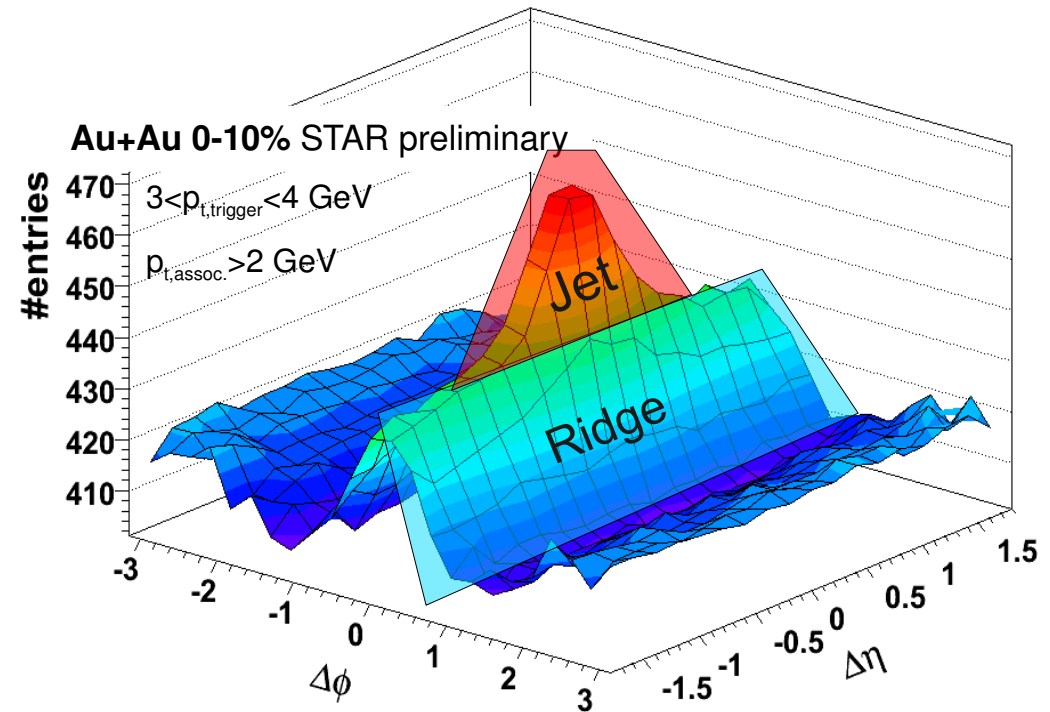


What we know about the *Ridge*

Christine Natrass
Yale University

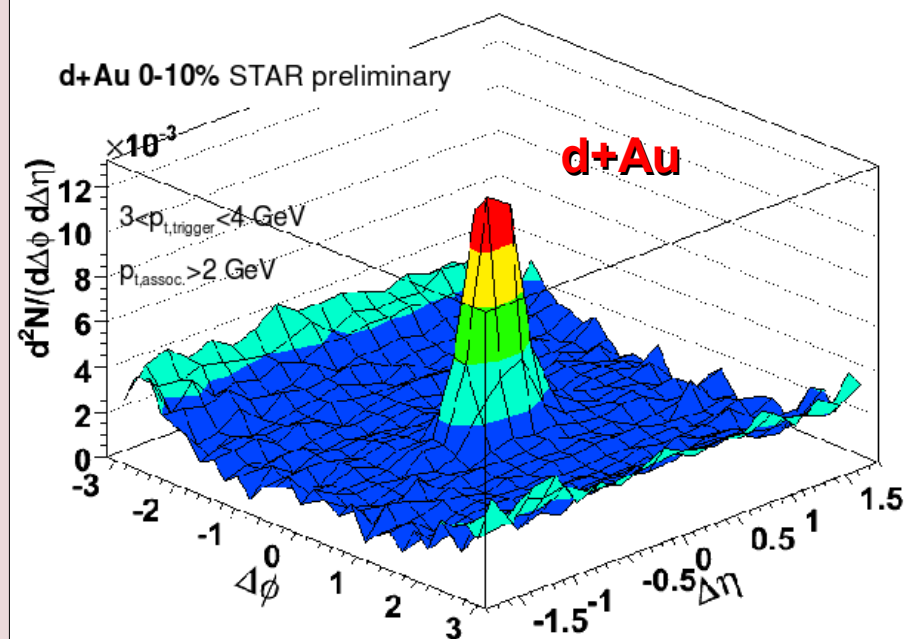
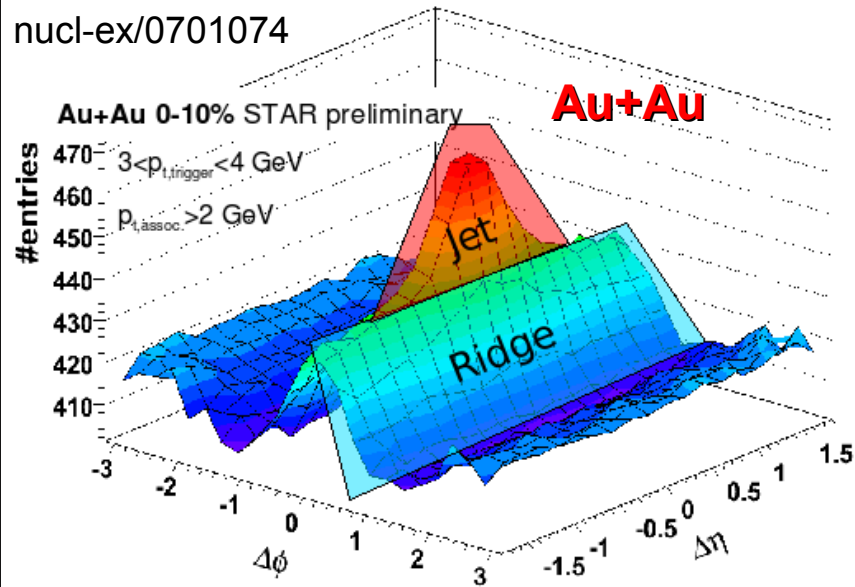
Outline

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



Introduction

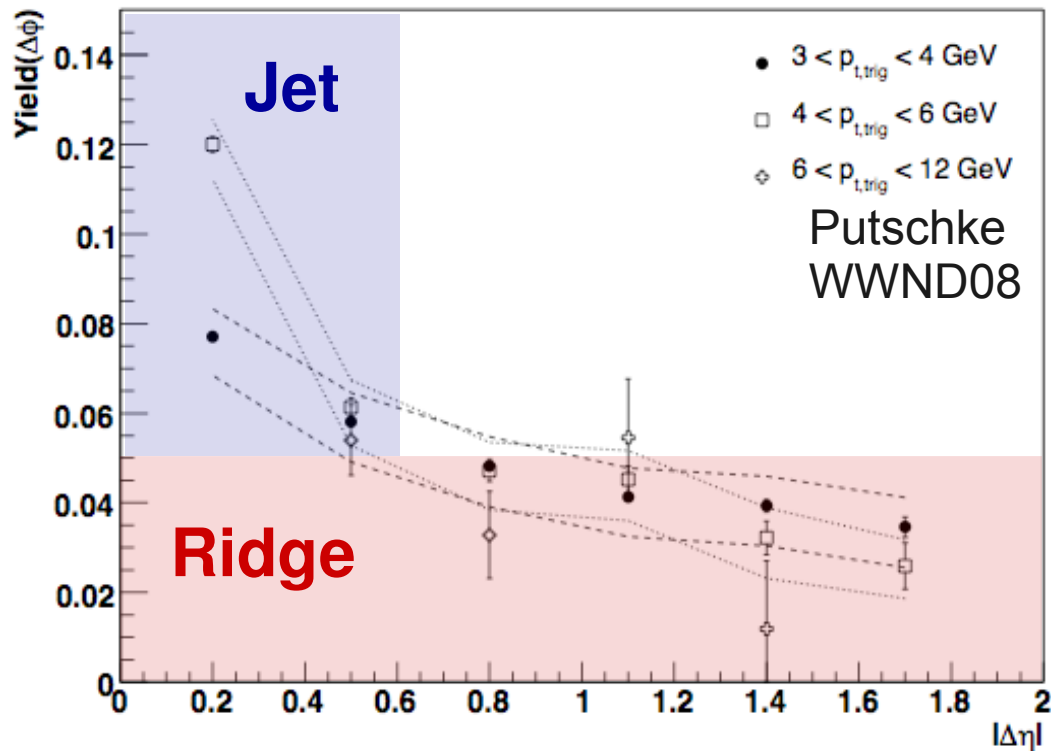
Motivation – *Jet and Ridge*



- 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 $\Delta\eta$

$$p_T^{\text{assoc}} > 2 \text{ GeV}$$



- *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

Au+Au 0-10% STAR preliminary

nucl-ex/0701074

h+h

- $-0.75 < \Delta\eta < 0.75$ **Jet + Ridge**

- $0.75 < |\Delta\eta| < 1.75$ **Ridge**

- $Jet = (Jet+Ridge) - Ridge \cdot .75/1.0$

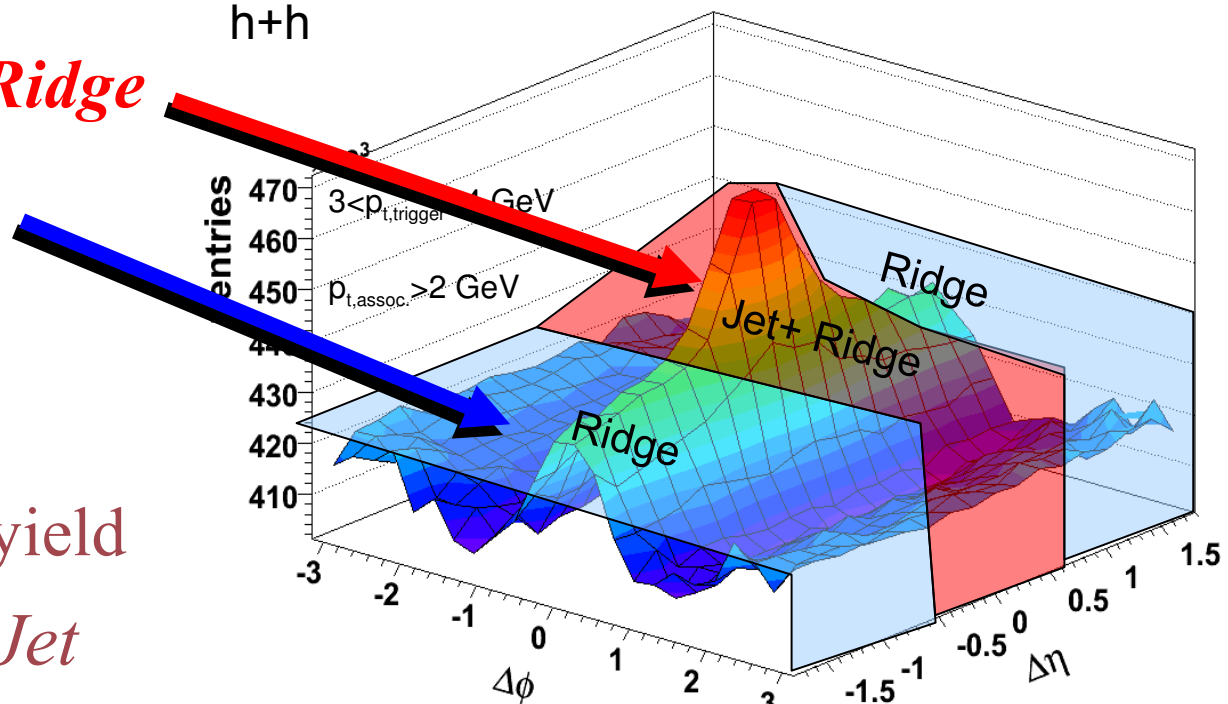
- $Ridge = \text{yield from } -1.75 < \Delta\eta < 1.75 - Jet \text{ yield}$

- Flow contributions to Jet cancel

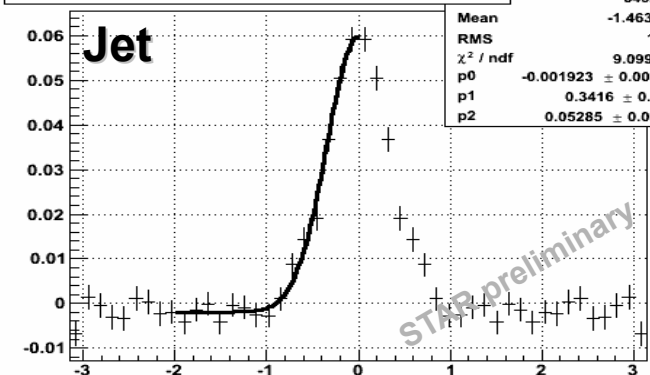
- v_2 independent of η for $|\eta| < 1$

• Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 12

- $3.0 < p_T^{\text{trigger}} < 6.0 \text{ GeV}/c; p_T^{\text{assoc}} > 1.5 \text{ GeV}$

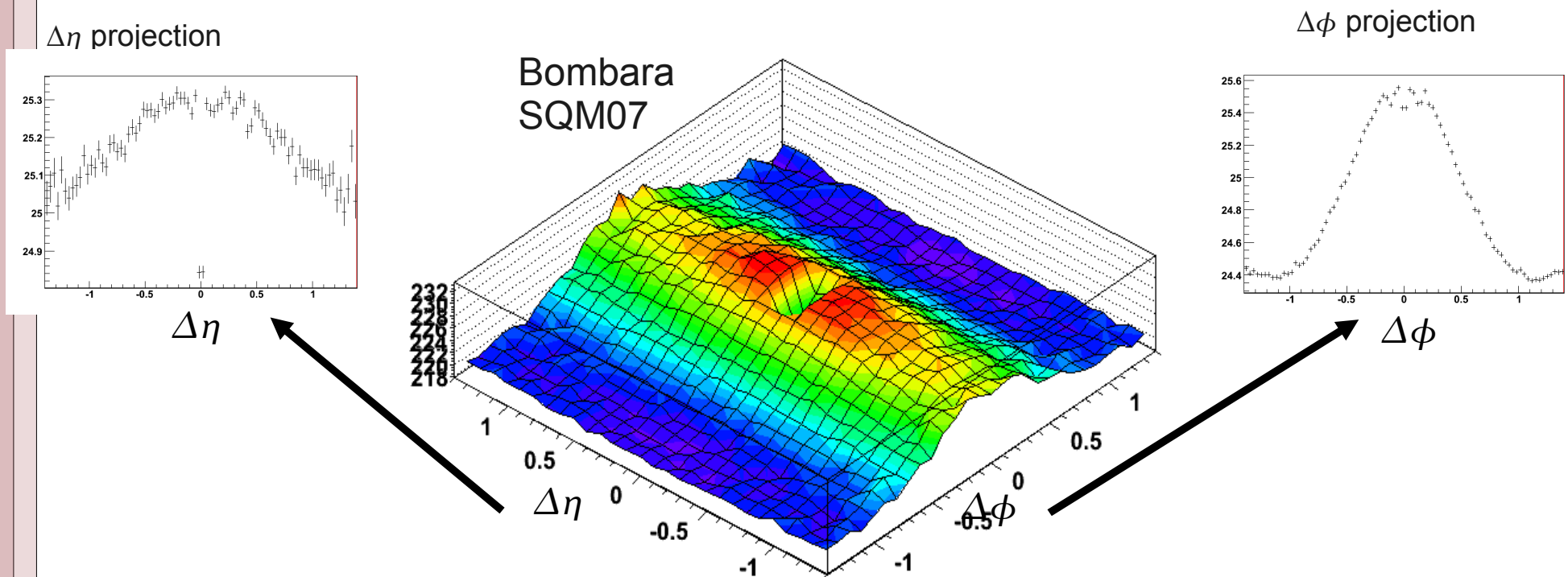


_h1_000001_0_0715_06_Cent0-10%_h+h	
Mean	6492408
RMS	-1.463e-17
χ^2 / ndf	1.819
p0	9.099 / 12
p1	-0.001923 \pm 0.000898
p2	0.3416 \pm 0.0162
p3	0.05285 \pm 0.00250



ed

Track merging



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

Determination of yields and errors

- Background:

$$B(1+2 v_2^{\text{trig}} v_2^{\text{assoc}} \cos(2\Delta\Phi))$$

- Different fit methods for determination of B

- Zero Yield At Minimum (ZYAM)
 - 1 point, 3 points

- B as Free parameter (used as best guess)

- v_2 error

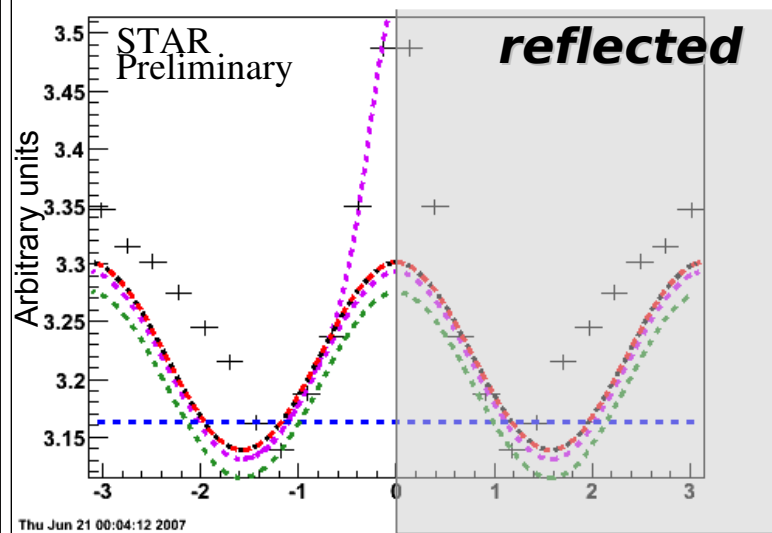
- v_2 measurements in Cu+Cu in progress

- Upper bound for v_2 measured
 - $v_2 \approx 10\text{-}15\%$ depending on p_T , centrality

- Estimate for lower bound, near 0

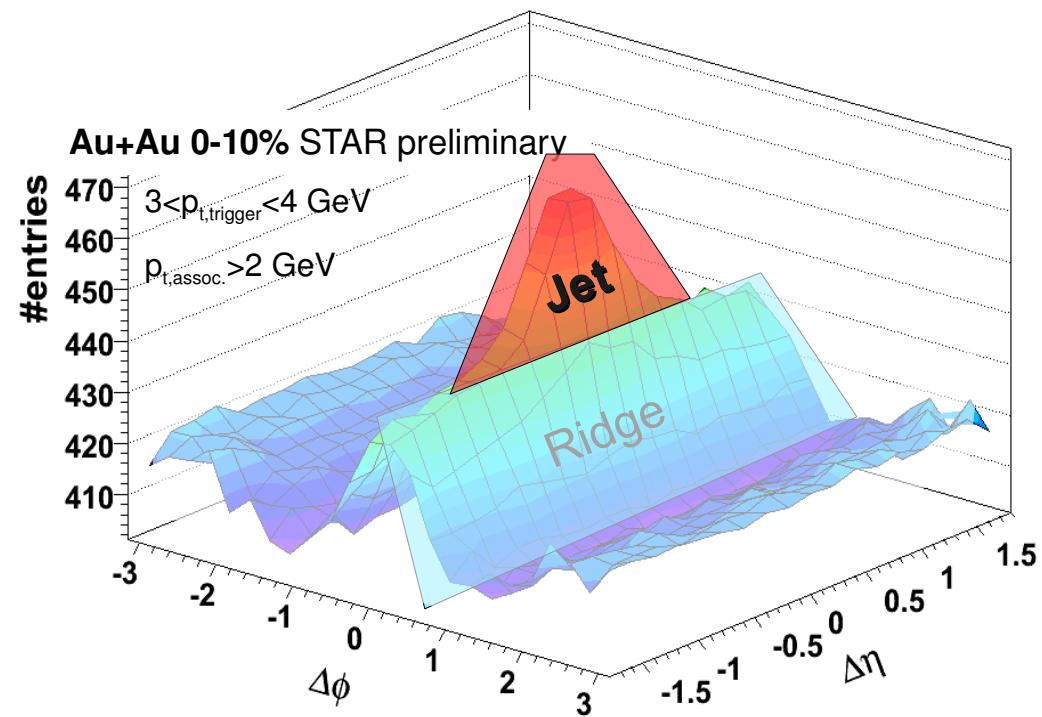
- $\Lambda, \bar{\Lambda}, K_s^0, \Xi^+, \Xi^- \dots v_2$ not currently used
 - Assume quark scaling of h v_2 in Cu+Cu

