Jet-like particle correlations

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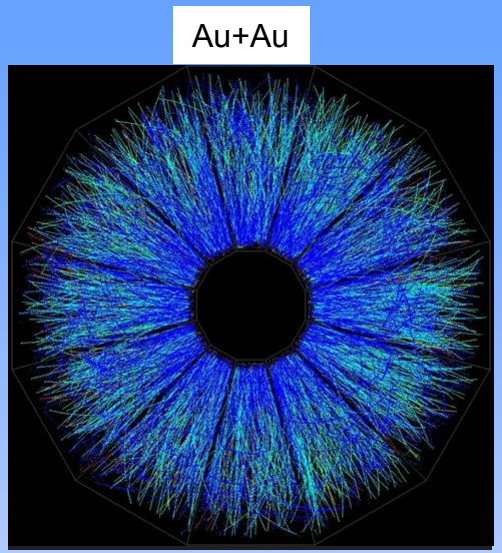
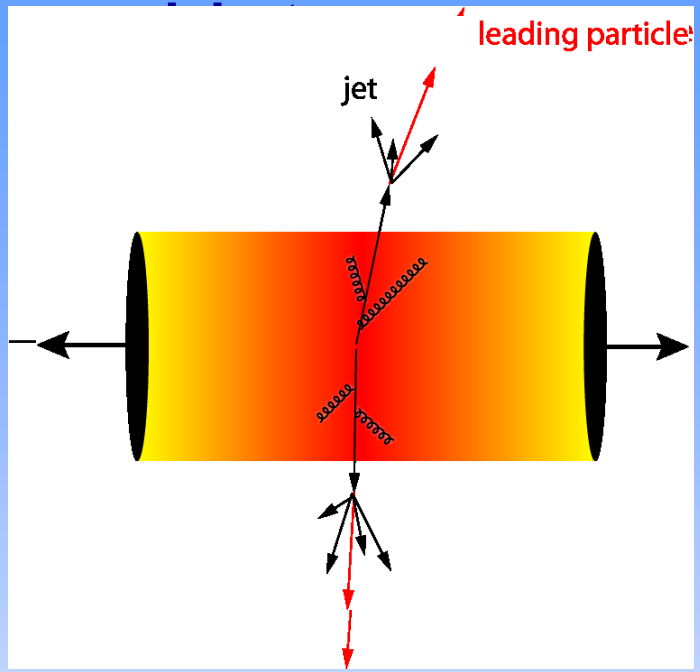
Outline:

- Motivation
- “Jet”-medium interaction via two and three-particle correlations at RHIC
  - conical emission
  - ridge
  - path length effects
- Two-particle correlations at the LHC: the CMS p+p ridge
- Summary

Probing QCD matter with high-p_T particles



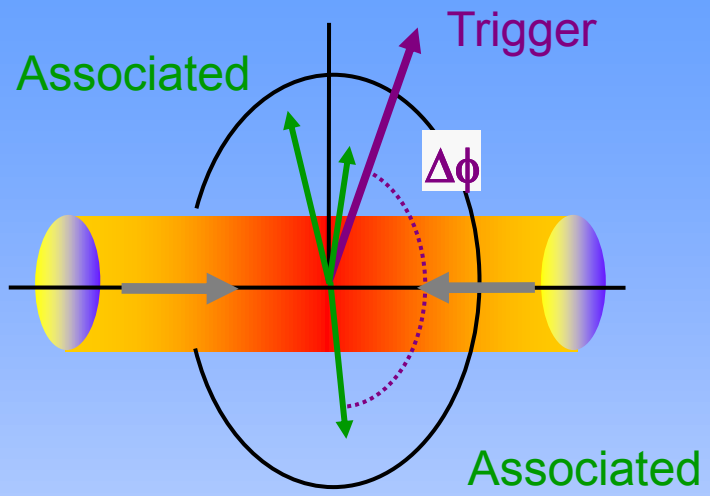


What happens to high-p_T particles/jets which pass through the medium?

Are they similar to p+p or modified by the medium?

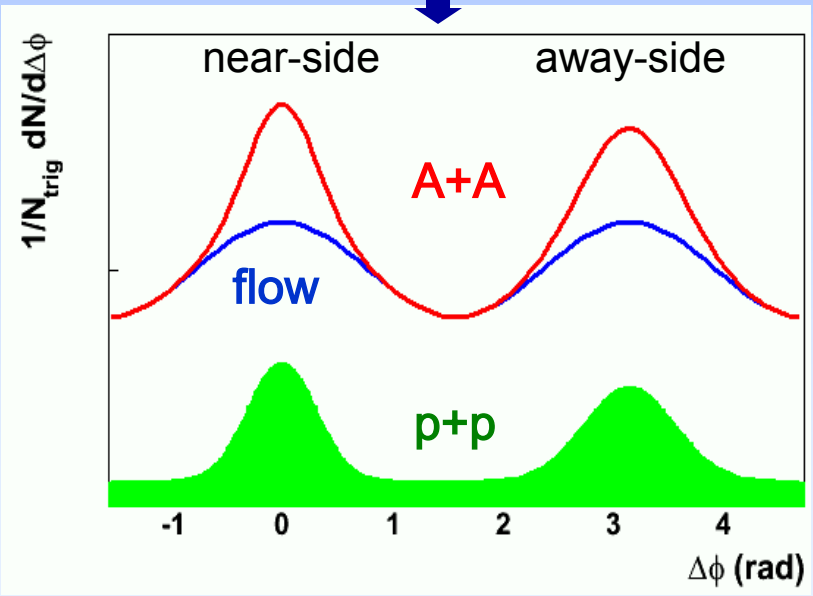
Tools:
- inclusive p_T spectra
- di-hadron correlations
- multi-hadron correlations
- jets, γ-jets

“Jet-like” correlations



Full jet reconstruction in A+A collisions at RHIC difficult due to underlying background:

use azimuthal correlations of high-p_T particles

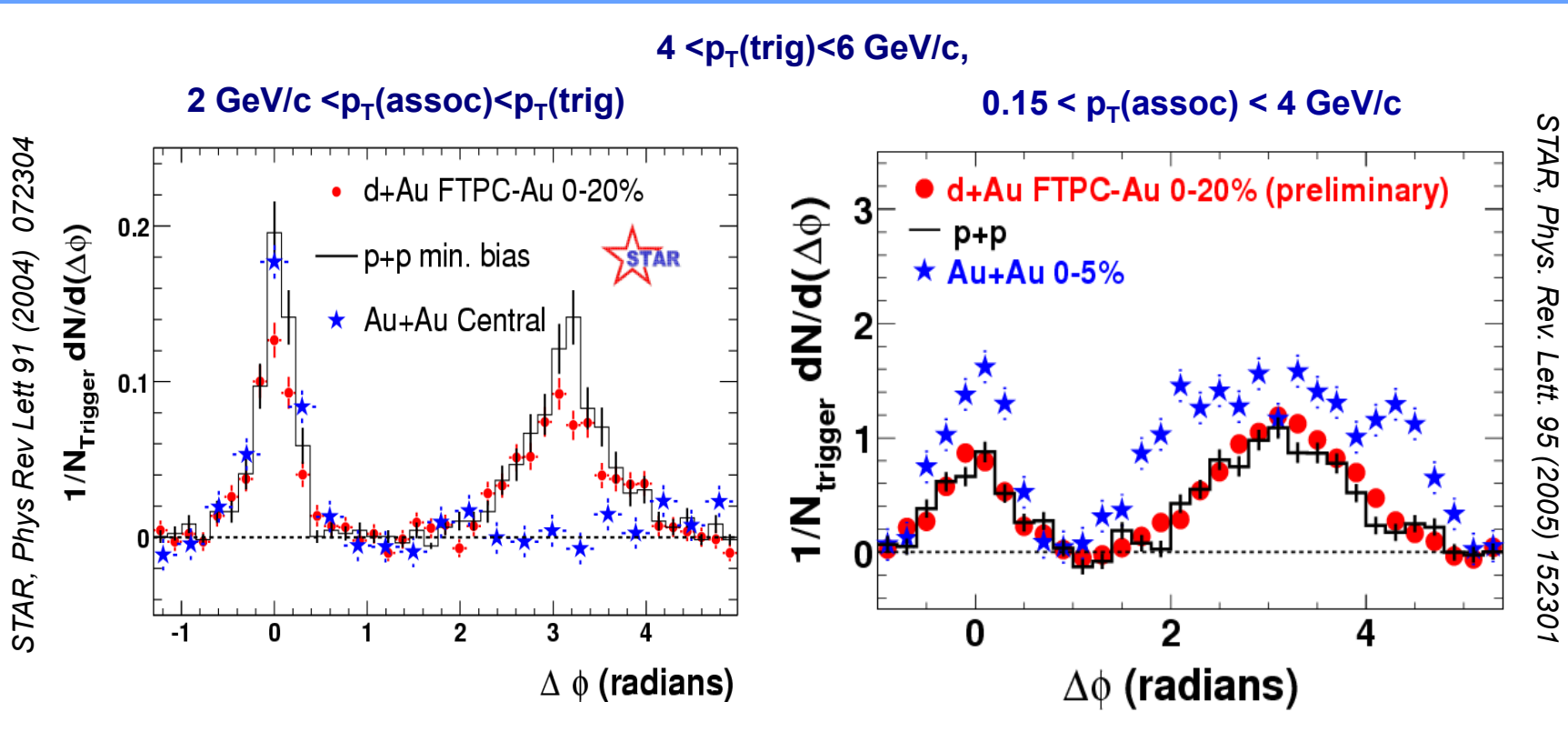


Correlated yield is related to ratio of di-hadron to single hadron fragmentation functions:

$$D^{h_1h_2}(z_T, p_T^{\mathrm{trig}}) = p_T^{\mathrm{trig}} \frac{d\sigma_{AA}^{h_1h_2}/dp_T^{\mathrm{trig}}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\mathrm{trig}}}$$

R_{AA} → $I_{AA} = \dfrac{D_{AA}(z_T, p_T^{\mathrm{trig}})}{D_{pp}(z_T, p_T^{\mathrm{trig}})}$ $z_T = p_{Tassoc}/p_{Ttrig}$

Jet-like correlations at RHIC

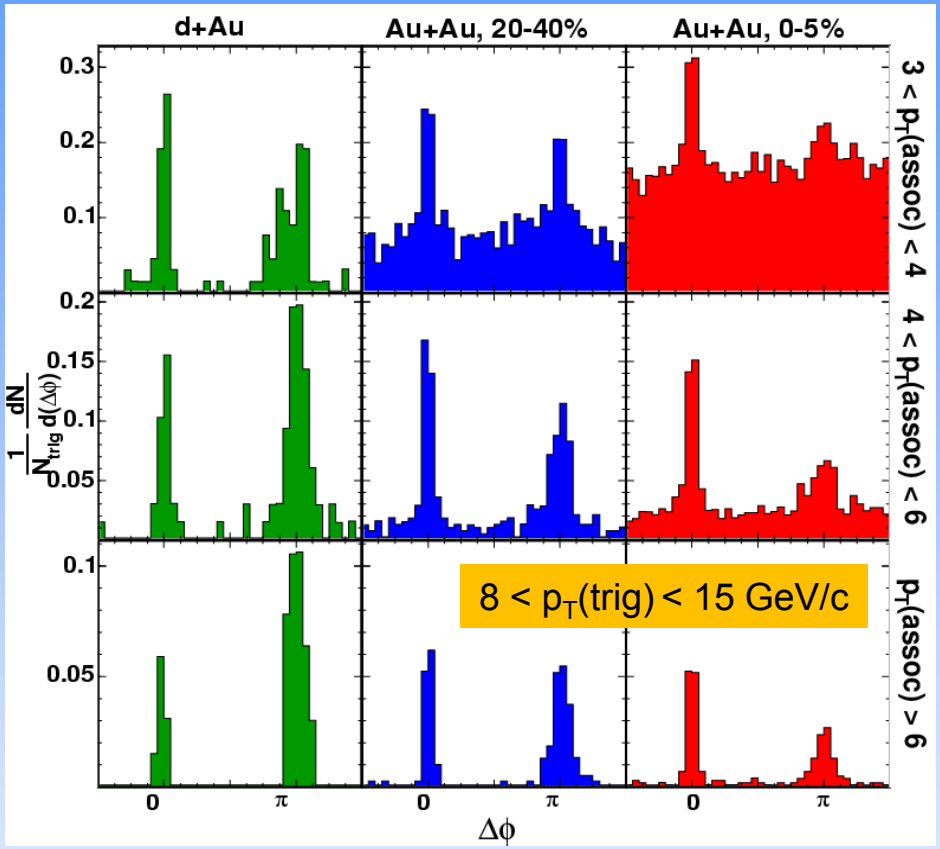


Central Au+Au collisions at 200 GeV:

