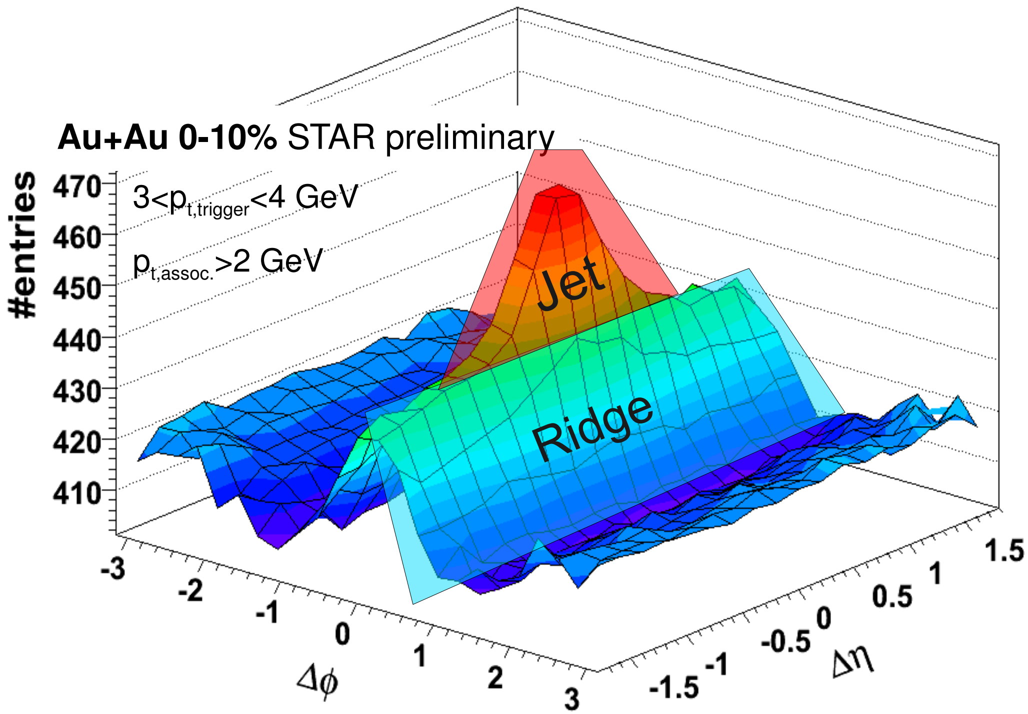
# System size and energy dependence of high-$p_T$ triggered correlations in STAR

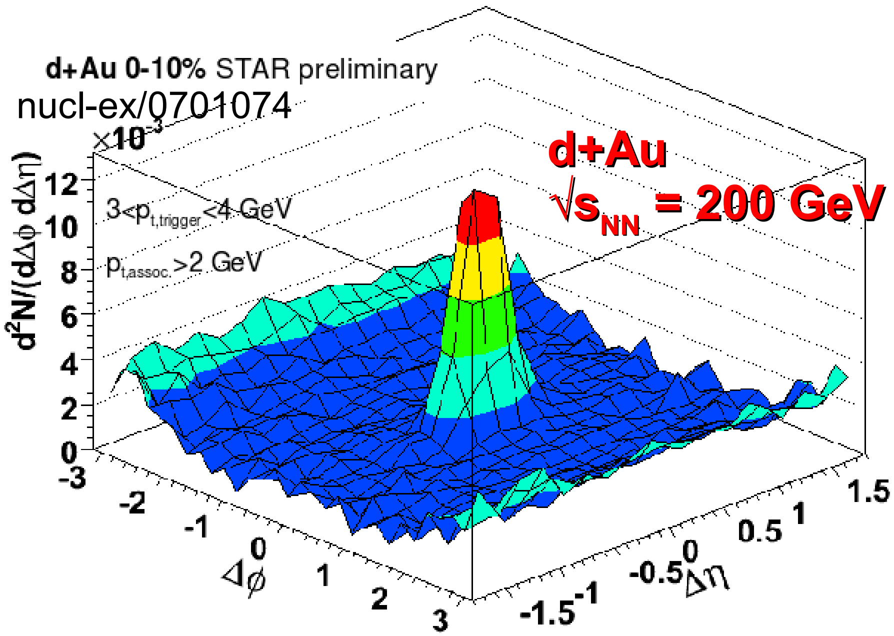
Christine Nattrass (Yale) for the STAR Collaboration

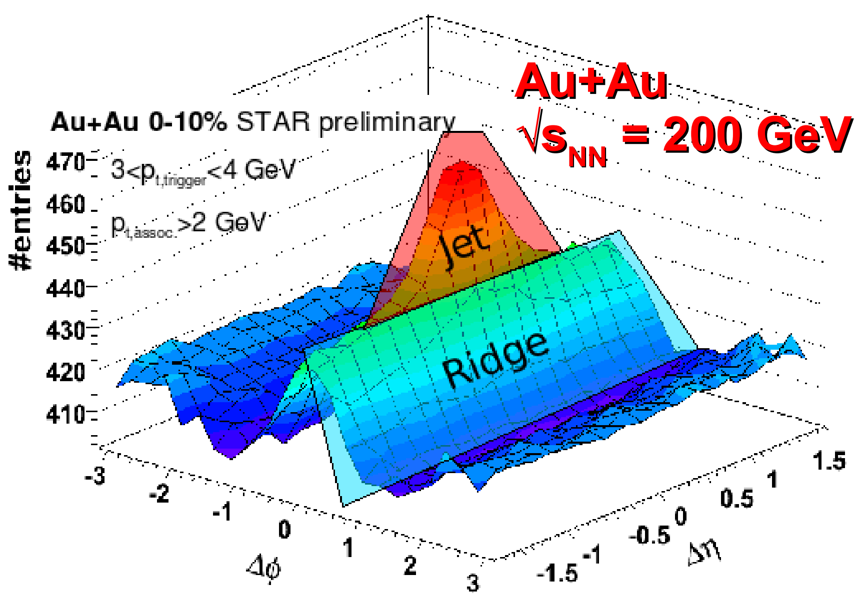
# Outline

- Introduction
- The *Jet*
- The *Ridge*
- Theory
- Conclusions



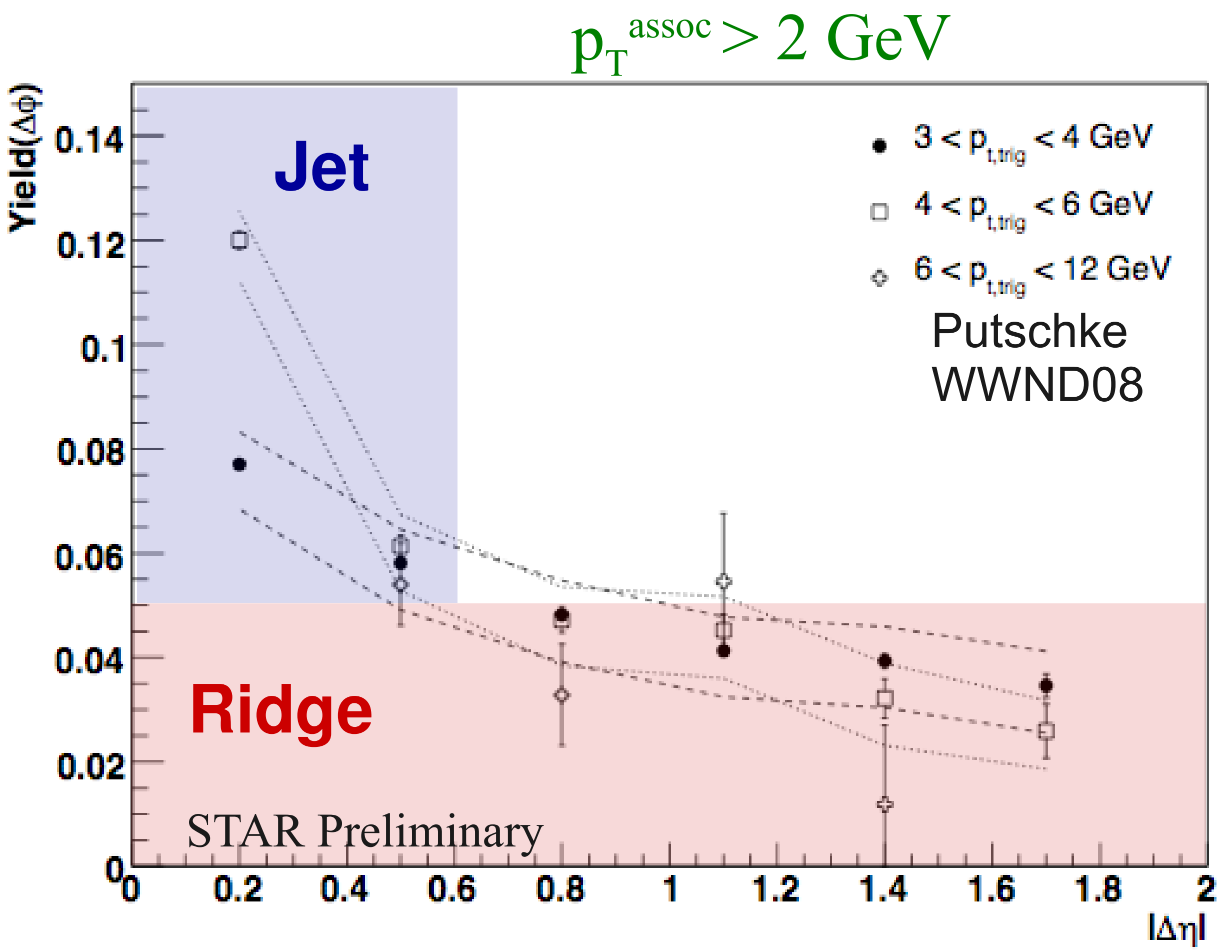
# Motivation – *Jet* and *Ridge*




- In d+Au narrow peak narrow in $\Delta\Phi$, $\Delta\eta$ even for small $p_T^{trigger}$
- Long-range pseudorapidity ($\Delta\eta$) correlations observed by STAR in Au+Au at intermediate $p_T$
- Significant contribution to the near-side yield in central Au+Au at intermediate $p_T^{assoc}$,$p_T^{trigger}$
- Yield/trigger – number of particles in $p_T^{assoc}$ range associated with trigger particle with $p_T^{trigger}$ range

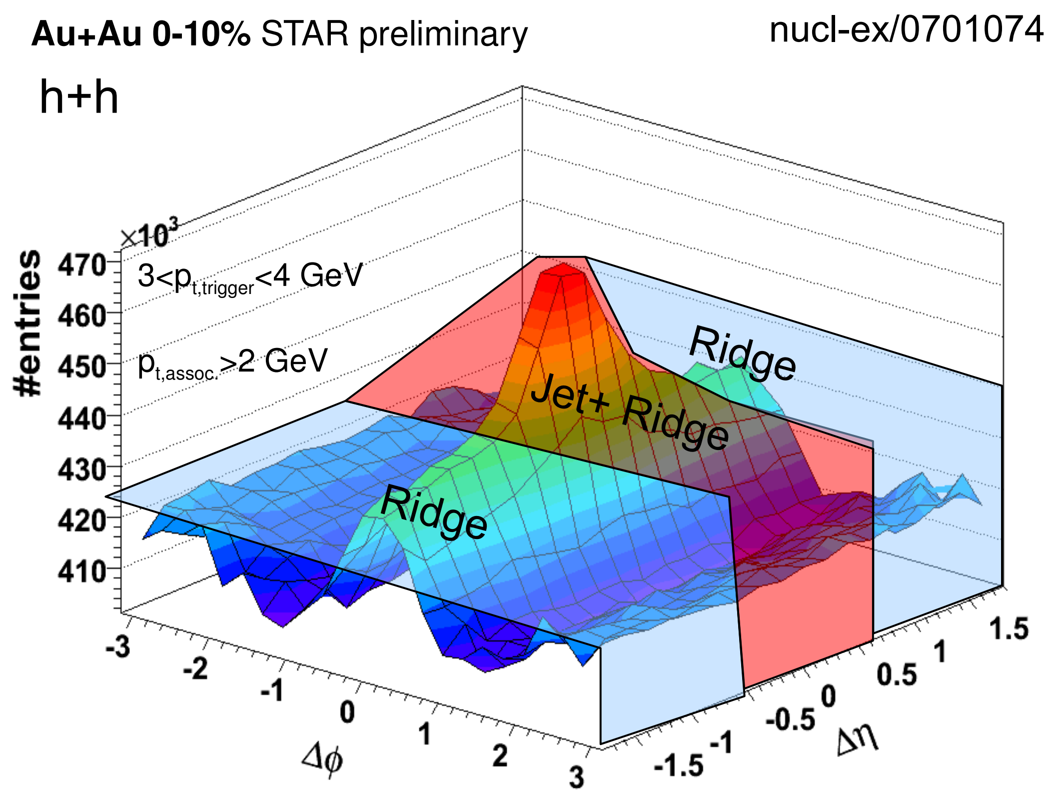
# Extent of *Ridge* in $\Delta\eta$




- *Ridge* yield approximately independent of $\Delta\eta$ in STAR acceptance
  - PHOBOS (arXiv:0804.3038v3) showed independence on $\Delta\eta$ out to $\Delta\eta = 4$
- *Jet* increases with $p_T^{trigger}$, *Ridge* roughly constant

# Method: Yield extraction

- *Ridge* previously observed to be independent in Δη in Au+Au
- To determine relative contributions, find yields for near-side (-1<ΔΦ<1), take ΔΦ projections in



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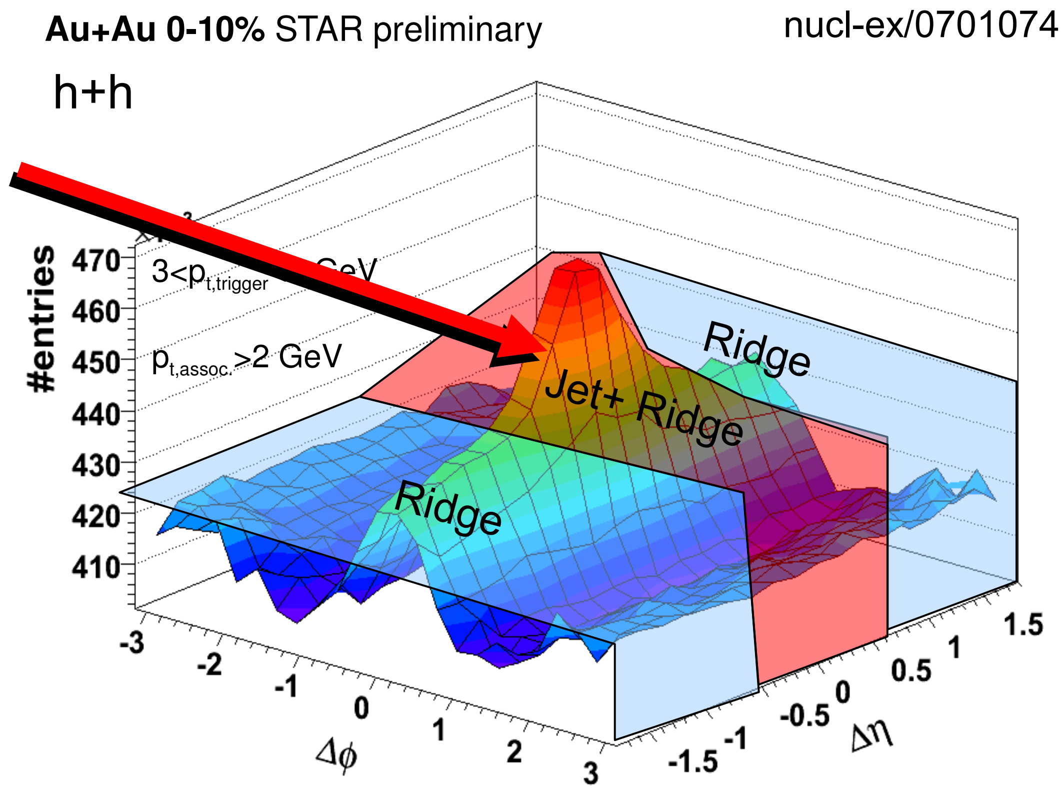
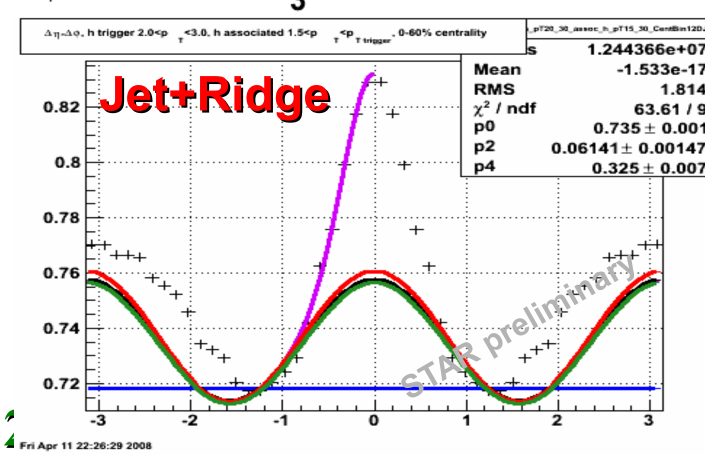
- *Ridge* previously observed to be independent in $\Delta\eta$ in Au+Au
- To determine relative contributions, find yields for near-side $(-1<\Delta\Phi<1)$, take $\Delta\Phi$ projections in
  - $-0.75<\Delta\eta<0.75$ ***Jet + Ridge***



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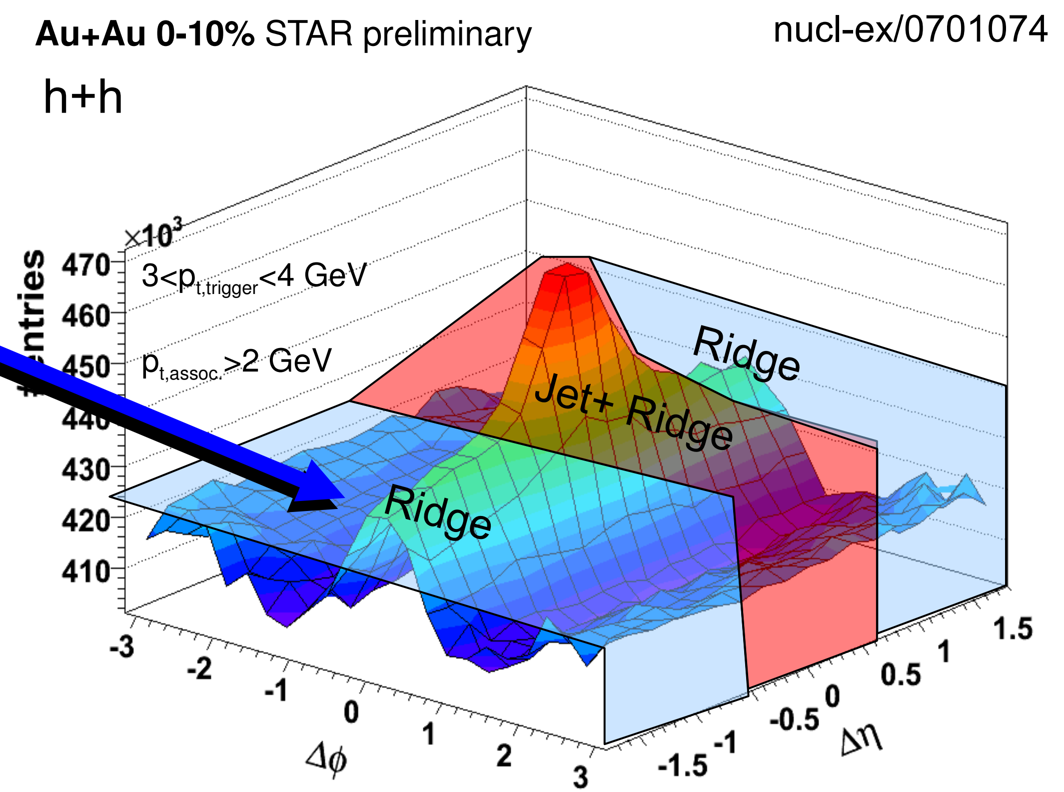