3.0 GeV < p_T^{trig} < 6.0 GeV, 1.5 GeV < p_T^{assoc} < p_T^{trig}
h-h, 0-20% Cu+Cu $\sqrt{s_{NN}} = 200$ GeV



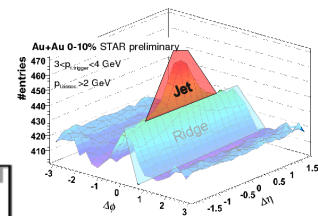
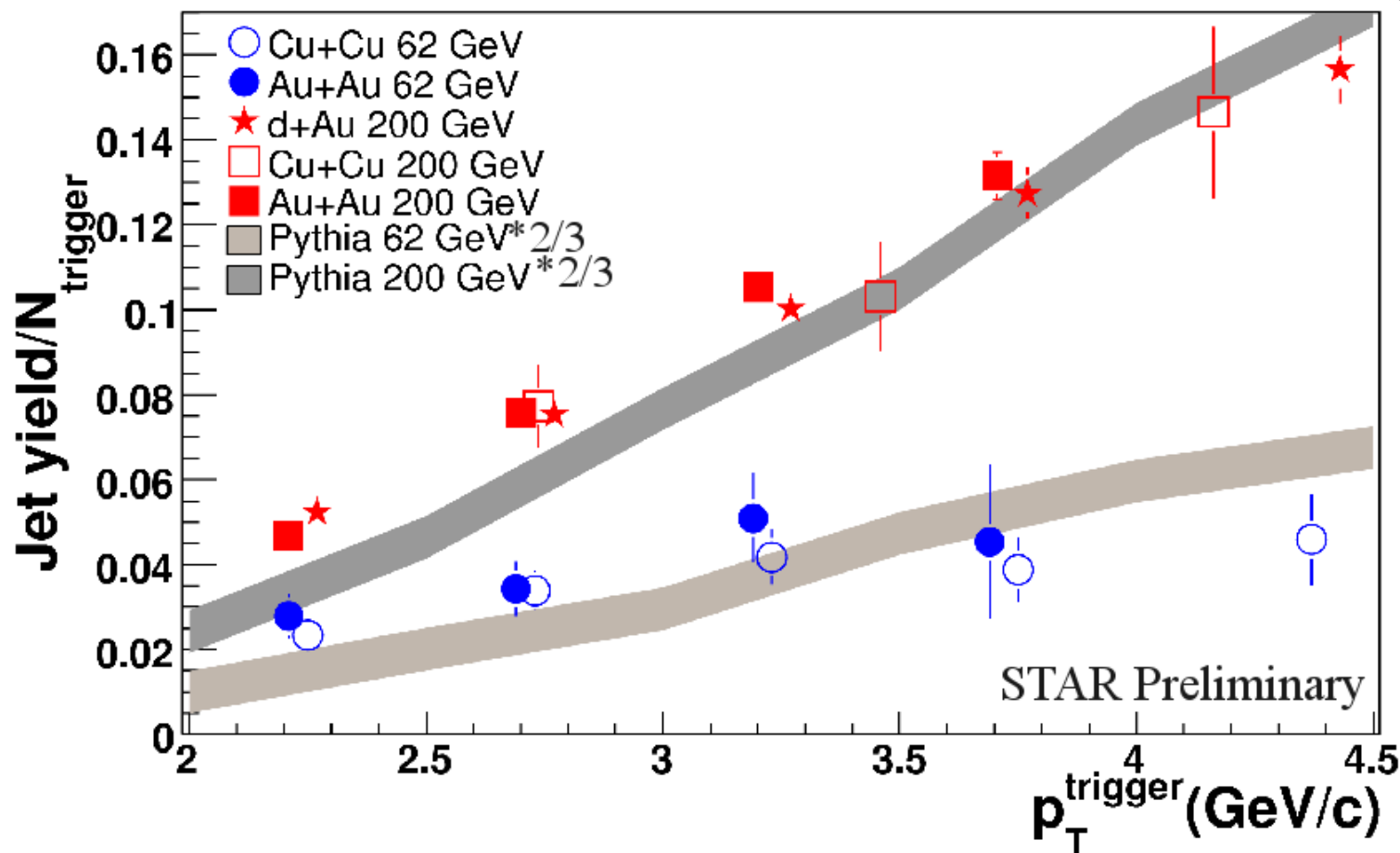
- - - - - - fit with ZYAM with 3 points, best v_2
- - . - . - fit with ZYAM with 3 points, high v_2
- - fit with ZYAM with 3 points, low v_2
- - . - . - fit with ZYAM with 1 point
- - . - . - fit with background as free parameter

The Jet



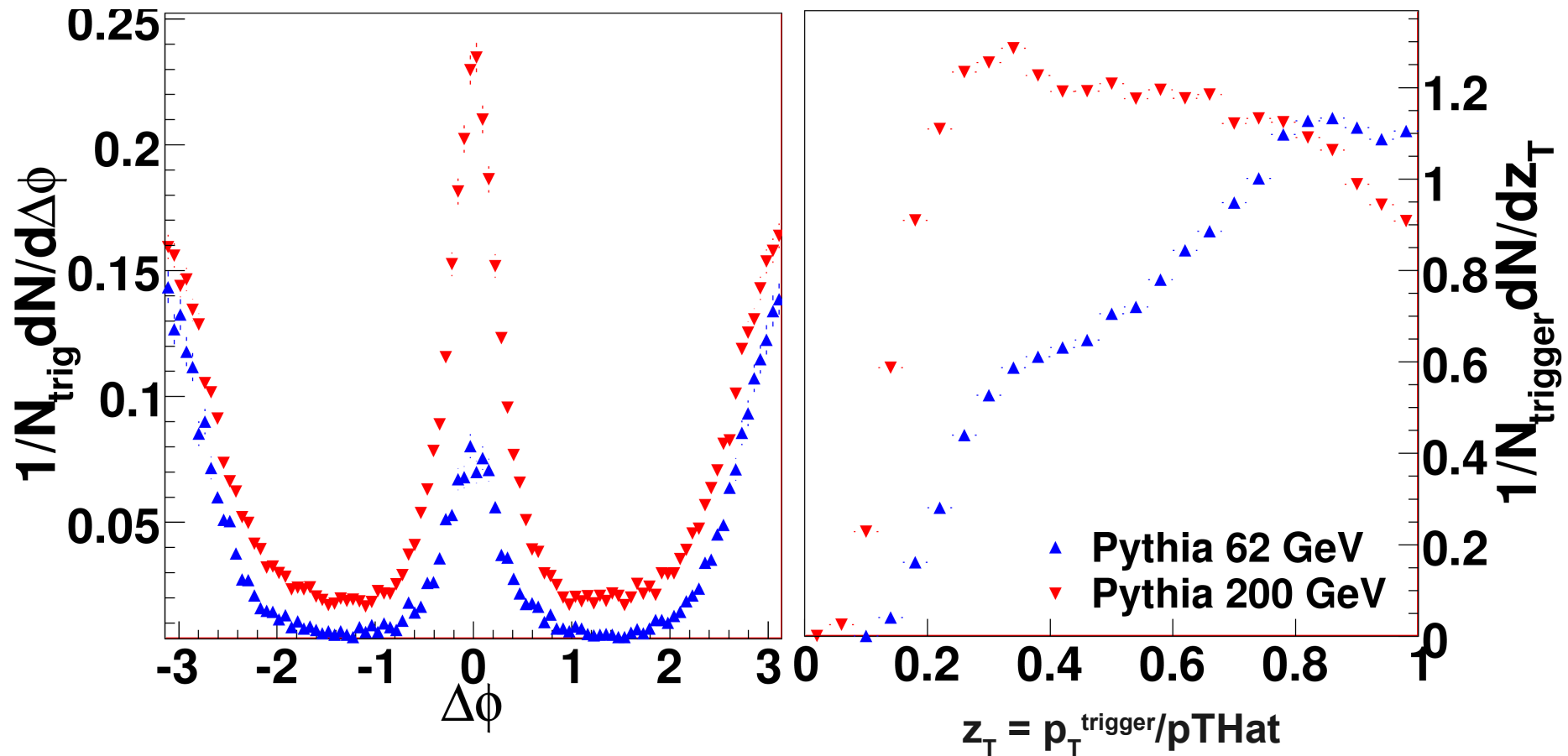
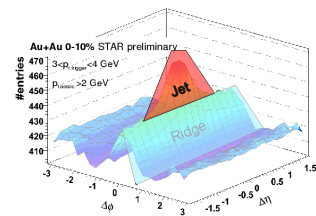
Energy and System dependence

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

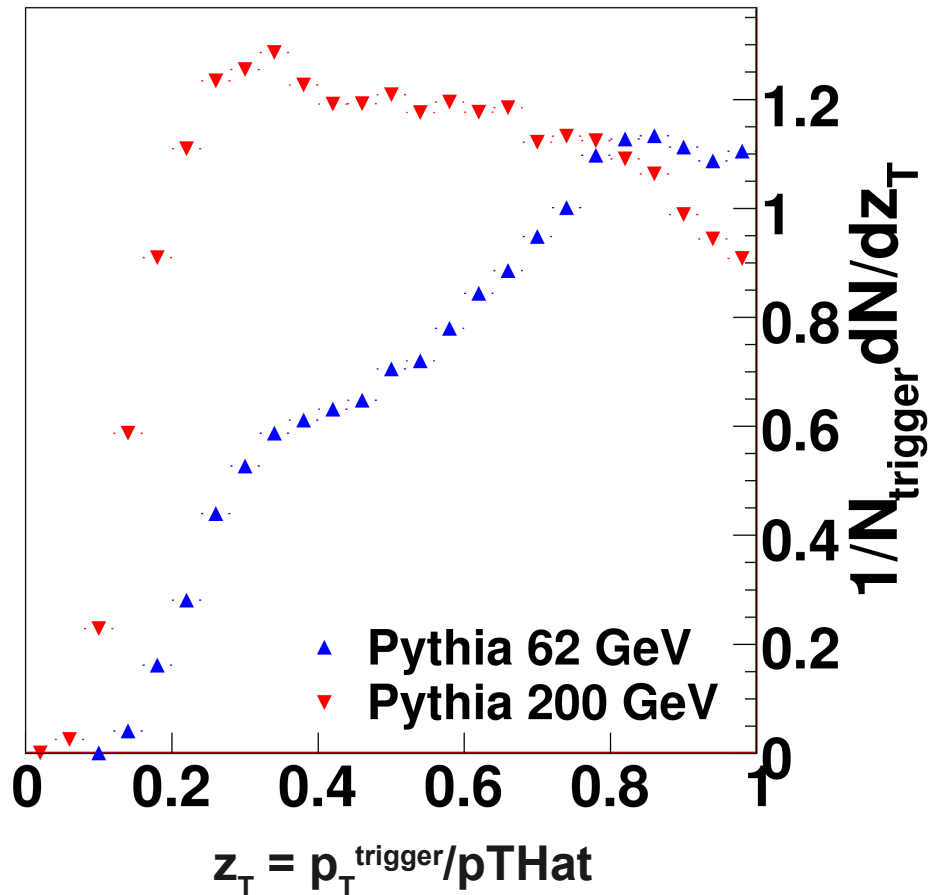
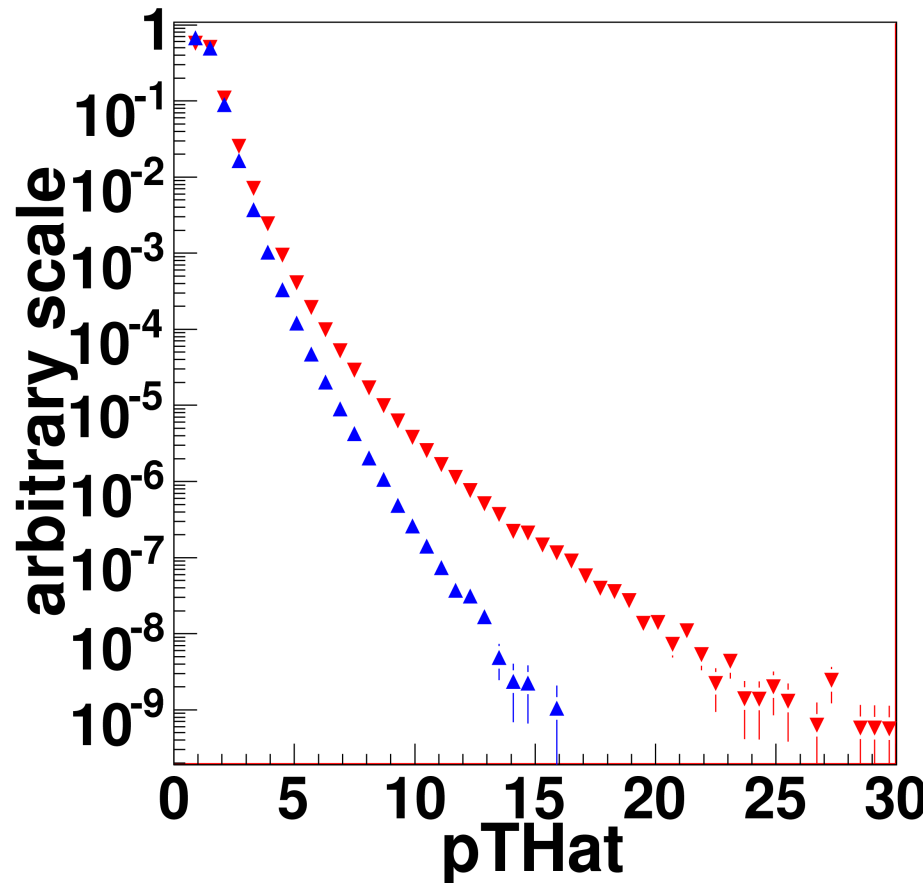
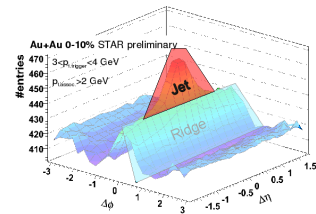
Pythia comparisons



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

$p_{T\text{HatMin}}$ = the parameter in Pythia for the minimum transverse momentum in the hard subprocess

Pythia comparisons

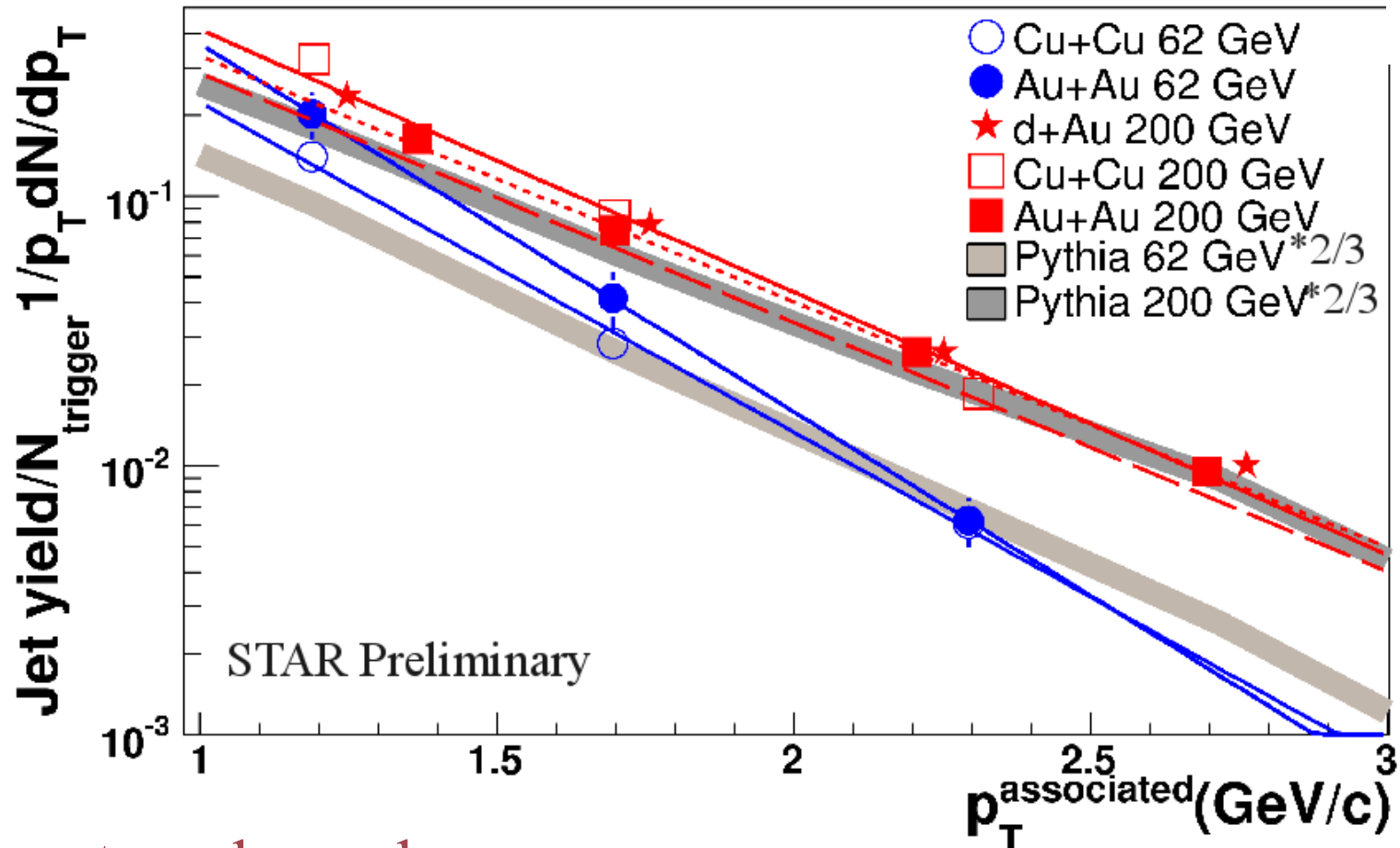
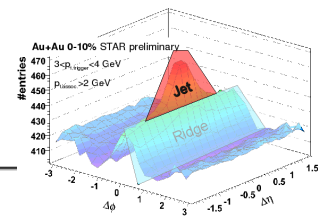


- What can Pythia tell us?