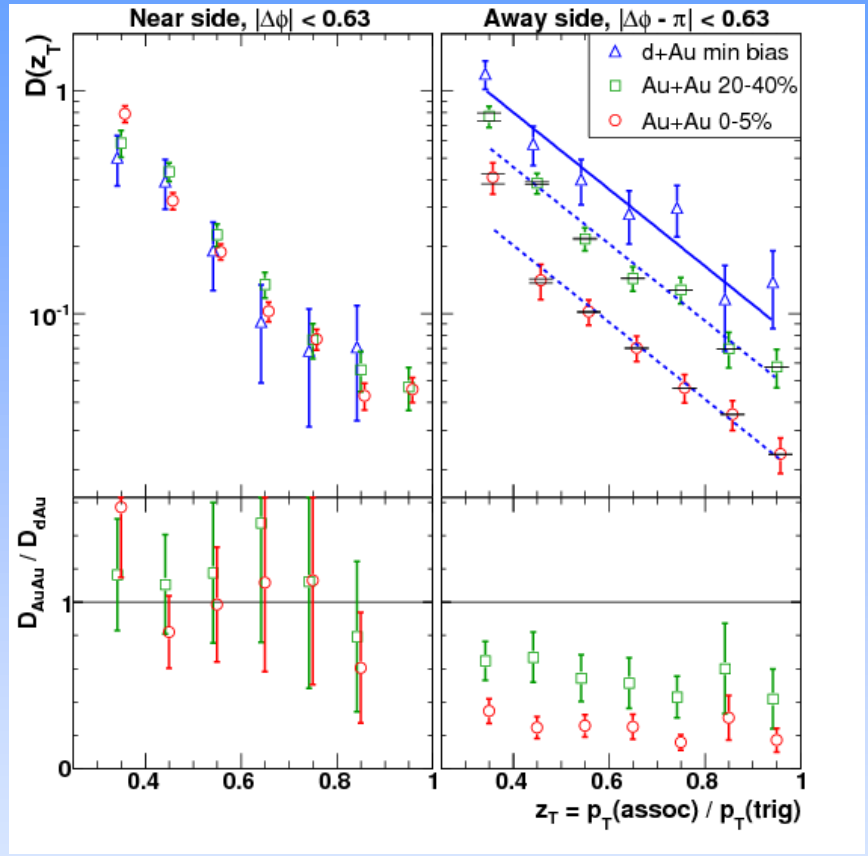
- intermediate p_T: disappearance of away-side correlations, but d+Au and p+p correlations are similar -> jet suppression is a final state effect
- lowering p_T threshold: resurrects correlated yield at away side
  - near/away-side yields are enhanced and away-side peak modified relative to p+p/d+Au

Jet-like correlations at high-p_T

STAR, Phys. Rev. Lett. 97 (2006) 162301



STAR, Phys. Rev. Lett. 97 (2006) 162301

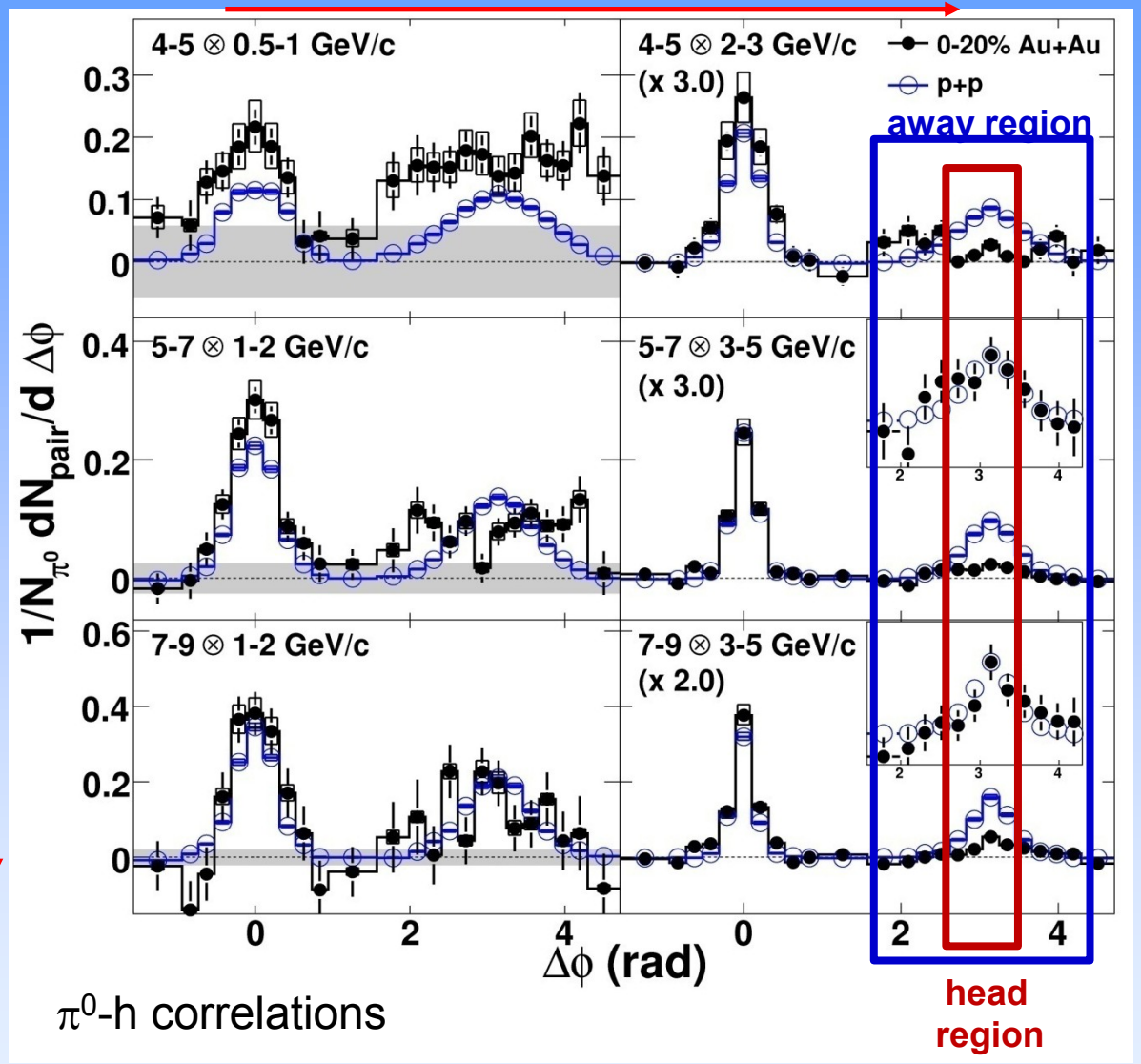


Central Au+Au collisions at 200 GeV:

- near side yield: no suppression
- away-side yield is suppressed: $R_{AA} \sim I_{AA}$
- suppression without angular broadening or medium modification

seeing those partons that fragment in vacuum?

Di-hadron correlations: p_T systematics



lower p_T:
shape modification
of the away-side peak
conical emission?

higher p_T:
shape of the away-side
peak identical for Au+Au
and p+p collisions

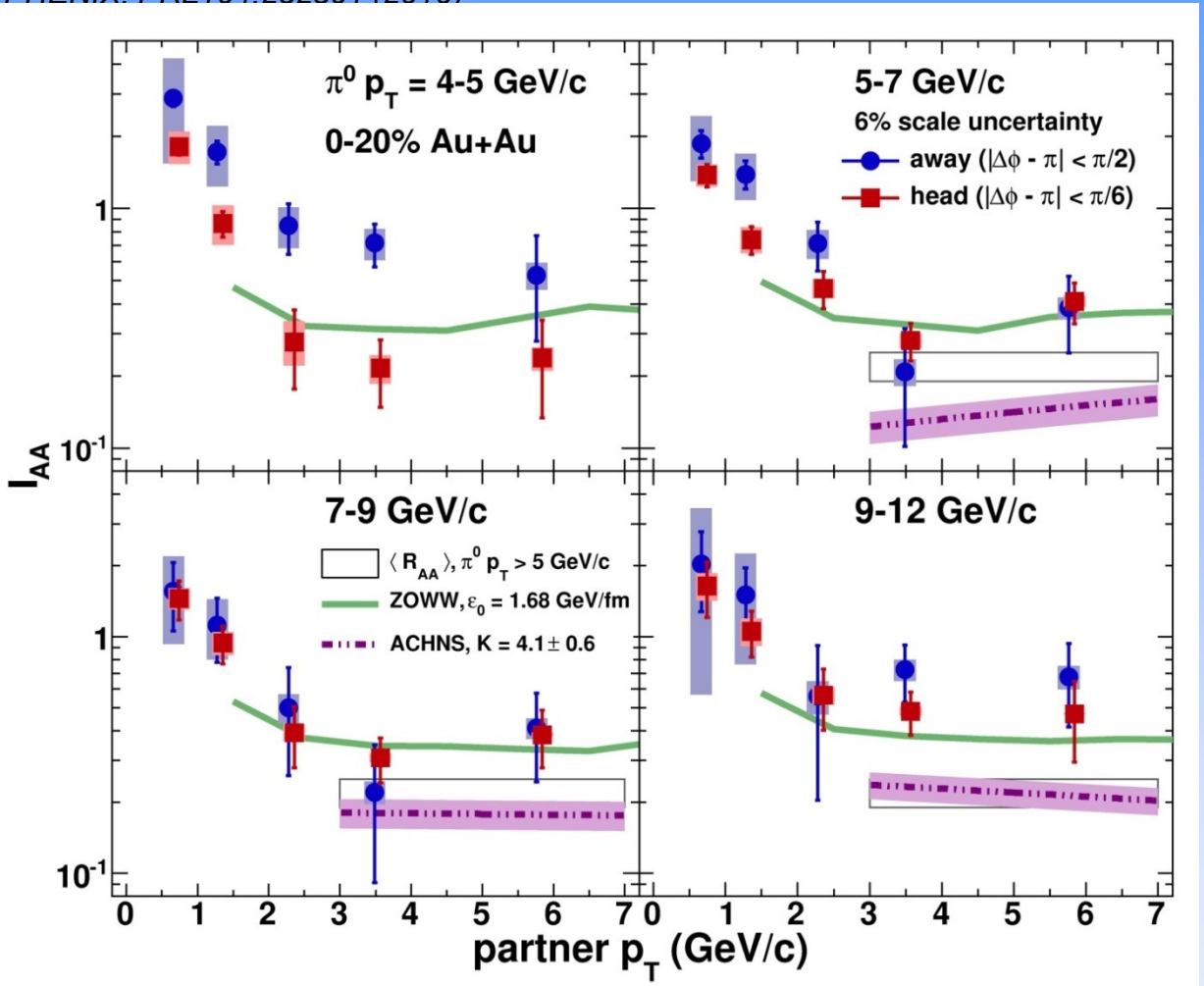
BUT

away-side jet-like yield
in central Au+Au collisions
suppressed relative to p+p

PHENIX, PRL104,252301 (2010)

I_{AA} : away-side jet-like yield suppression

PHENIX, PRL104,252301 (2010)



Recalculation with a common medium geometry in both models to pin down the source of the observed differences needed!

Data:

- lower p_T: $I_{AA}(\text{head}) < I_{AA}(\text{away})$
- lower p_T^{assoc}: $I_{AA} > 1$
- high p_T ^{trigger} and p_T^{assoc}: $I_{AA} > R_{AA}$!

Model comparisons:

ACHNS: hydrodynamic evolution of the medium + energy loss parameters constrained by RHIC data:

$I_{AA} < R_{AA}$

Armesto, Cacciari, Hirano, Nagle, Salgado, J. Phys. G37, 025104 (2010)

ZOWW: a simple spherical nuclear geom. + earlier RHIC data constraints

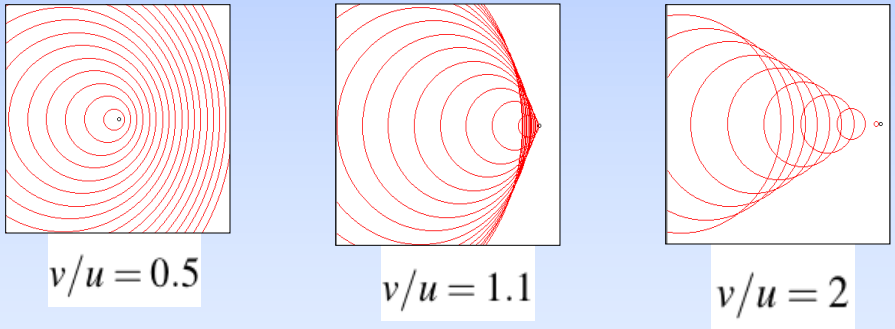
$I_{AA} > R_{AA}$

Zhang, Owens, Wang, Wang, Phys. Rev. Lett. 103, 032302 (2009)

Conical emission in A+A collisions?

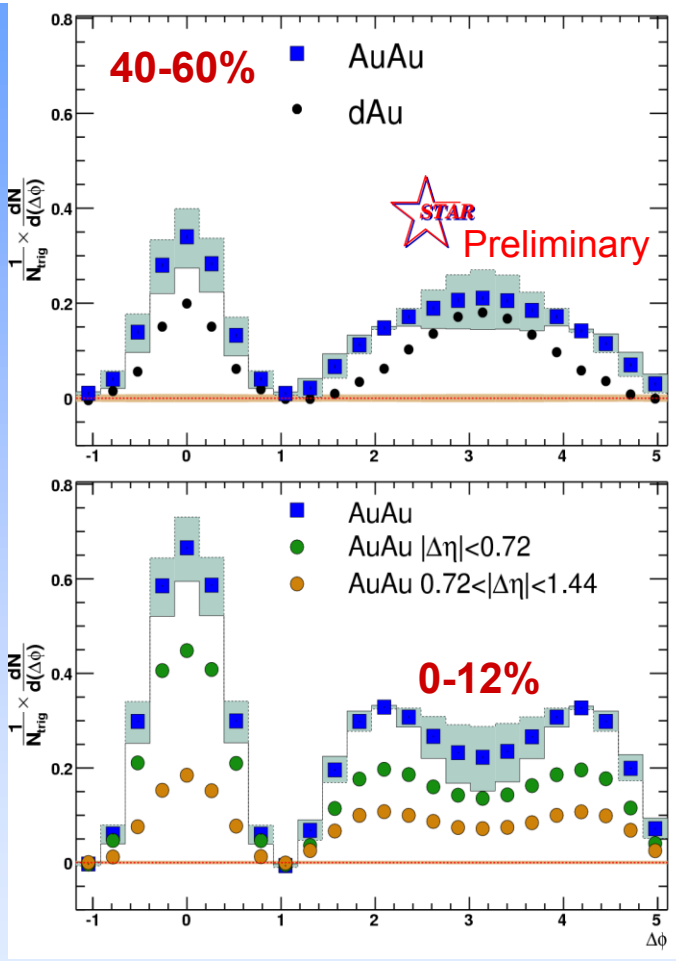
- Mach cone in heavy-ion physics introduced in1970's (Hofmann, Stöcker, Heinz, Scheid, Greiner)