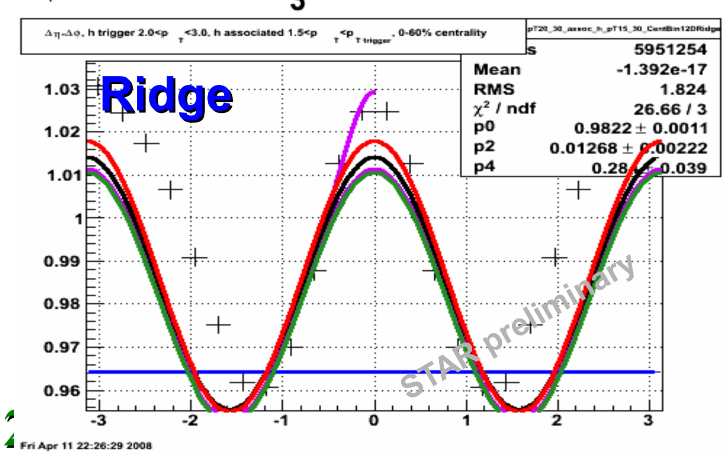

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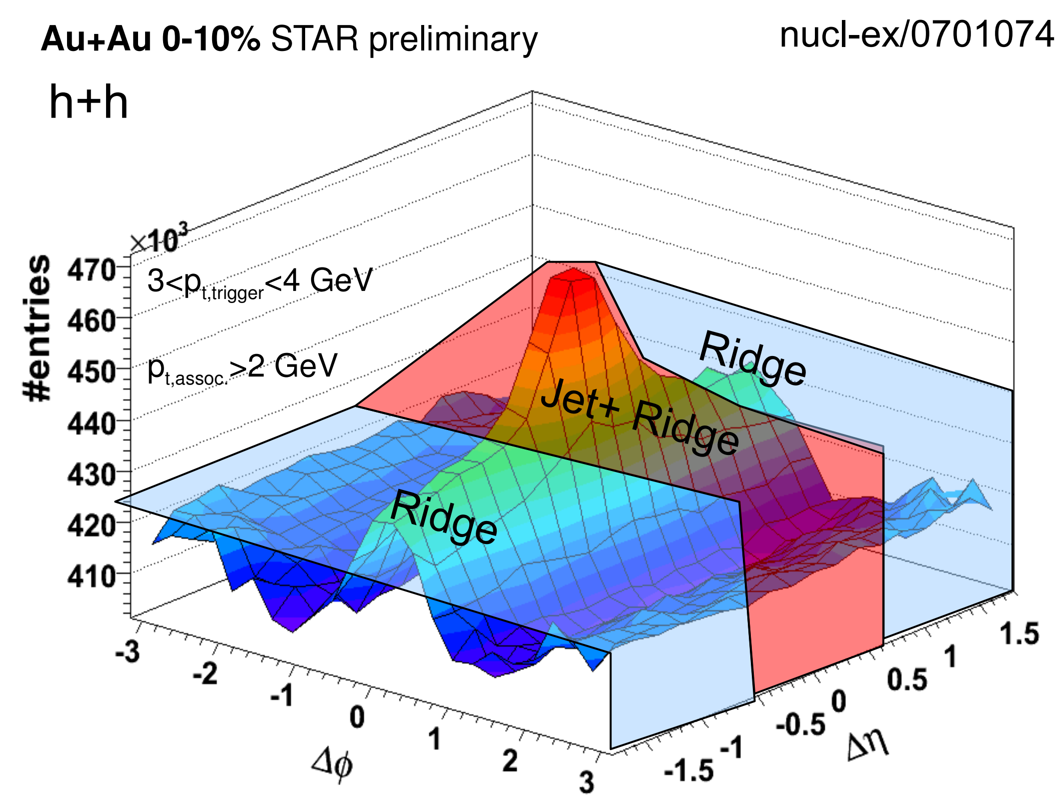


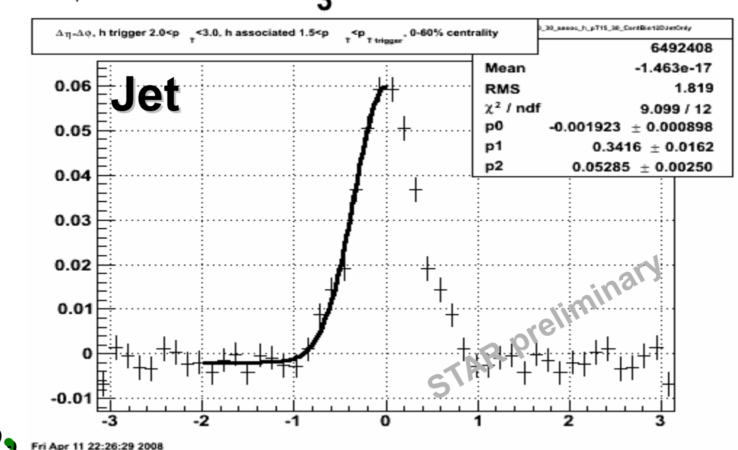

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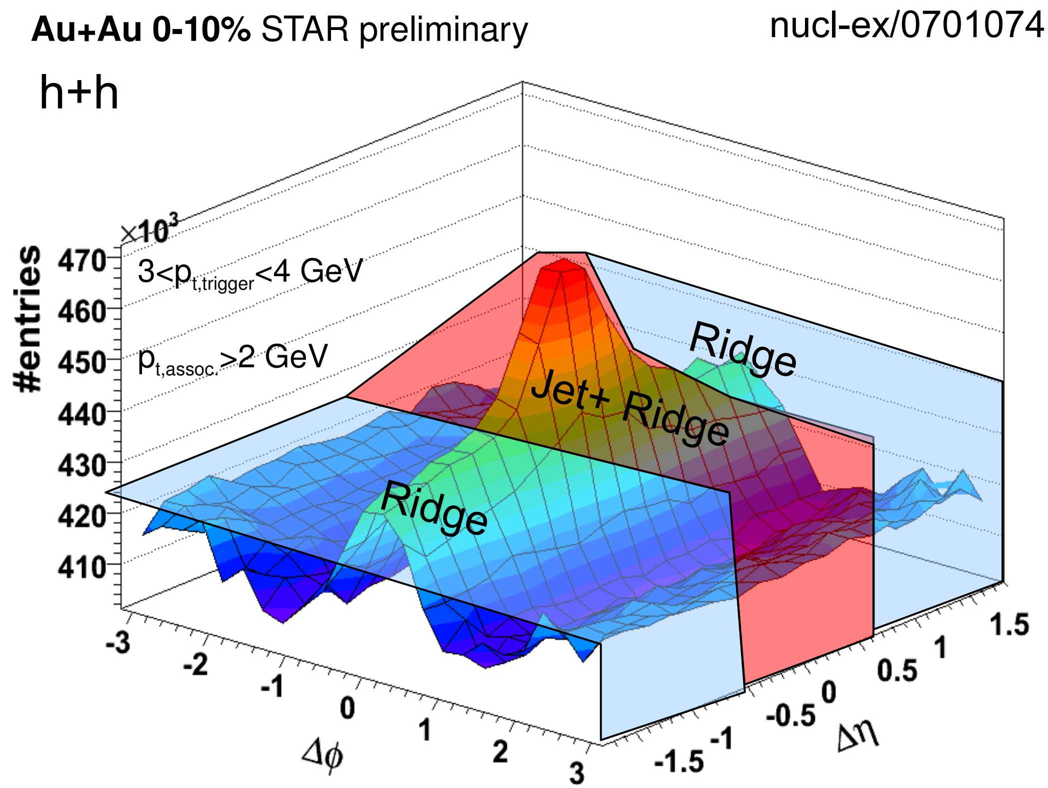

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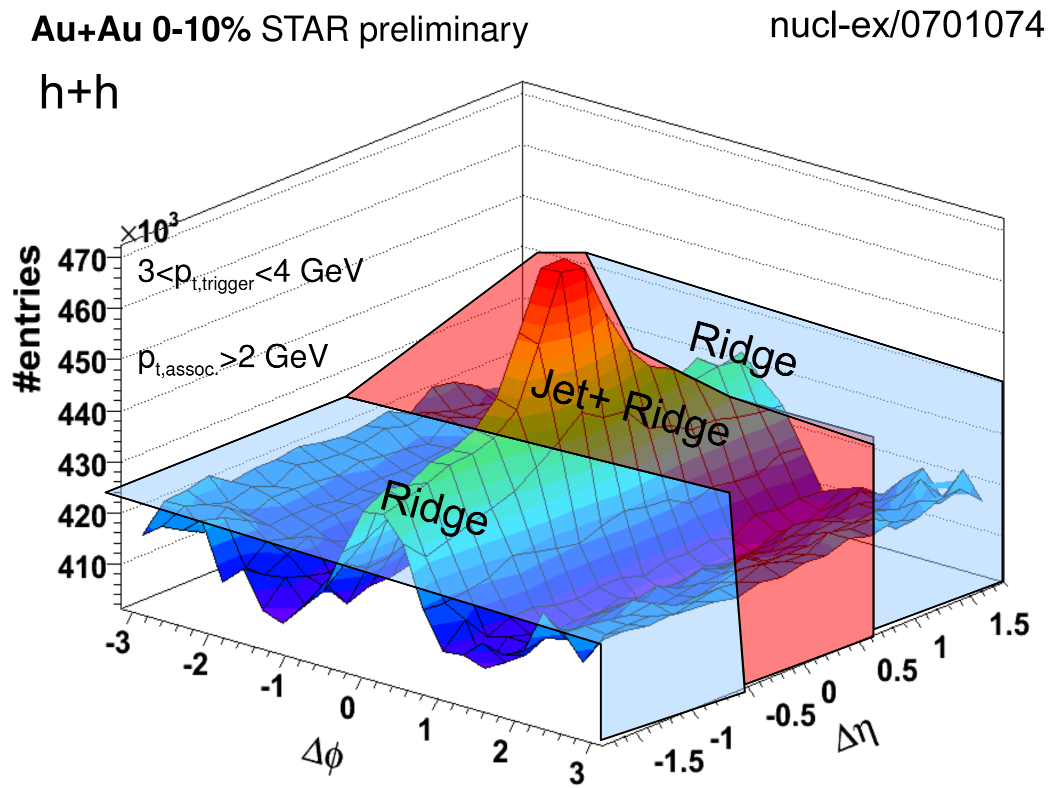


- Flow contributions to *Jet* cancel
  - $v_2$ independent of η for |η|<1
    - Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 122303 (2005)

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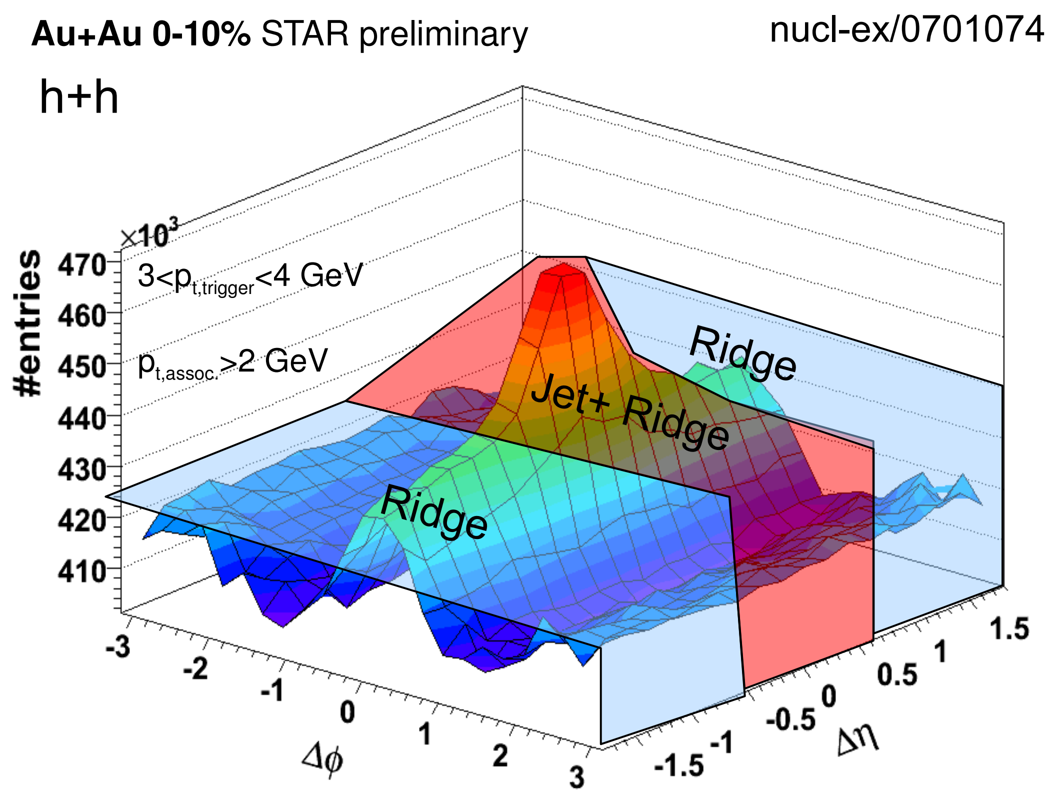
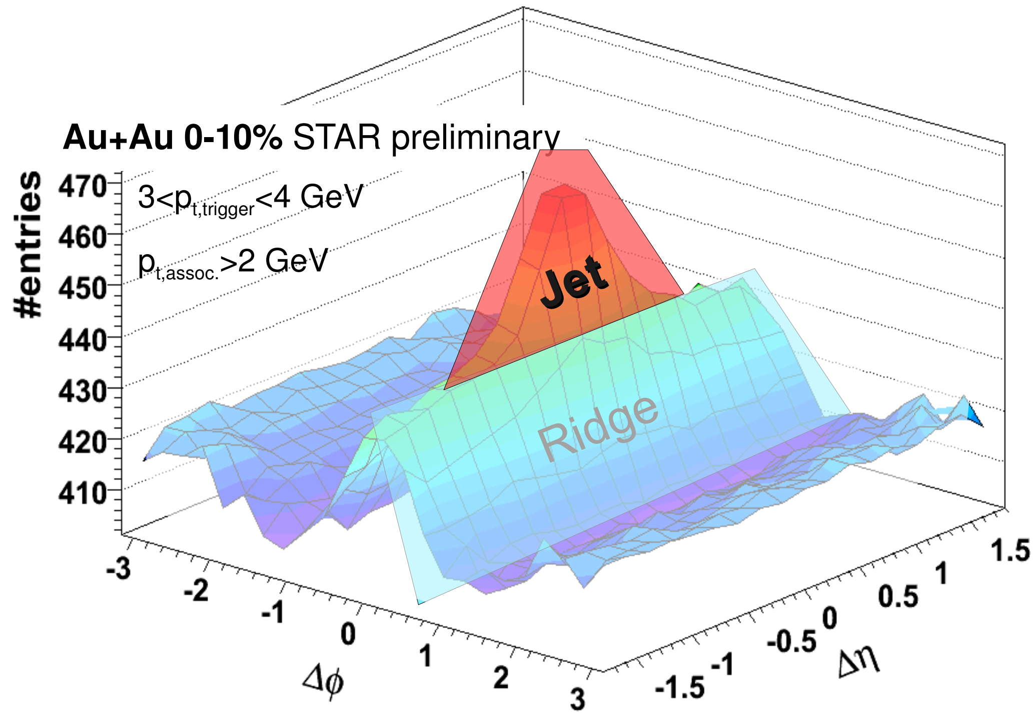
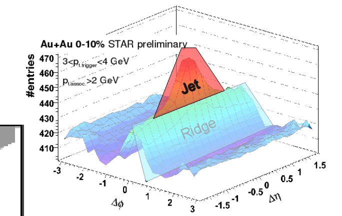


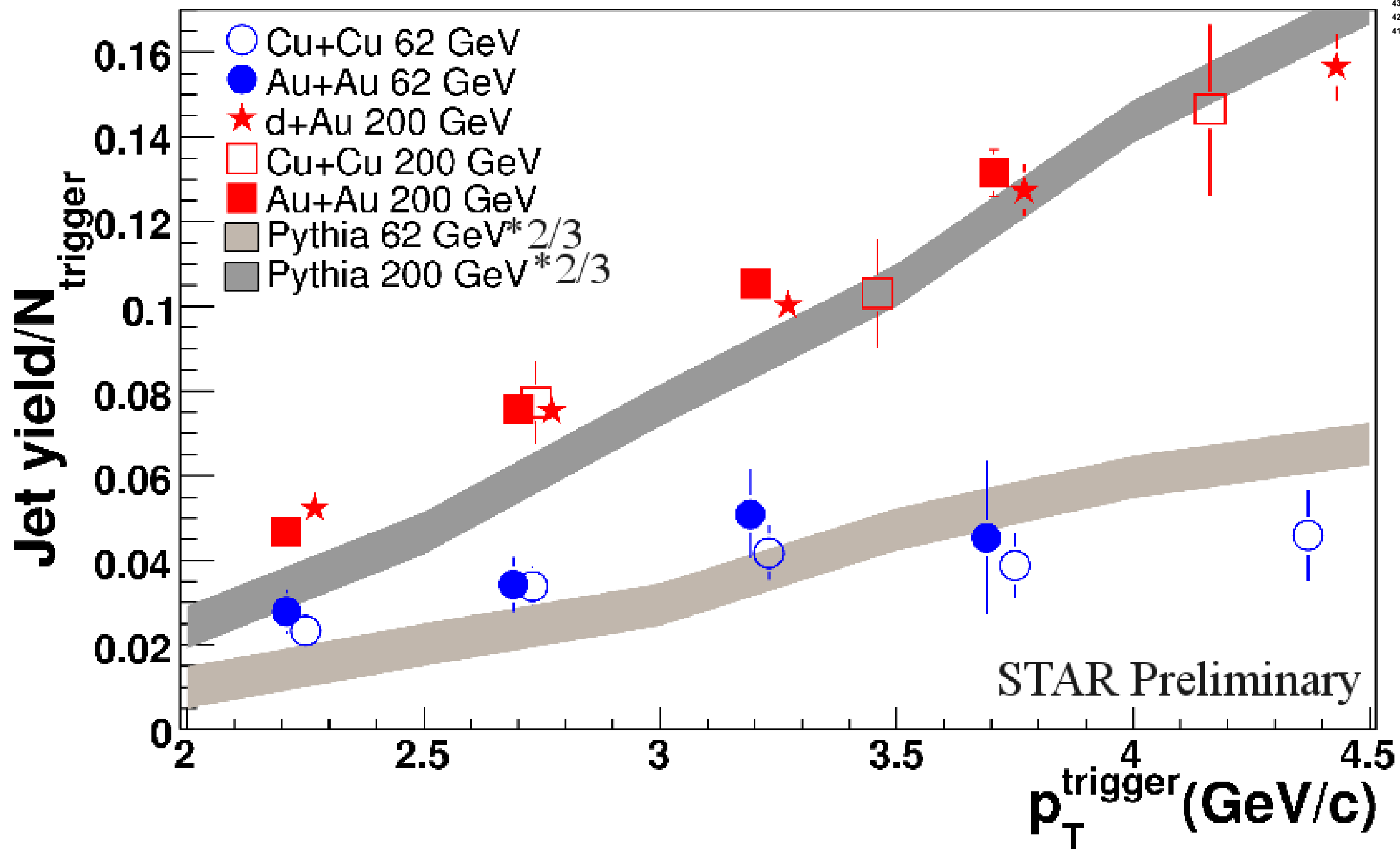

- Flow contributions to *Jet* cancel
  - $v_2$ independent of η for |η|<1
    - Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 122303 (2005)
- $3.0<p_T^{trigger}<6.0$ GeV/c; $p_T^{assoc}>1.5$ GeV/c unless otherwise stated

