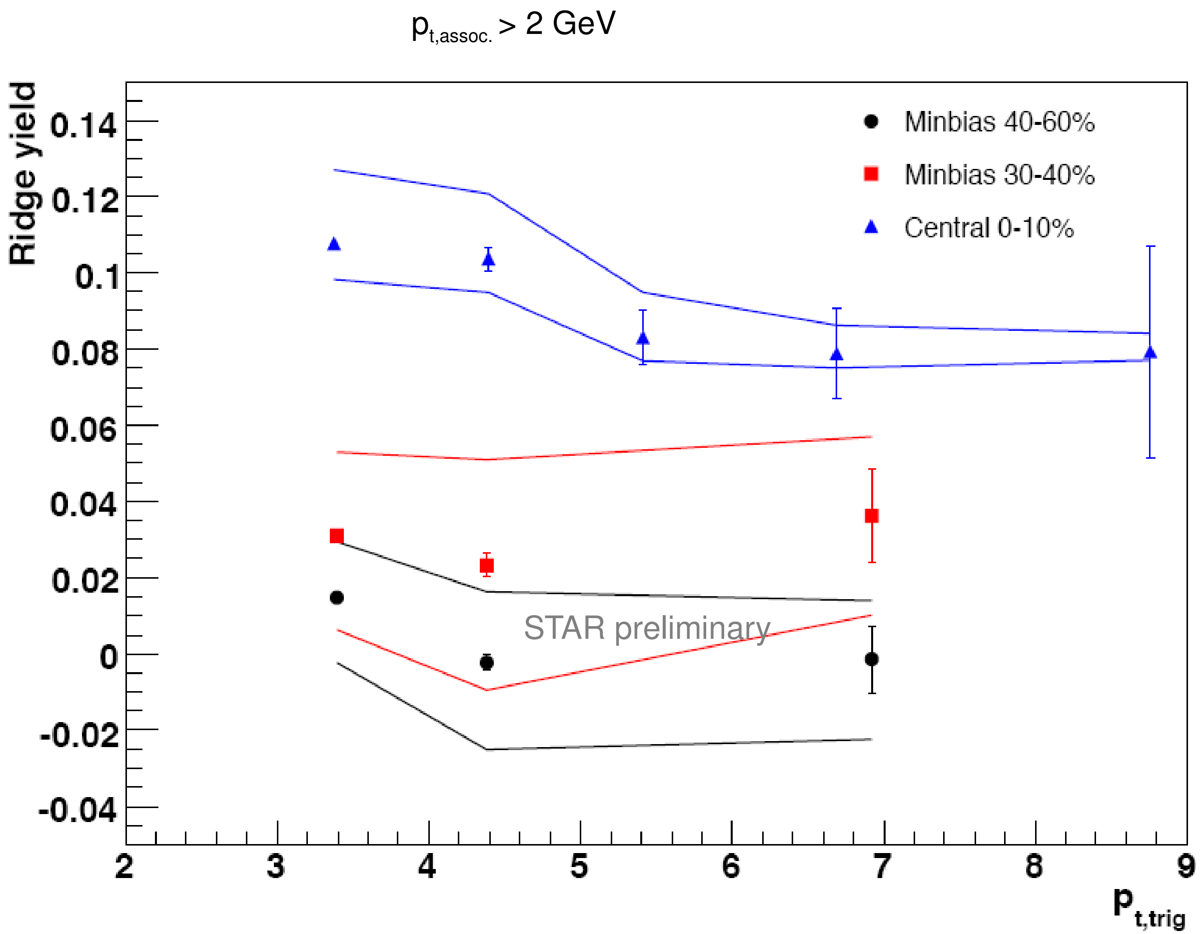
Ridge yield vs. pt,trig in Au+Au

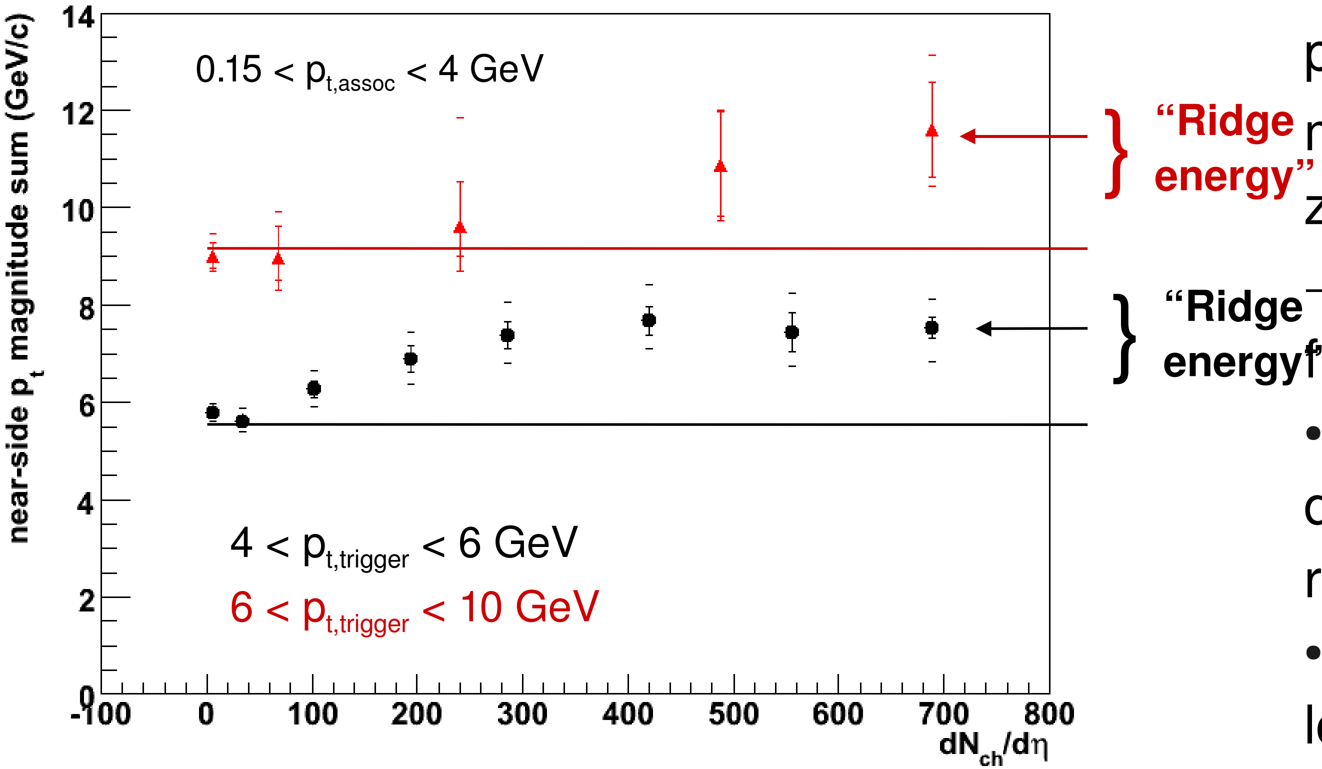


Putschke
WWND08

- *Ridge* yield persists to highest trigger pt ⇒ correlated with jet production

Ridge energy

STAR, Phys. Rev. Lett. 95 (2005) 15230

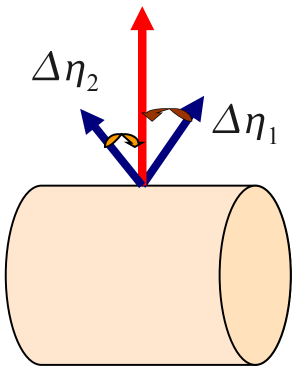


Putschke
WWND08

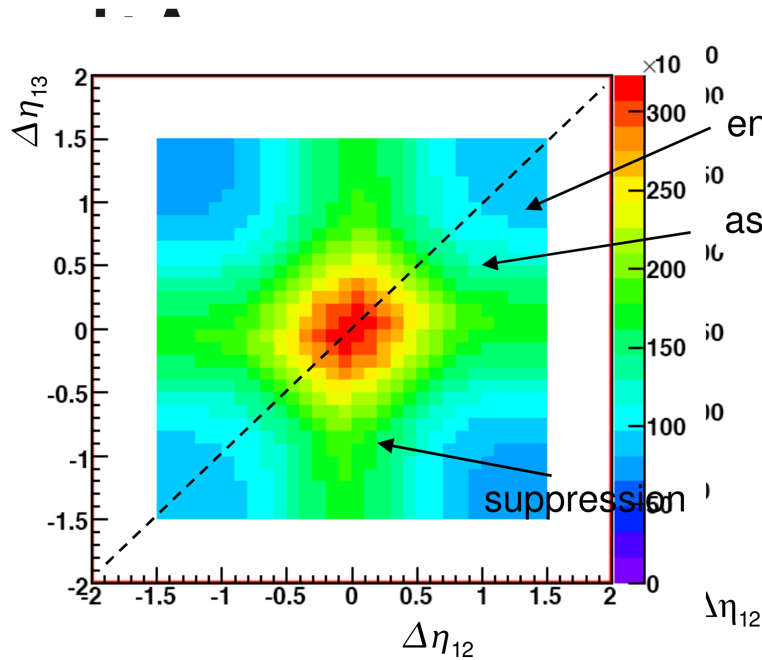
- Applying this "2-component picture" to lower $p_{t,assoc}$ measurements: $z_{t,jet}(Au+Au) \sim z_{t,jet}(d+Au)$ $\rightarrow$ subtracting p+p jet energy from Au+Au
- upper estimate of the energy deposit in the ridge ~ few GeV
- "Direct" measure of energy loss ?

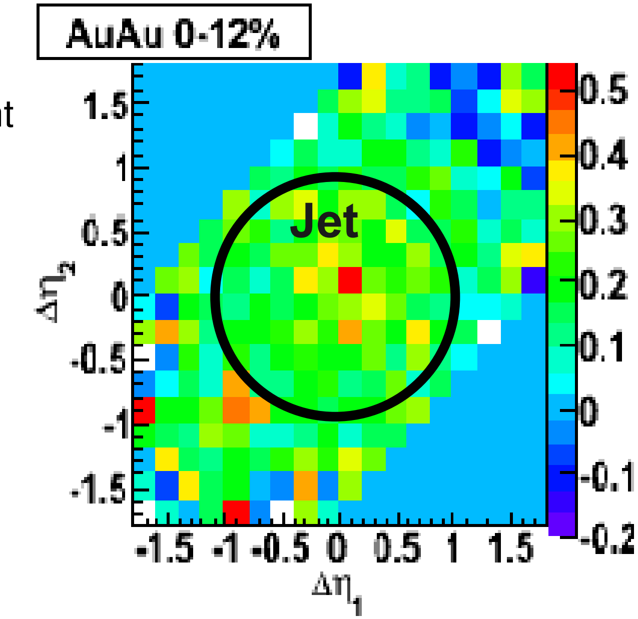
9

3-particle correlations



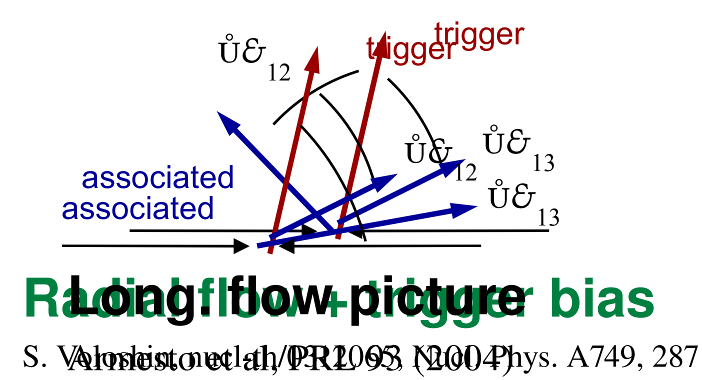
$\Delta\eta_1$ = A1-T
$\Delta\eta_2$ = A2-T





$3<p_T^{trigger}<10 \quad 1<p_T^{assoc}<3 \quad |\Delta\phi|<0.7$

- *Ridge* appears uniform event-by-event within STAR detector



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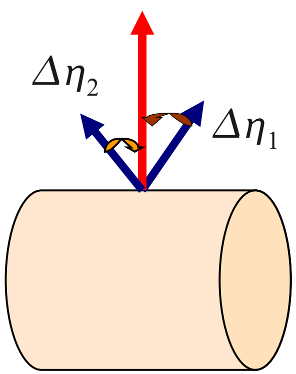