- a supersonic parton creates shock waves:
  - hydrodynamics
    Stöcker et al., NPA750 (2005) 121
    Casalderrey-Solana et al., NPA774 (2006) 577
    Renk, Ruppert, PRC73 (2006) 011901
  - colored plasma
    Ruppert, Mueller, PLB618 (2005) 123
  - AdS/CFT
    Gubser, Pufu, Yarom, PRL100, (2008) 012301



- Čerenkov gluon radiation by a superluminal parton
  Dremin, NPA750 (2006) 233
  Koch et. al., PRL96 (2006) 172302

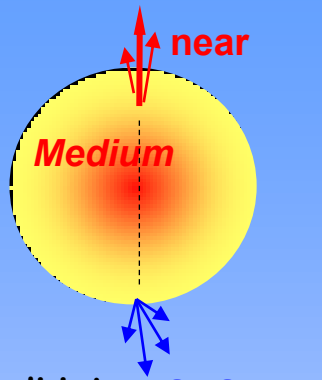
$2.5 < p_T^{trig} < 4$ GeV/c and $1 < p_T^{assoc} < 2.5$ GeV/c

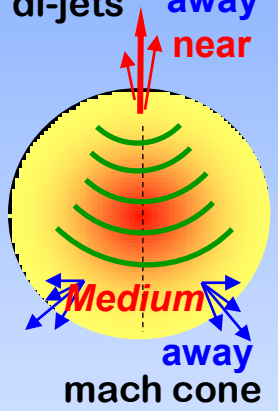


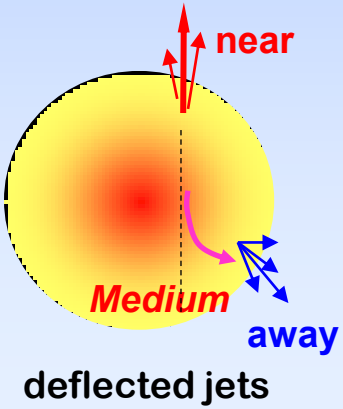
M. Horner (STAR), J.Phys.G34, S995,2007

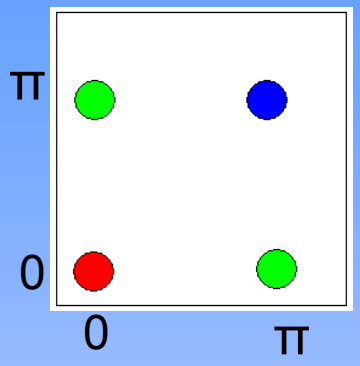
To distinguish from other mechanisms 3-particle correlation studies needed

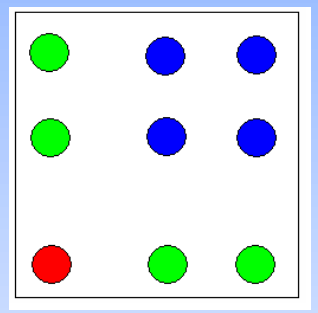
Conical flow or deflected jets? (I)

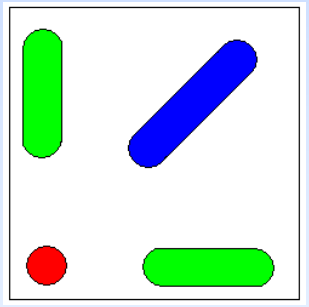












courtesy to J. Ulery

cartoons of 3-particle azimuthal correlations (1 trigger + 2 associated particles)

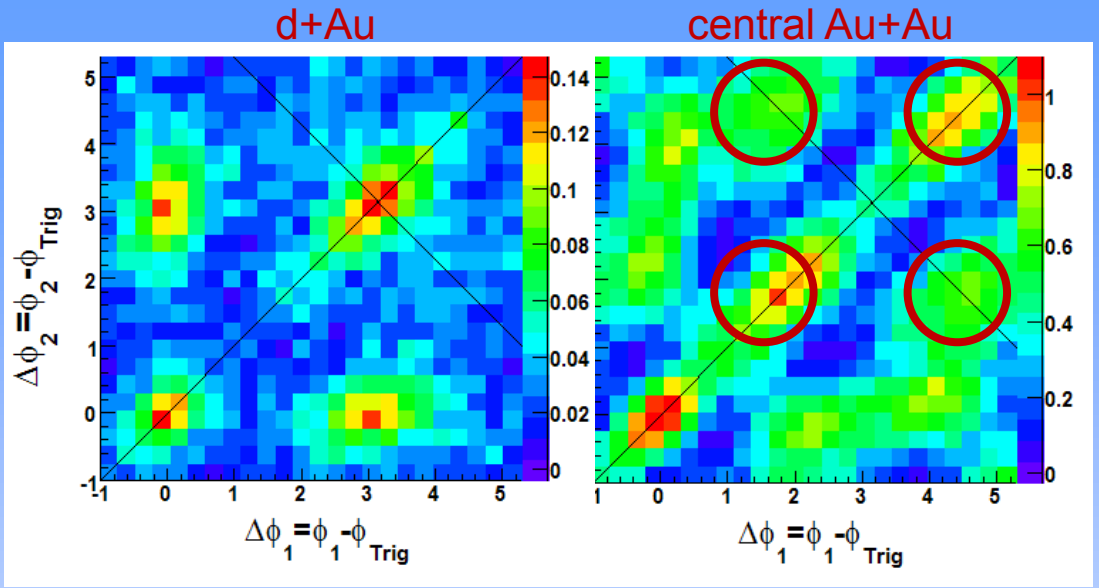
di-jets

conical emission

deflected jets
(by the collective movement, "flow", of the expanding medium)

Armesto , Salgado, Wiedemann, PRL 93, (2004) 242301

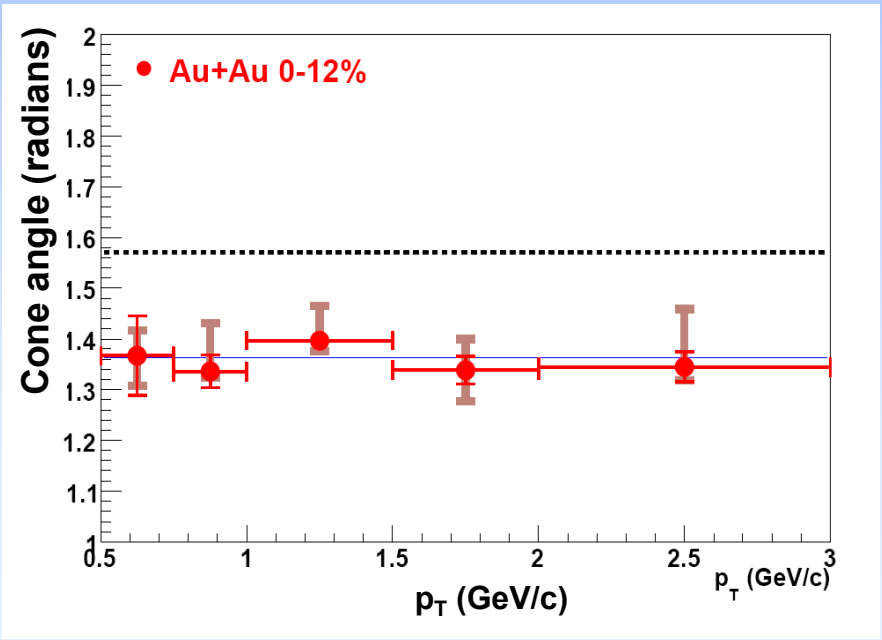
$\Delta\phi$–$\Delta\phi$ correlations



Note: Large and complicated backgrounds

Jet+flow background method

- model dependent analysis
- evidence for conical emission



Cone angle independent of p_T^{assoc}

$\theta = 1.37 \pm 0.02$ (stat.)± 0.06 (syst.)

x

Čerenkov gluon emission: cone angle decreases with p_T^{assoc}

Are those shock wawes?

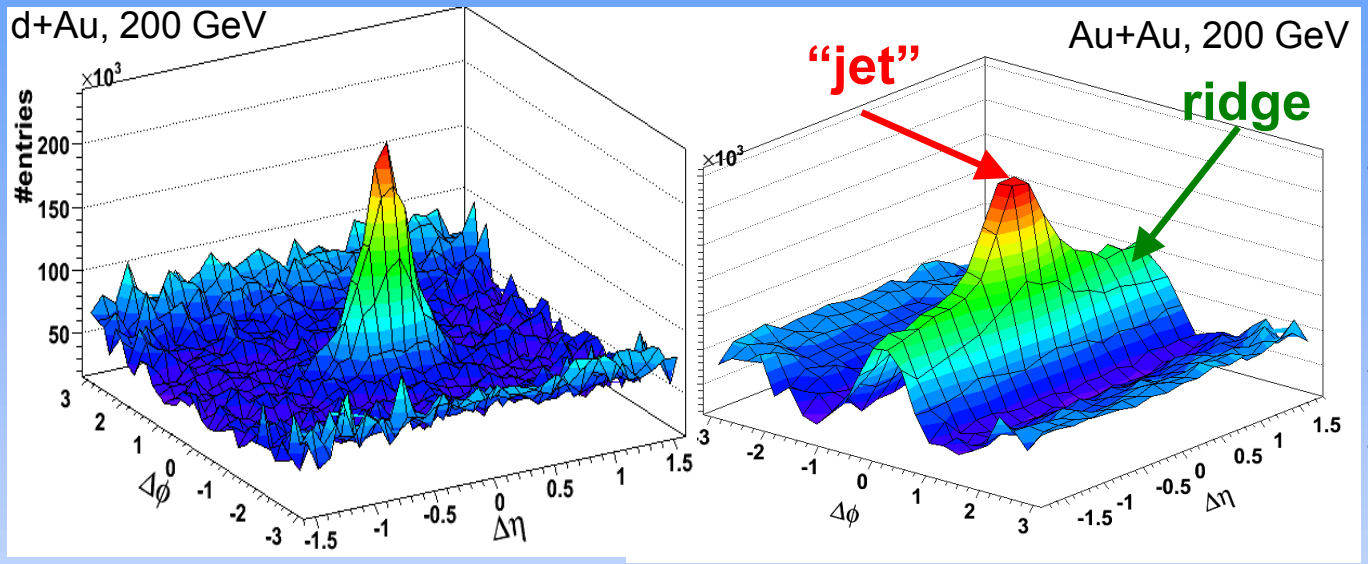
Speed of sound?

Requires medium modeling …

STAR, Phys. Rev. Lett. **102**, 052302 (2009)

A closer look at the near-side peak …

p_T^{trig}=3-4 GeV/c, 2 GeV/c <p_T^{assoc}< p_T^{trig}



D, Magestro (STAR), Hard Probes 2004
STAR, Phys. Rev. C ***80*** *(2009) 64912*

Additional near-side correlation in pseudorapidity ($\Delta\eta$) observed in central Au+Au collisions at RHIC!

- this structure is not present in p+p or d+Au collisions

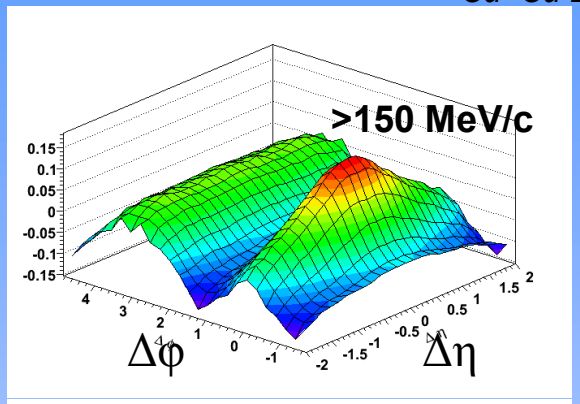
Jet-medium interaction?
parton recombination,
momentum kick,
gluon radiation+longitudinal flow …

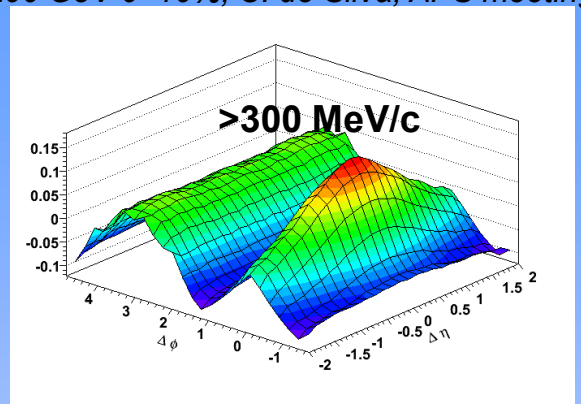
Initial state fluctuations and hydrodynamic flow?
glasma flux tubes,
participant fluctuations (triangular flow) …

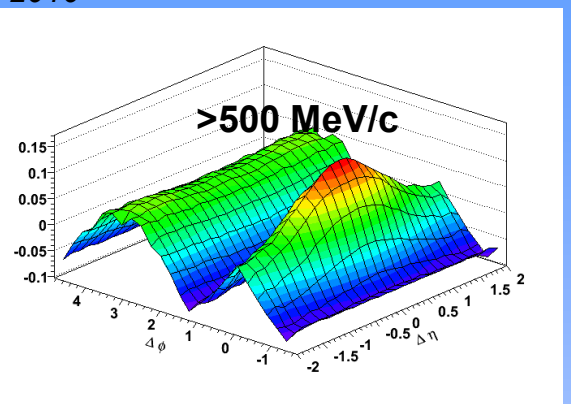
More quantitative model predictions needed!