# The *Jet*


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

# $p_T^{trigger}$ dependence



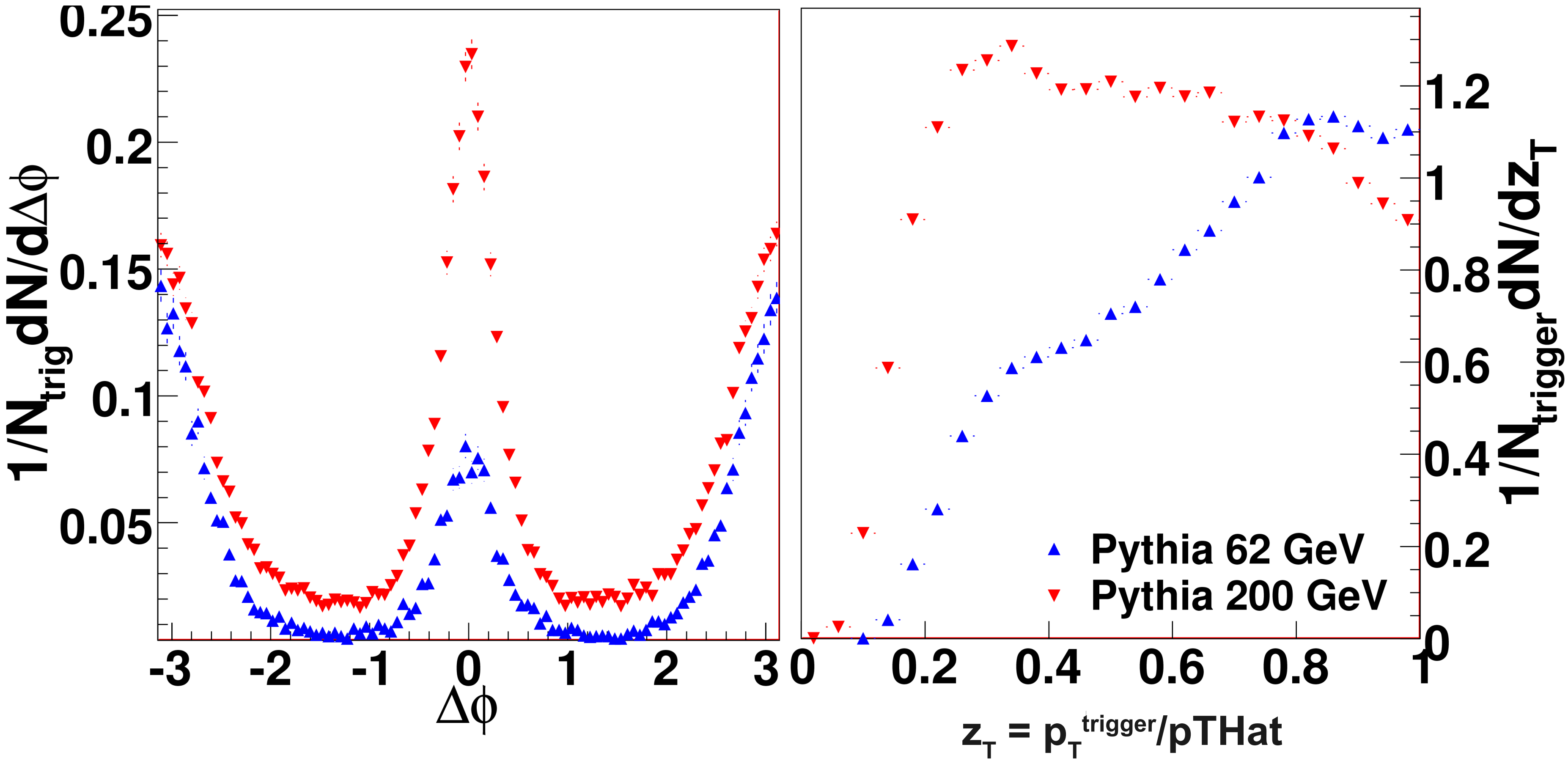




- Pythia 8.1 describes trends in data up to a scaling factor
  - Gets energy dependence right → this is a pQCD effect
  - Stronger deviations at low $p_T^{trigger}$, as expected



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

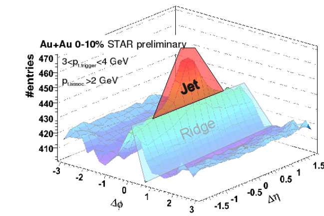
# Pythia comparisons

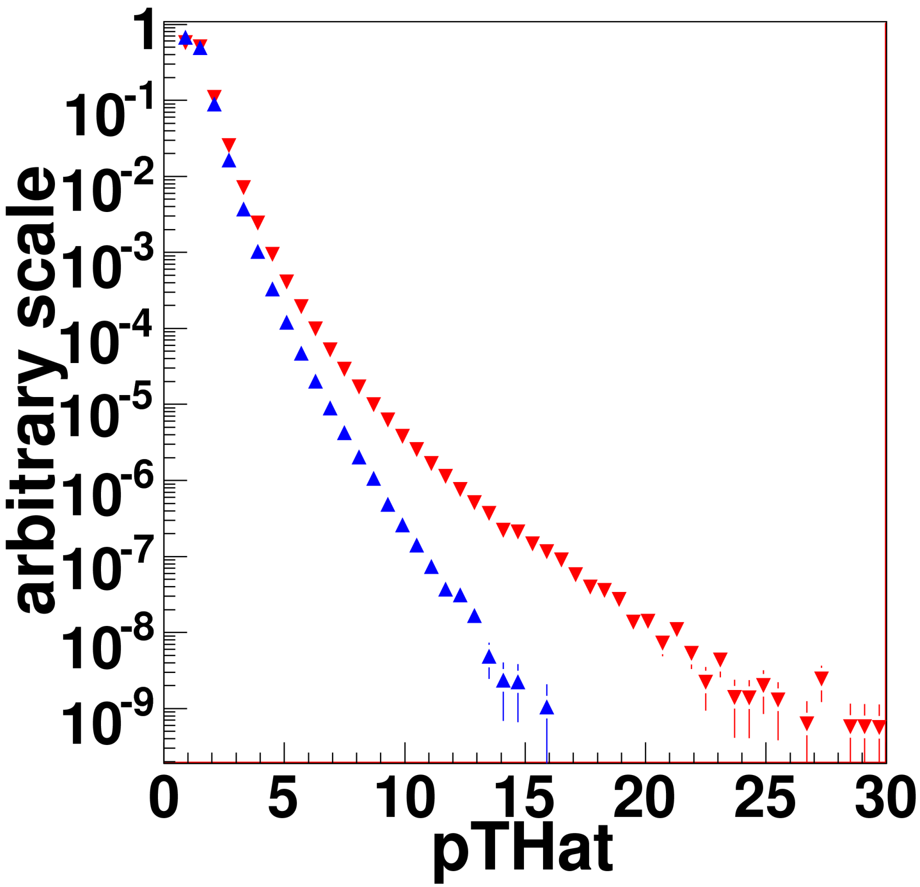


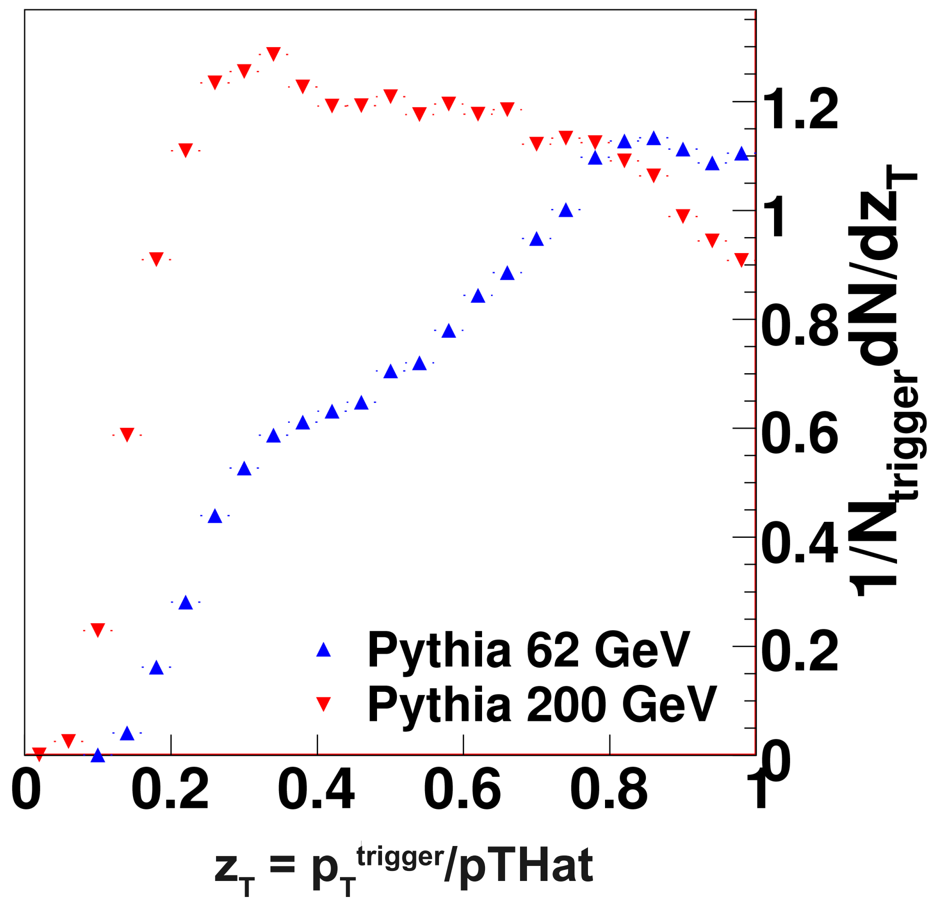

- What can Pythia tell us?
  - Higher $z_T$ (lower jet energy) in 62 GeV for same $p_T^{trigger}$

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

# Pythia comparisons

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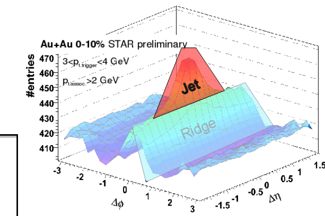
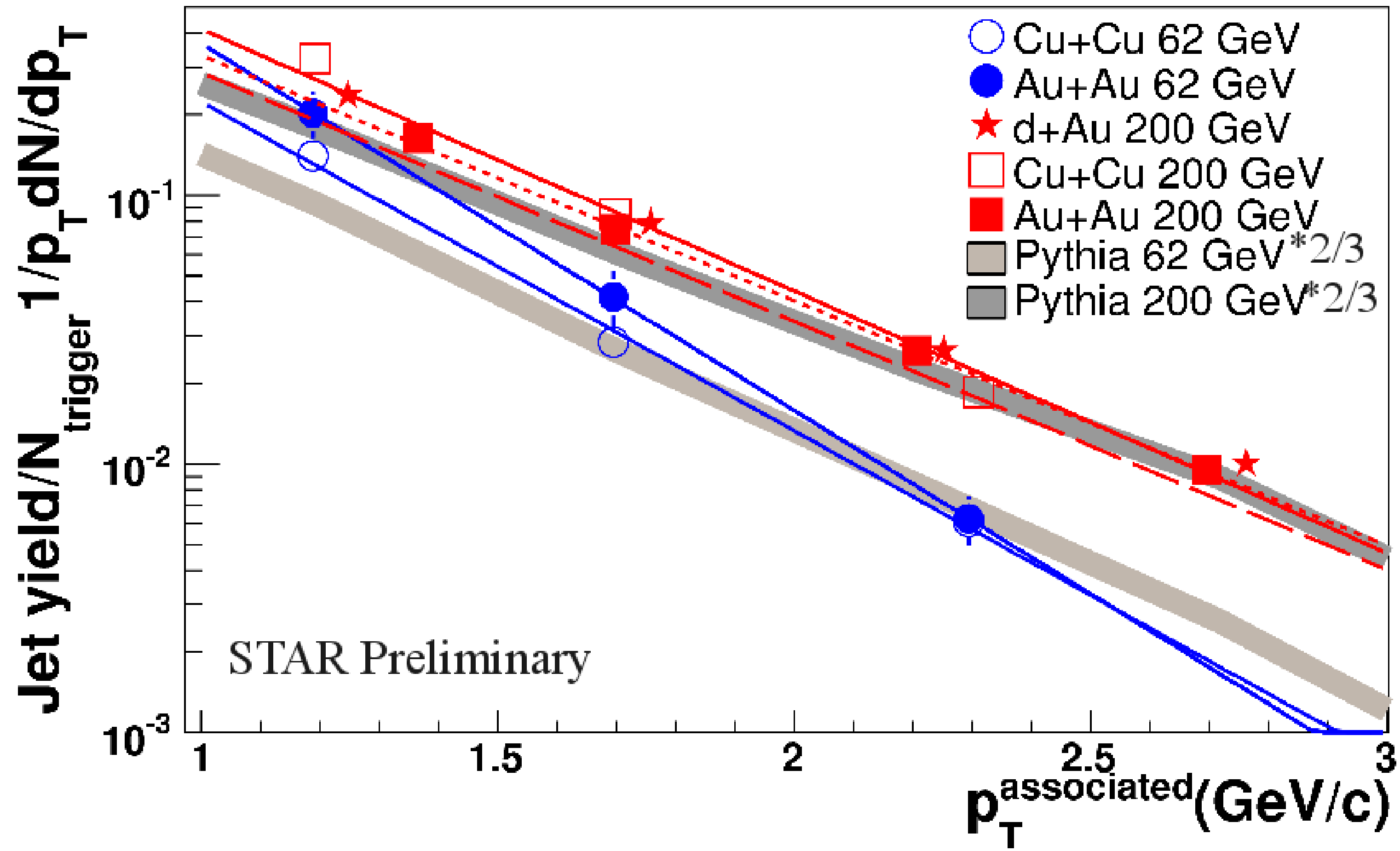
# $p_T^{associated}$ dependence




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

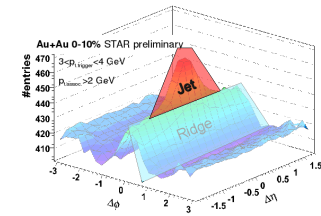
**Inverse slope parameter**

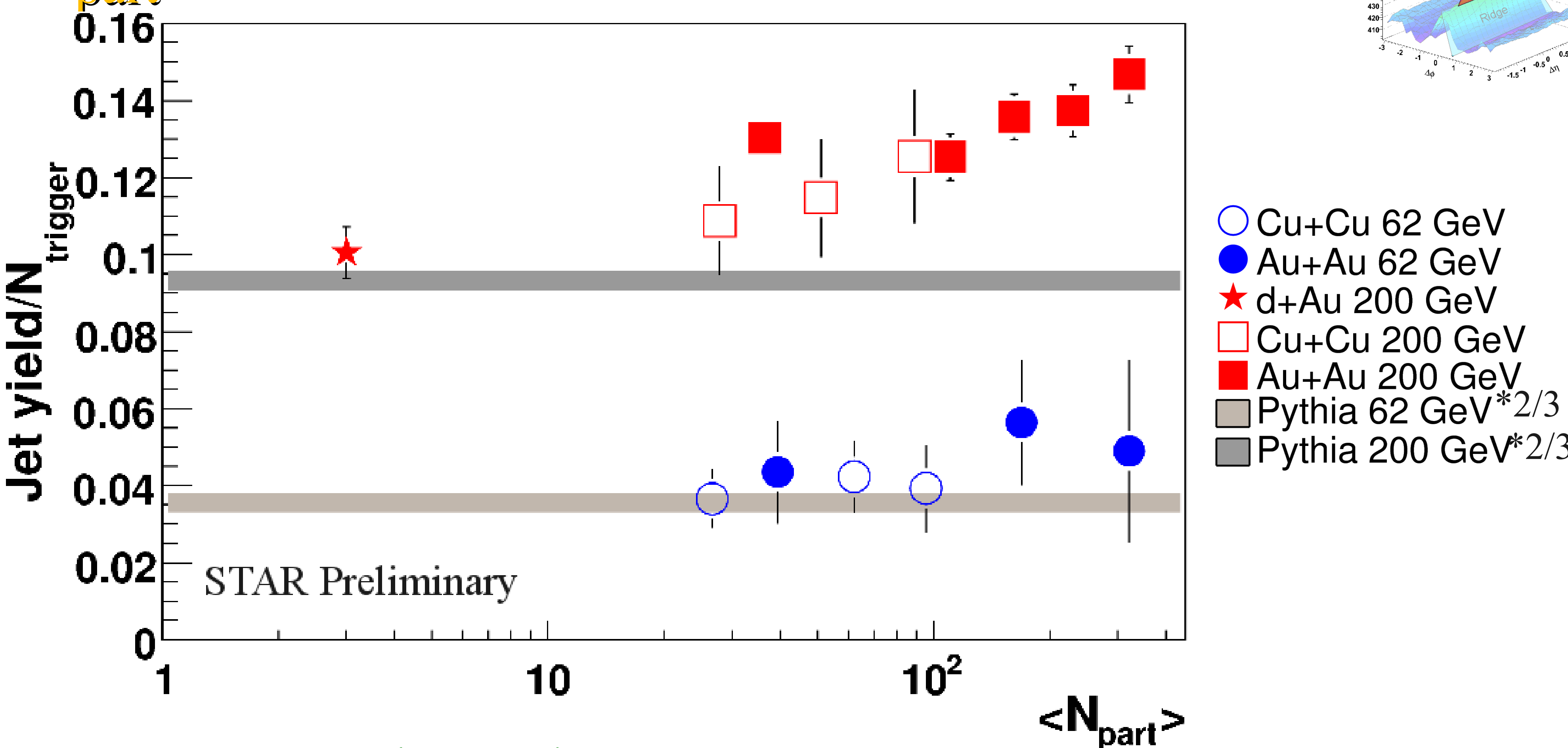
| | $\sqrt{s_{NN}}$ = 62 GeV | $\sqrt{s_{NN}}$ = 200 GeV |
|---|---|---|
| Cu+Cu | 317 ± 26 | 445 ± 20 |
| Au+Au | 355 ± 21 | 478 ± 8 |
| d+Au | | 469 ± 8 |
| Pythia | 417 ± 9 | 491 ± 3 |

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 $p_T$?



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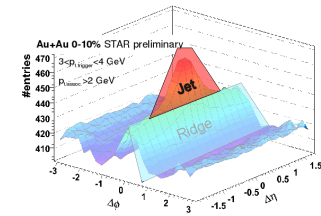
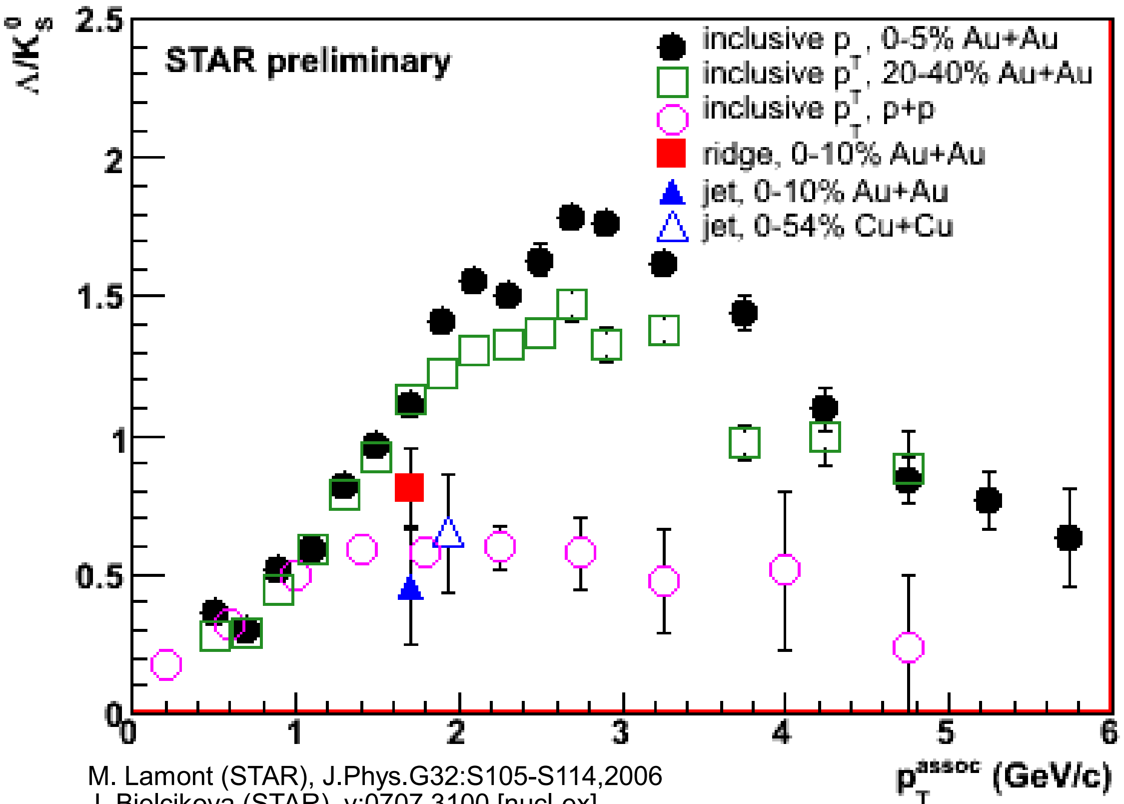
# *Jet* composition