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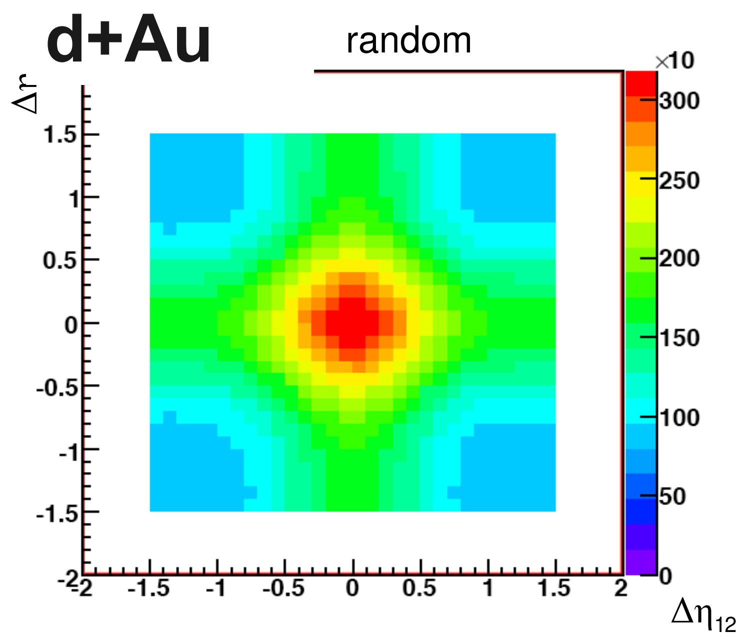

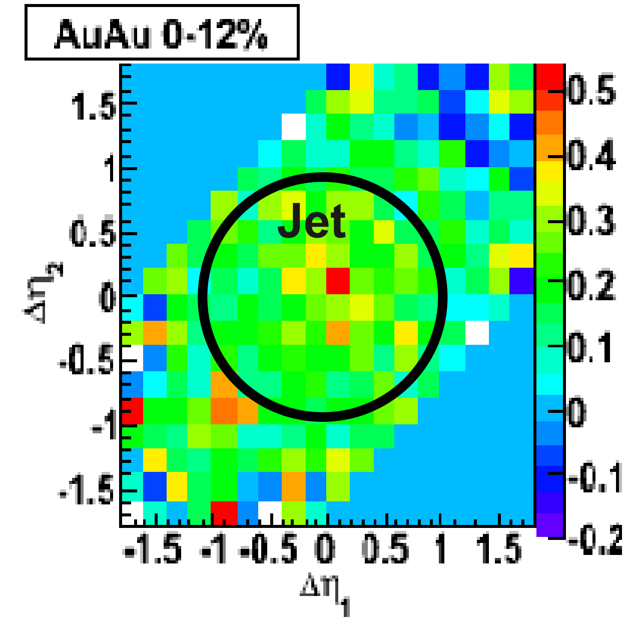

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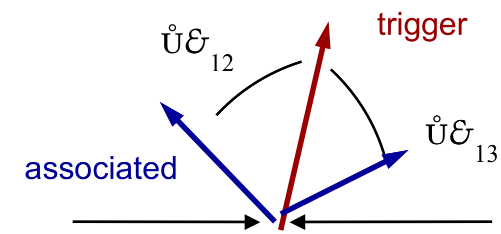
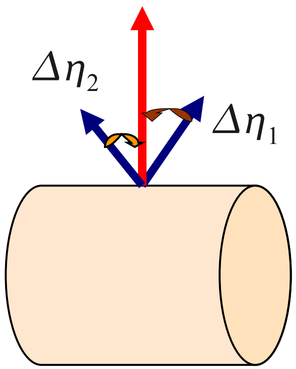


Radial flow + trigger bias

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

3-particle correlations



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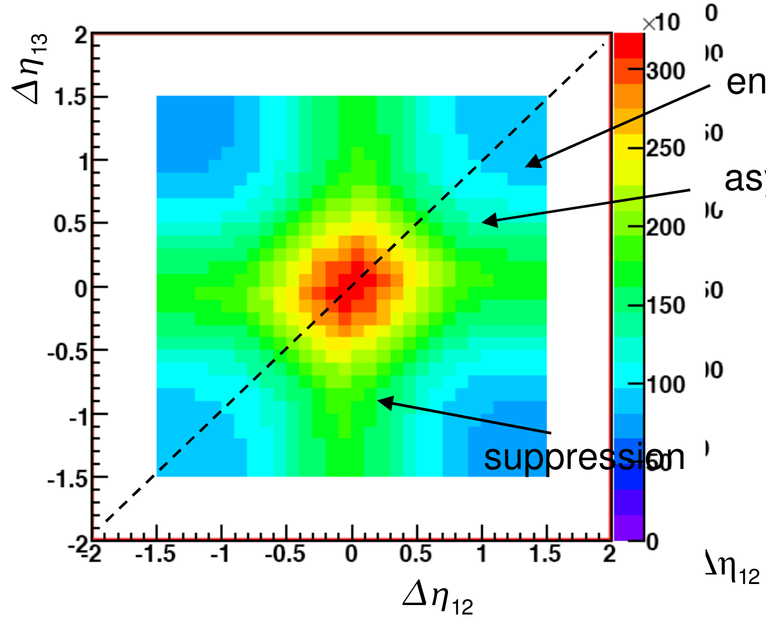

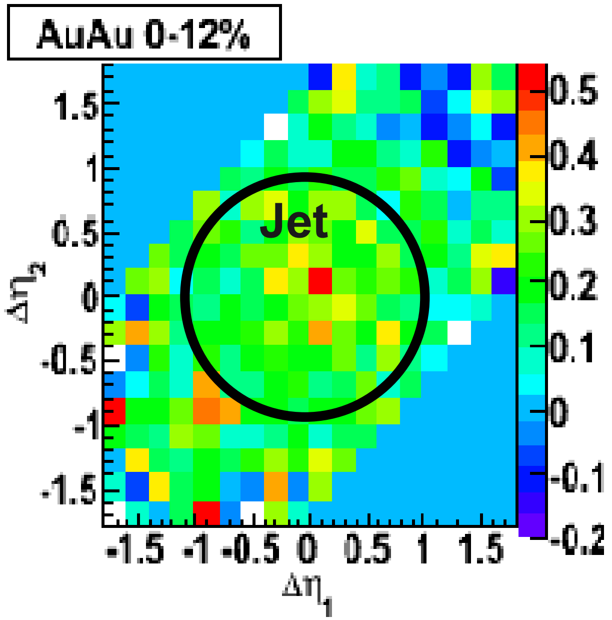

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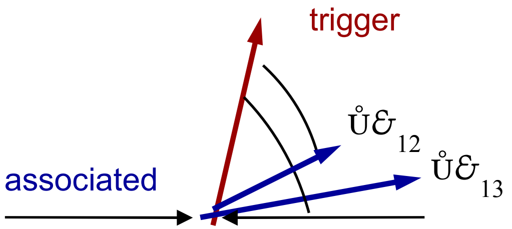
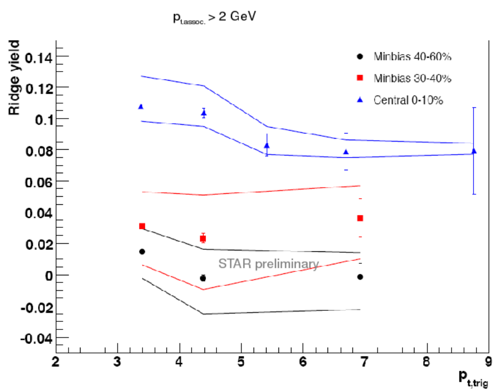


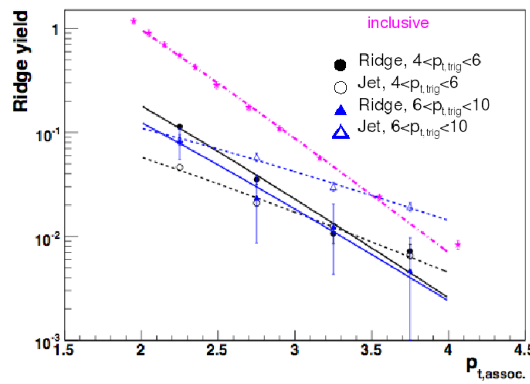
Long. flow picture

Armesto et al, PRL 93 (2004)

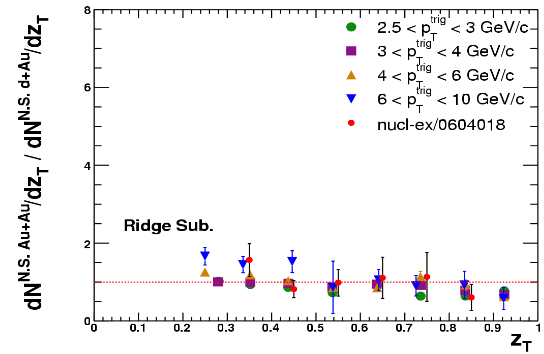
Au+Au $\sqrt{s}_{NN}$ *= 200 GeV Summary*



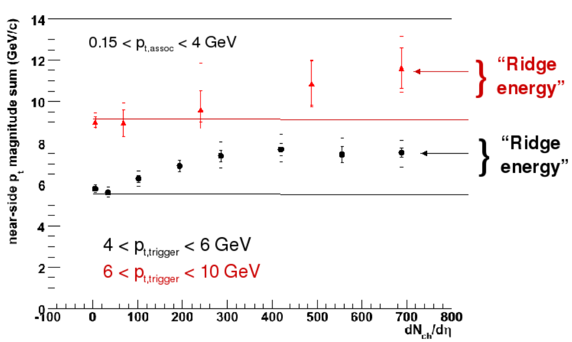
Ridge **persists to high $p_T^{trigger}$**



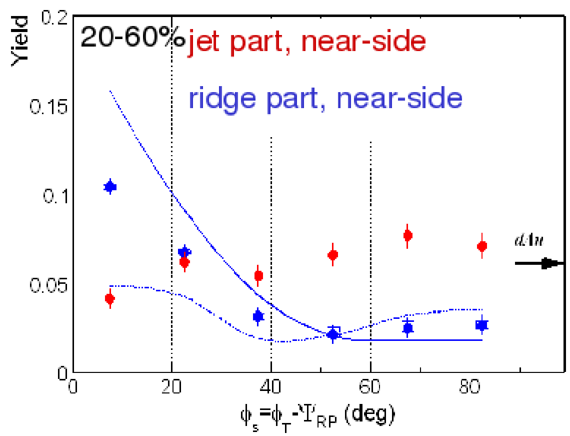
Ridge **is softer than Jet, comparable to inclusive**



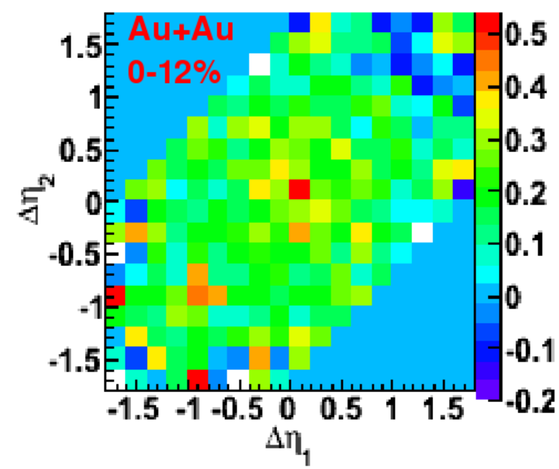
Fragmentation function with ***Ridge*** **subtracted similar in d+Au, Au+Au**