Correlation functions: evolution with p_T

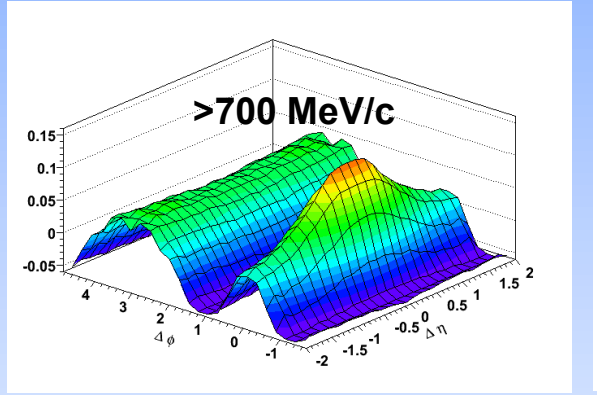
Cu+Cu 200 GeV 0–10%, C. de Silva, APS meeting, 2010

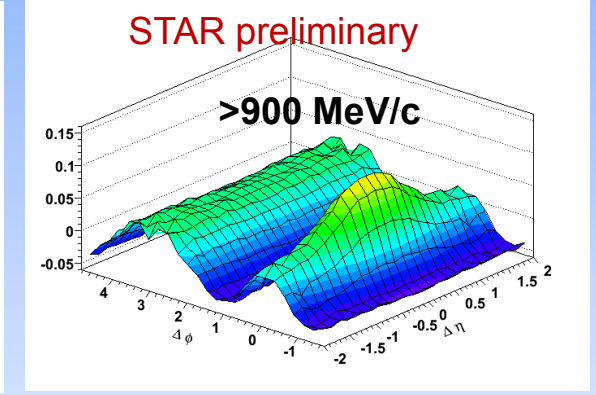


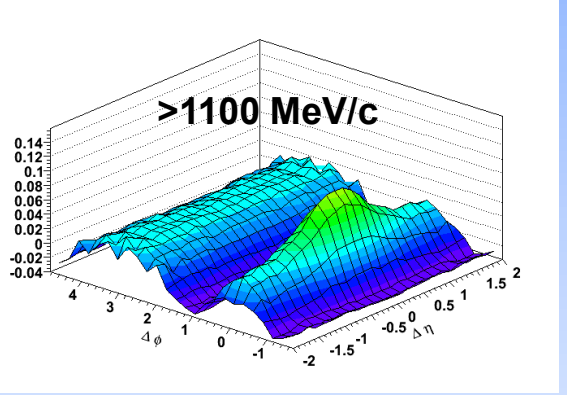


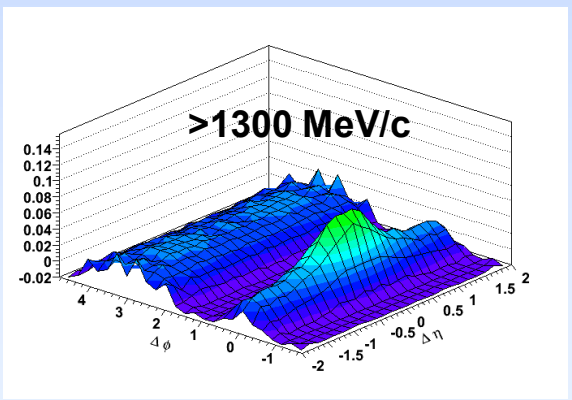


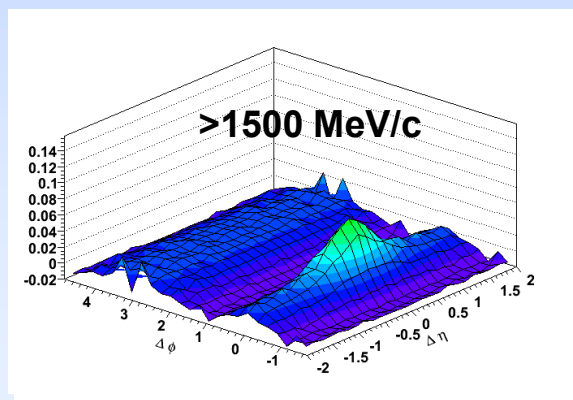
STAR preliminary

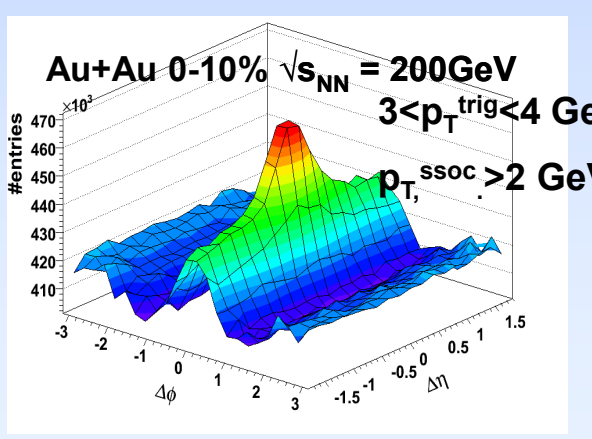




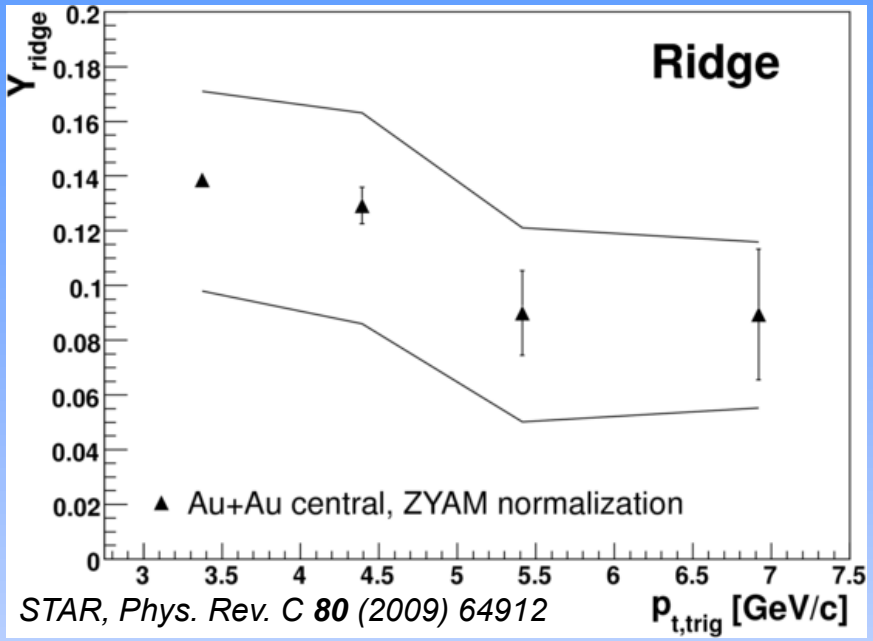




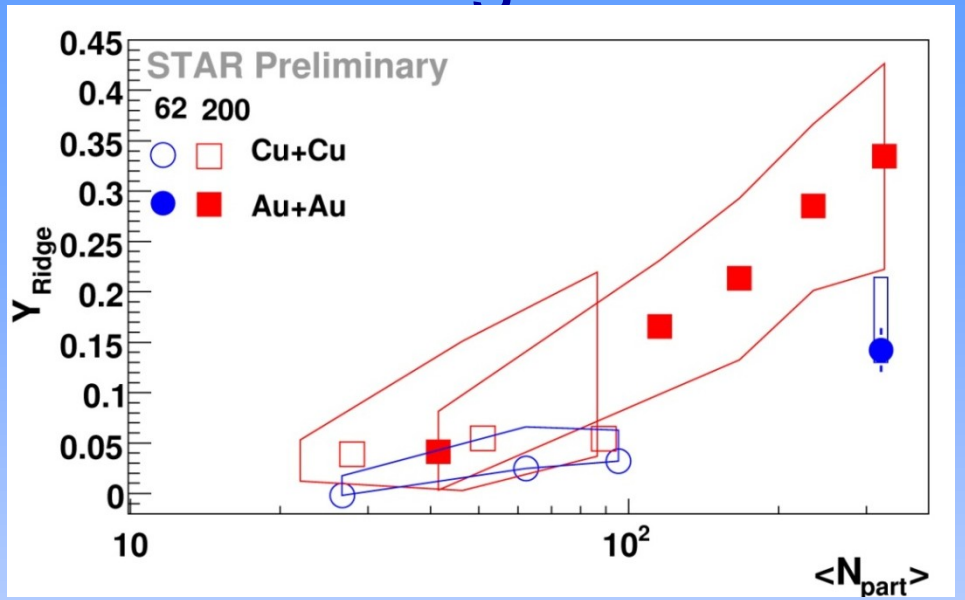




What is the near-side ridge?



*STAR, Phys. Rev. C **80** (2009) 64912*

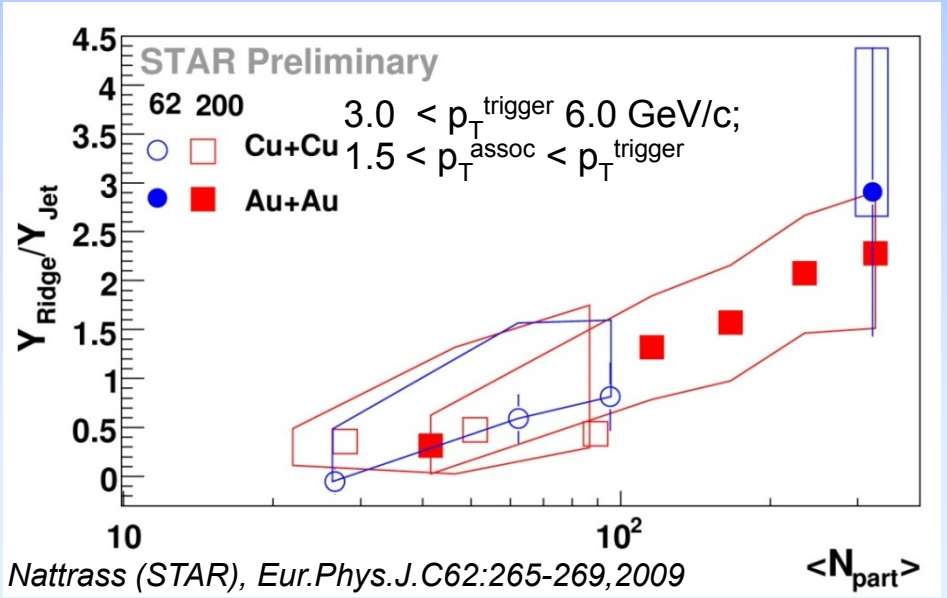


Ridge yield:

- persists to highest trigger p_T
- increases with N_{part}

BUT

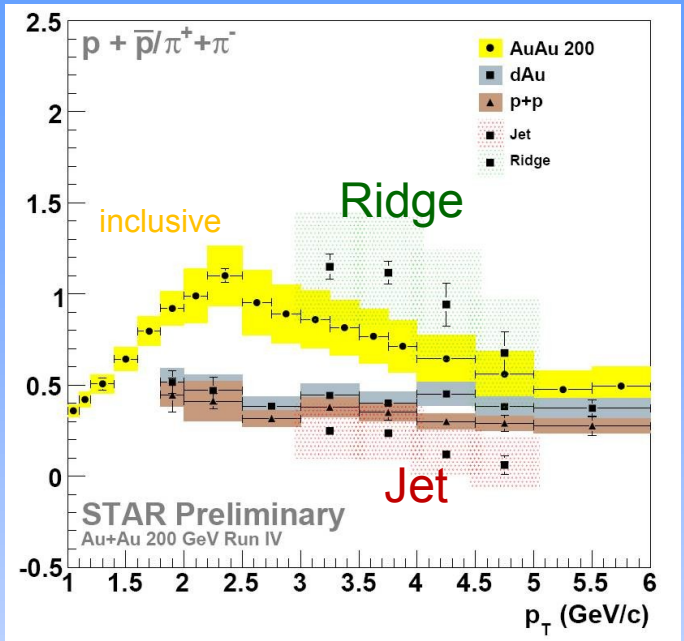
- ridge/jet ratio consistent between 200 and 62 GeV data



Nattrass (STAR), Eur.Phys.J.C62:265-269,2009

Medium modified jet?

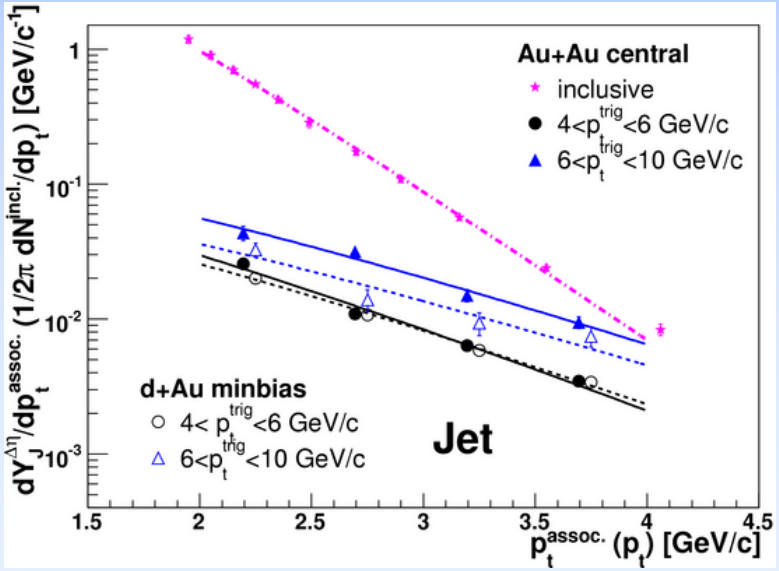
Ridge properties: bulk-like?