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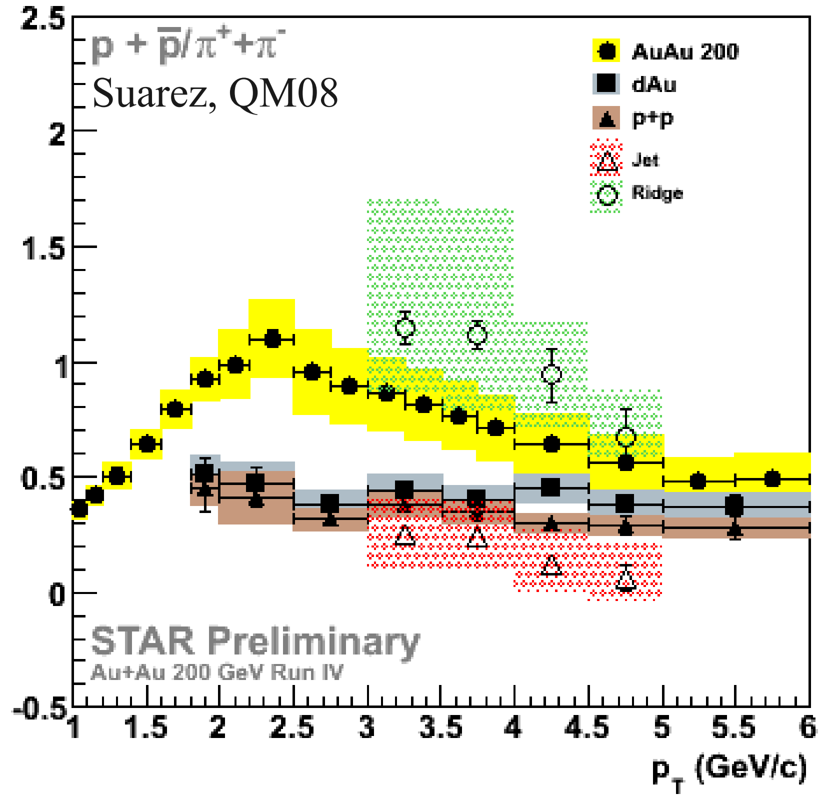
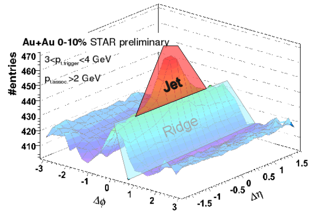



- Baryon/meson ratios in *Jet* in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles

# Conclusions: *Jet*

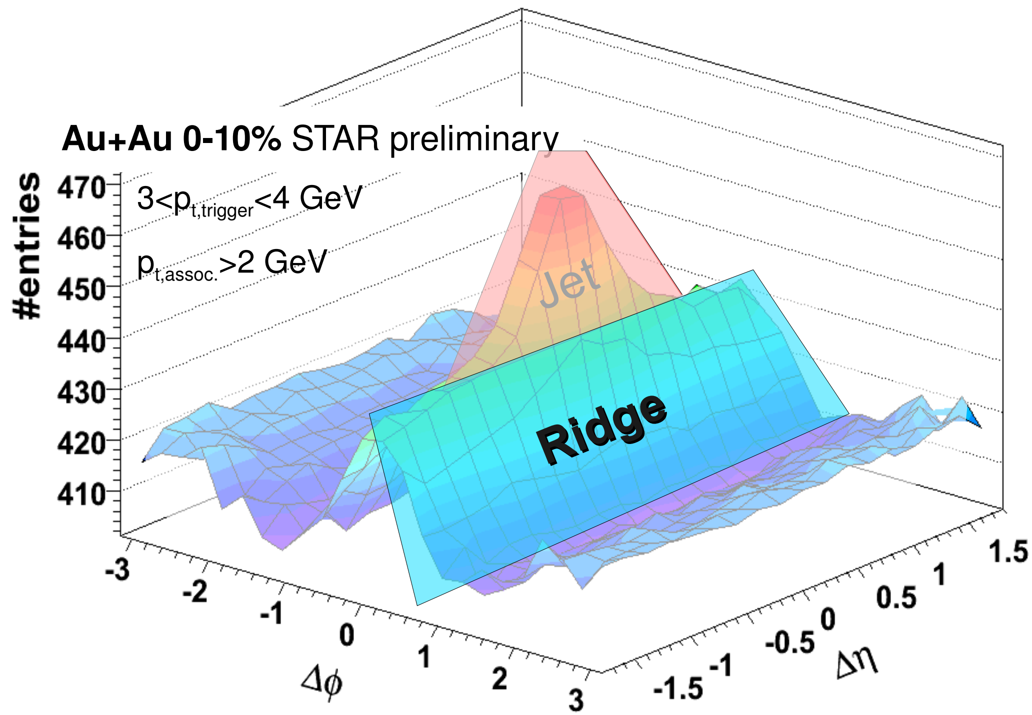



- Pythia describes data well
  - Scaling factor needed but Pythia 8.1 is not as tuned as earlier versions
  - Energy dependence in *Jet* is pQCD effect
  - Trends for $p_T^{trigger}$, $p_T^{assoc}$ dependence right
- Particle ratios similar to p+p

→ *Jet* production mechanism dominated by fragmentation

  - Separation of *Jet* and *Ridge* works

# The *Ridge*



Au+Au 0-10% STAR preliminary
$3<p_{t,trigger}<4$ GeV
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#entries
470
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-3
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1
2
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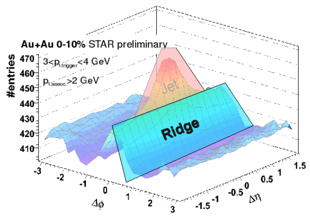
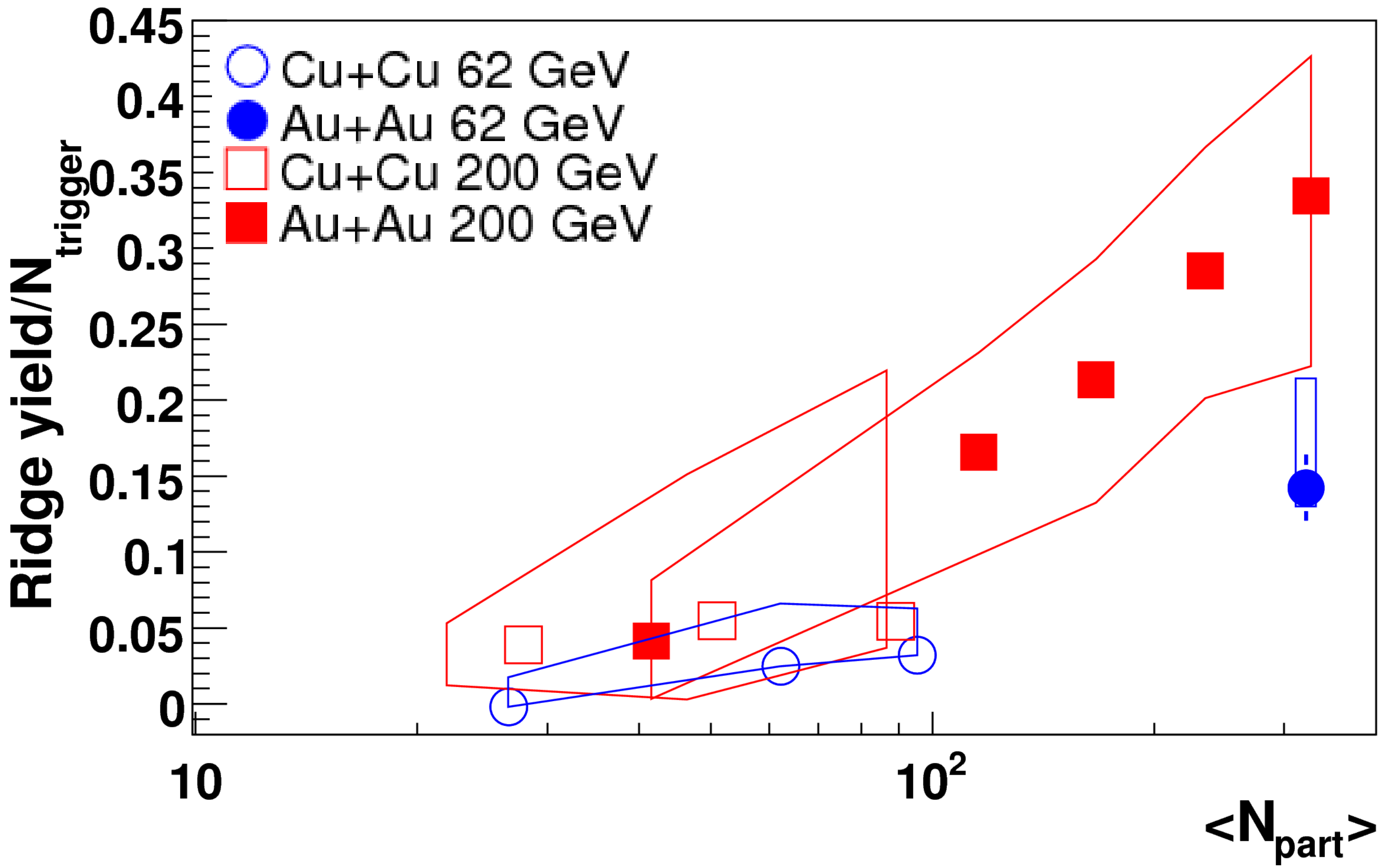
$\Delta\phi$
-1.5
-1
-0.5
0
0.5
1
1.5
$\Delta\eta$

# *Ridge* vs $N_{part}$




- No system dependence at given $N_{part}$



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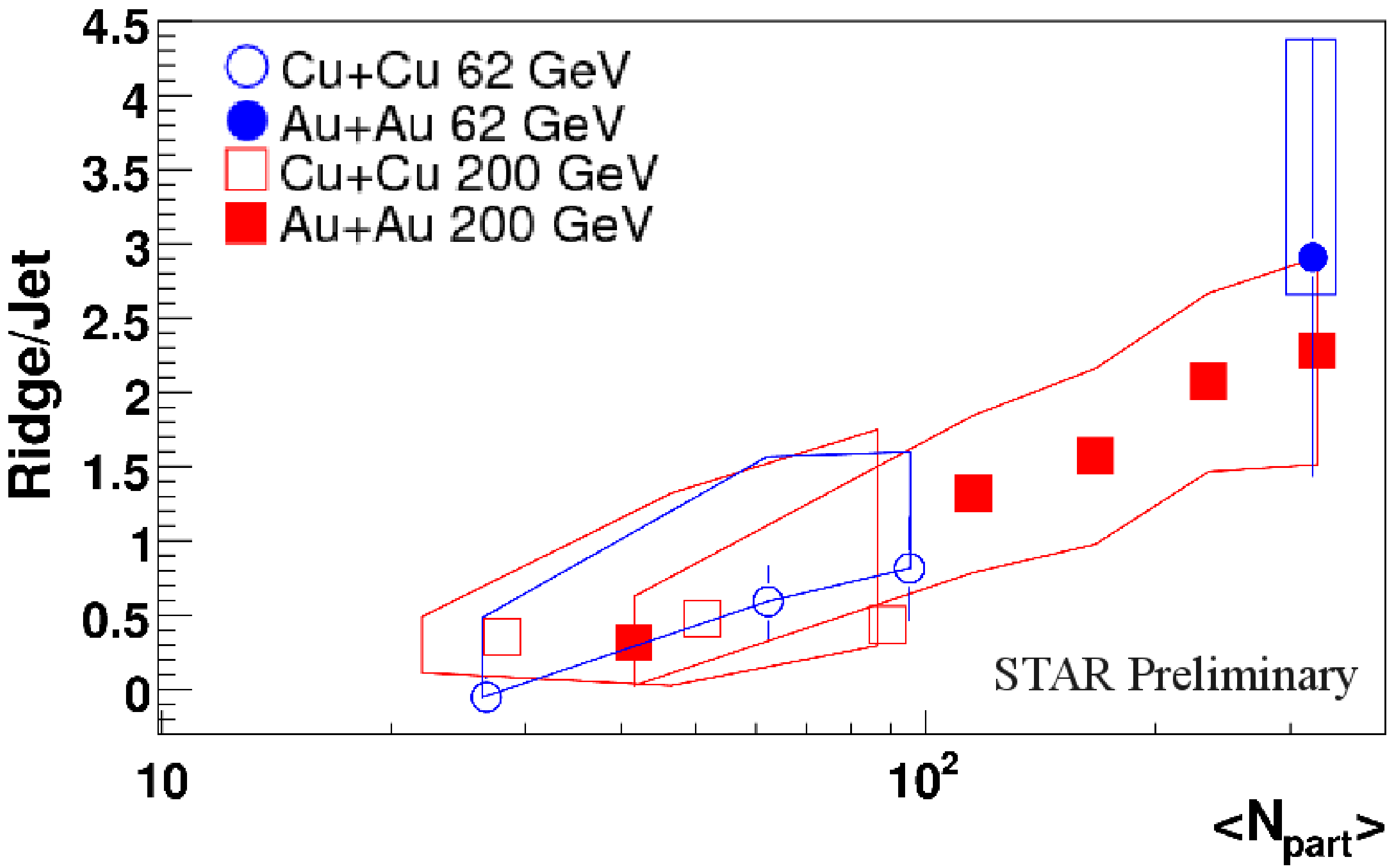


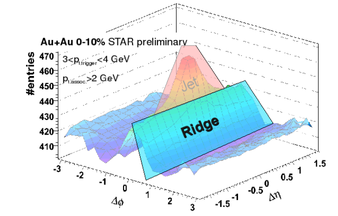


- No system dependence at given $N_{part}$
- *Ridge/Jet* Ratio independent of collision energy



J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
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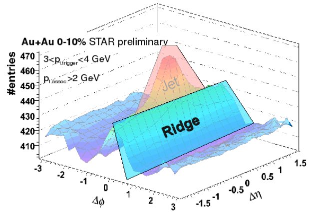
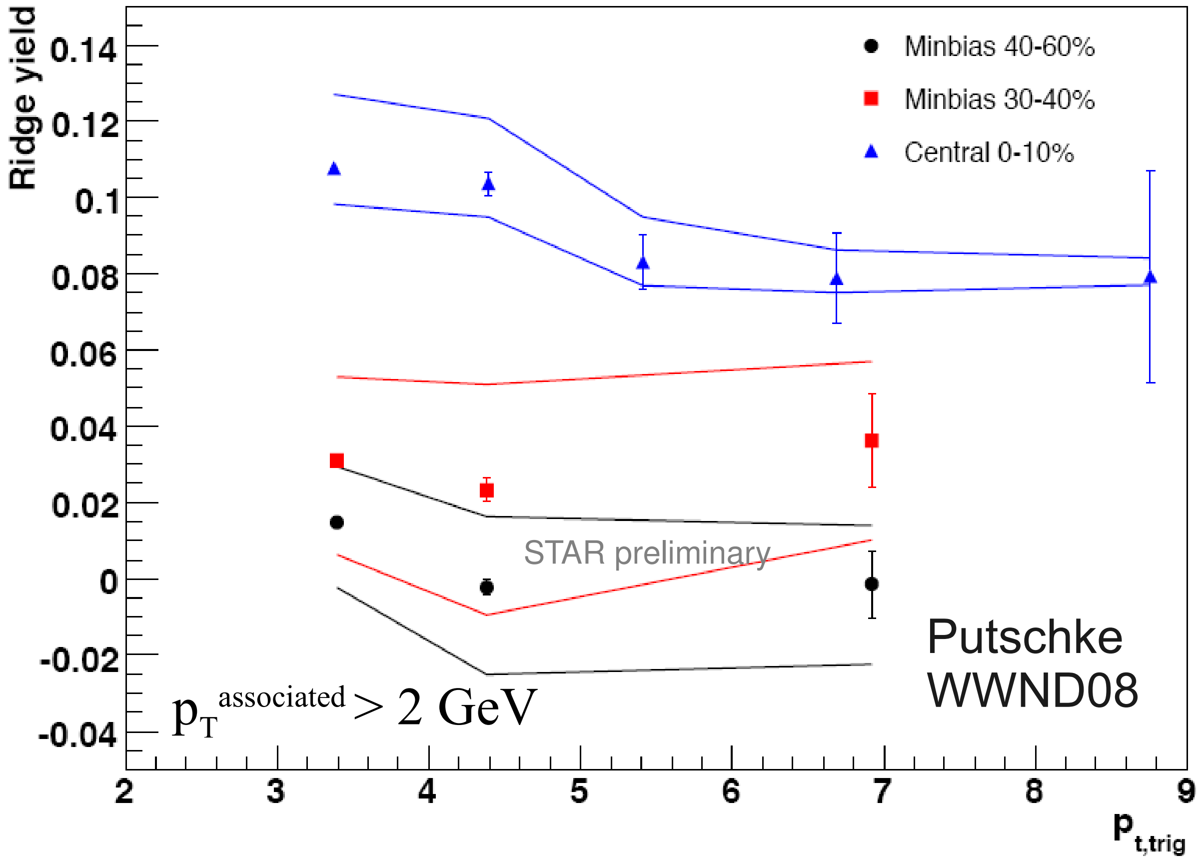
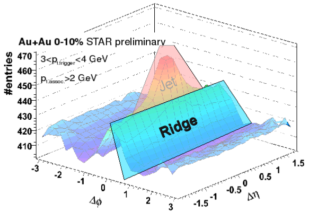
# *Ridge* yield vs. $p_T^{trigger}$ in Au+Au

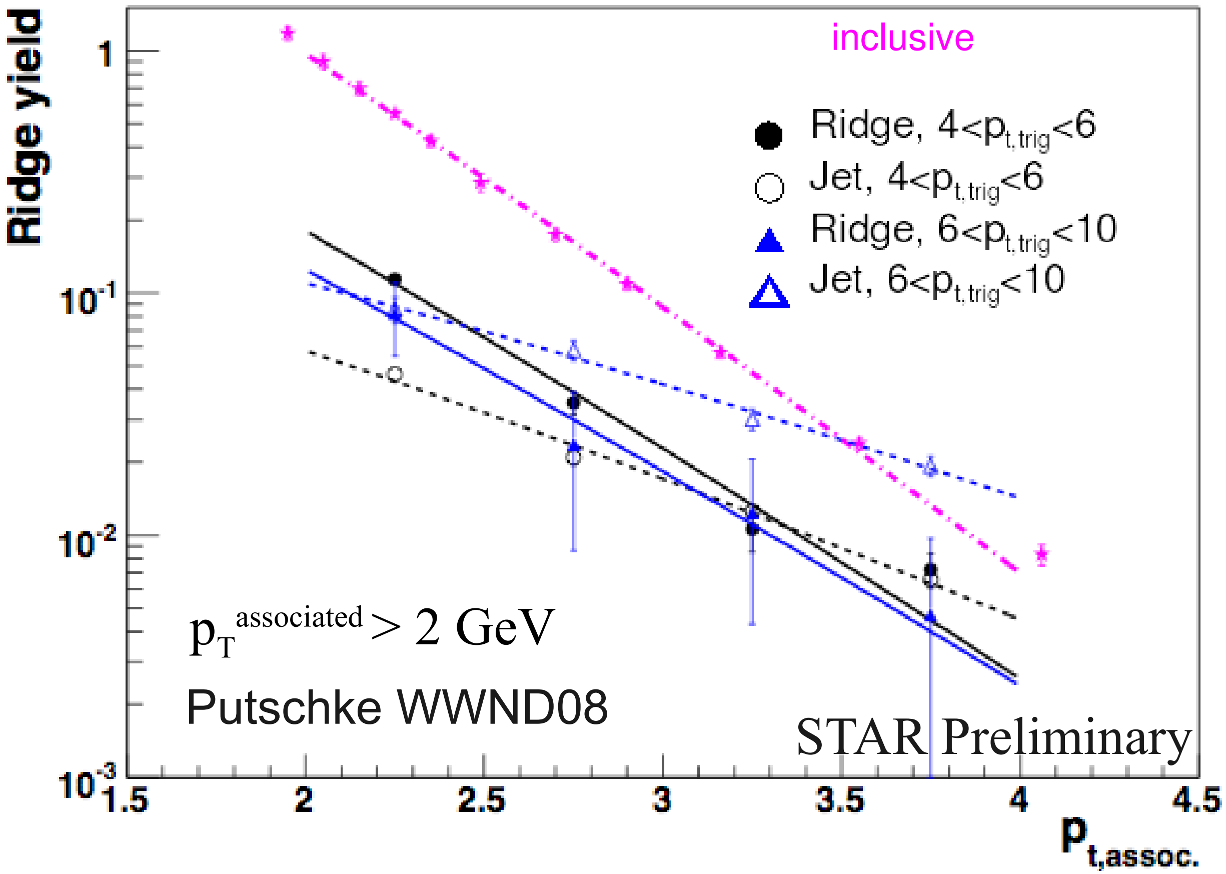



- *Ridge* yield persists to high $p_T^{trigger}$

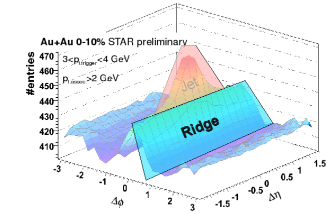
# *Ridge* yield vs. $p_T^{associated}$ in Au+Au

