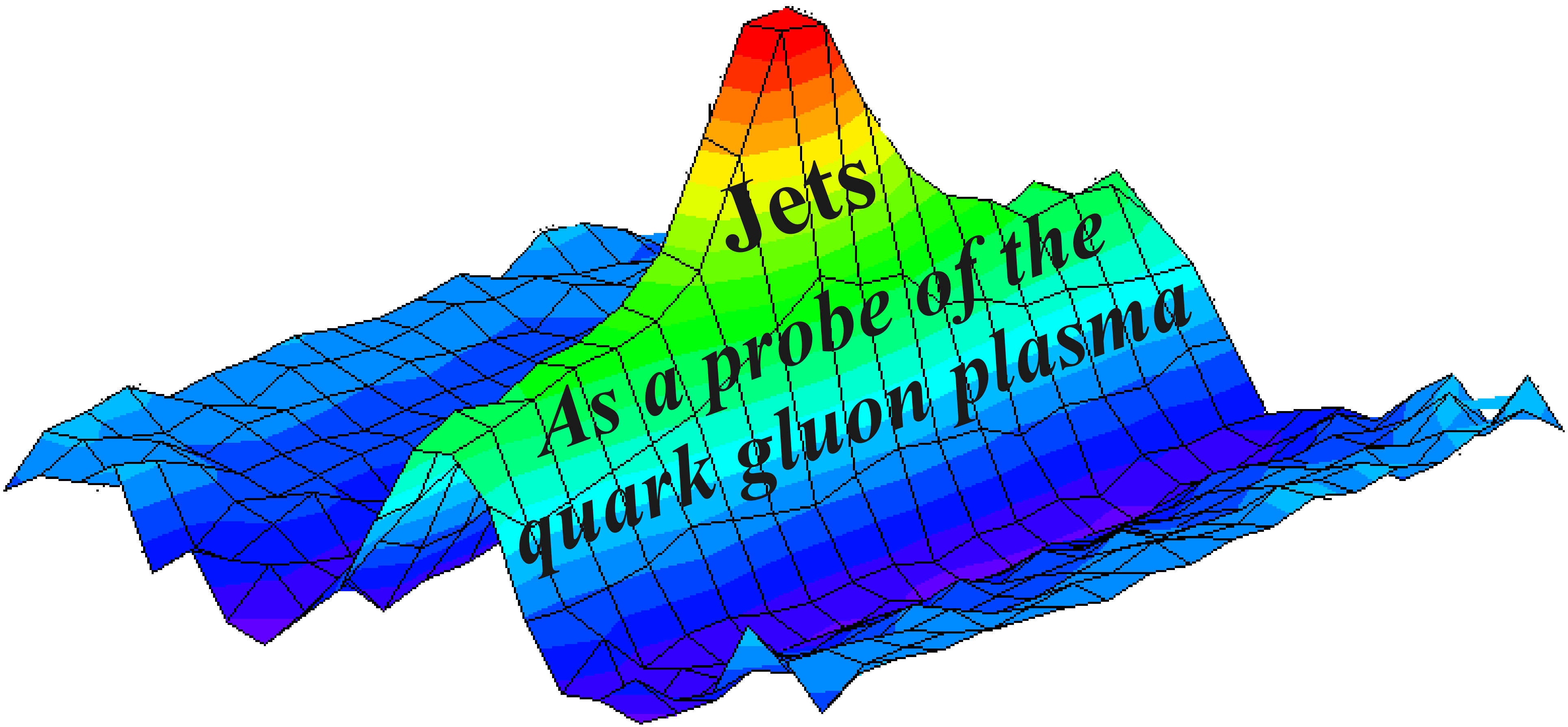
Jets
As a probe of the quark gluon plasma



Christine Nattrass

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Outline

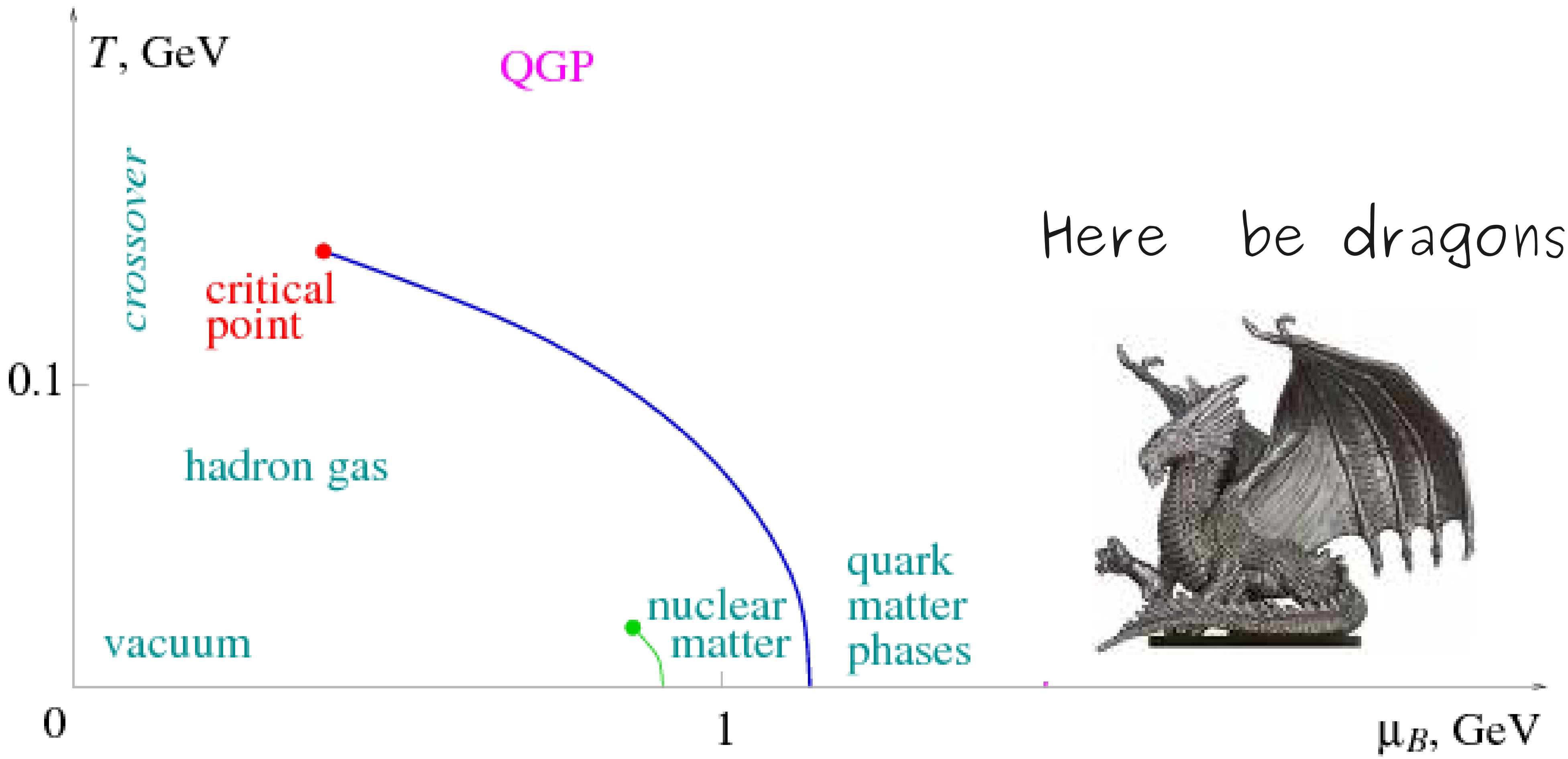
- Introduction to heavy ion collisions and the Quark Gluon Plasma
- Methods for using jets as a probe of the QGP
  - Single particles
  - Di-hadron correlations
  - Jet reconstruction
- Conclusion