- Higher z_T (lower jet energy) in 62 GeV for same p_T^{trigger}

p_{THatMin} = the parameter in Pythia for the minimum transverse momentum in the hard subprocess

p_T associated dependence



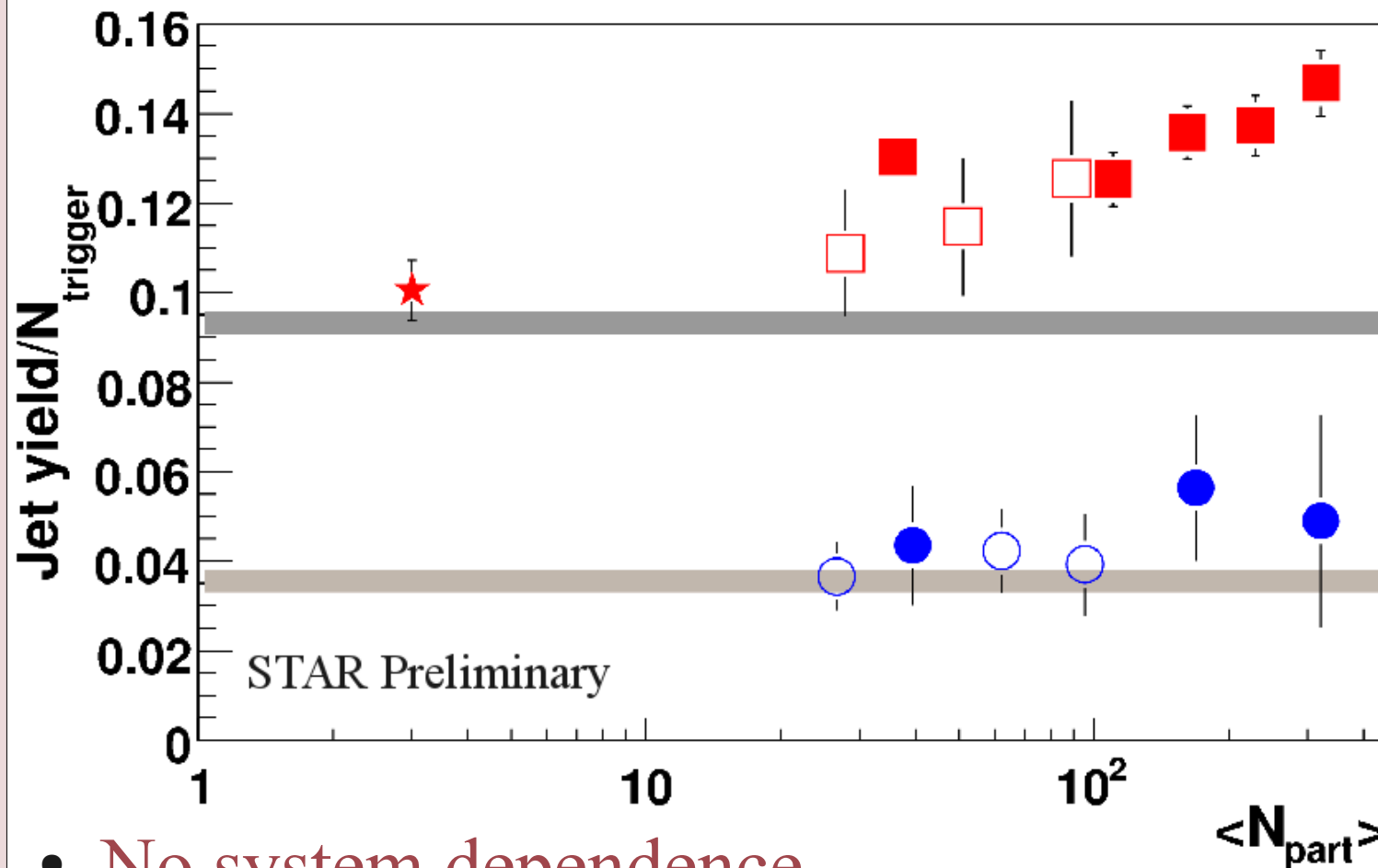
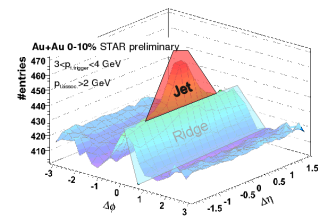
- No system dependence
- Pythia 8.1 slightly harder than data
- Diverges slightly from Pythia 8.1 at lower p_T associated

Inverse slope parameter

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

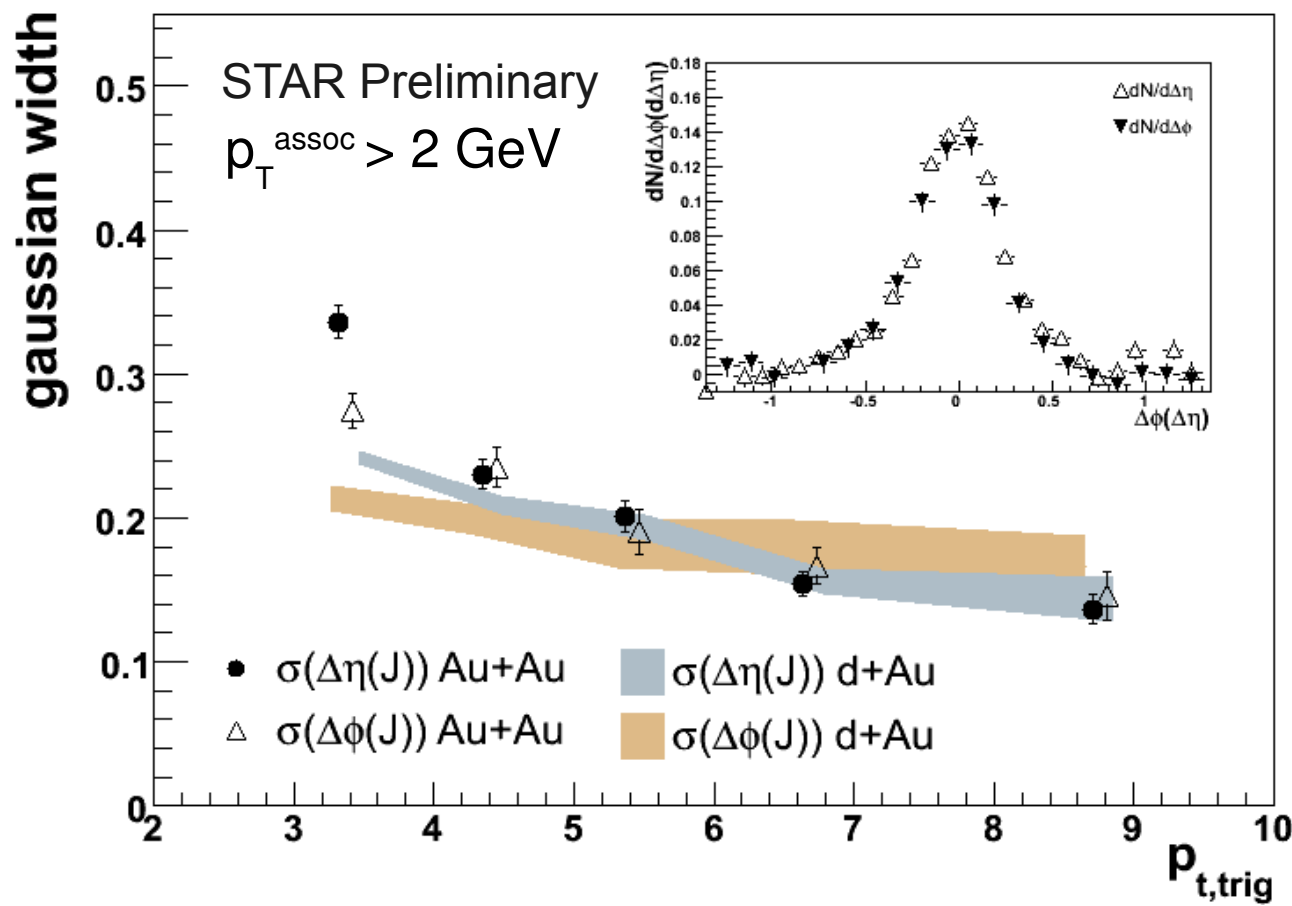
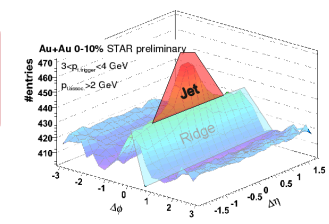
Statistical errors only

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 ?

Jet-like peak width in central Au+Au

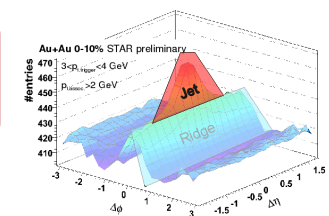


Putschke
 WWND08

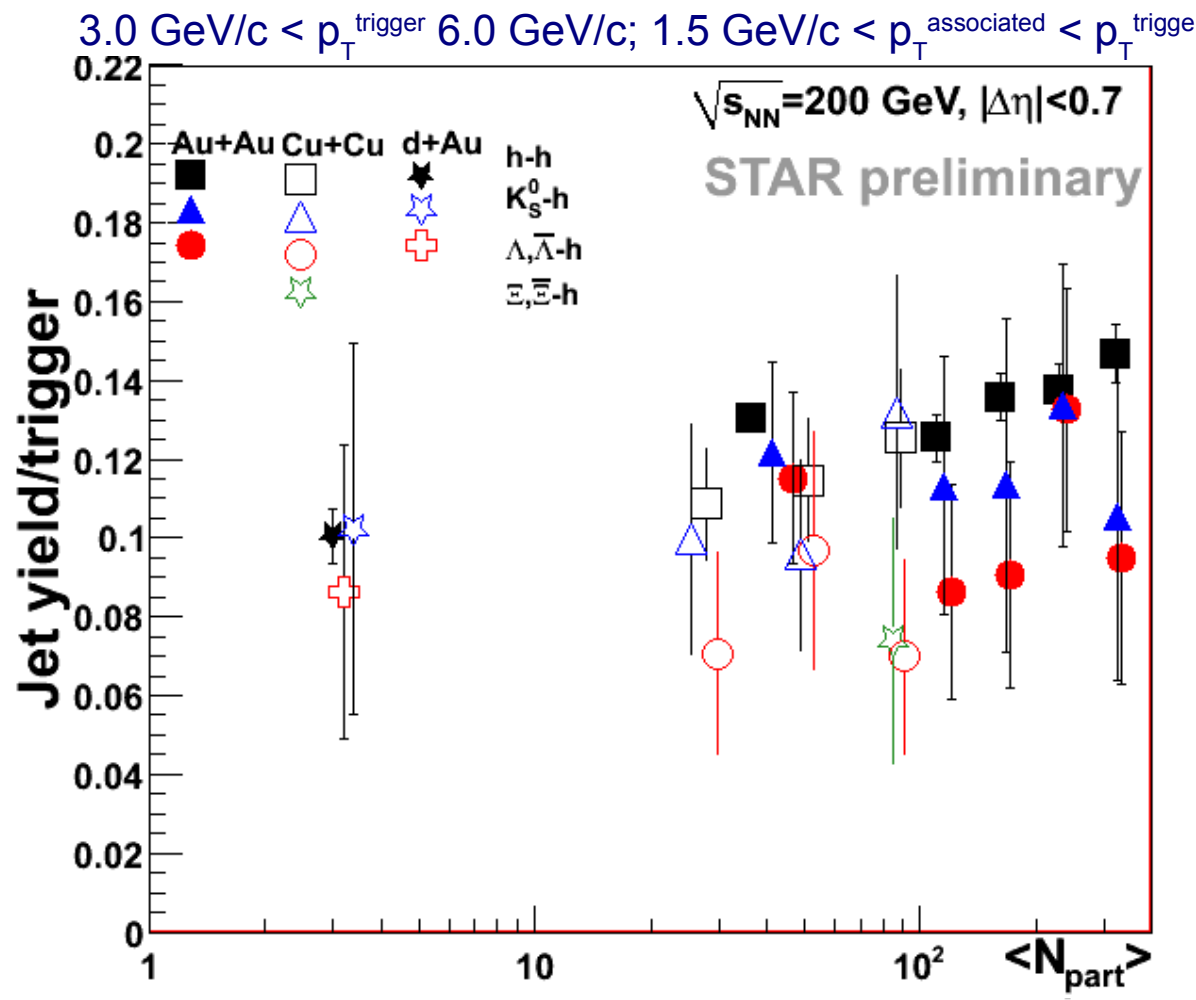
- *Jet* peak symmetric in $\Delta\eta$ and $\Delta\phi$ for $p_T^{\text{trigger}} > 4 \text{ GeV}$ and comparable to d+Au
- *Jet* peak asymmetric in $\Delta\eta$ for $p_T^{\text{trigger}} < 4 \text{ GeV}$ and significantly broader than d+Au

Particle type dependence

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



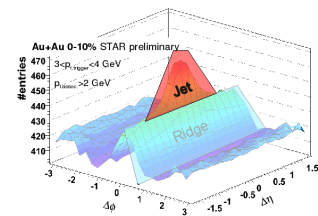
*Jet yield -
 No trigger type
 dependence*



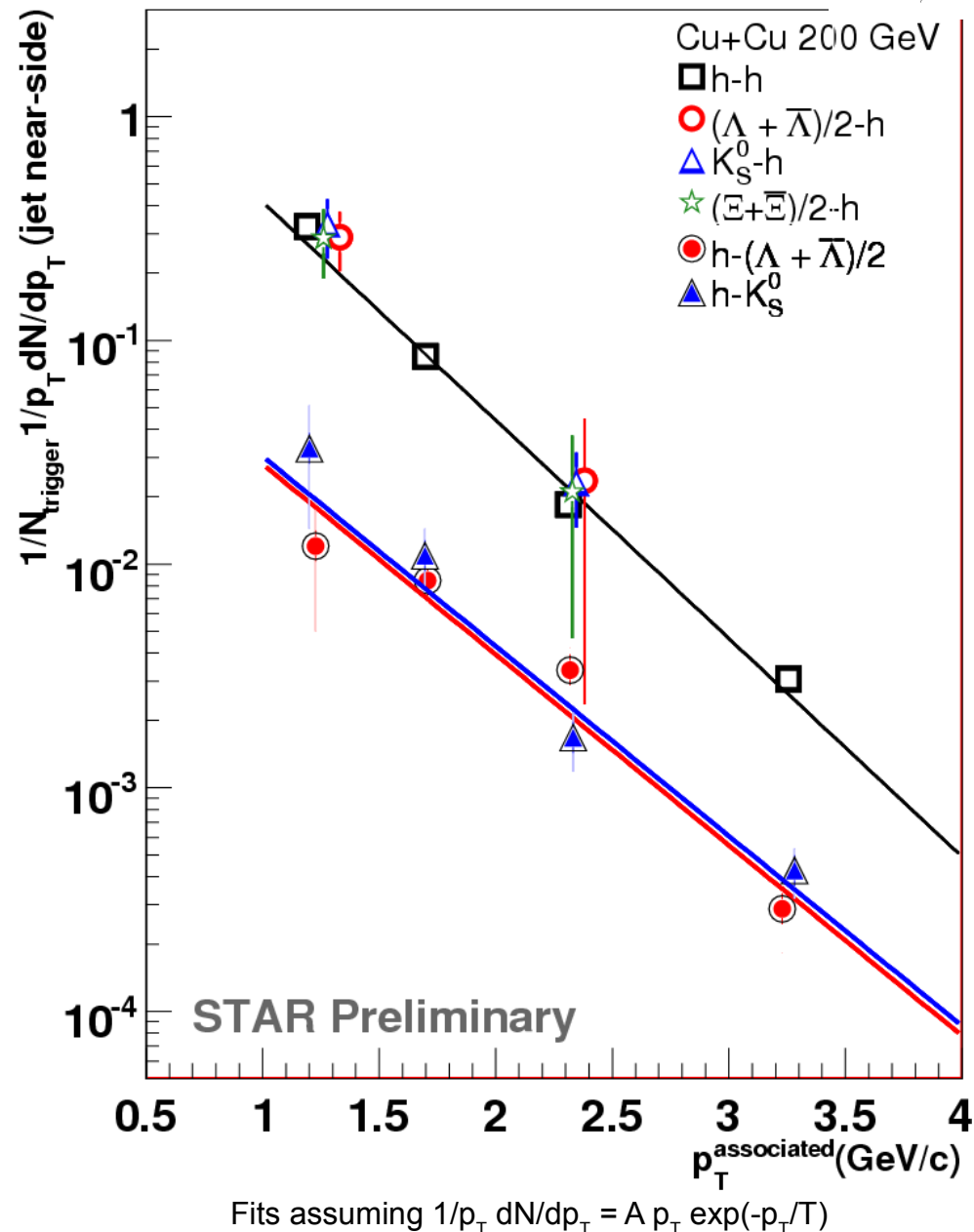
d+Au, Au+Au $\sqrt{s_{NN}} = 200$ GeV from nucl-ex/0701047
 Cu+Cu $\sqrt{s_{NN}} = 200$ GeV from SQM2007

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

p_T -distribution of associated particles



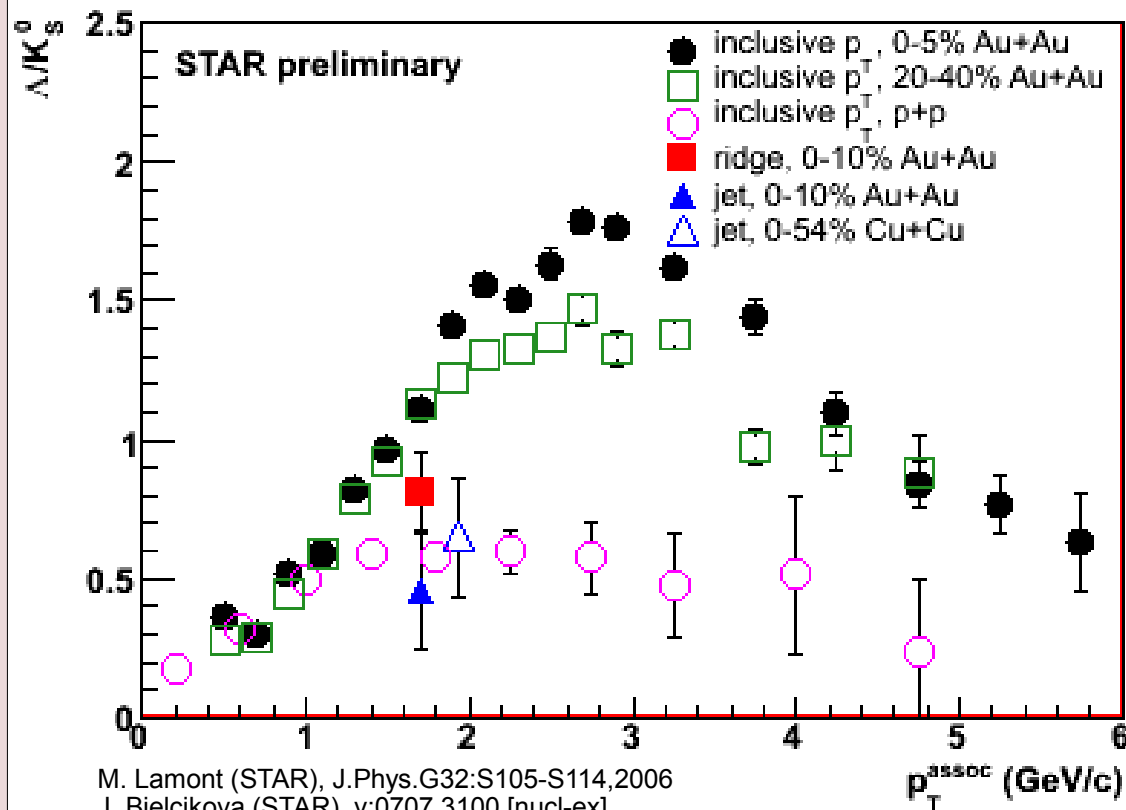
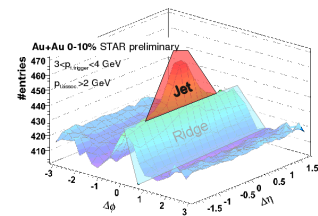
- Associated baryons and mesons in *Jet* similar