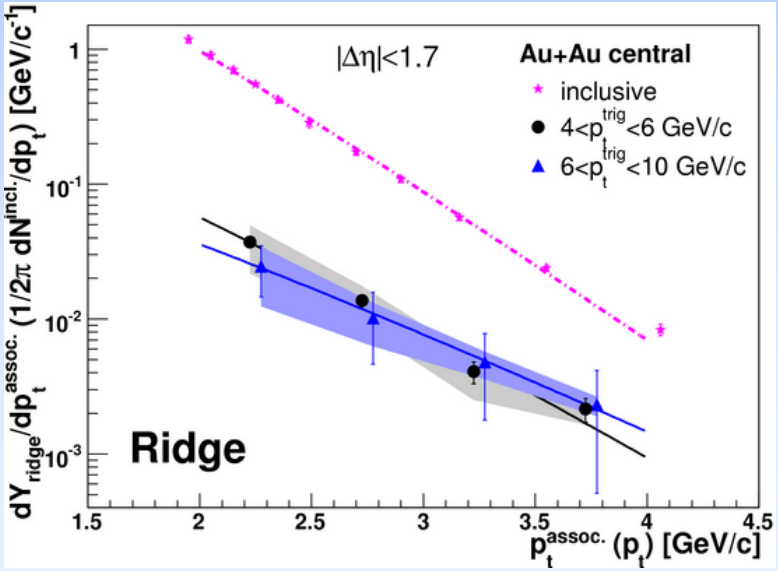


Ridge yield:

- baryon/meson composition ~ bulk
- inverse slopes of p_T -spectra are 'bulk-like'

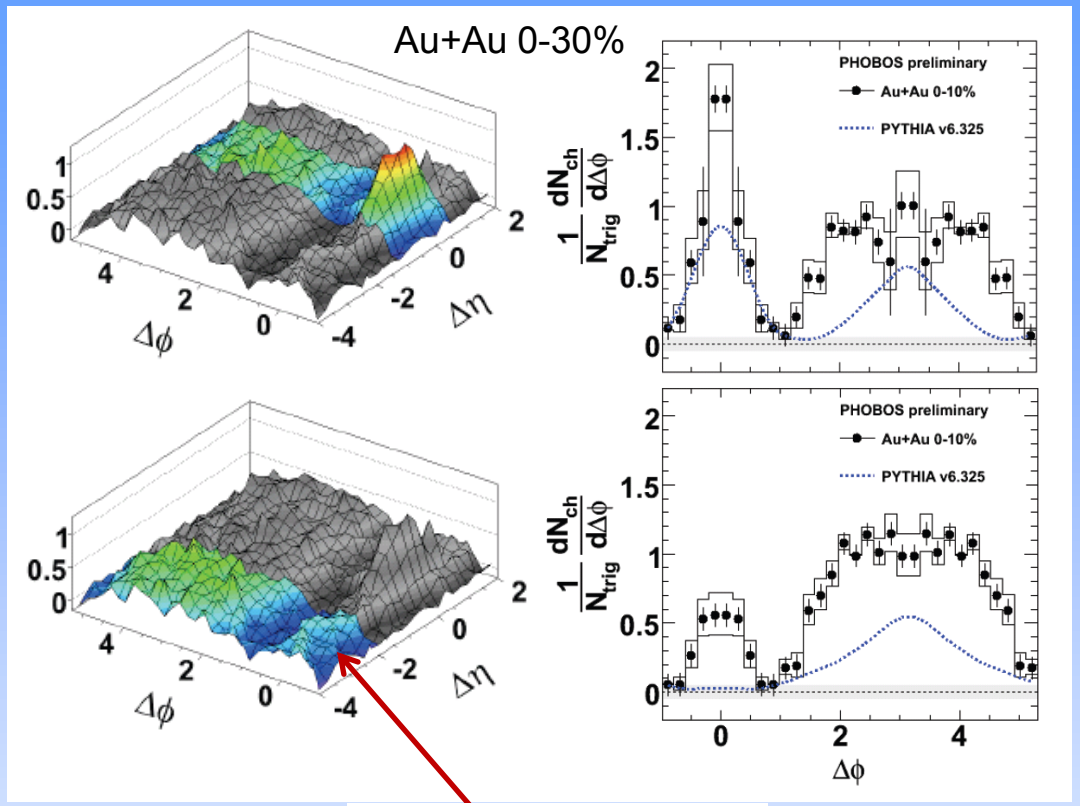
Medium modified by jet?

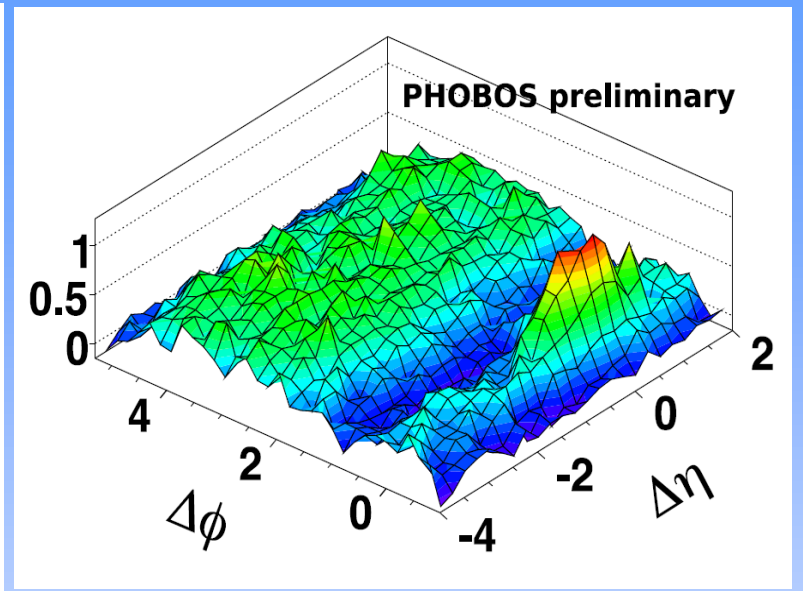




STAR, Phys. Rev. C **80** (2009) 64912

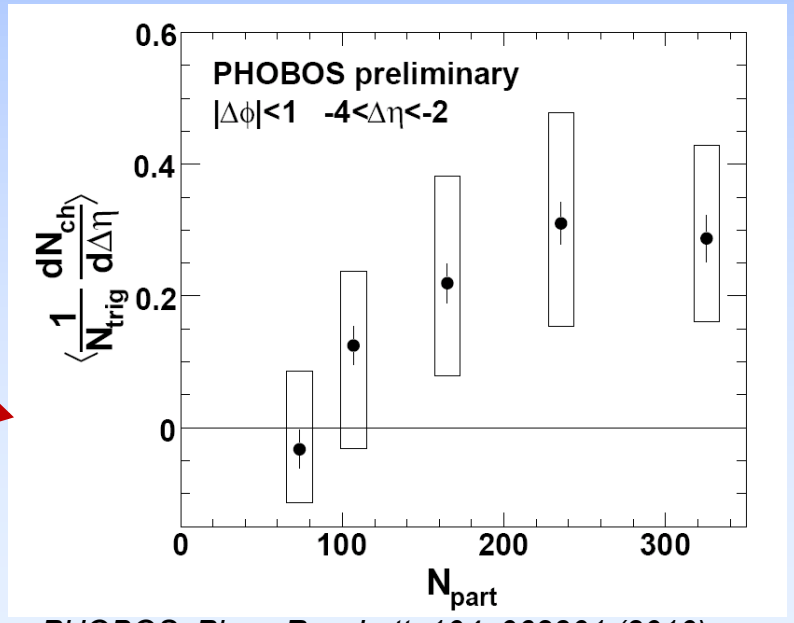
Ridge at forward rapidity at RHIC





$p_T^{trig} > 2.5$ GeV/c
$p_T^{assoc} > 20$ MeV/c

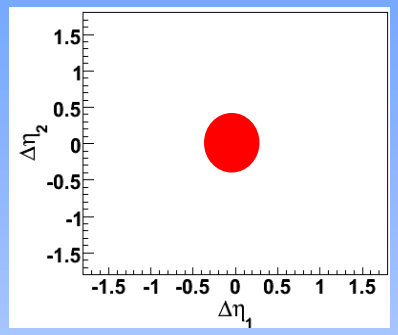
N_{part} dependence of ridge yield at $-4 < \Delta\eta < -2$:
decreases with decreasing N_{part} and vanishes around $N_{part} \sim 80$

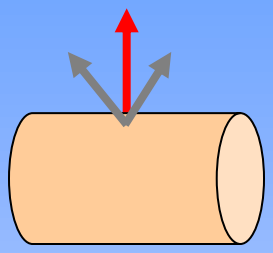


PHOBOS, Phys. Rev. Lett. 104, 062301 (2010)

3-particle $\Delta\eta x \Delta\eta$ correlations

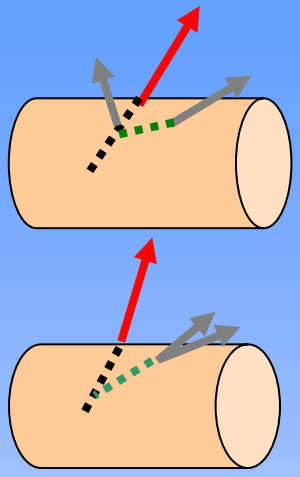
1) Jet fragmentation in vacuum

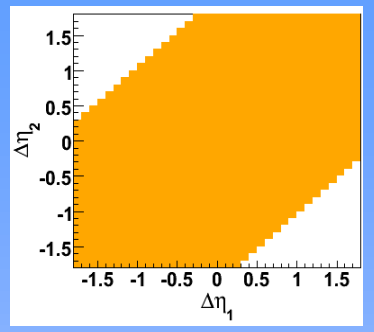




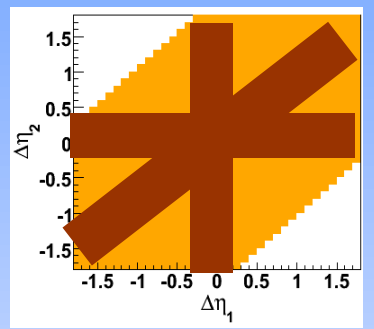
2) In medium radiated gluons diffused in η

3) In medium radiated gluons collimated by longitudinal flow



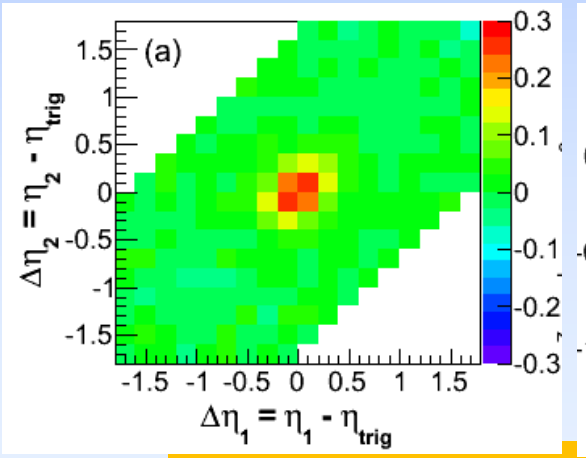


4) Combination of jet fragmentation and diffused gluons

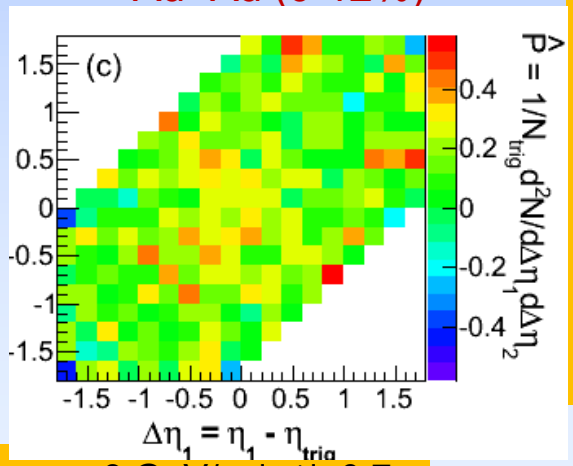


STAR, PRL 105, 022301 (2010)

d+Au



Au+Au (0-12%)



Uniform overall excess of associated particles observed at intermediate p_T

This disfavours models based on longitudinal flow.

