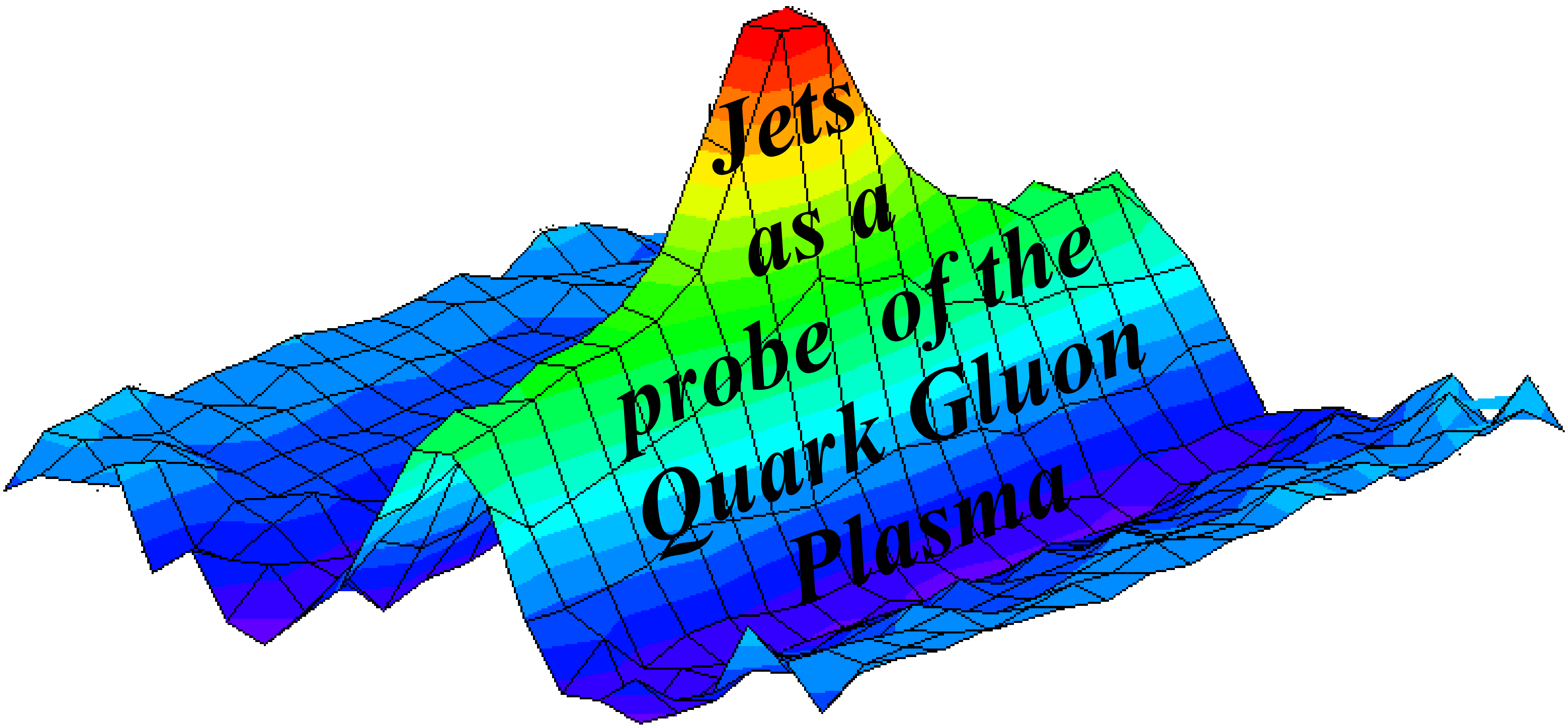


Jets as a probe of the Quark Gluon Plasma

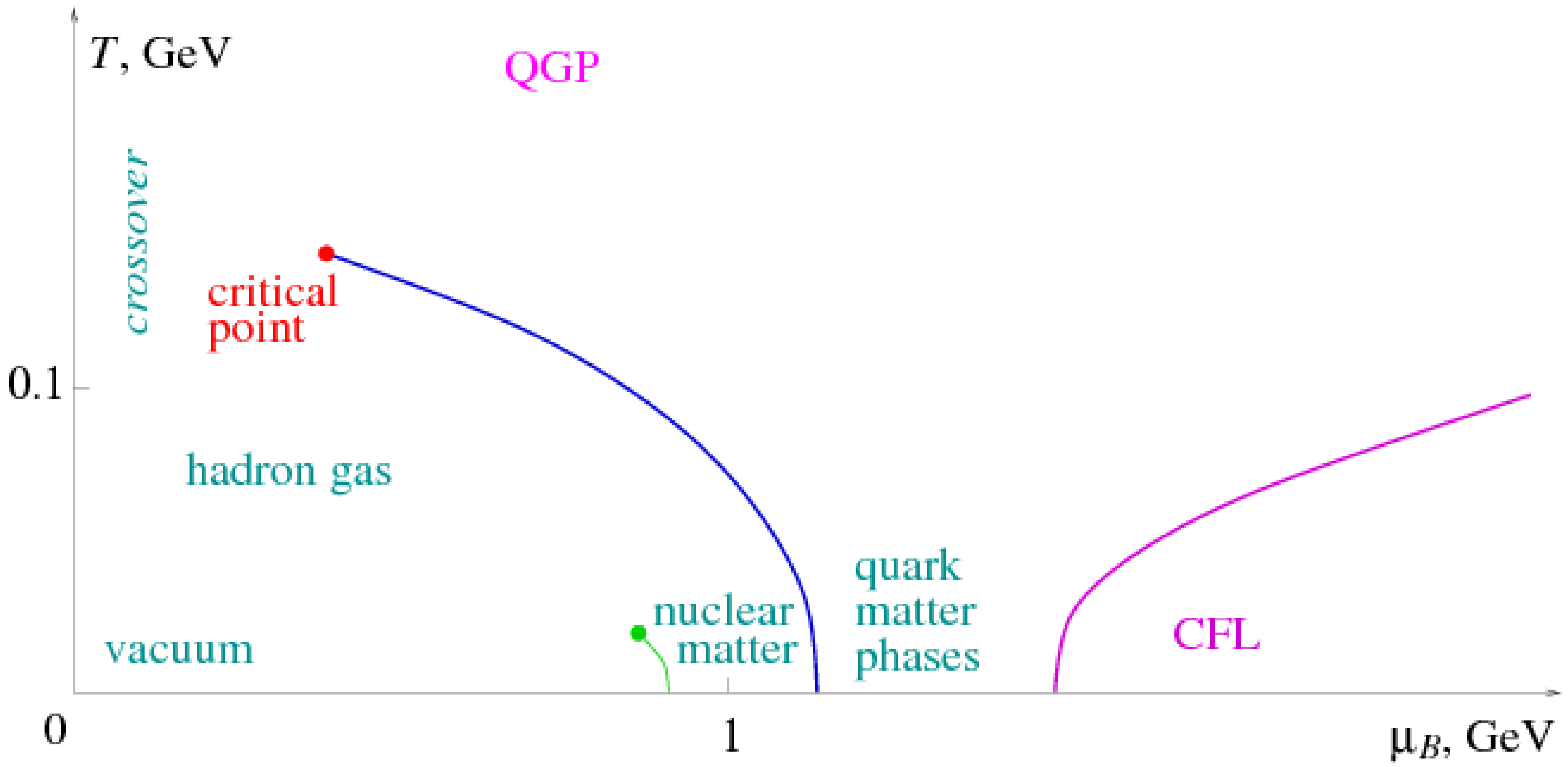
Christine Nattrass

University of Tennessee at Knoxville

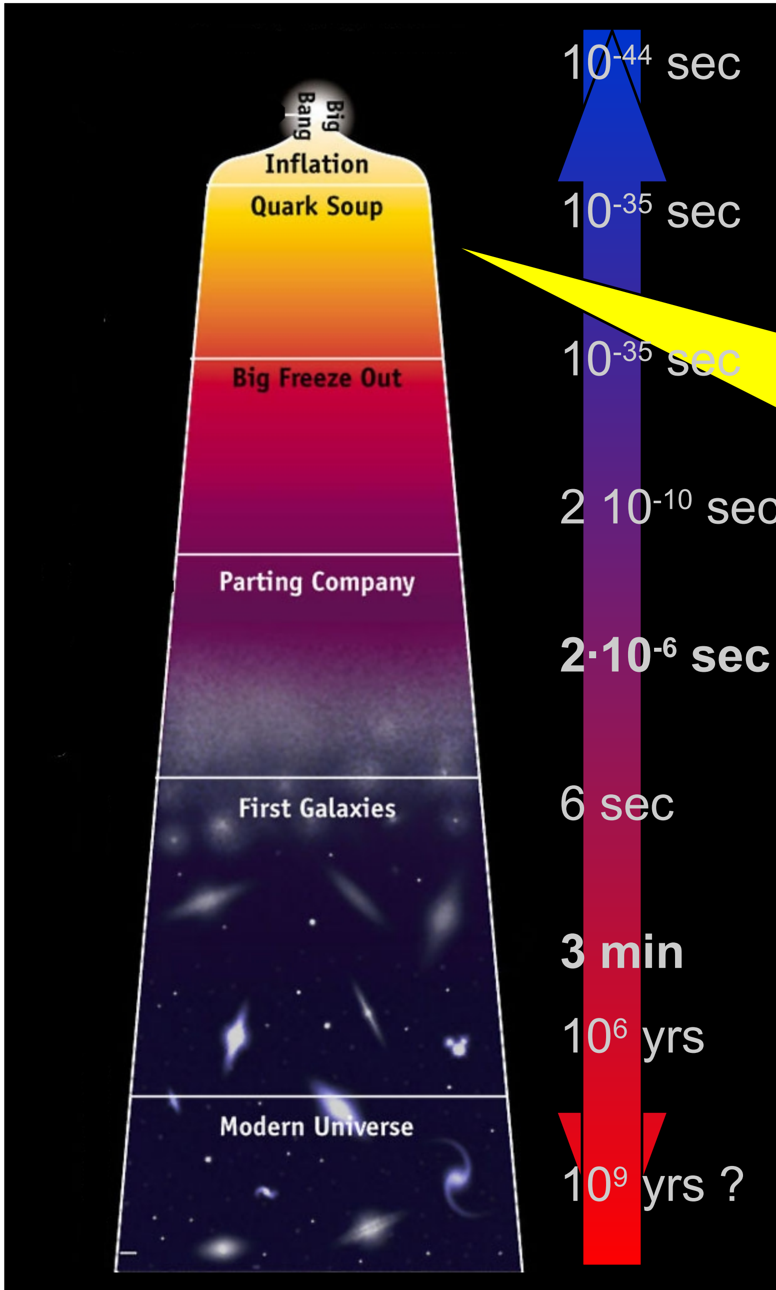
Outline

- Introduction to heavy ion collisions and the Quark Gluon Plasma
- The jet-like correlation
- The *Ridge*
- Comparison to theories
- Conclusion

Phase diagram of nuclear matter



Evolution of the Universe



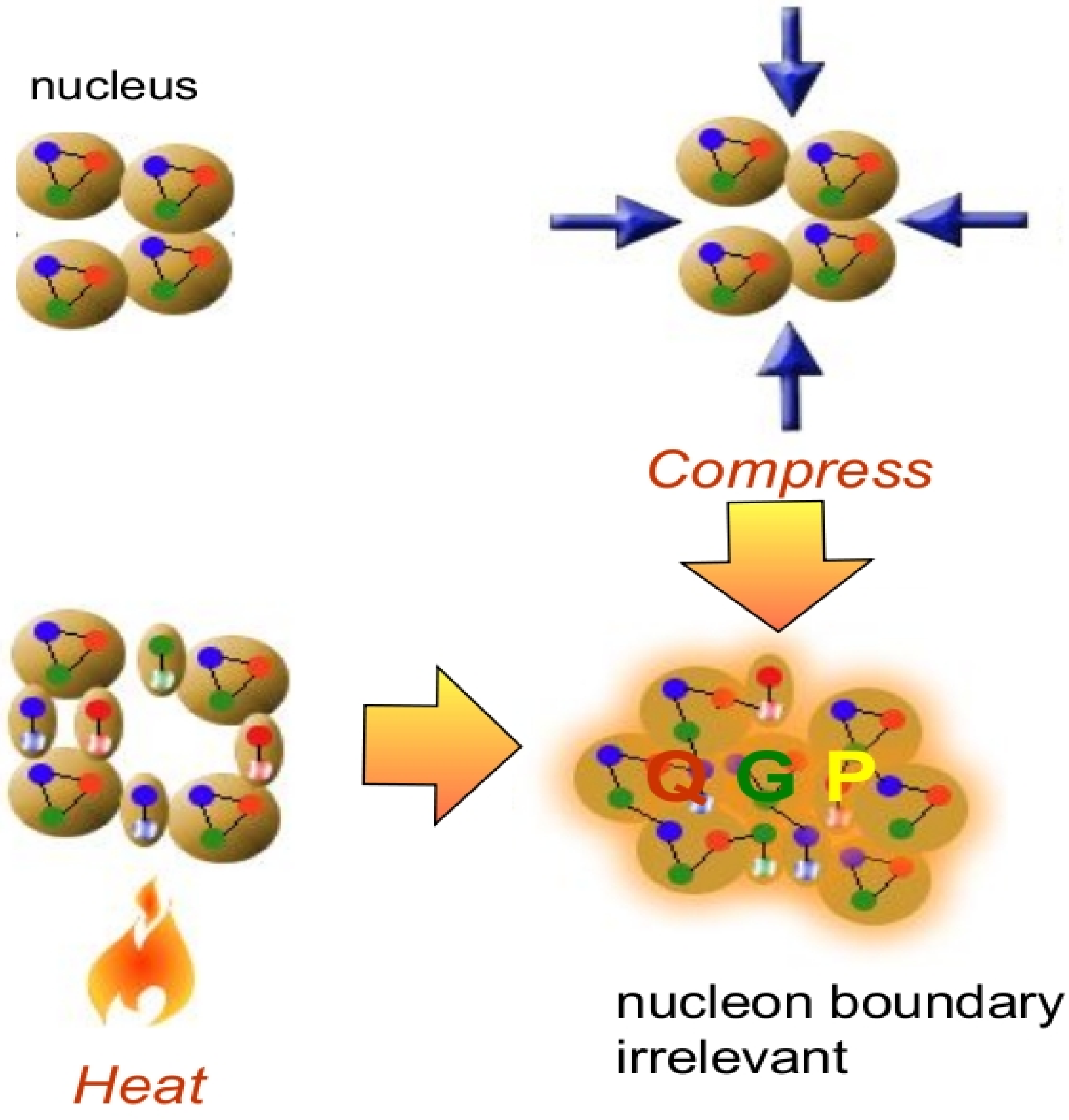
The universe gets cooler !

?

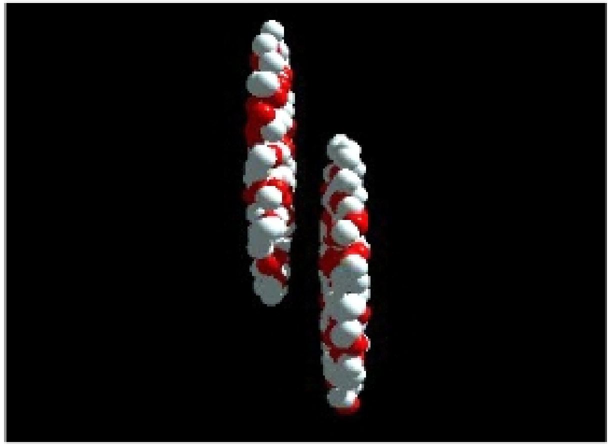
Need temperatures around $1.5\cdot10^{12}$ K

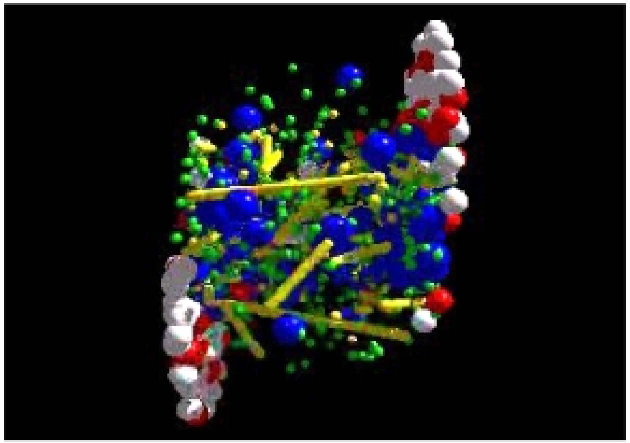
~10^{5} times hotter than the core of the sun

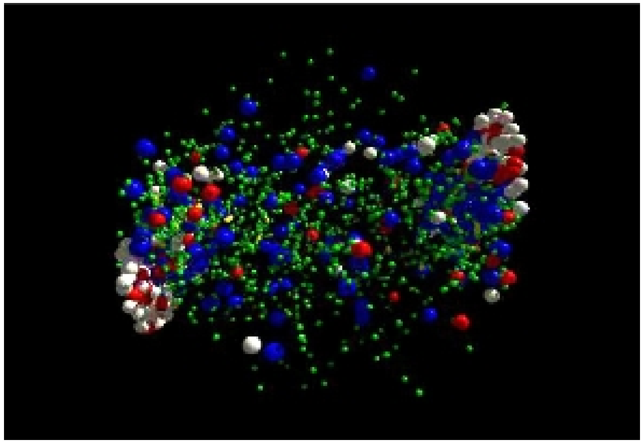
How to make a Quark Gluon Plasma

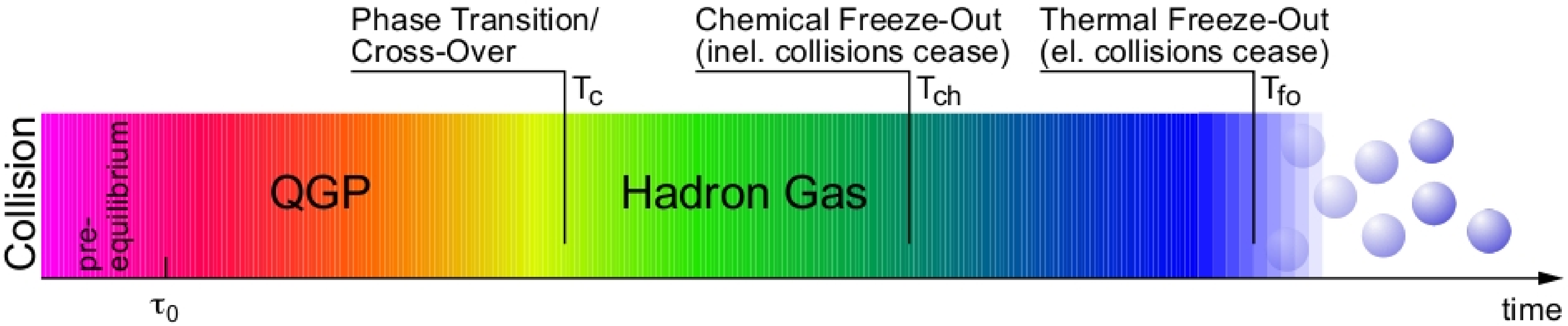


The phase transition in the laboratory

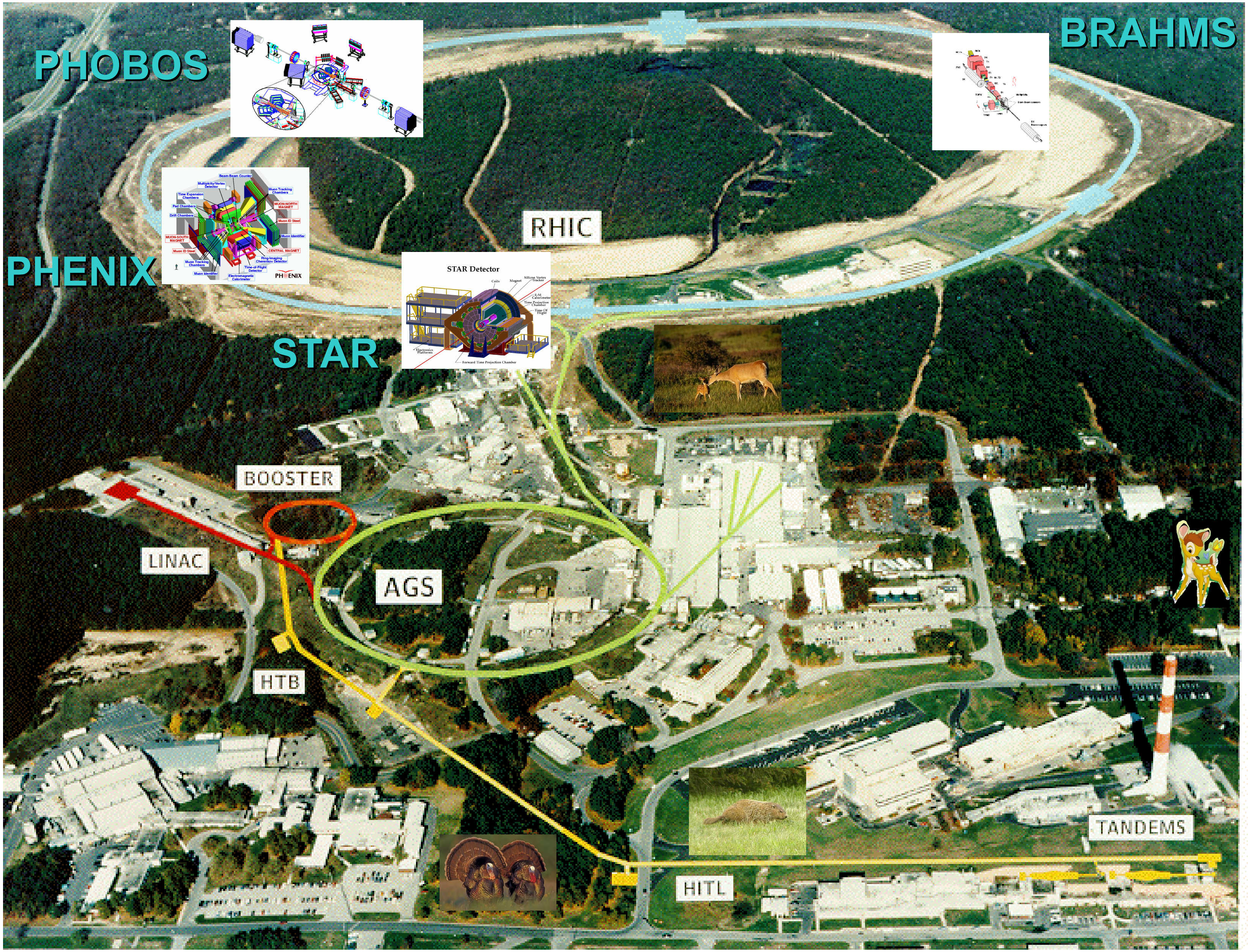








Relativistic Heavy Ion Collider



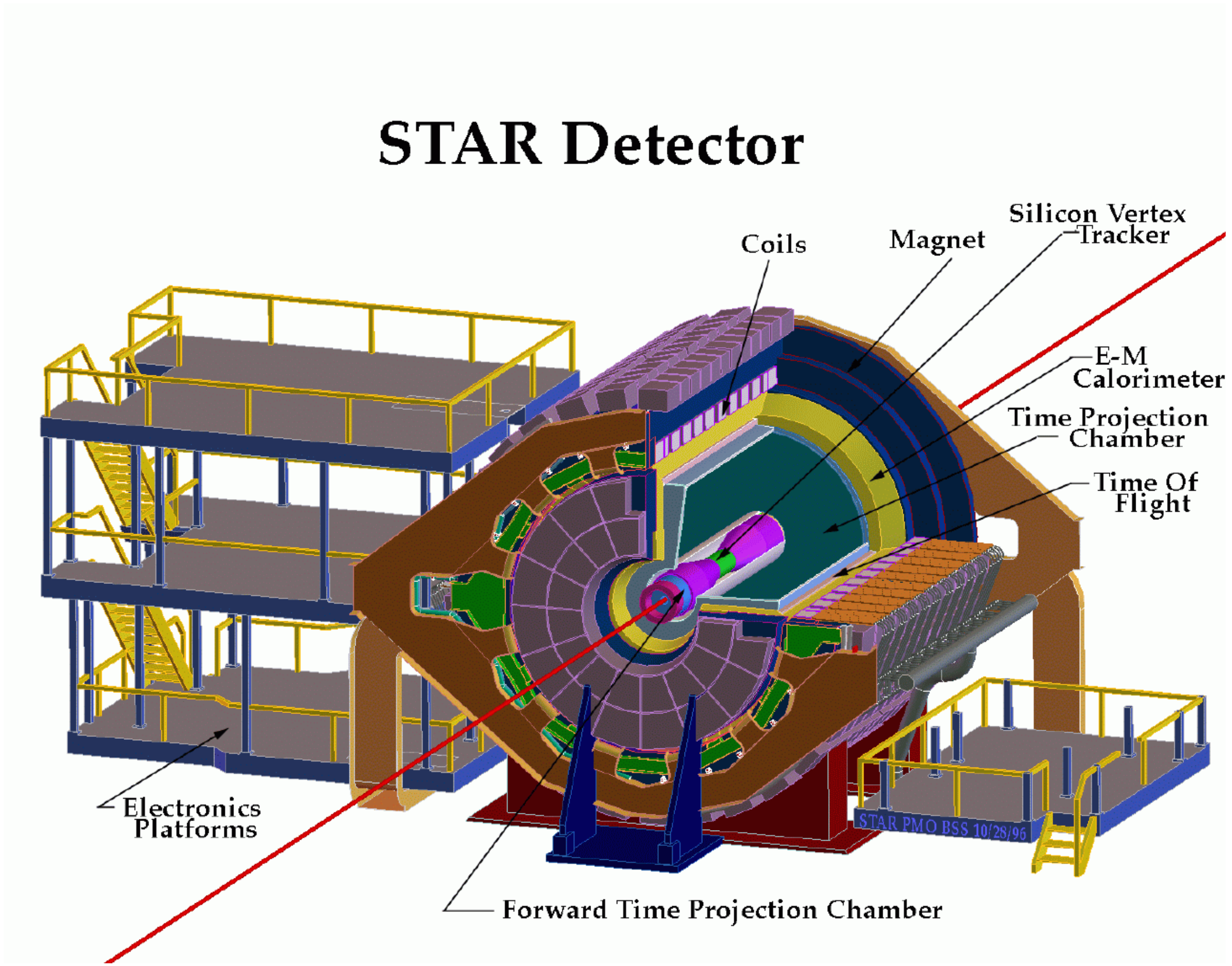
STAR

Coverage:

$0<\phi<2\pi$

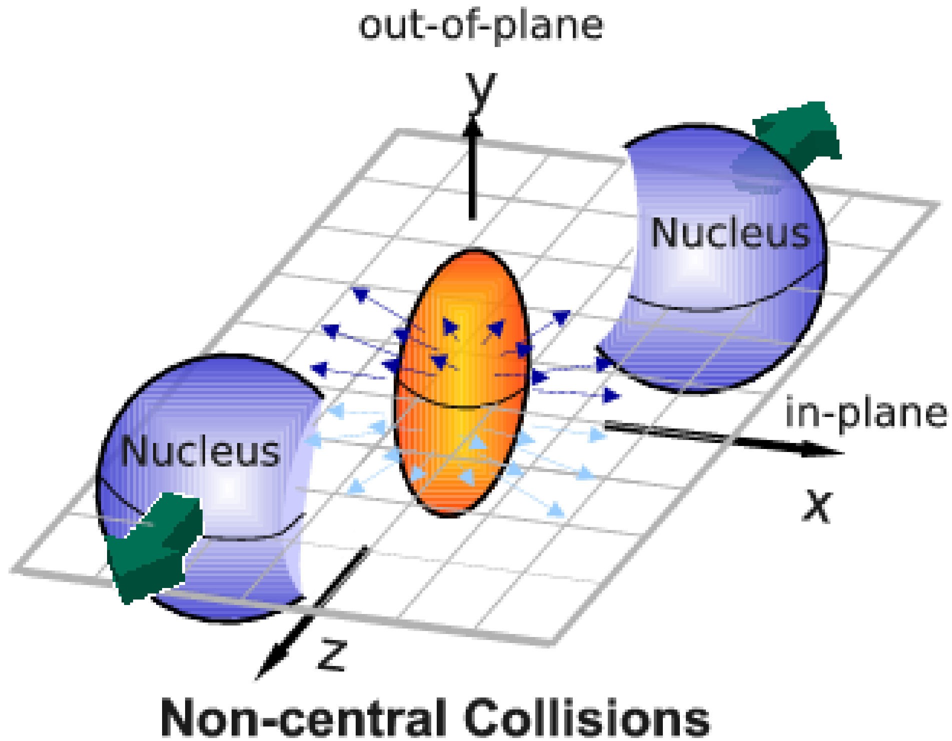
$-1<\eta<1$

Electromagnetic Calorimeter allows triggering



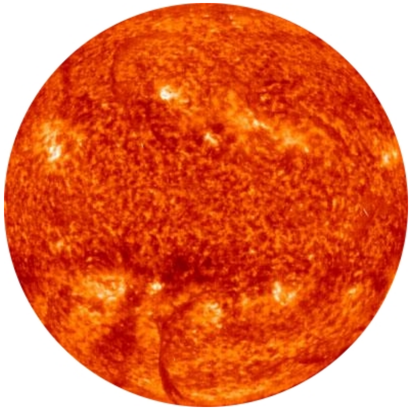
*Some key features of a heavy ion collision**

- Particles exhibit collective flow relative to the reaction plane, behaving like a fluid of quarks and gluons
- For this measurement, that is a background
- The majority of particles produced are low p_T light hadrons (π,K,p)
- The production of these particles is described reasonably well by statistical ("thermal") models
- These low p_T particles are often called "the bulk"
  - At local equilibrium?
- A hard parton is a probe of "the bulk"

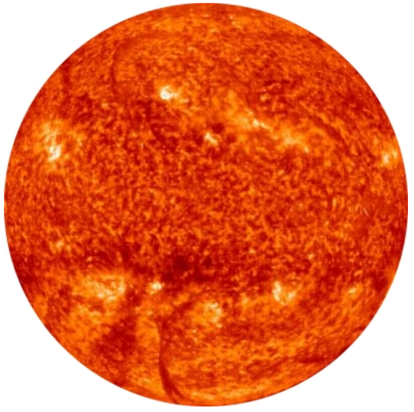


*I am glossing over details and disagreements within the field

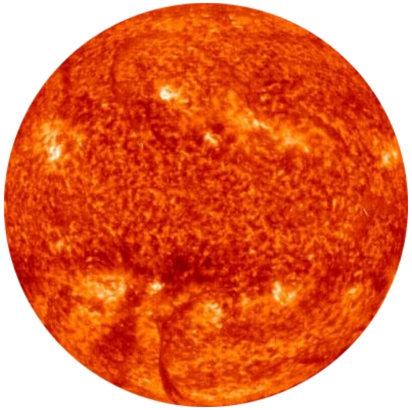
A simple picture of a heavy ion collision



Jets as a probe of the quark gluon plasma



One jet "absorbed" by the medium



Studying jets through di-hadron correlations

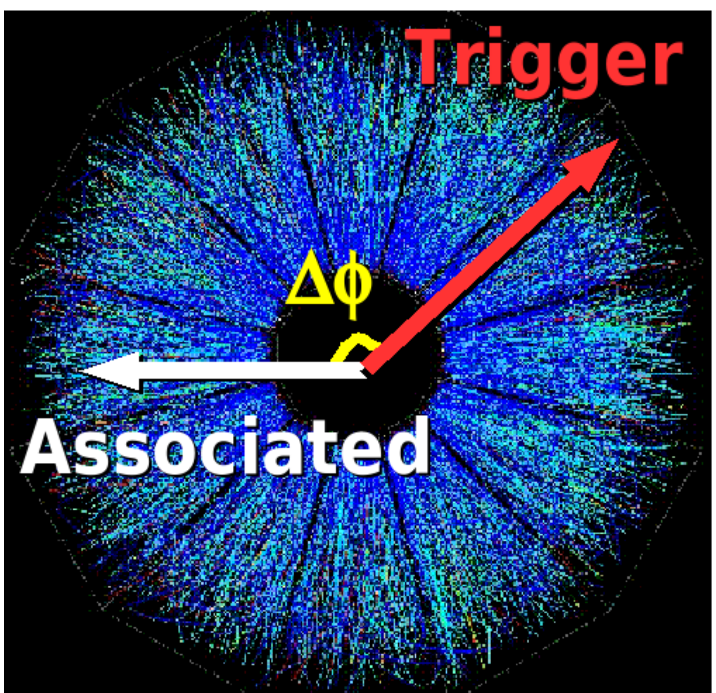
Hard parton scattering ⇒ back-to-back jets

Good (calibrated?) probe of the medium

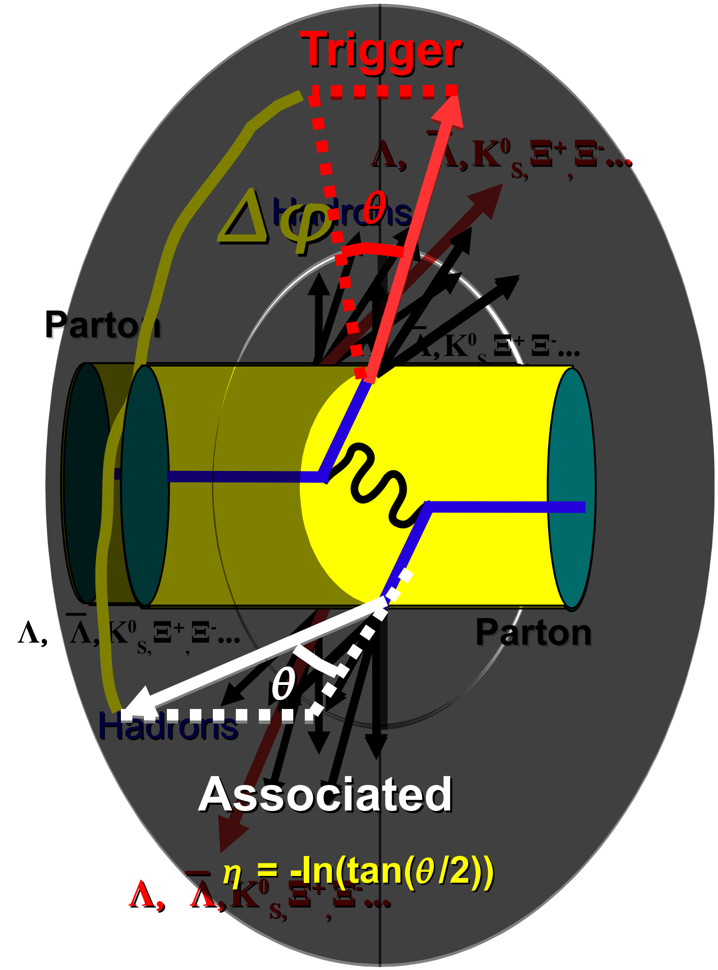
High multiplicity in A+A collisions

Individual jets difficult to reconstruct

Study jets via correlations of particles in space

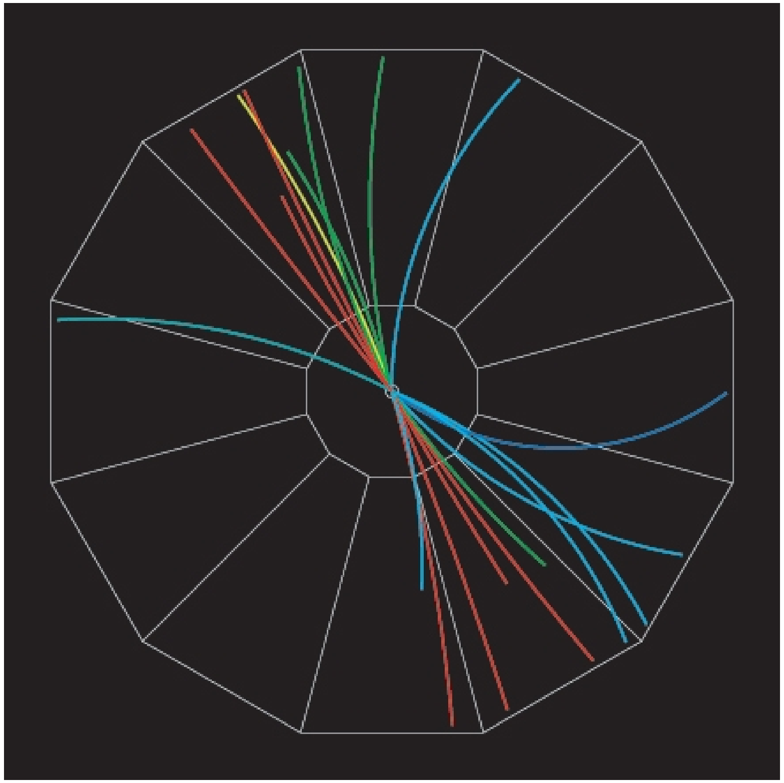


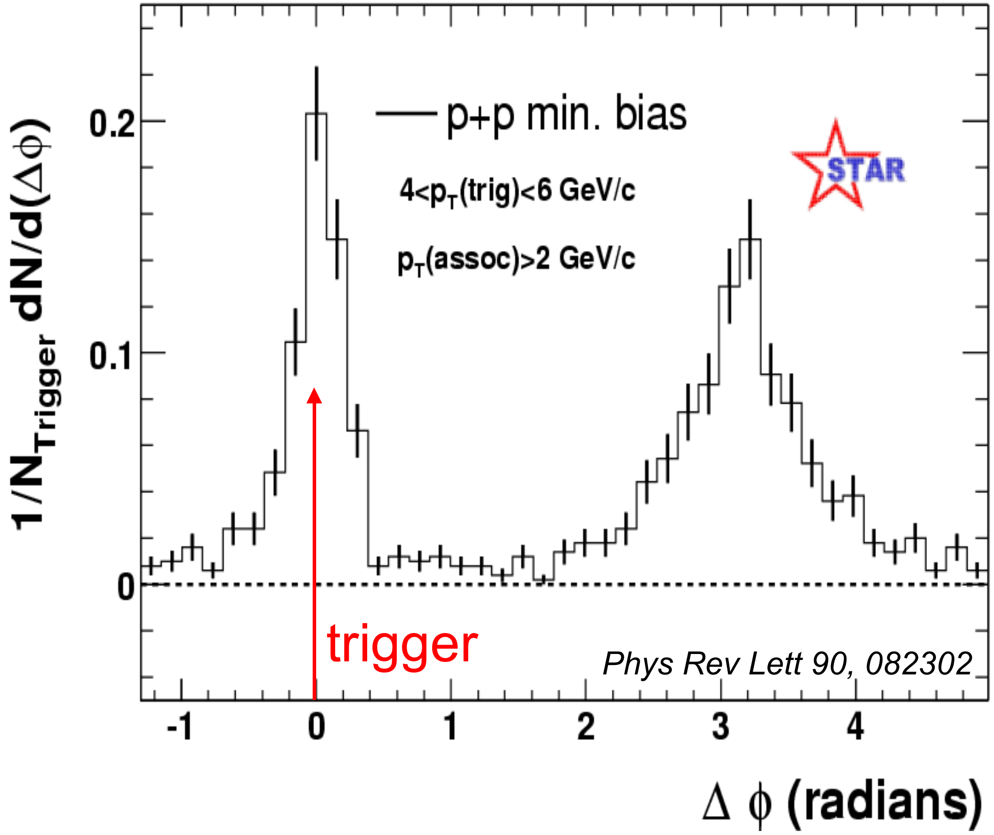
both azimuth and pseudorapidity



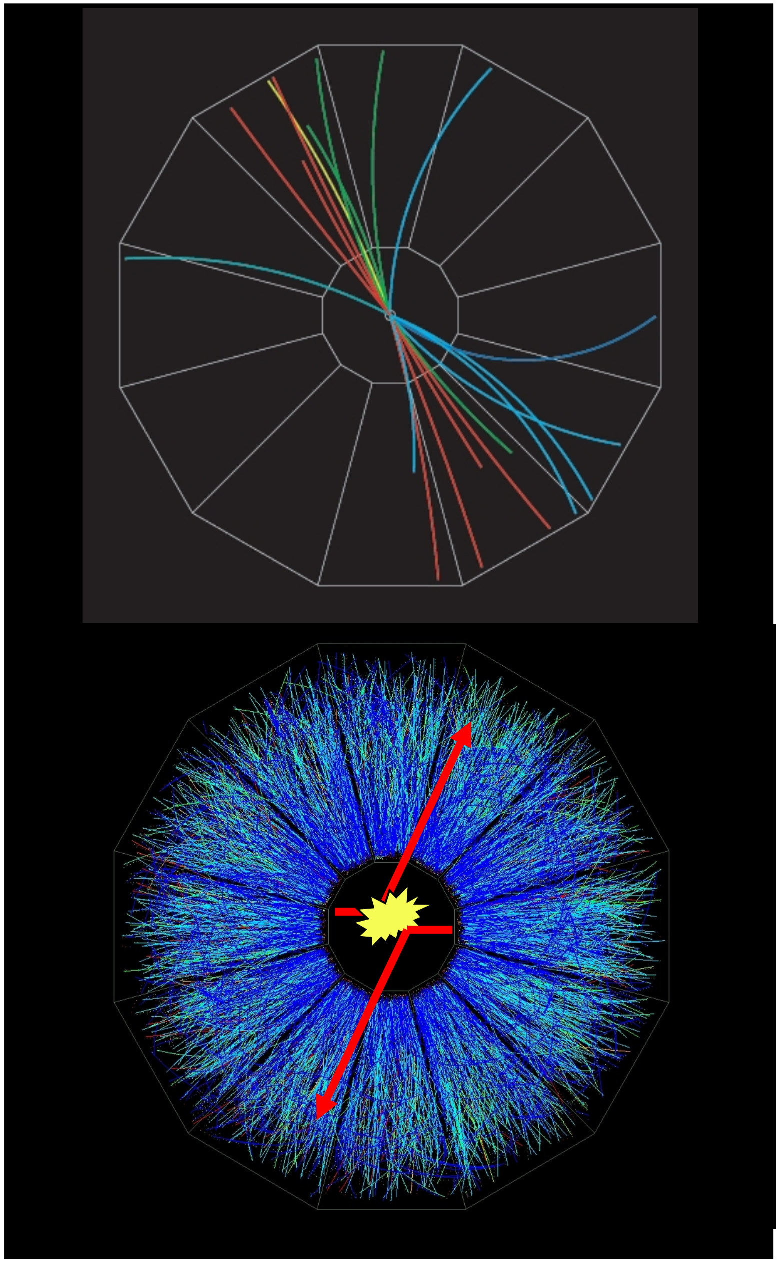
Jets – azimuthal correlations

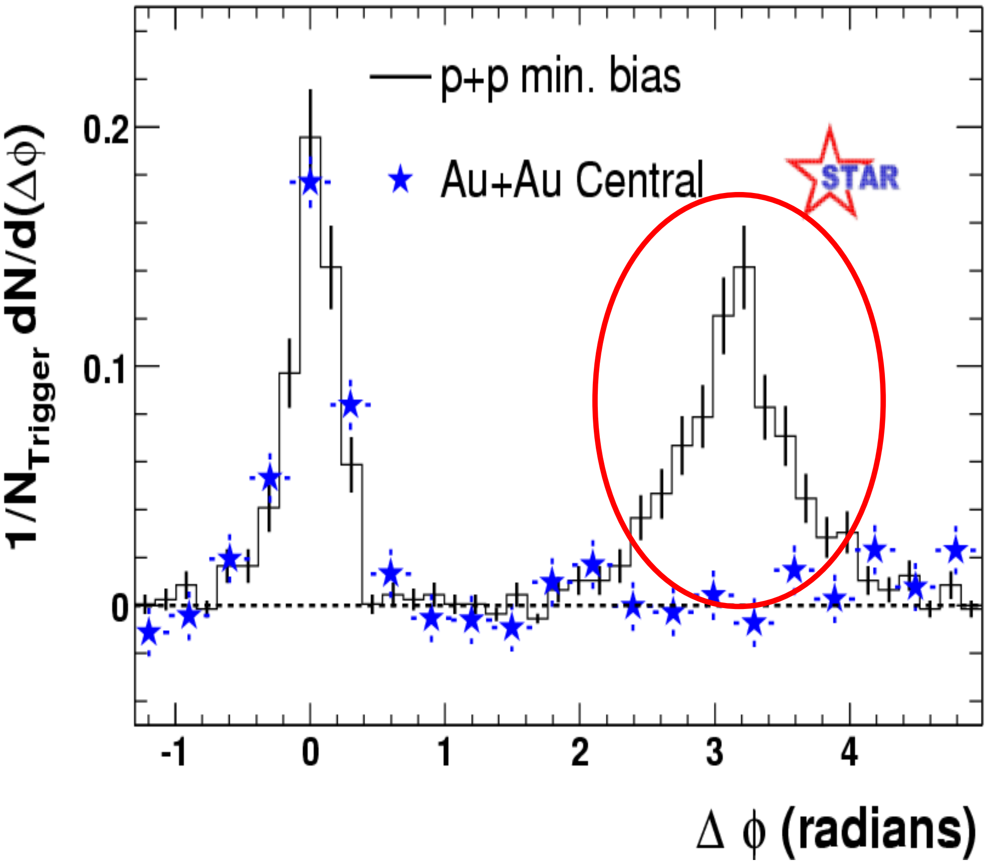
p+p → dijet





Jets – azimuthal correlations

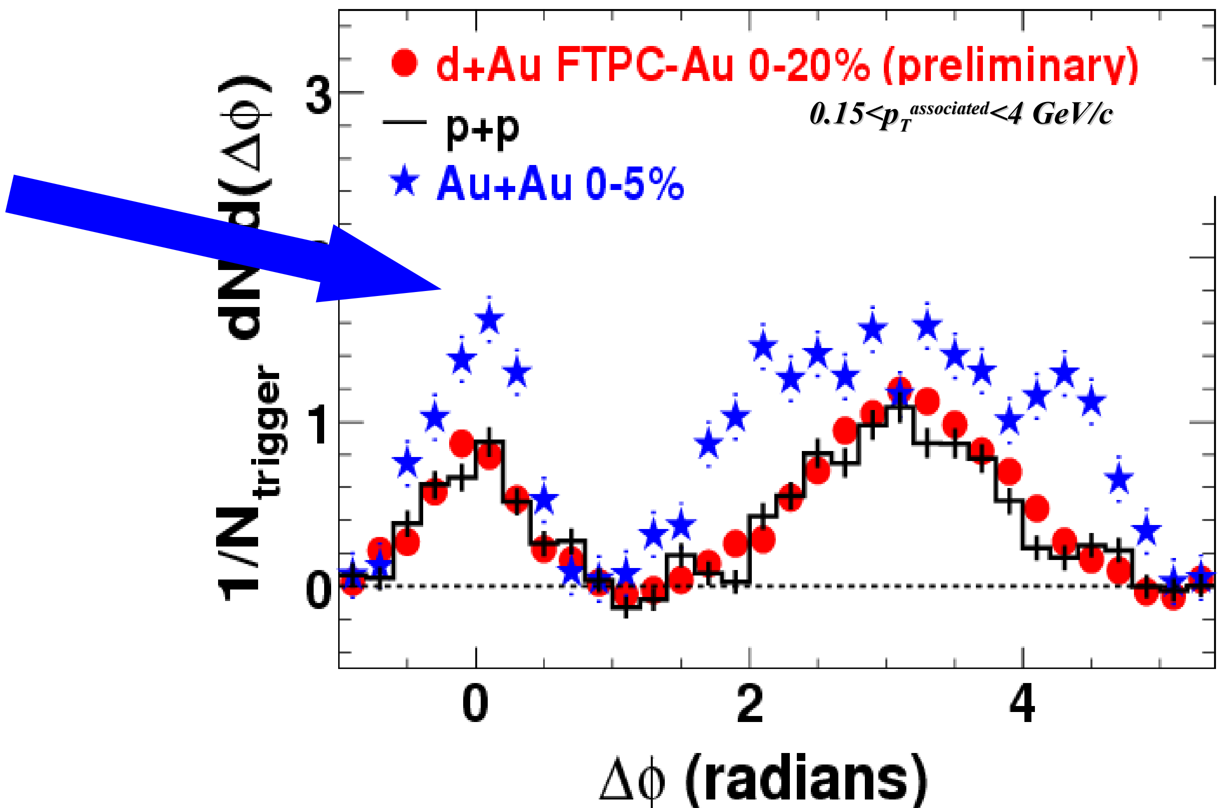




But at lower p_T...