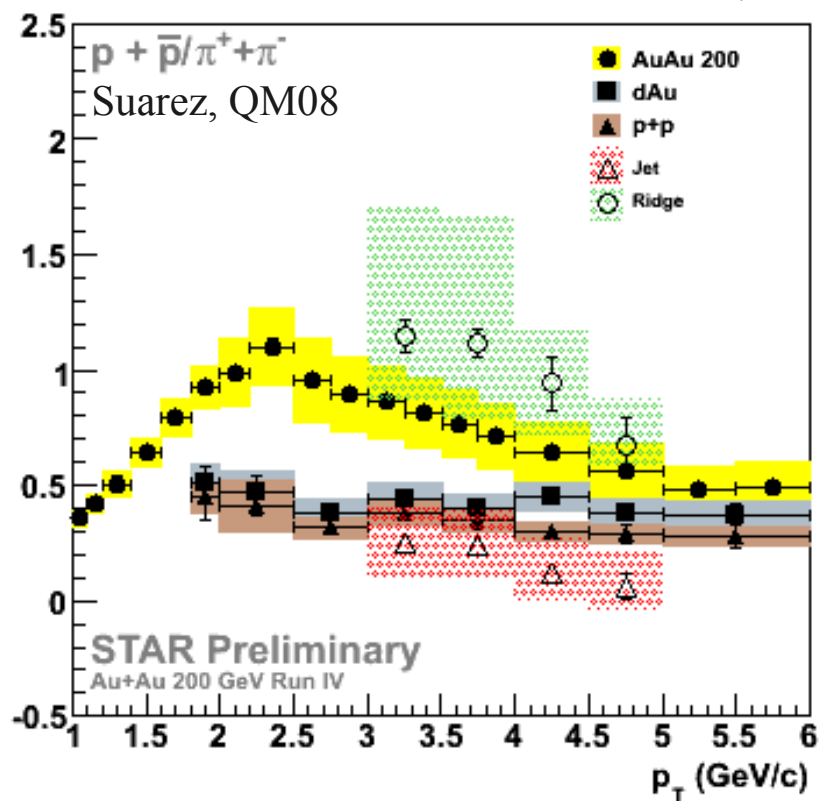
$\sqrt{s_{NN}} = 200$ GeV Au+Au 0-10% Cu+Cu: 0-54%
 $\sqrt{s_{NN}} = 62$ GeV Au+Au 0-80% Cu+Cu: 0-60%

nucl-ex/0701047, SQM2007

Ridge composition

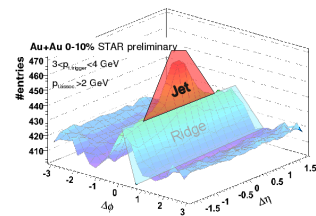


M. Lamont (STAR), J.Phys.G32:S105-S114,2006
 J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
 C. Nattrass (STAR), arXiv:0804.4683/nucl-ex



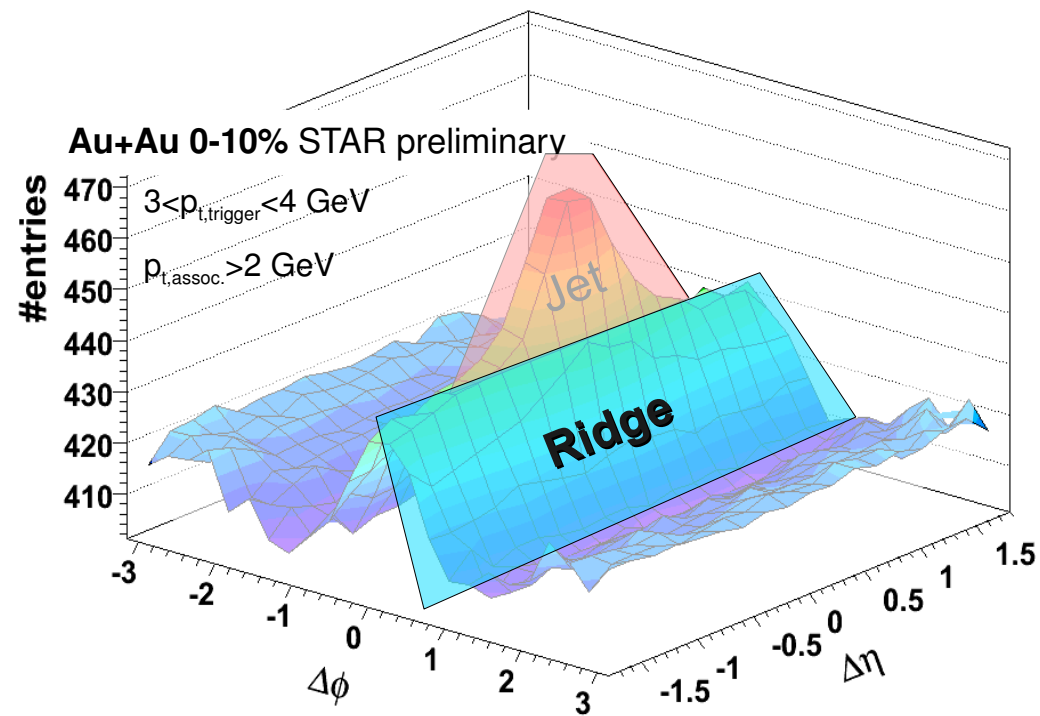
- Baryon/meson ratios in *Jet* in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles

Conclusions: *Jet*



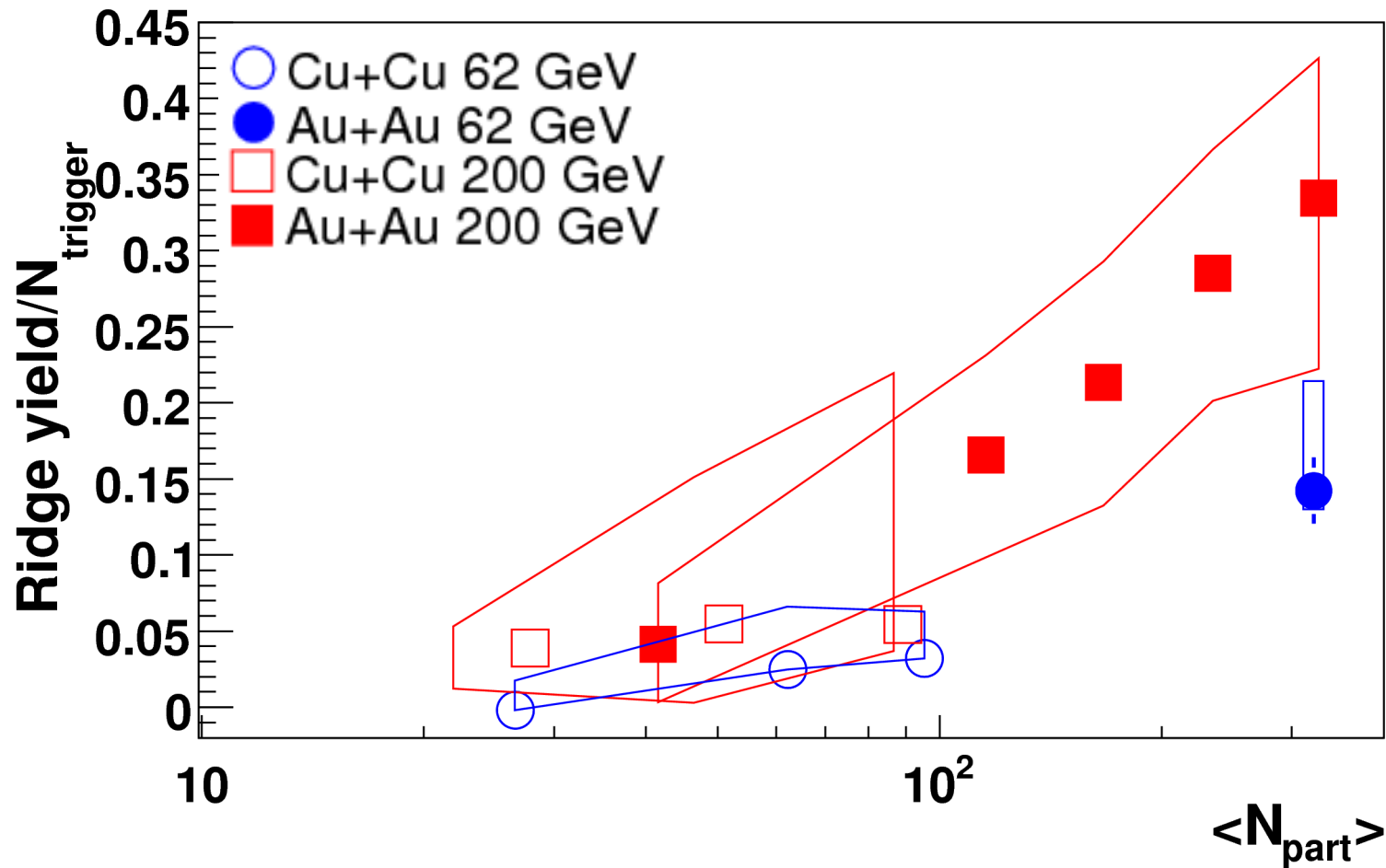
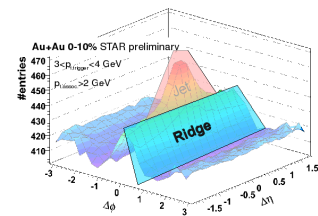
- Pythia describes data well
 - Scaling factor needed but Pythia 8.1 is not as tuned as earlier versions
 - Energy dependence in *Jet* is pQCD effect
 - Trends for p_T^{trigger} , p_T^{assoc} dependence right
- Particle ratios similar to p+p
 - *Jet* production mechanism dominated by fragmentation
 -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



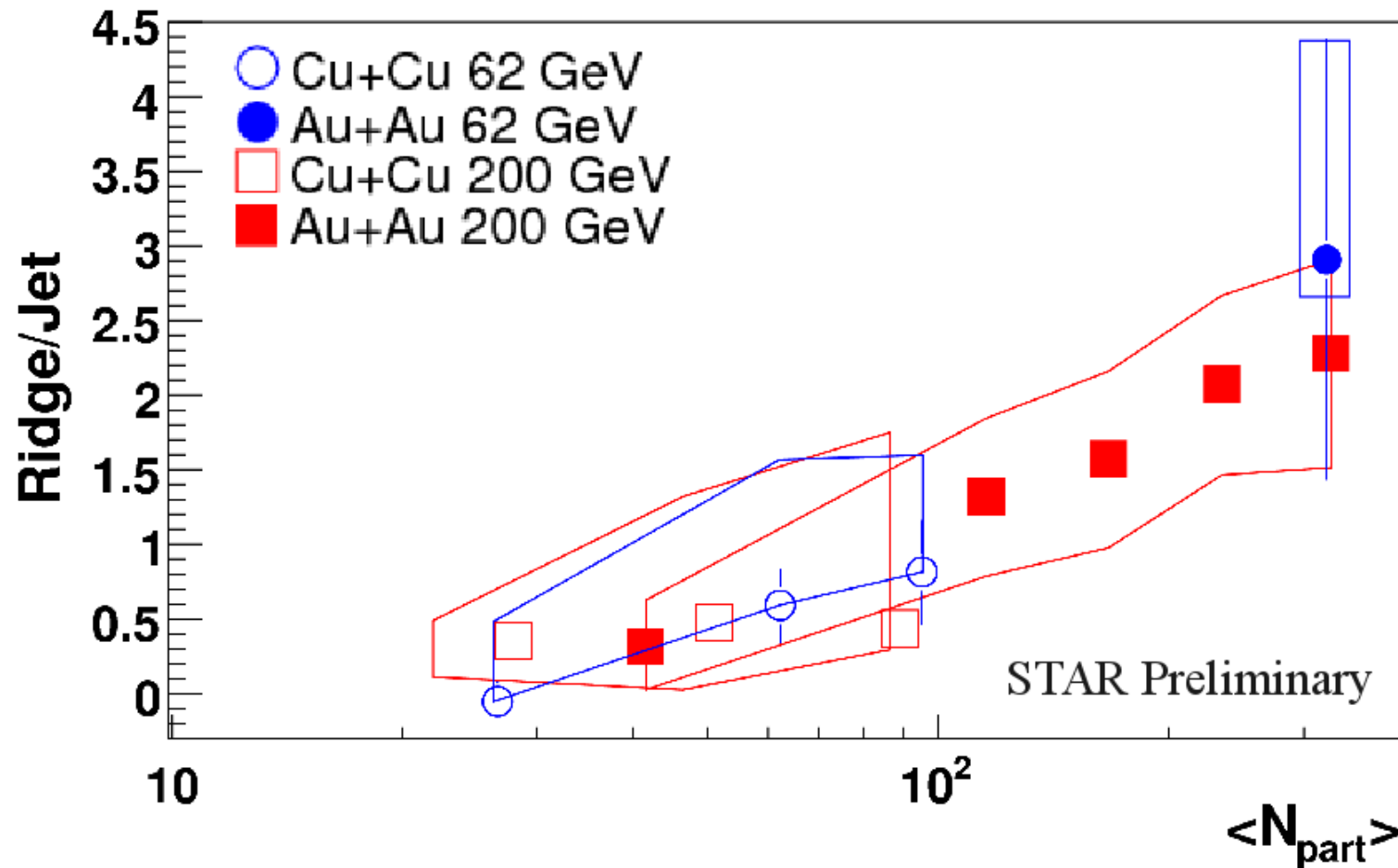
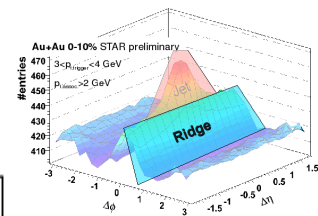
Energy and System dependence