Easier to measure

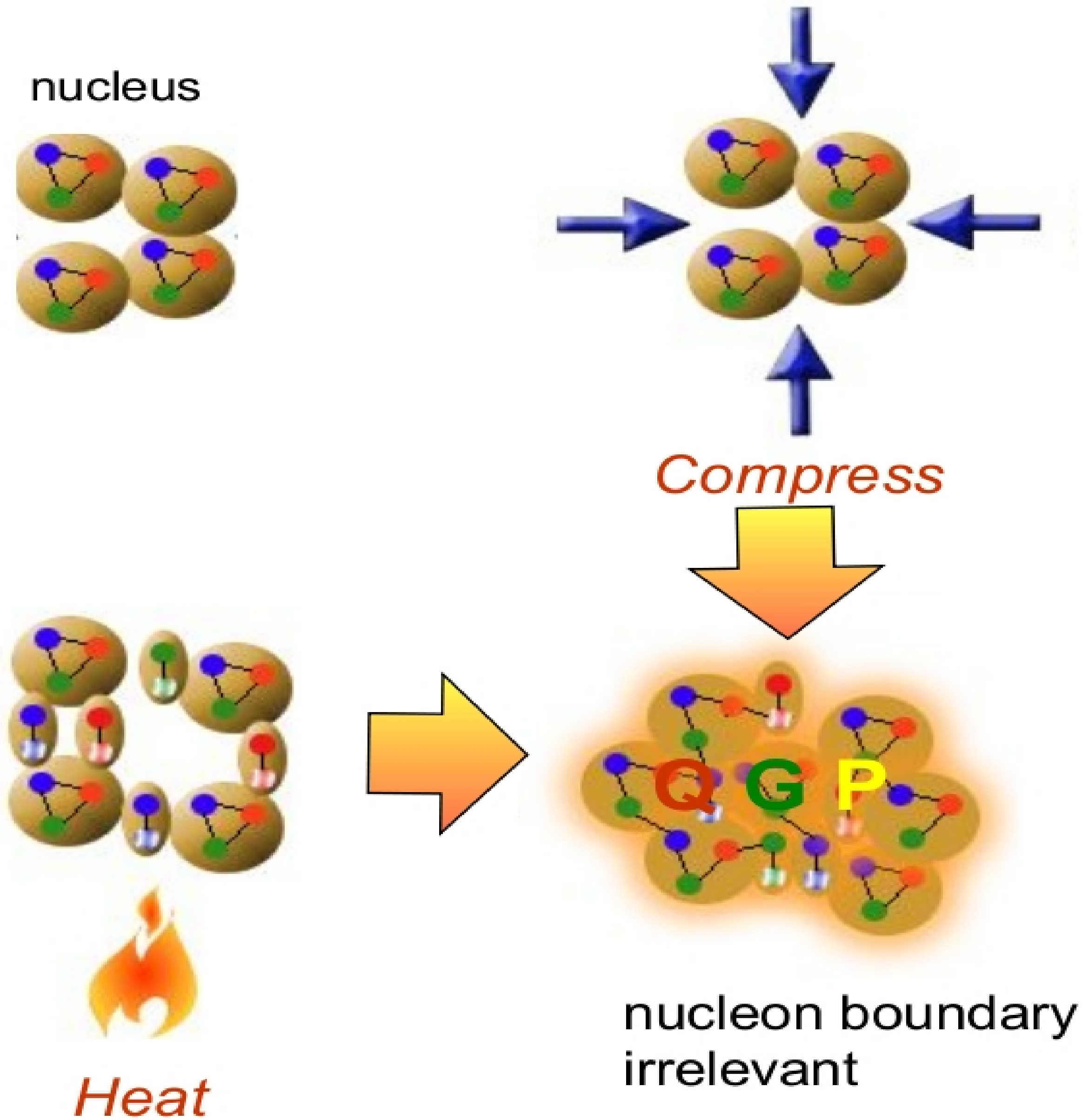
↕

Easier to understand theoretically

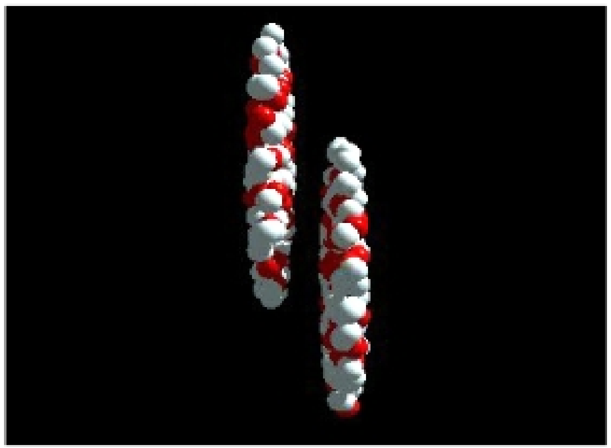
Phase diagram of nuclear matter

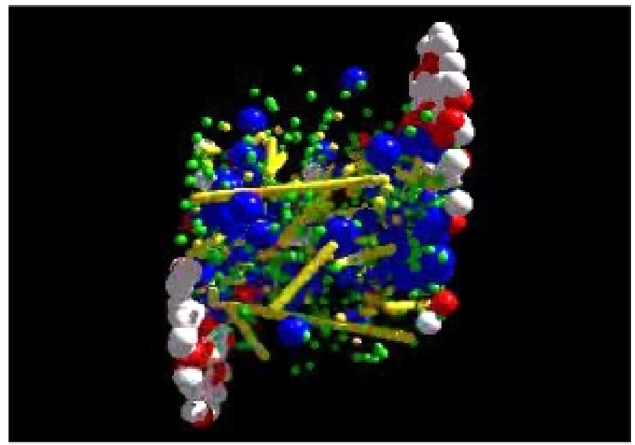


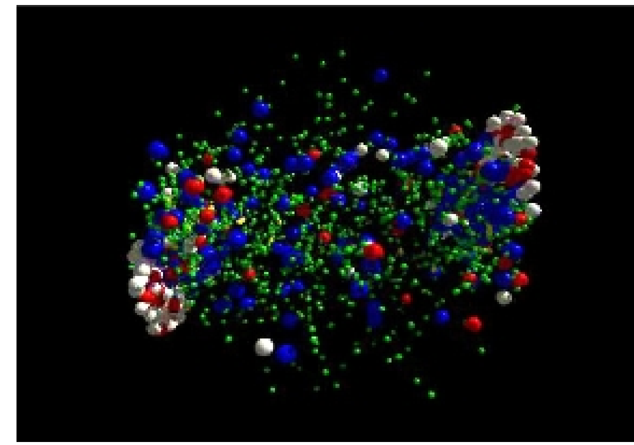
How to make a Quark Gluon Plasma

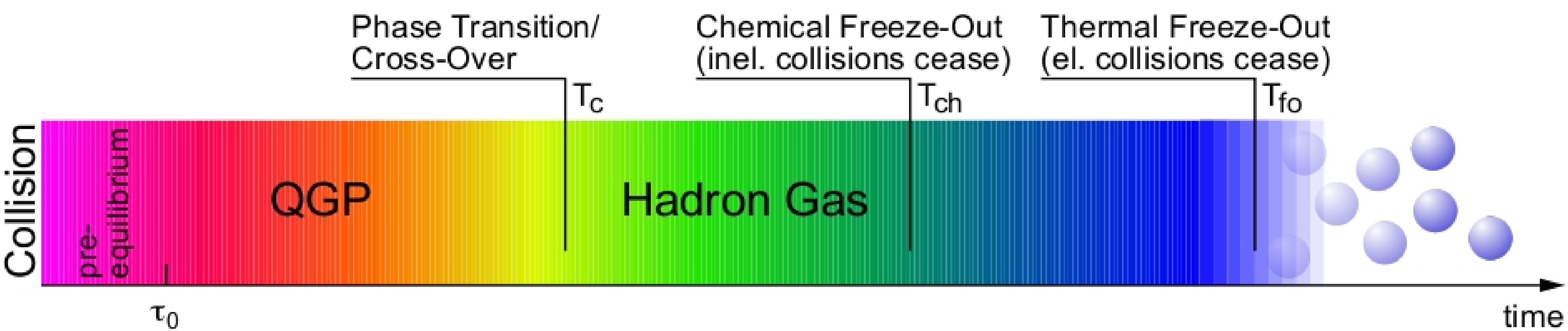


The phase transition in the laboratory

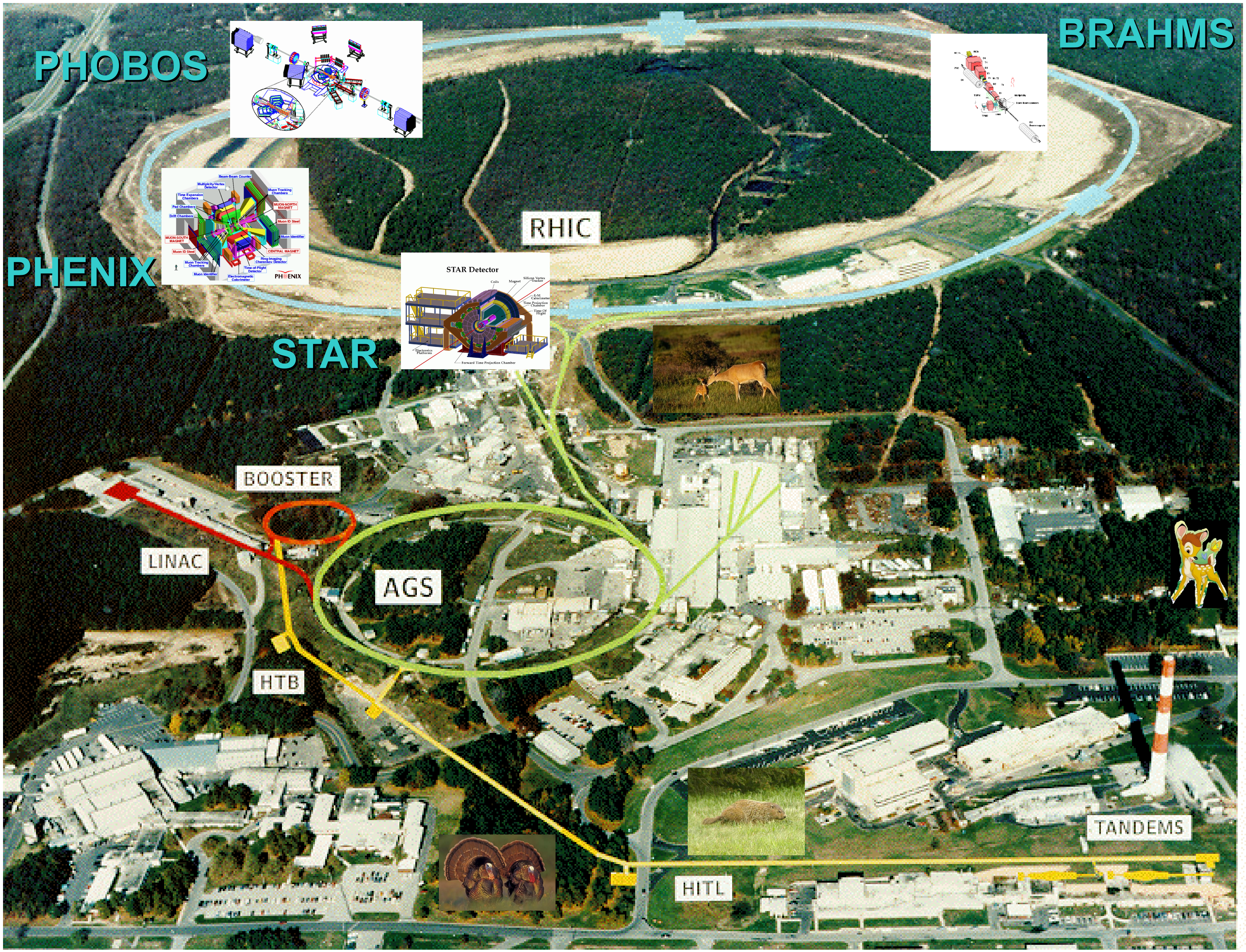




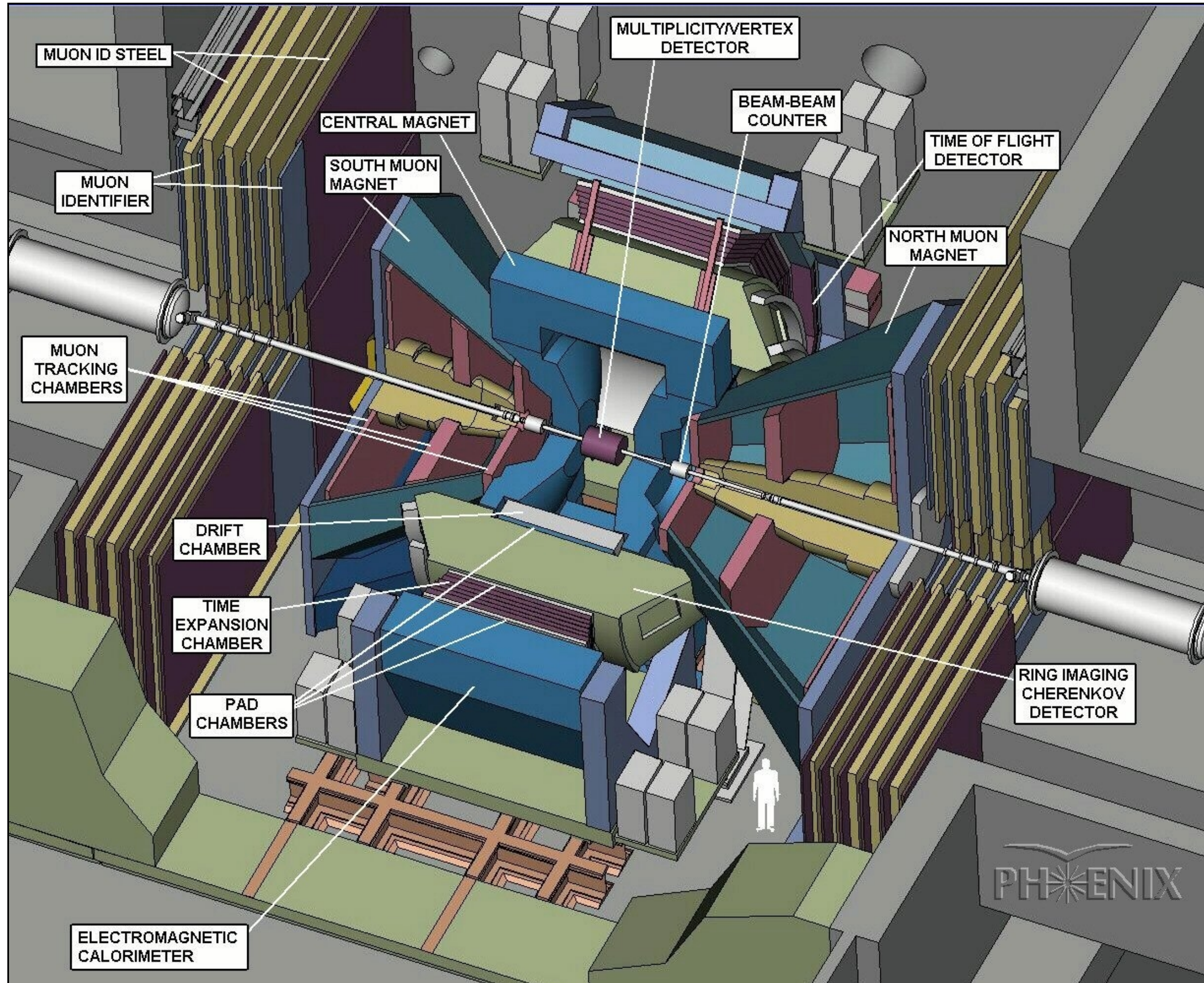




Relativistic Heavy Ion Collider



PHENIX



Coverage:

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

$-0.35<\eta<0.35$

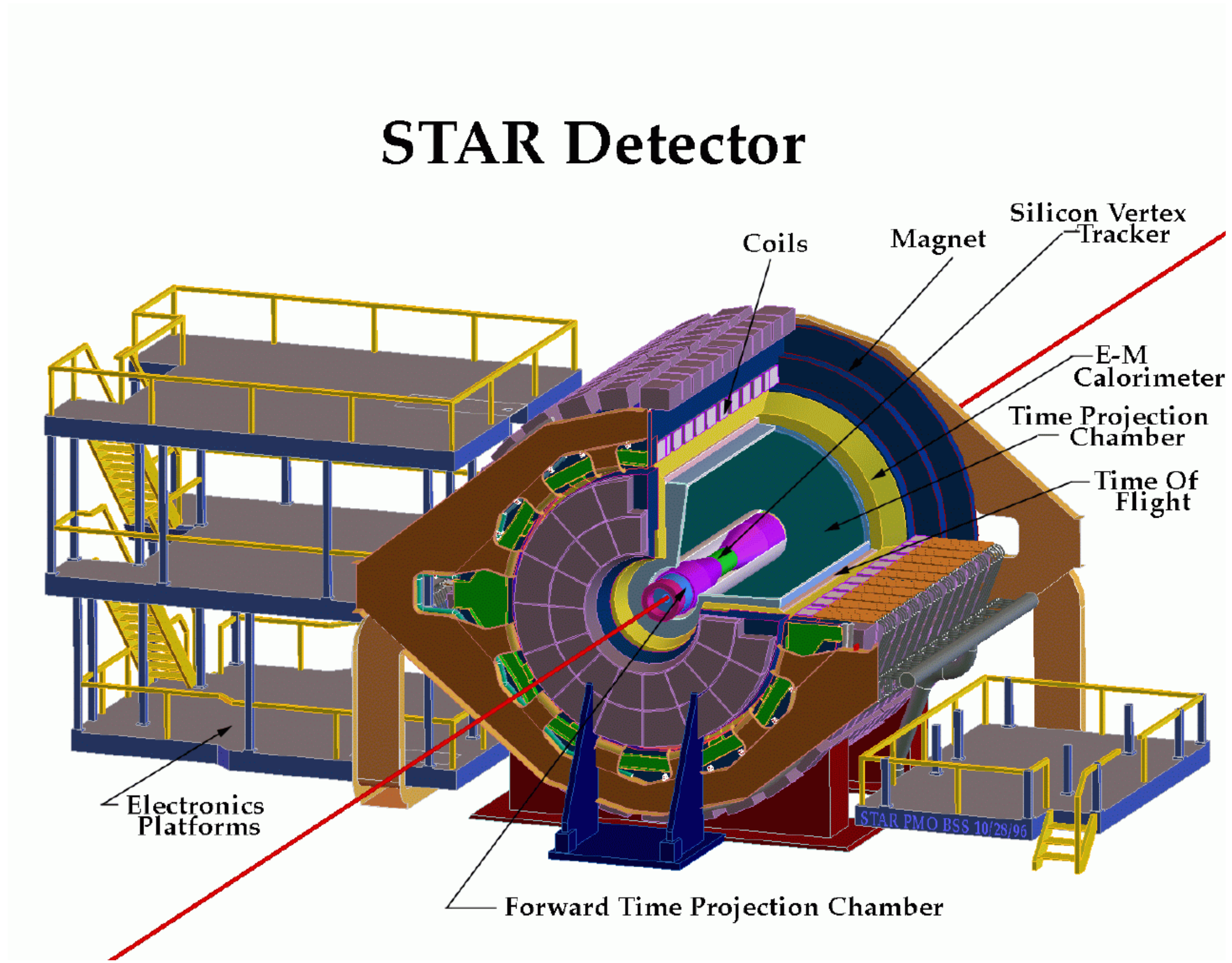
STAR

Coverage:

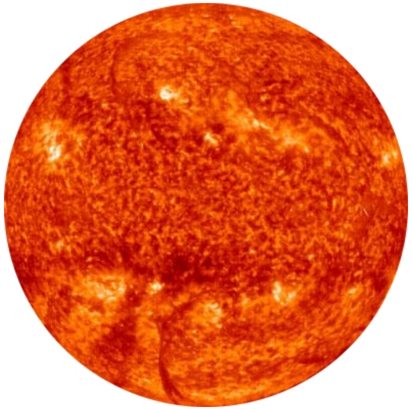
$0<\phi<2\pi$

$-1<\eta<1$

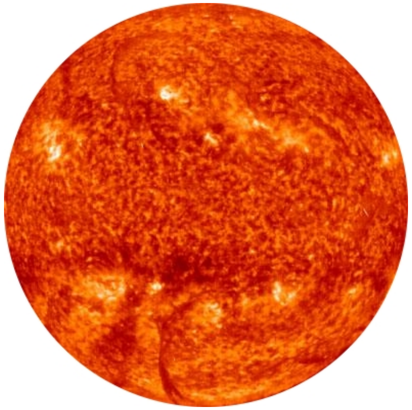
Electromagnetic Calorimeter allows triggering



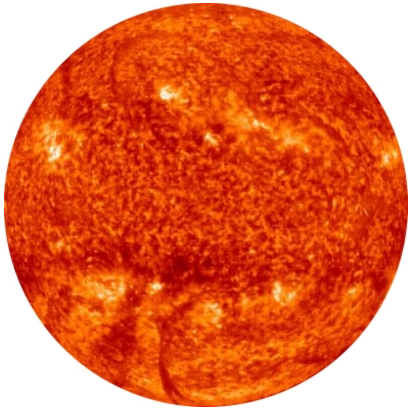
A simple picture of a heavy ion collision



Jets as a probe of the quark gluon plasma



One jet "absorbed" by the medium



Single particles

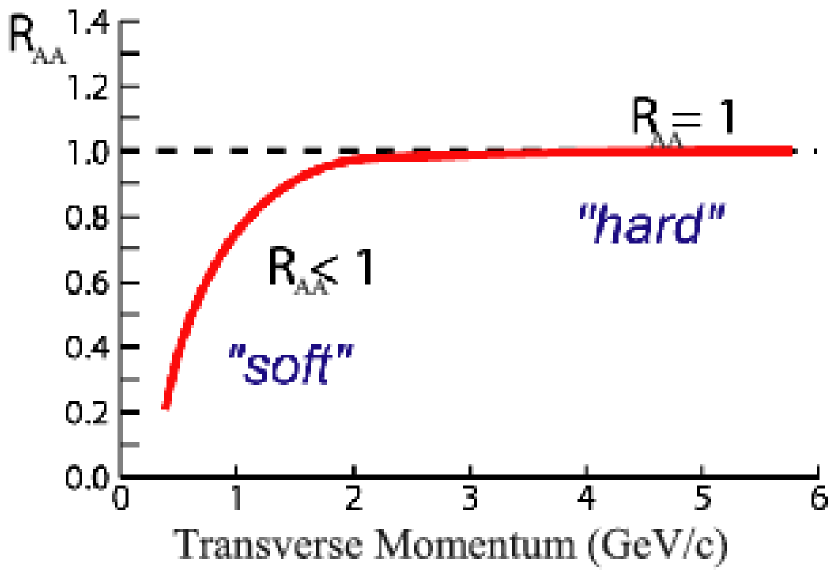
Measure spectra of hadrons and compare to those in p+p collisions or peripheral A+A collisions

If high-p_T hadrons are suppressed, this is evidence of jet quenching

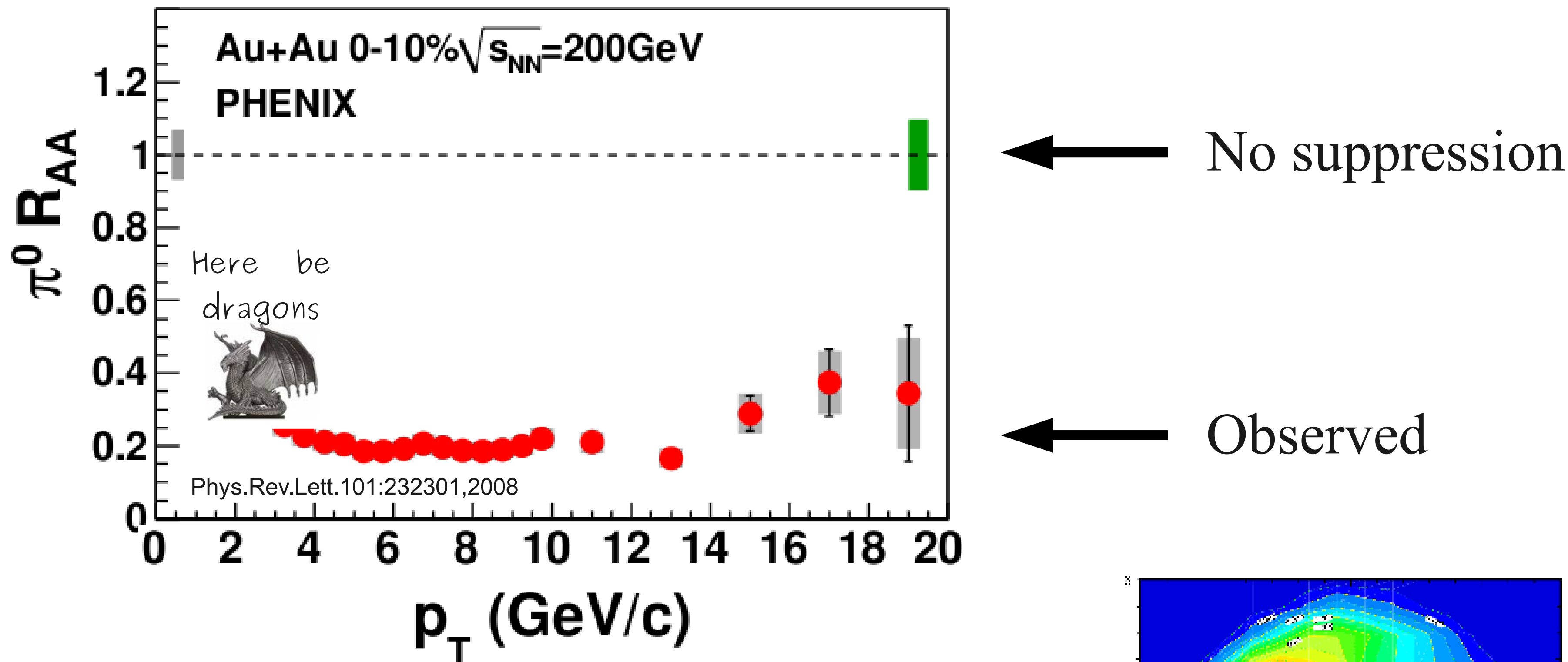
Assumption: sufficiently high-p_T hadrons mostly come from jets