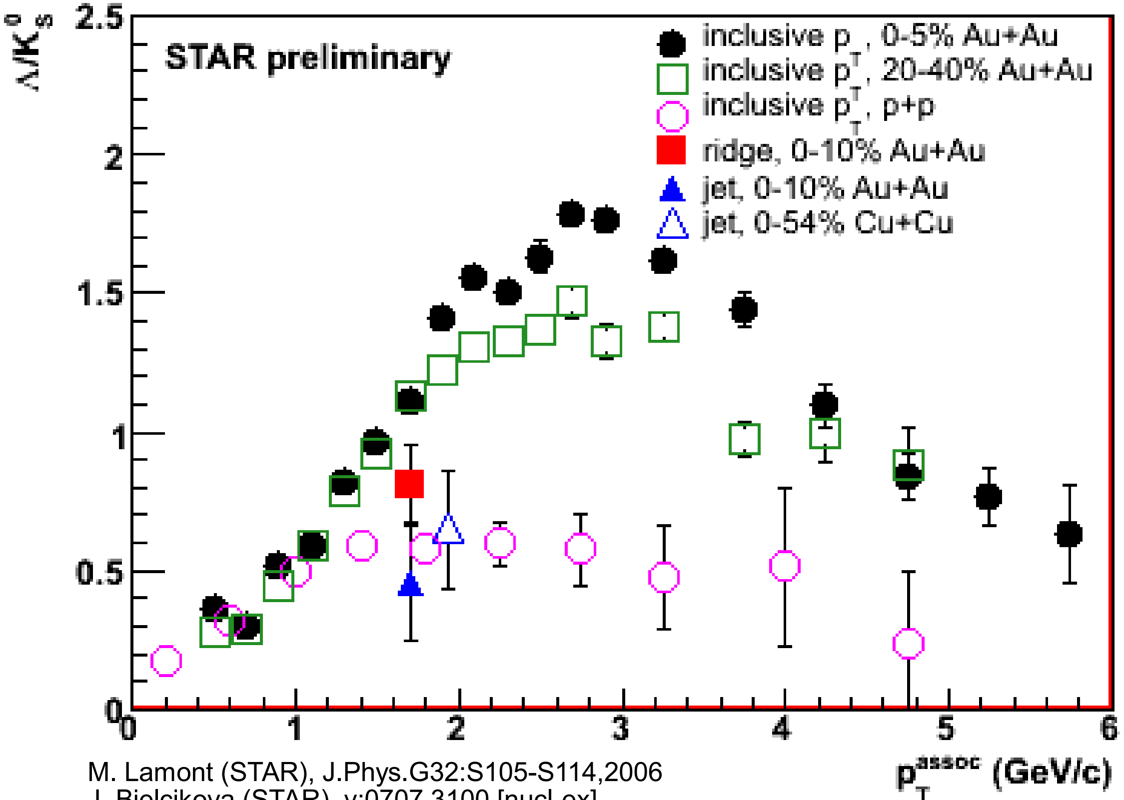



- Spectra of particles associated with *Ridge* similar to inclusive

# *Ridge* composition

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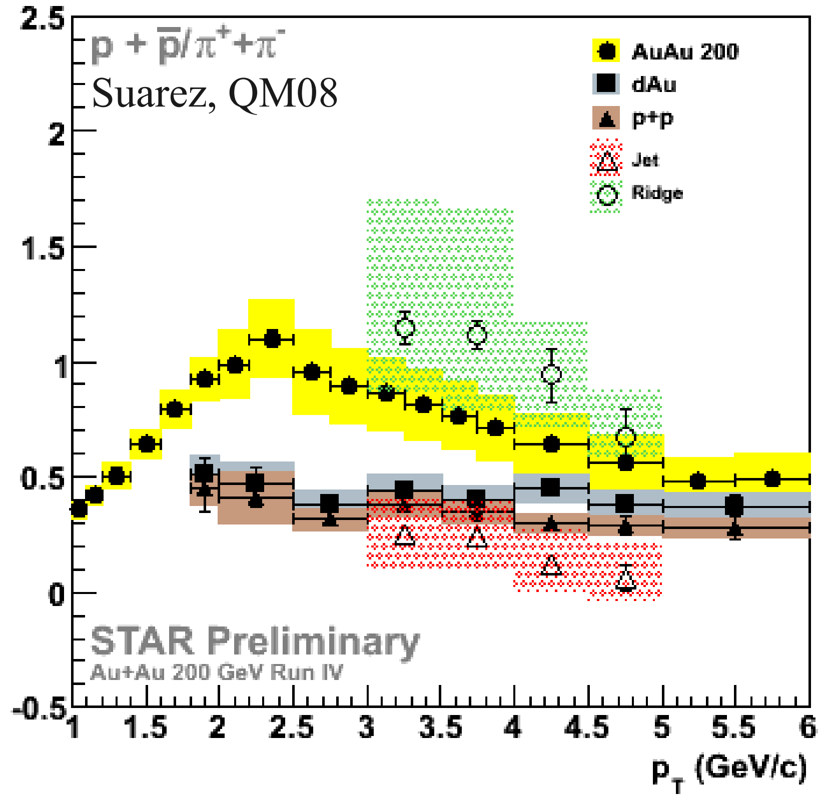
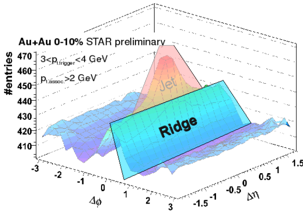



- Baryon/meson ratios in *Ridge* similar to bulk for both strange and non-strange particles

# 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
  - *Ridge* larger in plane (not shown, arXiv:0807.4606v1)
  - Particles in *Ridge* not correlated with each other in $\Delta\eta$ (not shown, arXiv:0804.4417v1)
- *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

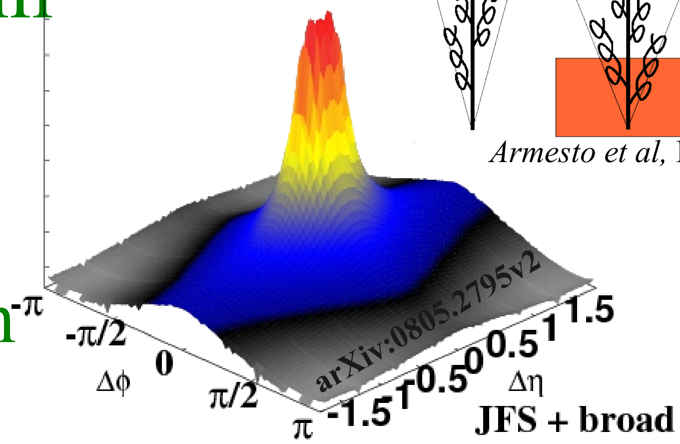
# Models

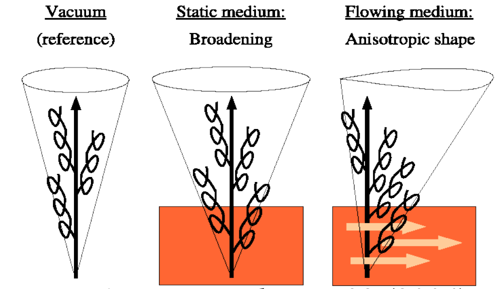
# Models

- Radiated gluons broadened in pseudorapidity

  Longitudinal flow, Armesto et al, PRL 93 (2004)
  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*

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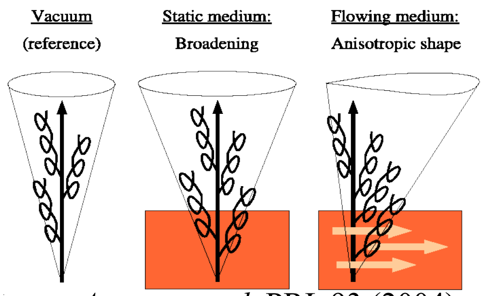


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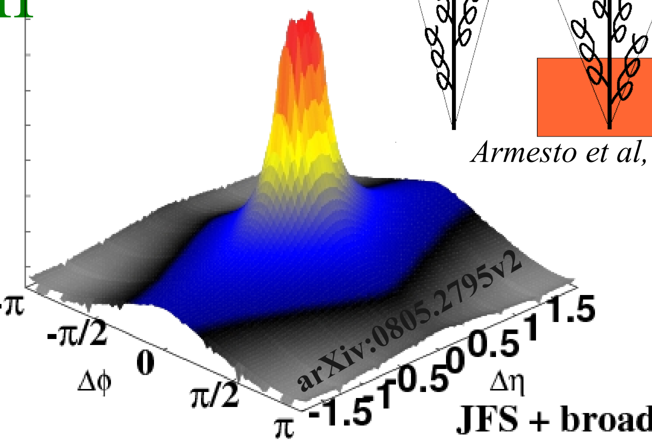
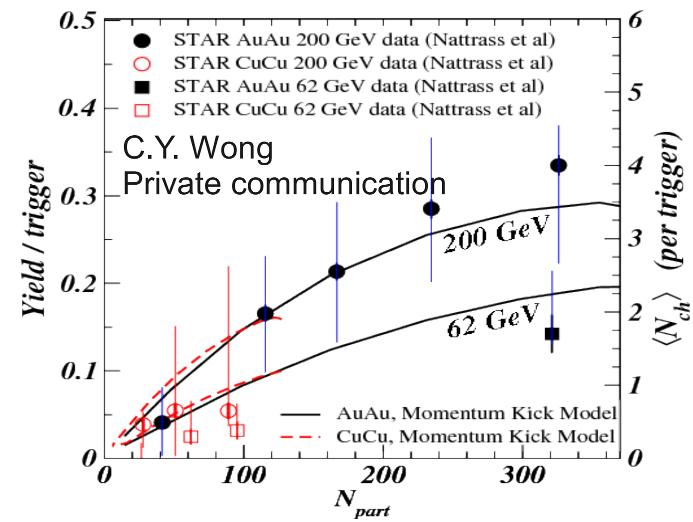



- Interaction of jet+medium

  Momentum kick from jet, C.-Y. Wong , Phys.Rev.C76:054908,2007
  Medium heating + recombination, Chiu & Hwa, PRC72, 034903

  – Agrees with data but lots of fits to the data




$N_{part}$

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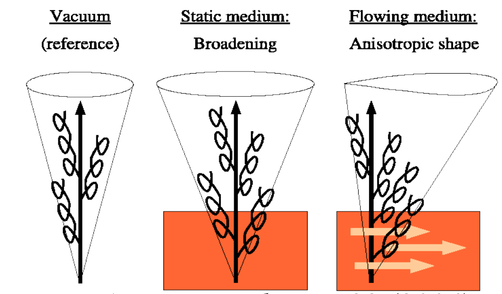
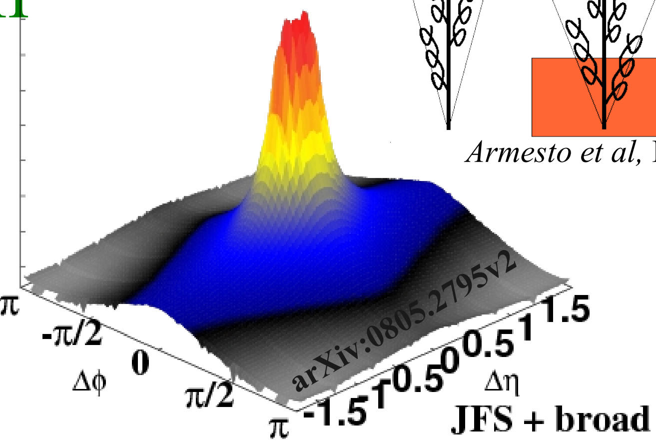


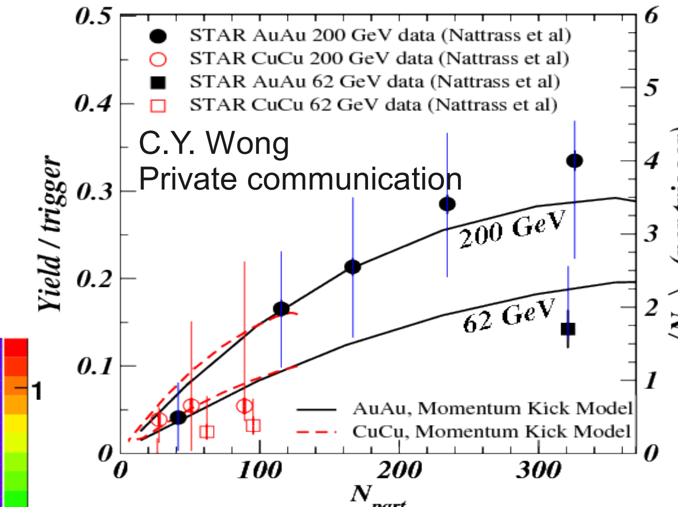

*Armesto et al,* PRL 93 (2004)




- Interaction of jet+medium

  Momentum kick from jet, C.-Y. Wong , Phys.Rev.C76:054908,2007
  Medium heating + recombination, Chiu & Hwa, PRC72, 034903

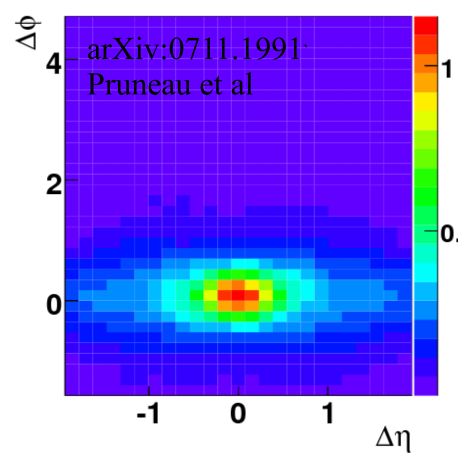
  - Agrees with data but lots of fits to the data

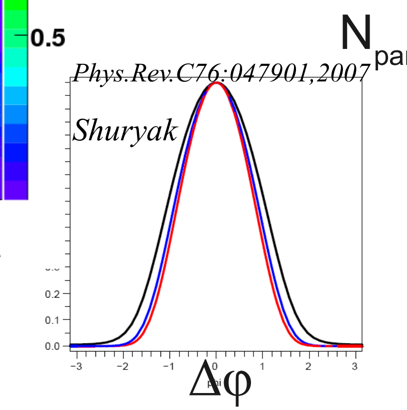



- Radial flow+trigger bias

  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*

  - Need more detailed comparisons



# Models

- Radiated gluons broadened in pseudorapidity

  Longitudinal flow, Armesto et al, PRL 93 (2004)
  QCD magnetic fields, Majumder et al,Phys.Rev.Lett.99:042301,2007
  Anisotropic plasma, P. Romatschke, PRC,75014901 (2007)

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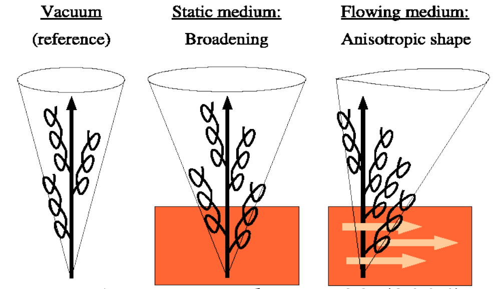
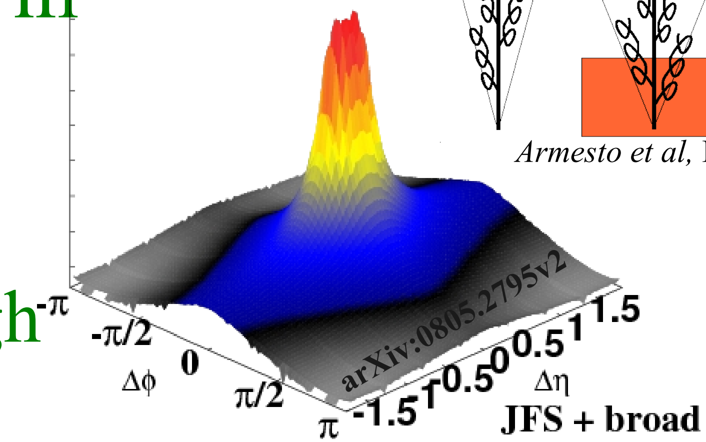



*Armesto et al,* PRL 93 (2004)

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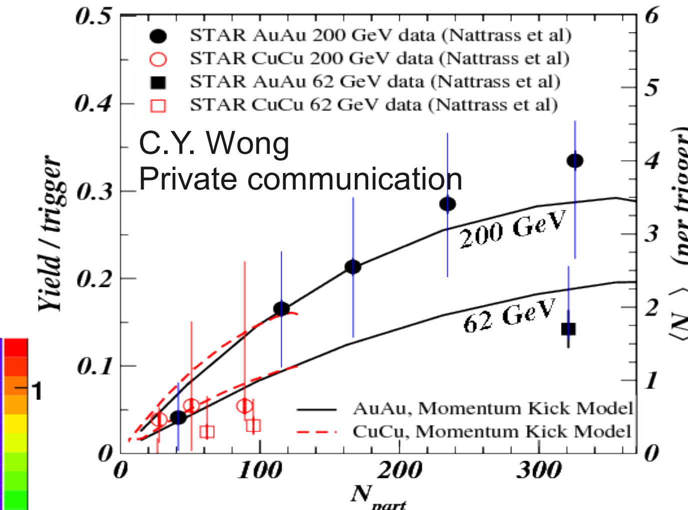


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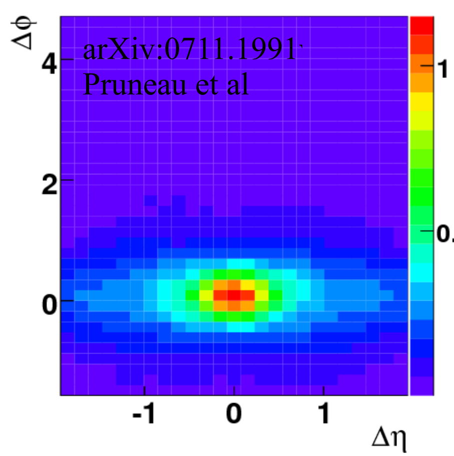
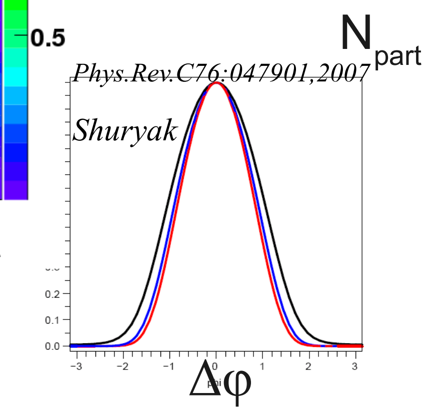
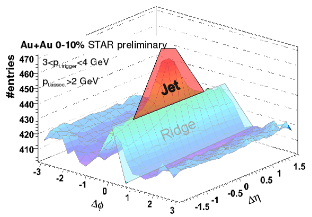



→ **No preferred model**

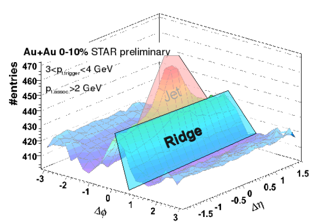
# Conclusions

*Jet*




- Pythia explains trends in data well
  - Needs scaling factor but amazing it does so well
  - Energy, $p_T^{trigger}$, $p_T^{associated}$ dependence
- Separation of *Jet* and *Ridge* works well
- *Jet* production dominated by fragmentation
- Deviations from fragmentation/Pythia indicate modification of jet

*Ridge*




- Extensive experimental data
- Models need more rigorous comparisons to data, more signatures to distinguish production mechanism
- Reasonable agreement of *Jet* with Pythia