$3<p_T^{trig}<10$ GeV/c, $1<p_T^{assoc}<3$ GeV/c, $|\Delta\phi|<0.7$

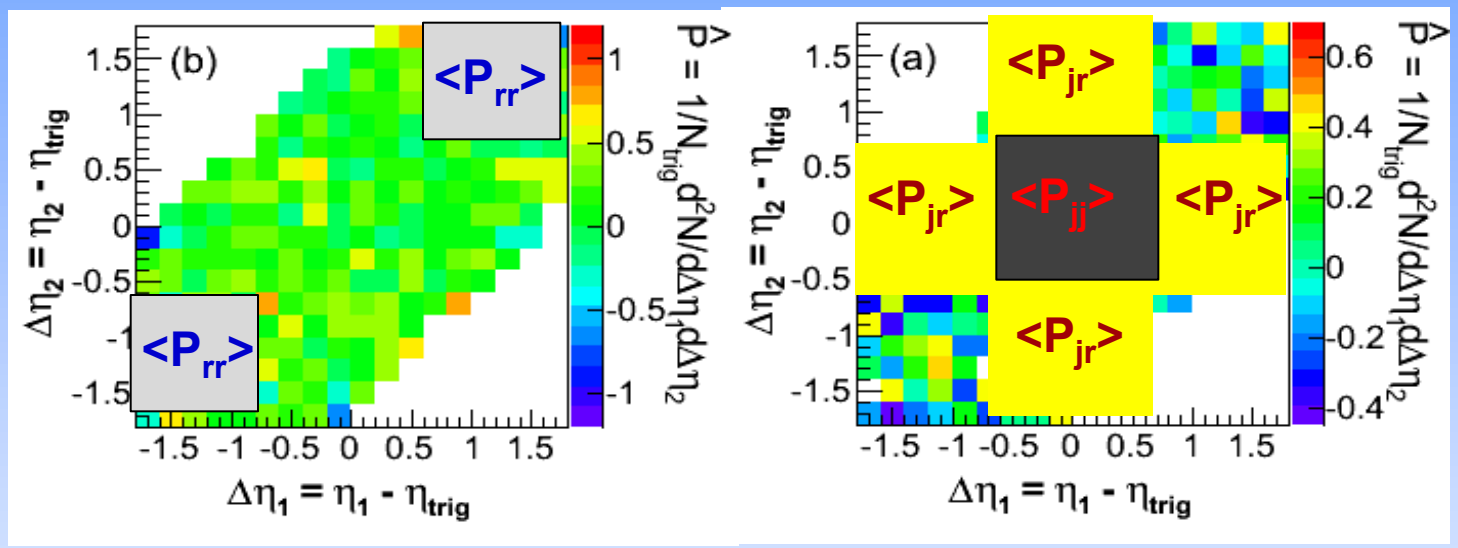
Note: Involves complicated bkg. subtraction

$\Delta\eta x \Delta\eta$ correlations: average pair densitities

Au+Au (0-12%), $|\Delta\phi|<0.7$
$3<p_T^{trig}<10$ GeV/c, $1<p_T^{assoc}<3$ GeV/c

Ridge

Jet-like



STAR, PRL 105, 022301 (2010)

ridge-ridge pairs
$\langle P_{rr} \rangle$ = 0.114 ± 0.039

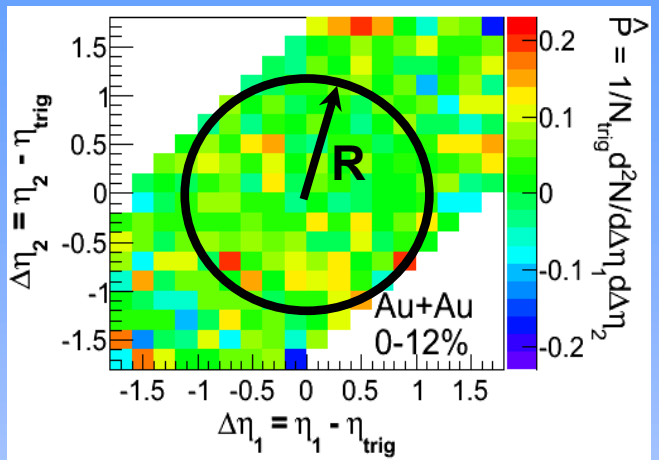
"jet-jet" pairs
$\langle P_{jj} \rangle$ = 0.081 ± 0.034

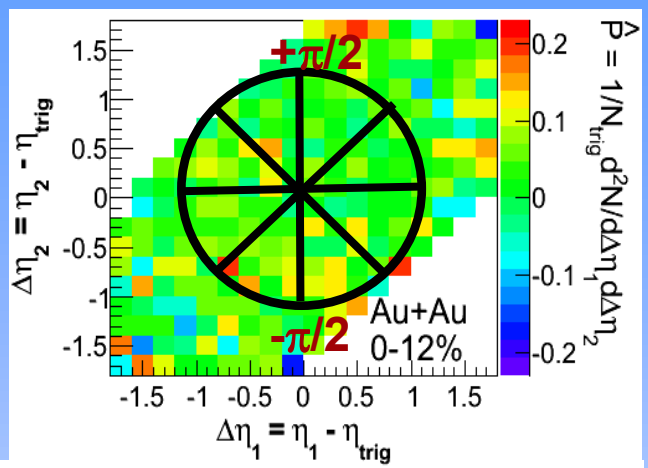
"jet"-ridge cross pairs
$\langle P_{jr} \rangle$ = -0.001 ± 0.030

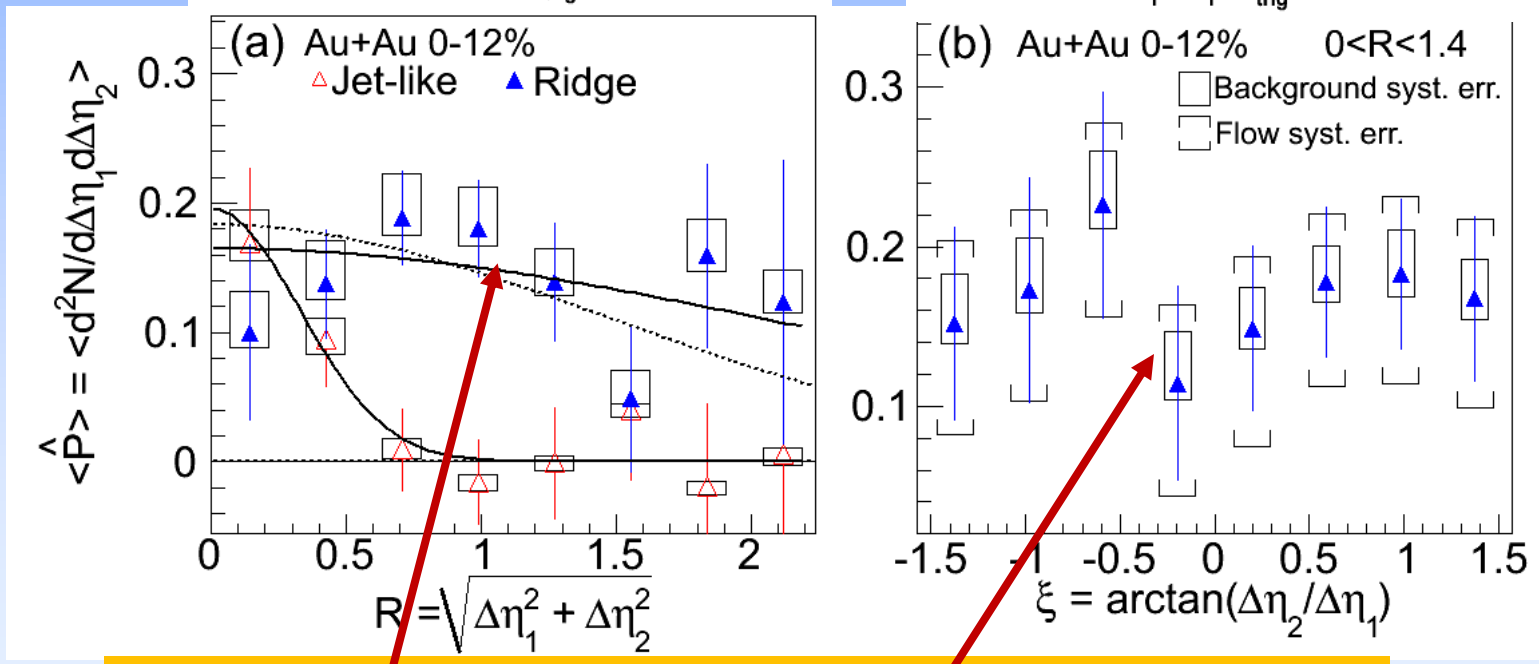
Data suggests that the ridge production and production of jet-like particles maybe uncorrelated

→ sensitive tool to rule out some of the ridge models.

$\Delta\eta x \Delta\eta$: radial and angular dependence





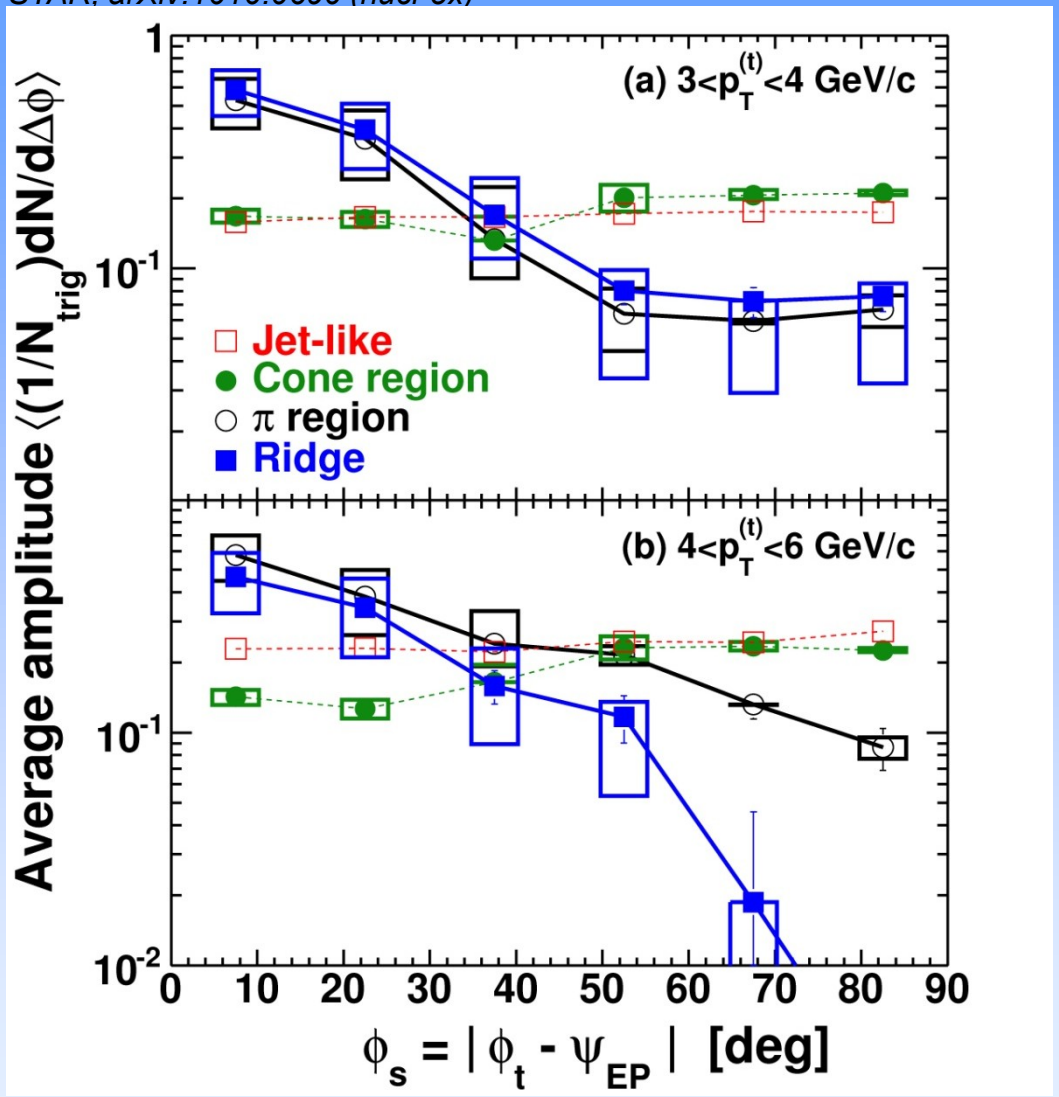


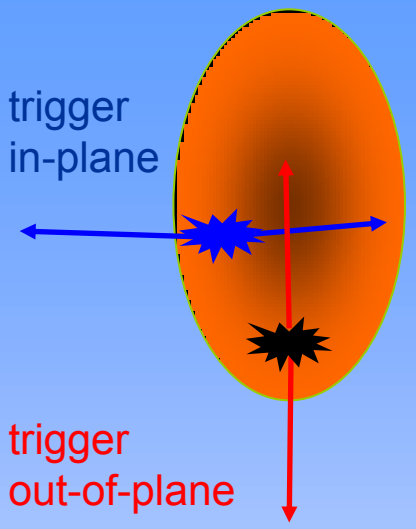
STAR, PRL 105, 022301 (2010)

Ridge is broad and has no prominent substructures.

Path length effects in di-hadron correlations

STAR, arXiv:1010.0690 (nucl-ex)





Cone and jet-like amplitudes independent of ϕ_s

x

Ridge and "π region (head)" show a strong dependence on ϕ_s:

→ they are largest in-plane

Jet and ridge not related?

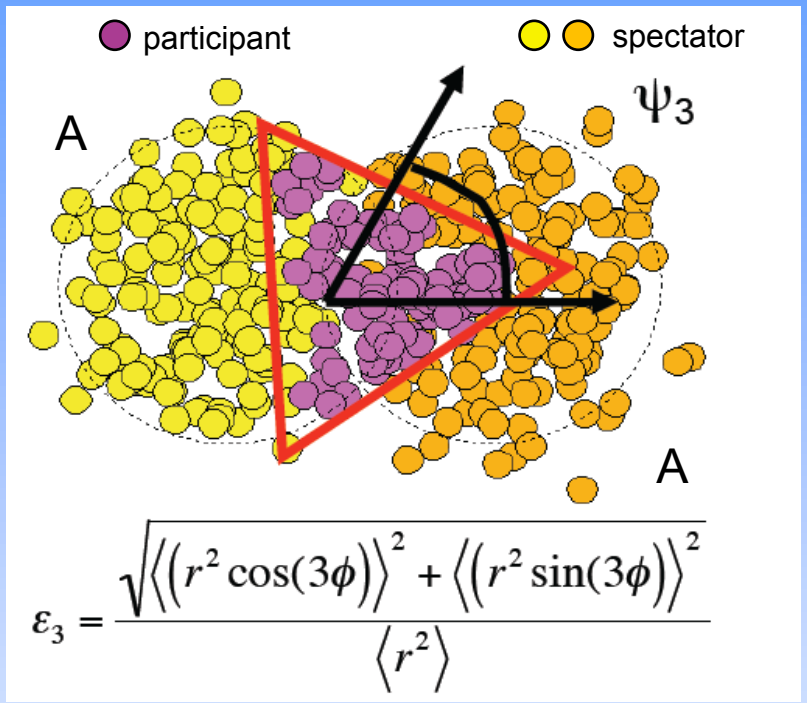
Triangular flow v_3

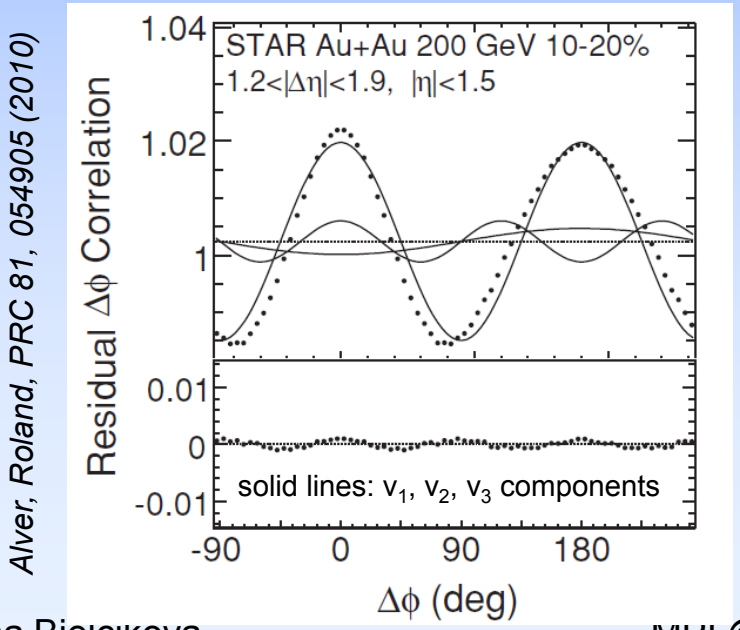
- v_3 reflects the triangular anisotropy in the initial collision geometry due to event-by-event fluctuations in the participant collisions points
- Fourier re-analysis of RHIC data including v_1, v_2, v_3 components describes data well

Are "ridge" and "cone" due to v_3?