Near-side shows modification

Excess yield in Au+Au relative to p+p



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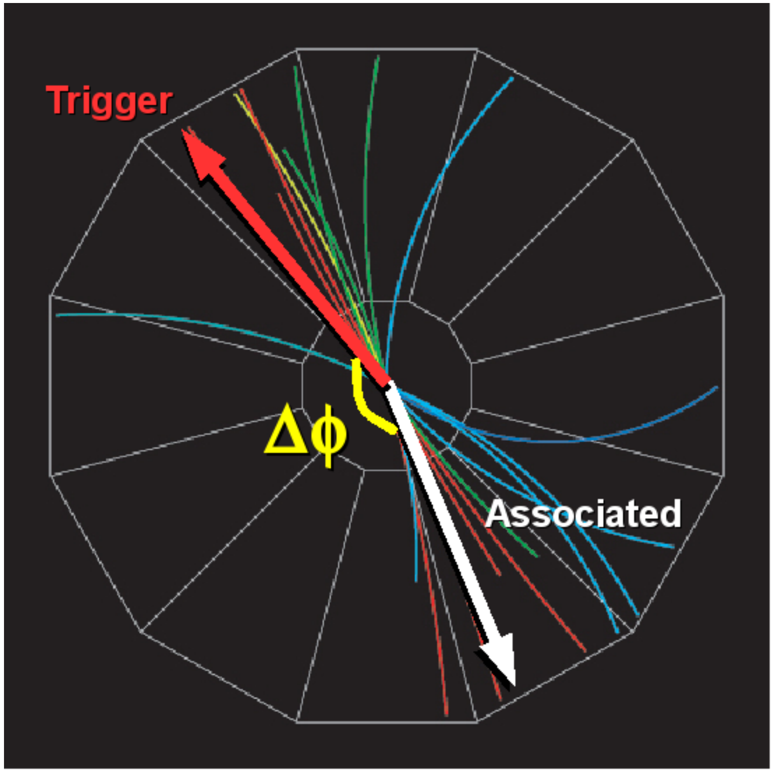
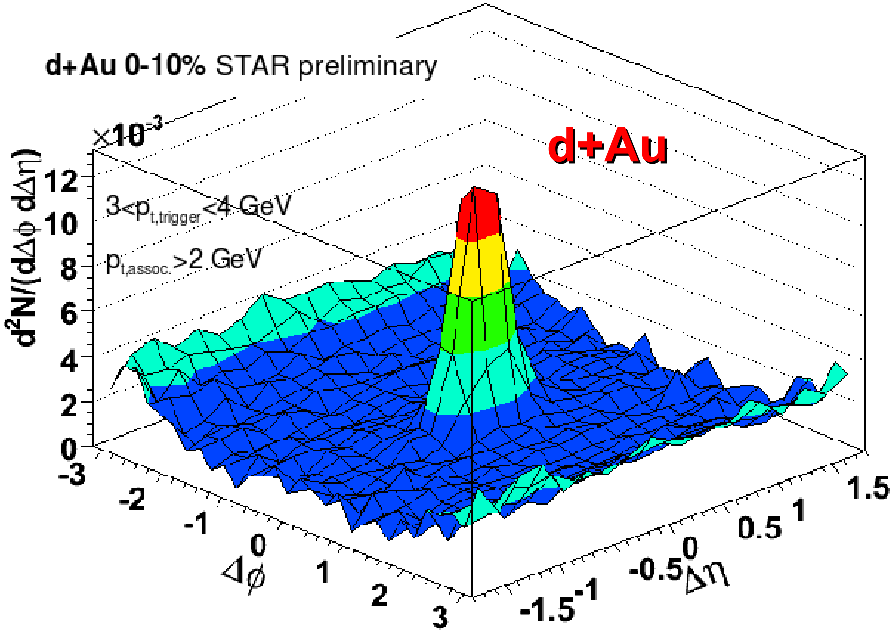
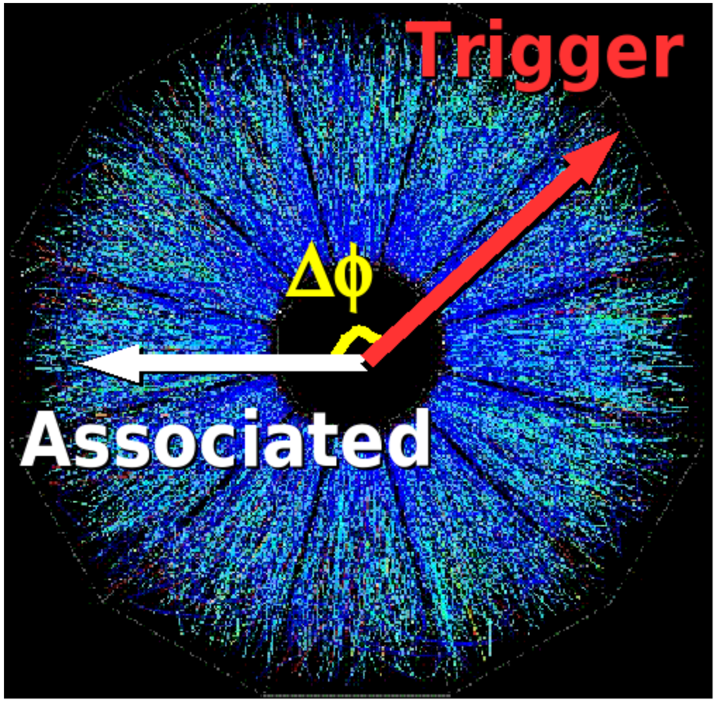
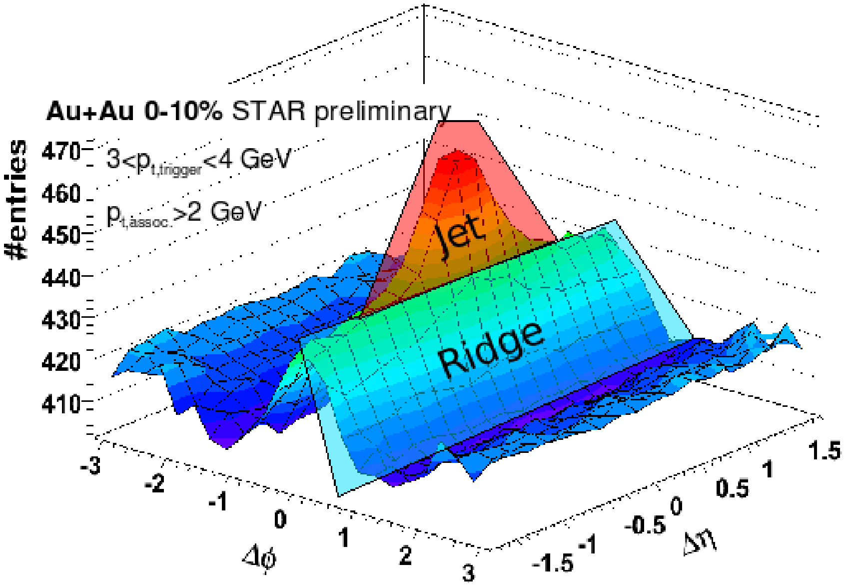
Looking in two dimensions





In two dimensions in Au+Au





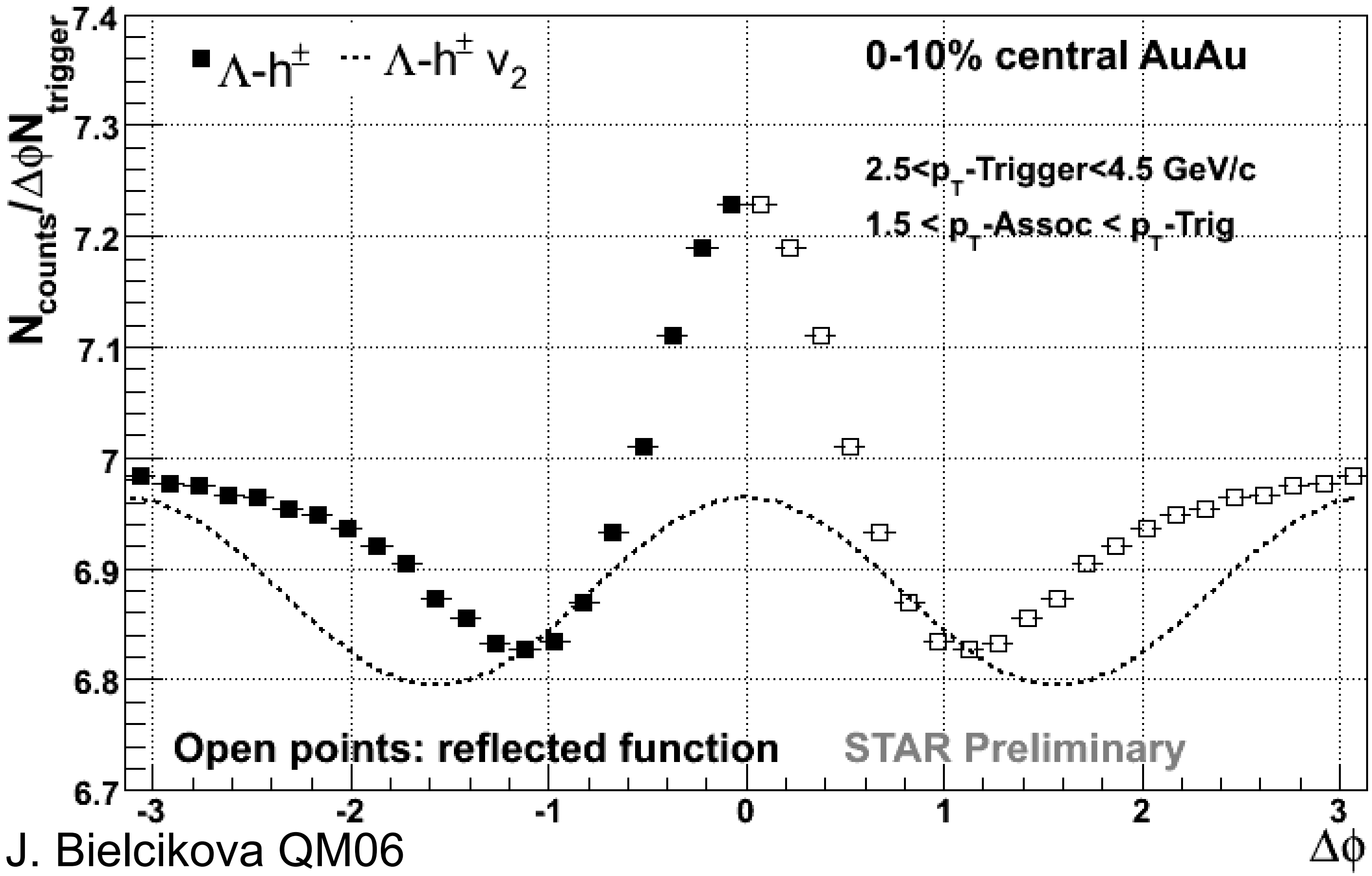
A caveat...

Large background subtraction...

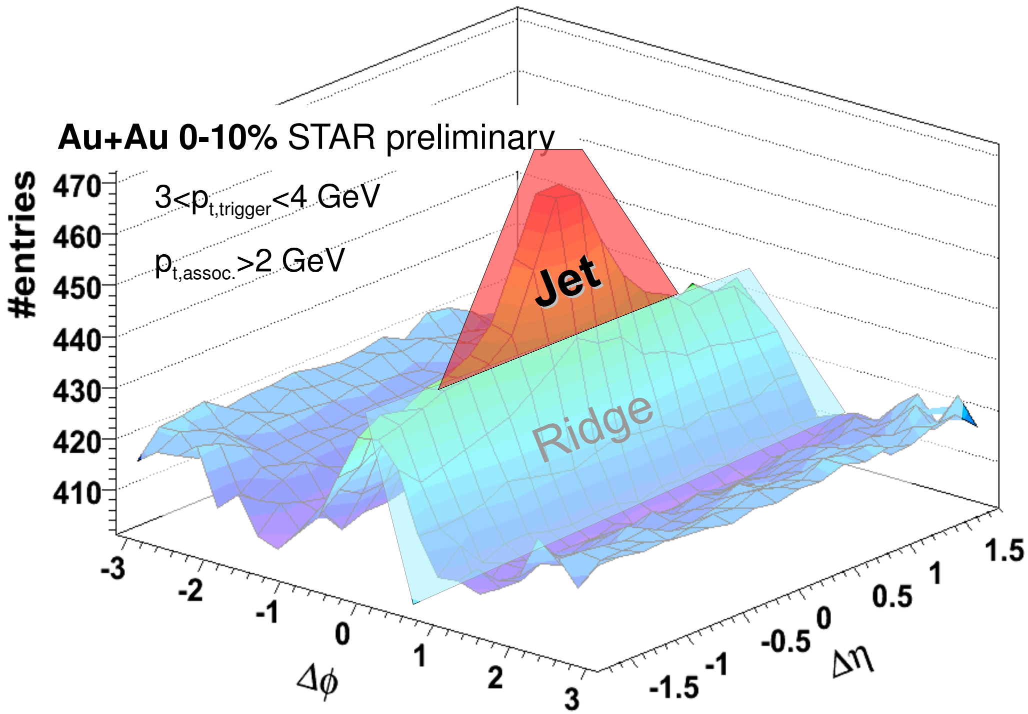
Signal/Background ≈ 0.05 in central Au+Au

Depends on kinematic region

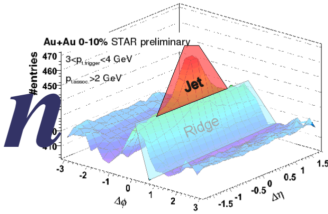
Signal/Background higher at higher p_T

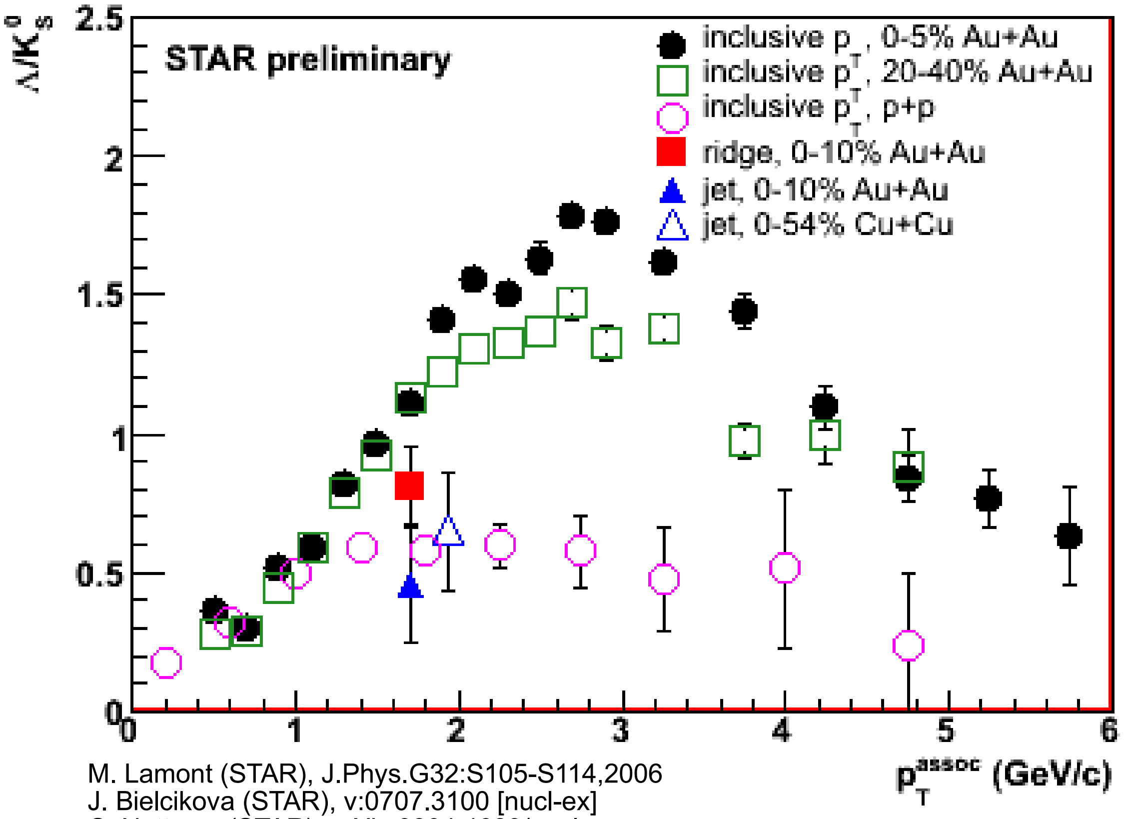


The jet-like correlation

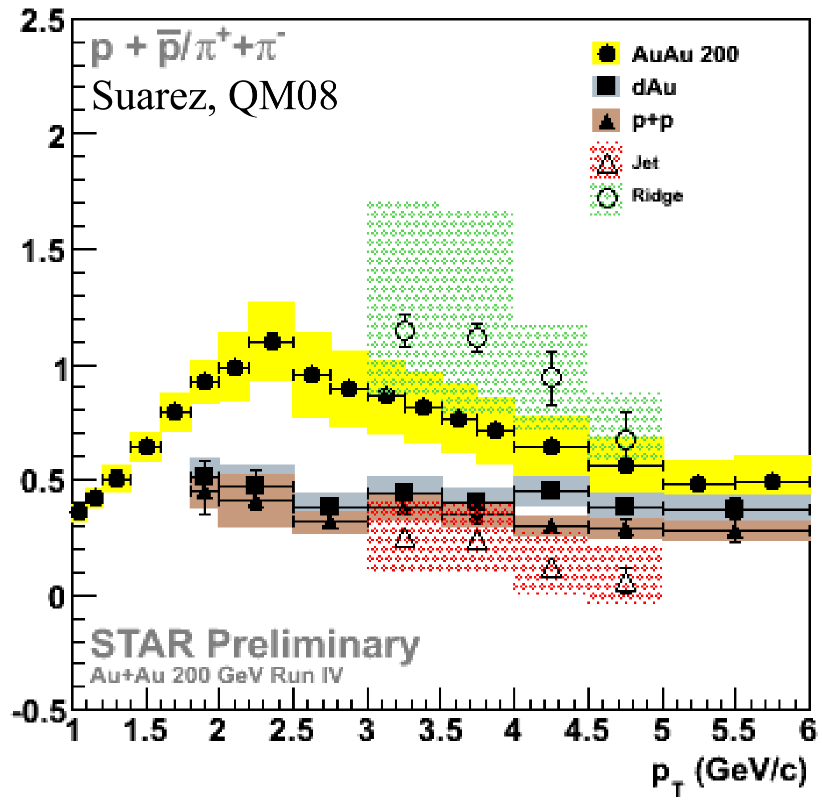


Jet-like correlation composition



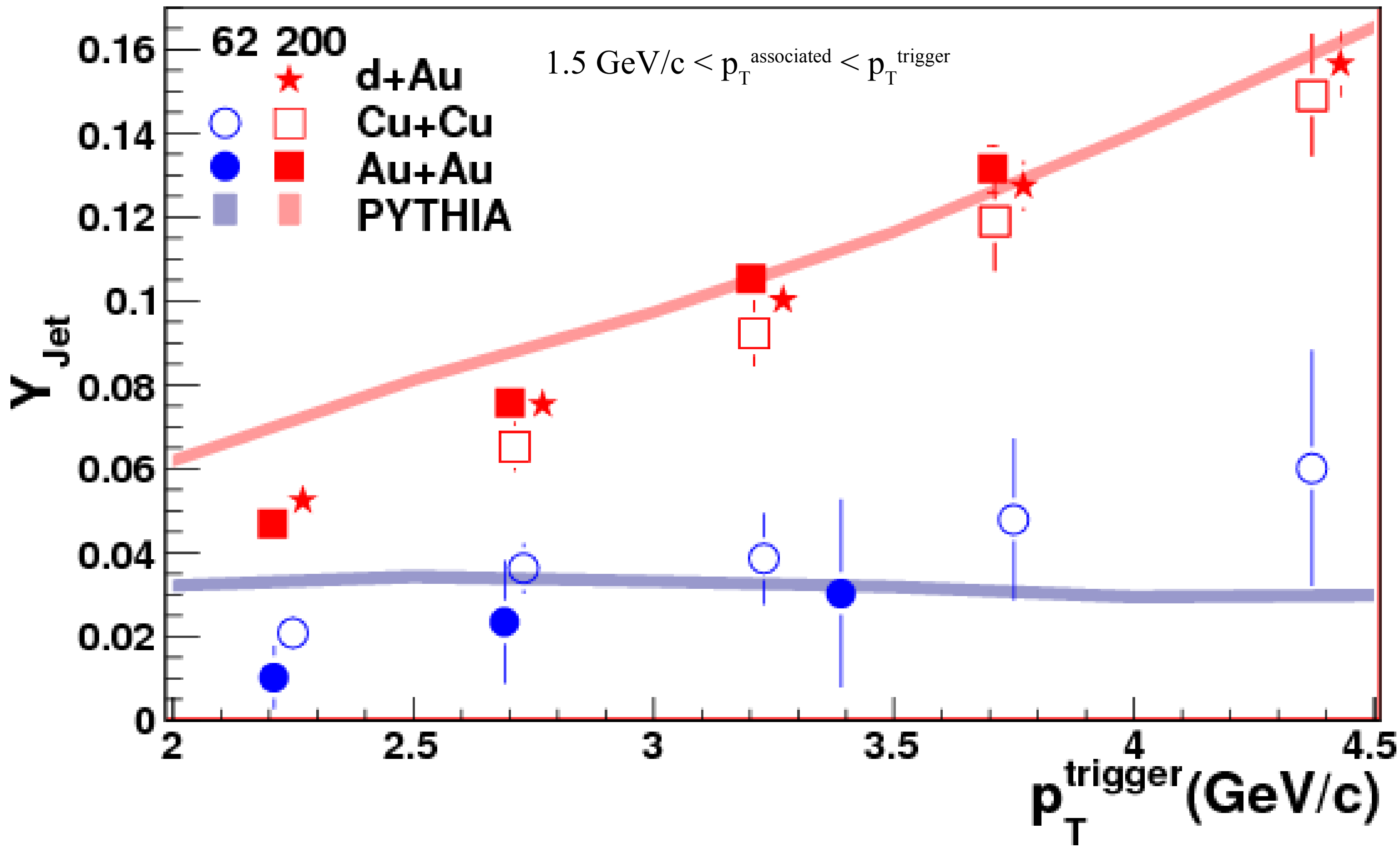


M. Lamont (STAR), J.Phys.G32:S105-S114,2006
J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex



Baryon/meson ratios in jet-like correlation in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles

$p_T^{trigger}$ dependence

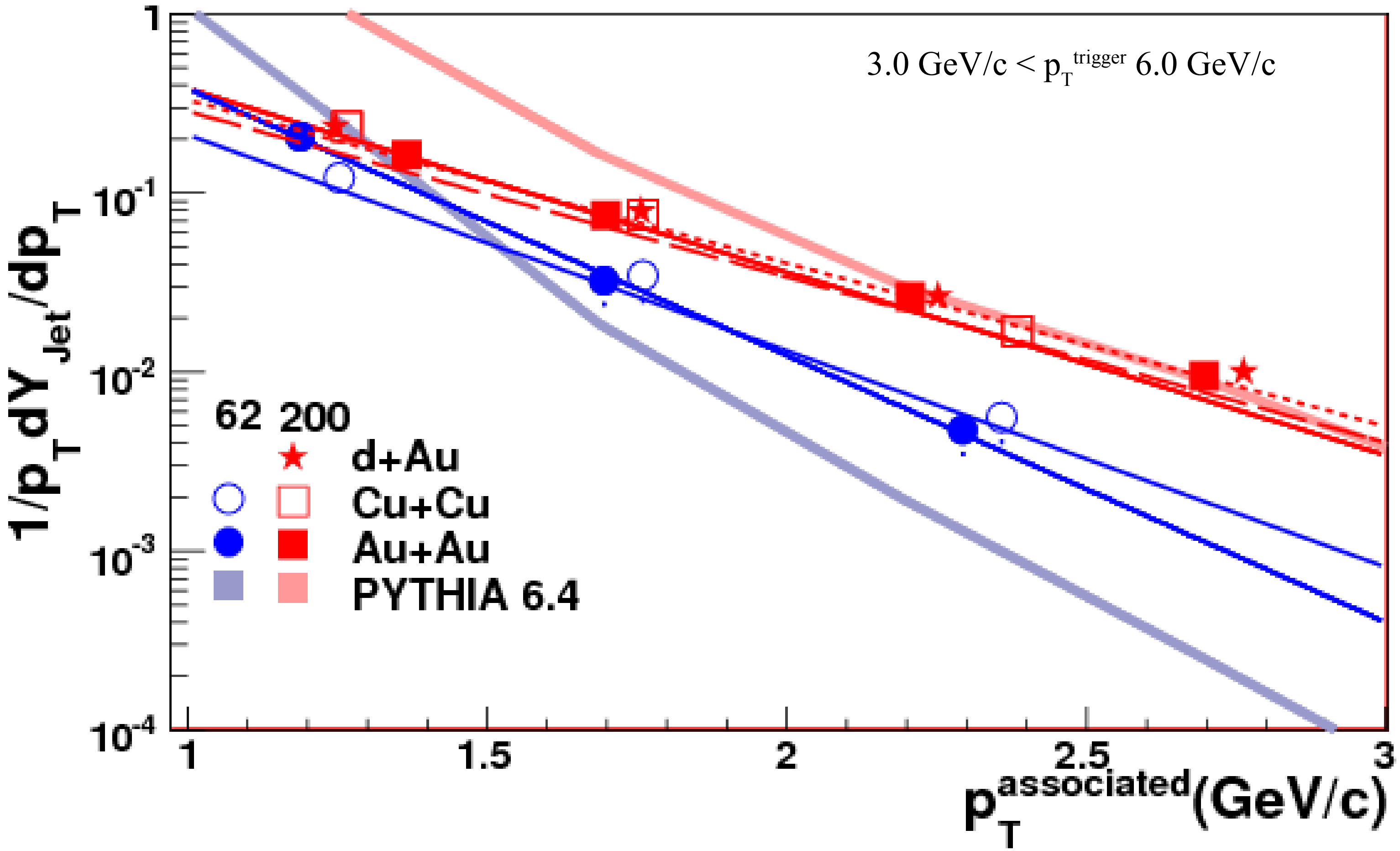


Yield increases with $p_T^{trigger}$

No collision system dependence

PYTHIA – Monte Carlo p+p event generator tuned to data and incorporating many features of pQCD

$p_T^{associated}$ dependence



No collision system dependence

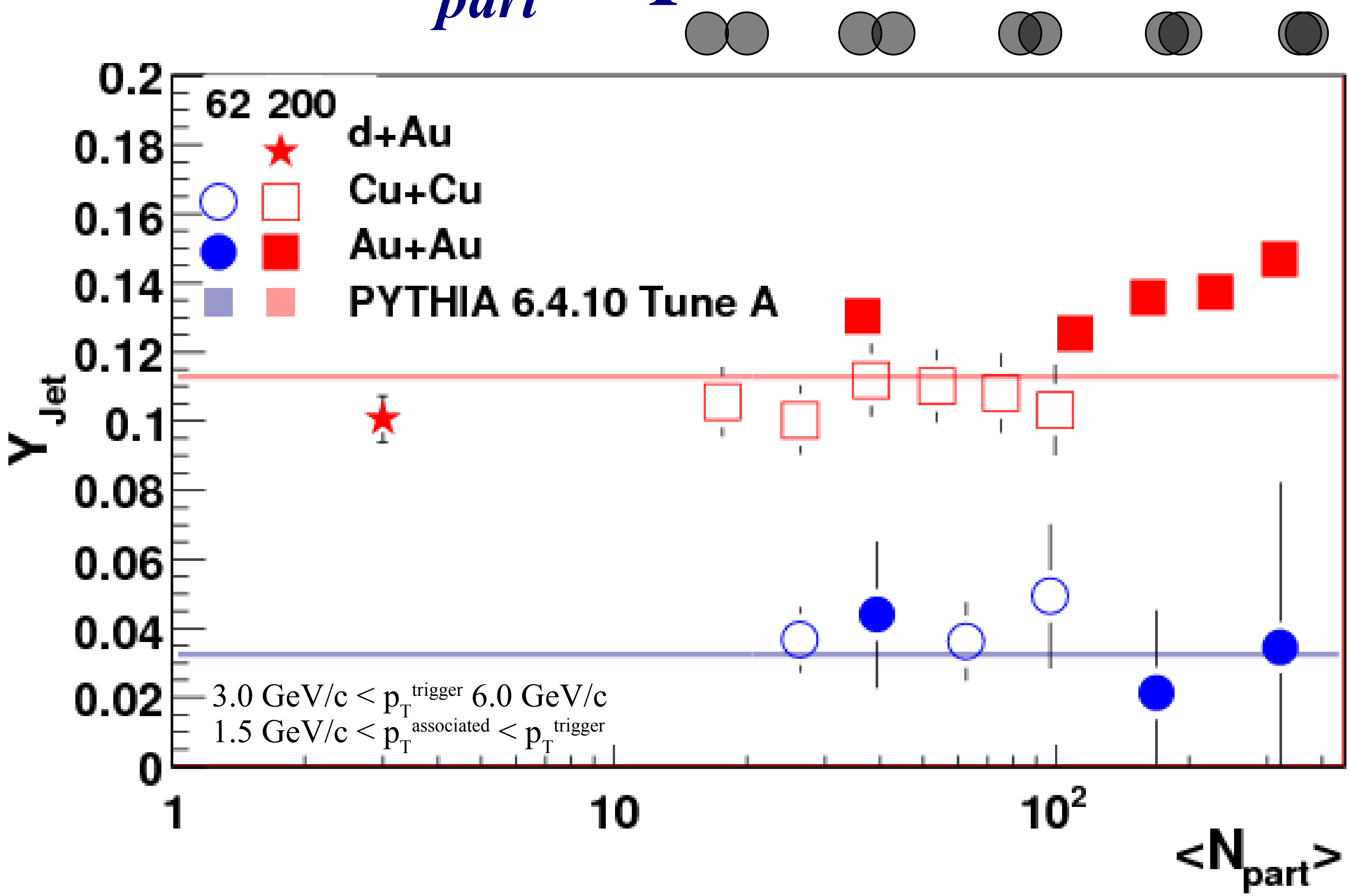
PYTHIA does not describe the data

Inverse slope parameter

	$\sqrt{s_{NN}}$ = 62 GeV	$\sqrt{s_{NN}}$ = 200 GeV
Cu+Cu	359 ± 41	424 ± 20
Au+Au	291 ± 28	478 ± 8
d+Au		469 ± 8

Statistical errors only

N_{part} dependence

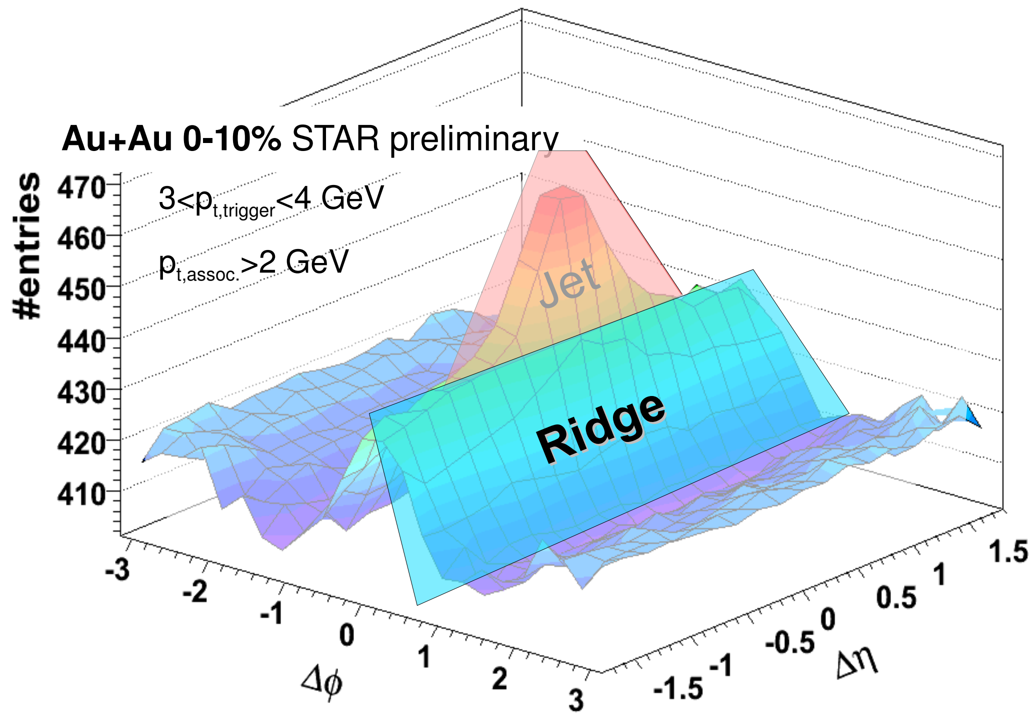


No collision system dependence at a given N_{part}

Jet-like yield increases with N_{part}

PYTHIA describes data at lower N_{part}

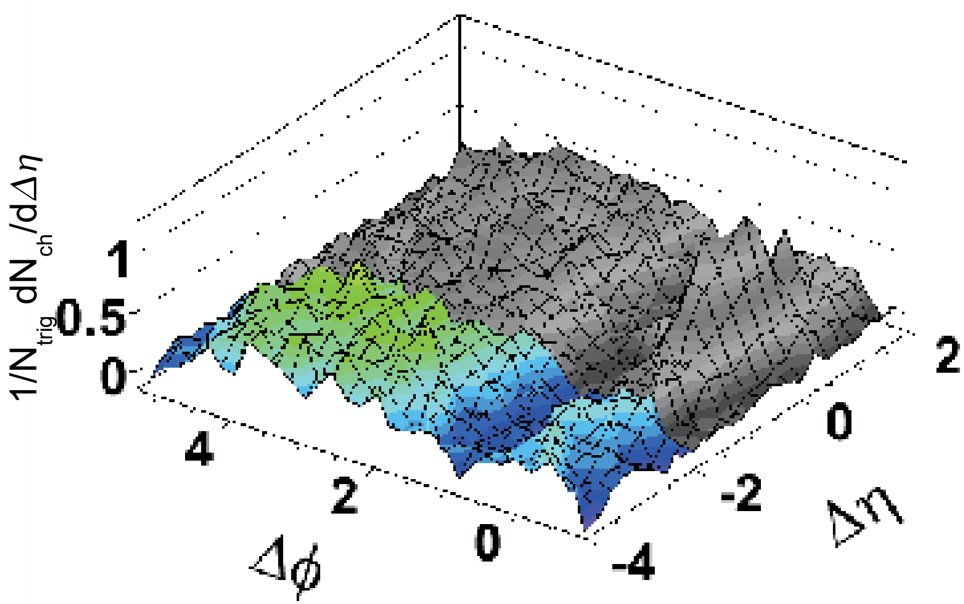
The *Ridge*



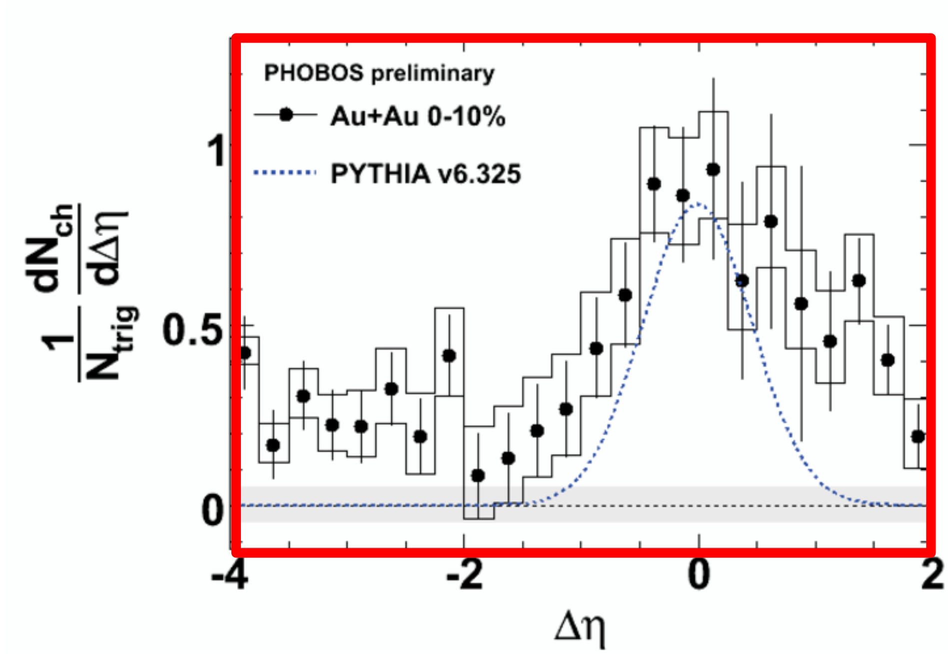
Au+Au 0-10% STAR preliminary
3<p_t,trigger<4 GeV
p_t,assoc.>2 GeV
#entries
470
460
450
440
430
420
410
Jet
Ridge
-3
-2
-1
0
1
2
3
Δφ
-1.5
-1
-0.5
0
0.5
1
1.5
Δη

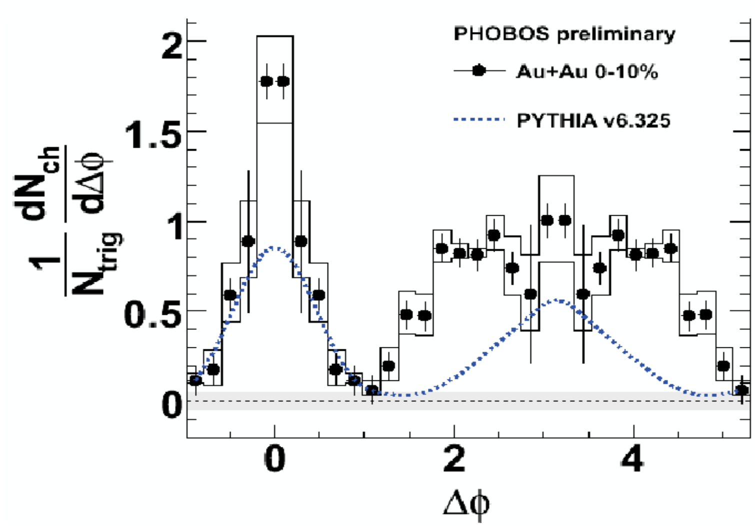
Extent of Ridge in Δη

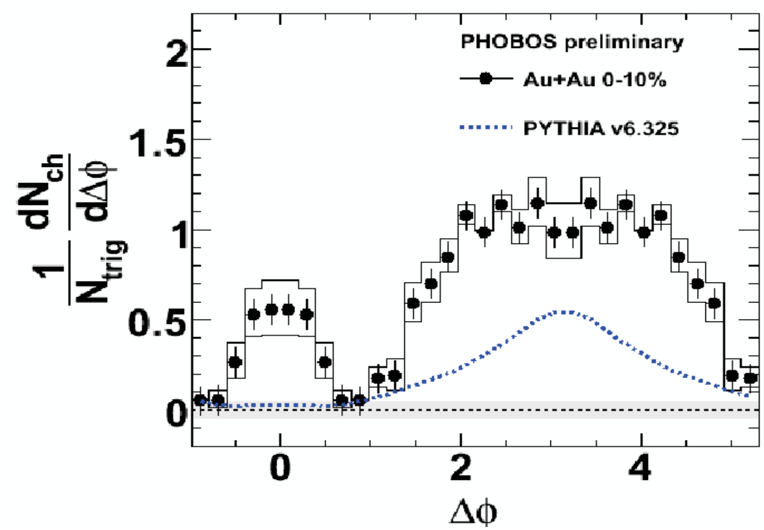
Au+Au 0-30% central



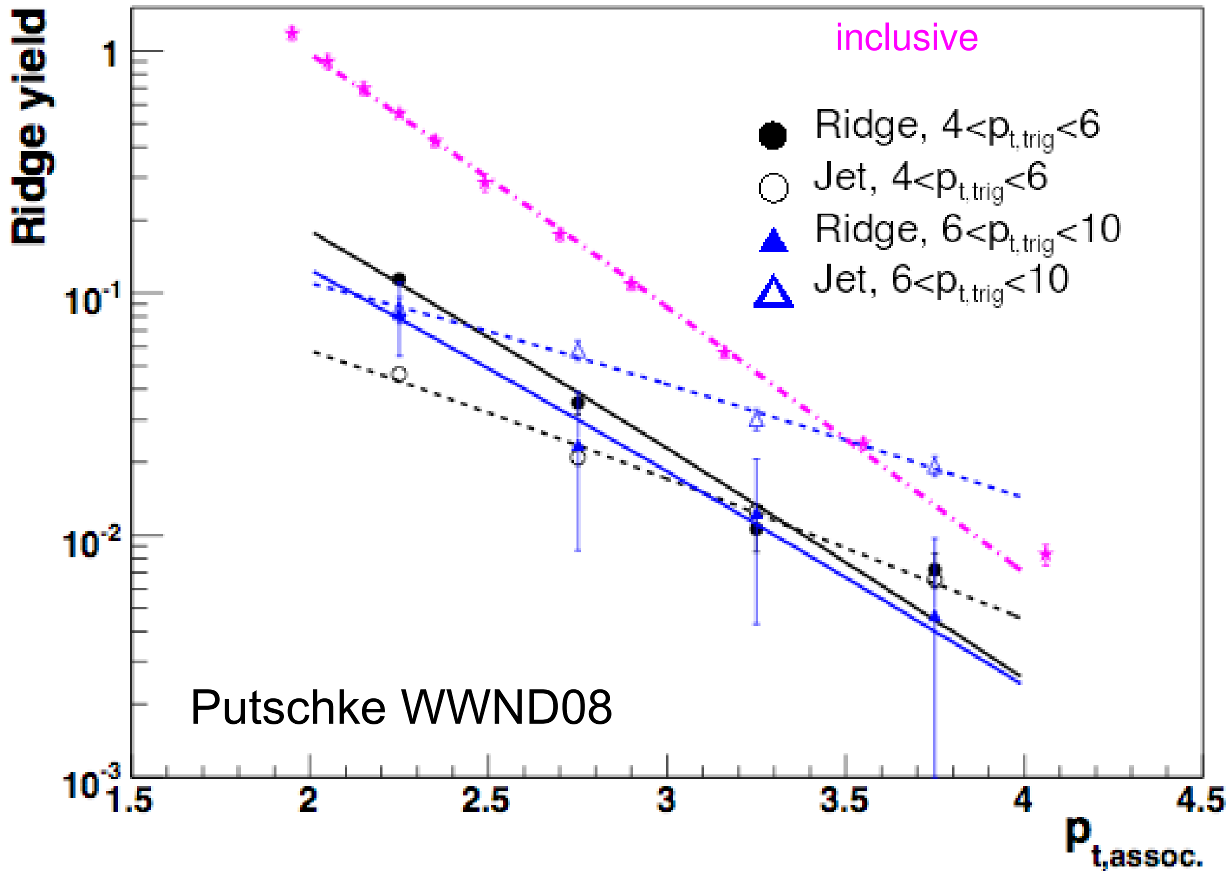
Wenger QM08







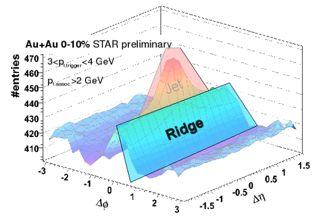
Jet-like correlation is like p+p, Ridge is like bulk