Ridge **contains a few GeV of energy**

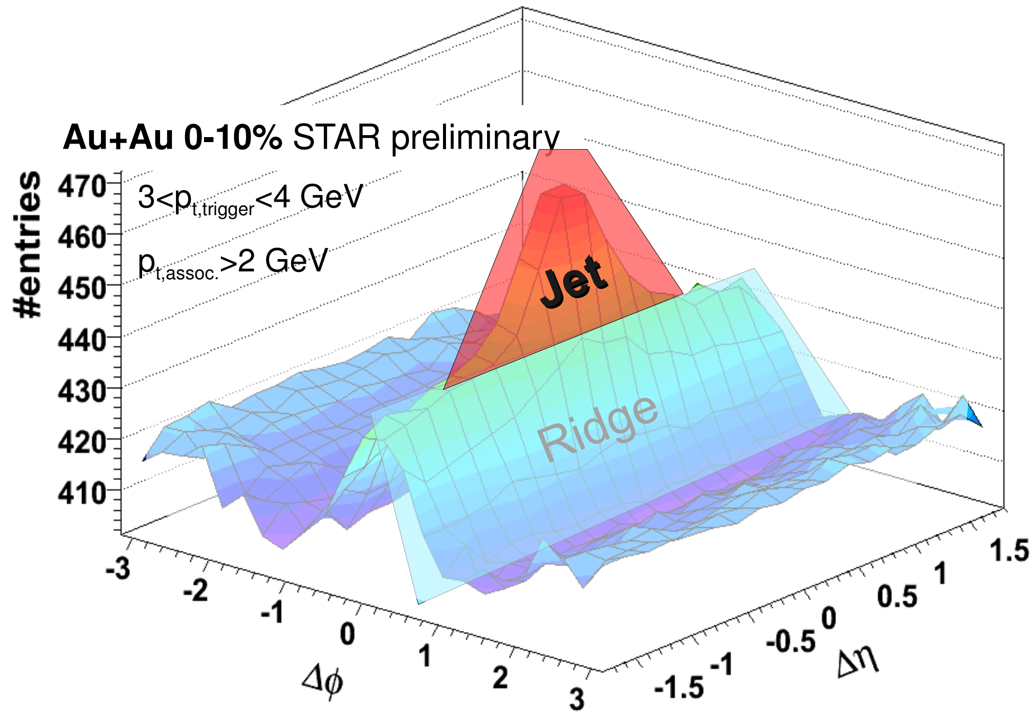


Jet **almost independent of reaction plane;** ***Ridge*** **dominantly in plane**



Ridge **uniform event-by-event**

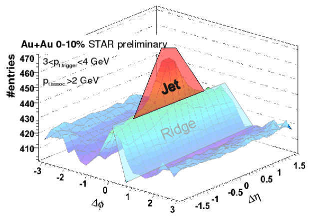
The *Jet*



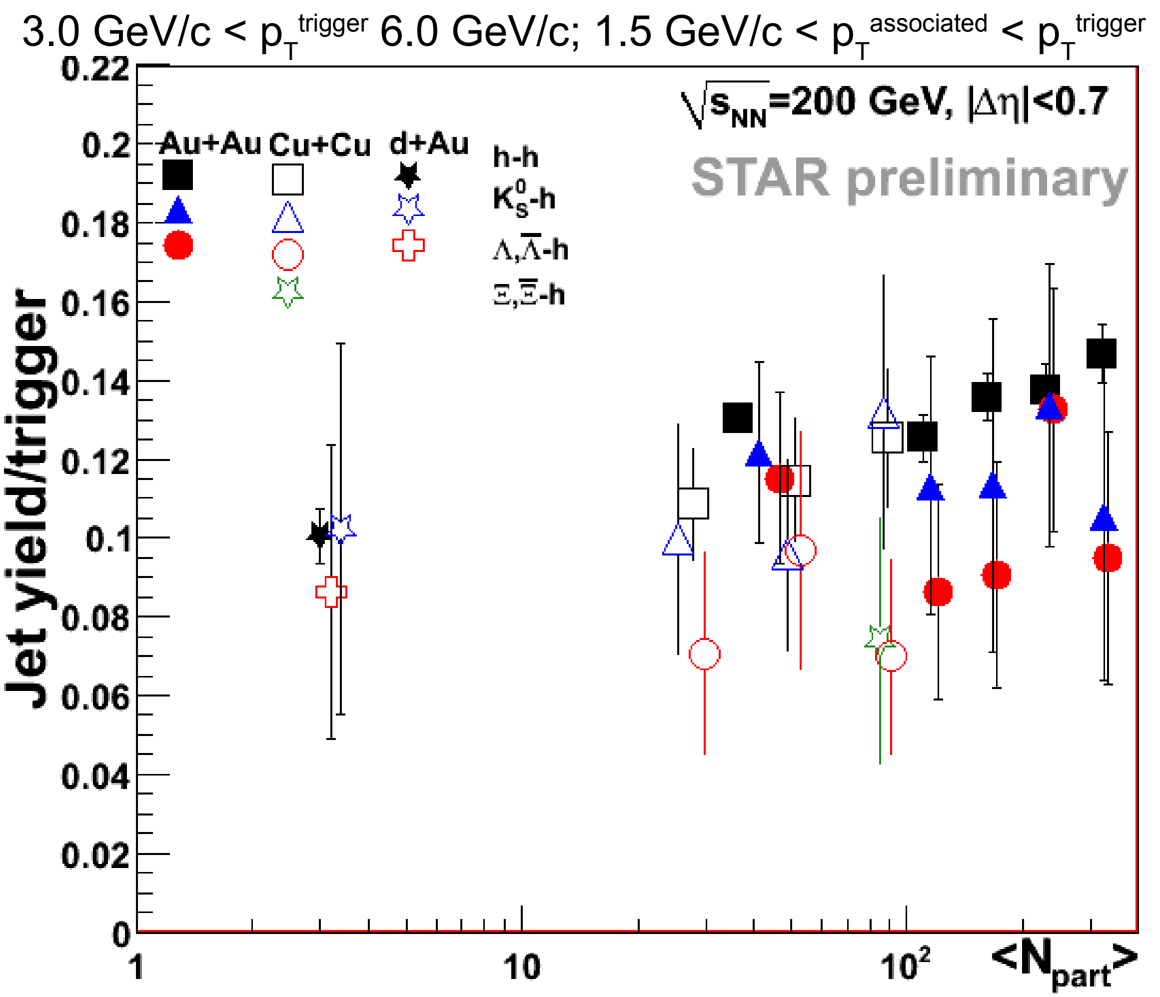
Au+Au 0-10% STAR preliminary
#entries
470
460
450
440
430
420
410
3<p_{t,trigger}<4 GeV
p_{t,assoc.}>2 GeV
Jet
Ridge
-3
-2
-1
0
1
2
3
Δφ
-1.5
-1
-0.5
0
0.5
1
1.5
Δη

Particle type dependence

Identified trigger: Near-side Yield vs N_{part}



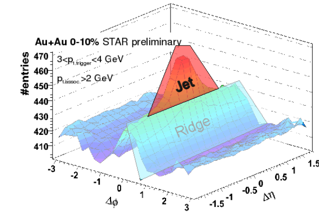
Jet yield -
No trigger type dependence



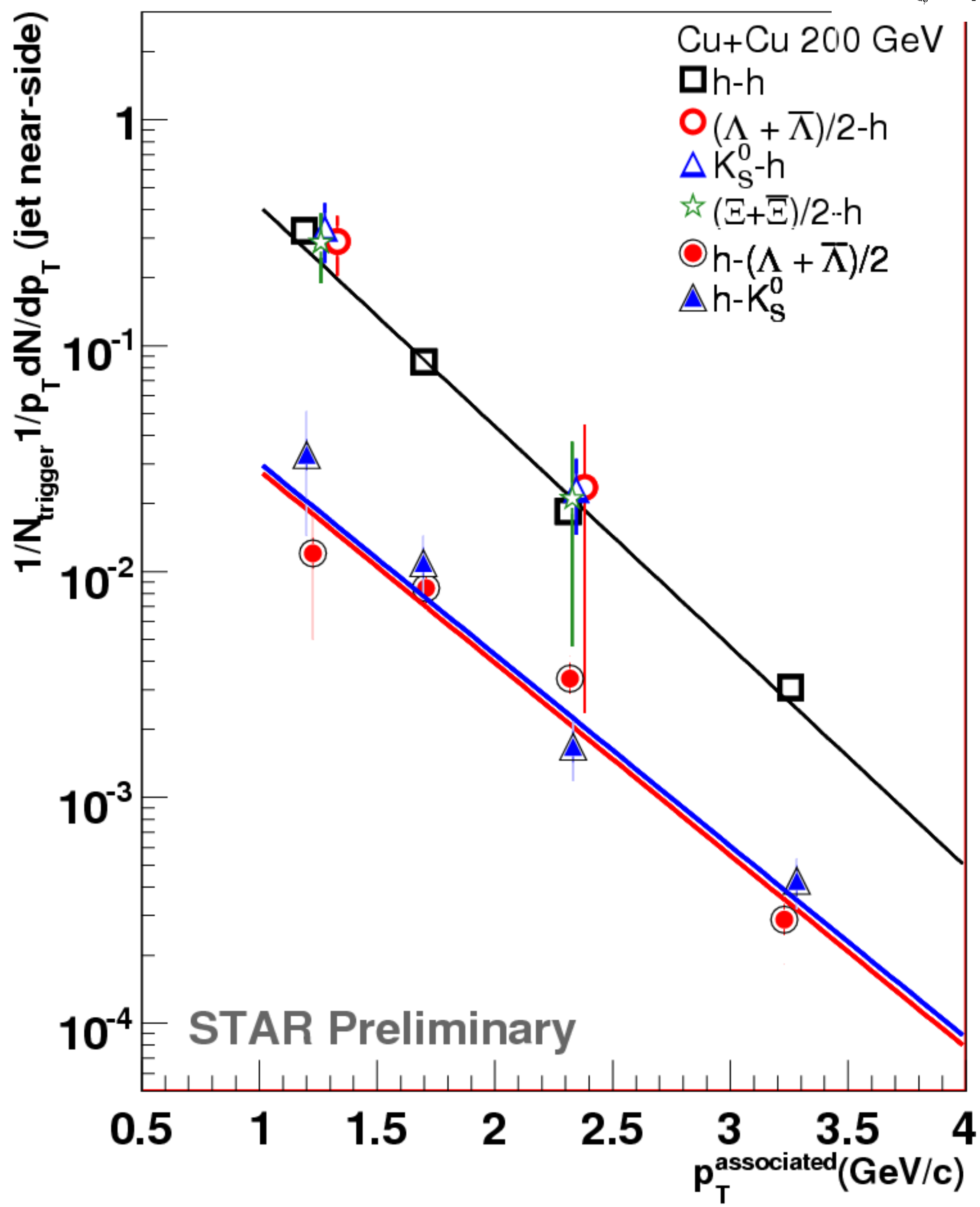
d+Au, Au+Au $\sqrt{s_{NN}}$=200 GeV from nucl-ex/0701047
Cu+Cu $\sqrt{s_{NN}}$=200 GeV from SQM2007