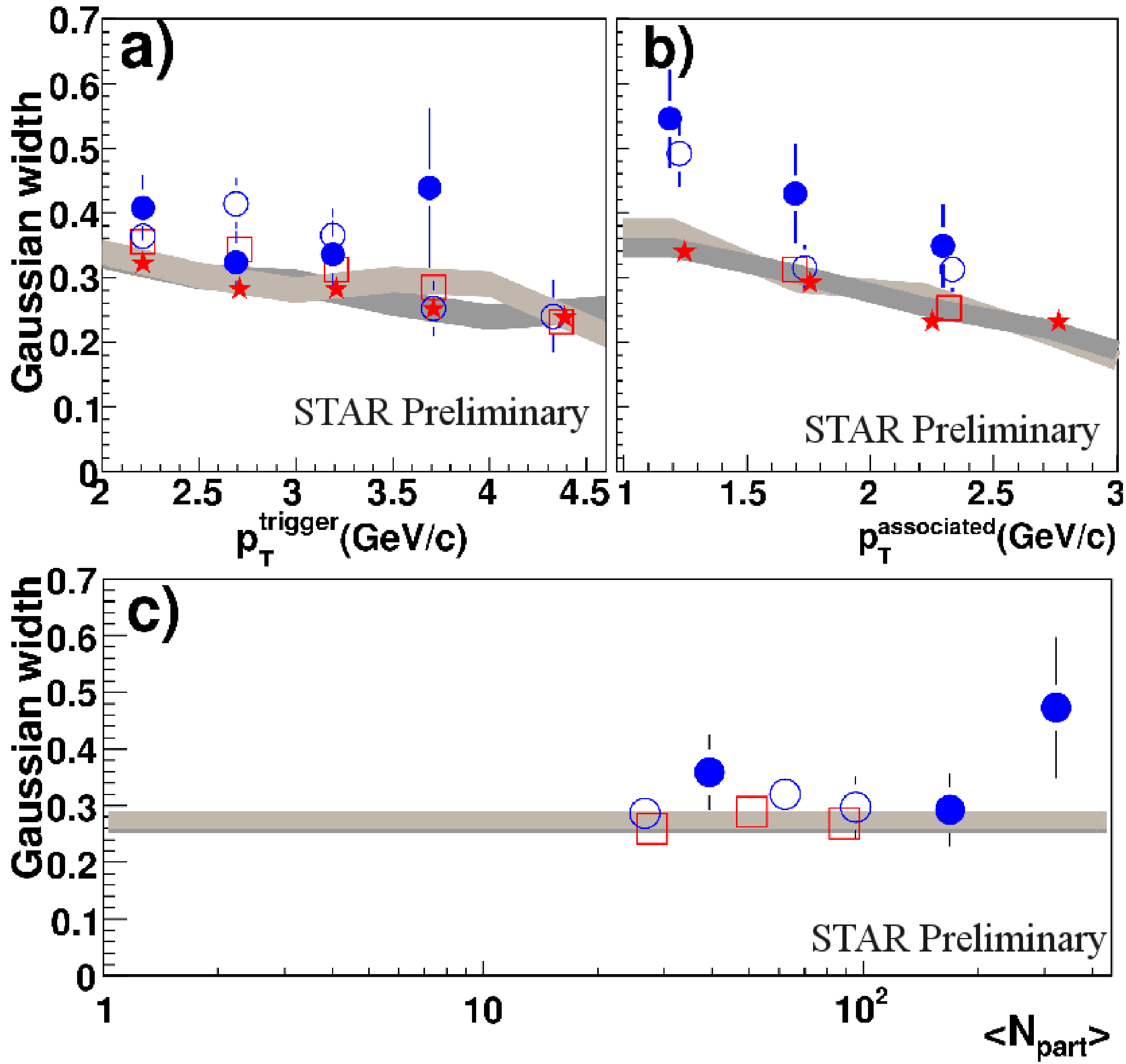
  → simulations can be used to convert from $p_T^{trigger}$ to distribution of jet energies

  → Greater surface bias in 62 GeV could explain lower *Ridge* yield

# STAR Collaboration

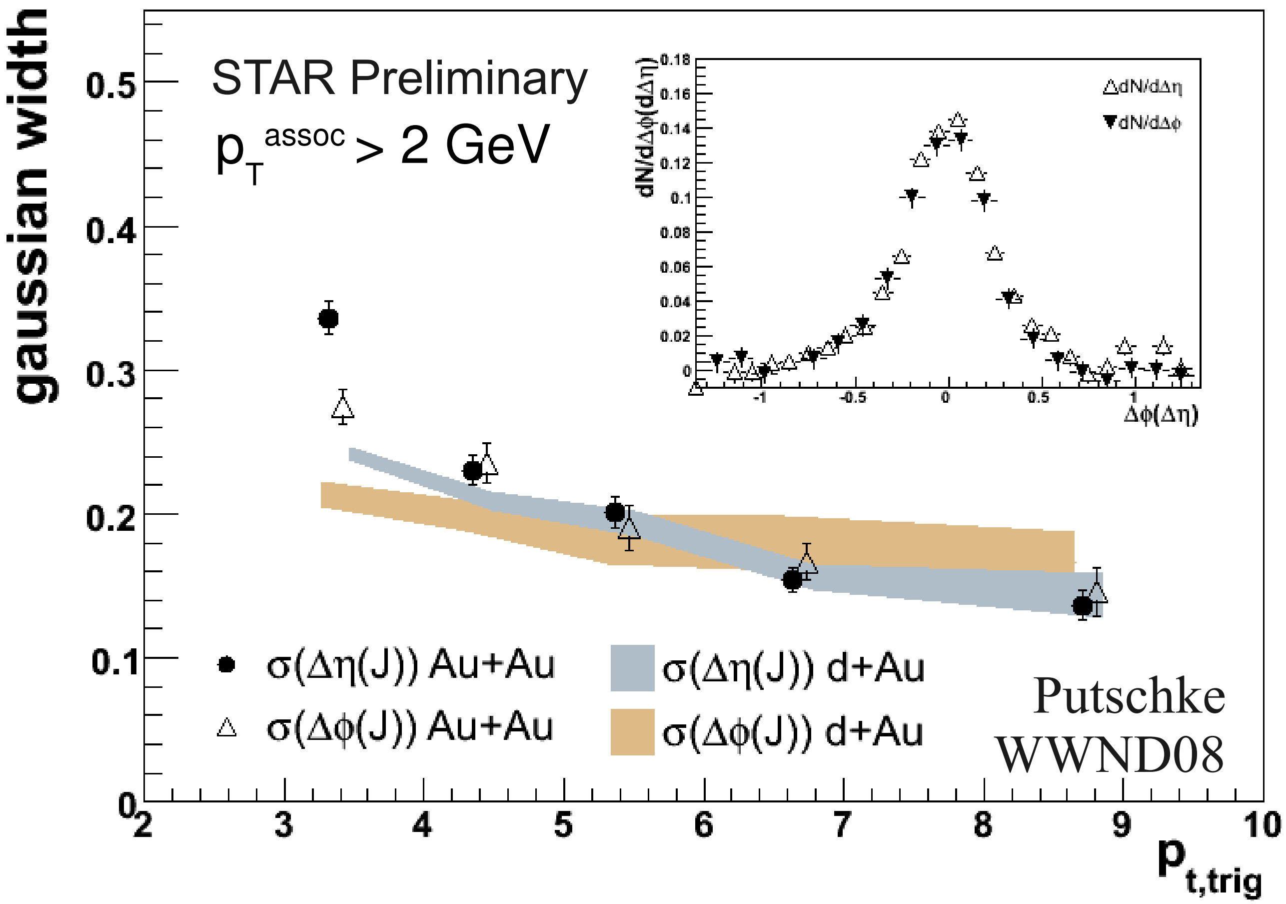
**Argonne National Laboratory - University of Birmingham - Brookhaven National Laboratory - California Institute of Technology - University of California, Davis - University of California - University of California, Los Angeles - Carnegie Mellon University - University of Illinois at Chicago - Creighton University - Nuclear Physics Institute Prague - Laboratory for High Energy (JINR) - Particle Physics Laboratory (JINR) - University of Frankfurt - Institute of Physics, Bhubaneswar - Indian Institute of Technology, Mumbai - Indiana University, Bloomington - Institut de Recherches Subatomiques - University of Jammu - Kent State University - Institute of Modern Physics, Lanzhou - Lawrence Berkeley National Laboratory - Massachusetts Institute of Technology - Max-Planck-Institut fuer Physik - Michigan State University - Moscow Engineering Physics Institute - City College of New York - NIKHEF and Utrecht University - Ohio State University, Columbus - Panjab University - Pennsylvania State University - Institute of High Energy Physics, Protvino, Russia - Purdue University - Pusan National University, Pusan, Republic of Korea - University of Rajasthan, Jaipur - Rice University - Universidade de Sao Paulo - University of Science & Technology of China - Shanghai Institute of Applied Physics - SUBATECH, Nantes, France - Texas A&M University - University of Texas - Tsinghua University - Valparaiso University - Variable Energy Cyclotron Centre, Kolkata, India - Warsaw University of Technology - University of Washington - Wayne State University - Institute of Particle Physics, CCNU (HZNU), Wuhan - Yale University - University of Zagreb**

# Backup slides



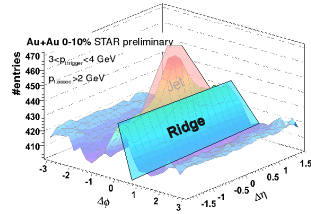
a)
b)
c)
Gaussian width
Gaussian width
STAR Preliminary
STAR Preliminary
STAR Preliminary
$p_T^{trigger}$(GeV/c)
$p_T^{associated}$(GeV/c)
<$N_{part}$>

# Jet-like peak width in central Au+Au

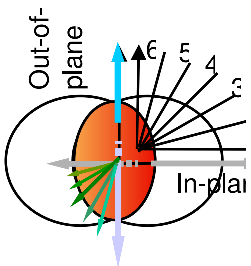


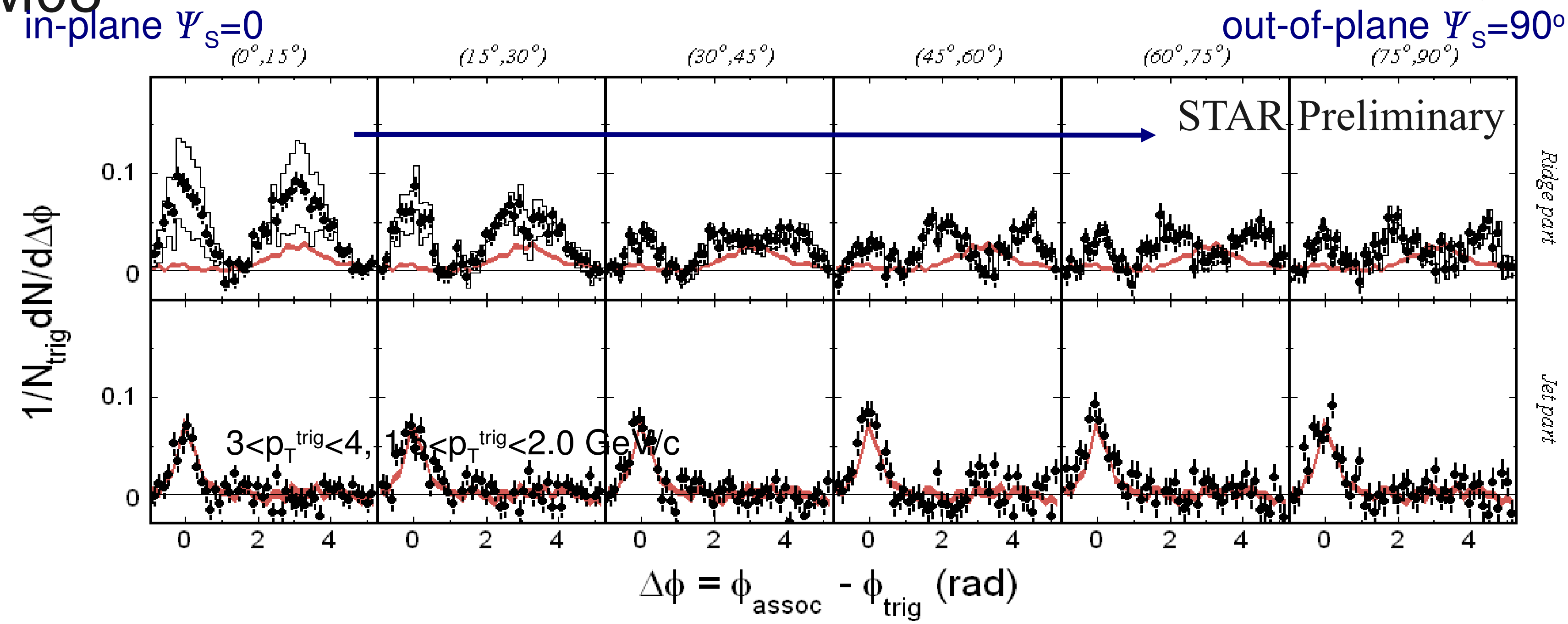

- *Jet* peak symmetric in Δη and Δφ for $p_T^{trigger} > 4$ GeV and comparable to d+Au
- *Jet* peak asymmetric in Δη for $p_T^{trigger} < 4$ GeV and significantly broader than d+Au

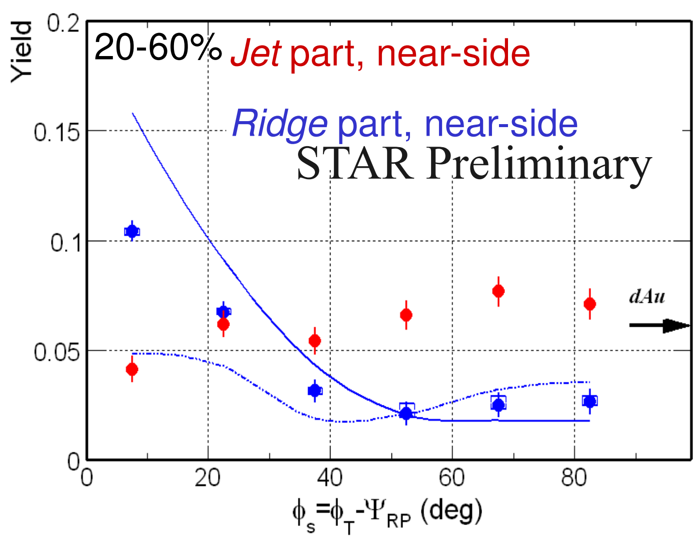
# *Ridge* relative to reaction plane




Feng QM08



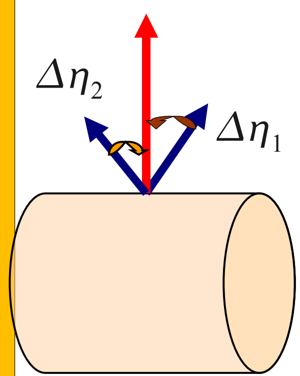



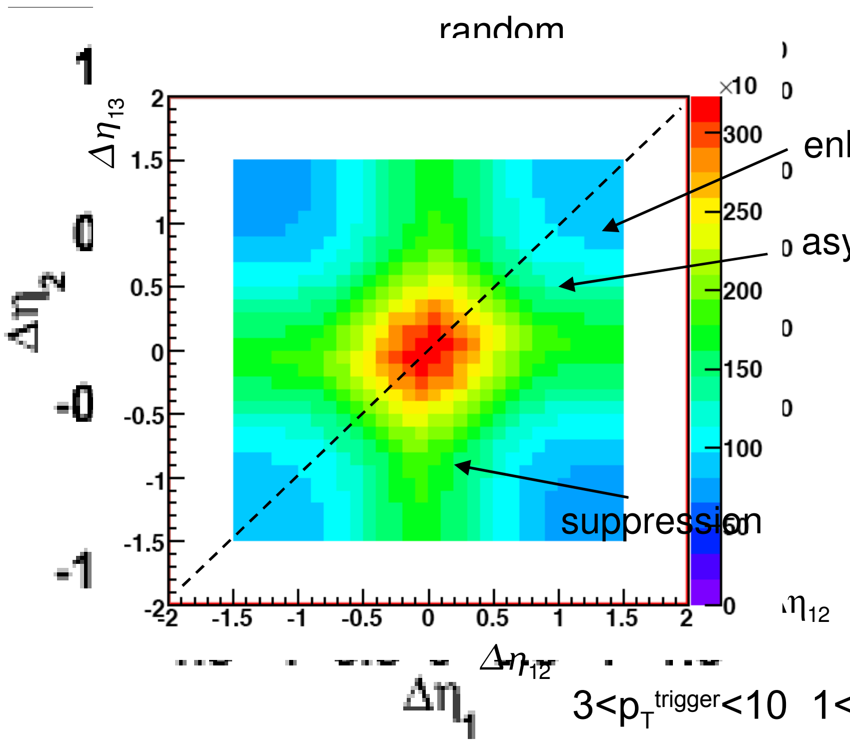

- *Ridge* yield decreases with $\varphi_S$. Smaller ridge yield at larger $\varphi_S$
- *Jet* yield approx. independent of $\varphi_S$ and comparable with d+Au

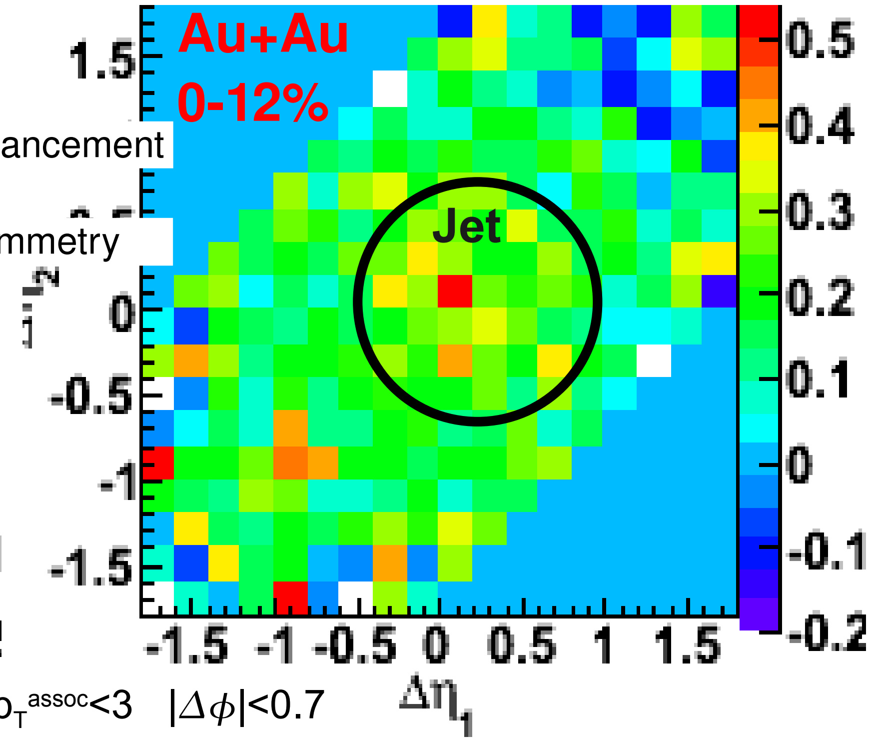
*Jet* yield independent of $\varphi_S$, consistent with vacuum fragmentation after energy loss and lost energy deposited in ridge, if medium is "black" out-of-plane and more "gray" in-plane for surviving jets.