Unmodified spectra:

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$

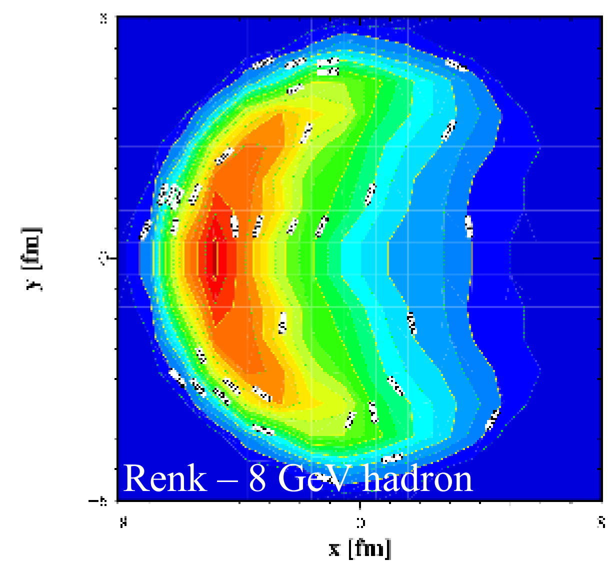


Experimental results

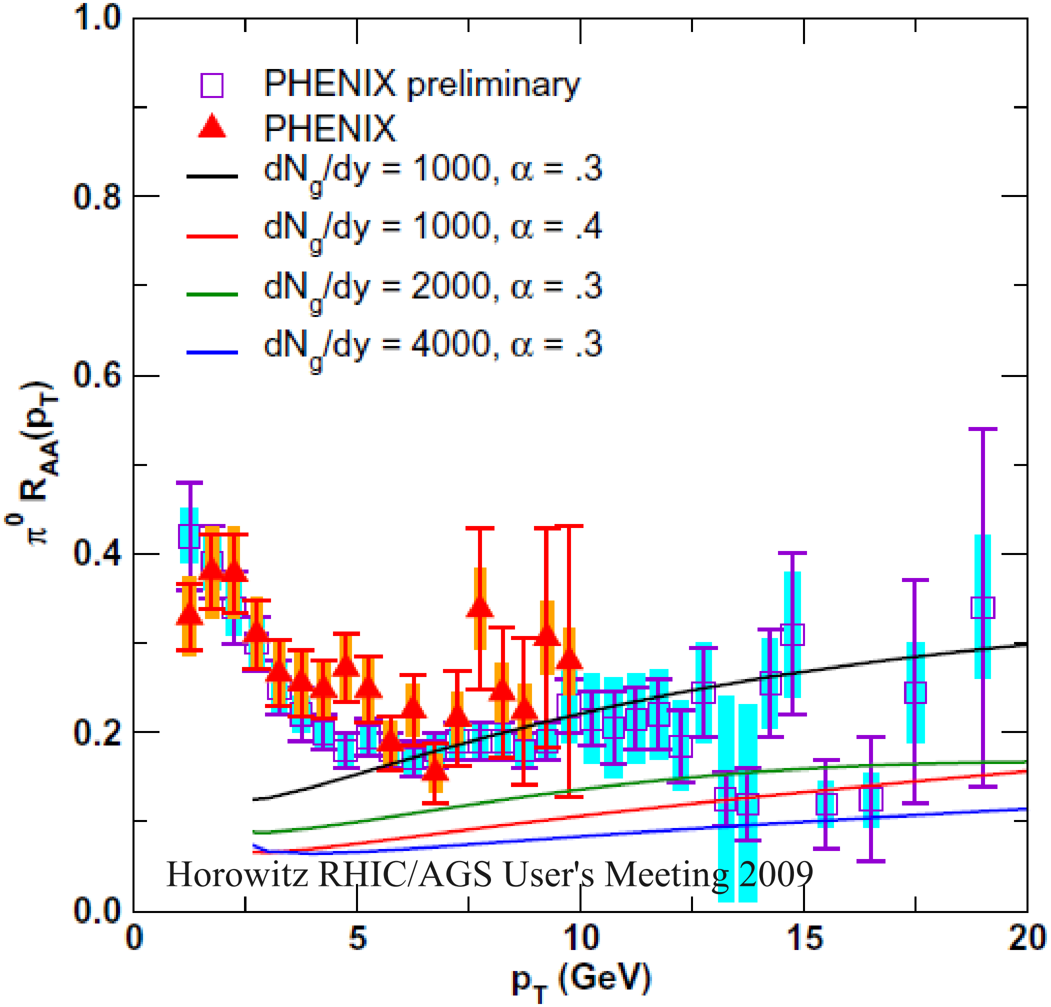


Factor of five suppression observed

Can be measured to high precision



Comparisons to theory



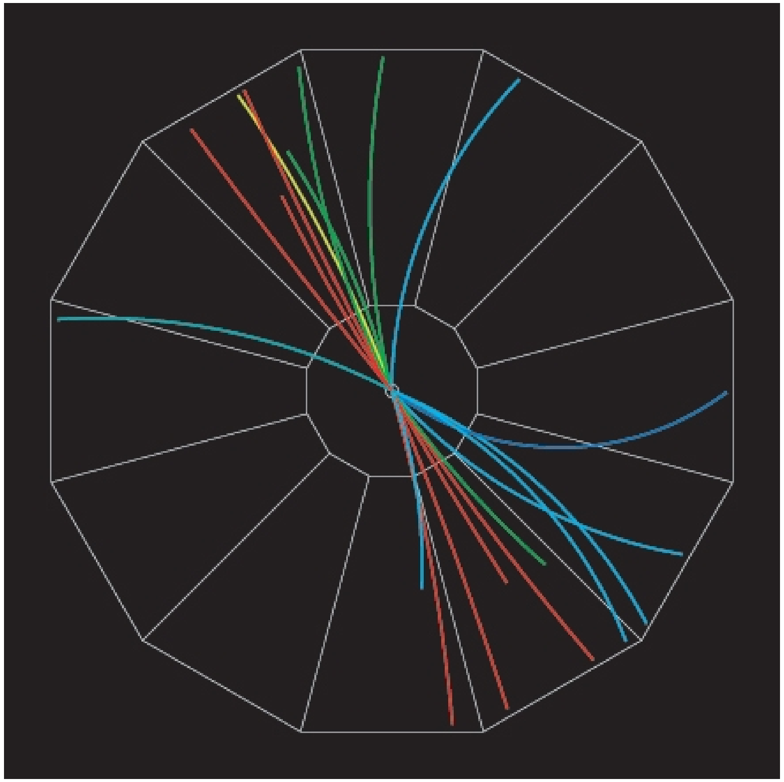
Jets – azimuthal correlations

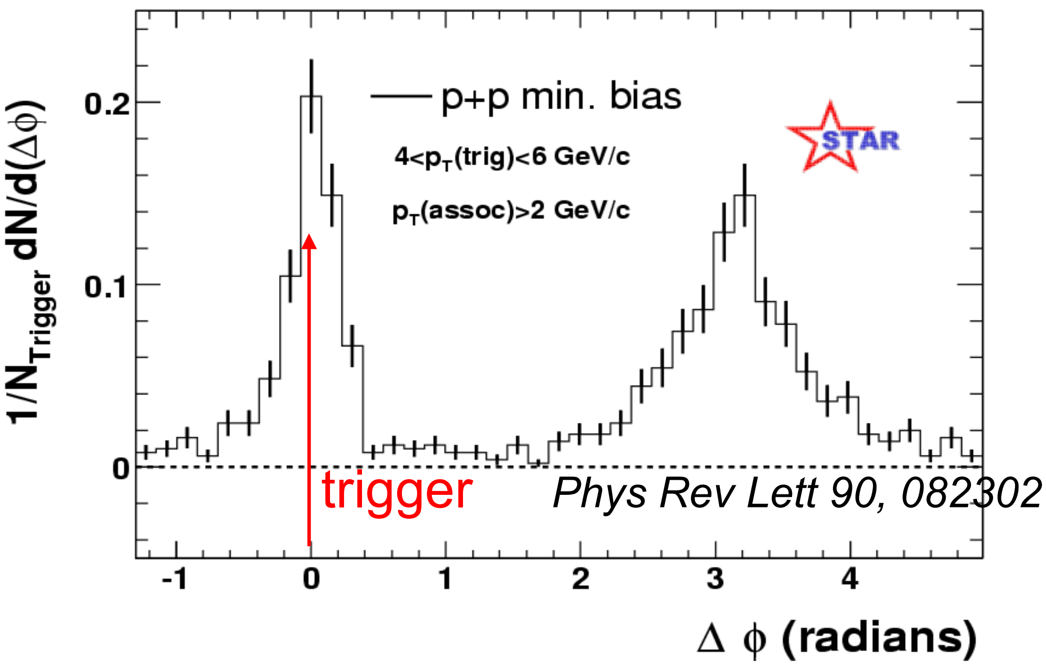
At RHIC energies, jets are dominantly produced as di-jets

Assume that a high-p_T trigger particle comes from a jet

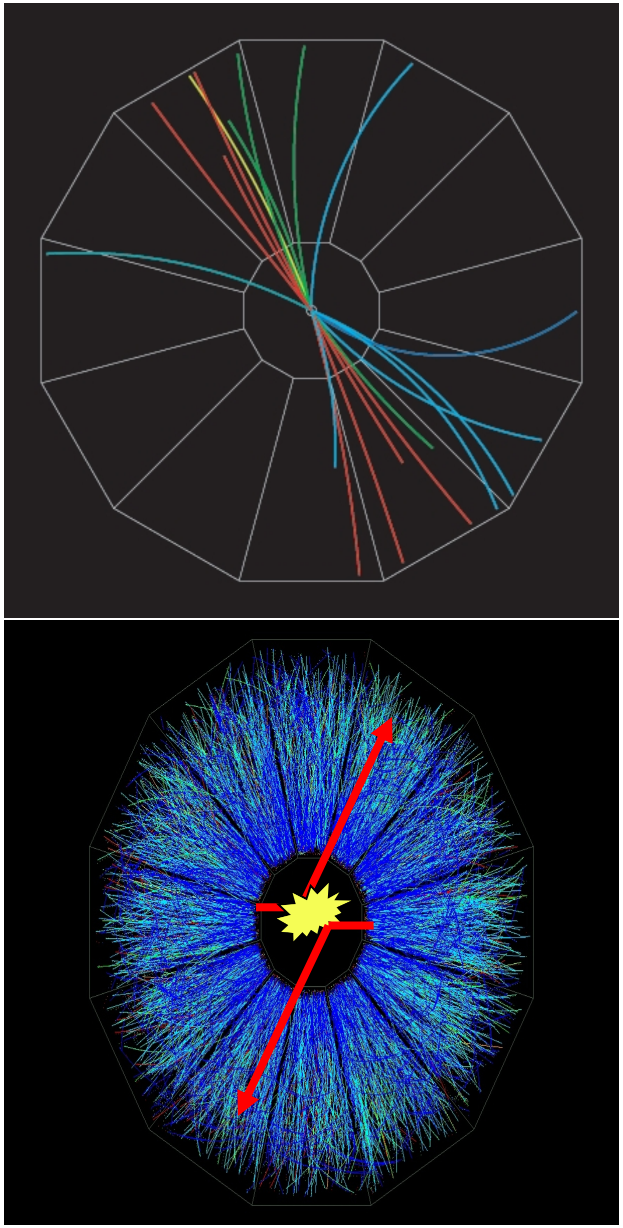
Look at distribution of high-p_T associated particles relative to trigger

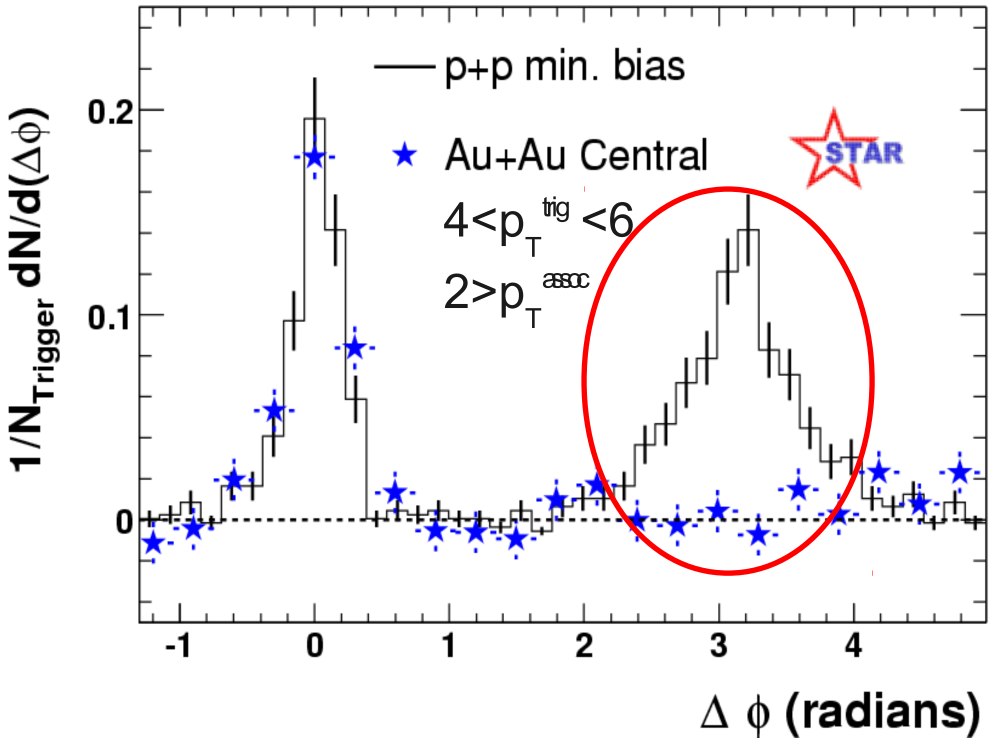
p+p → dijet





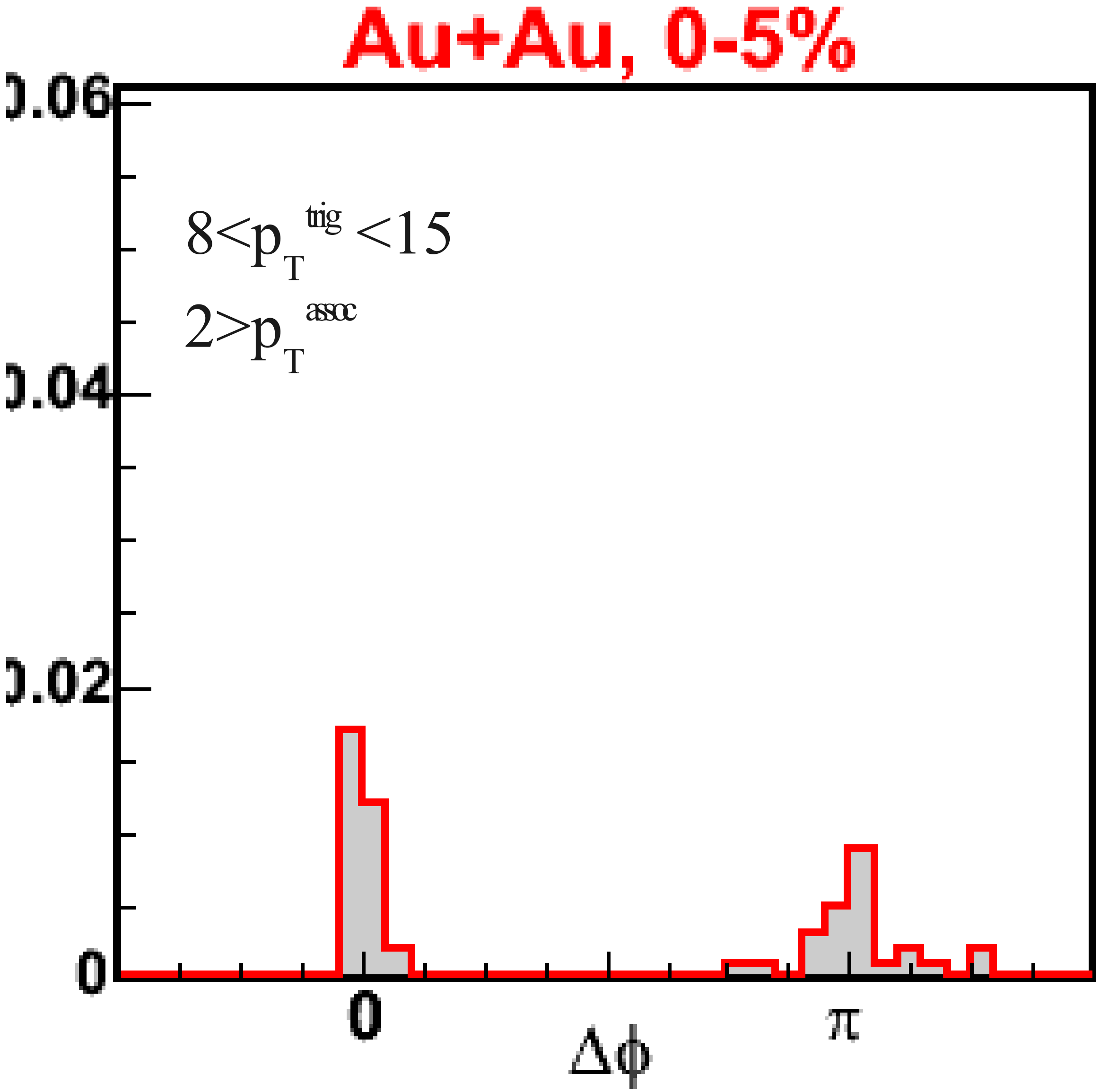
Jets – azimuthal correlations





The away-side jet is quenched

At higher pT...