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

Identified associated particles



- Associated baryons and mesons in *Jet* similar

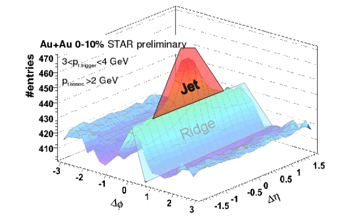


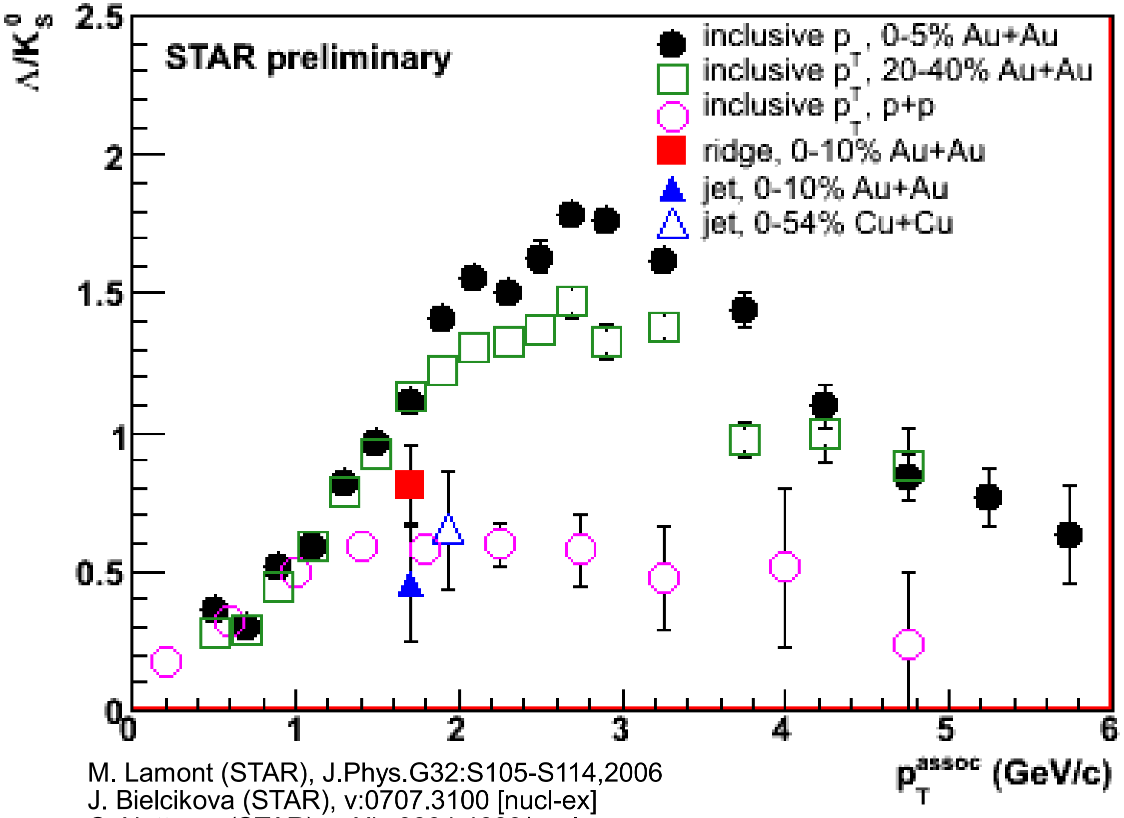
Fits assuming $1/p_T\, dN/dp_T = A\, p_T \exp(-p_T/T)$

$\sqrt{s_{NN}}$=200 GeV Au+Au 0-10% Cu+Cu: 0-54%
$\sqrt{s_{NN}}$=62 GeV Au+Au 0-80% Cu+Cu: 0-60%

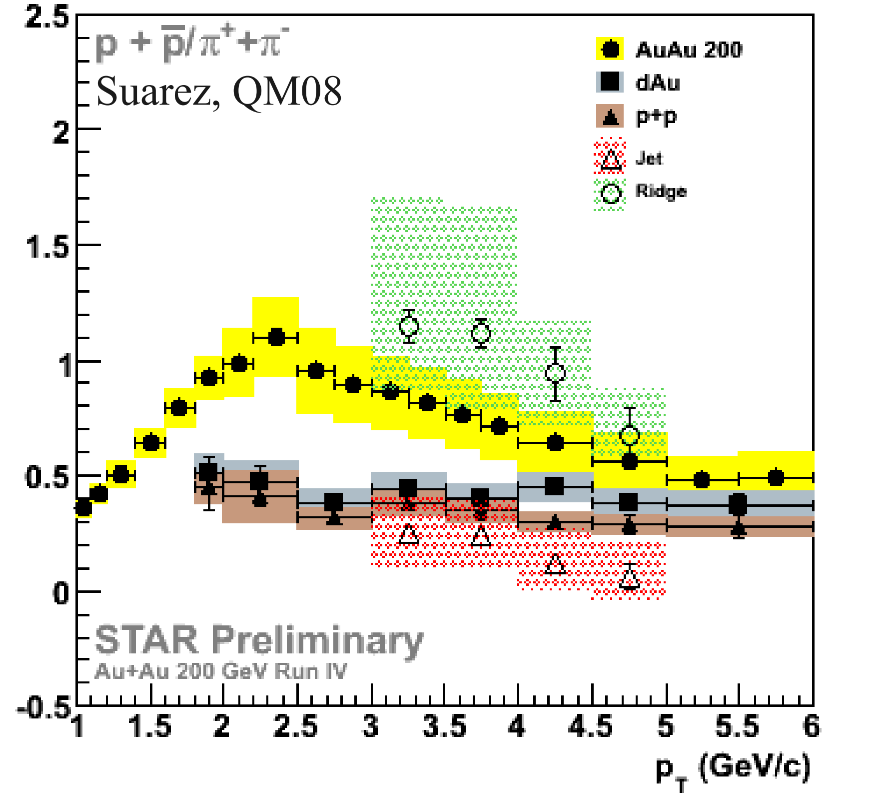
nucl-ex/0701047, SQM2007

Ridge composition





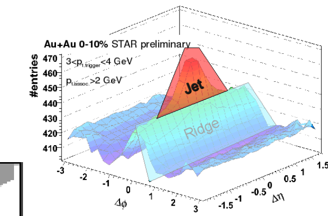
M. Lamont (STAR), J.Phys.G32:S105-S114,2006
J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

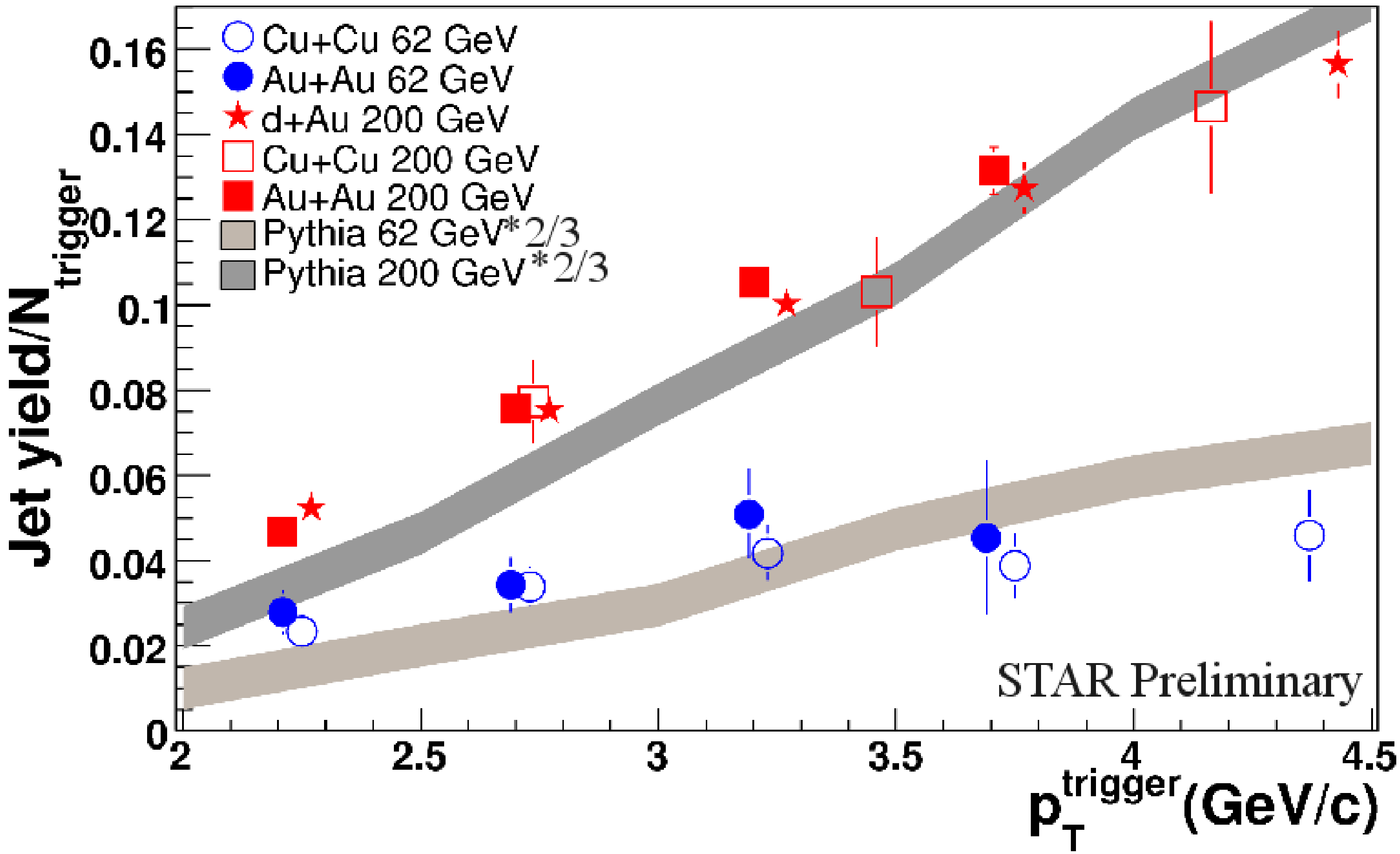


- Baryon/meson ratios in *Jet* in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles

Energy and System dependence

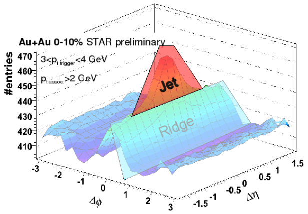
$p_T^{trigger}$ dependence

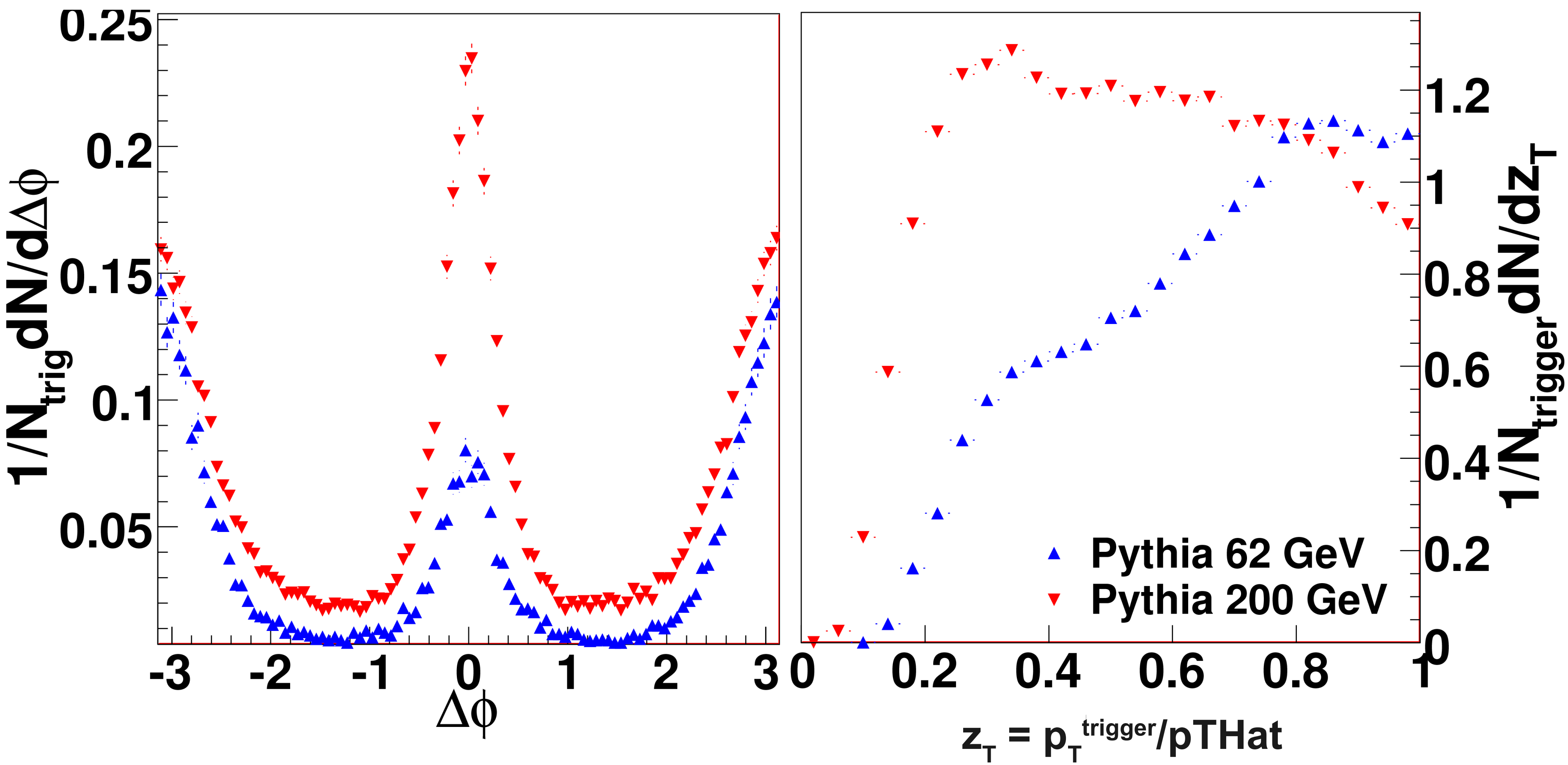




- Pythia 8.1 describes trends in data up to a scaling factor
  - Gets energy dependence right → this is a pQCD effect
  - Stronger deviations at low $p_T^{trigger}$, as expected