# 3-particle correlations



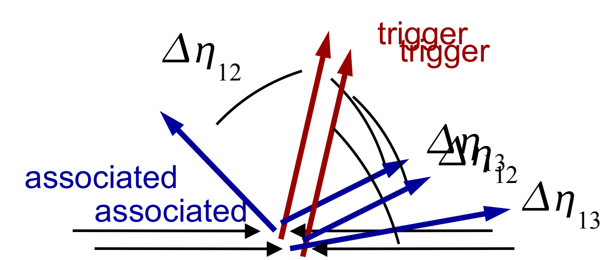

$\Delta\eta_1$ = A1-T
$\Delta\eta_2$ = A2-T




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

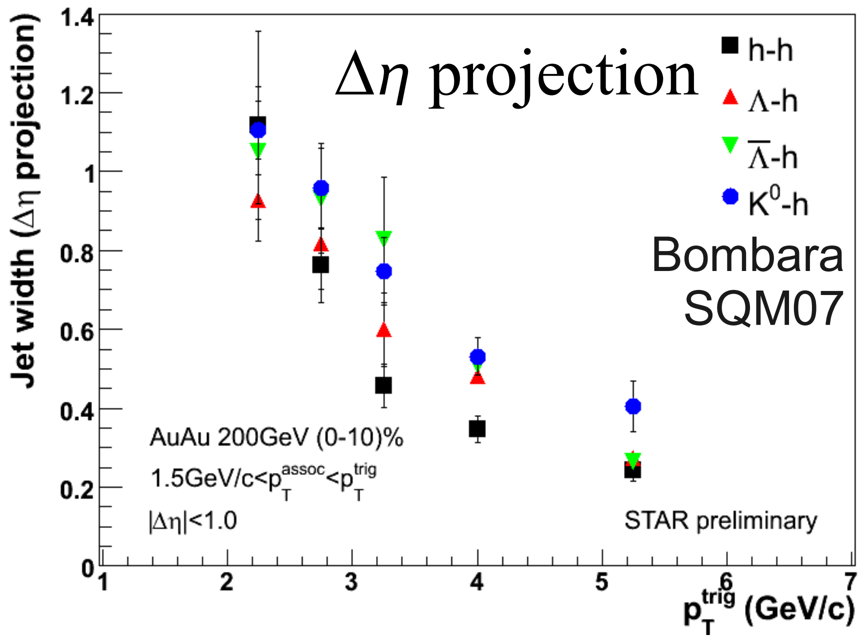
- *Ridge* appears uniform event-by-event within STAR detector

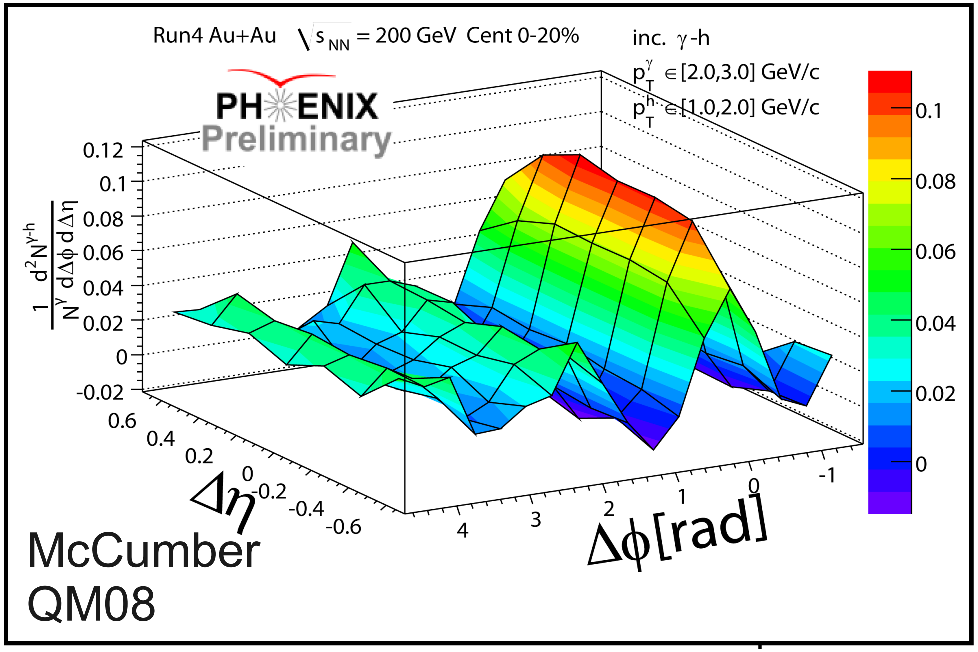



Radial flow + trigger bias / Long. flow picture

S. Voloshin, nucl-th/0312065, Nucl. Phys A749, 287 / Armesto et al, PRL 93 (2004)

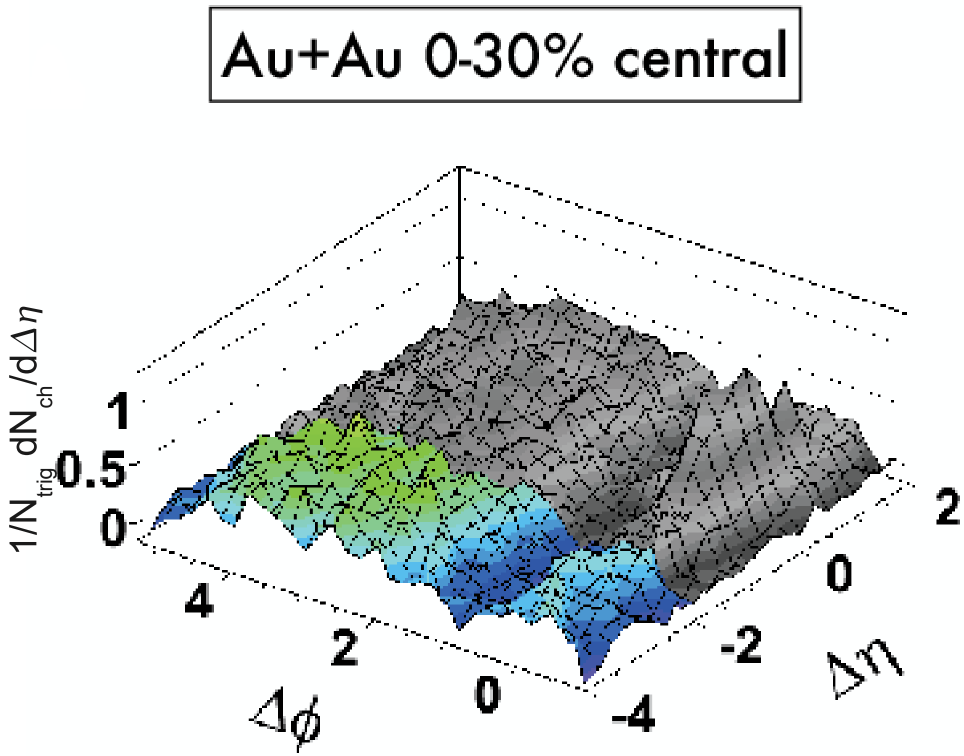
# Jet-like peak width in central Au+Au



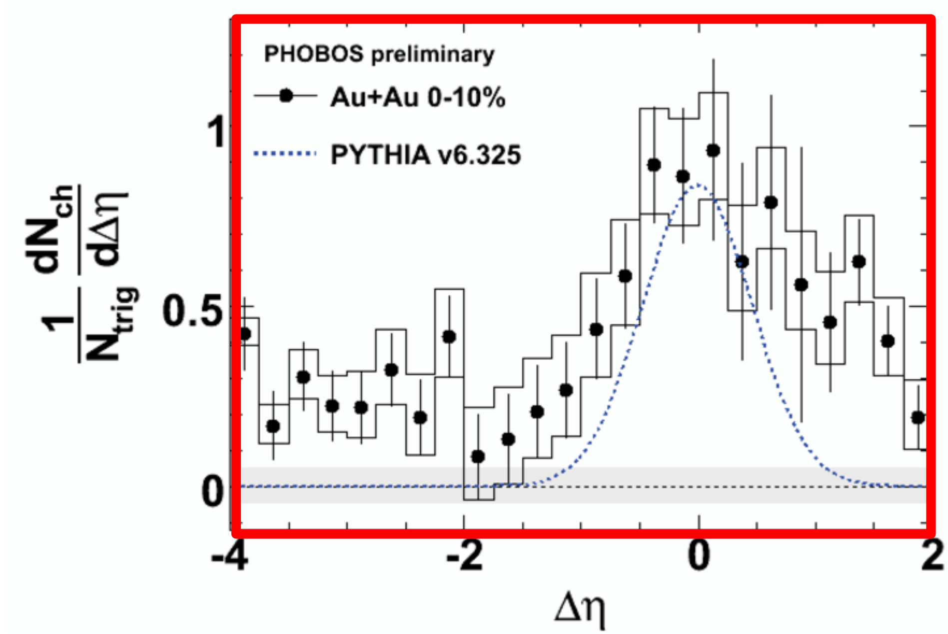



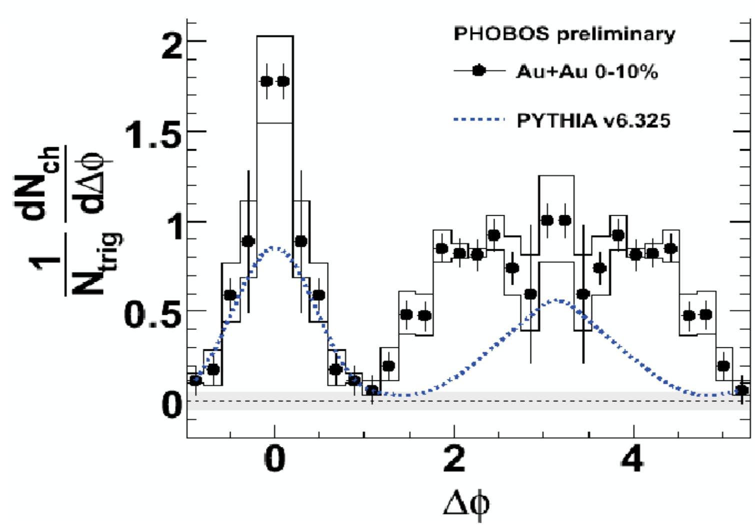

- Peak gets broader at higher $p_T^{trigger}$, lower $p_T^{assoc}$
- Width in PHENIX kinematic range close to PHENIX acceptance

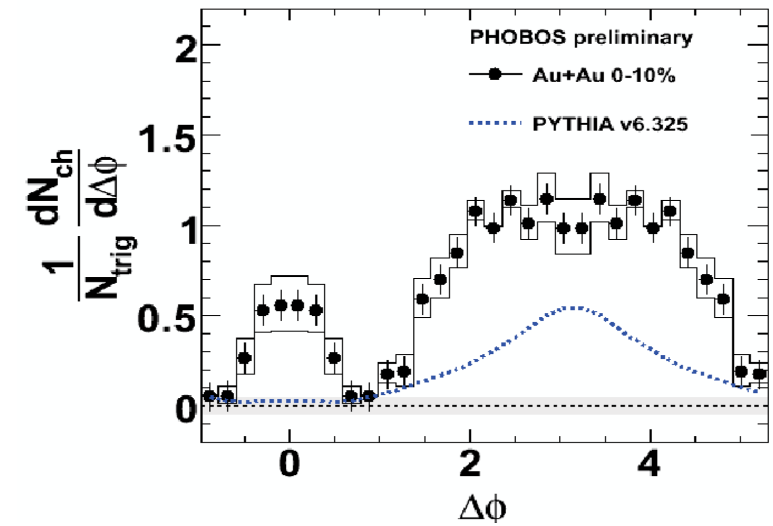
# Extent of *Ridge* in $\Delta\eta$



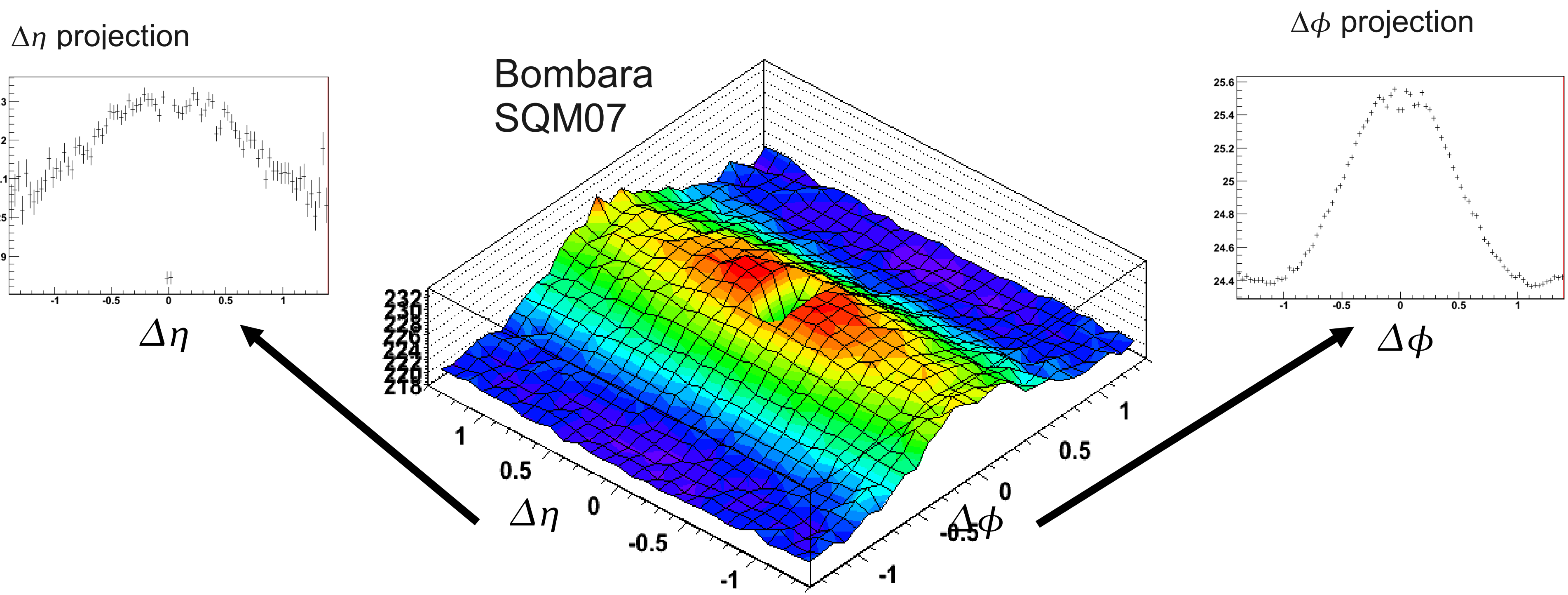

Wenger QM08



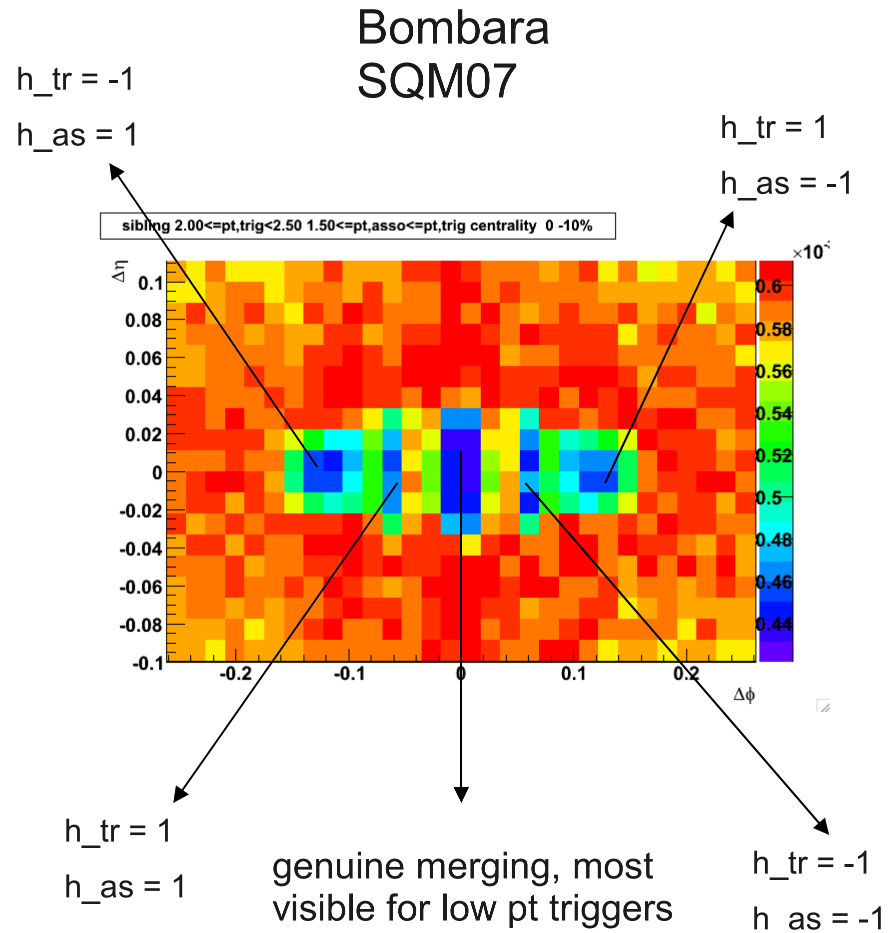
# Track merging




- 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 ($K^0_S$, $\Lambda$, $\Xi$) 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



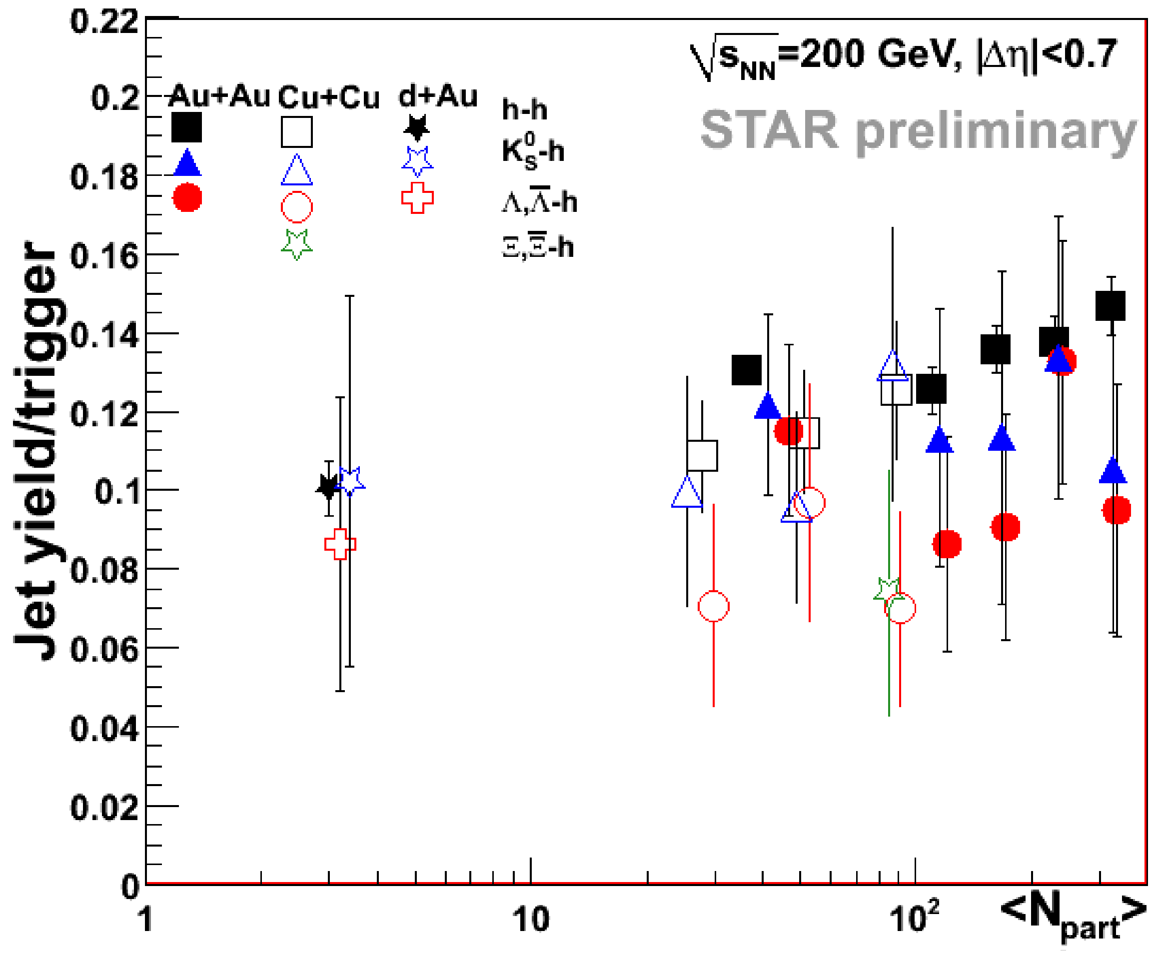

h_tr - helicity of trigger

h_as - helicity of associated

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

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

*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

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

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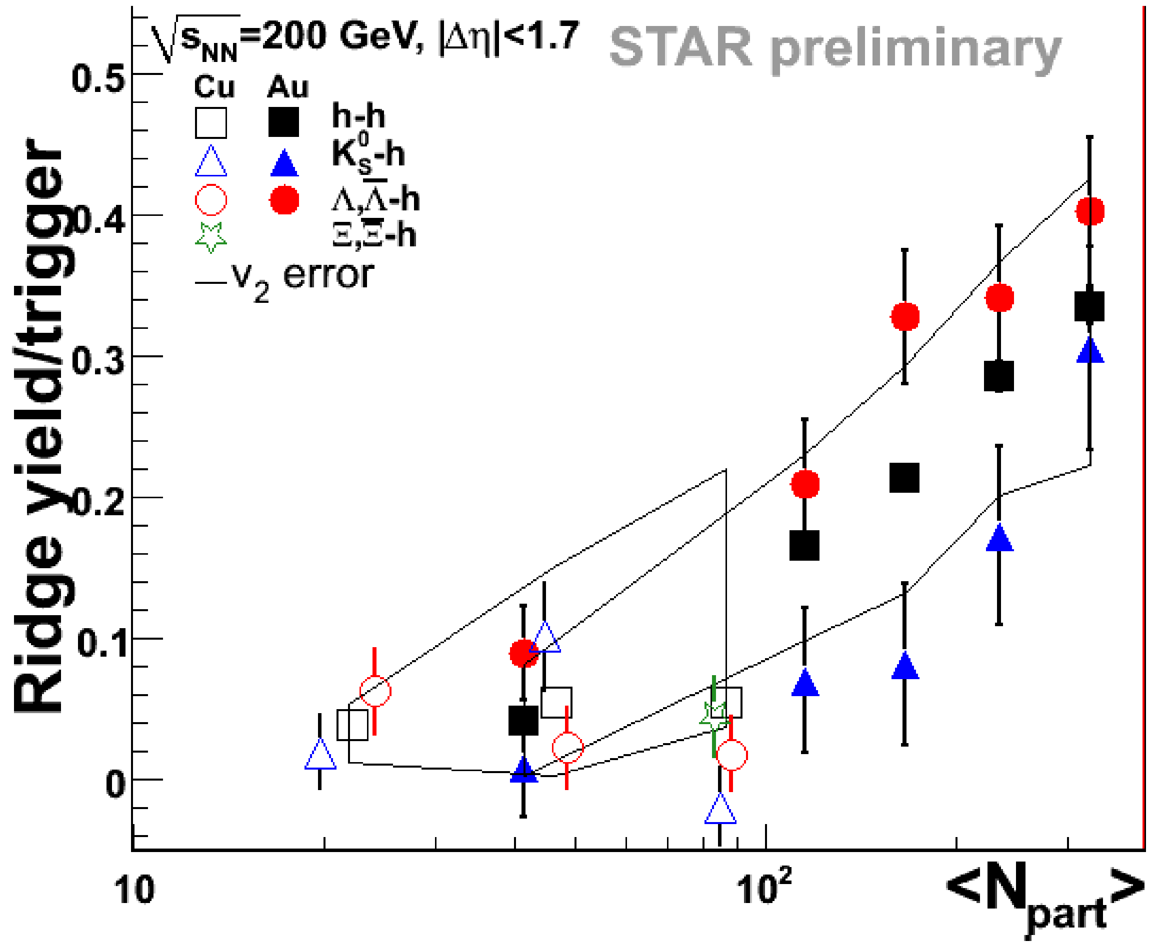