Ridge vs N_{part}



- No system dependence at given N_{part}

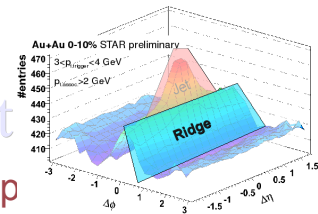
Ridge vs N_{part}



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

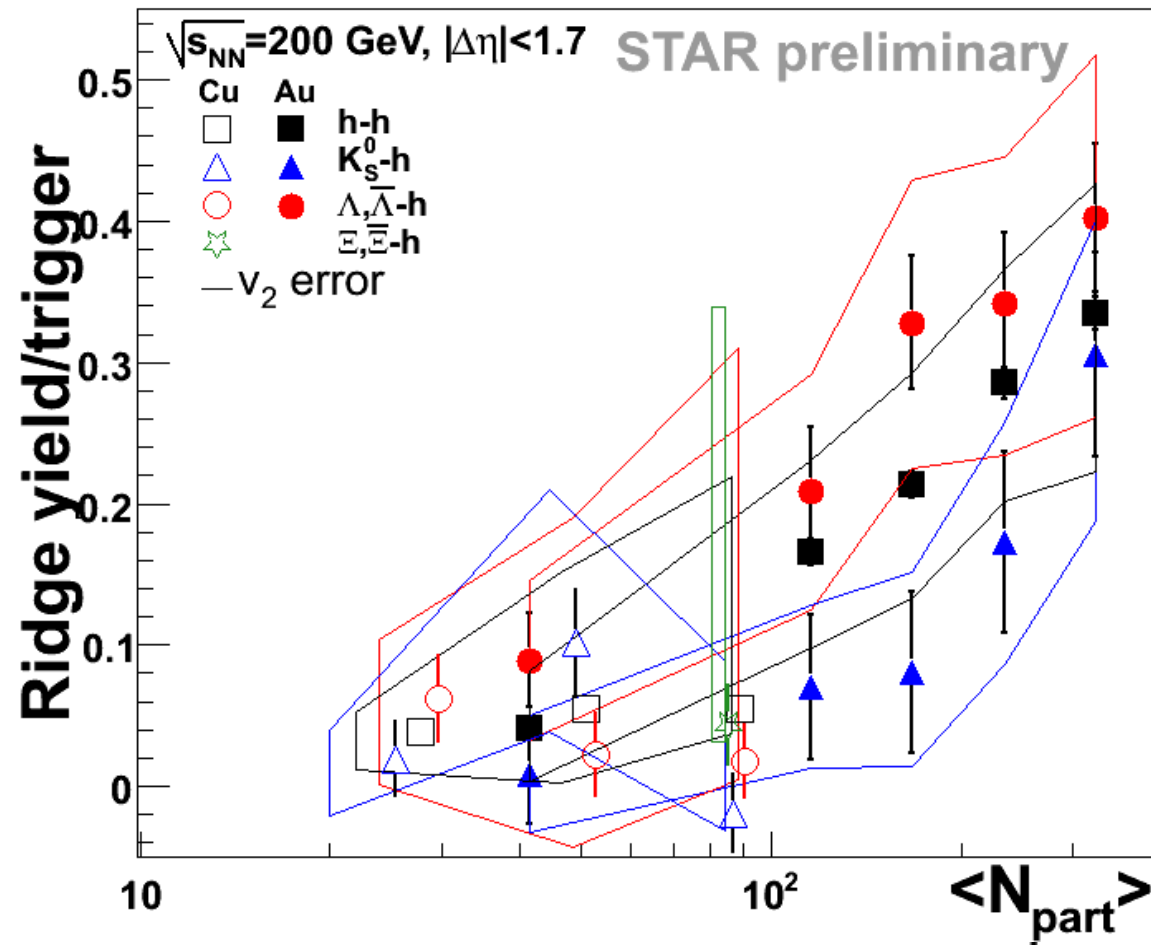
Particle type dependence

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



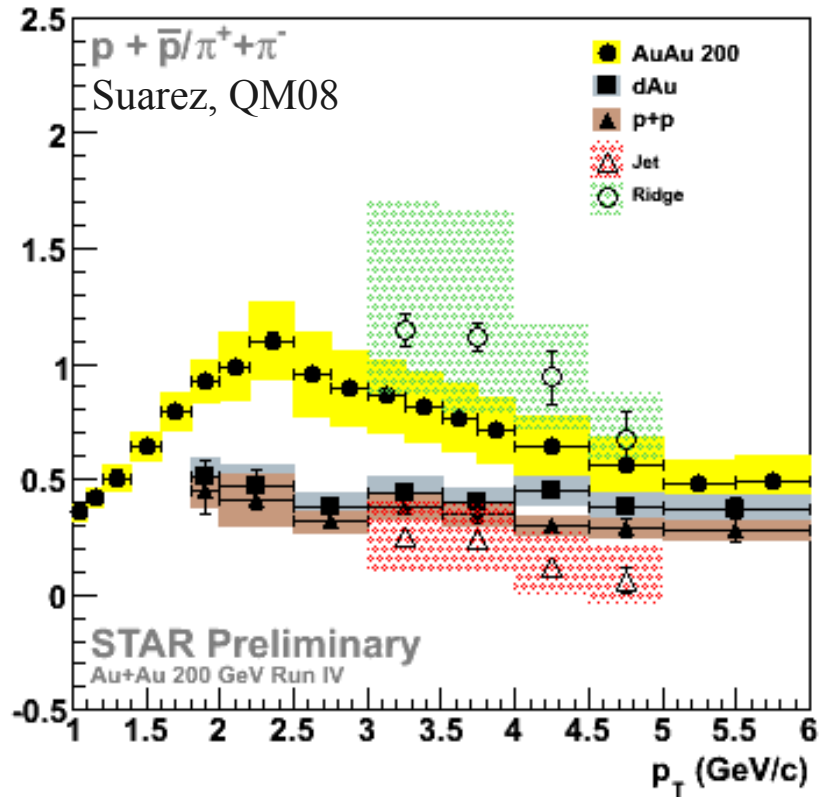
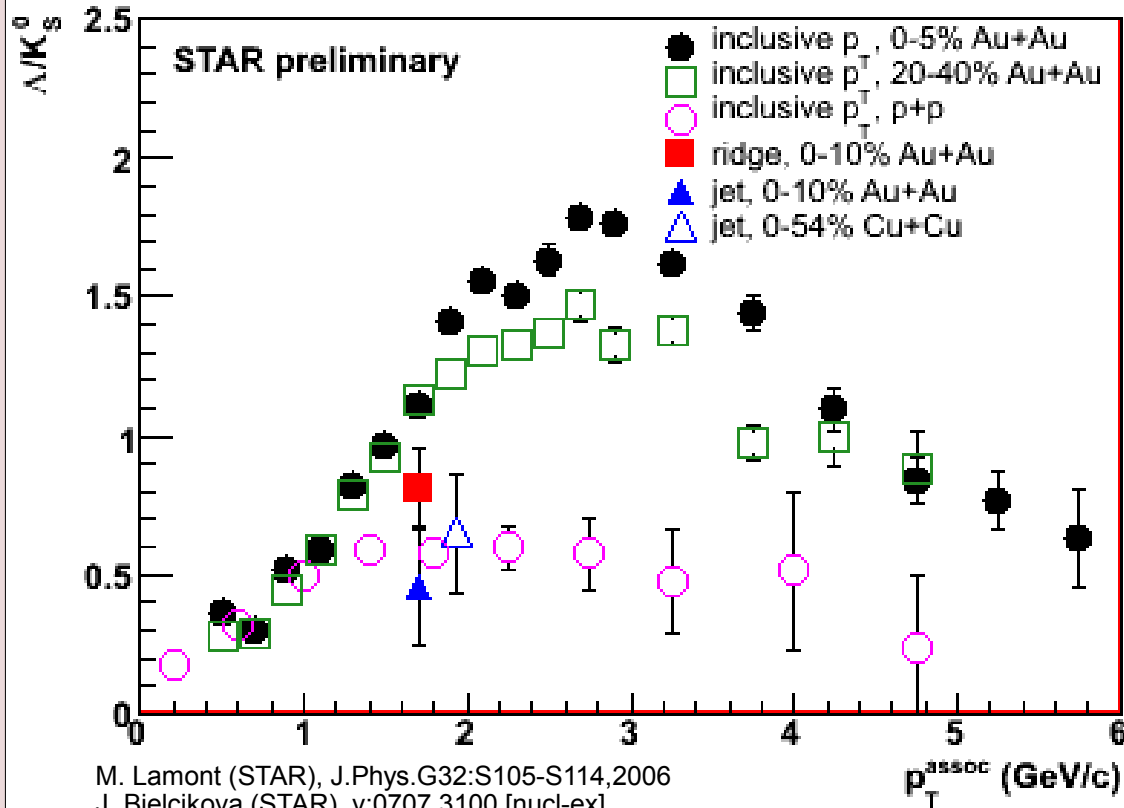
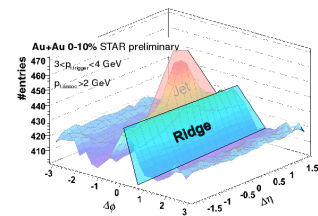
$3.0 \text{ GeV}/c < p_T^{\text{trigger}} < 6.0 \text{ GeV}/c$; $1.5 \text{ GeV}/c < p_T^{\text{associated}} < p_T^{\text{trigger}}$

*Ridge yield -
No trigger type
dependence*



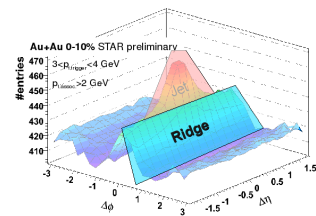
Au+Au $\sqrt{s_{NN}}=200 \text{ GeV}$ from nucl-ex/0701047
 Cu+Cu $\sqrt{s_{NN}}=200 \text{ GeV}$ from SQM2007
 Data points at same N_{part} offset for visibility

Ridge composition



- 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
- *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 \rightarrow stronger bias towards unmodified/surface jets
 - Could explain smaller Ridge yield in 62 GeV

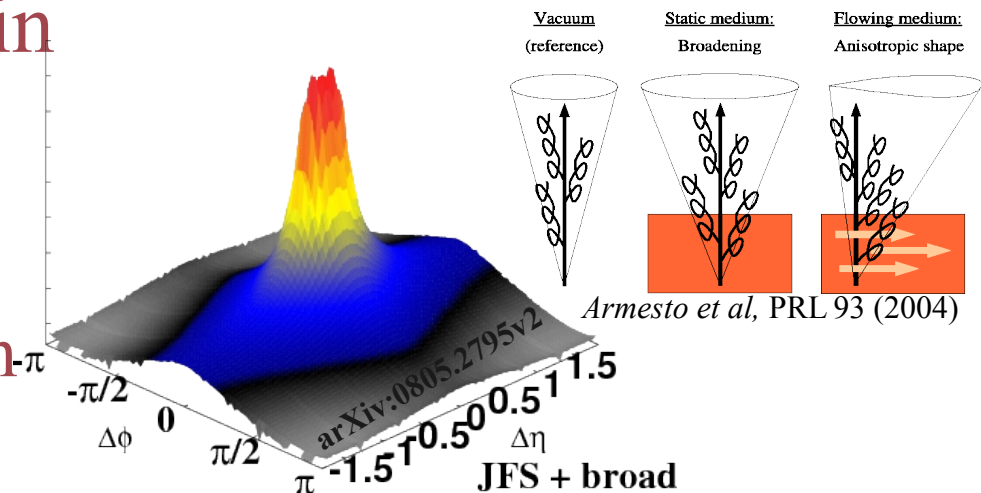
Comparisons to theories

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*



- Interaction of jet+medium

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

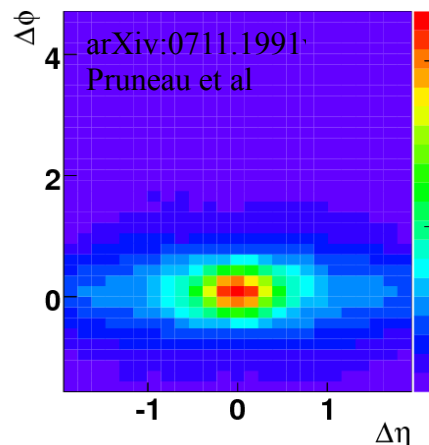
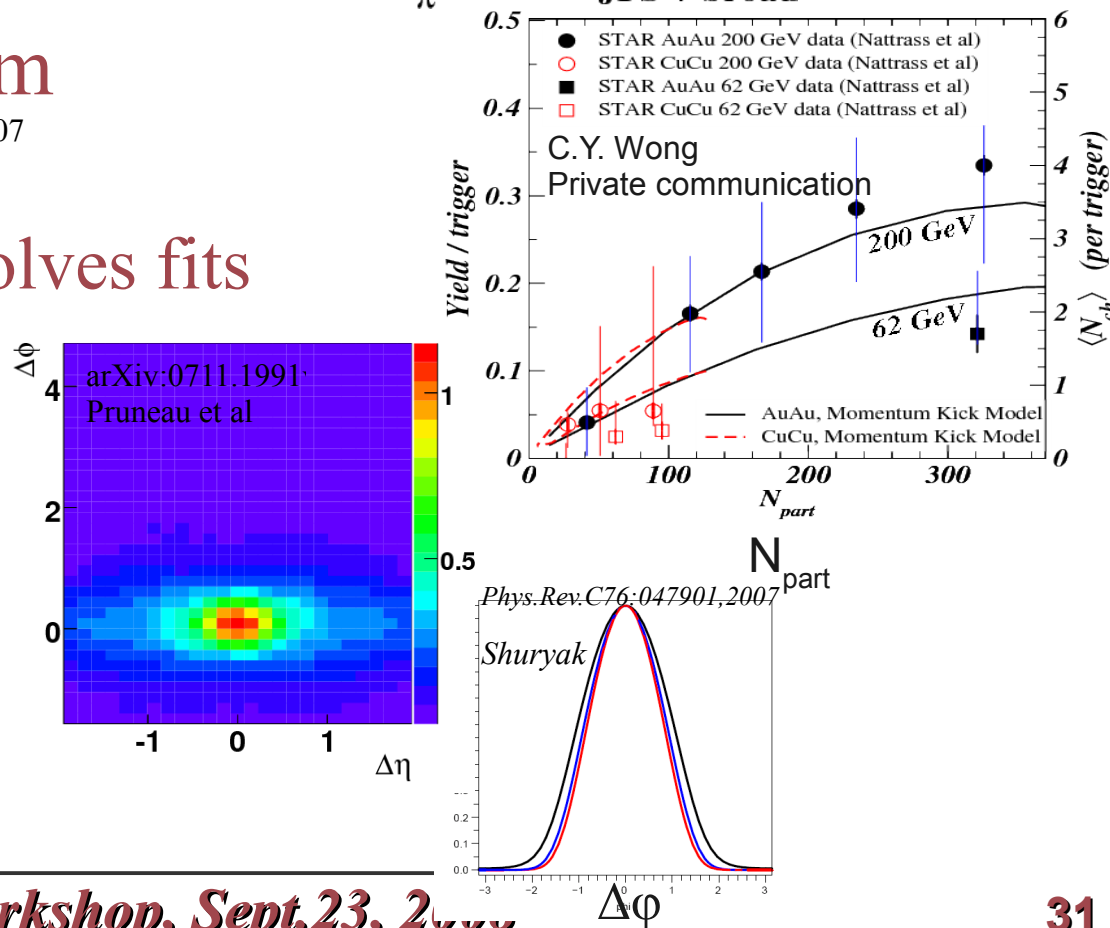
- Agrees with data but involves fits to the data

- 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

→ **No preferred model**



Conclusions

- Most of the experimental data have caveats and large systematic errors...
...but there's a lot of data
- The *Jet*
 - Has nearly the same shape in all systems (d+Au, Au+Au, Cu+Cu) and is roughly independent of centrality
 - Has the energy dependence we would expect in p+p
 - Is roughly independent of reaction plane
 - Has the same particle composition as p+p
 - Has the p_T^{trigger} dependence we would expect in p+p
 - Has the p_T^{assoc} dependence we would expect in p+p
- The *Jet* is consistent with vacuum fragmentation

Conclusions

- *The Ridge*
 - Is roughly independent of $\Delta\eta$, with some hints it may be a broad peak
 - Has a spectrum similar to the bulk, but a little harder
 - Has a particle composition similar to the bulk
 - At least at low p_T^{assoc} extends to $\Delta\eta = 4$
 - Persists to high p_T^{trigger} , with little dependence on p_T^{trigger}
 - Contains a few GeV of energy
 - Is dominantly in-plane
 - Grows with centrality
- The data powerful enough to constrain the models well
- Qualitative comparisons can constrain models
- Models need to catch up!

Some speculation...

- *Jet* looks like fragmentation
 - Room for slight modifications – slight increase in yield with centrality, differences in $\Delta\phi$ & $\Delta\eta$ width
 - Either there the fraction of triggers which comes from jets is almost independent of system and the production of the *Ridge* does not alter the *Jet* OR some *really* convenient cancellation happens – the latter isn't likely
- The picture in my head: *Ridge* formation happens at partonic stage. Partons leaving the medium fragment as usual.
 - If formation of the *Ridge* significantly alters the production of the *Jet*, how does the end up looking like vacuum fragmentation?

The way forward?

- A simple model such as Pythia can be used to interpret the effect of kinematic restrictions on p_T^{trigger} , p_T^{assoc}
- This could make calculations easier
- With insight from Pythia, perhaps models could make definitive statements on the expectations for energy and system dependence.
 - Does Jet yield increase or decrease with energy?
System size?

Backups

PHOBOS

- Coverage:

With tracking:

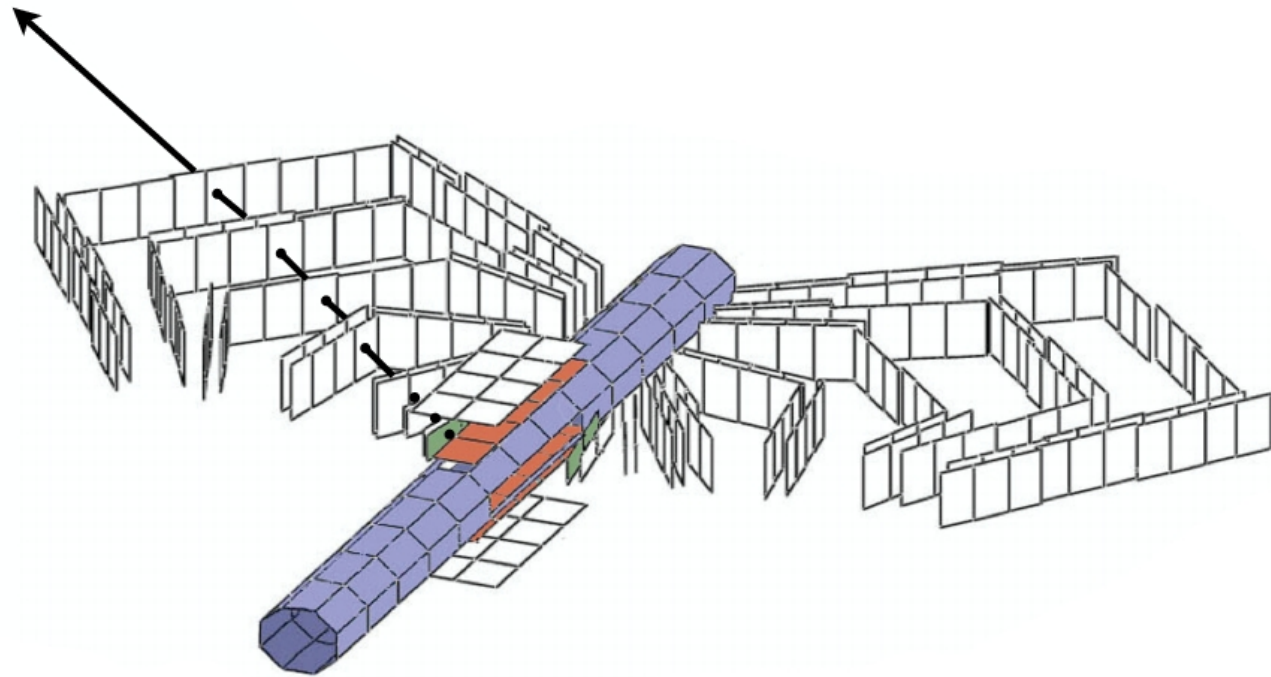
$$0 < \phi < 0.2, \times 2$$

$$0 < \eta < 1.5$$

Without tracking:

$$0 < \phi < 2\pi$$

$$-3 < \eta < 3$$

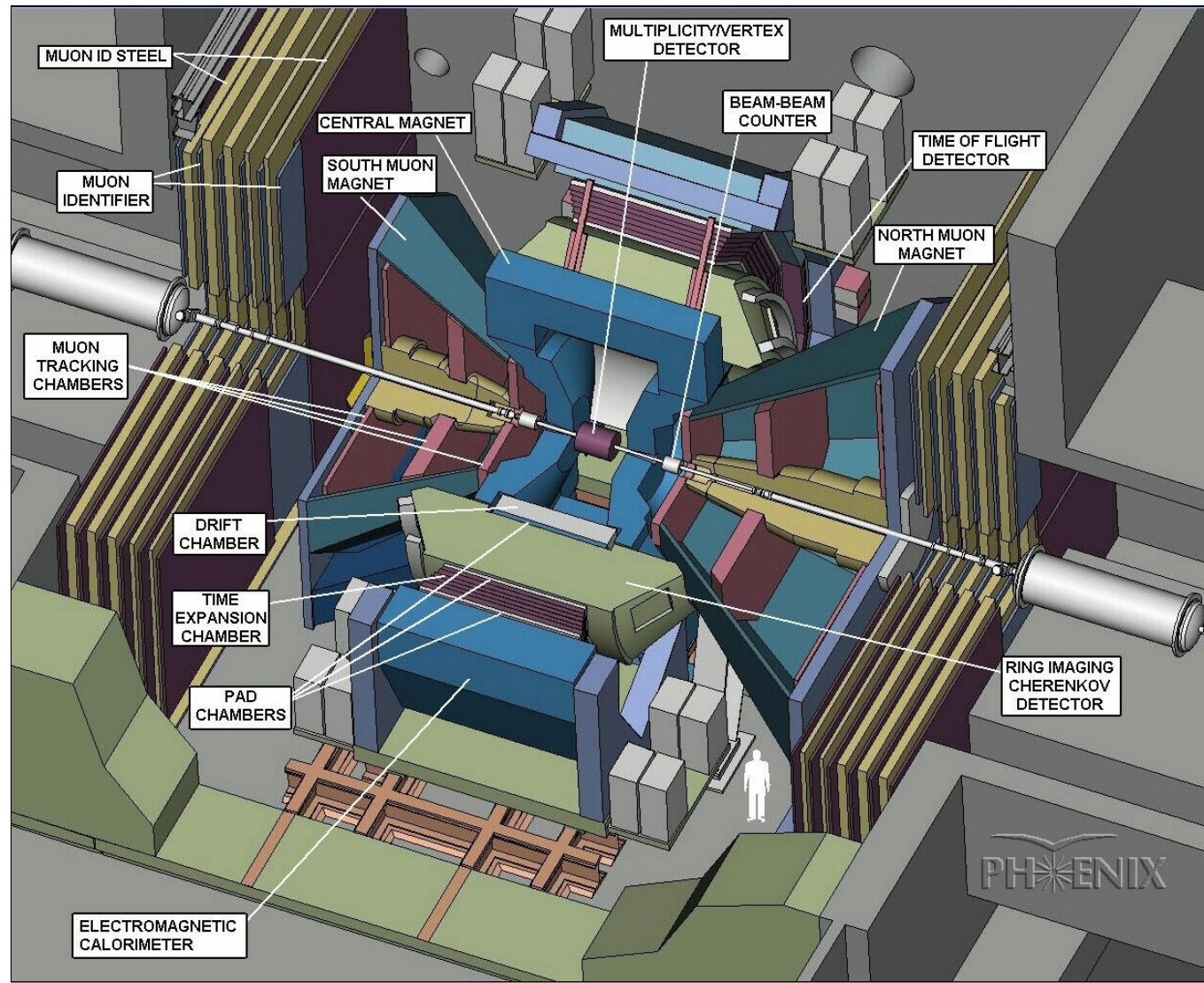


PHENIX

- Coverage:

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

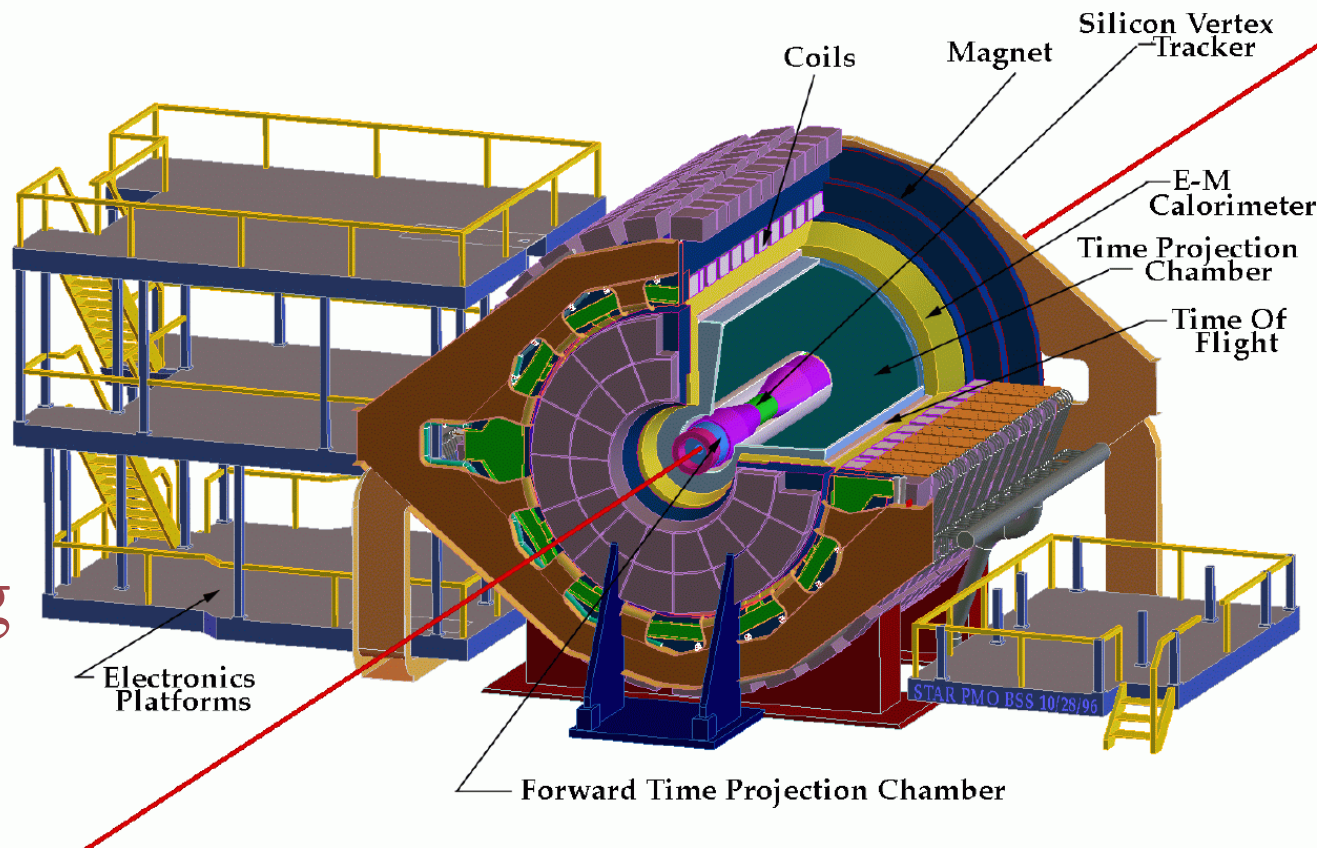
$$-0.35 < \eta < 0.35$$



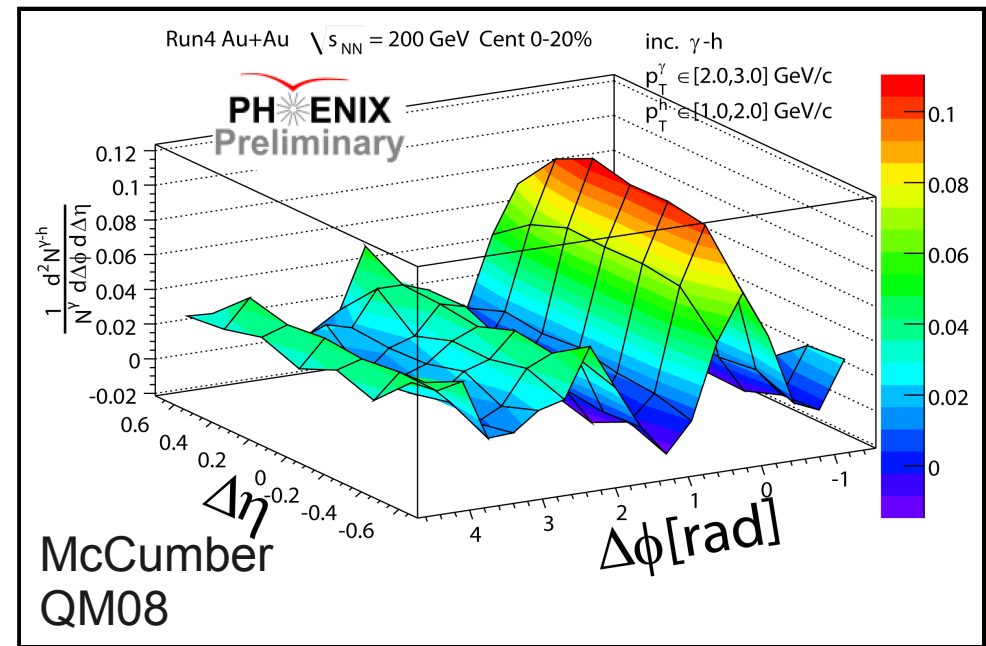
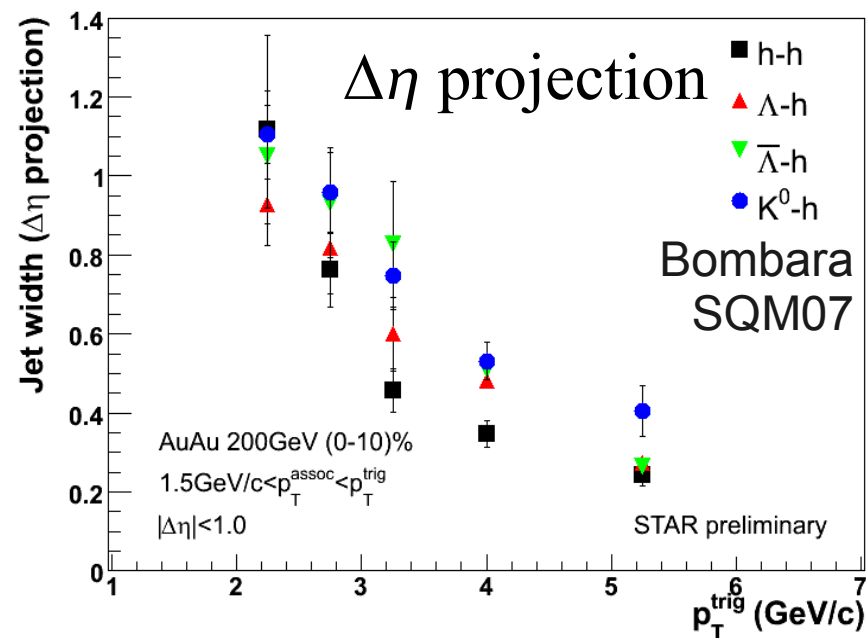
STAR

STAR Detector

- Coverage:
 $0 < \phi < 2\pi$
 $-1 < \eta < 1$
- Electromagnetic Calorimeter allows triggering



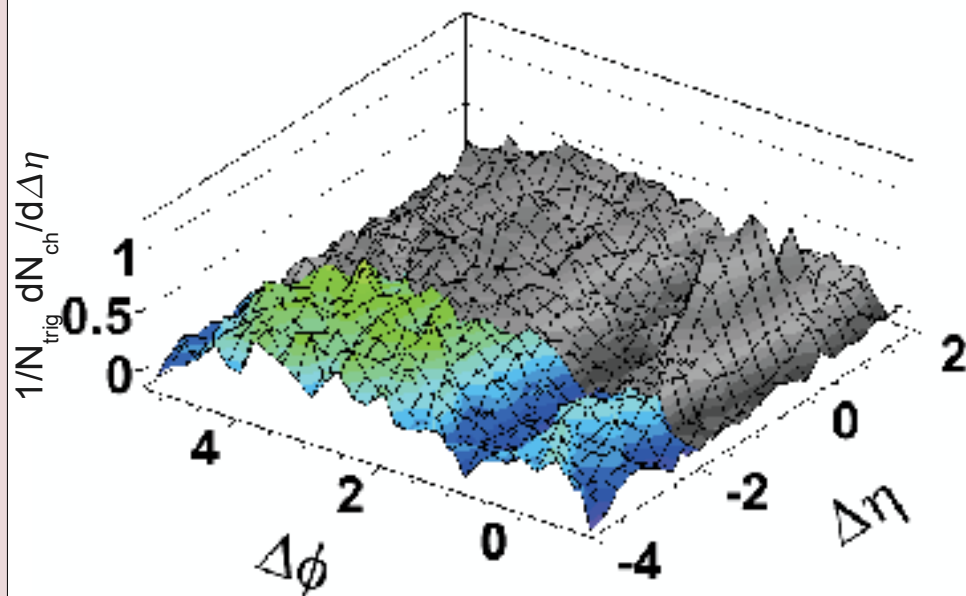
Jet-like peak width in central Au+Au



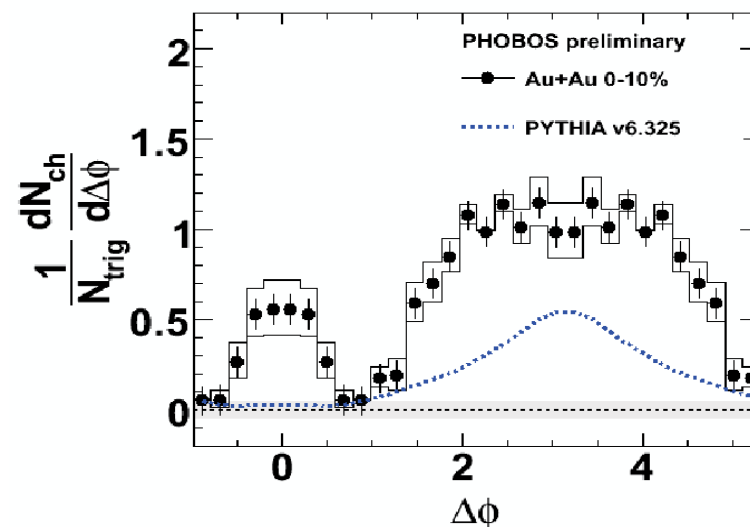
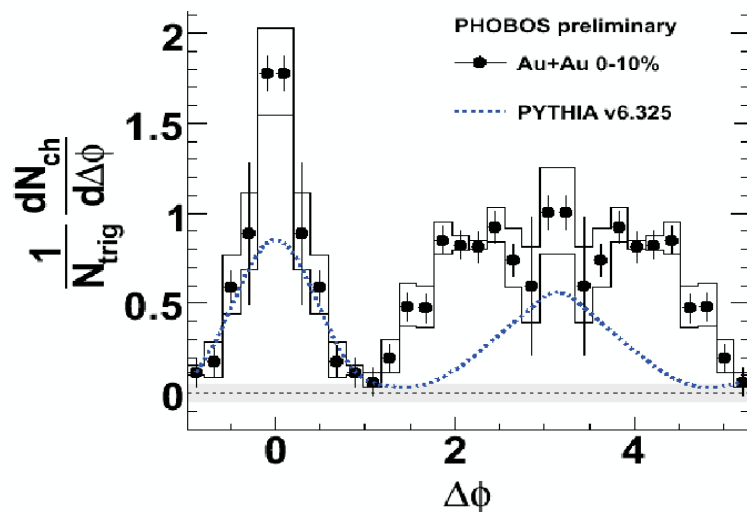
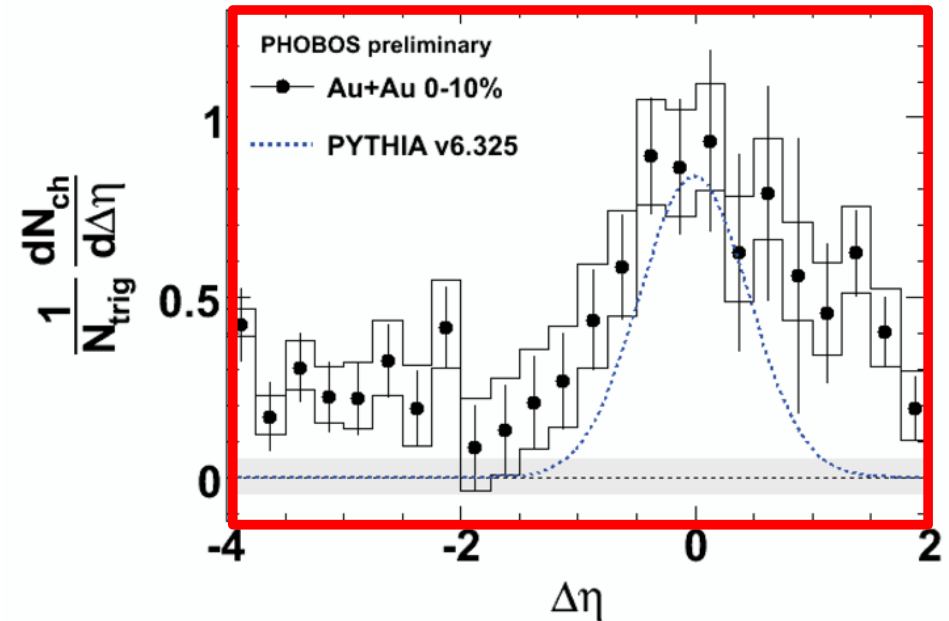
- Peak gets broader at higher p_T^{trigger} , lower p_T^{assoc}
- Width in PHENIX kinematic range close to PHENIX acceptance