BUT: ridge shows strong event plane dependence while v_3 should be independent of it …

Participant triangularity





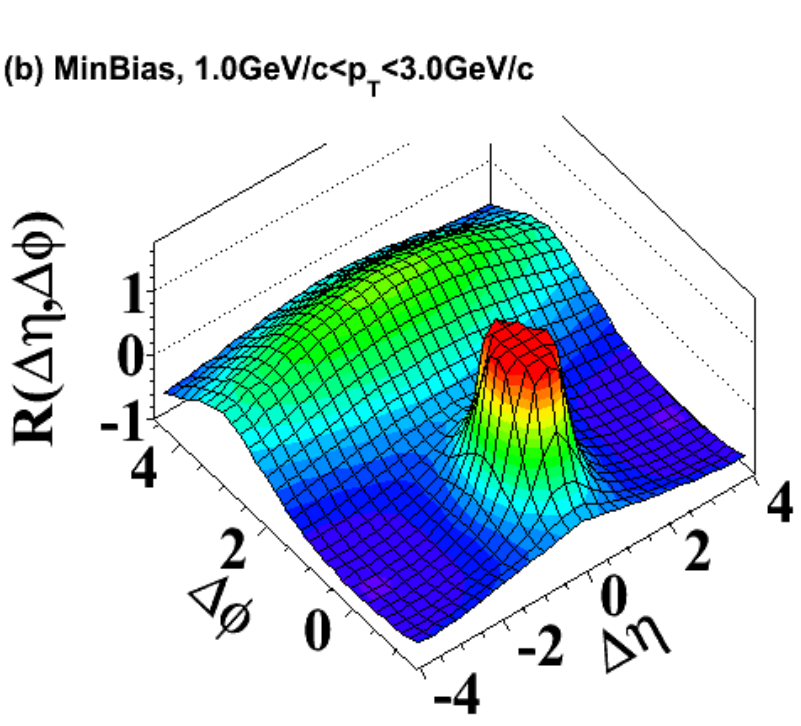
Alver, Roland, PRC 81, 054905 (2010)

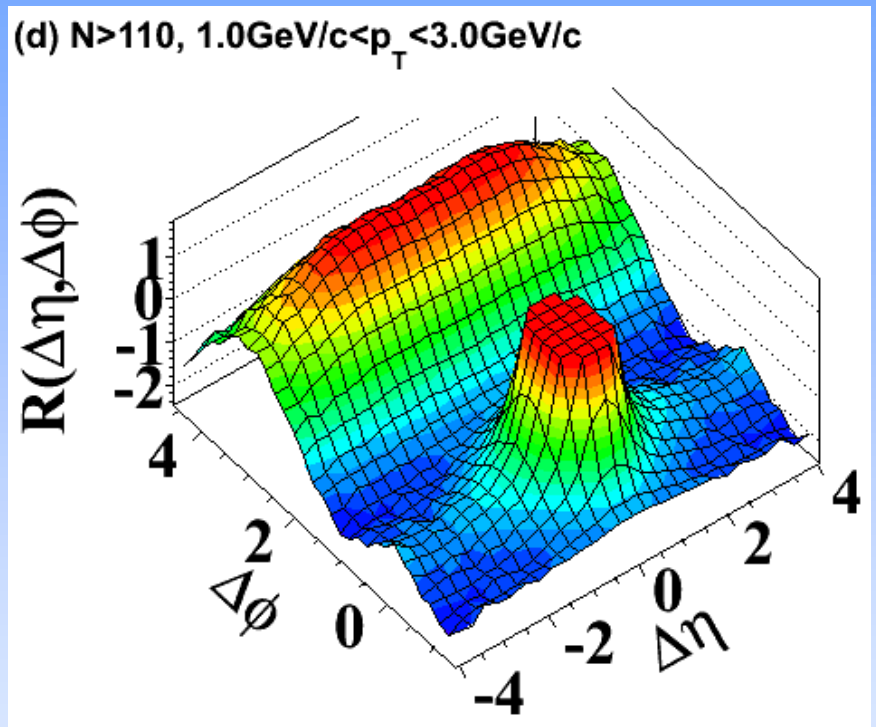
Alver, Roland, PRC 81, 054905 (2010)
Alver, Gombeaud,Luzum, Ollitrault, PRC 82, 034913 (2010)
Petersen, Qin, Bass, Mueller, PRC 82, 041901(R) (2010)

Also NEXSPHERIO calculations:
non-smooth fluctuations in the initial state
+ hydrodynamical evolution
Takahashi et al., PRL 103 , 242301 (2009)

Long-range near-side angular correlations in p+p collisions @ 7TeV

Intermediate p_T=1-3 GeV/c

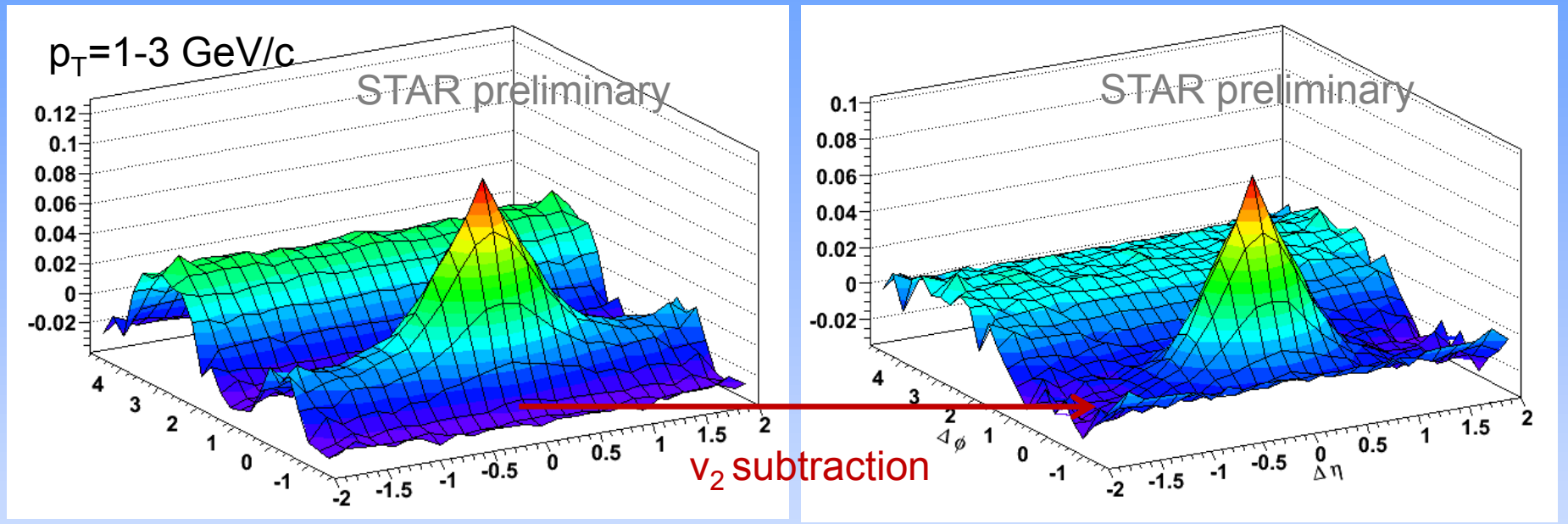




CMS observed in large multiplicity p+p collisions at 7 TeV
and at intermediate p_T pronounced long-range rapidity structure at small $\Delta\phi$!

Is the ridge a multiplicity/density effect?

STAR: Cu+Cu @ 200 GeV, multiplicity~N_{ch}(CMS_{p+p}@7TeV)

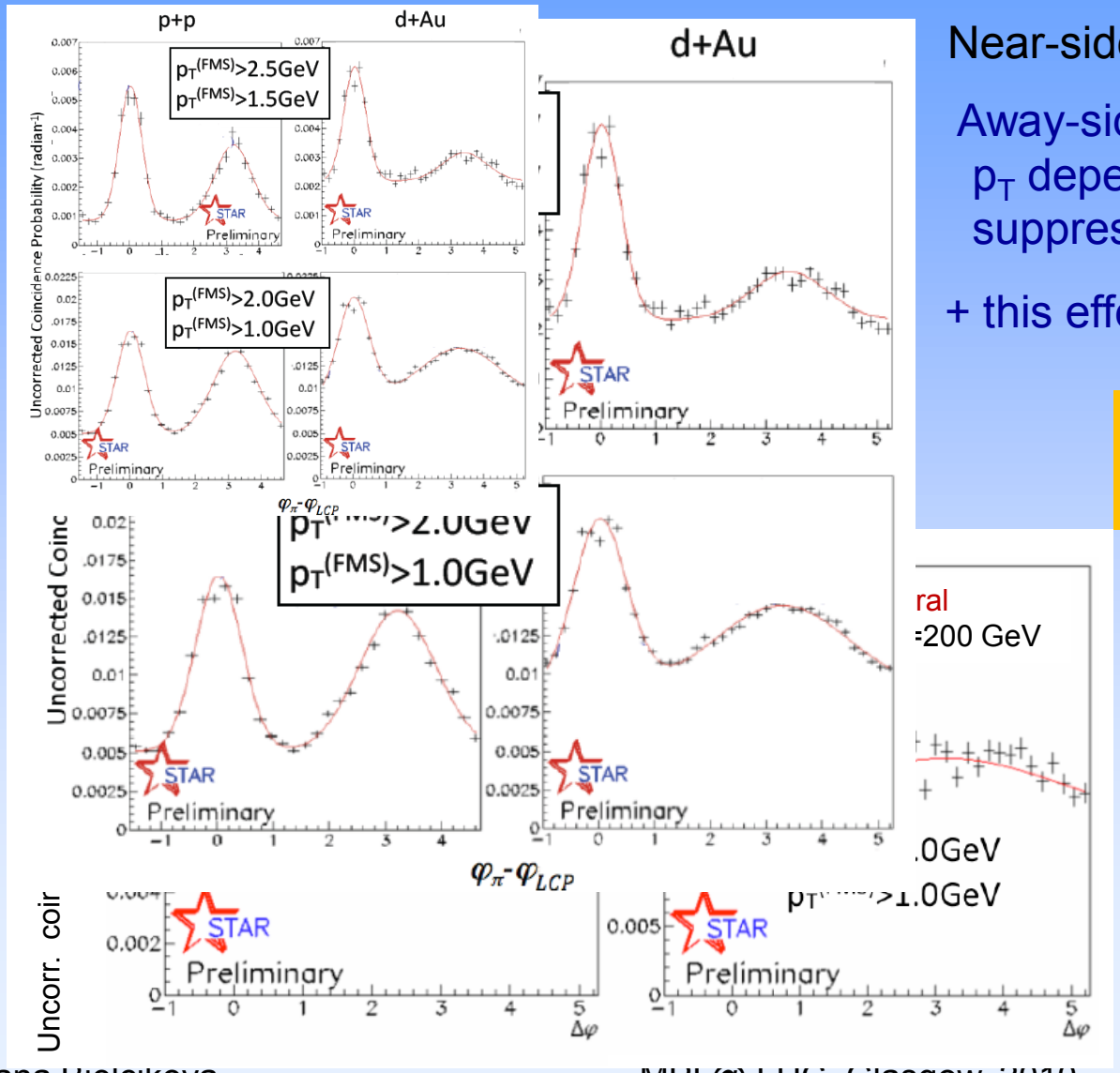


J. Putschke et al, (STAR), Hard Probes, 2010

The near-side peak in Cu+Cu collisions at RHIC with similar multiplicity as measured by CMS in p+p collisions at 7TeV is mainly dominated by elliptic flow.

CGC at forward η in d+Au collisions at RHIC?

Forward π^0-π^0 correlations (x~10^{-3}): study onset of saturation/CGC



Near-side correlations: p+p~d+Au

Away-side correlations:
p_T dependent broadening and suppression observed in d+Au

+ this effect is also centrality dependent

Qualitatively consistent with CGC picture.

Summary

- Strong modification of correlation patterns in central A+A collisions at RHIC:
  - broadening of away-side peak with angular substructure
    possible evidence for conical emission
  - medium responds through "ridge" formation in pseudo-rapidity
    bulk-like properties (spectra, particle composition)
    medium density/path length effects (dominated in the event plane)

How large is the triangular flow contribution to these effects?