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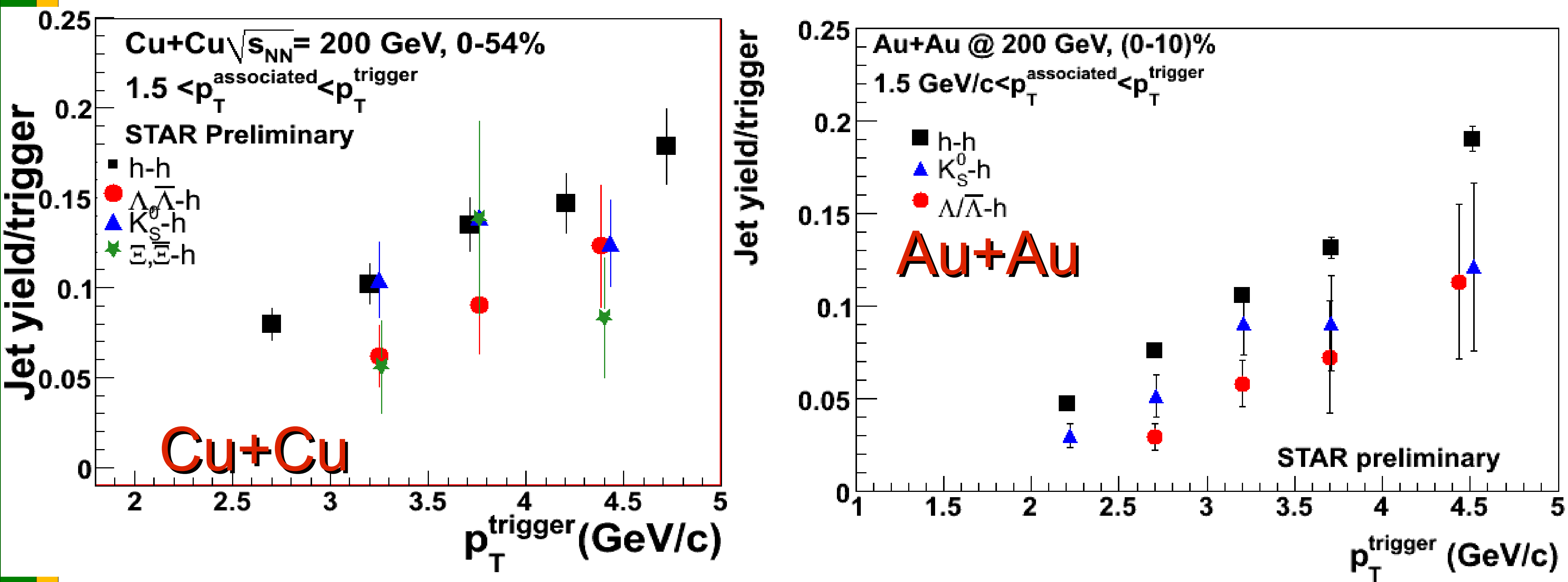
Data points at same $N_{part}$ offset for visibility
Jet yields: 10% error added to $V^0$ and h triggers to account for track merging, 15% to Ξ triggers
$v_2$ errors shown only for h-h. $K^0_S$-h error bars comparable to h-h. Λ-h and Ξ-h errors roughly 1.5 times as large as h-h.

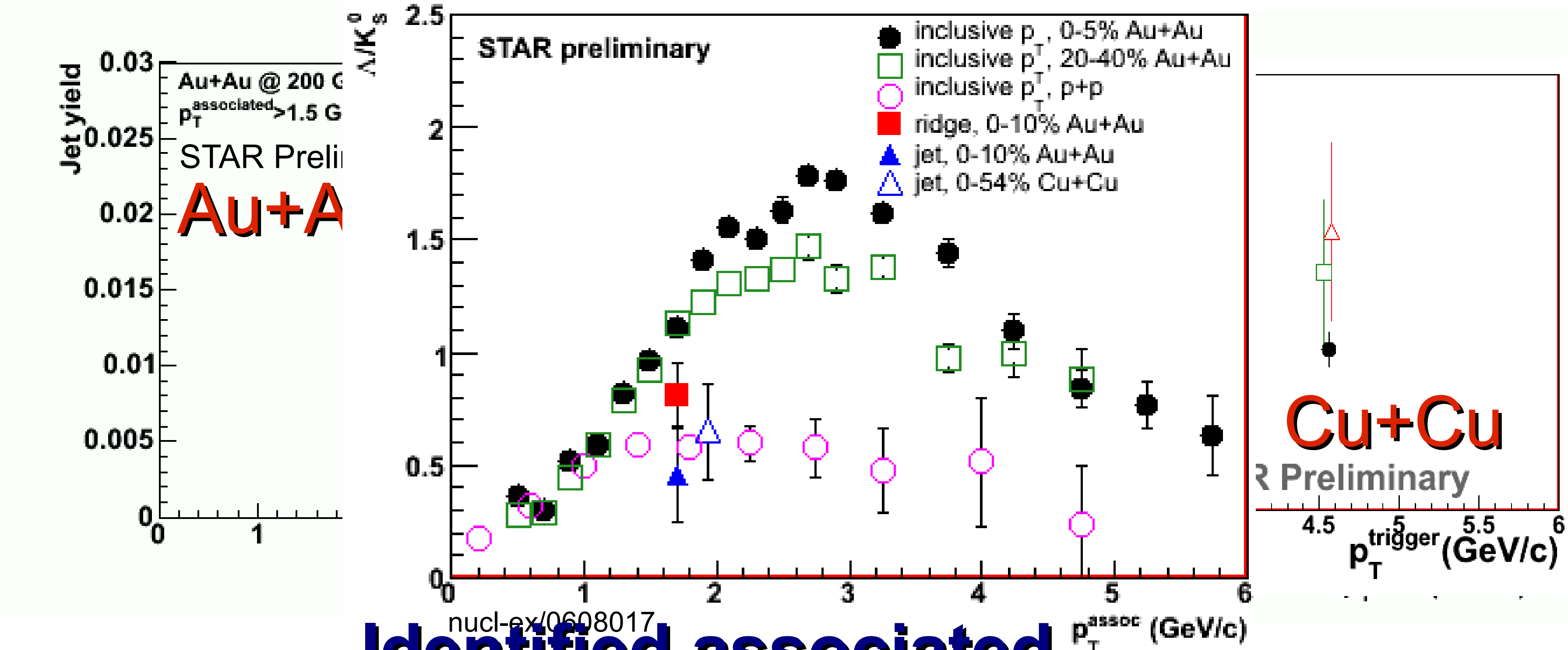
# Identified trigger: *Jet* yield vs $p_T^{trigger}$




## No trigger type dependence

Au+Au $\sqrt{s_{NN}}$ = 200 GeV from nucl-ex/0701047
Data points at same $p_T^{trigger}$ offset for visibility
Jet yields: 10% error added to $V^0$ and h triggers to account for track merging, 15% to $\Xi$ triggers

# Identified associated yield vs $p_T^{trigger}$




**Identified associated**

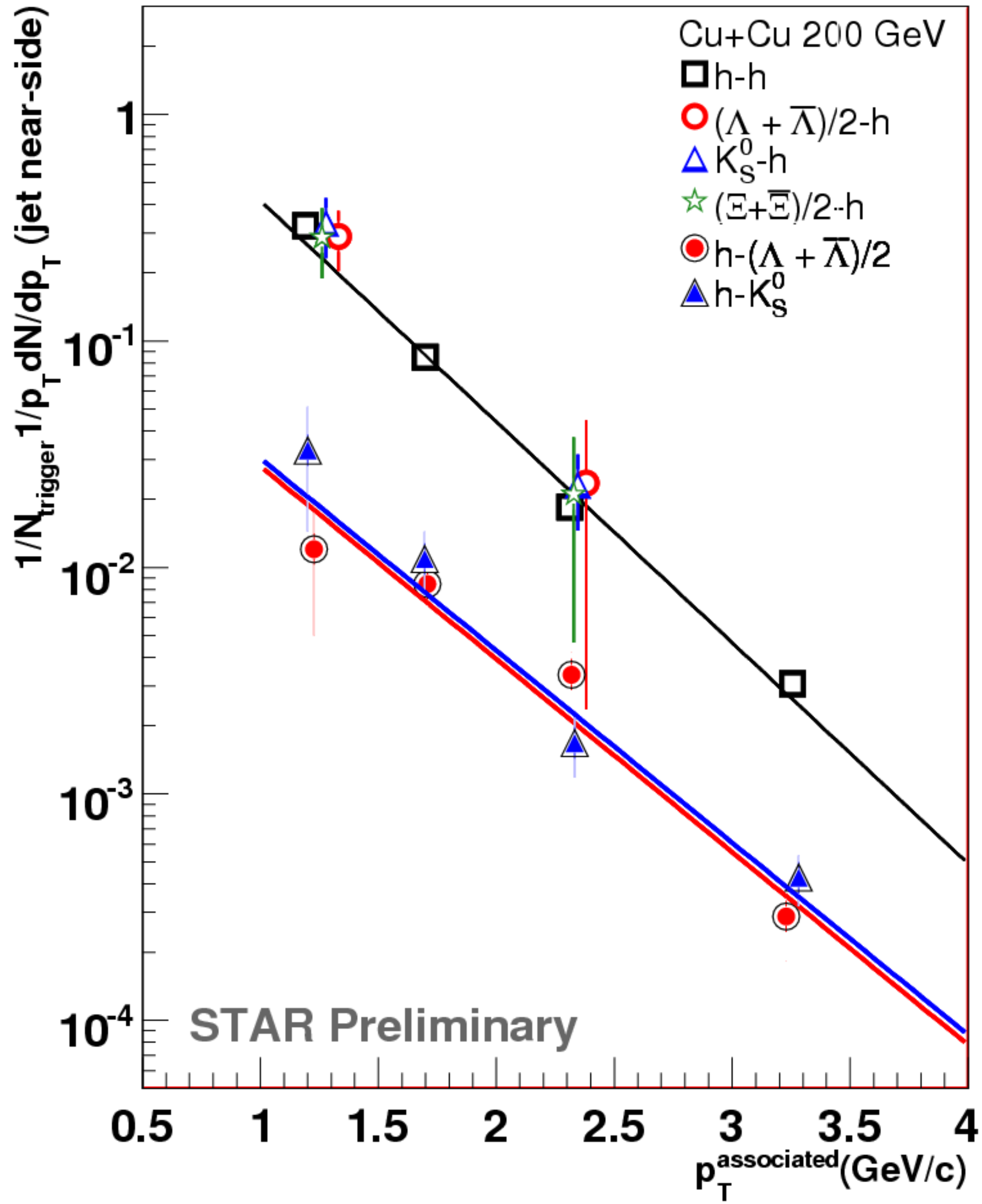
- In Au+Au
  - *Jet:* $(\bar{\Lambda}+\Lambda)/K^0_s \approx 1$
    - similar to vacuum fragmentation
  - *Ridge:* $\Lambda/K^0_s \approx 2$
    - similar to the bulk

- In Cu+Cu
  - *Jet:* $(\bar{\Lambda}+\Lambda)/K^0_s \approx 1$
  - *Ridge: Ratio not attainable*

**Particle ratios in Jet similar to those in p+p**

# $p_T$-distribution of associated particles

- No trigger type dependence
- Jet – Associated baryons and mesons similar



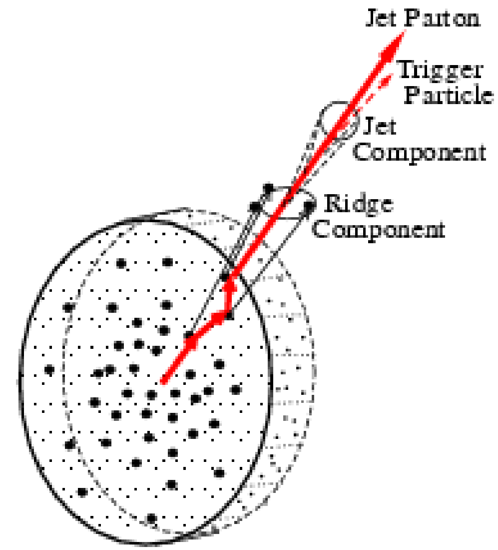

Fits assuming $1/p_T\, dN/dp_T = A\, p_T \exp(-p_T/T)$

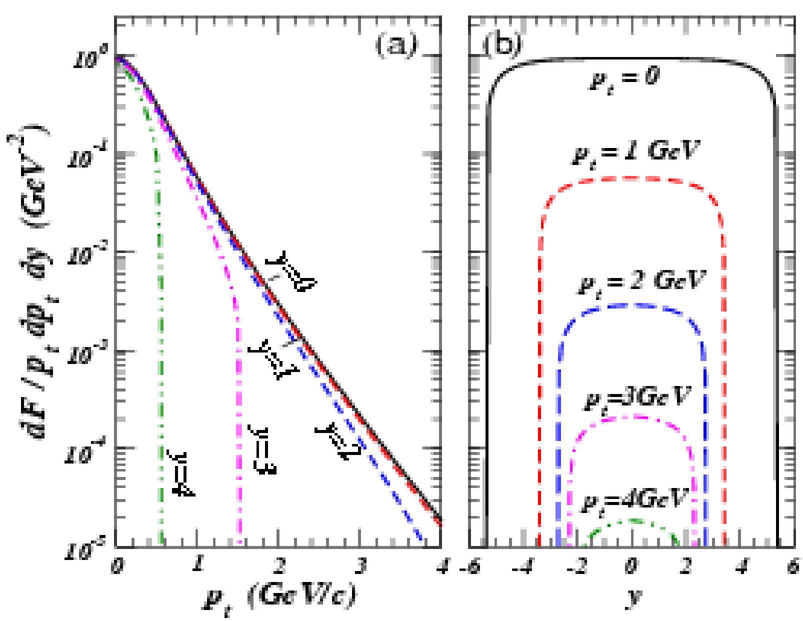
$\sqrt{s_{NN}}$=200 GeV Au+Au 0-10% Cu+Cu: 0-54%
$\sqrt{s_{NN}}$=62 GeV Au+Au 0-80% Cu+Cu: 0-60%

nucl-ex/0701047, SQM2007

# Momentum kick model

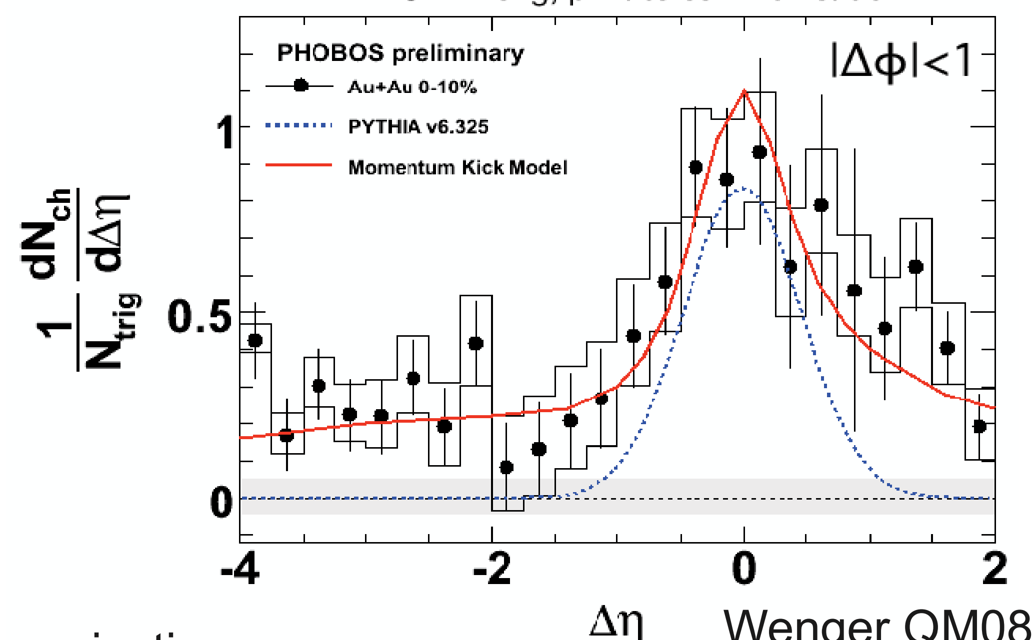
- Collisional energy loss of parton after hard scattering
- Fits shape in $\Delta\eta$
- Predicts sharp drop off with y




Theory plots from C.Y. Wong, private communications

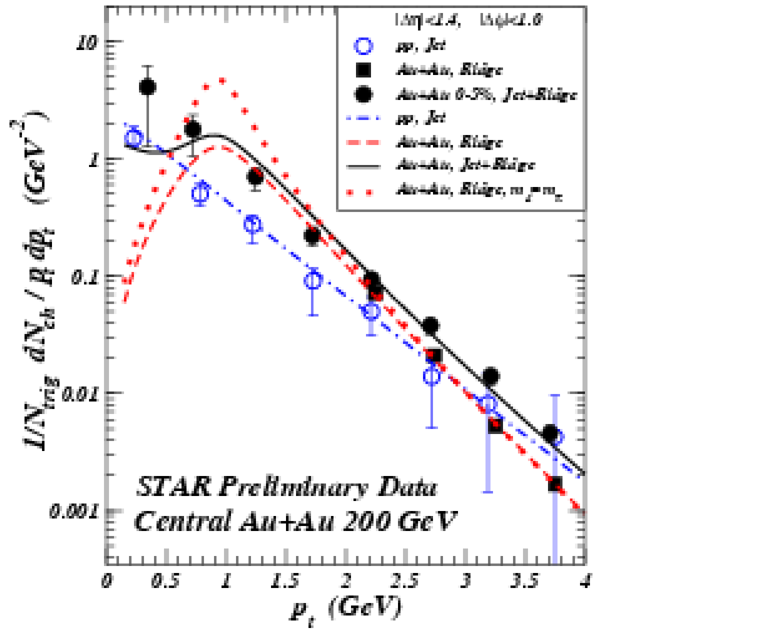
C.Y. Wong, private communication

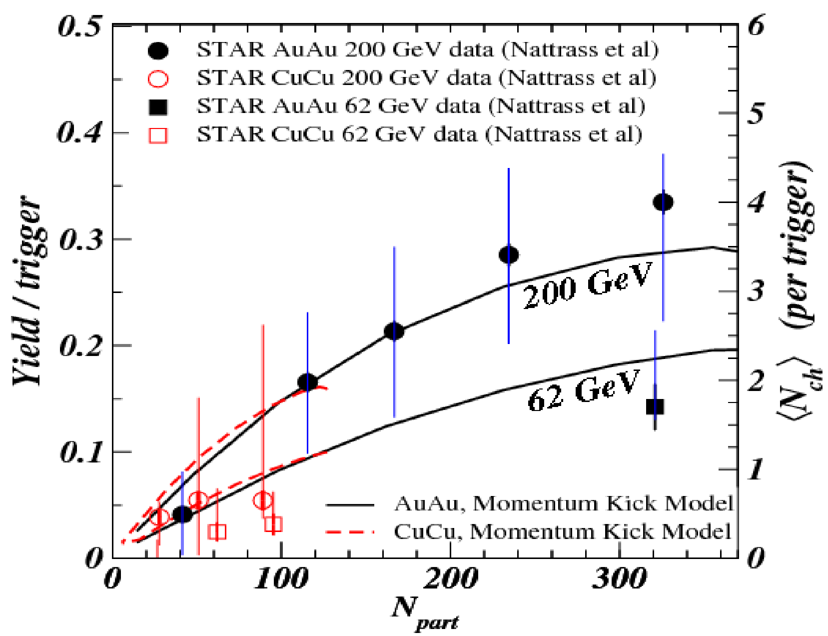



Wenger QM08

# Momentum kick model

- Describes energy dependence
- Predicts unusual *Ridge* spectrum
  - Probably not measurable

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