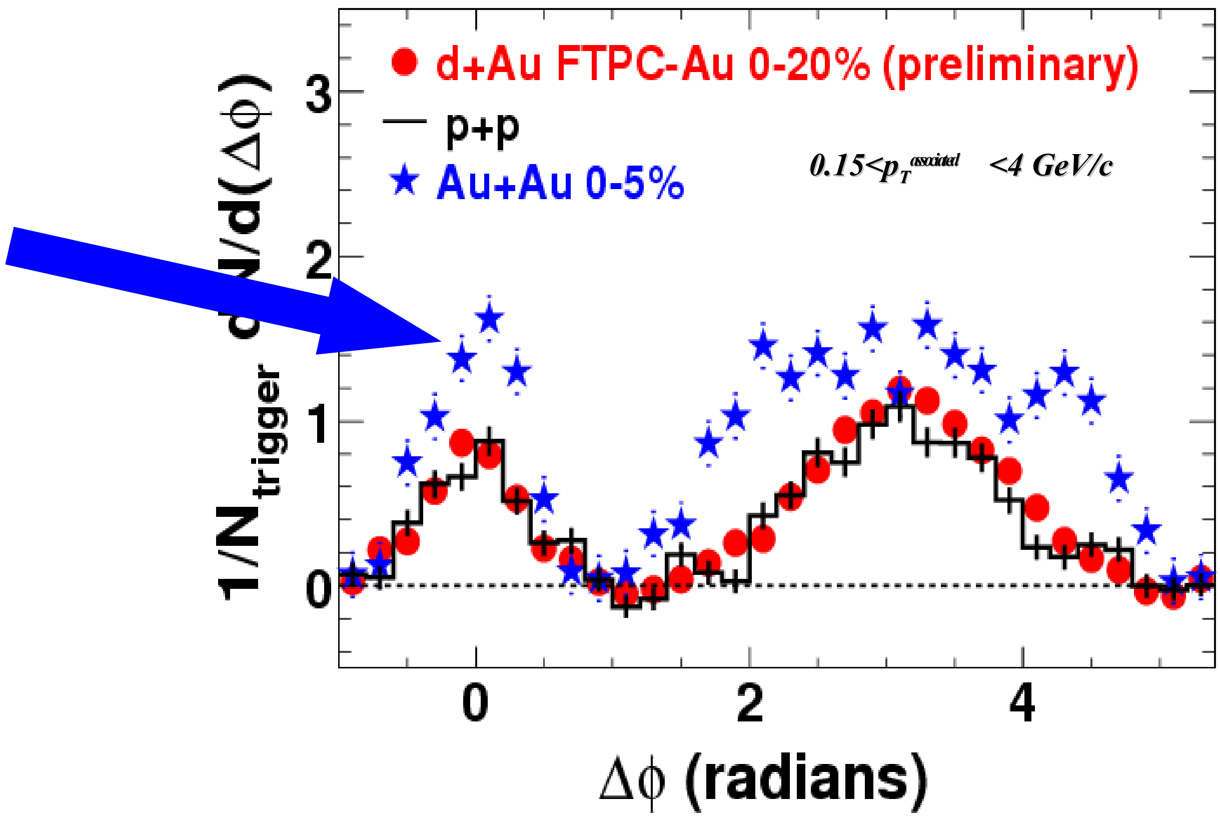


The away-side jet punches through the medium

But at lower p_T...

Near-side, away-side show modification

Excess yield in Au+Au relative to p+p



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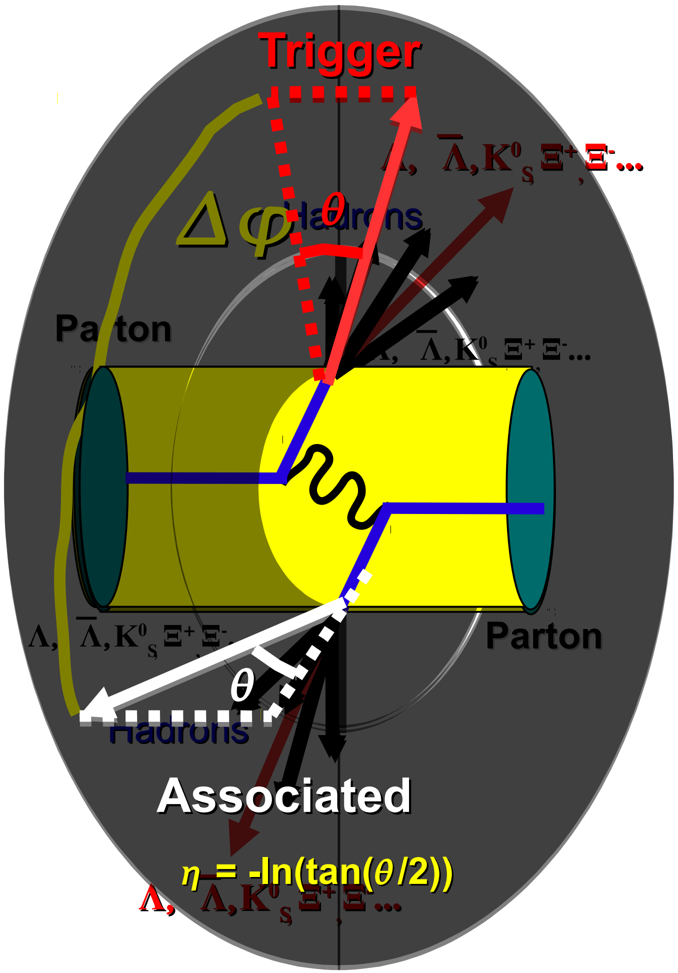
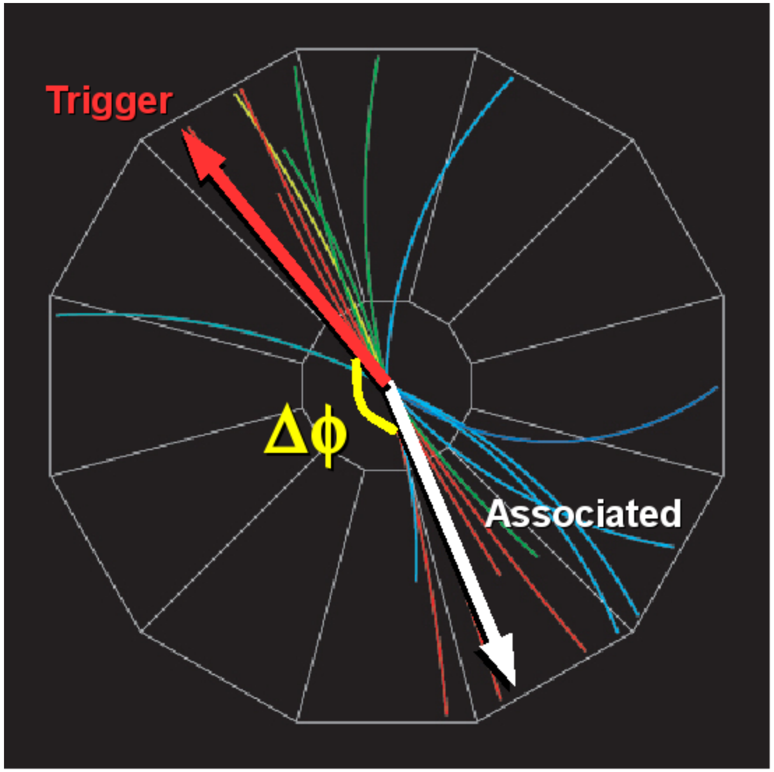
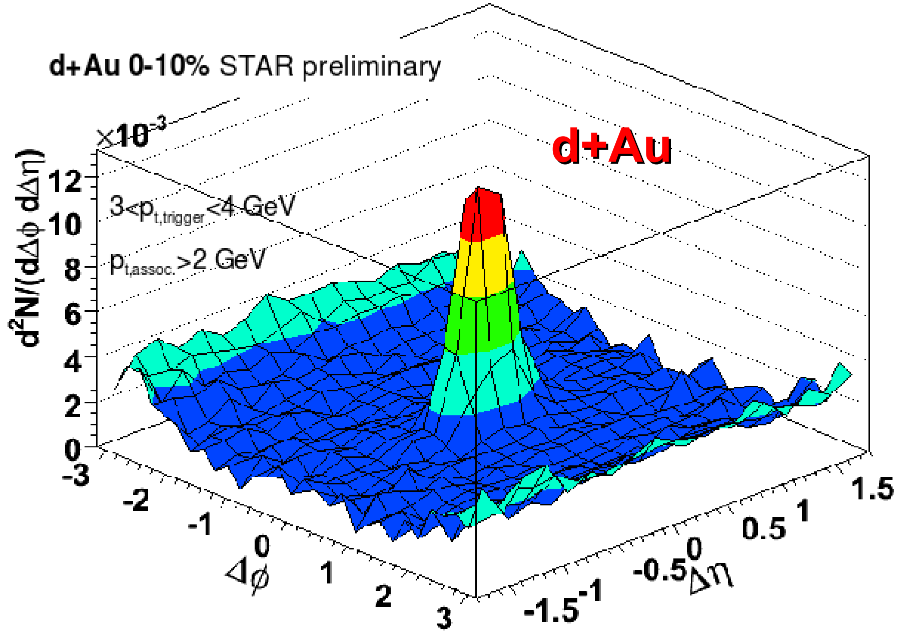
Look in two dimensions



d+Au

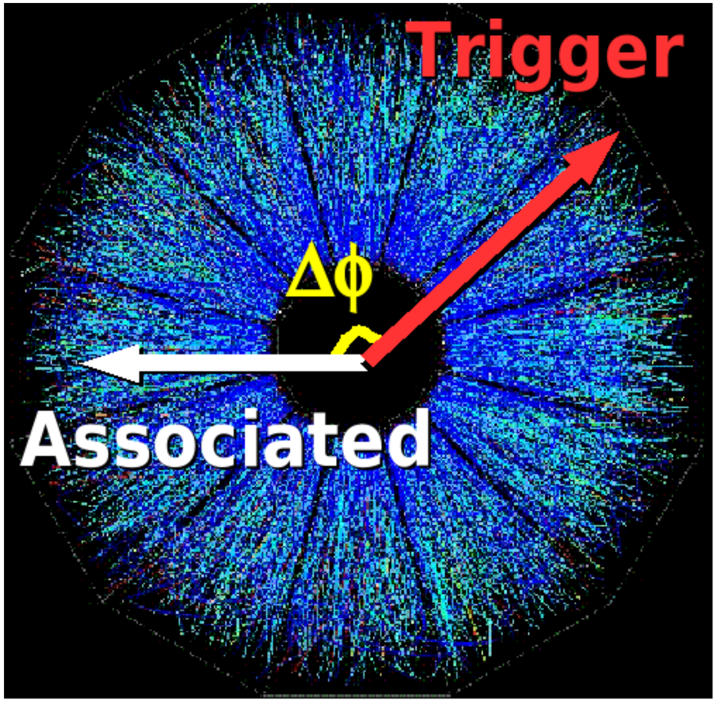


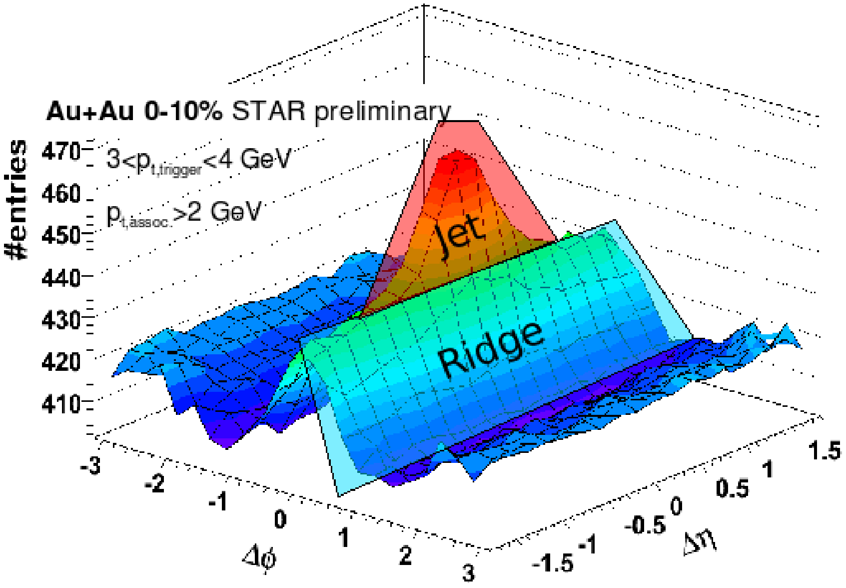
Trigger
Δφ
Associated



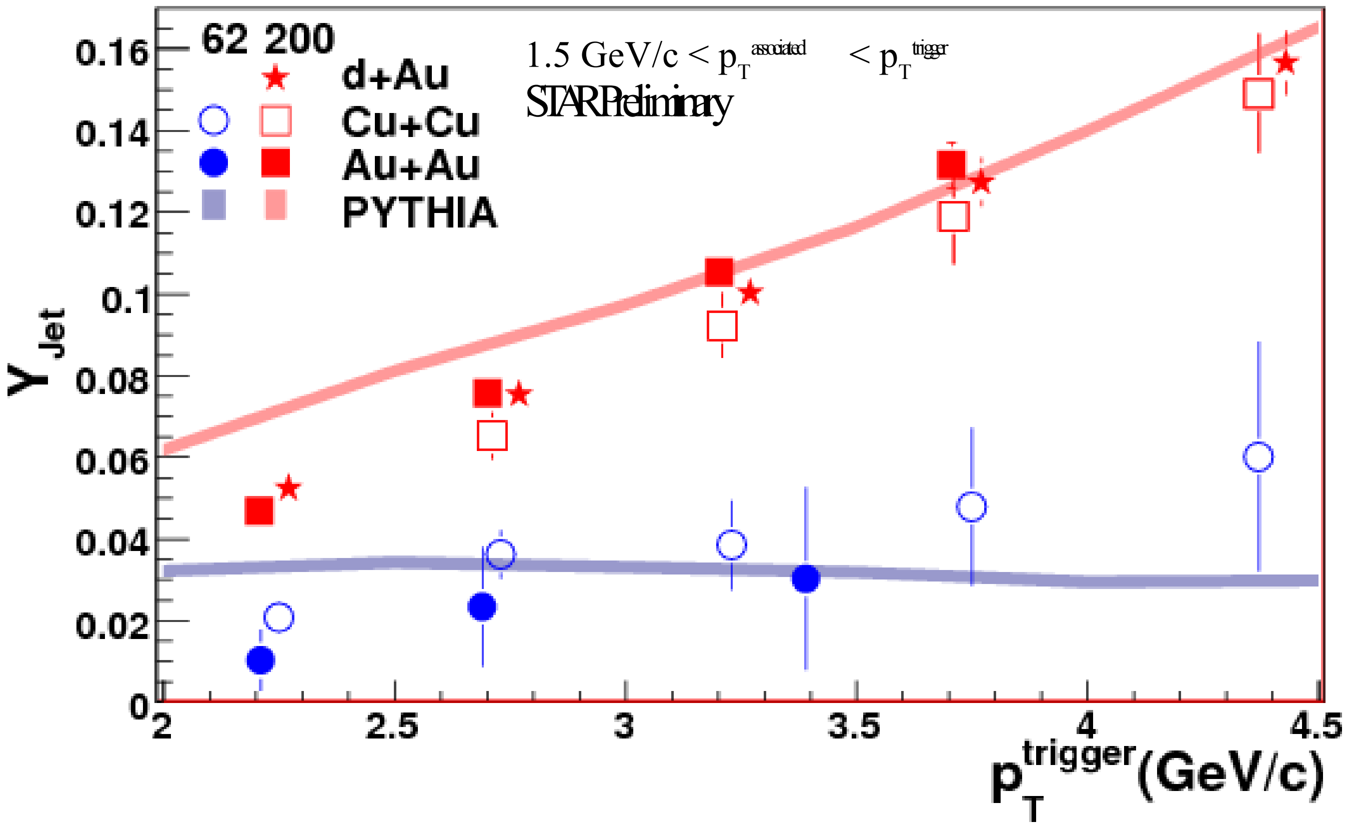
d+Au 0-10% STAR preliminary
×10⁻³
d+Au
3<p_{t,trigger}<4 GeV
p_{t,assoc.}>2 GeV
d²N/(dΔφ dΔη)
12
10
8
6
4
2
0
-3
-2
-1
0
1
2
3
Δφ
-1.5
-1
-0.5
0
0.5
1
1.5
Δη