Pythia comparisons

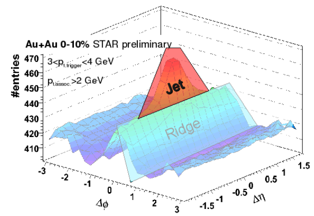


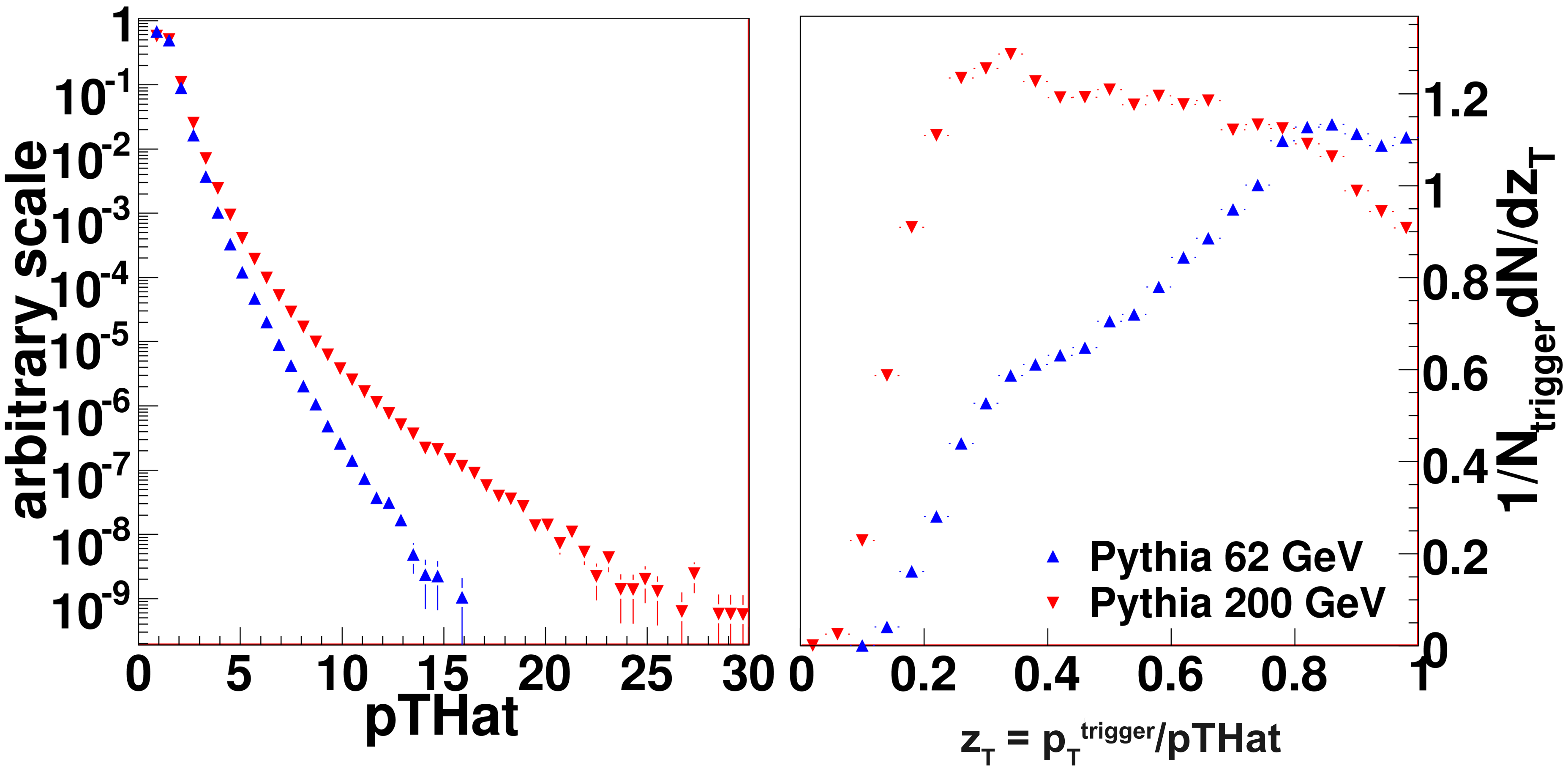


- What can Pythia tell us?
  - Higher z_T (lower jet energy) in 62 GeV for same $p_T^{trigger}$

pTHatMin = the parameter in Pythia for the minimum transverse momentum in the hard subprocess

Pythia comparisons

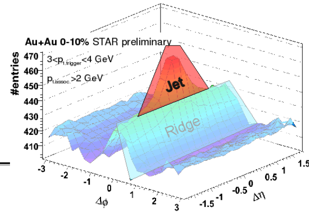


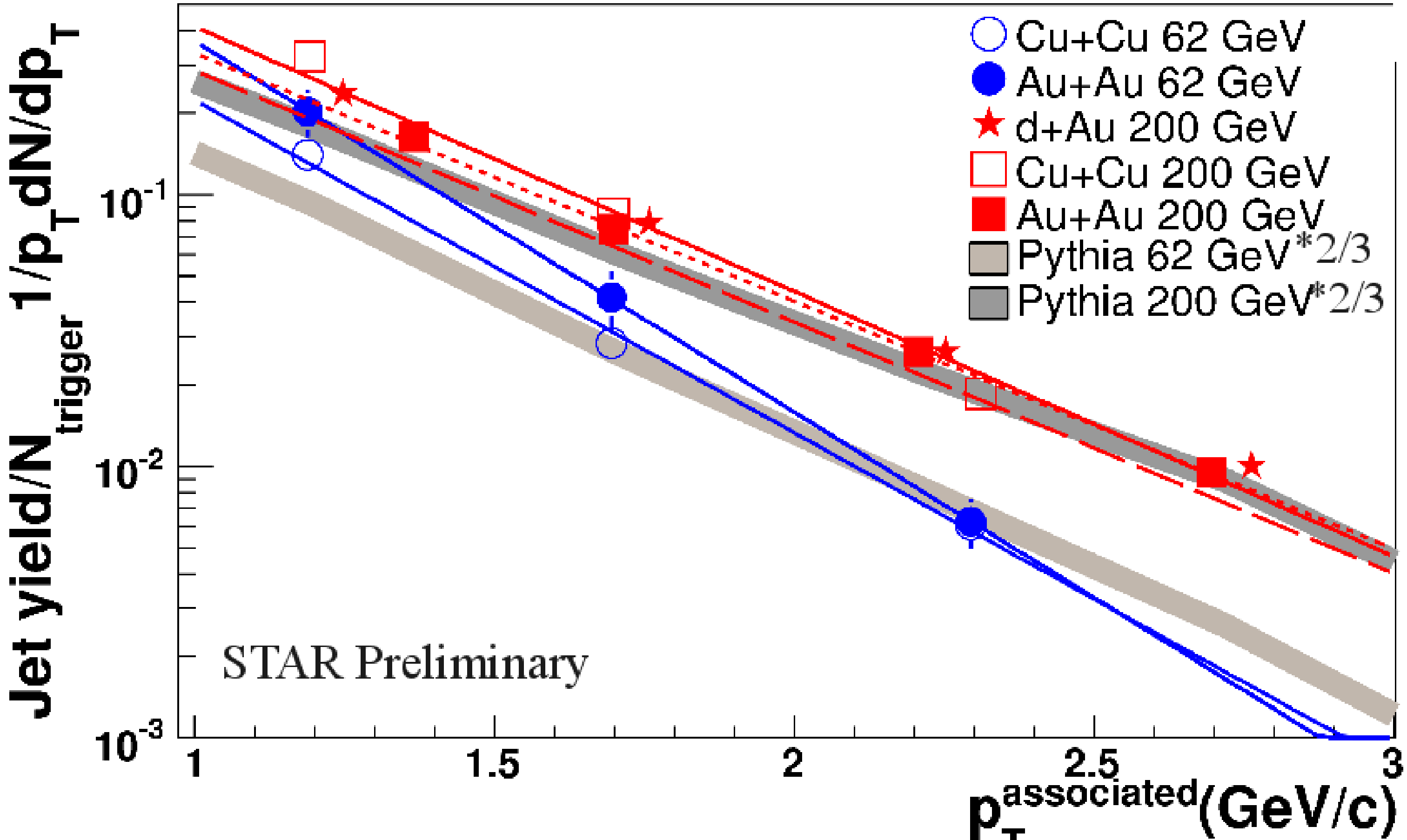


- What can Pythia tell us?
  - Higher z_T (lower jet energy) in 62 GeV for same $p_T^{trigger}$

pTHatMin = the parameter in Pythia for the minimum transverse momentum in the hard subprocess

$p_T^{associated}$ dependence





- No system dependence
- Pythia 8.1 slightly harder than data
- Diverges slightly from Pythia 8.1 at lower $p_T^{associated}$

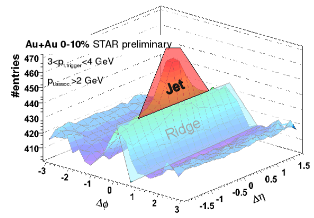
Inverse slope parameter

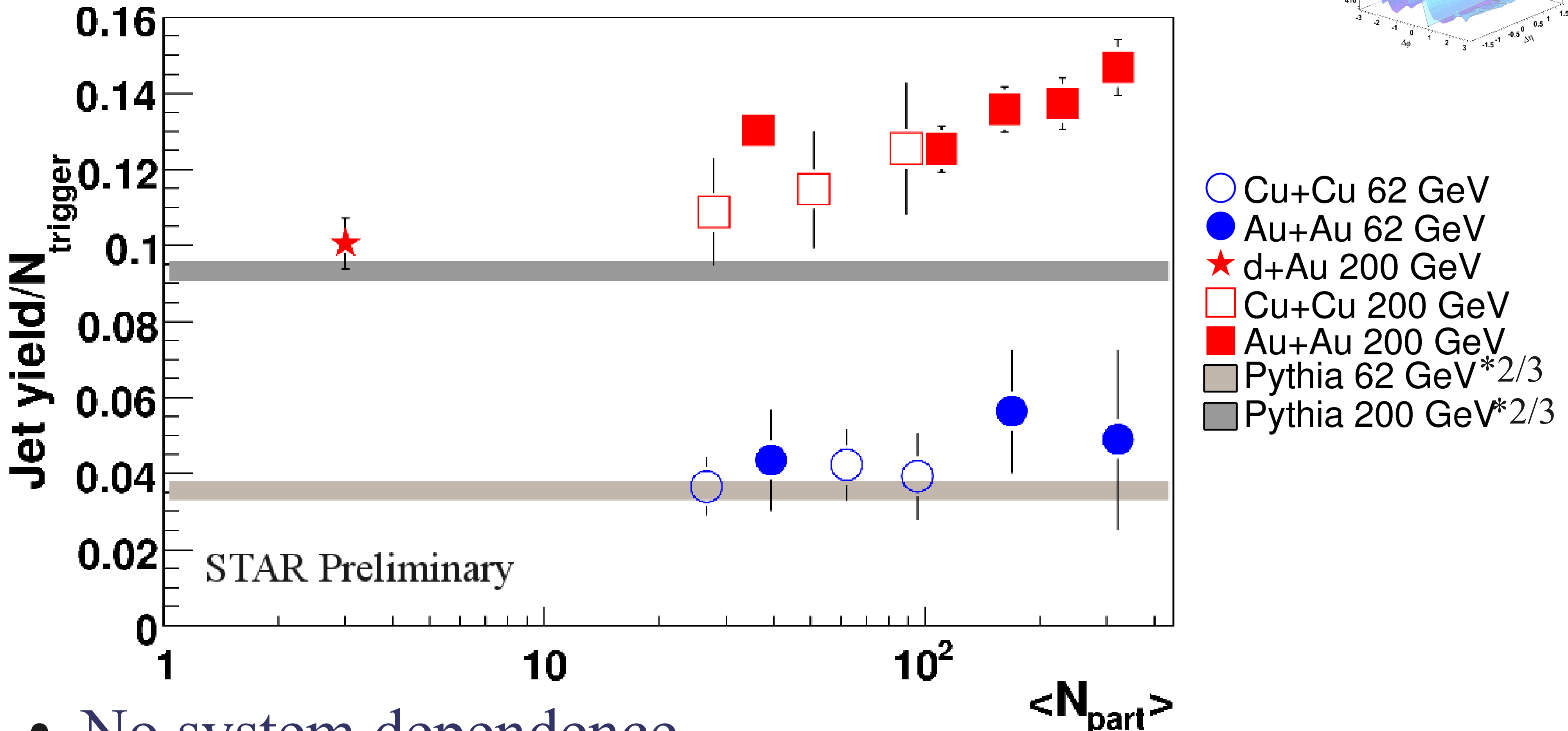
	$\sqrt{s_{NN}}$ = 62 GeV	$\sqrt{s_{NN}}$ = 200 GeV
Cu+Cu	317 ± 26	445 ± 20
Au+Au	355 ± 21	478 ± 8
d+Au		469 ± 8
Pythia	417 ± 9	491 ± 3

Statistical errors only

J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

N_{part} dependence

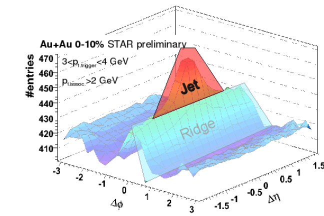




- No system dependence
- Some deviations from Pythia 8.1 with increase in N_{part}
  - Incomplete *Ridge* subtraction?
  - *Jet* modification at low p_T?