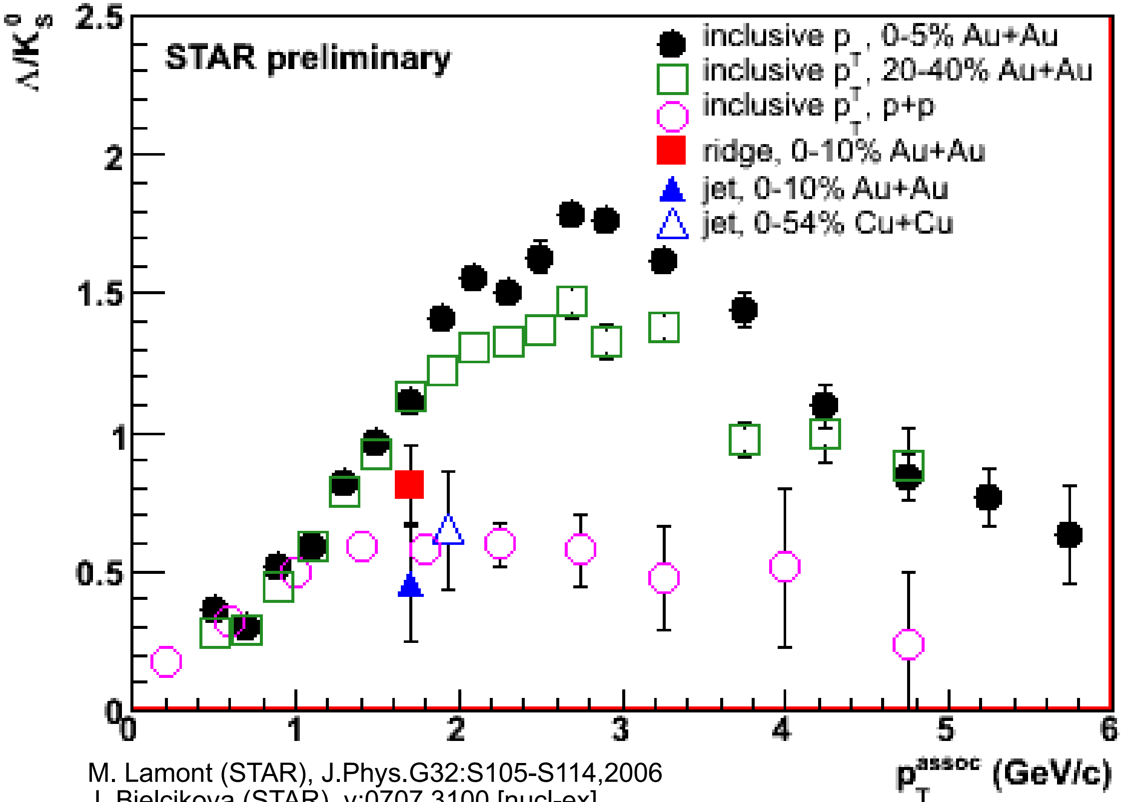


Spectra of particles associated with *Ridge* similar to inclusive

Spectra of particles associated with jet-like correlation harder

Ridge composition





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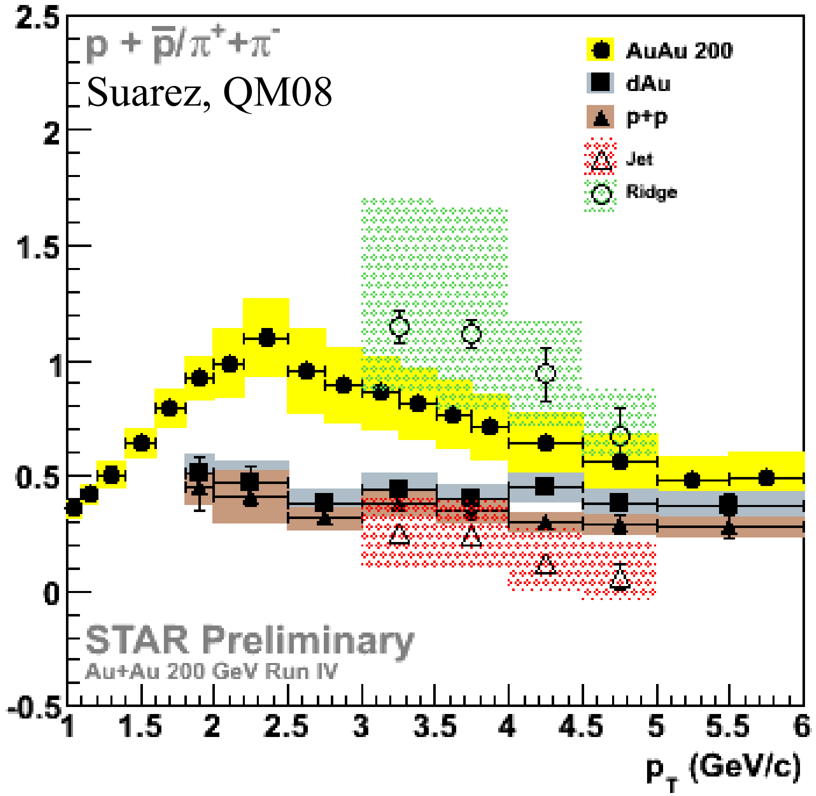


Baryon/meson ratios in *Ridge* similar to bulk for both strange and non-strange particles

"Fragmentation functions"

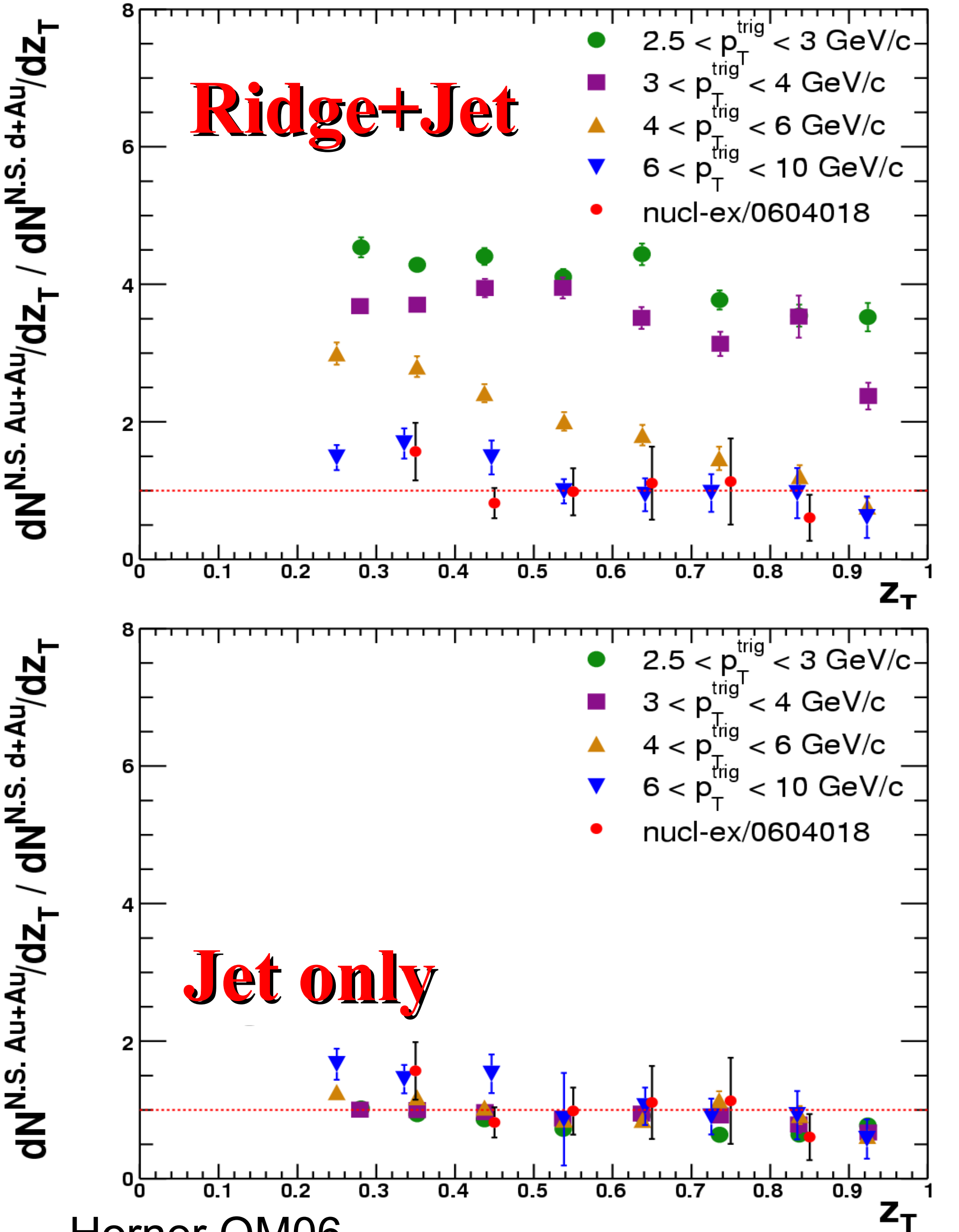
Measure hadron triggered fragmentation functions:

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

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

Jet-like correlation +Ridge: $D^{h1,h2}(z_T)$ different for d+Au, Au+Au

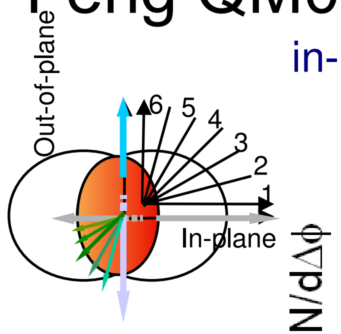
Jet-like correlation only: $D^{h1,h2}(z_T)$ within errors for d+Au, Au+Au

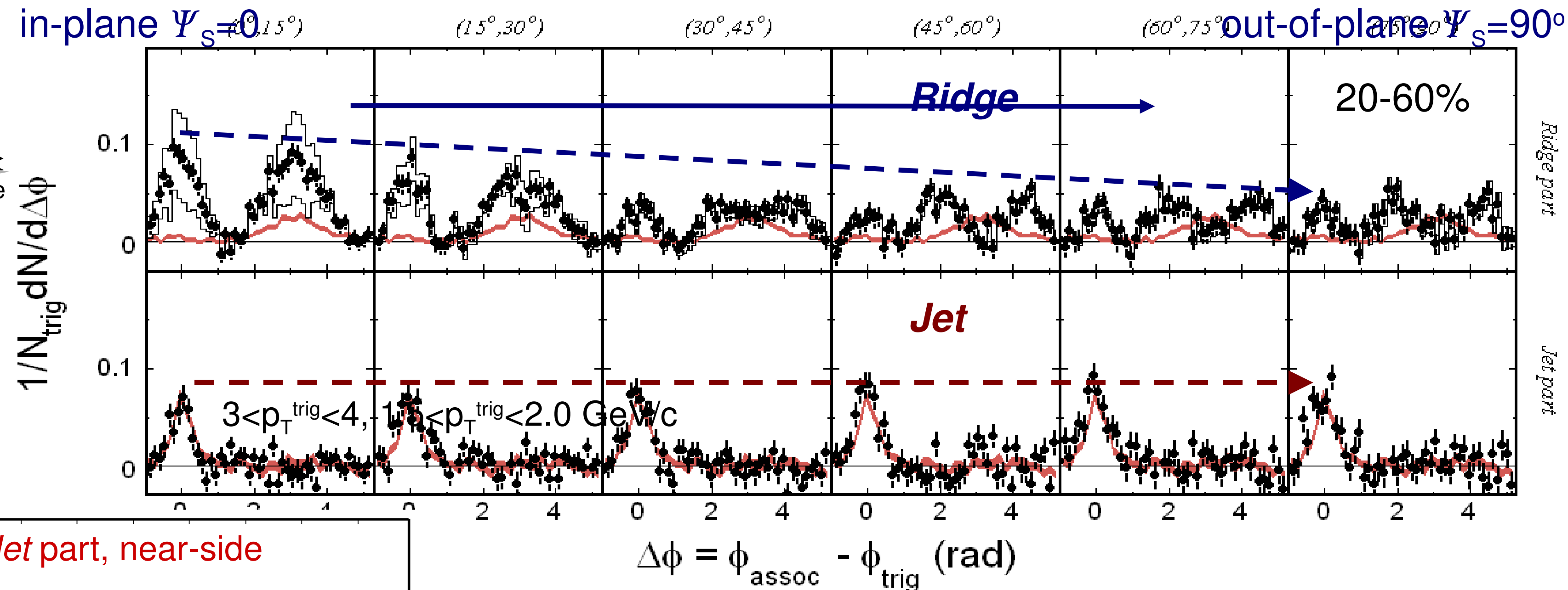


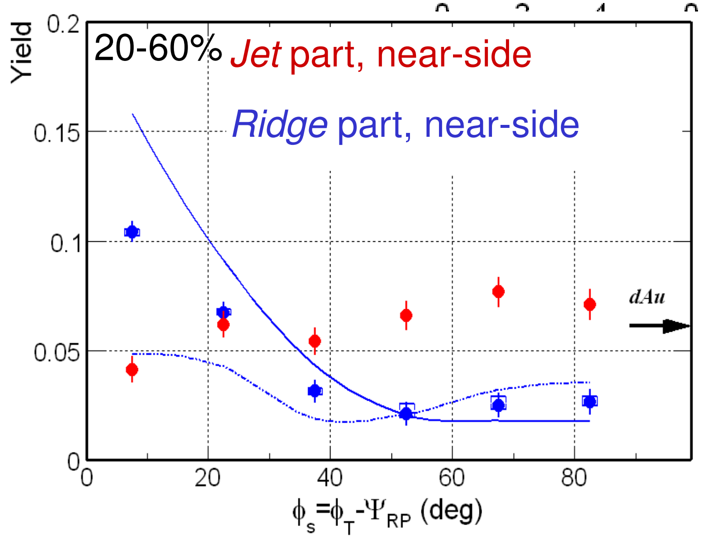
Horner QM06

Jet/Ridge w.r.t. reaction plane

Feng QM08







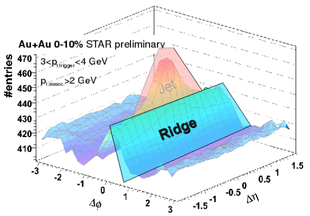
Ridge yield decreases with φ_S. Smaller ridge yield at larger φ_S

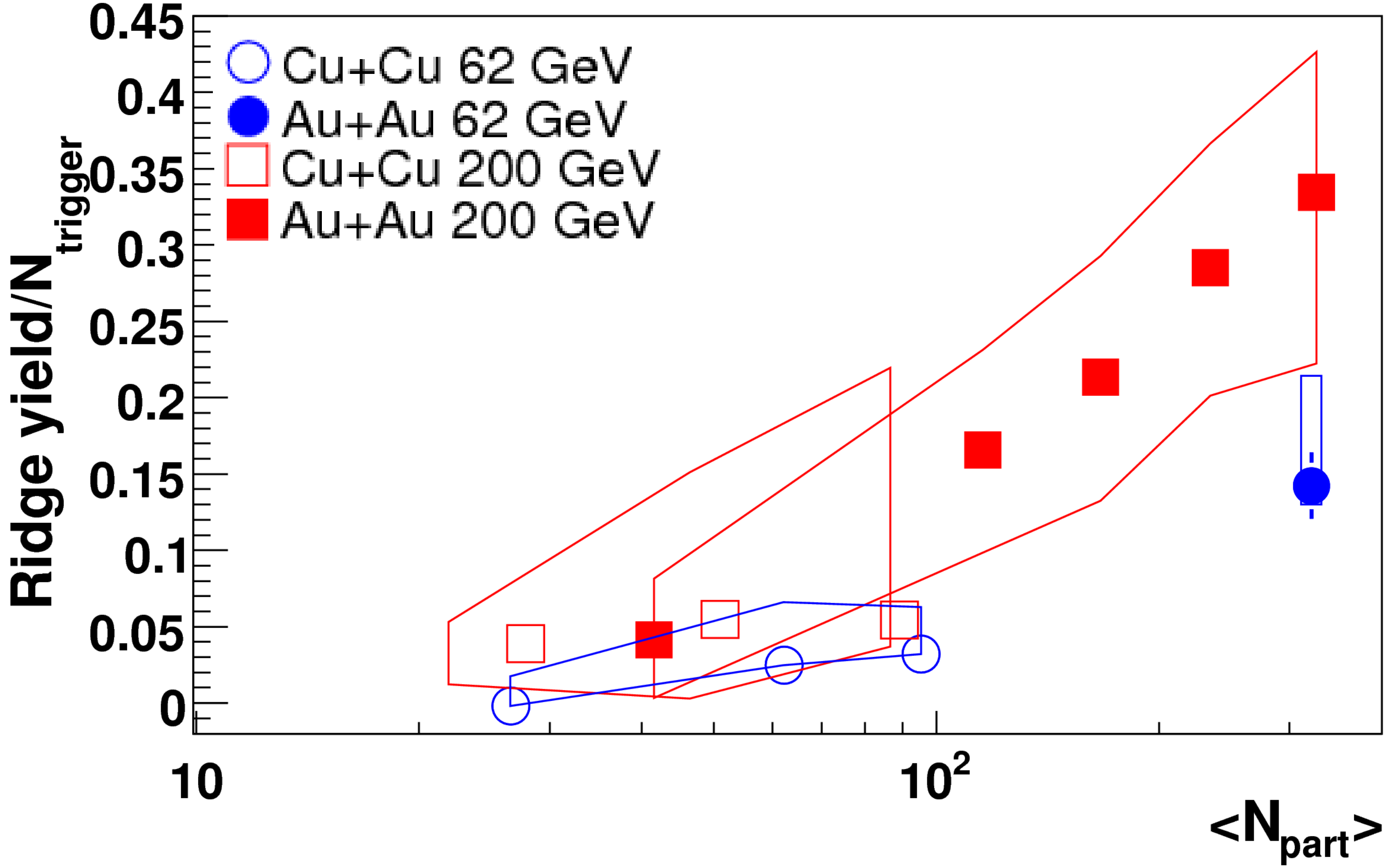
Jet yield approx. independent of φ_S and comparable with d+Au

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.

19

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

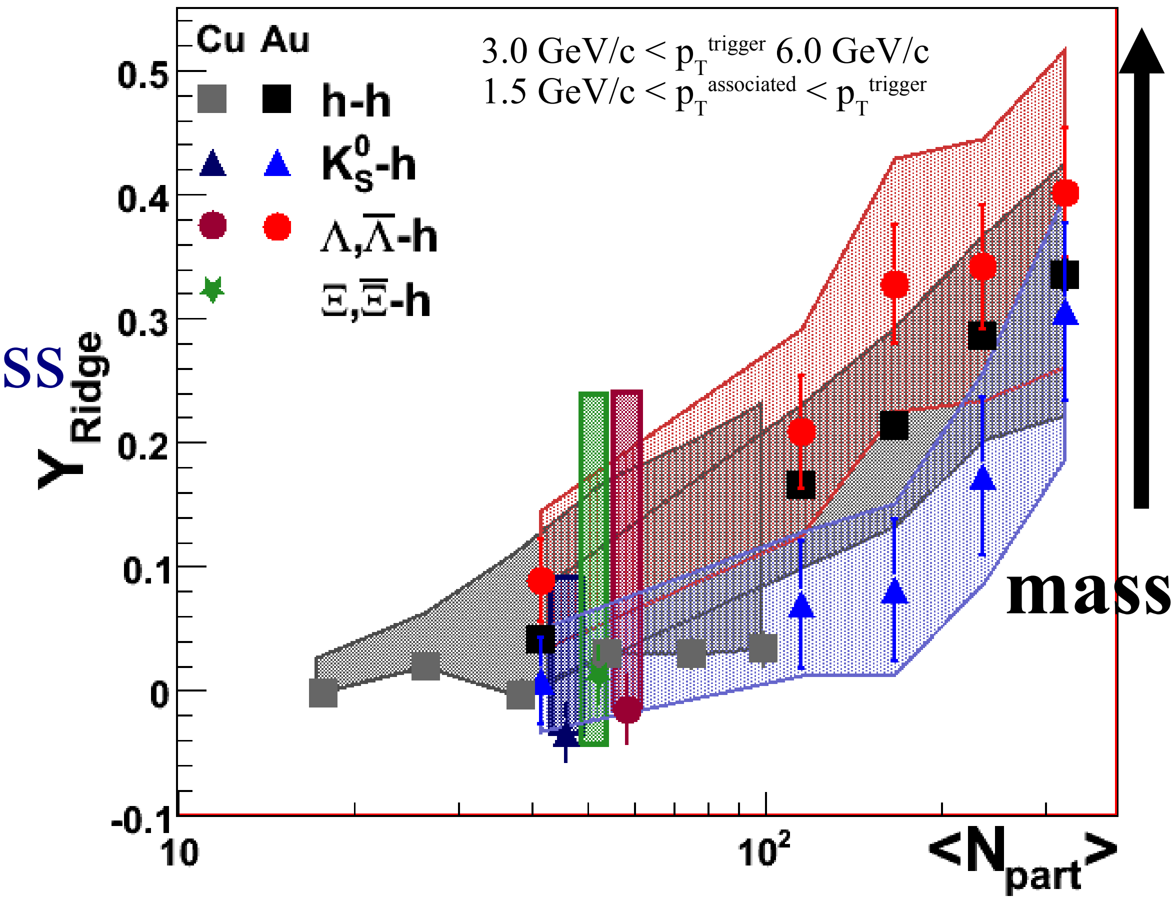
Identified trigger: Near-side Yield vs N_{part}

Cu+Cu consistent with Au+Au at same N_{part}

If systematic errors in Au+Au are not correlated, there is no evidence of mass ordering

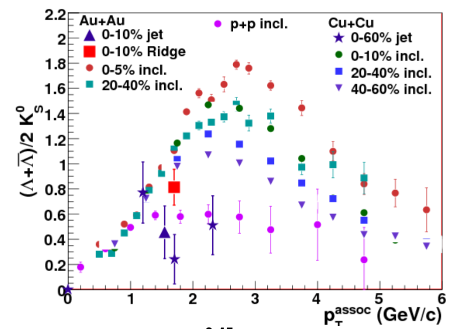
If systematic errors are correlated, Ridge is larger for larger mass

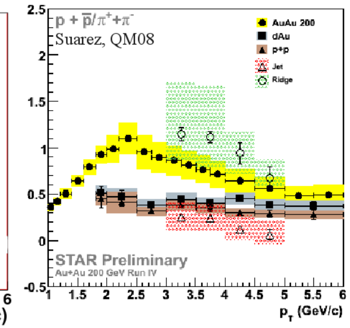
h are 50% p, 50% π



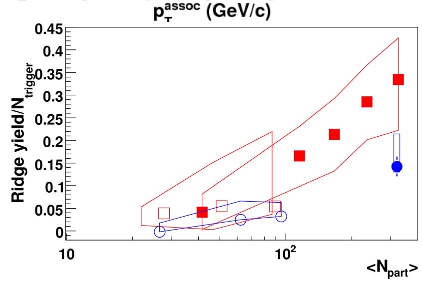
Key experimental results

Jet-like correlation is dominantly produced by fragmentation → *Ridge* production must not affect formation of jet-like correlation

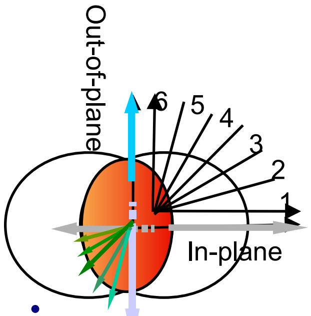




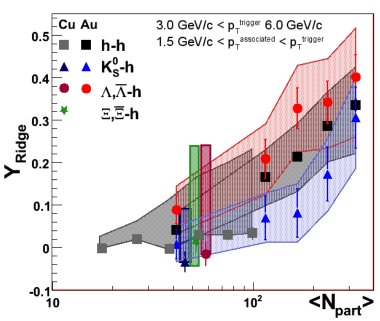
Particle ratios in *Ridge* comparable to bulk



The *Ridge* is smaller in collisions at $\sqrt{s_{NN}}$ = 62 GeV than 200 GeV



Ridge is larger in plane than out of plane



If there is a mass ordering, *Ridge* increases with increasing trigger mass

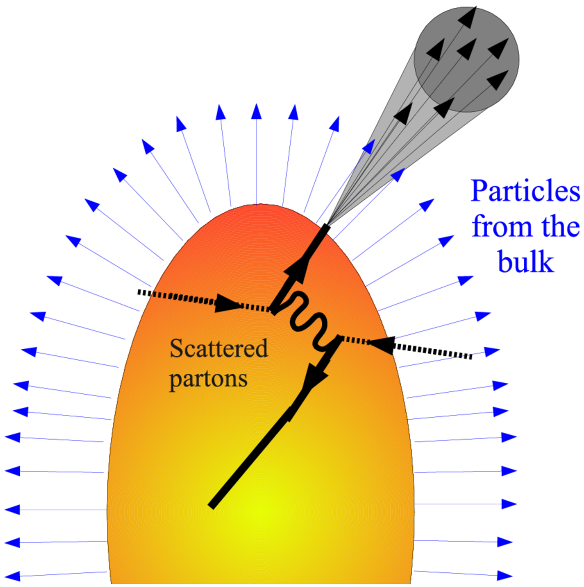
The Ridge is broad in Δη

Comparisons to theories

Radial flow + trigger bias

Radial flow means that most particles are moving out from the surface of the medium

If hard partons are also surface biased, hadrons from fragmenting partons will also be surface biased



This will lead to a correlation between hard partons and medium partons → the *Ridge*

Several implementations of this mechanism

A boost in momentum mimicking radial flow added to PYTHIA (Voloshin, Pruneau, Gavin)