In two dimensions in Au+Au





The jet-like correlation



Number of particles (Y_{jet}) 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

Describes data well except at lowest $p_T^{trigger}$

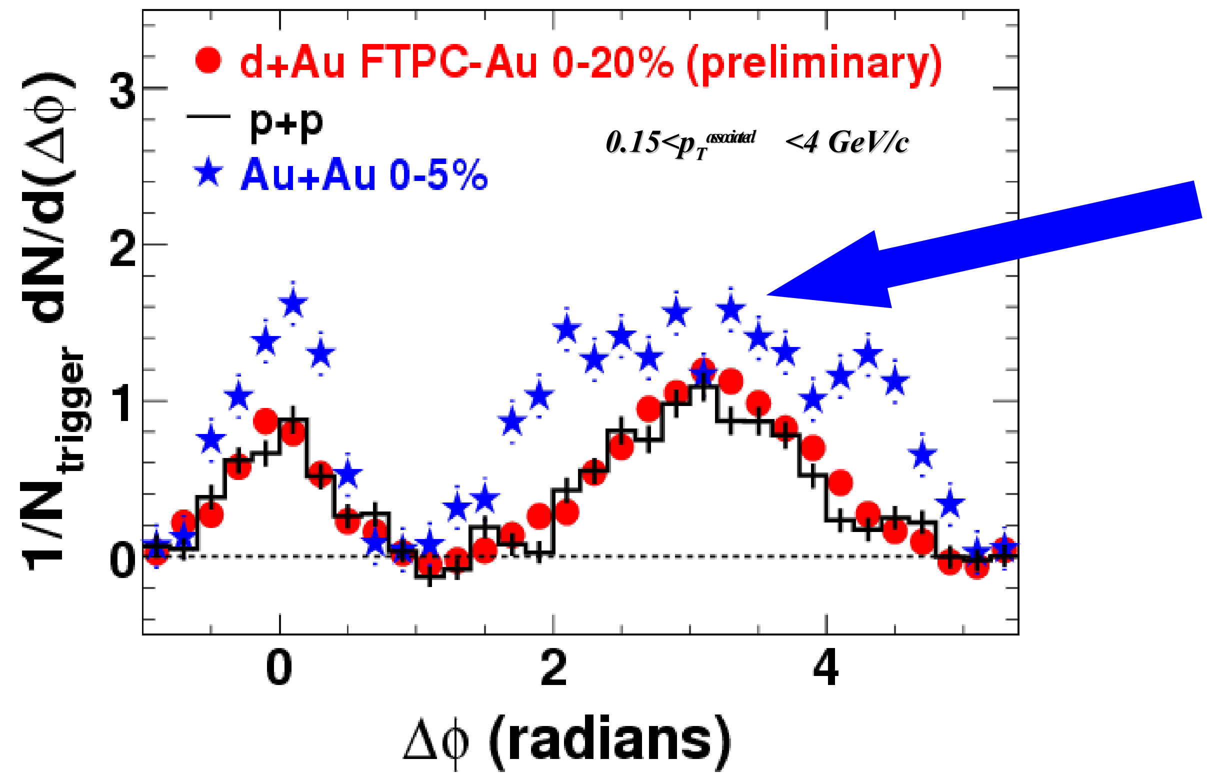
The Ridge

- Unpredicted
- Properties like the bulk
  - Spectra similar to bulk
  - Particle composition similar to bulk
- Larger in more central collisions
- Several models on the market, but not settled yet

Away-side

Shape change on away-side

Excess yield at low p_T on away-side



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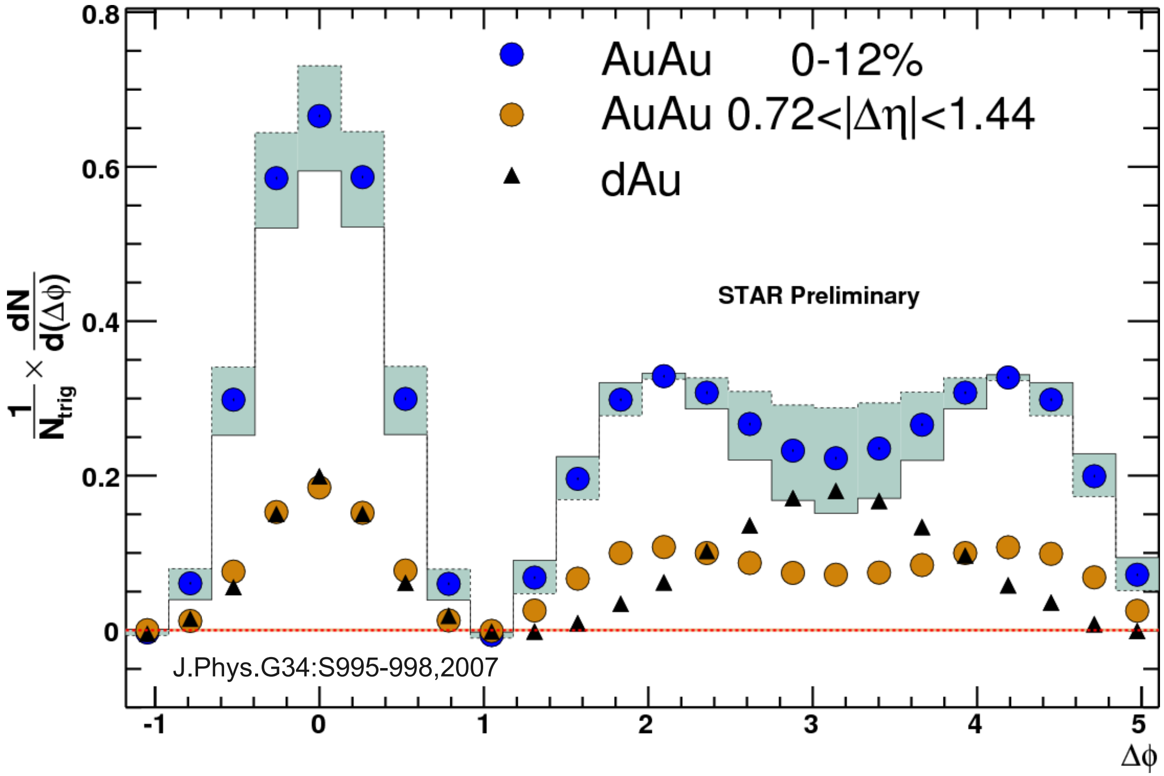
Away-side



$1.0 < p_T^{assoc} < 2.5$ GeV/c

$2.5 < p_T^{trig} < 4.0$ GeV/c

Structure has a dip

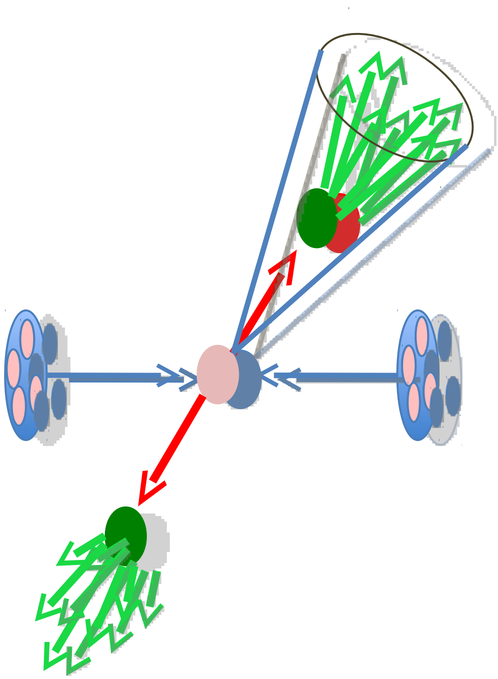
Mach cone?

Deflected jet?

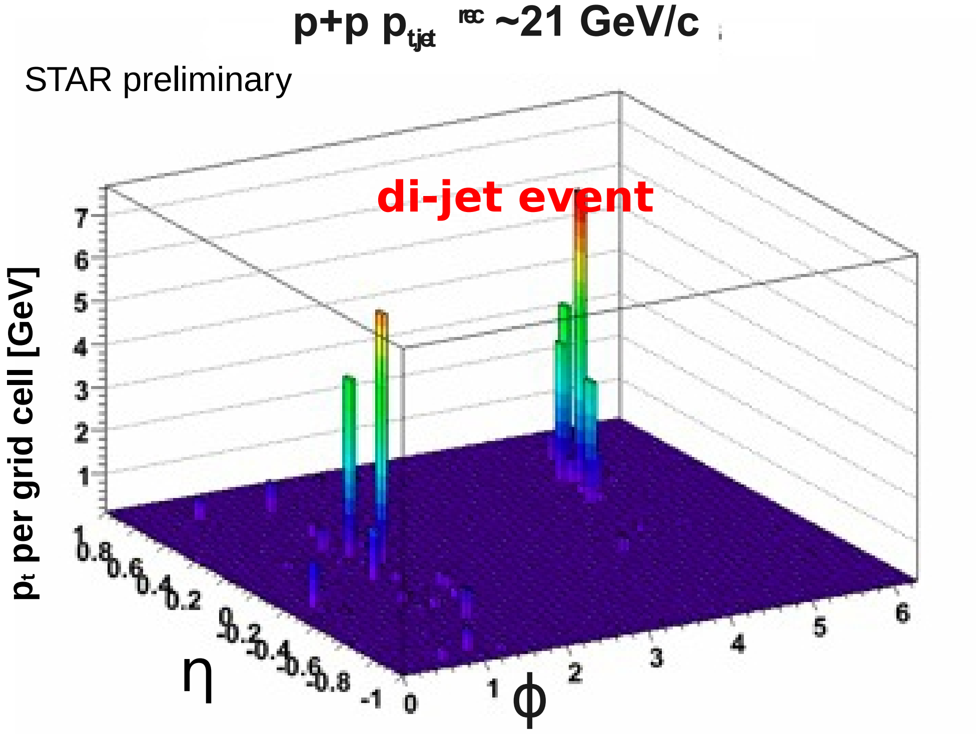
Jets in Heavy-Ion Collisions

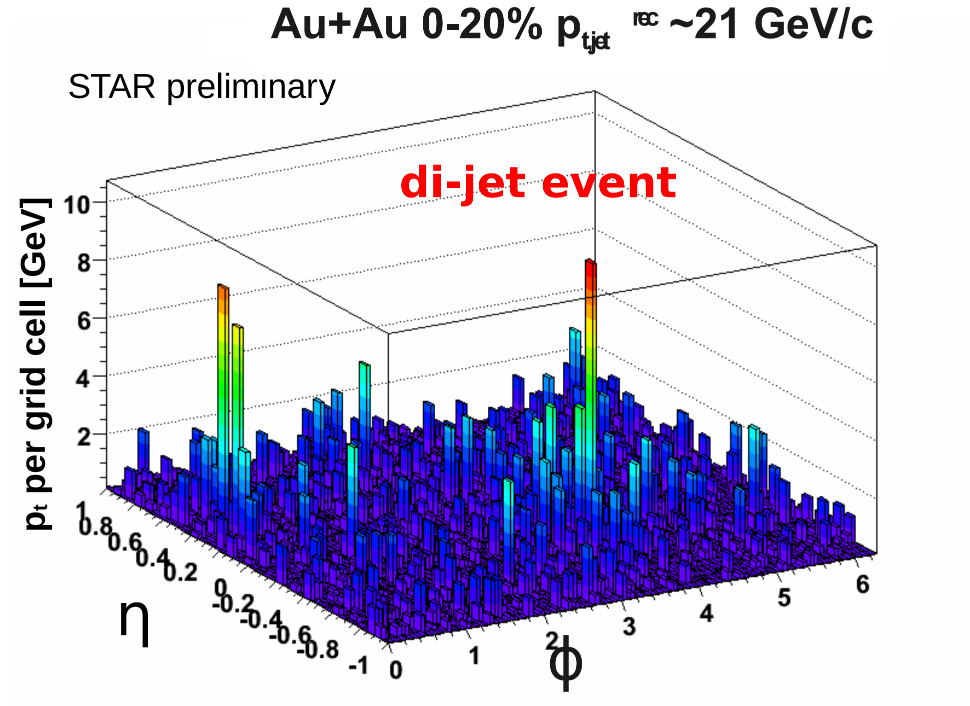
Goal

Reconstruct the full jet→ kinematics of hard scattering in unbiased way, even in presence of (underlying) heavy-ion collision.



Jets at RHIC





Jets clearly visible in p+p

Full jet reconstruction: a challenge in A+A

We have the tools:

Modern jet-finding algorithms

Background fluctuation estimates

Conclusions

- Jets are a useful tool for studies of the QGP
- Single hadron
  - Precise measurement
  - Ambiguous interpretation
- Di-hadron correlations
  - Less precise
  - Less ambiguous
- Jet reconstruction
  - Difficult measurement
  - Most straightforward interpretation

Backups

PHOBOS

Coverage:

With tracking:

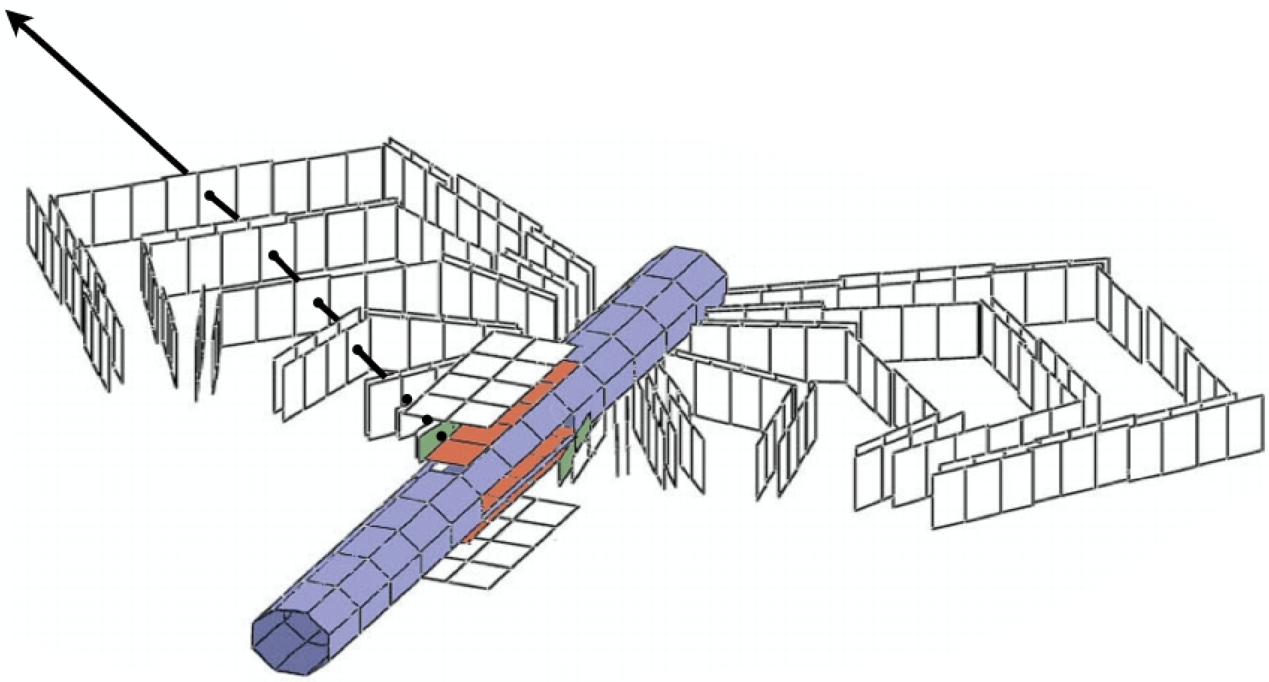
$0<\phi<0.2$, x2

$0<\eta<1.5$

Without tracking:

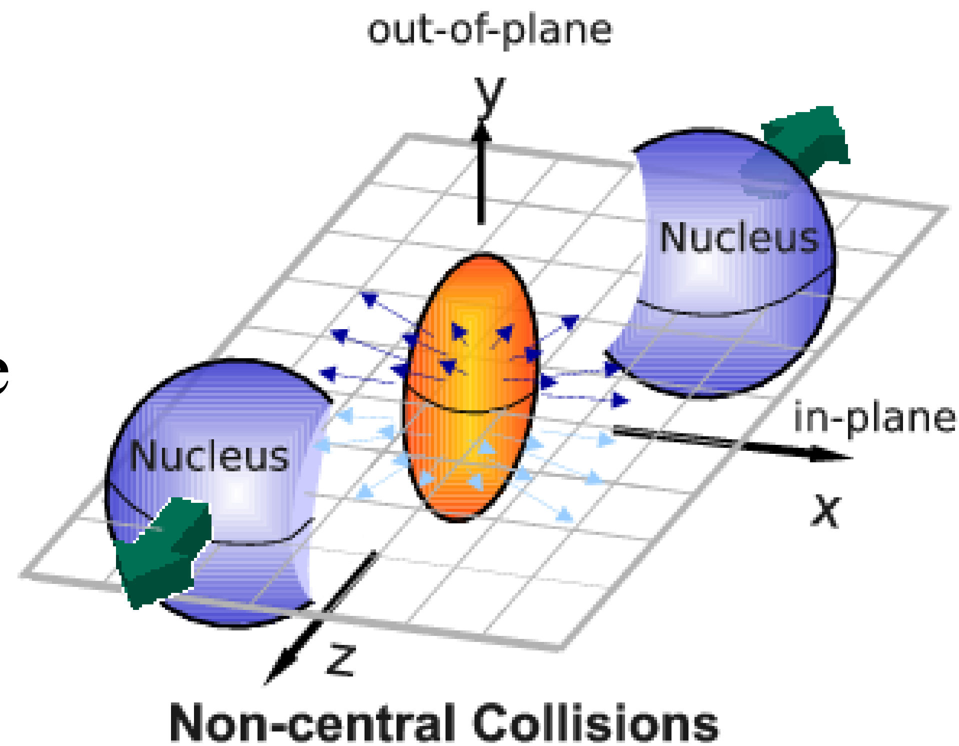
$0<\phi<2\pi$

$-3<\eta<3$



*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 hadrons produced are low p_T light particles (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

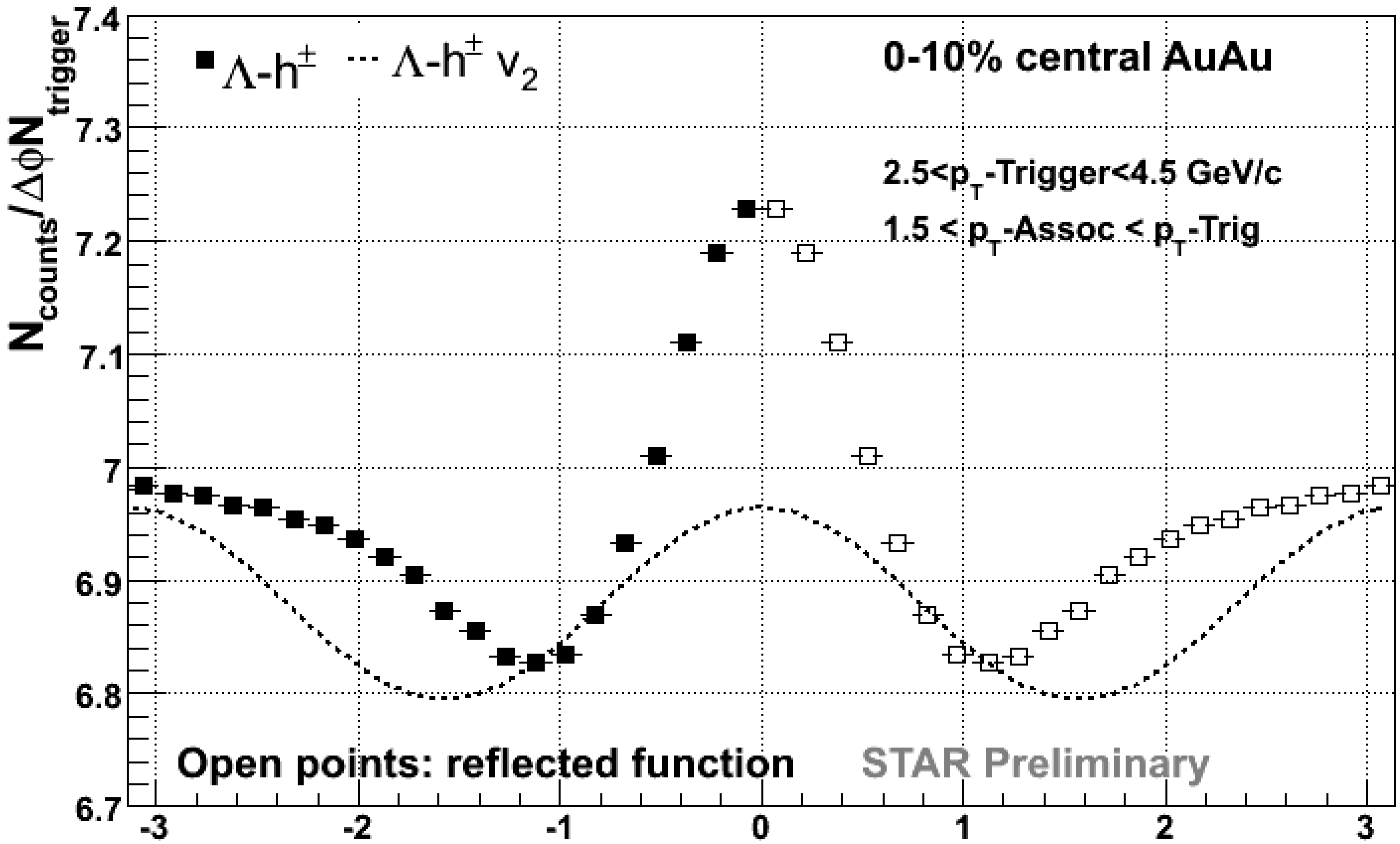
Large background subtraction...

A caveat...

Signal/Background ≈ 0.05

Depends on kinematic region

Signal/Background higher at higher p_T

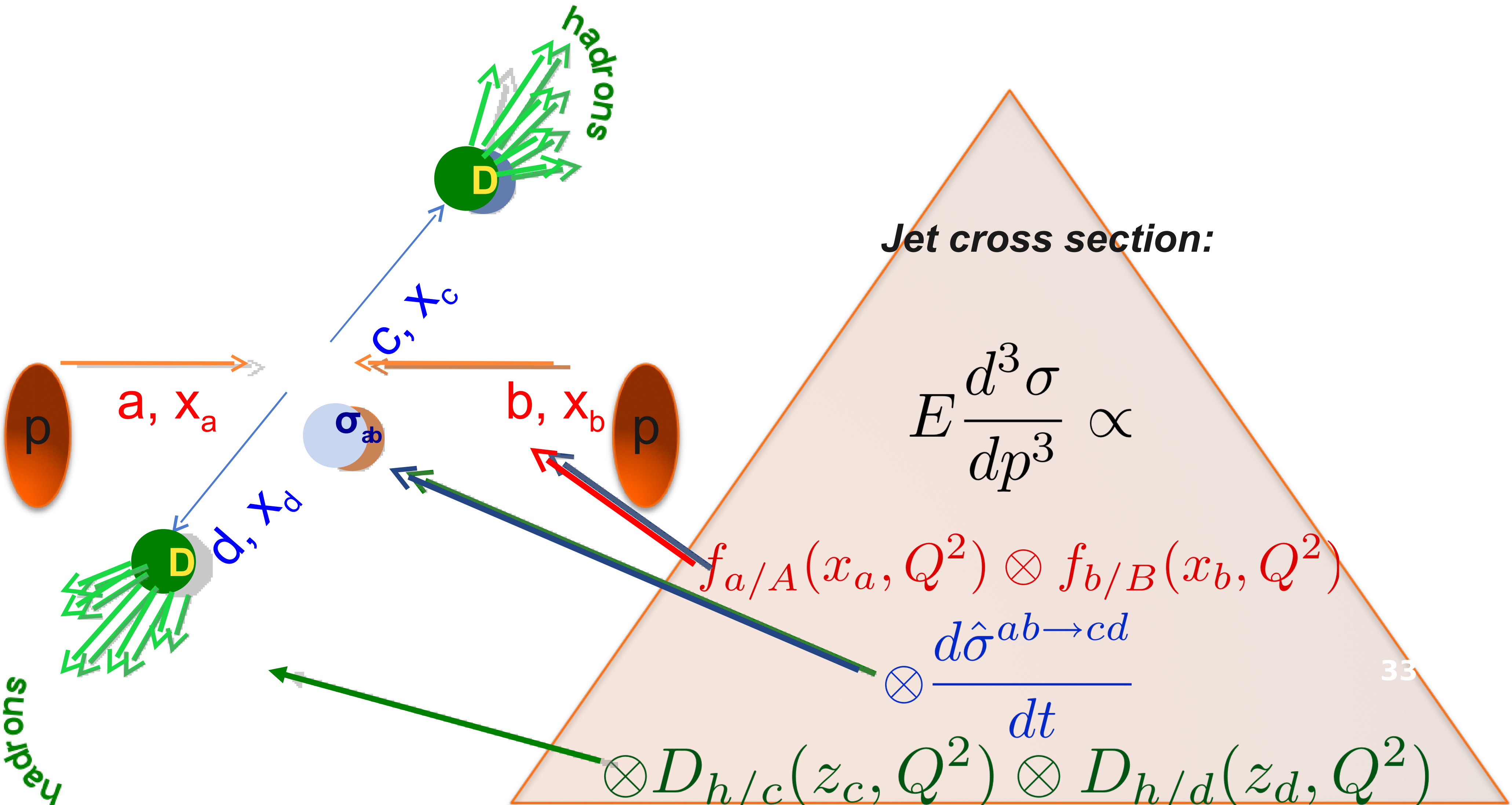


J. Bielcikova QM06

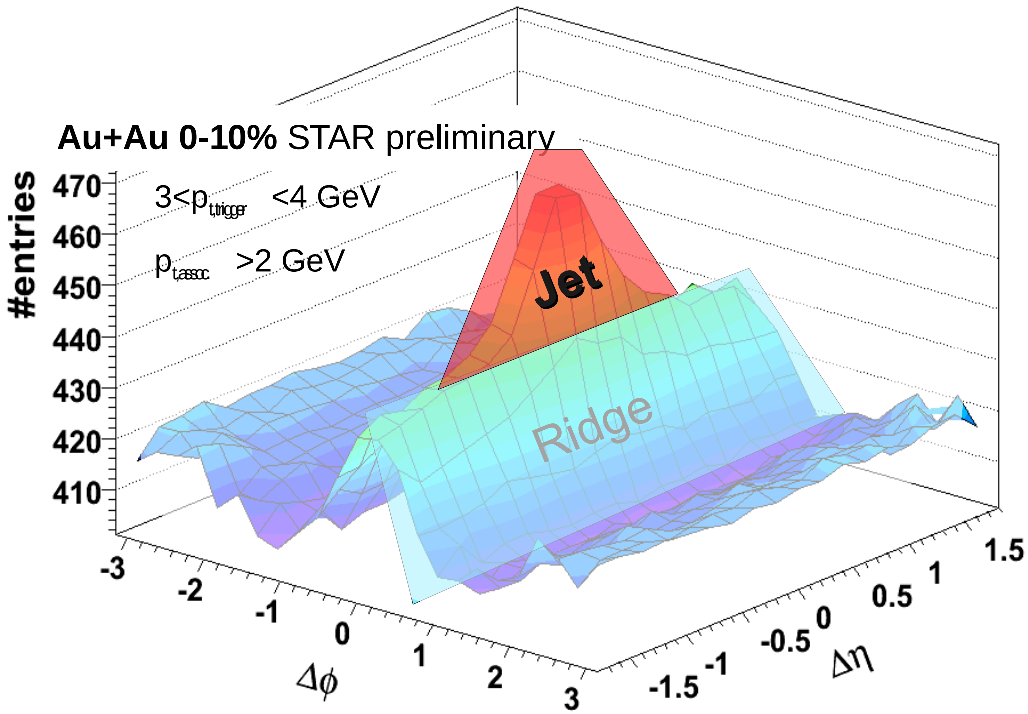
Jets in p+p collisions

Hard probes → early times

Calculable in pQCD: factorization theorem

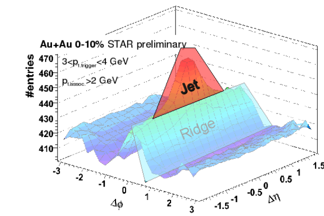


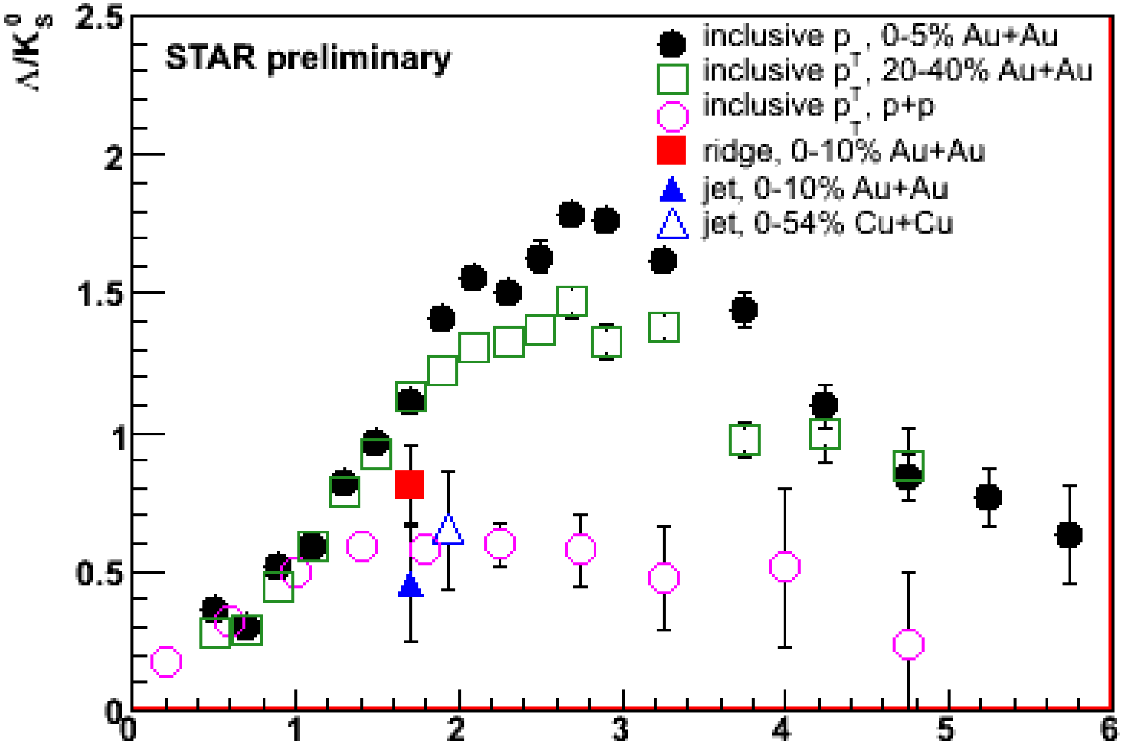
The *Jet*



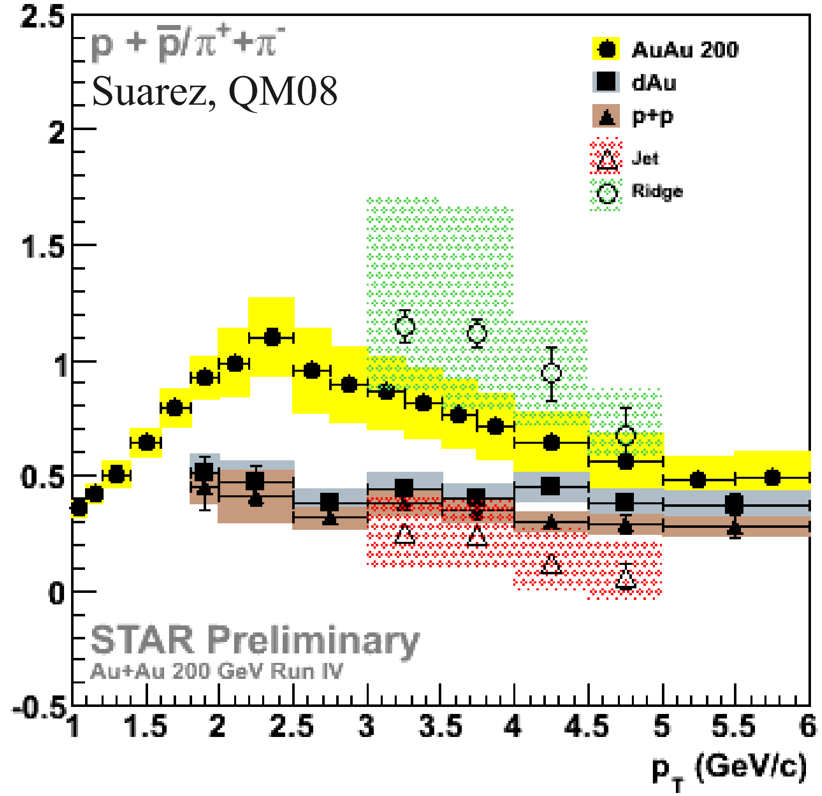
Au+Au 0-10% STAR preliminary
3<p_t,trigger <4 GeV
p_t,assoc. >2 GeV
#entries
470
460
450
440
430
420
410
Jet
Ridge
-3
-2
-1
0
1
2
3
Δφ
-1.5
-1
-0.5
0
0.5
1
1.5
Δη