J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

Conclusions: Jet

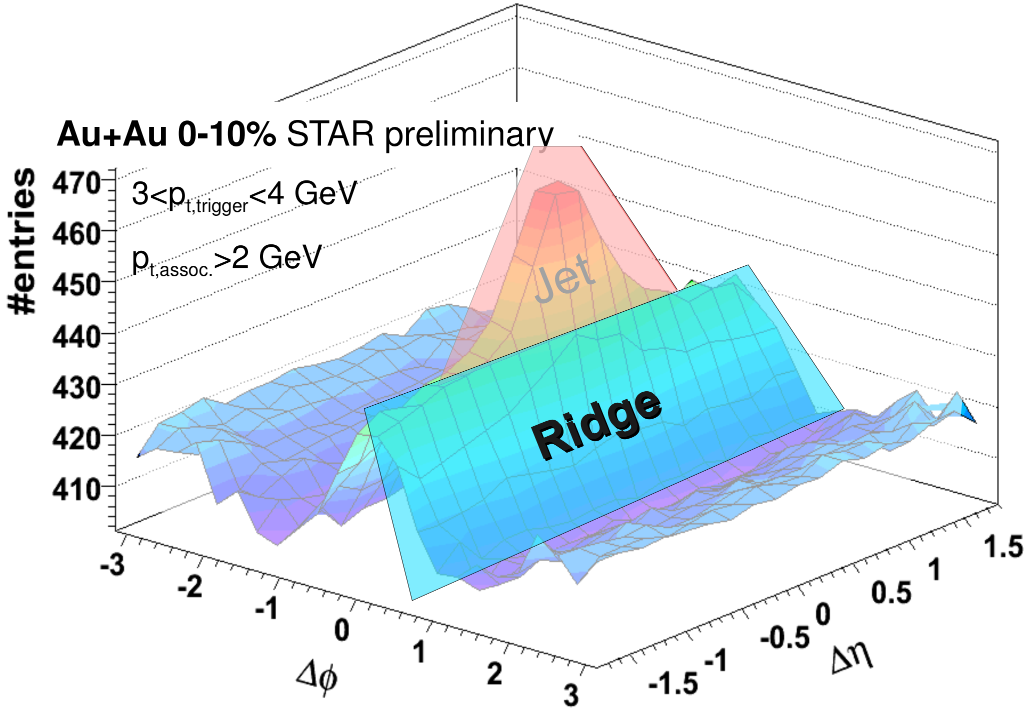


- Pythia describes data well
  - Scaling factor needed but Pythia 8.1 is not as tuned as earlier versions
  - Energy dependence in *Jet* is pQCD effect
  - Trends for $p_T^{trigger}$, p_T^{assoc} dependence right
- Particle ratios similar to p+p

→ *Jet* production mechanism dominated by fragmentation

  - Separation of *Jet* and *Ridge* works
  - Effects of triggers which don't come from jets small
  - Pythia can be used to estimate z_T distributions, jet energy

The *Ridge*



Au+Au 0-10% STAR preliminary
3<p_t,trigger<4 GeV
p_t,assoc.>2 GeV
#entries
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-1.5
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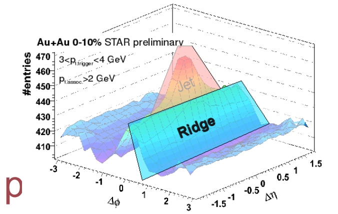
0.5
1
1.5
Δη

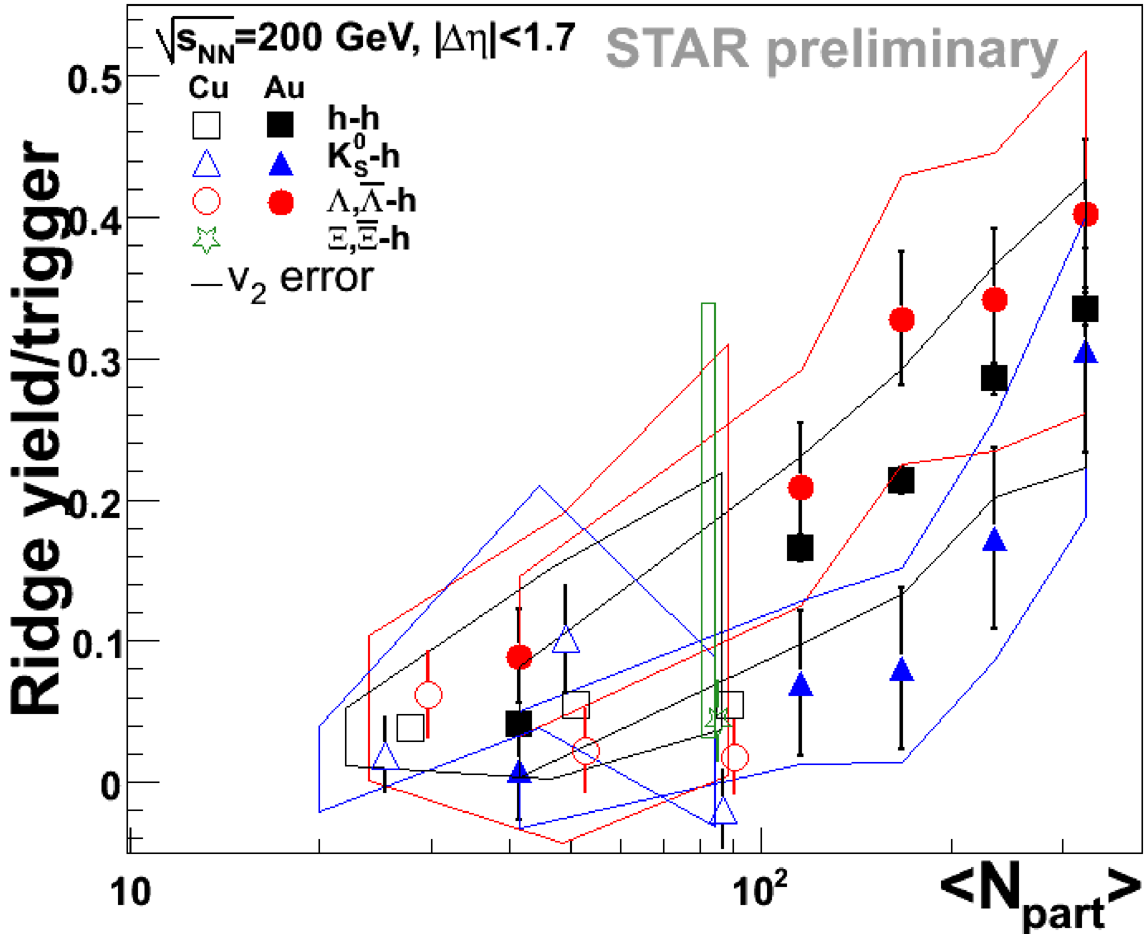
Particle type dependence

Identified trigger: Near-side Yield vs N_{part}

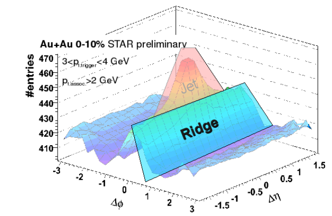


3.0 GeV/c < $p_T^{trigger}$ 6.0 GeV/c; 1.5 GeV/c < $p_T^{associated}$ < p

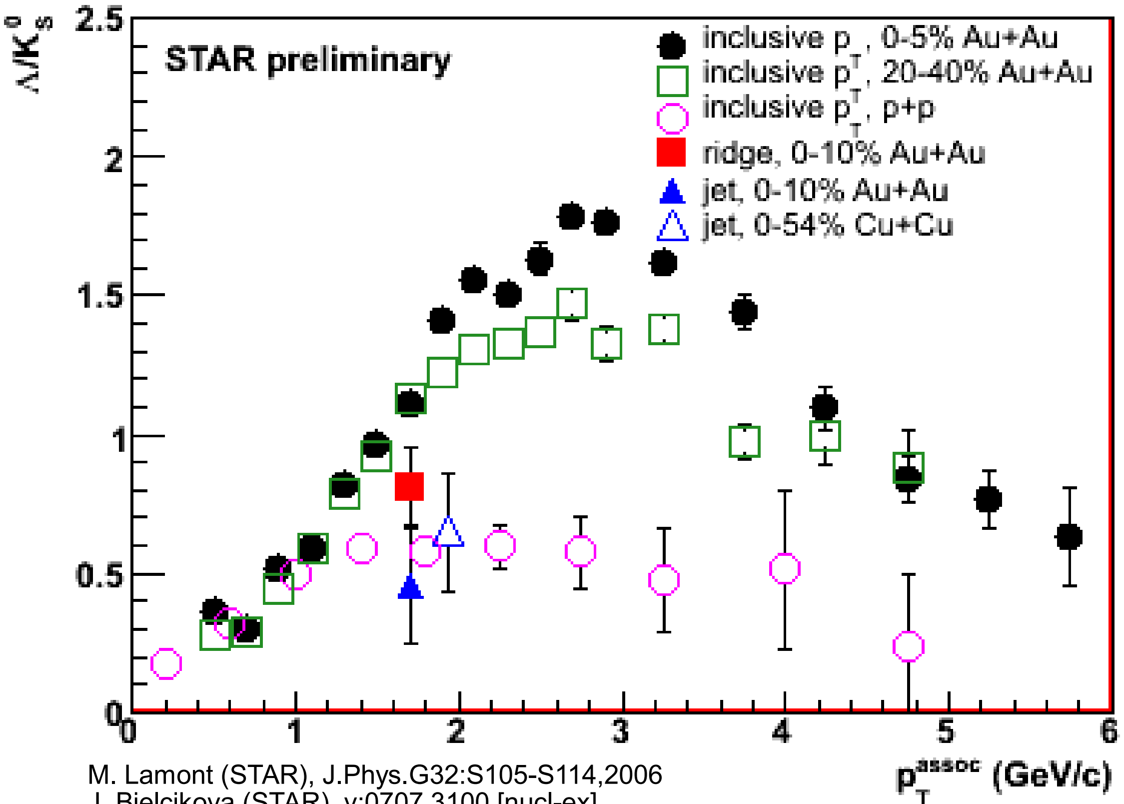
Ridge yield -
No trigger type dependence



Au+Au $\sqrt{s_{NN}}$=200 GeV from nucl-ex/0701047
Cu+Cu $\sqrt{s_{NN}}$=200 GeV from SQM2007
Data points at same N_{part} offset for visibility