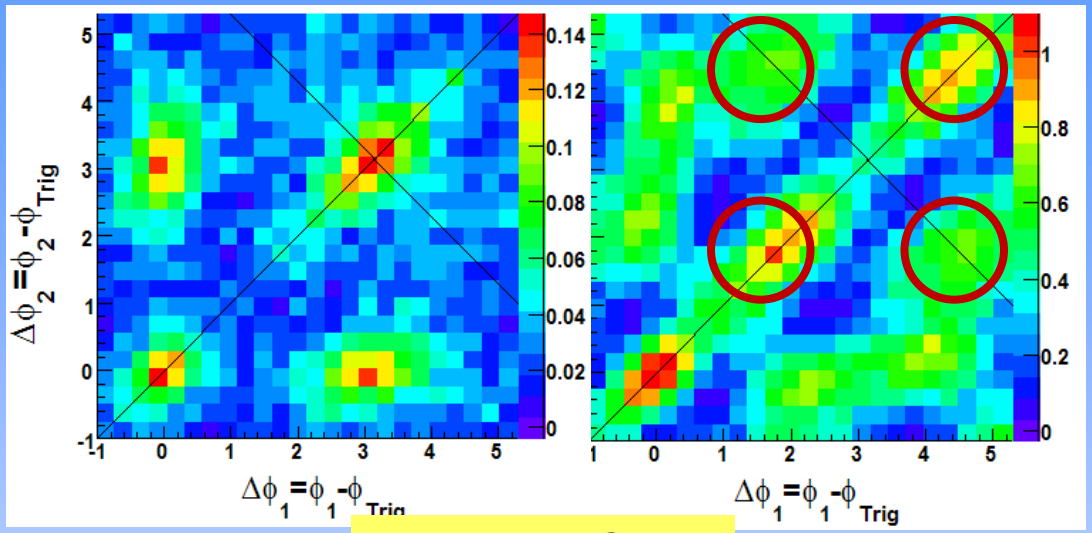
- Ongoing and future studies at RHIC:
  γ-triggered correlation (no near-side jet-medium interaction)
  Is there a ridge?
  heavy-flavor triggered correlations
  Mach cone?
  higher statistics: 3-particle and PID correlations, jet-hadron correlations
- Models: more quantitative predictions needed!

Can models describe energy content in the ridge, R_{AA} and interplay of near and away-side modification at the same time?

Stay tuned for the LHC Pb+Pb correlation measurements…

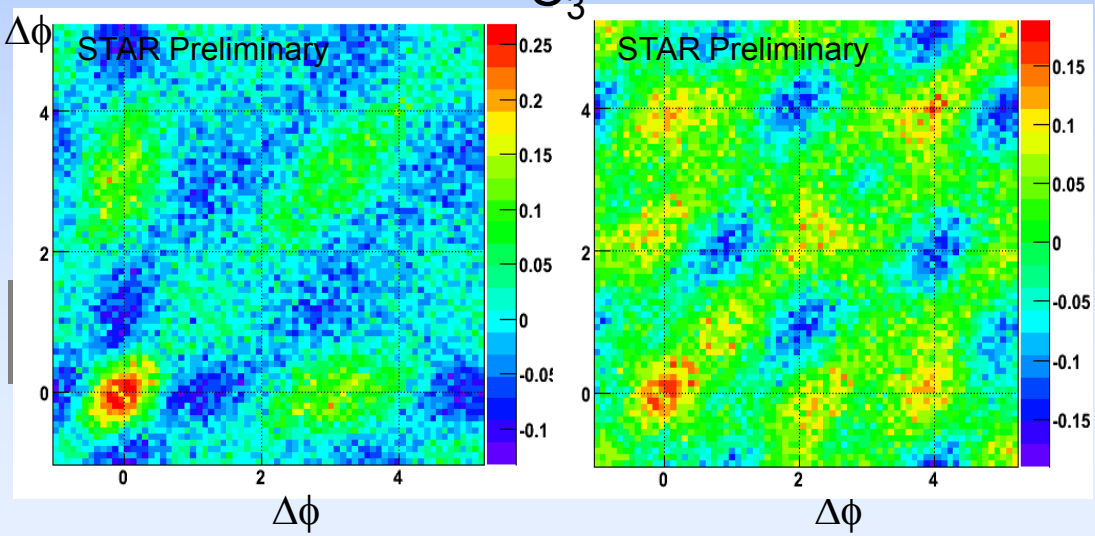
Conical flow or deflected jets? (II)

d+Au central Au+Au



$3 < p_{T,trig} < 4$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c

central Au+Au C_3 central Au+Au



Subtraction of $v_2v_2v_4$ terms using $v_4 = 0.06$

Subtraction of v_1v_3 term using $v_2 = 0.12$

Note: Large and complicated backgrounds

STAR uses 2 methods:

1. Jet+flow background

*Abelev et al (STAR), arXiv:*0805.0622

- model dependent analysis
- evidence for conical emission

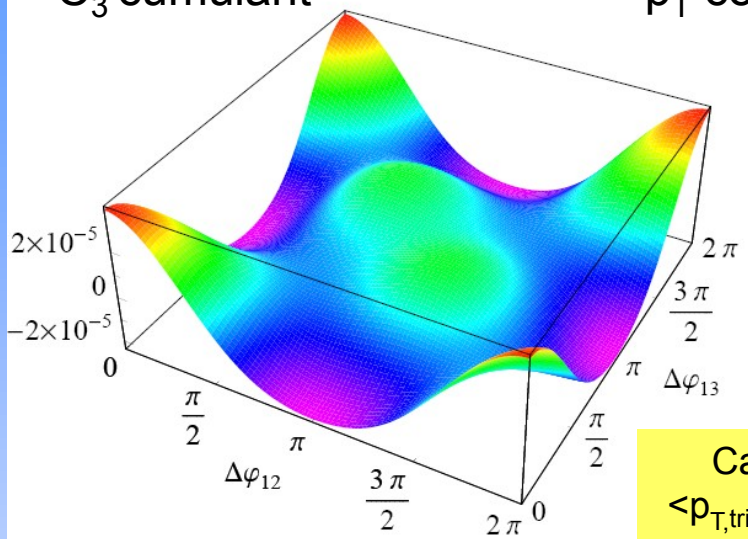
2. Cumulant method

C. Pruneau (STAR),J.Phys.G34 (667),2007;
C. Pruneau, PRC 74 (2006) 064910

- unambiguous evidence for 3-particle correlations
- strength and shape of away-side structures depend on magnitude of flow coefficients
- no conclusive evidence for conical emission
- an improved analysis with rotating EP shows conical structures

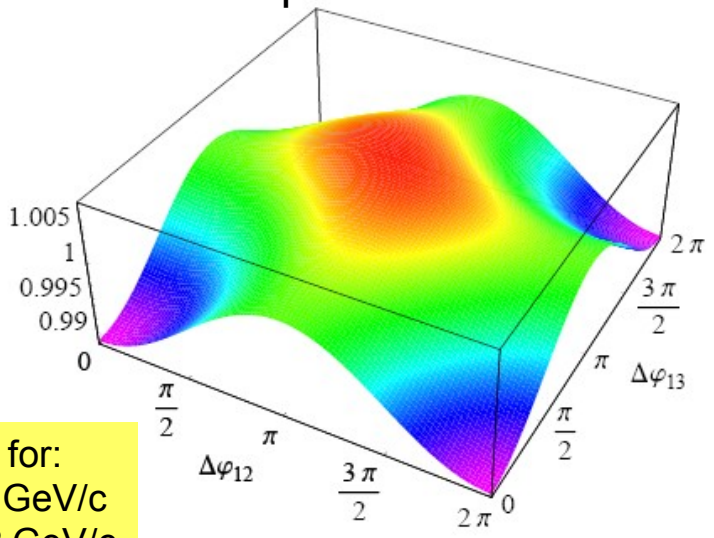
Momentum conservation in correlation analyses

C_3 cumulant



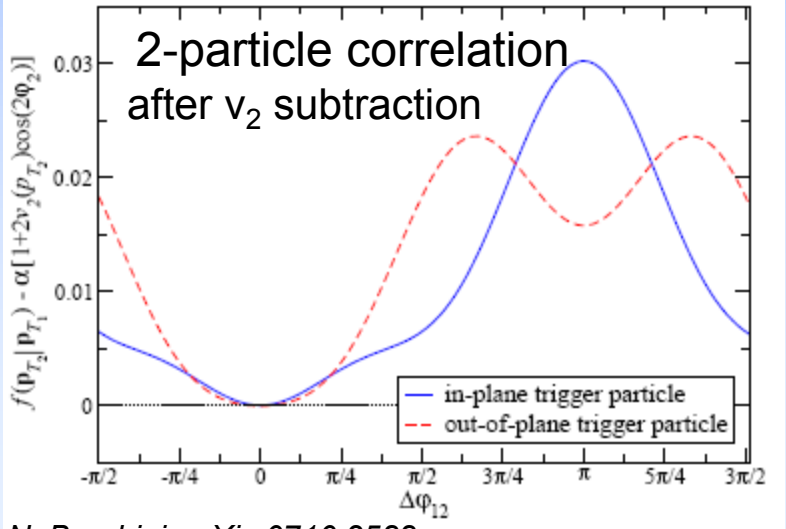
p_T conservation

3-particle correlation



Calculation for:
$\langle p_{T,trig} \rangle$ = 3.2 GeV/c
$\langle p_{T,assoc} \rangle$ = 1.2 GeV/c

N. Borghini, PRC 75 (2007) 021904



N. Borghini, arXiv:0710.2588

Calculation by N. Borghini:
momentum conservation → sizable correlation between pairs or triplets of high-p_T particles in central Au+Au collisions at RHIC

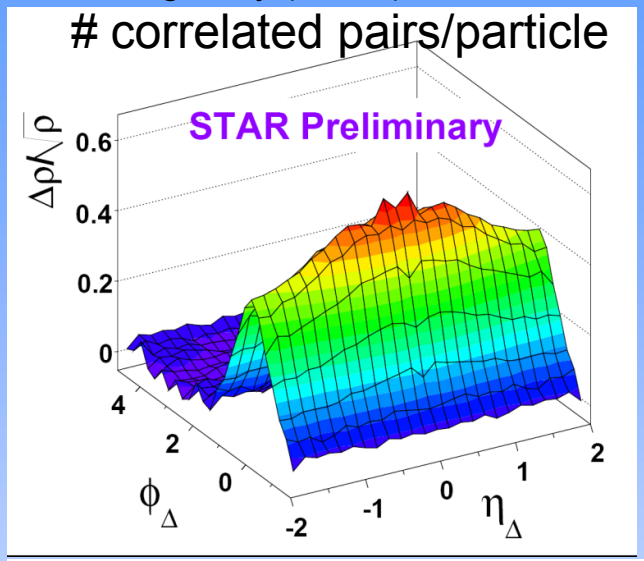
→ $C_3(p_T) \sim C_3$(flow)

→ jet "distorts" the event

Data: possibly a fraction of stat. conservation: assuming bkg follows exp. drop → a small effect for p_T^{trig}~3-4 GeV/c

The ‘soft’ ridge in non-triggered correlations

M. Daugherity (STAR), QM08

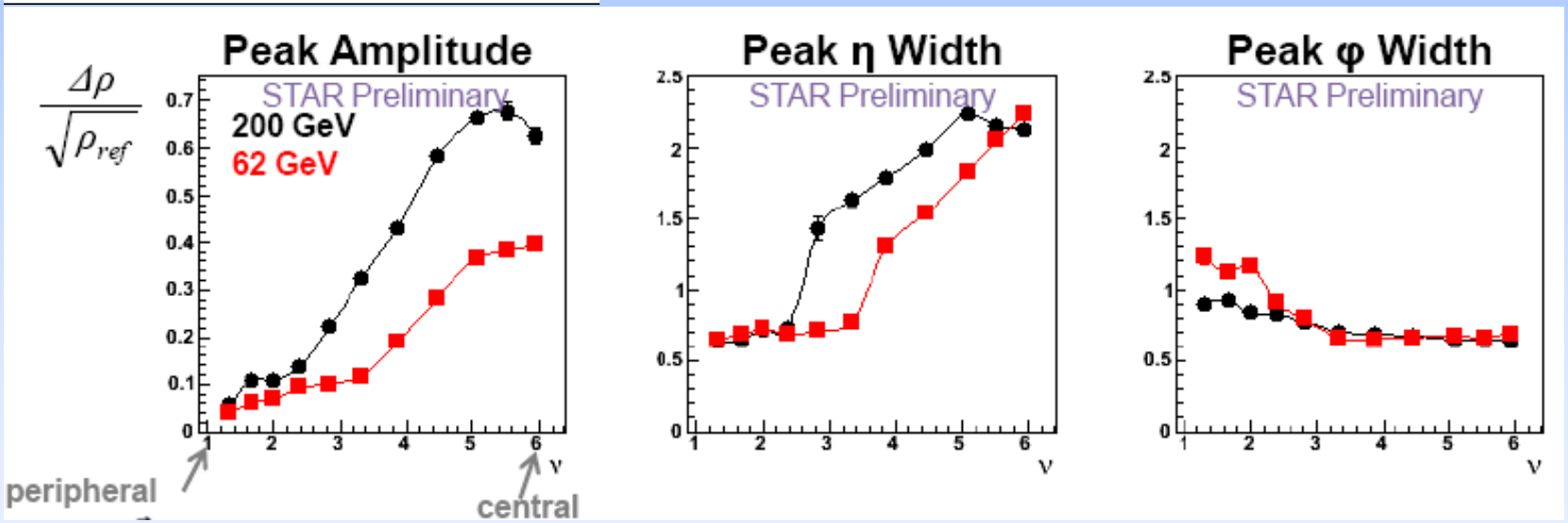


- “Minijet” near-side peak amplitude and $\Delta\eta$ width experience a sharp transition at ~55% centrality for 200 GeV and ~40% for 62 GeV Au+Au data.

x

- $\Delta\phi$ width is const. from mid-central to central Au+Au collisions

stat. errors only, syst.errors 9% (correlation amplitude)



M. Daugherity (STAR), QM08