Radial flow + trigger bias added to a Glasma initial state (Gavin, Moschelli, McLerrin)

Correlated Emission Model adds this mechanism to Recombination (Hwa)

Radial flow + trigger bias

Jet-like correlation: not affected ☺

Particle ratios: from bulk → comparable to bulk ☺

Ridge in 62 vs 200 GeV: not clear 😐

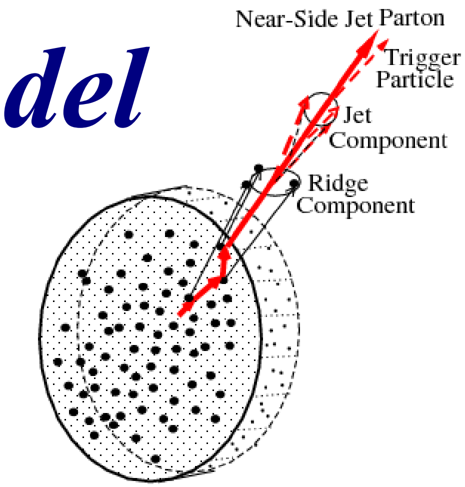
Reaction plane dependence: described by data ☺

Mass ordering: If surface bias is from radial flow, ridge should be larger for lighter trigger particles because lighter particles have greater flow. The opposite trend is observed → if this is the mechanism, surface bias must come from jet quenching 😐

Ridge is broad in $\Delta\eta$: described by model ☺

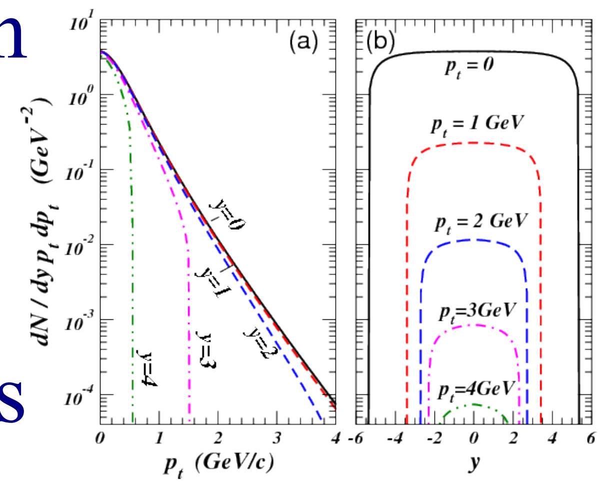
→ Consistent with most observations but need more quantitative calculations

Momentum kick model



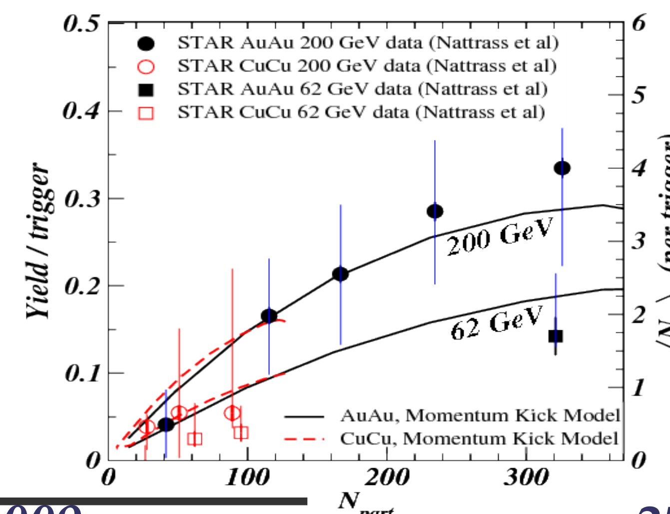
Hard partons moving through the medium collide with partons from the medium

These partons acquire a momentum kick in the direction of the hard parton, leading them to be correlated with the hard parton → the *Ridge*



Since the distribution of medium partons is broad in Δη, the *Ridge* is broad in Δη

Causal limit to how far in Δη the correlation in Δη can extend → unusual distribution in Δη, strongly p_T dependent



Able to describe energy dependence

Momentum kick model

Jet-like correlation: not affected ☺

Particle ratios: from bulk → comparable to bulk ☺

Ridge in 62 vs 200 GeV: agrees with data ☺

Reaction plane dependence: naively greater for longer path length ☹

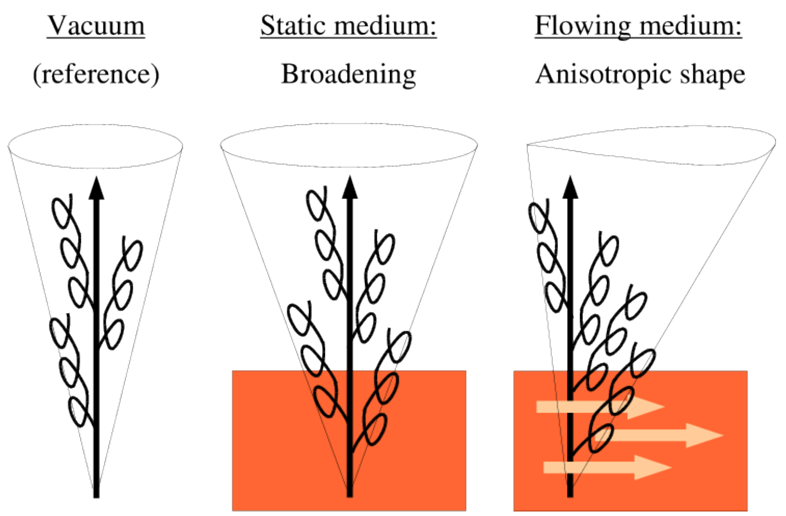
Mass ordering: unclear 😐

Ridge is broad in $\Delta\eta$: described by model ☺

→ Consistent with most observations but needs to be reconciled with reaction plane dependence

Gluon radiation

Hard partons moving through the medium emit gluon bremsstrahlung



Longitudinal flow:

Longitudinal flow sweeps these gluons in pseudorapidity →the Ridge

Plasma instabilities

Plasma instabilities form due to the rapidly fluctuating strong fields early in the formation of the collision

These fluctuating strong fields make the plasma unstable and deflect gluons radiated by hard partons

Gluon radiation

Jet-like correlation: not affected ☺

Particle ratios: from gluon fragmentation, likely comparable to ratios in p+p ☹

Ridge in 62 vs 200 GeV: not clear 😐

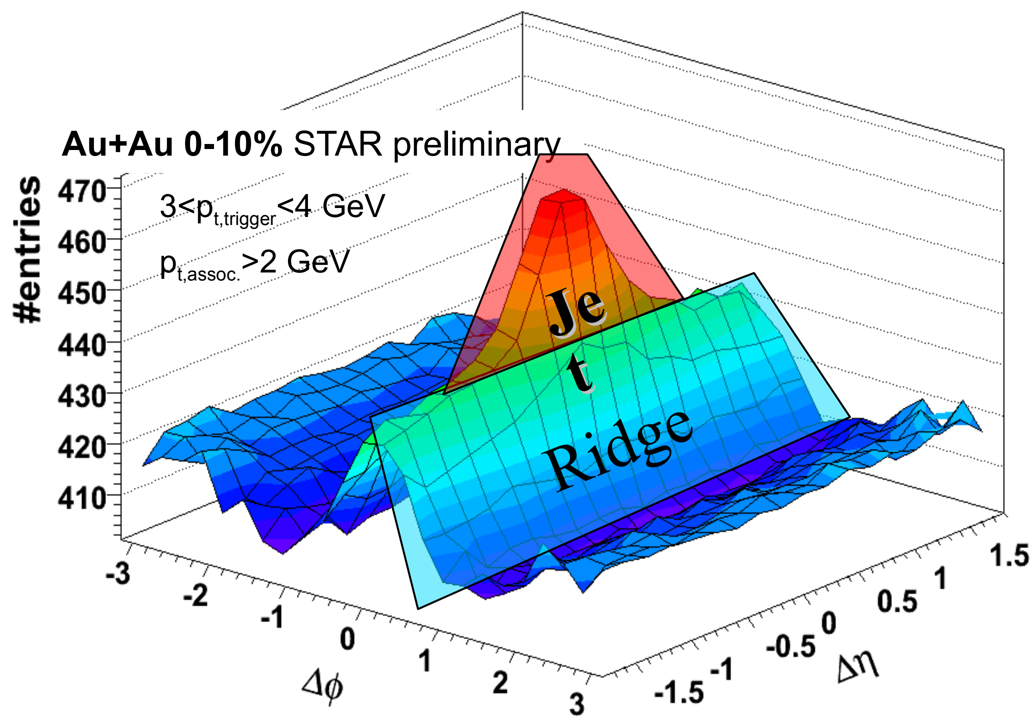
Reaction plane dependence: naively greater for longer path length ☹

Mass ordering: For longitudinal flow mechanism, also expect greater *Ridge* for lighter particles because flow is greater. ☹

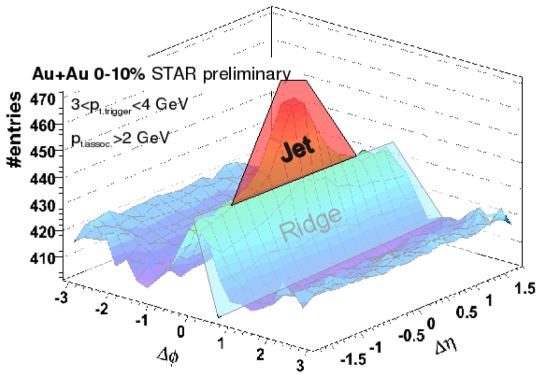
Ridge is broad in $\Delta\eta$: not consistent with current calculations, may have causal problems ☹

→ Several aspects not likely consistent with data

Conclusions



Jet-like correlation



Particle dependence consistent with vacuum fragmentation

No system dependence

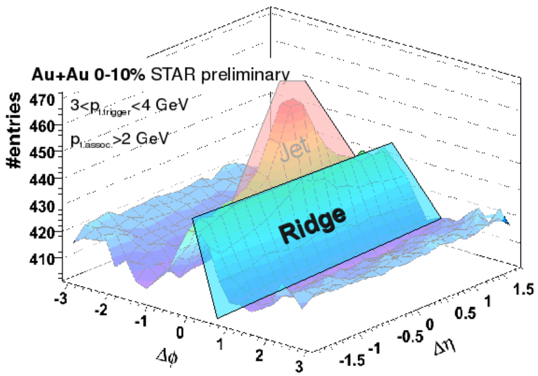
PYTHIA quantitatively describes data except at lowest $p_T^{trigger}$, p_T^{assoc}

→ Jet-like correlation is dominantly produced by vacuum fragmentation

→ Can understand the effects of kinematic cuts on parton sample through jet-like correlation

→Deviations from vacuum fragmentation either come from the *Ridge* or from a slight modification fragmentation in A+A

The *Ridge*



Several models on the market

Radial flow + trigger bias able to describe most aspects of the data

Momentum kick model consistent with data

Gluon bremsstrahlung models have several apparent inconsistencies with data → likely excluded

Radial flow + trigger bias mechanism dependent on validity of hydrodynamics, less speculative

But need more quantitative calculations!

Outlook

- More studies of energy dependence possible
  - RHIC beam energy scan
  - LHC
- Better studies of Ridge, jet-like correlation at RHIC
  - EMCal triggered data
  - Full jet reconstruction

Backups

PHOBOS

Coverage:

With tracking:

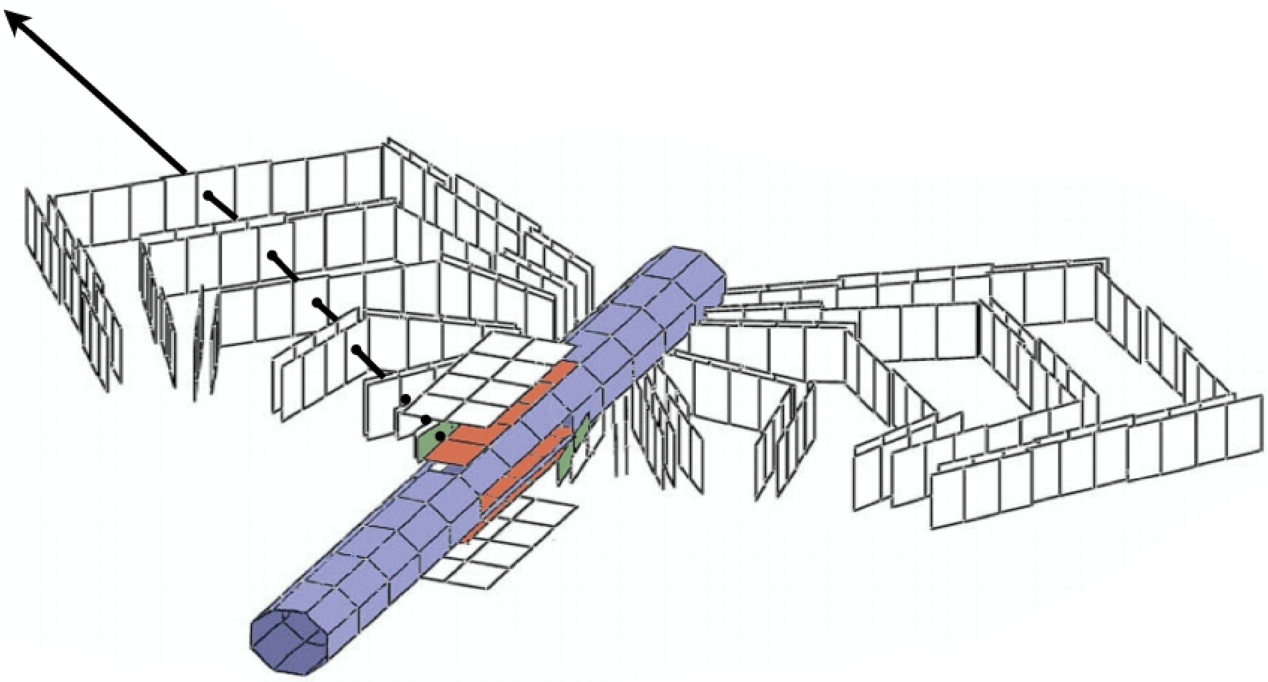
$0<\phi<0.2$, x2

$0<\eta<1.5$

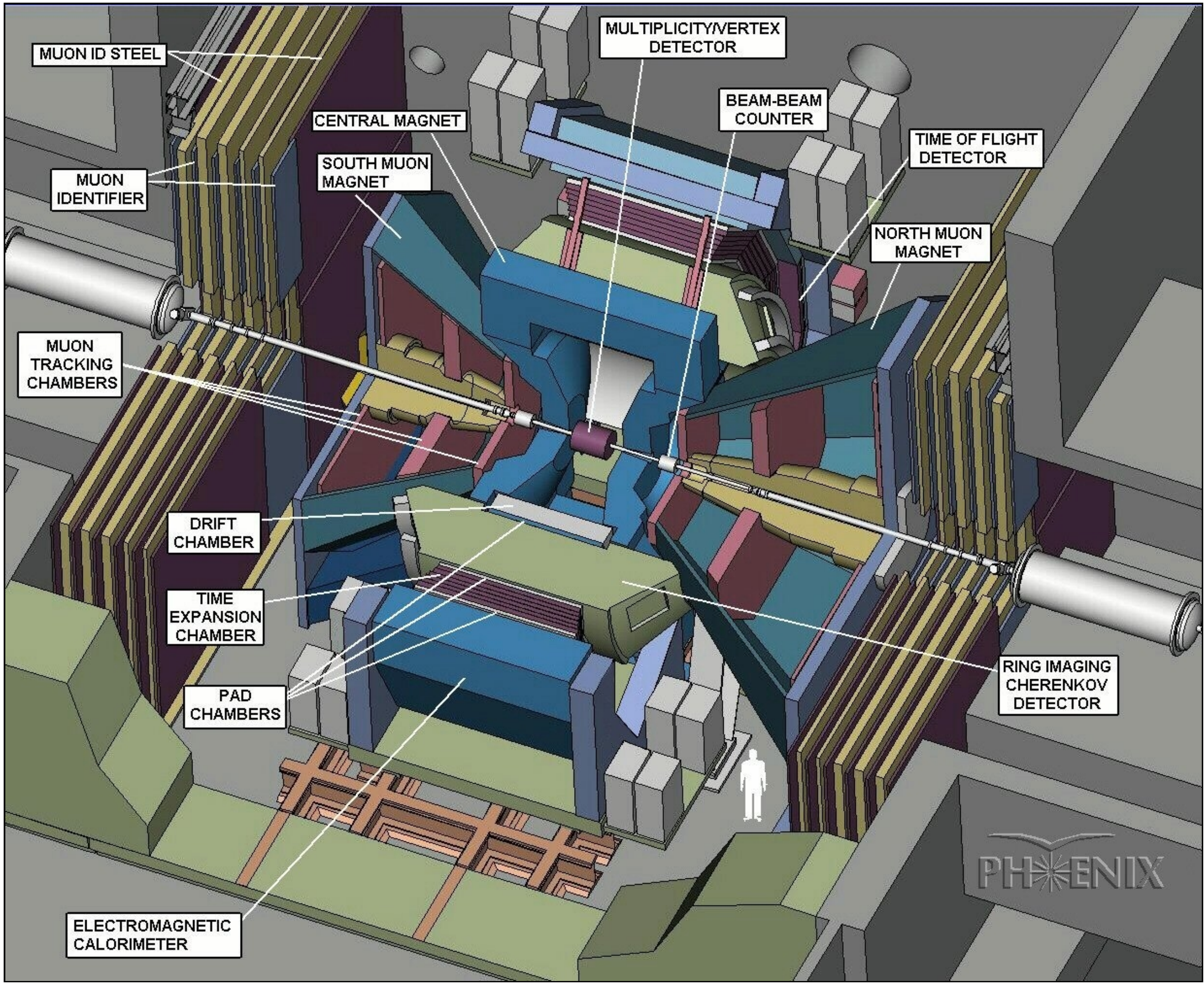
Without tracking:

$0<\phi<2\pi$

$-3<\eta<3$



PHENIX

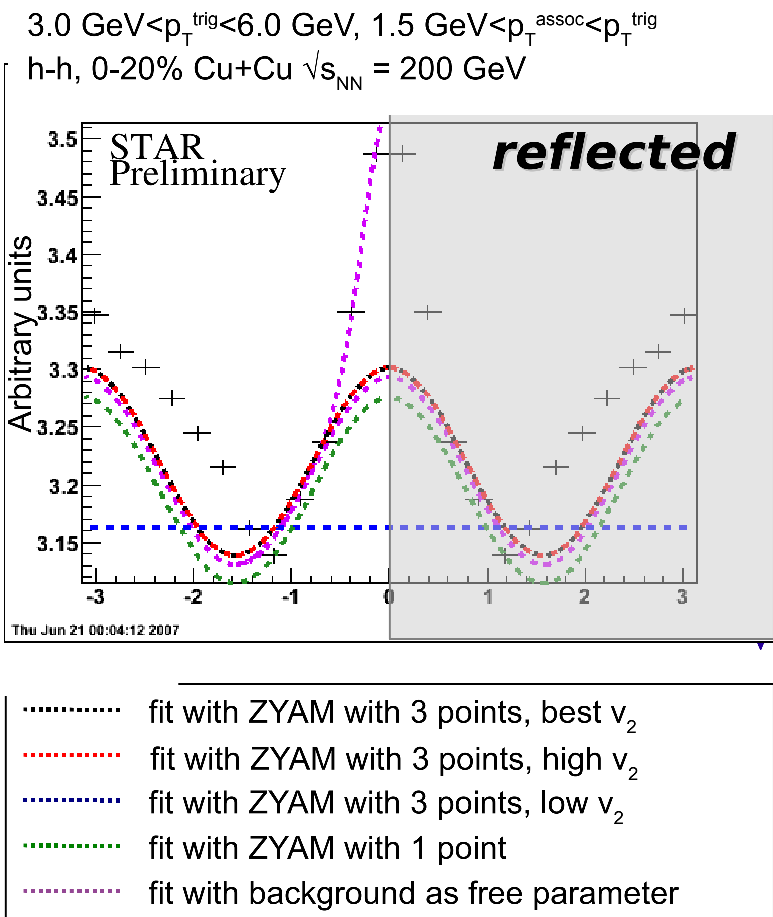


Coverage:

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

$-0.35<\eta<0.35$

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

Zero *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

Method: Yield extraction

Ridge previously observed to be independent in Δη in Au+Au

To determine relative contributions, find yields for near-side, take ΔΦ projections in

-0.75<Δη<0.75 ***Jet + Ridge***

0.75<|Δη|<1.75 ***Ridge***

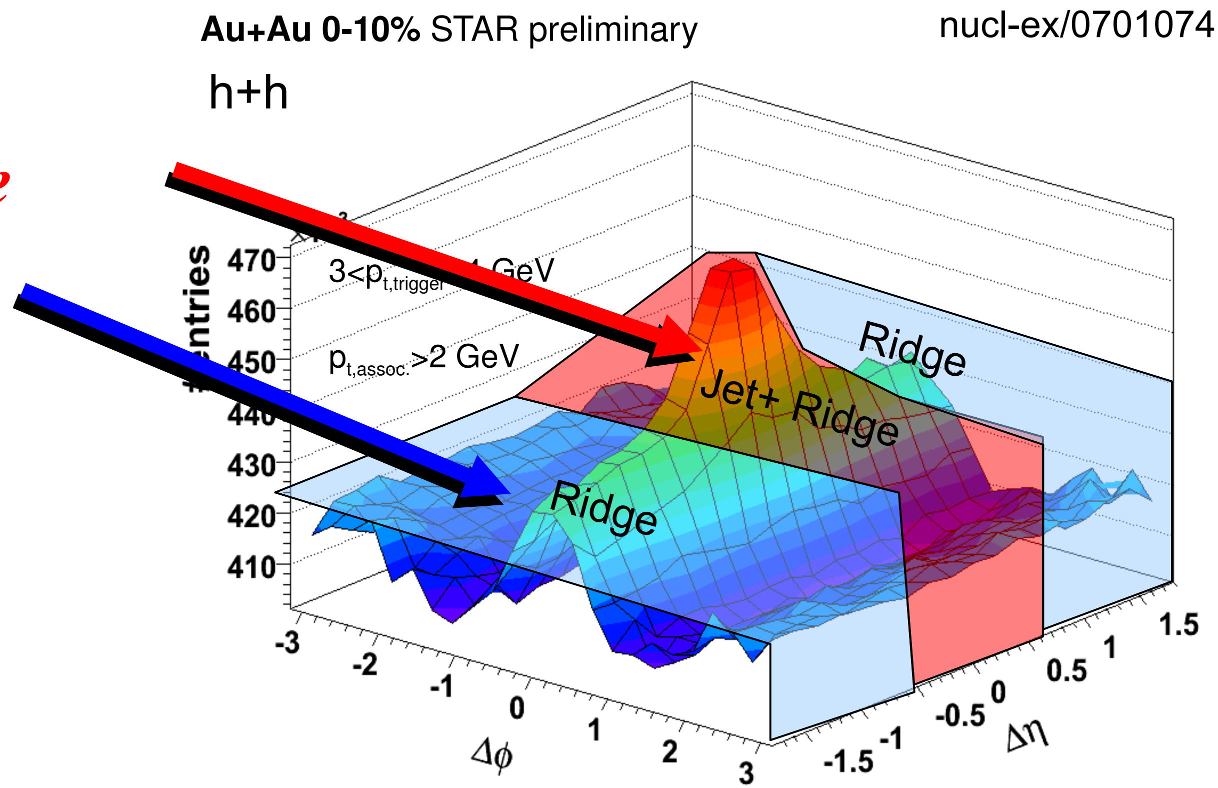
Jet = (*Jet+Ridge*) – *Ridge**.75/1.0

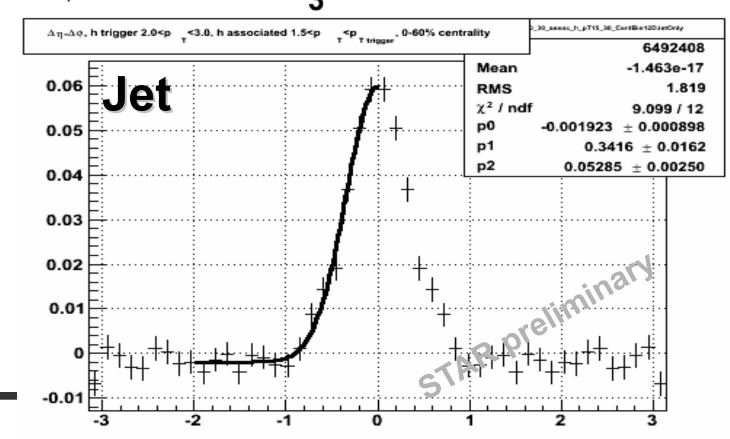
Ridge = yield from -1.75<Δη<1.75 – *Jet* yield