Ridge composition



M. Lamont (STAR), J.Phys.G32:S105-S114,2006
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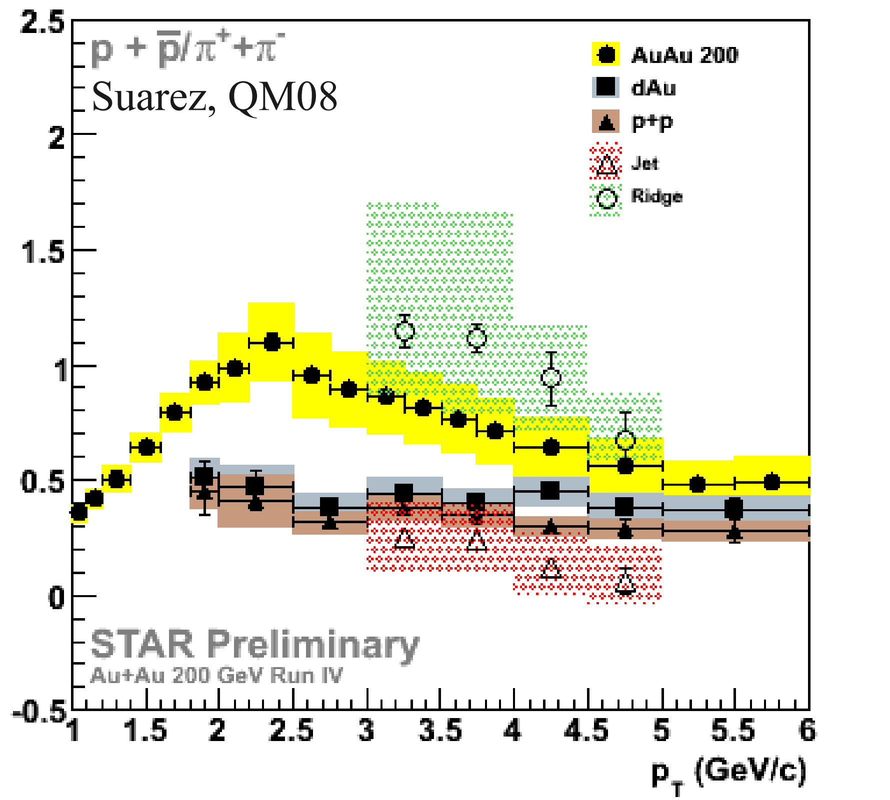
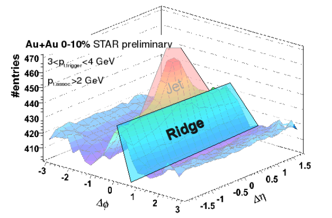
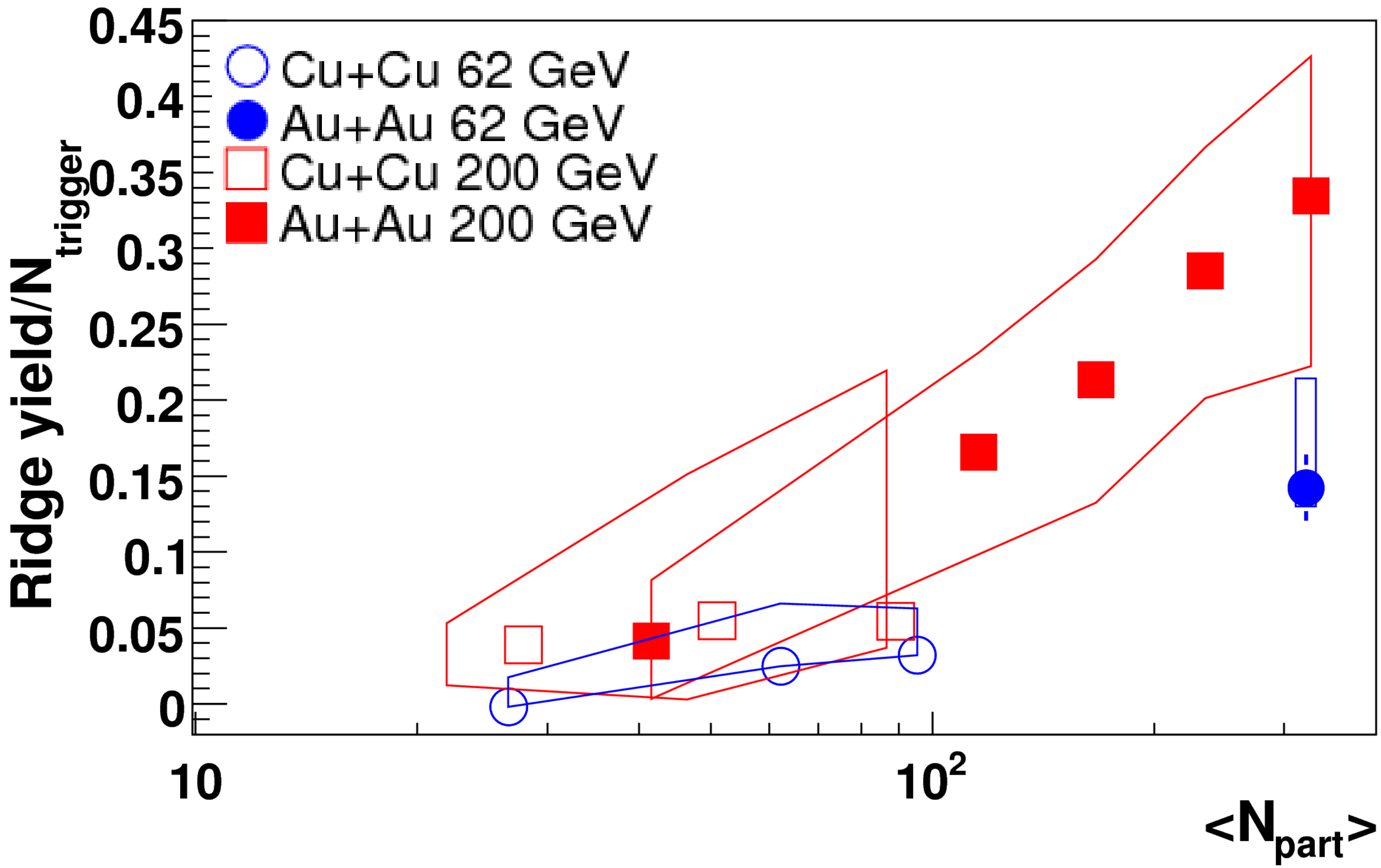


- Baryon/meson ratios in *Ridge* similar to bulk for both strange and non-strange particles

Energy and System dependence

Ridge vs N_{part}

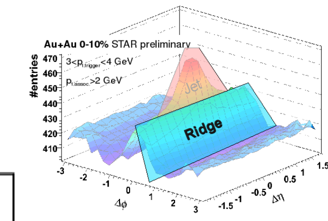


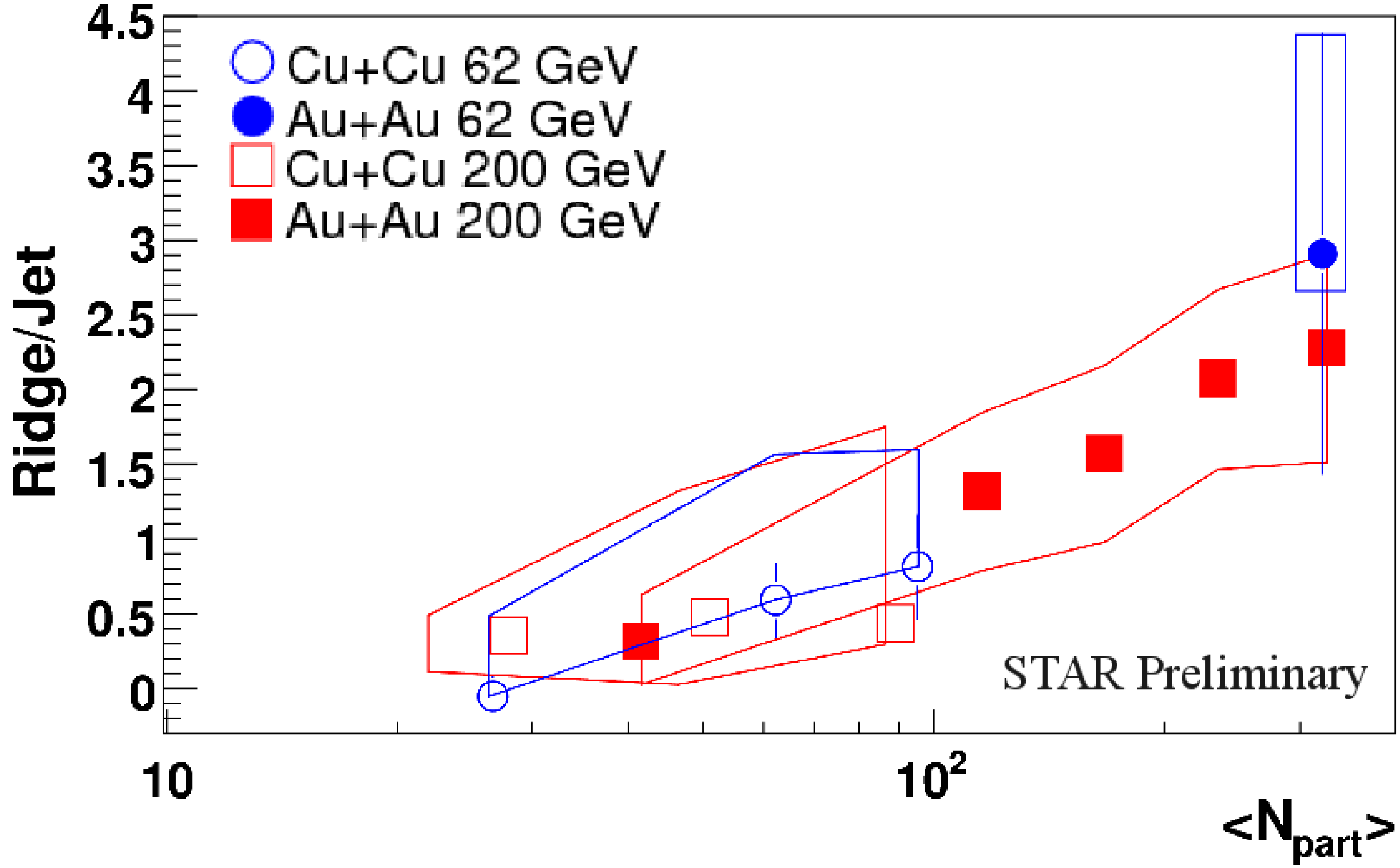


- No system dependence at given N_{part}

J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

Ridge vs N_{part}

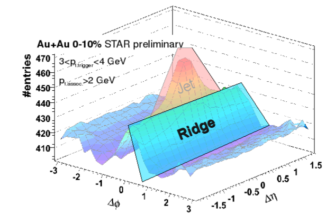




- No system dependence at given N_{part}
- *Ridge/Jet* Ratio independent of collision energy

J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

Conclusions: Ridge



- Extensive data on Ridge
  - Cu+Cu, Au+Au consistent at same N_{part}
  - *Ridge/Jet* ratio independent of energy
  - Persists to high $p_T^{trigger}$
  - *Ridge* looks like bulk
    - $p_T^{associated}$ dependence, particle composition
- *Jet* agreement between different systems, with scaled Pythia
  - Simulations can be used to approximate z_T distribution for comparisons of data to models
  - More steeply falling jet spectrum in 62 GeV → stronger bias towards unmodified/surface jets
    - Could explain smaller Ridge yield in 62 GeV

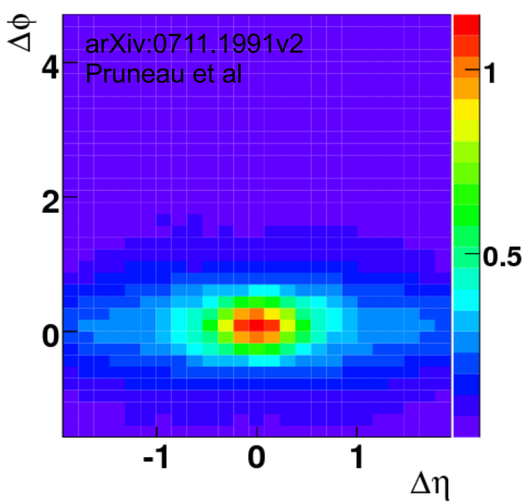
Comparisons to theories

Models

- Radial flow+trigger bias

  S. Voloshin, nucl-th/0312065, Nucl. Phys. A749, 287
  C.. Pruneau, S. Gavin, S. Voloshin, arXiv:0711.1991v2
  E. Shuryak, *Phys.Rev.C76:047901,2007*