Extent of Ridge in $\Delta\eta$

Au+Au 0-30% central

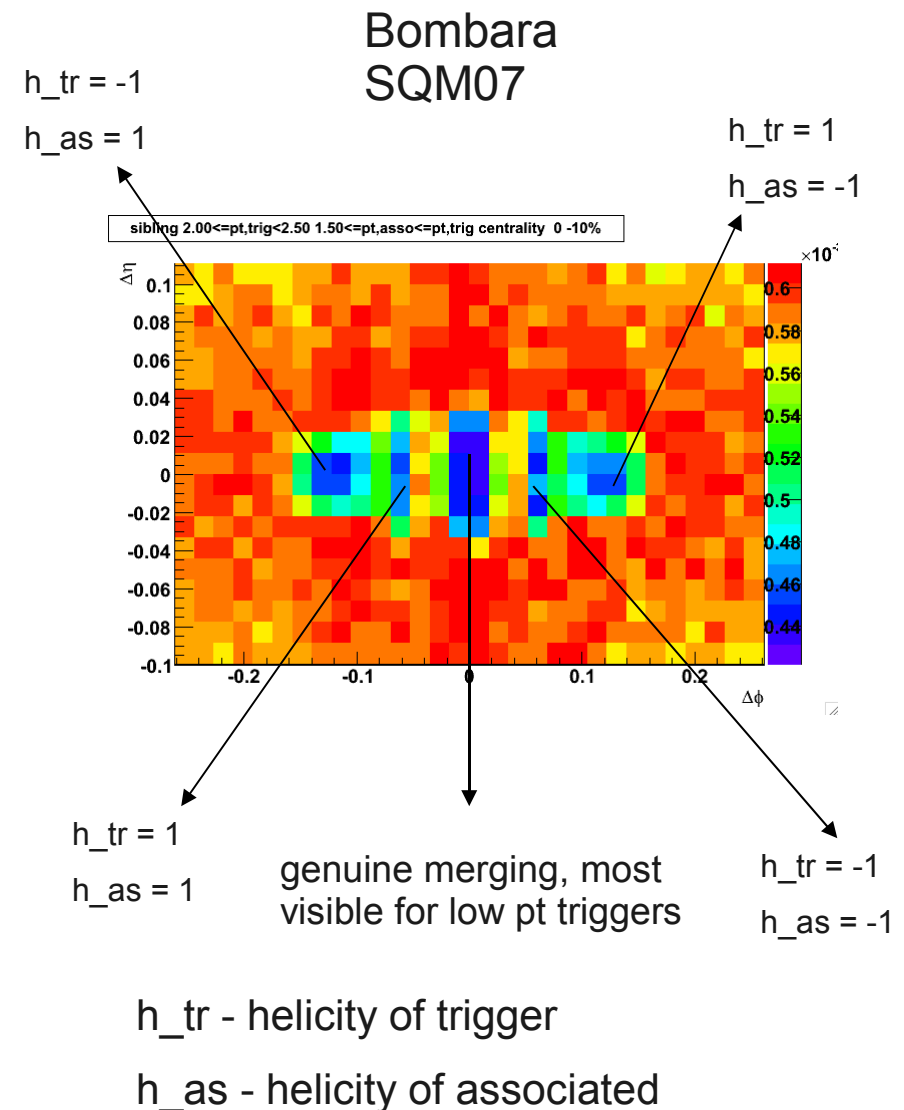


Wenger QM08



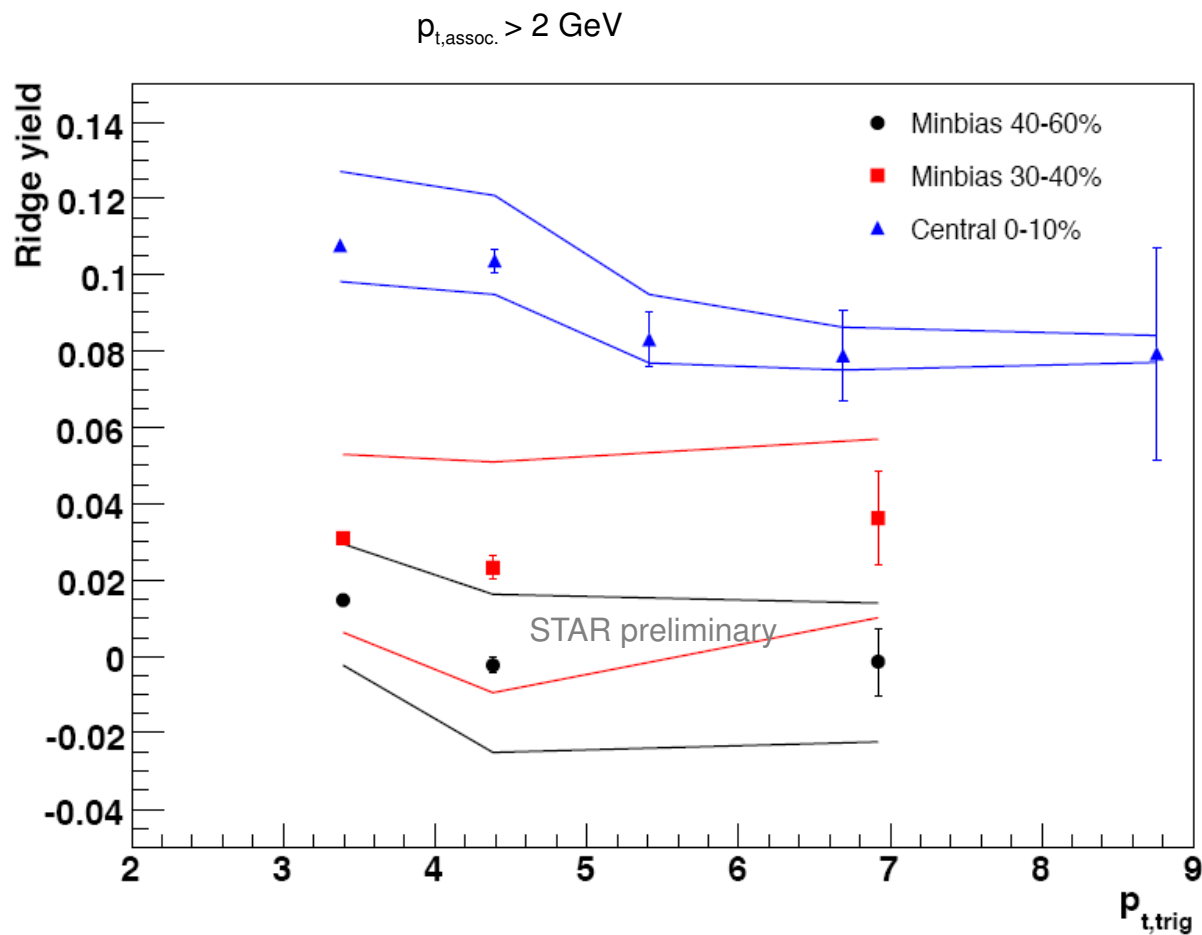
Track merging correction

- 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



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

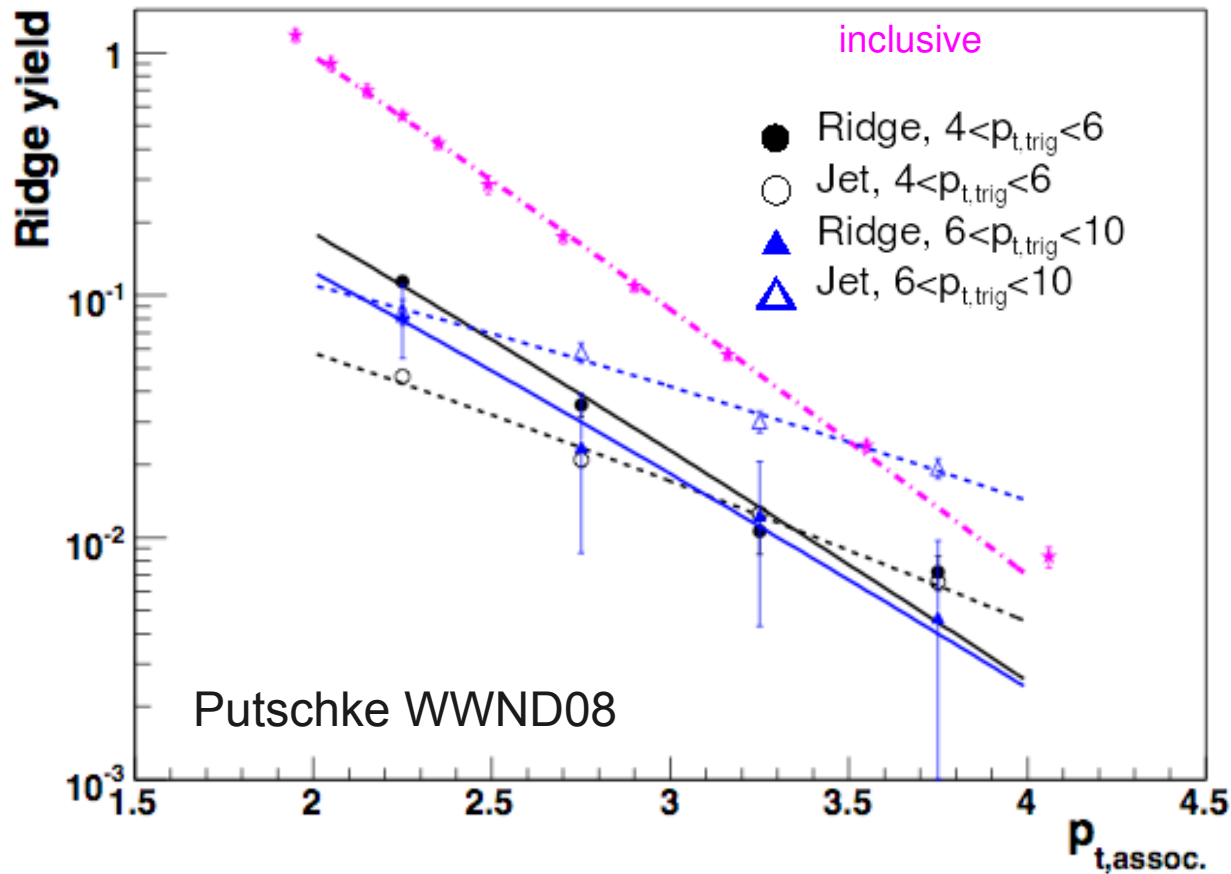
Ridge yield vs. pt, trig in Au+Au



Putschke
WWND08

- Ridge yield persists to highest trigger pt \Rightarrow correlated with jet production

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

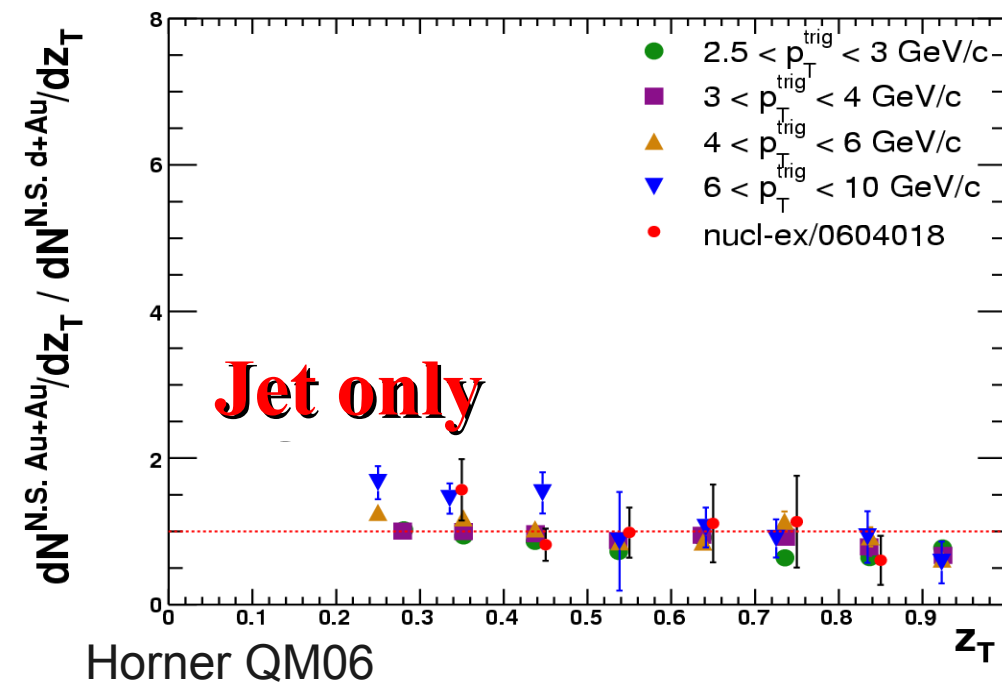
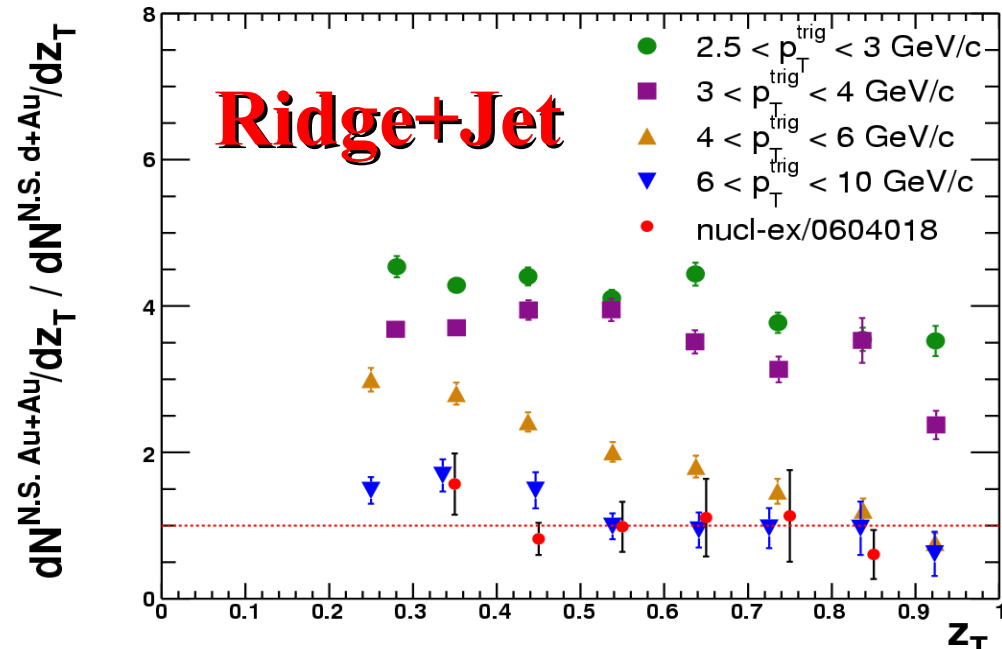
Fragmentation functions

- Measure hadron triggered fragmentation functions:

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

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

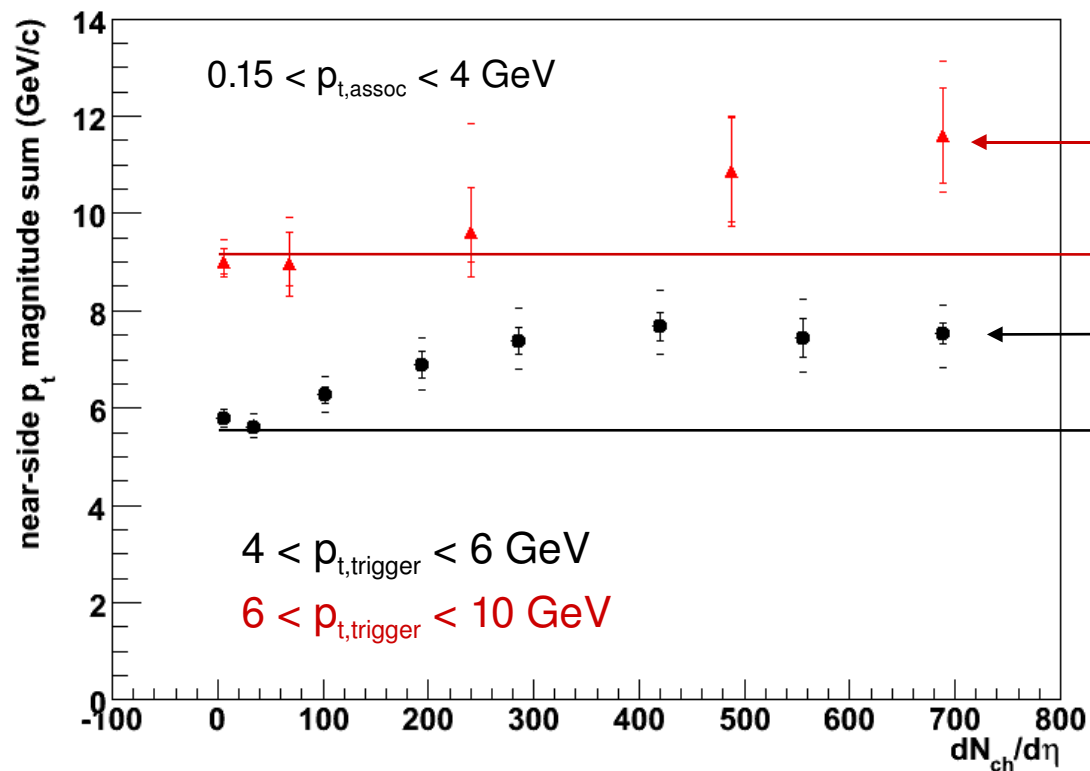
- *Jet+Ridge*: $D^{h1,h2}(z_T)$ different for d+Au, Au+Au
- *Jet only*: $D^{h1,h2}(z_T)$ within errors for d+Au, Au+Au



Horner QM06

Ridge energy

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



Putschke
WWND08

} “Ridge energy”

- Applying this “2-component picture” to lower $p_{t,assoc}$

measurements:

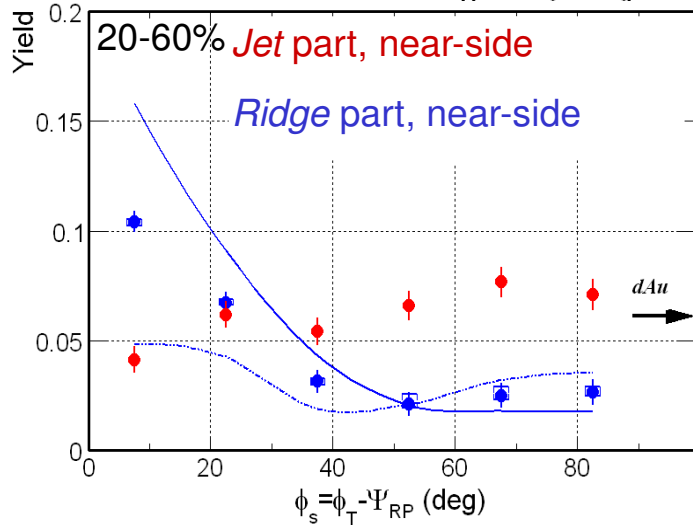
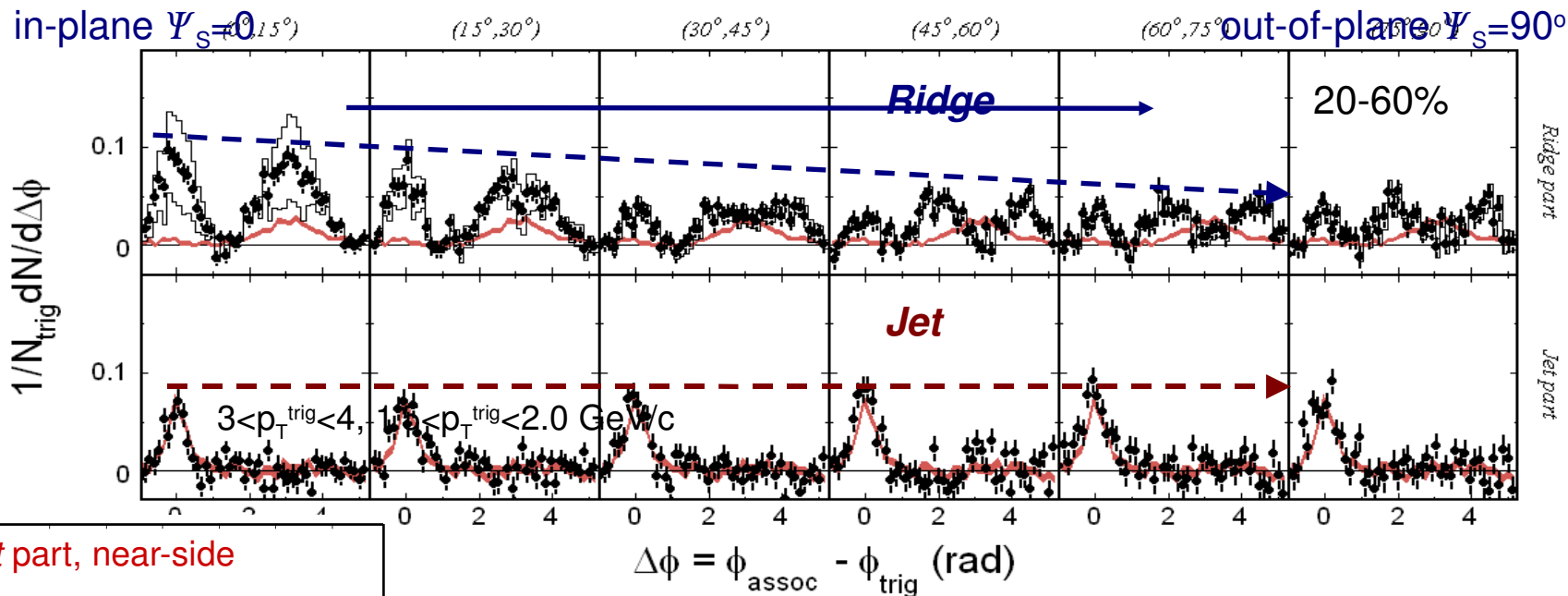
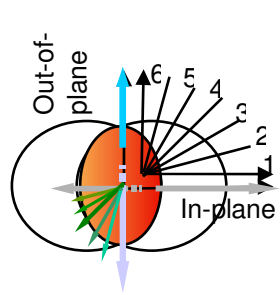
$$z_{t,jet}(Au+Au) \sim z_{t,jet}(d+Au)$$

→ subtracting p+p jet energy
} “Ridge energy” from Au+Au

- upper estimate of the energy deposit in the ridge ~ few GeV
- “Direct” measure of energy loss ?

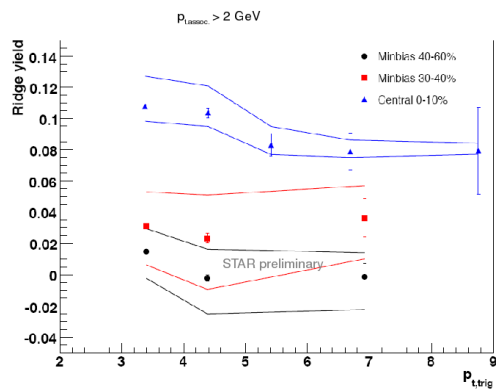
Jet/Ridge w.r.t. reaction plane

Feng QM08

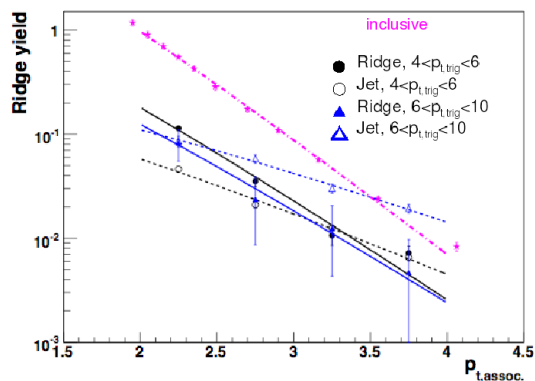


- Ridge yield decreases with φ_s . Smaller ridge yield at larger φ_s
 - Jet yield approx. independent of φ_s and comparable with d+Au
- Jet yield independent of φ_s , consistent with vacuum fragmentation after energy loss and lost energy deposited in ridge, if medium is “black” out-of-plane and more “gray” in-plane for surviving jets.