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)





Background – hydrodynamical flow

Particles exhibit collective flow relative to the reaction plane

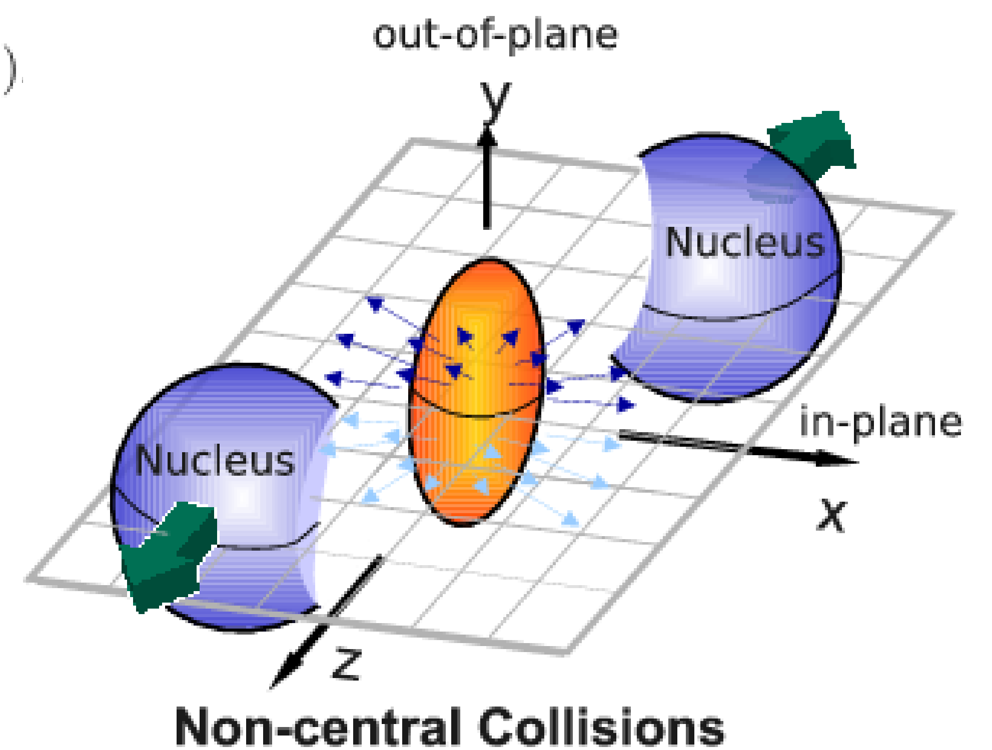
$$E\frac{d^3N}{d^3p_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+\sum_{n=1}^{\infty} 2v_n cos(n(\phi - \psi_{RP})))$$

If neither the trigger particle nor the associated particle comes from a jet, they will be correlated with the reaction plane

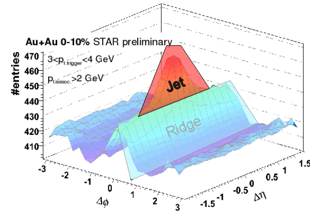
This is a background in di-hadron correlation analyses:
$B(1+2\ v_2^{trig}\ v_2^{assoc}\ \cos(2\Delta\Phi))$

v_2 independent of η for $|\eta|<1$

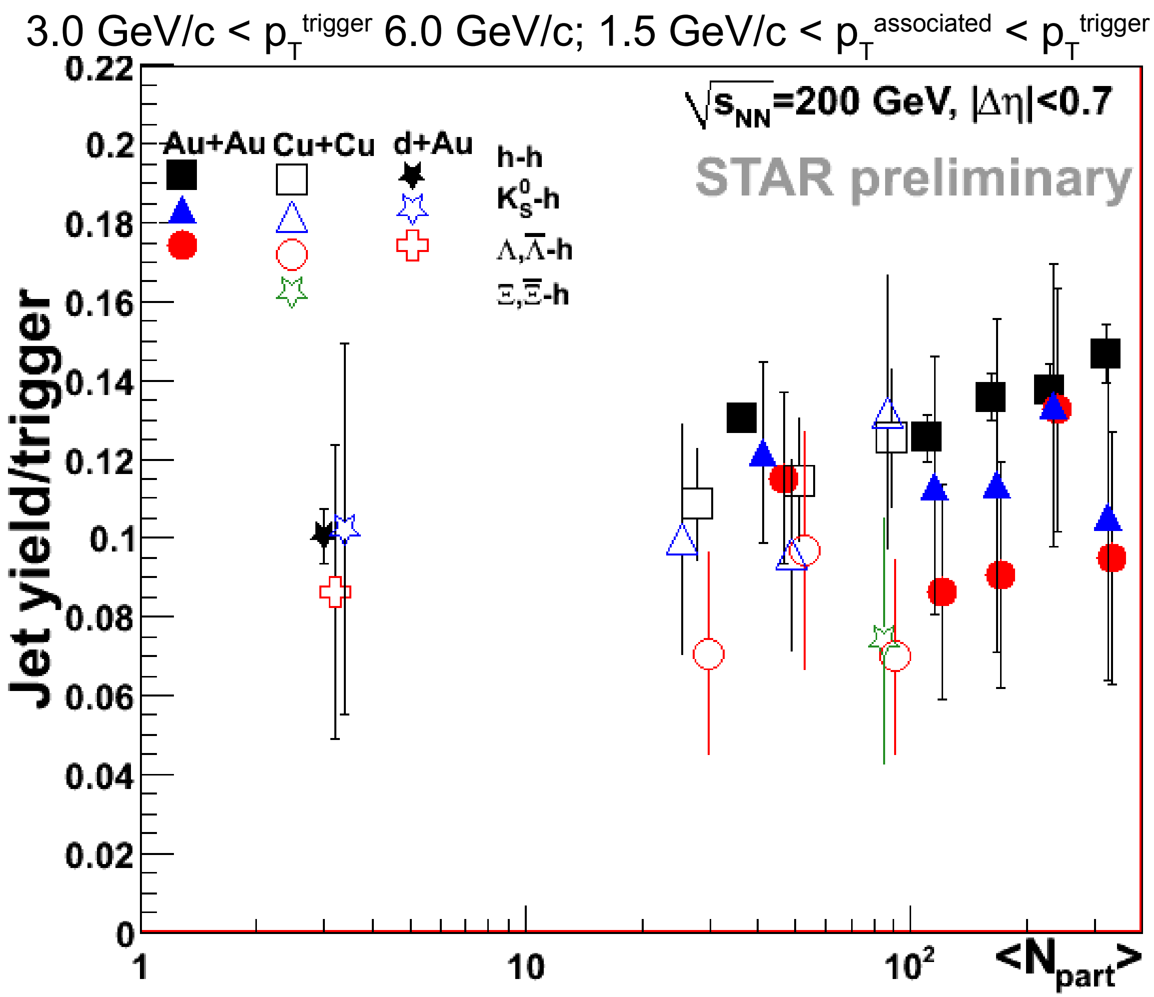
Phys. Rev. C72, 051901(R) (2005), Phys. Rev. Lett. 94, 122303 (2005)



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



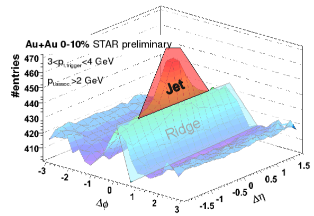
Jet yield -
No trigger type dependence



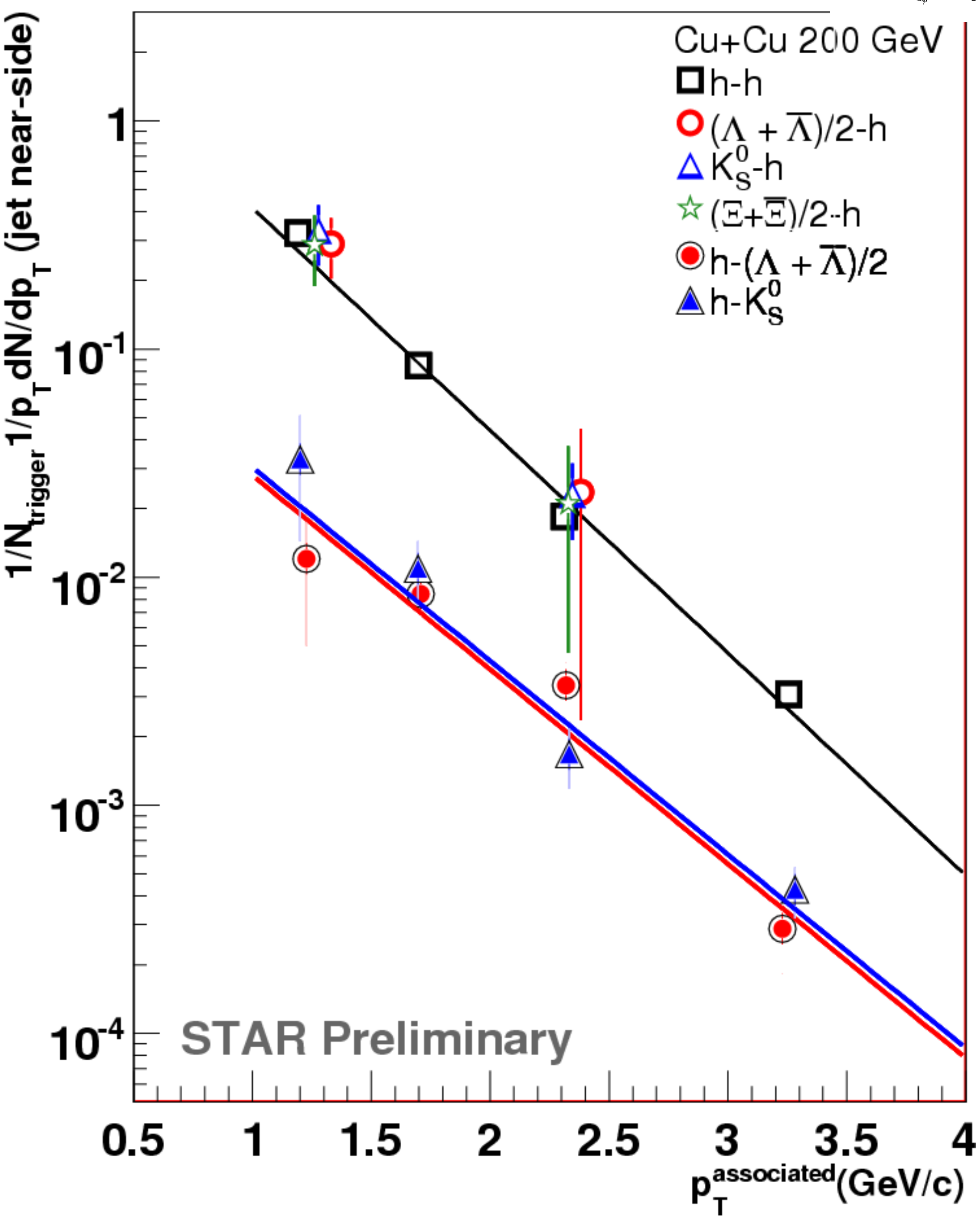
d+Au, Au+Au $\sqrt{s_{NN}}$=200 GeV from nucl-ex/0701047
Cu+Cu $\sqrt{s_{NN}}$=200 GeV from SQM2007

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

Identified associated particles



Associated baryons and mesons in *Jet* similar

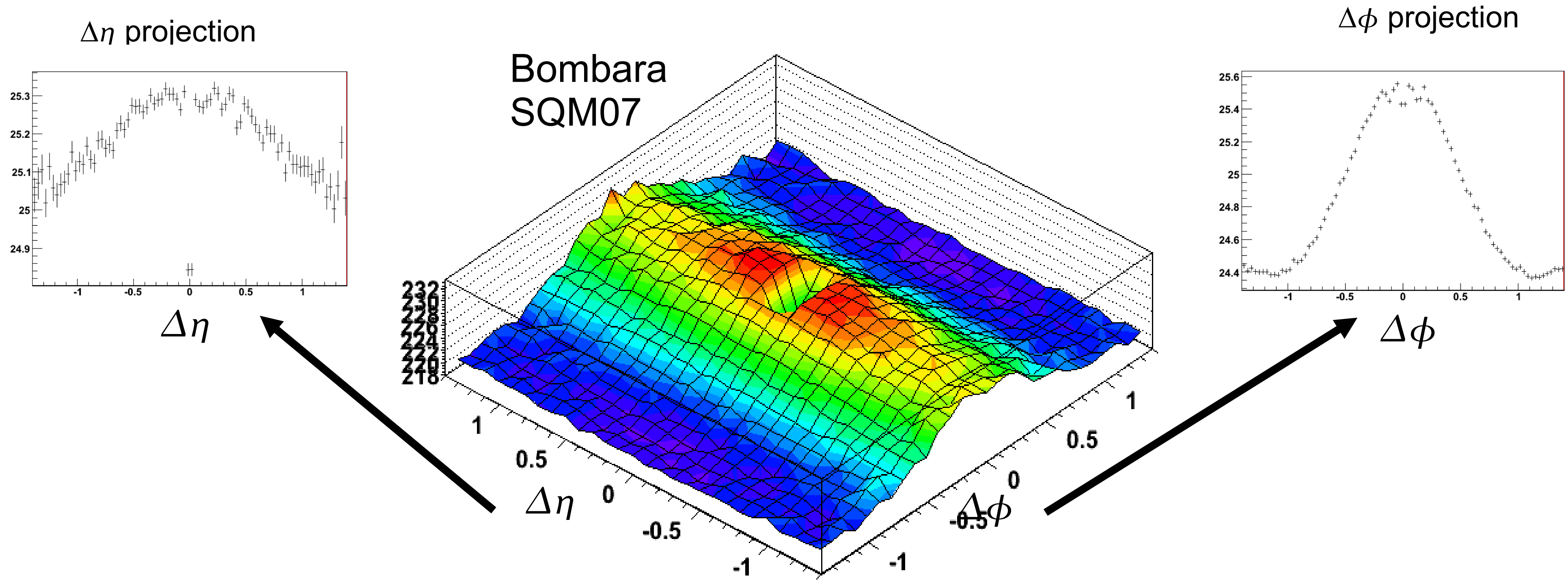


Fits assuming $1/p_T\ dN/dp_T = A\ p_T \exp(-p_T/T)$

$\sqrt{s_{NN}}$=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

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

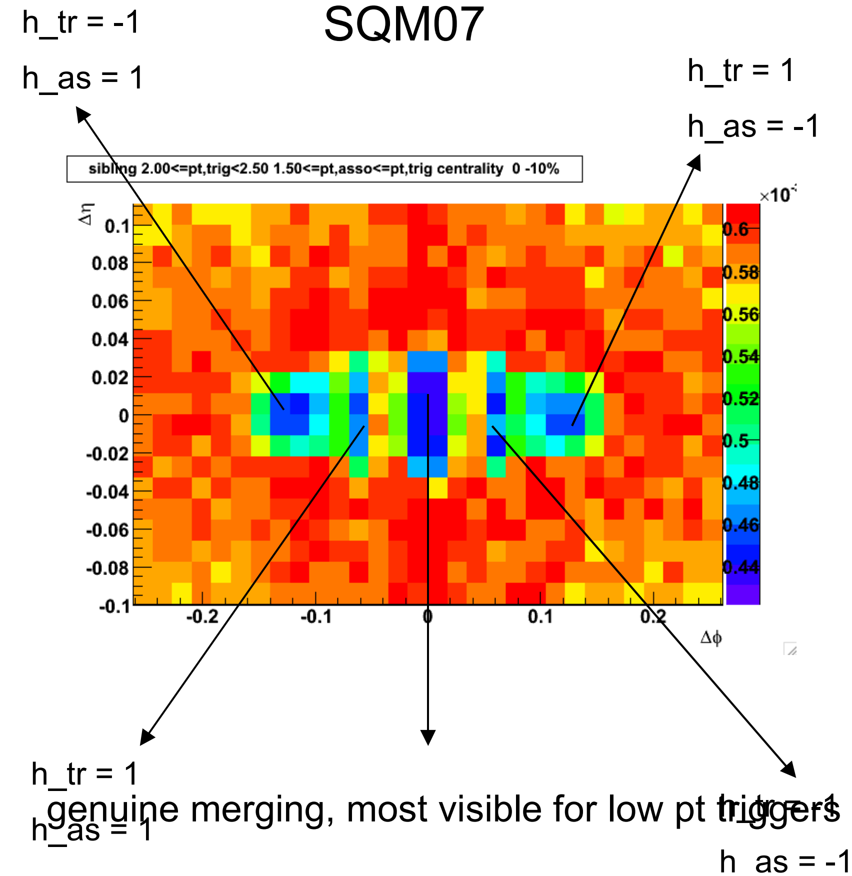
Dependent on p_T: affects lower $p_T^{trigger}$, p_T^{assoc} more