Ridge composition



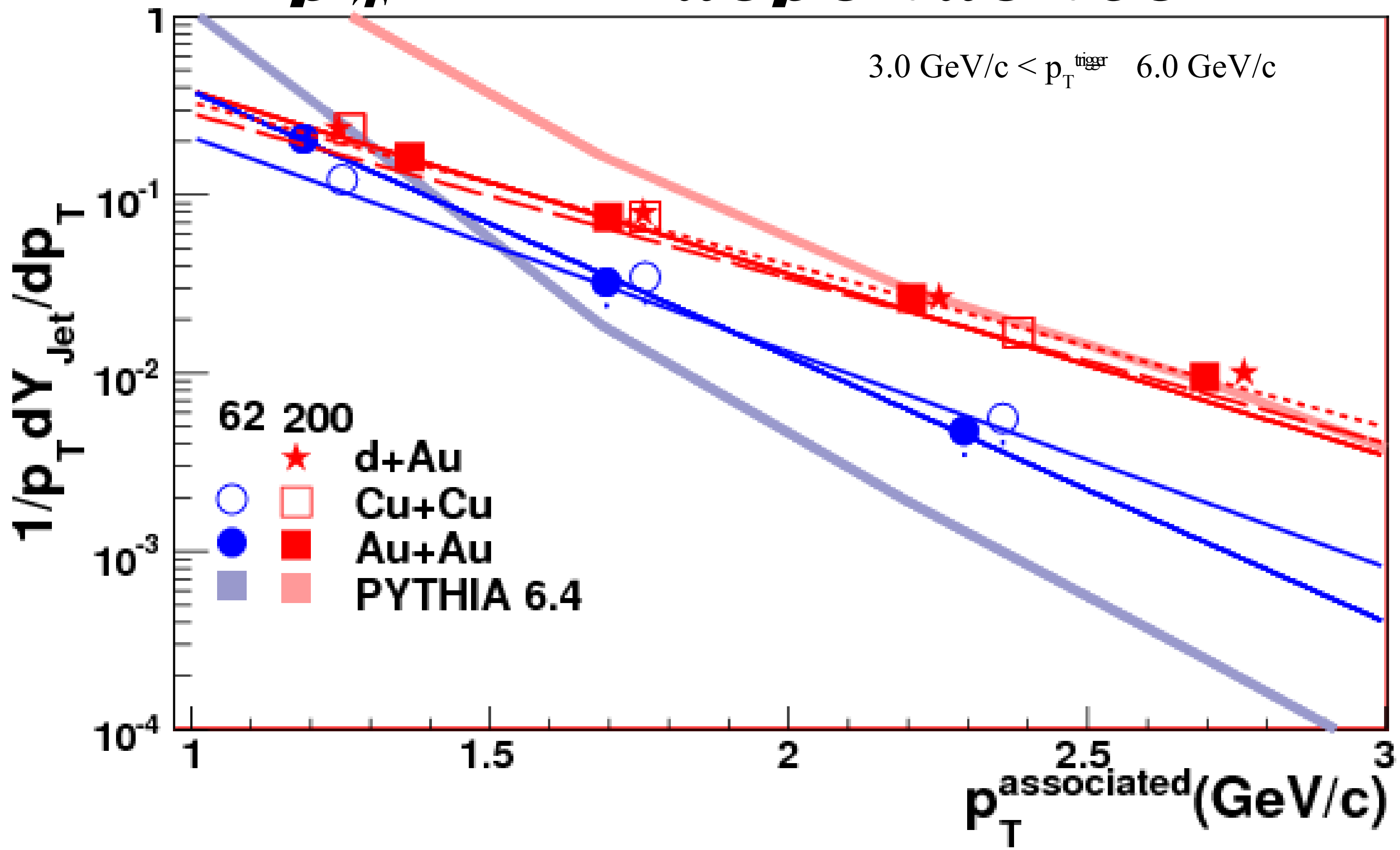


M. Lamont (STAR), J.Phys.G32:S105-S114,2006
J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex



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

$p_T^{associated}$ dependence



No collision system dependence

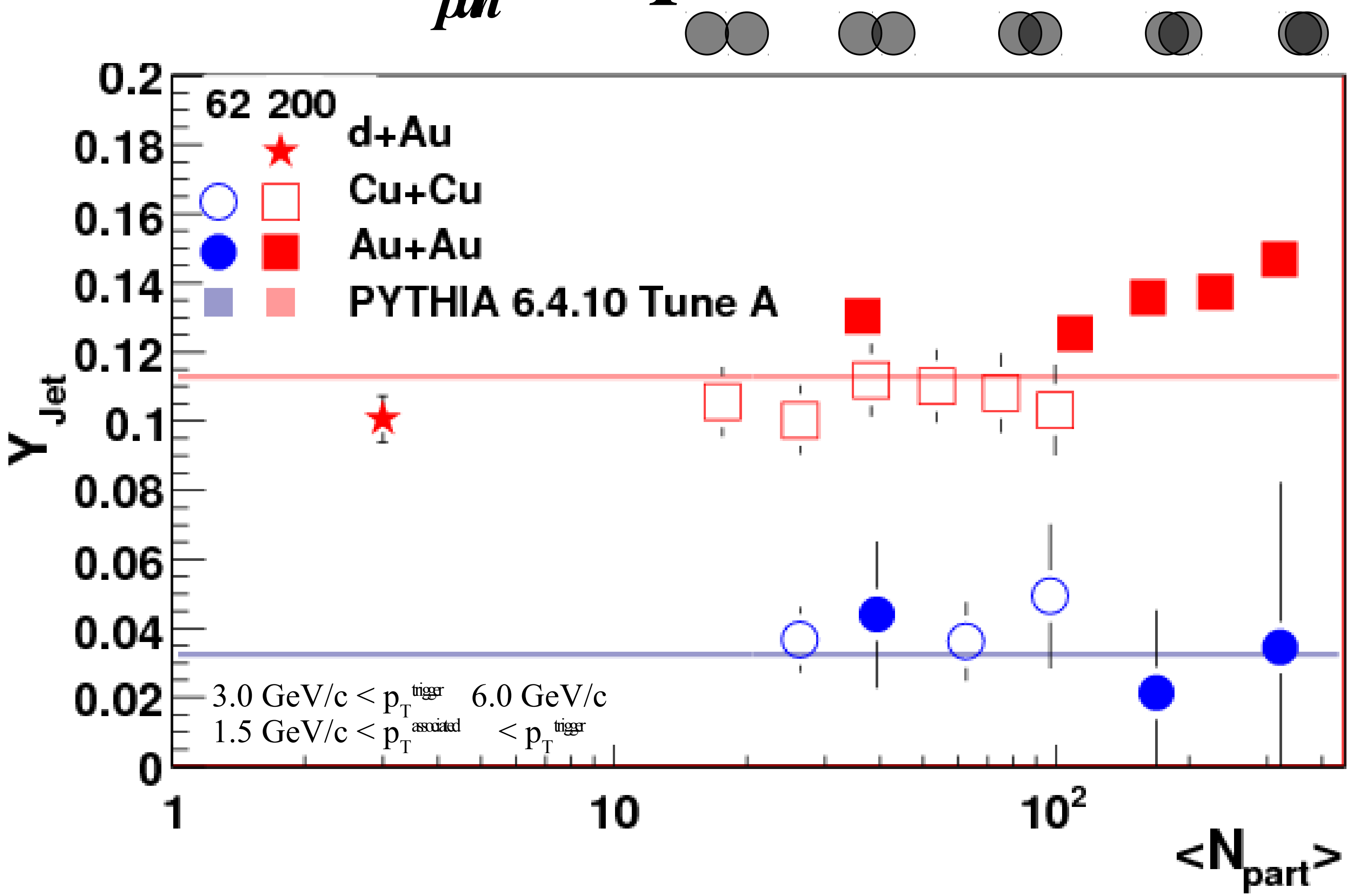
PYTHIA does not describe the data

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

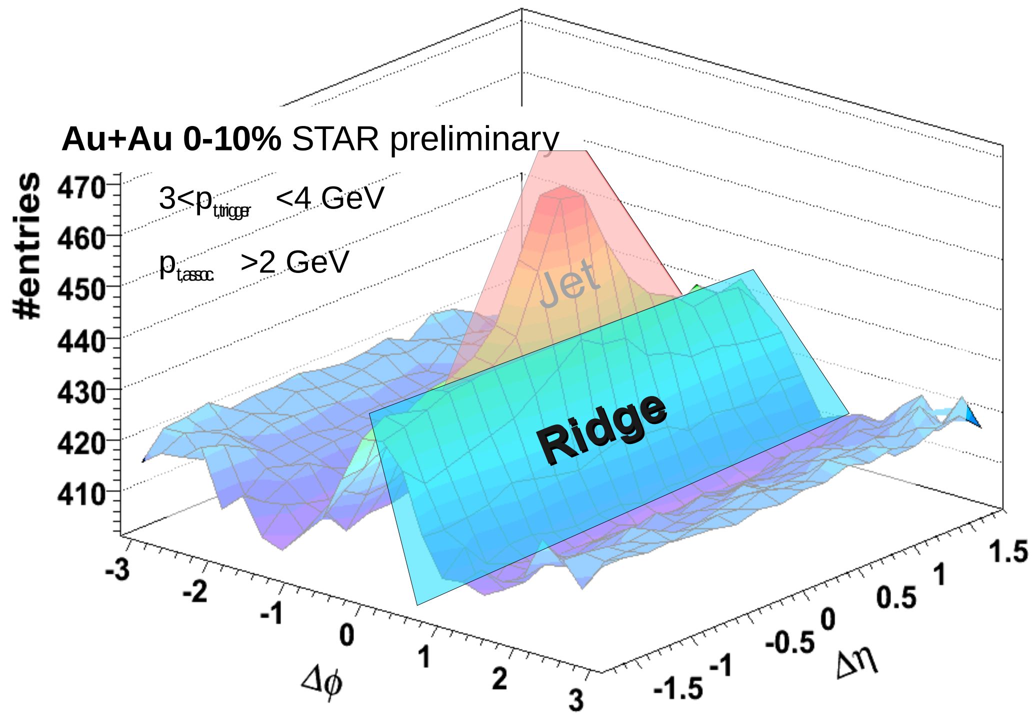


No collision system dependence at a given N_{part}

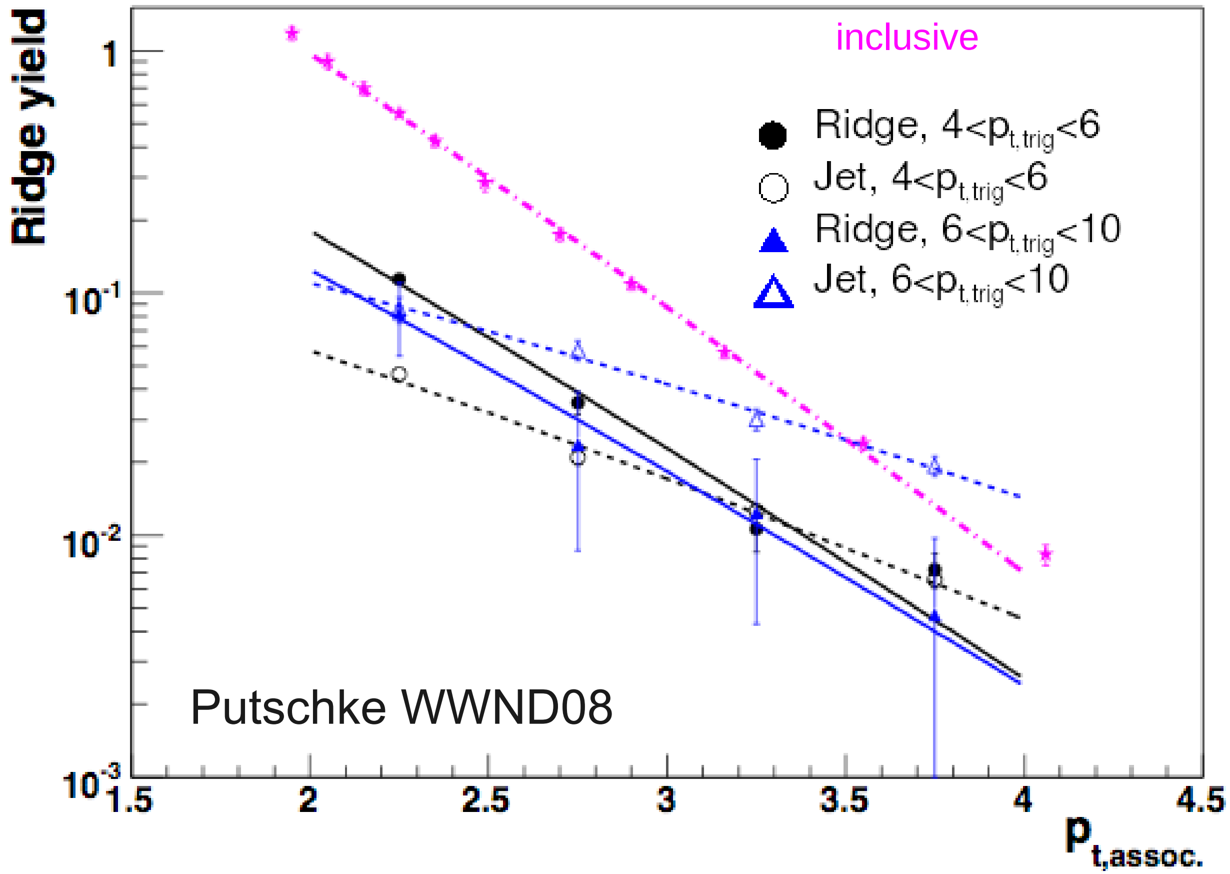
Jet-like yield increases with N_{part}

PYTHIA describes data at lower N_{part}

The *Ridge*

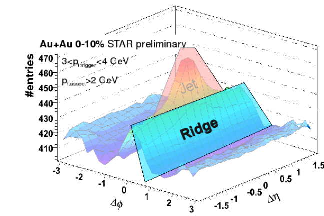

Au+Au 0-10% STAR preliminary
3<p_{t,trigger}<4 GeV
p_{t,assoc.}>2 GeV
#entries
Jet
Ridge
Δφ
Δη