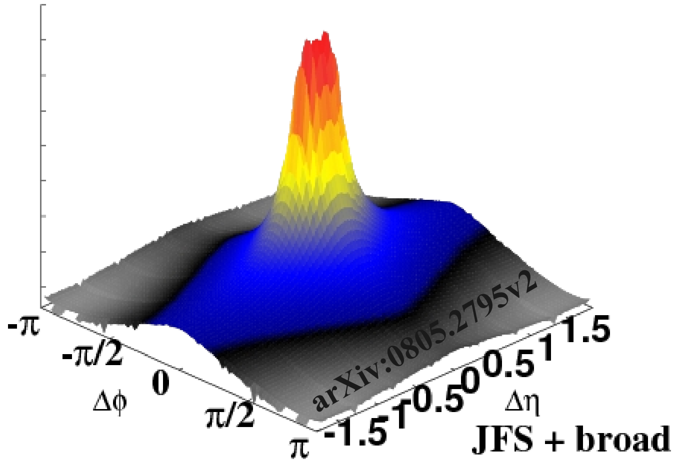
  – Works for one set of kinematic cuts in central Au+Au at 200 GeV
  – Need more detailed comparisons (energy dependence)
  – Model needs some refinements (momentum conservation)



- Plasma instability

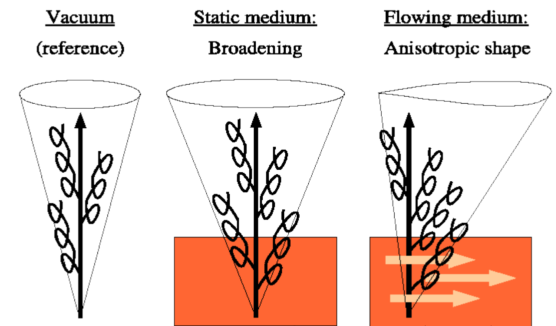
  QCD magnetic fields, Majumder et al,Phys.Rev.Lett.99:042301,2007
  Anisotropic plasma, P. Romatschke, PRC,75014901 (2007)

  – So far unable to make enough *Ridge* without Radial flow+trigger bias



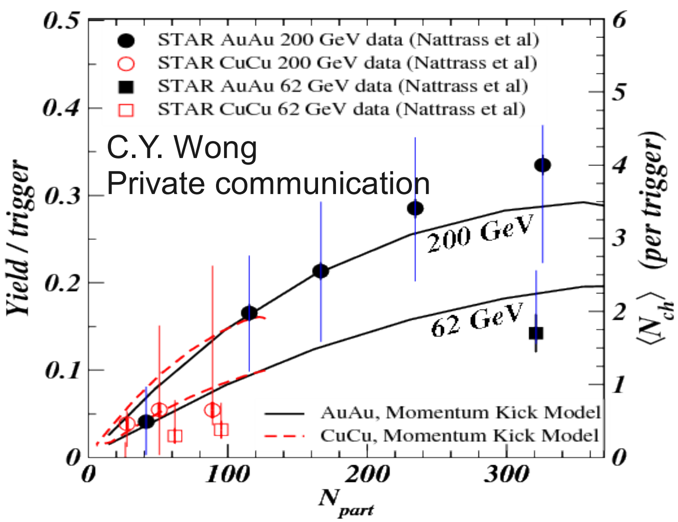
Models

- Longitudinal flow
  Longitudinal flow, Armesto et al, PRL 93 (2004)
  – Problems due to Δη width



Armesto et al, PRL 93 (2004)

- Momentum kick
  Momentum kick from jet, C.-Y. Wong , Phys.Rev.C76:054908,2007
  – Fits data well, including energy dependence



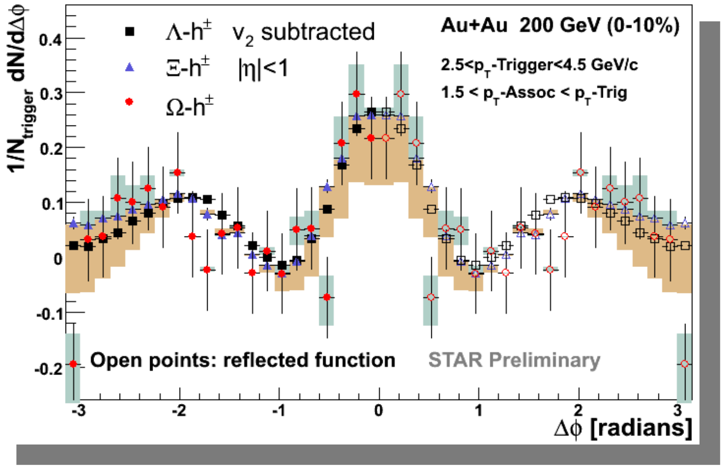
- Recombination
  Medium heating + recombination, Chiu & Hwa, PRC72, 034903
  – No quantitative comparisons

Conclusions

- Considerable evidence that *Jet* is dominantly produced by fragmentation
  - Can we use this information to learn more about the *Ridge*?
- Several models for the *Ridge*, few quantitative comparisons
  - Several depend on hydrodynamics
  - Need better calculations – more quantitative, more than central Au+Au
- Future:
  - More energy dependence (RHIC beam energy scan, LHC)
  - Jet reconstruction – more detailed studies of *Ridge*?

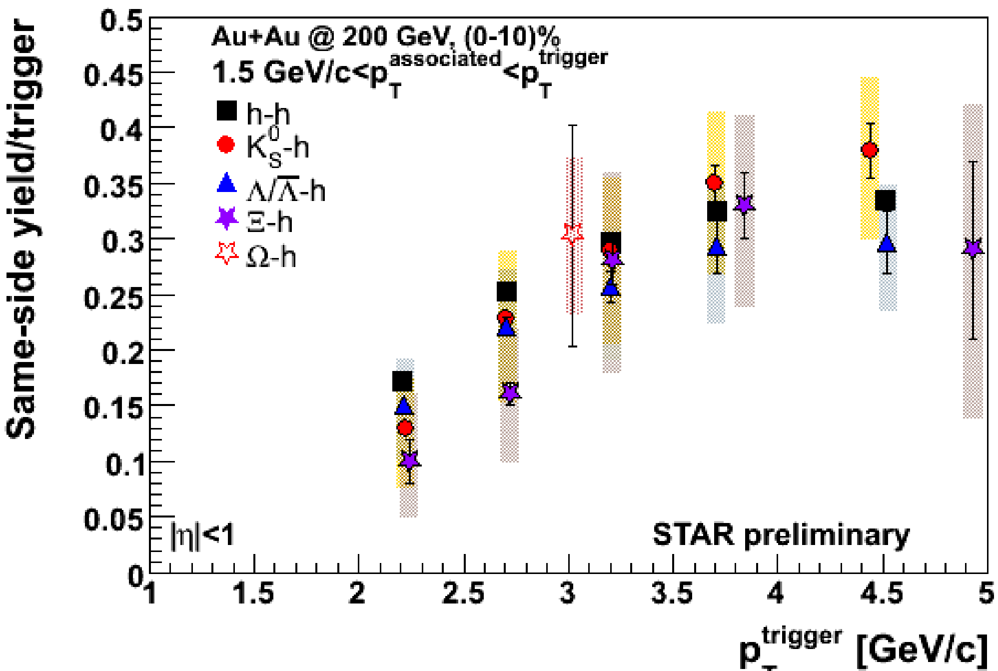
Backups

Ω triggered correlations

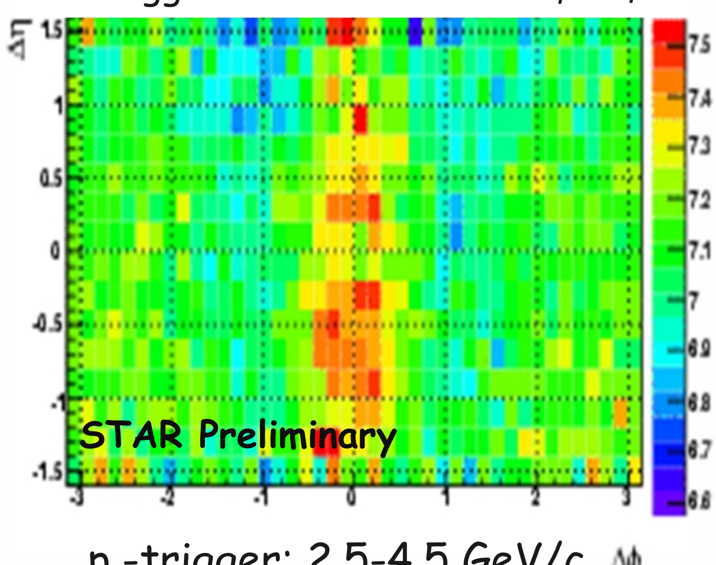


- Azimuthal correlations of comparable strengths seen with Λ (uds), Ξ(dss), and Ω (sss) triggers

- In Δη Λ-triggered correlations can be separated in jet and ridge
- Ξ-triggered Δφ correlations appear smeared in Δη direction (all ridge?)

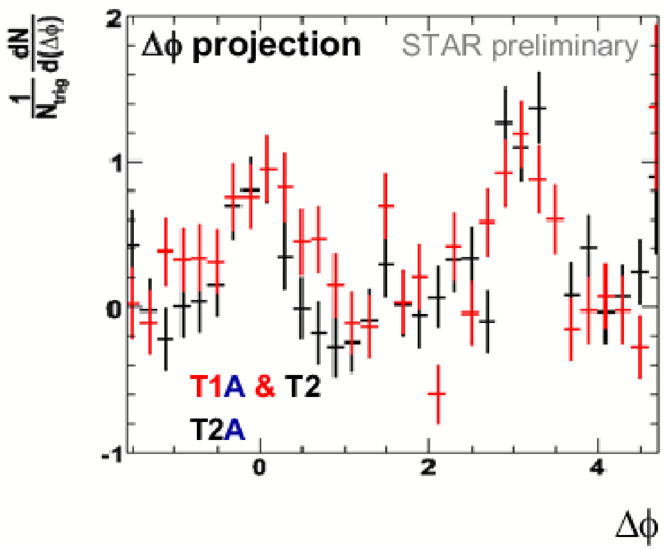


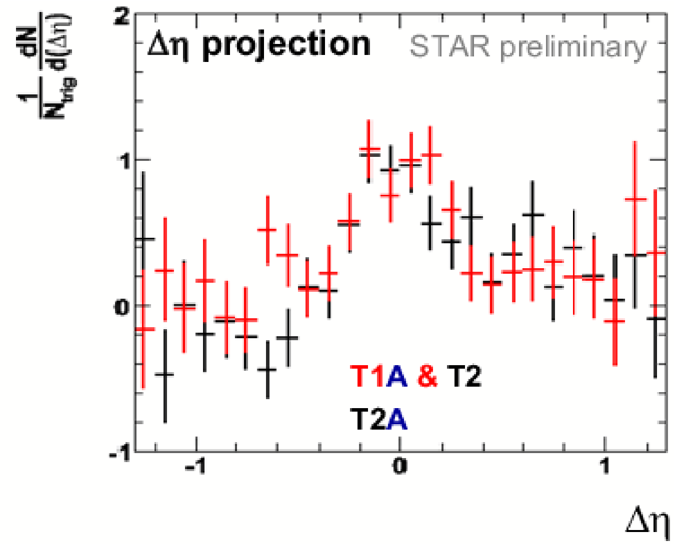
Ω triggered correlation in Δφ-Δη



p_t-trigger: 2.5-4.5 GeV/c

Di-hadron triggered correlations





T1: p_T>5GeV/*c*

T2: p_T>4GeV/*c*

A : p_T>1.5GeV/*c*

Di-jet measurements suggest that neither the widths in Δη and Δφ (ridge/mach cone) are modified nor the yields are suppressed and comparable to d+Au

Caveat: Non-trivial bkg. subtraction

Surviving (di-jet) pairs at high p_t seem to favor conditions with small energy loss

⇒ **ridge correlated with energy loss !(?)**