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

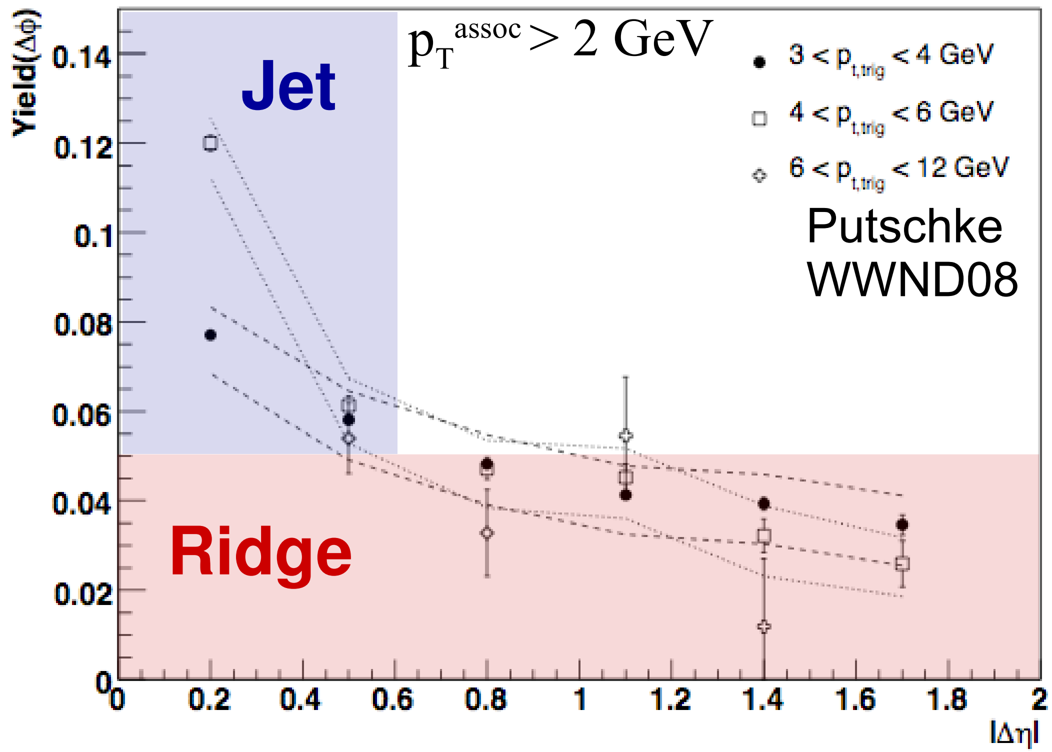
Bombara SQM07



h_tr - helicity of trigger

h_as - helicity of associated

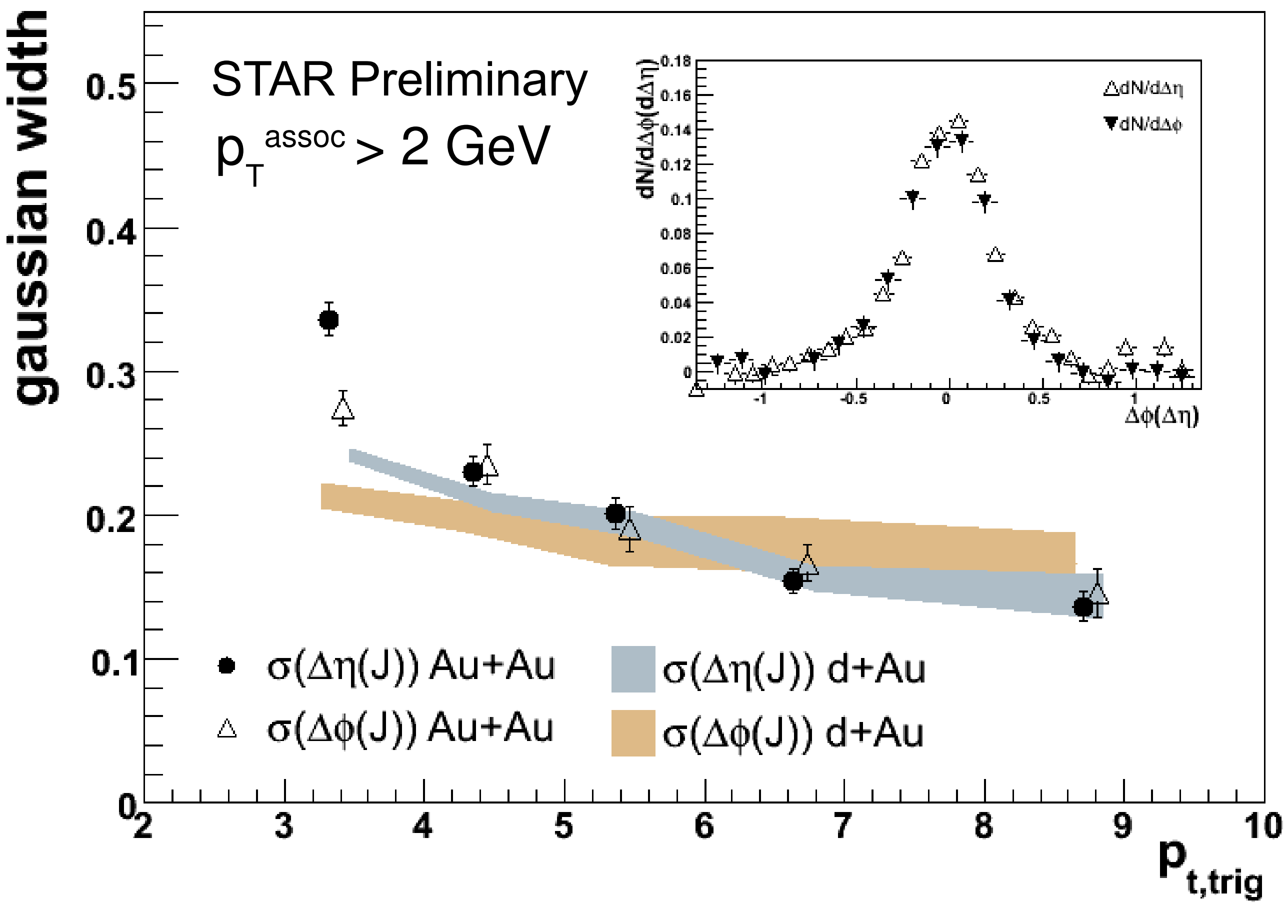
Extent of Ridge in $\Delta\eta$



Ridge yield approximately independent of $\Delta\eta$

Jet increases with $p_T^{trigger}$

Jet-like peak width in central Au+Au

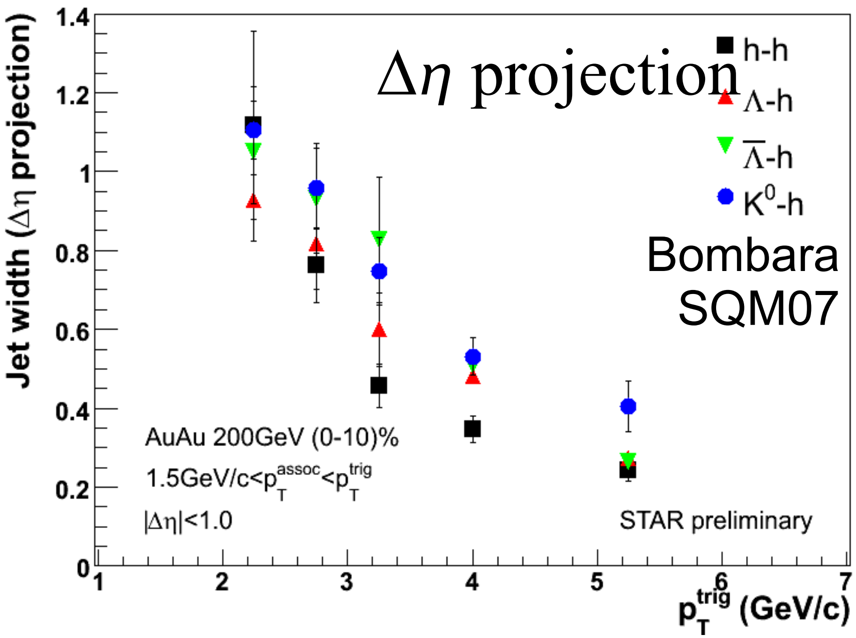


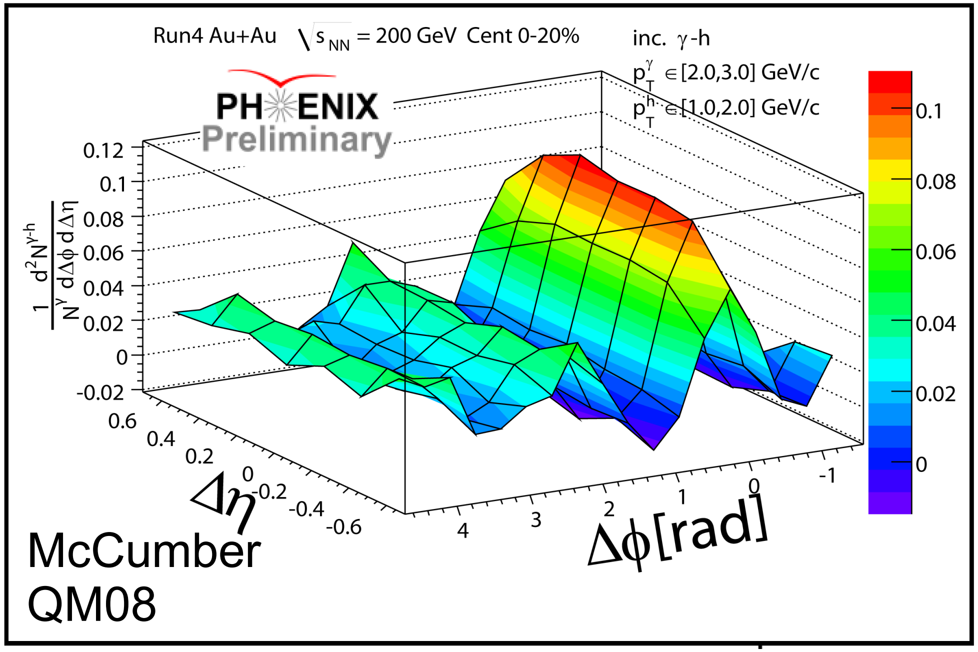
Putschke
WWND08

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

Jet-like peak width in central Au+Au

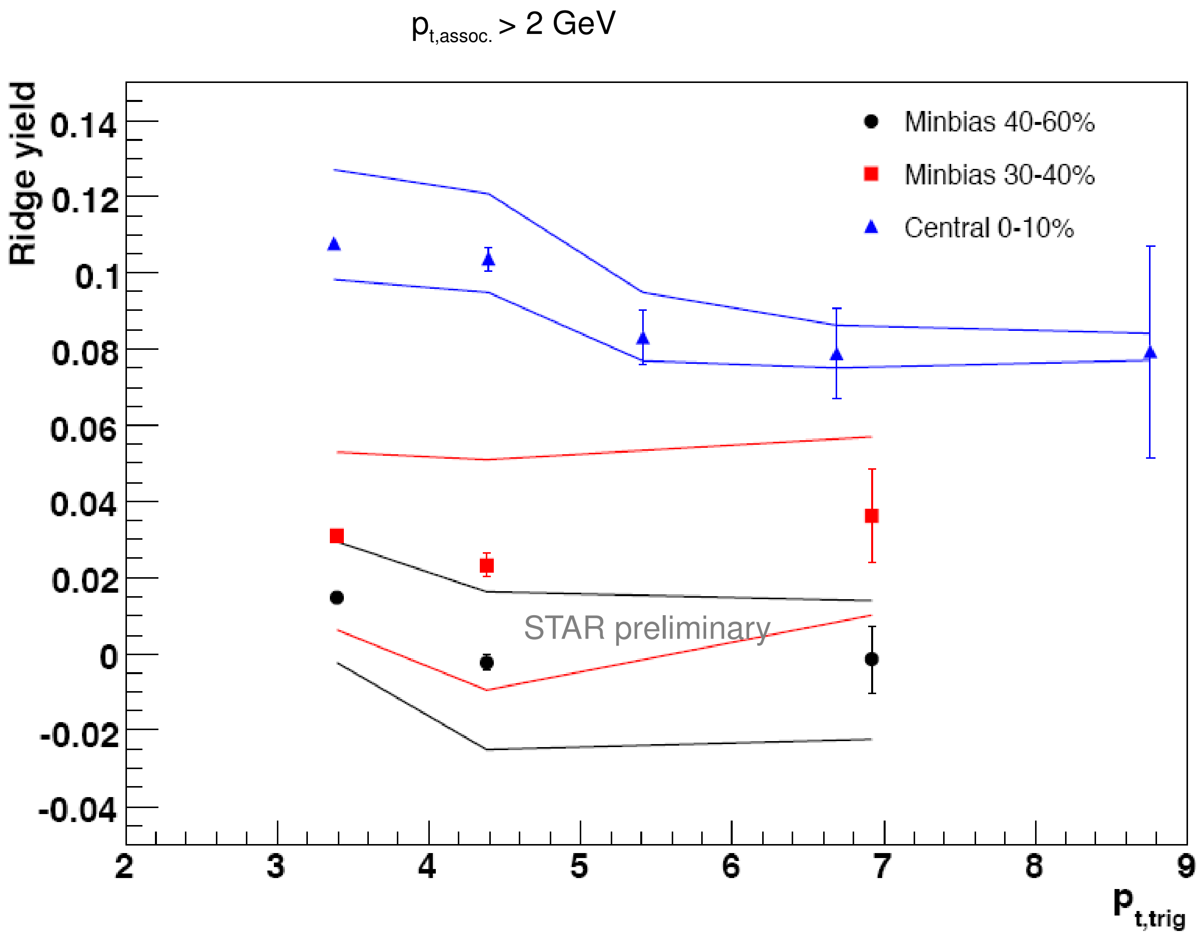




Peak gets broader at higher $p_T^{trigger}$, lower p_T^{assoc}

Width in PHENIX kinematic range close to PHENIX acceptance

Ridge yield vs. pt,trig in Au+Au

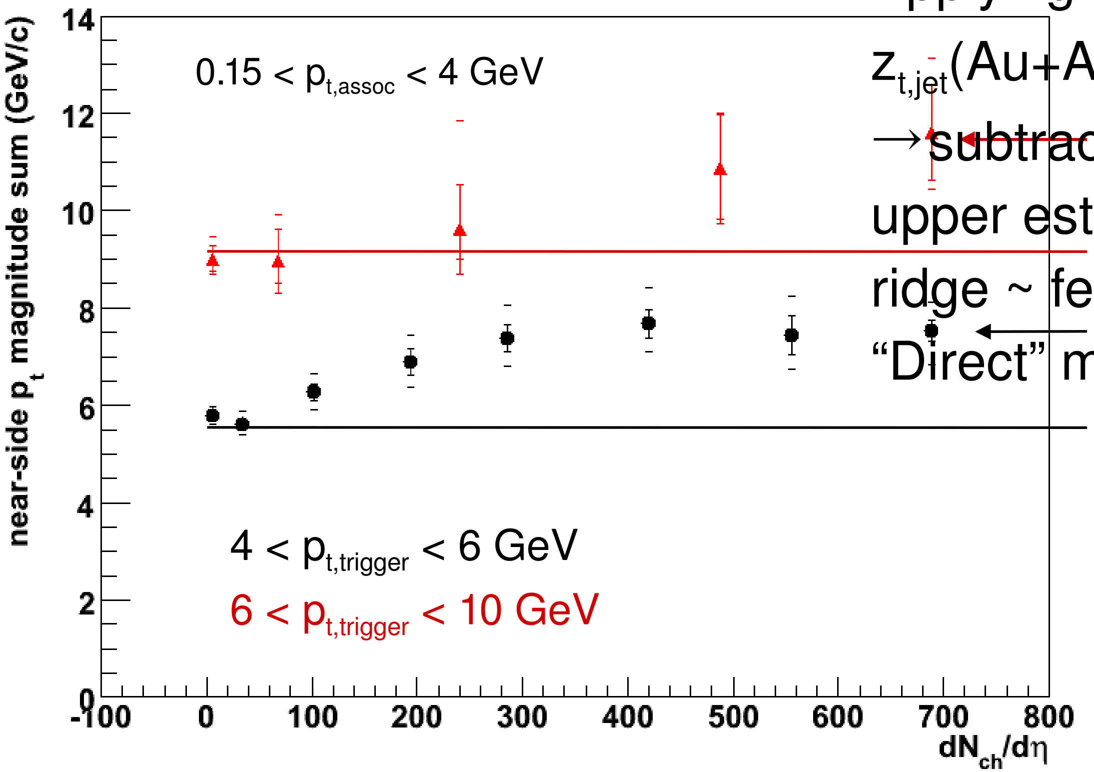


Putschke
WWND08

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

Ridge energy

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



Applying this "2-component picture" to lower $p_{t,ass}$

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

→ subtracting p+p jet energy from Au+Au

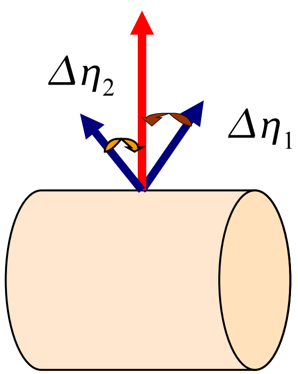
upper estimate of the energy deposit in the ridge ~ few GeV

"Direct" measure of energy loss ?

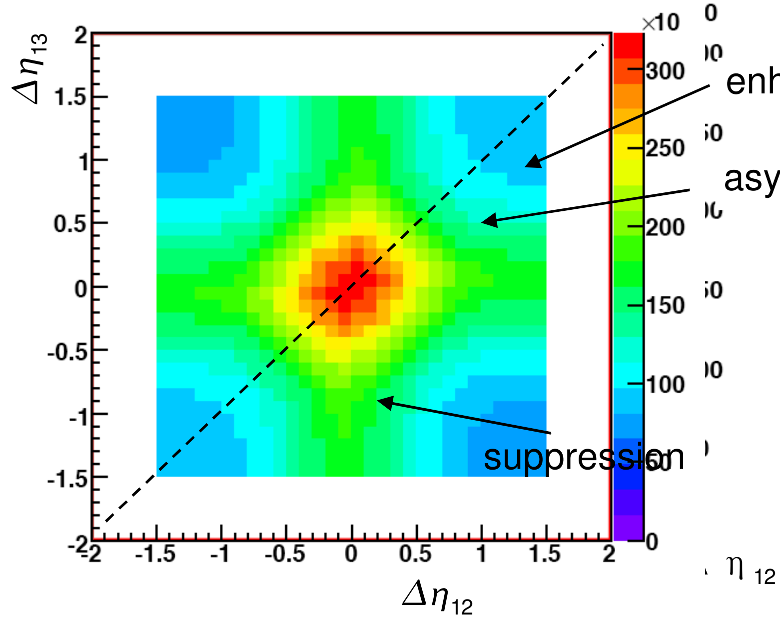
Putschke
WWND08

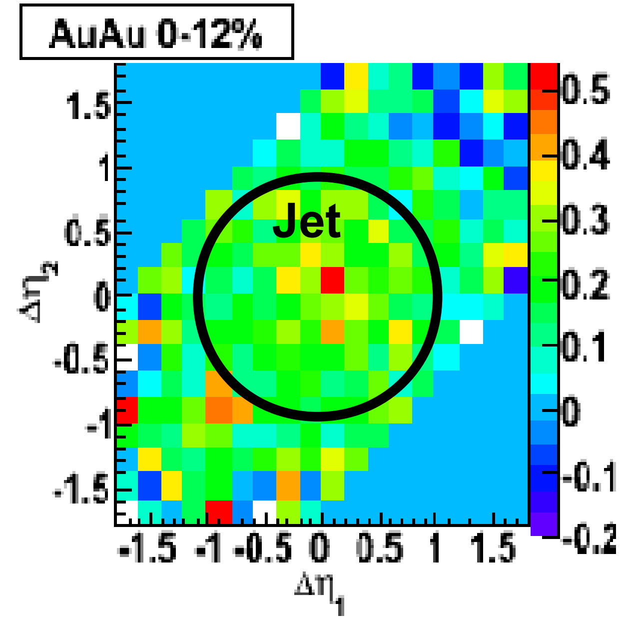
9

3-particle correlations



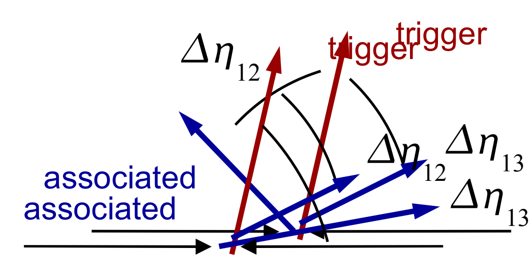
$\Delta\eta_1$ = A1-T
$\Delta\eta_2$ = A2-T





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

Ridge appears uniform event-by-event within STAR detector



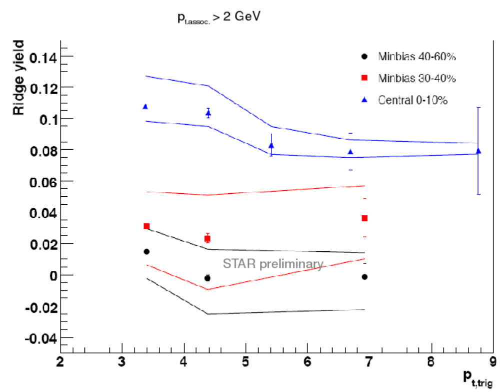
Long. flow picture

Radial flow + trigger bias

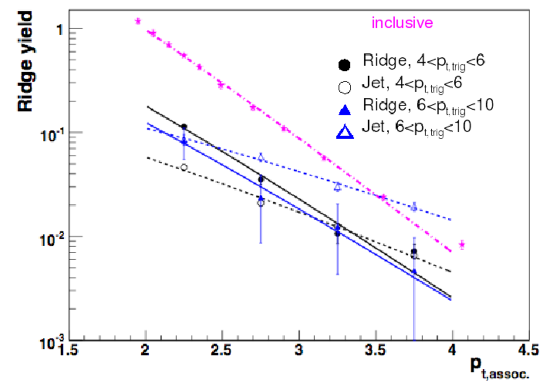
S. Voloshin, nucl-th/0312065, Nucl. Phys. A749, 287

Armesto et al, PRL 93 (2004)

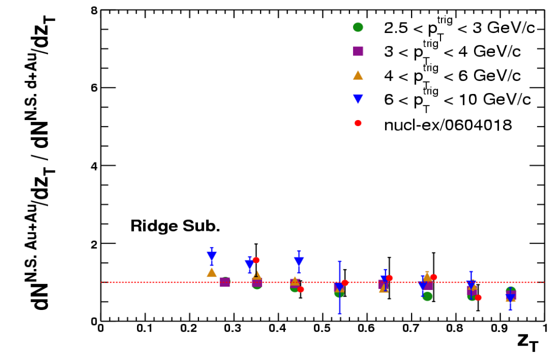
Au+Au $\sqrt{s}_{NN}$ = 200 GeV Summary



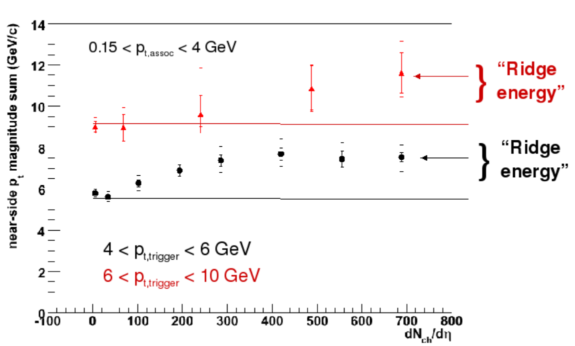
Ridge **persists to high $p_T^{trigger}$**



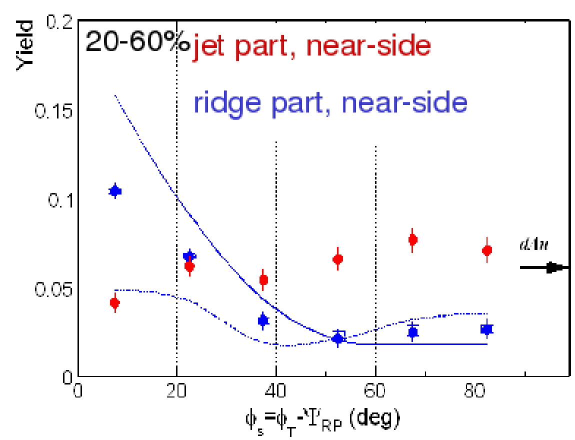
Ridge **is softer than Jet, comparable to inclusive**



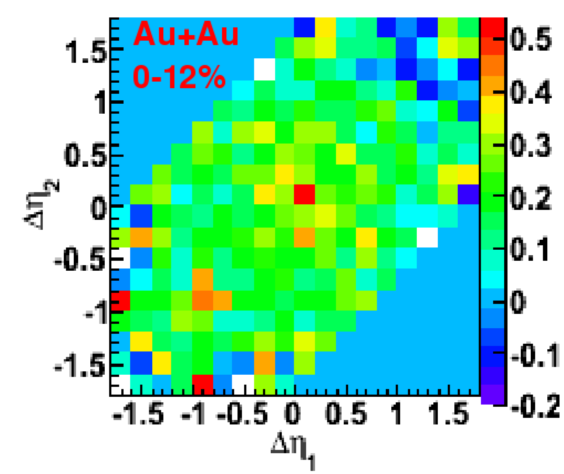
Fragmentation function with *Ridge* subtracted similar in d+Au, Au+Au



Ridge **contains a few GeV of energy**

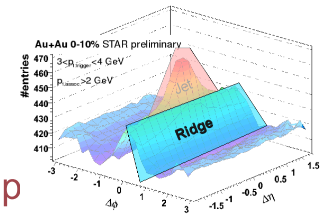


Jet **almost independent of reaction plane; *Ridge* dominantly in plane**



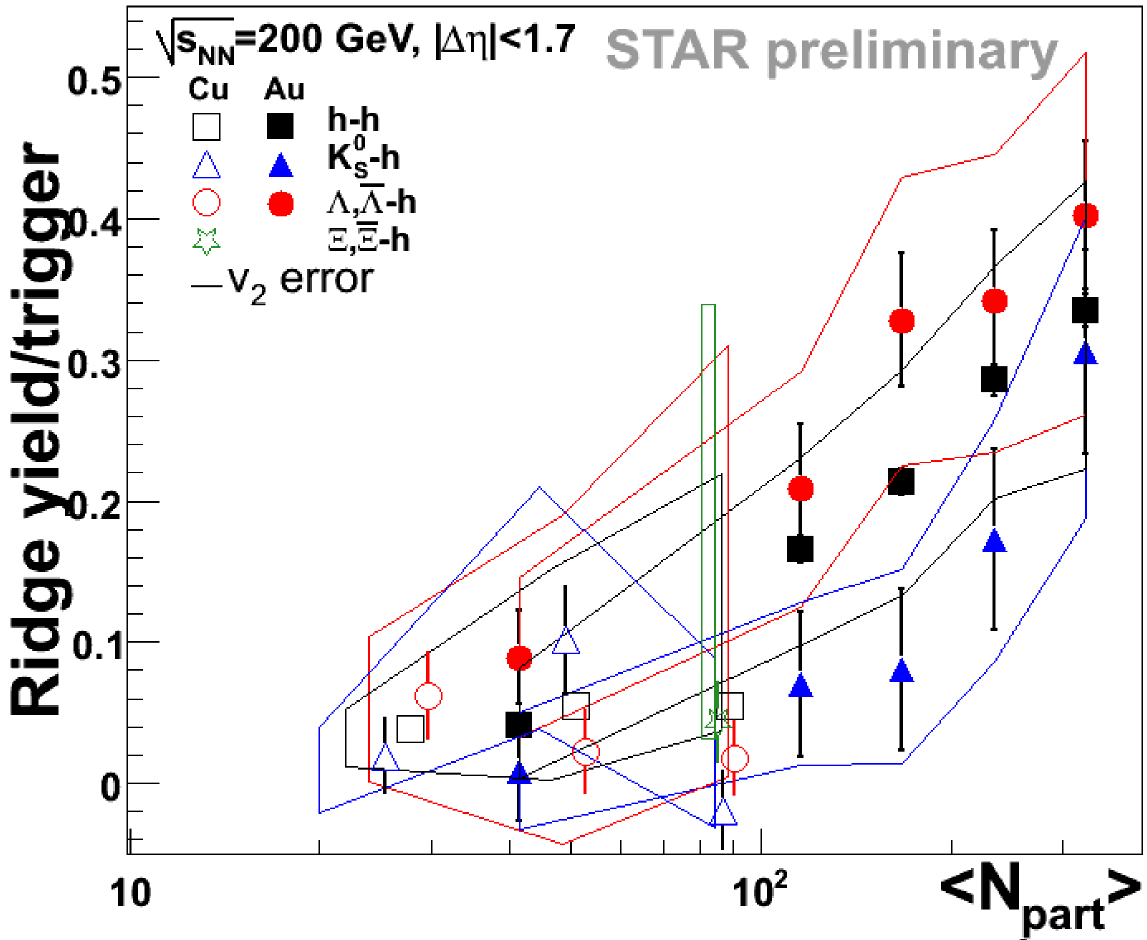
Ridge **uniform event-by-event**

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