Jet is like p+p, Ridge is like bulk

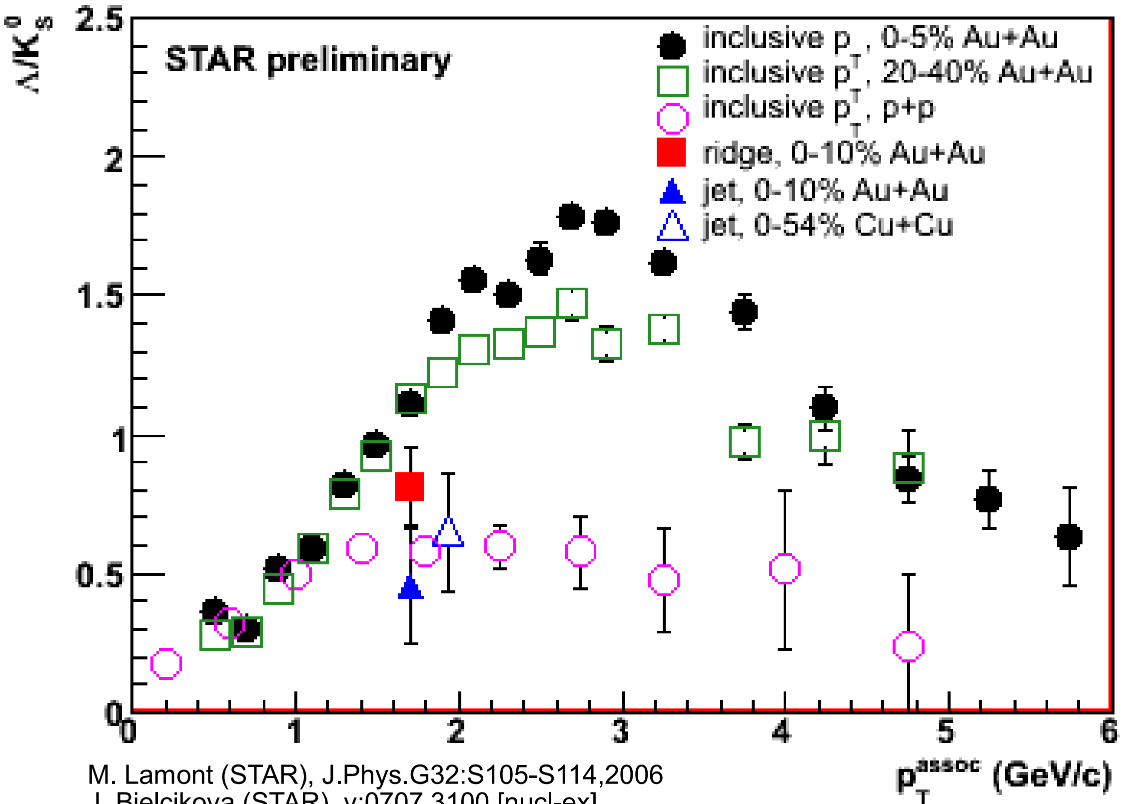


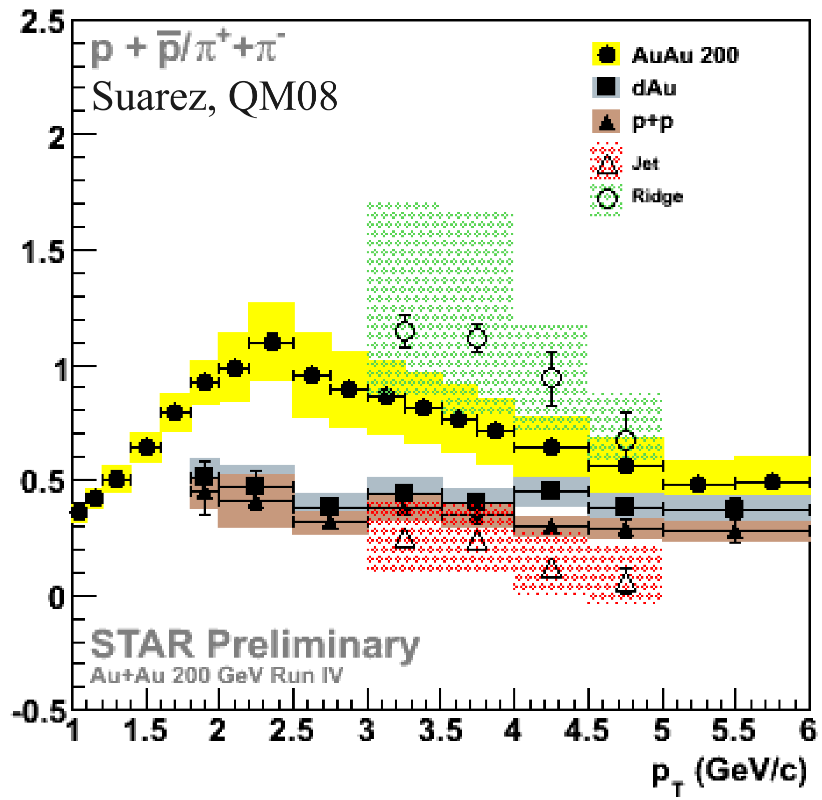
Spectra of particles associated with *Ridge* similar to inclusive

Spectra of particles associated with *Jet* harder



Ridge composition





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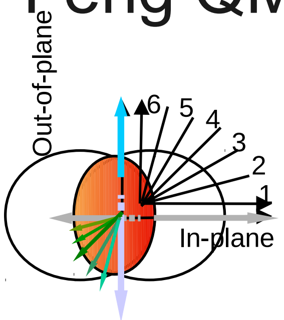
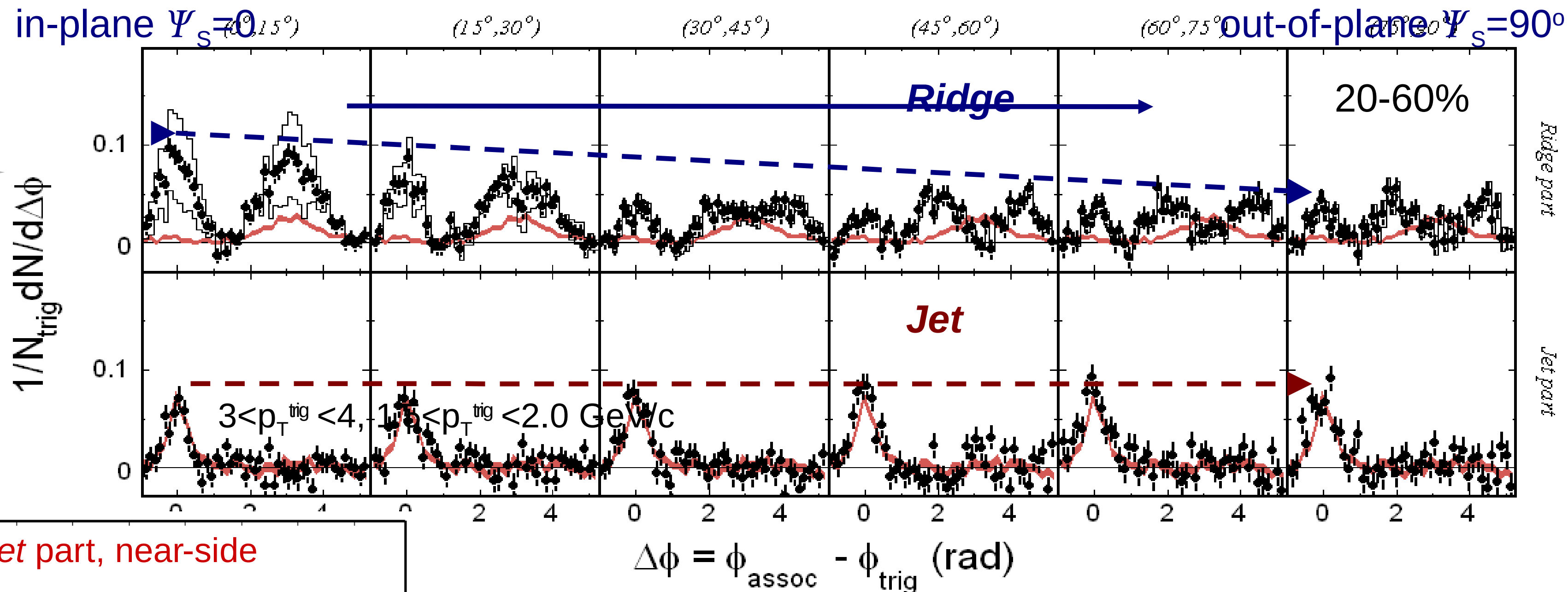
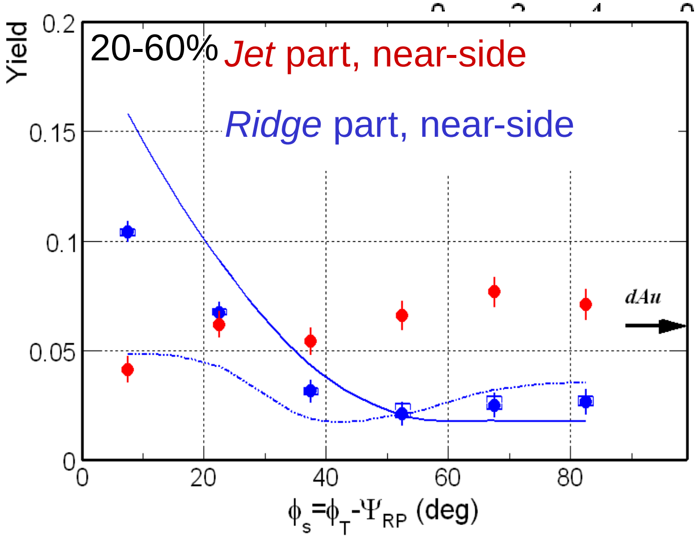
Baryon/meson ratios in *Ridge* similar to bulk for both strange and non-strange particles

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.

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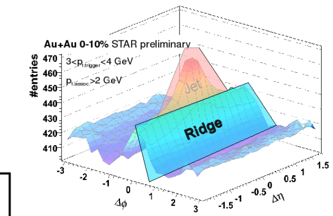
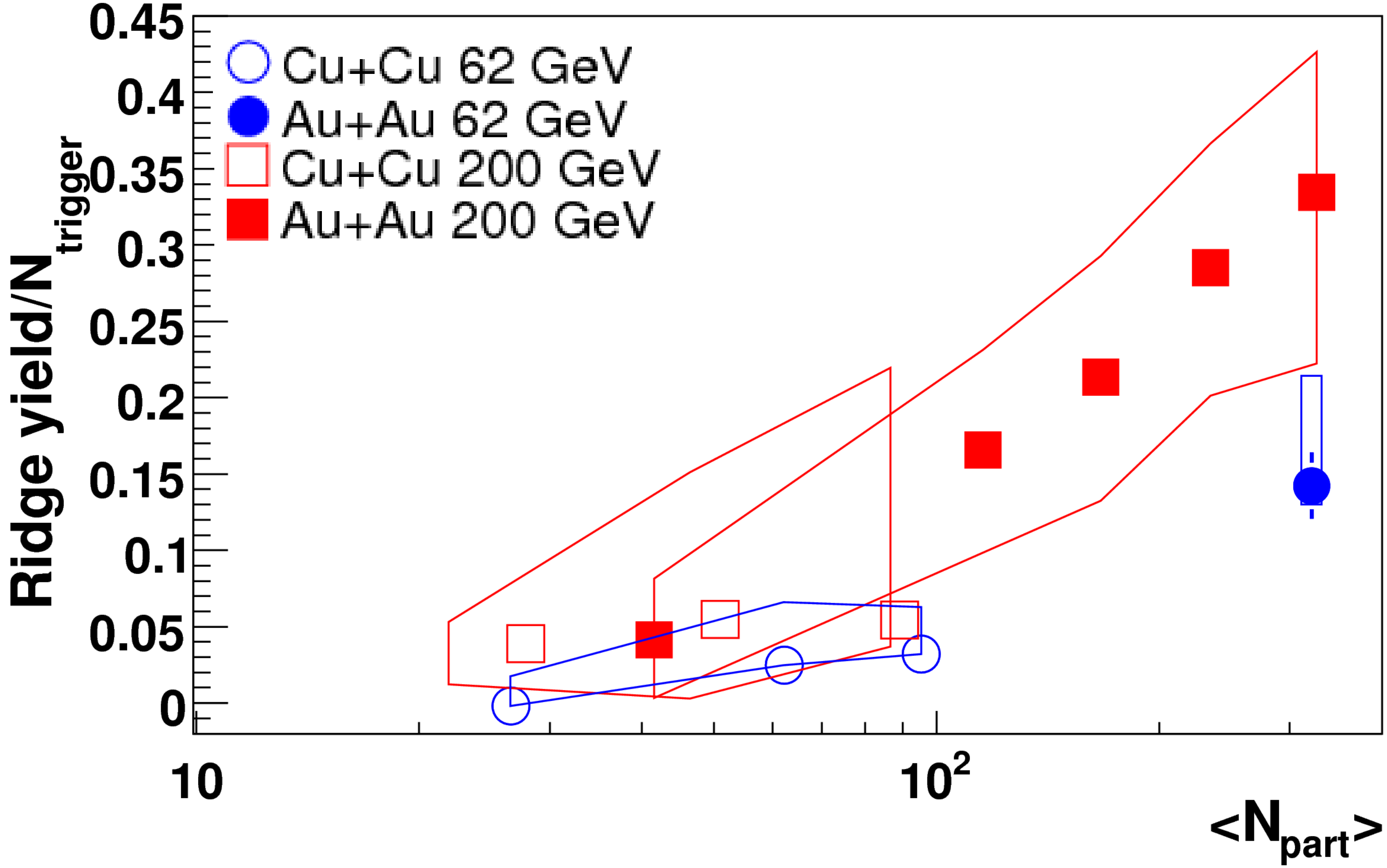
Ridge vs N_{part}





No system dependence at given N_{part}

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

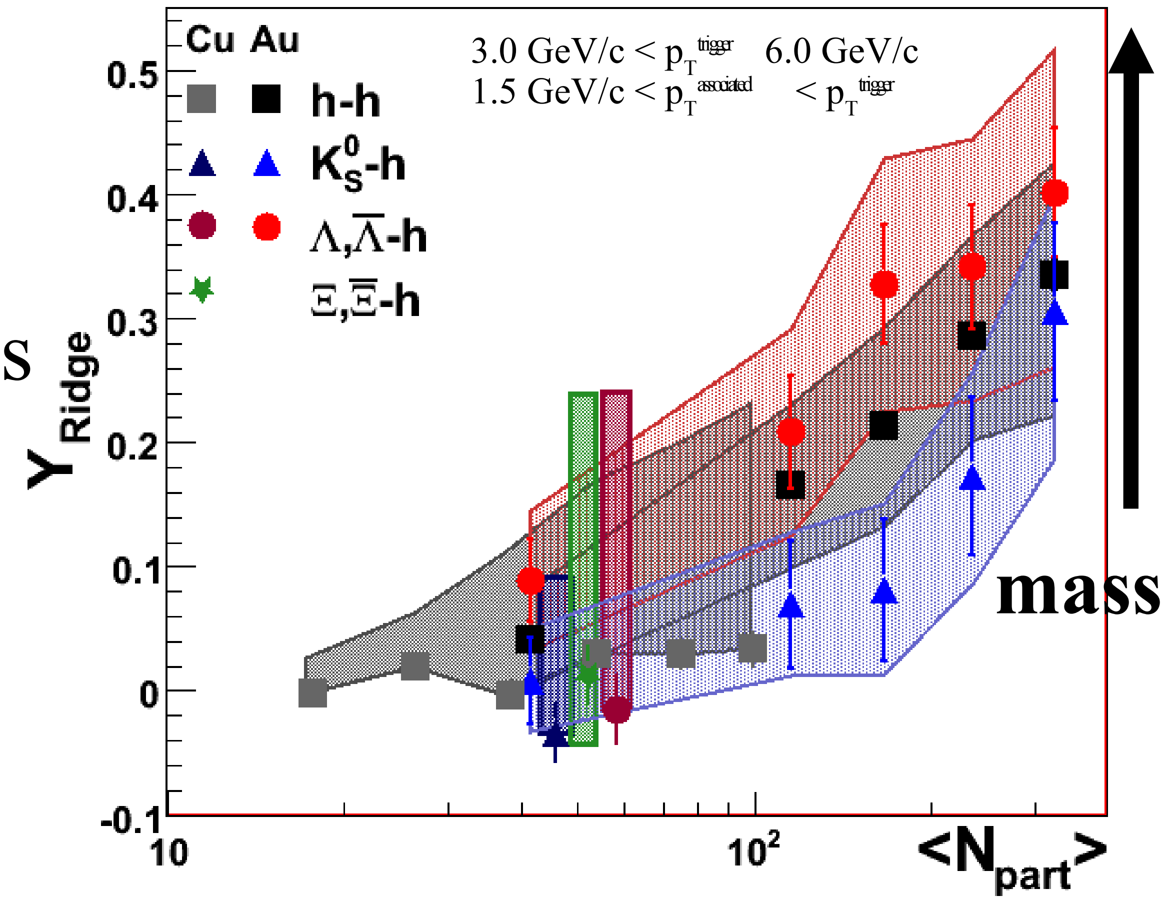
Identified trigger: Near-side Yield vs N_{part}

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

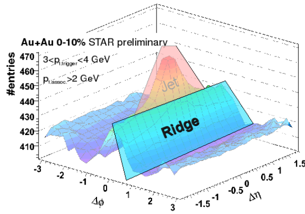
If systematic errors in Au+Au are not correlated, there is no evidence of mass ordering

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

h are 50% p, 50% π



Conclusions: Ridge



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