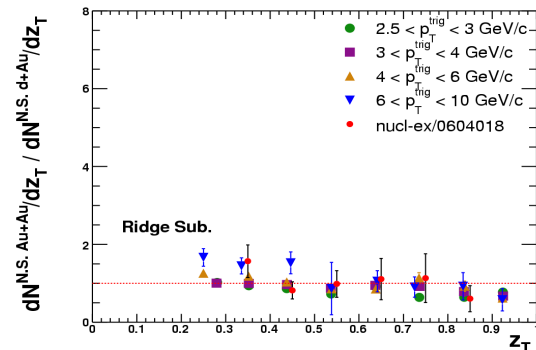
Au+Au $\sqrt{s}_{NN} = 200$ GeV Summary



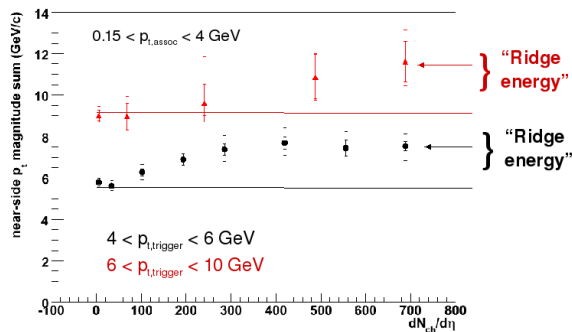
Ridge persists to high p_T^{trigger}



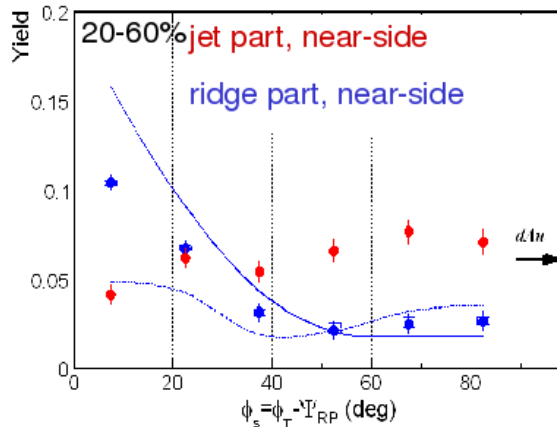
Ridge is softer than Jet, comparable to inclusive



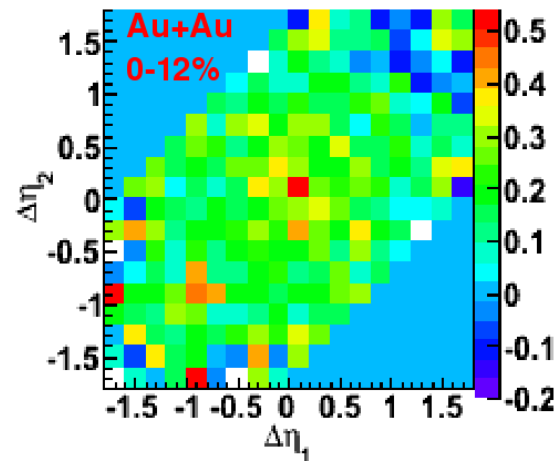
Fragmentation function with Ridge subtracted similar in d+Au, Au+Au



Ridge contains a few GeV of energy

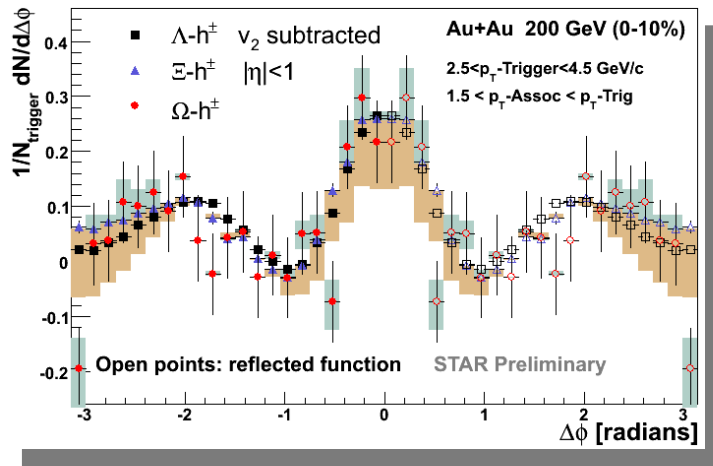


Jet almost independent of reaction plane; Ridge dominantly in plane



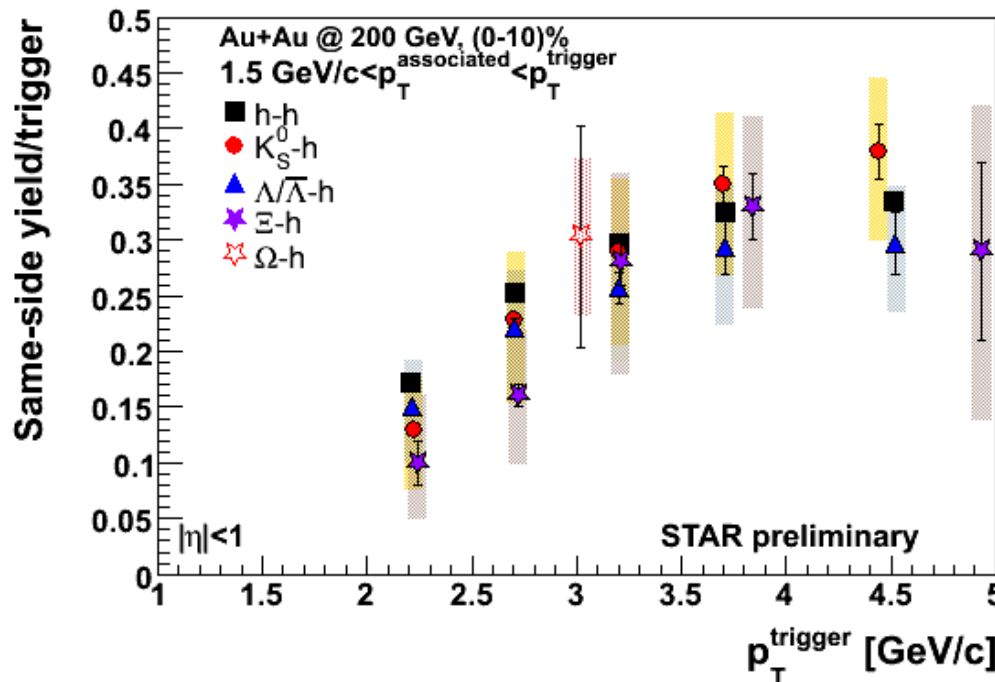
Ridge uniform event-by-event

Ω triggered correlations

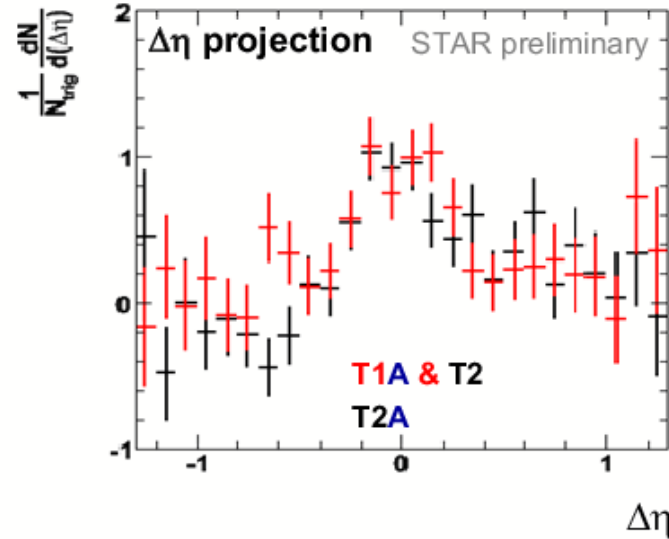
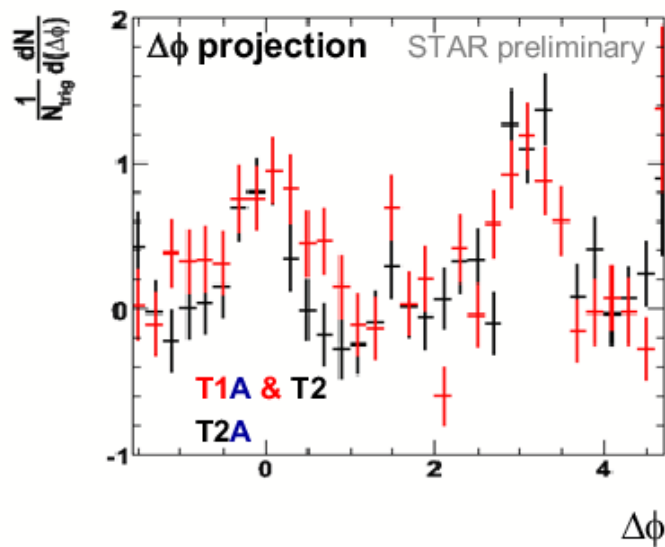


- Azimuthal correlations of comparable strengths seen with Λ (uds), Ξ (dss), and Ω (sss) triggers

- In $\Delta\eta$ Λ -triggered correlations can be separated in jet and ridge
- Ξ -triggered $\Delta\phi$ correlations appear smeared in $\Delta\eta$ direction (all ridge?)



Di-hadron triggered correlations



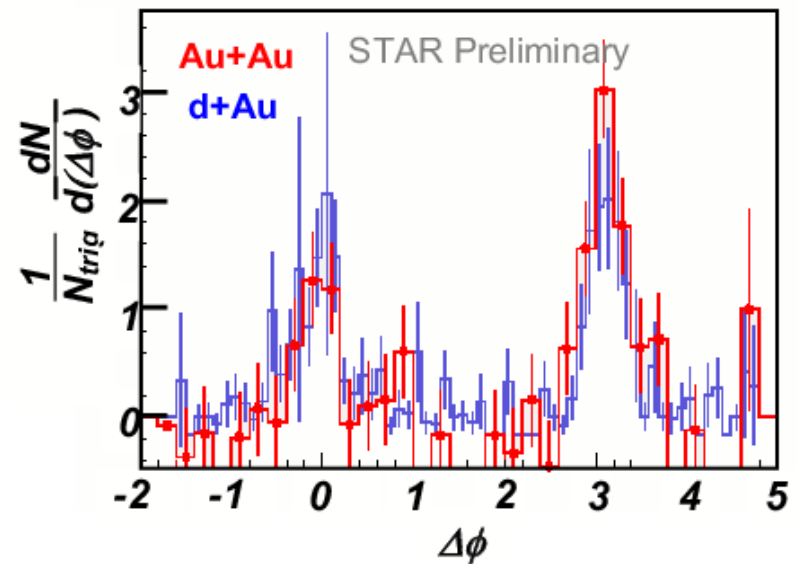
T1: $p_T > 5 \text{ GeV}/c$
T2: $p_T > 4 \text{ GeV}/c$
A : $p_T > 1.5 \text{ GeV}/c$

Di-jet measurements suggest that neither the widths in $\Delta\eta$ and $\Delta\phi$ (ridge/mach cone) are modified nor the yields are suppressed and comparable to d+Au

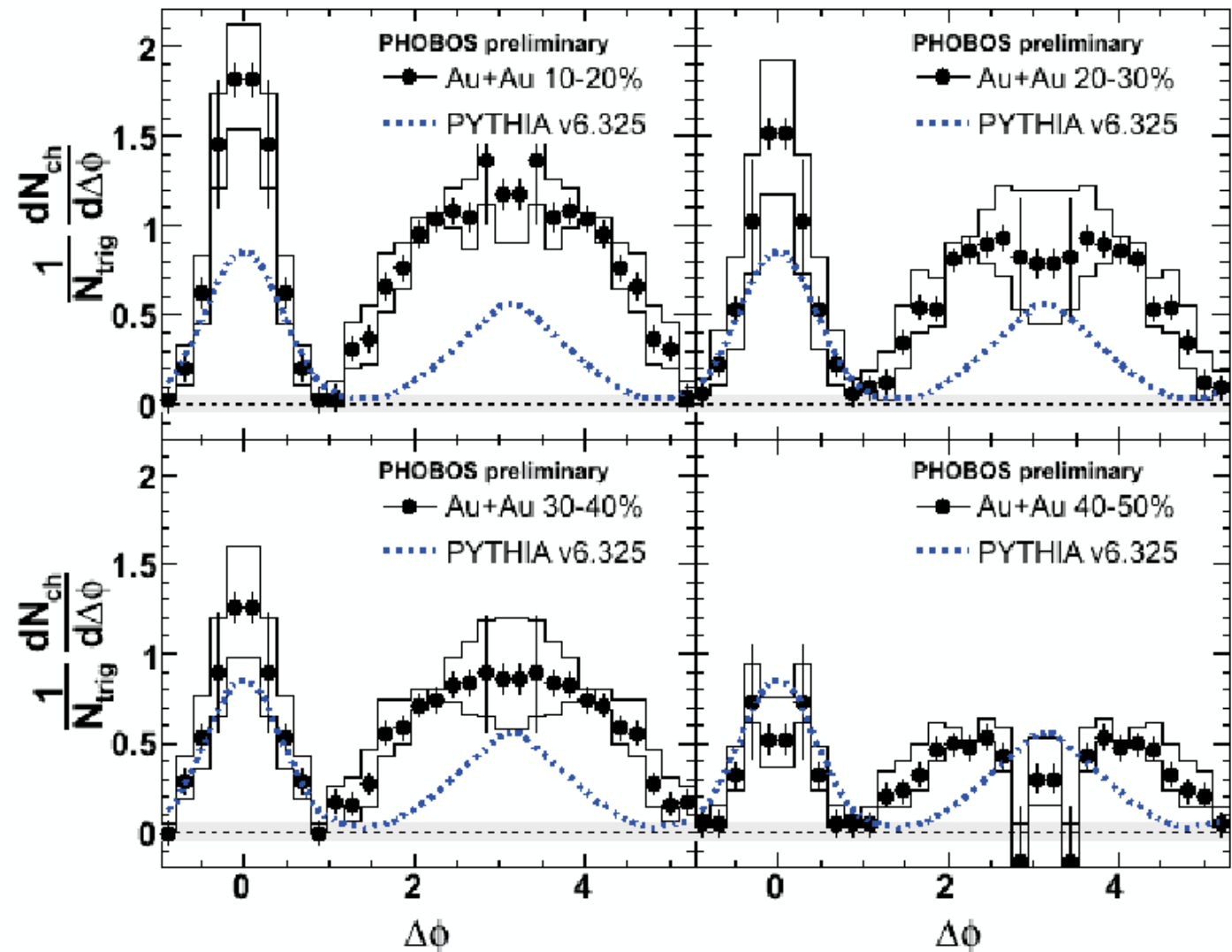
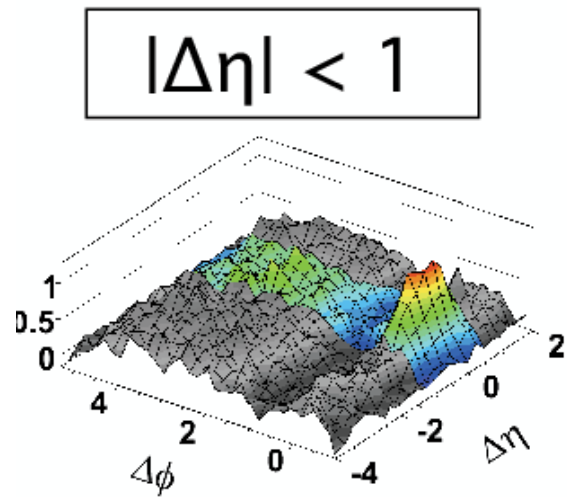
Caveat: Non-trivial bkg. subtraction

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

\Rightarrow **ridge correlated with energy loss !(?)**

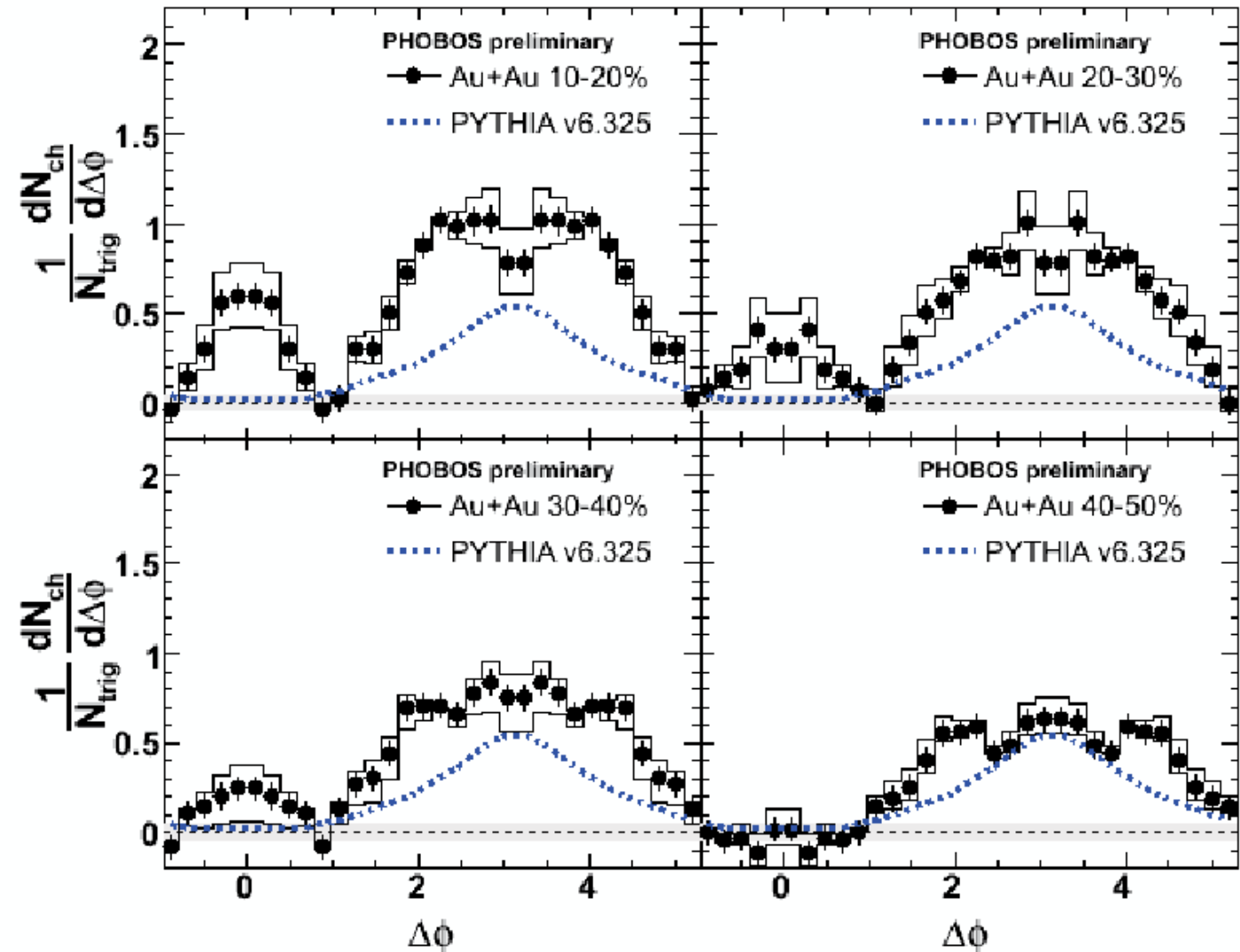
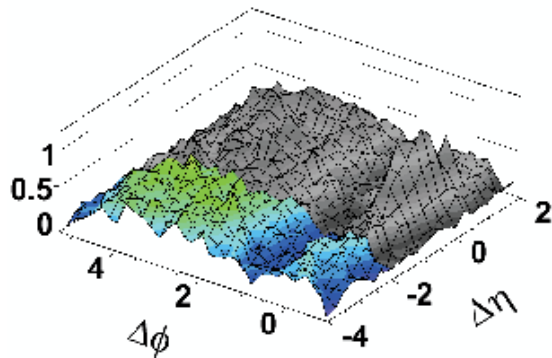


Stolen PHOBOS plots - mid-rapidity



Stolen PHOBOS plots – forward rapidity

$-4 < \Delta\eta < -2$



No trigger dependence

