High-p_T correlations at RHIC

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for the STAR Collaboration
(NPI ASCR)

Many thanks to the PHENIX Collaboration
for providing their results

High-p_T Probes of High-Density QCD at the LHC,
Ecole Polytechnique, Palaiseau, May 30 - June 1, 2011

Outline:

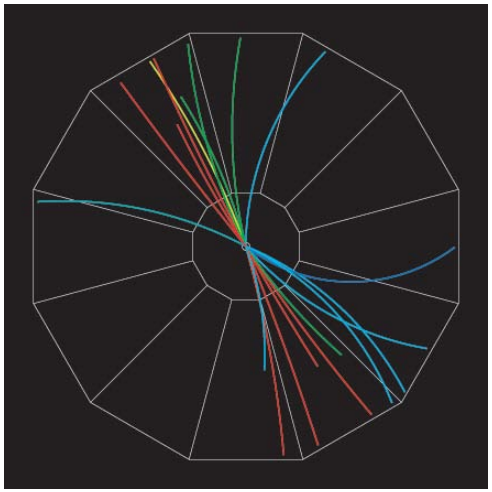
- Motivation
- Ridge+conical emission vs triangular flow in A+A collisions

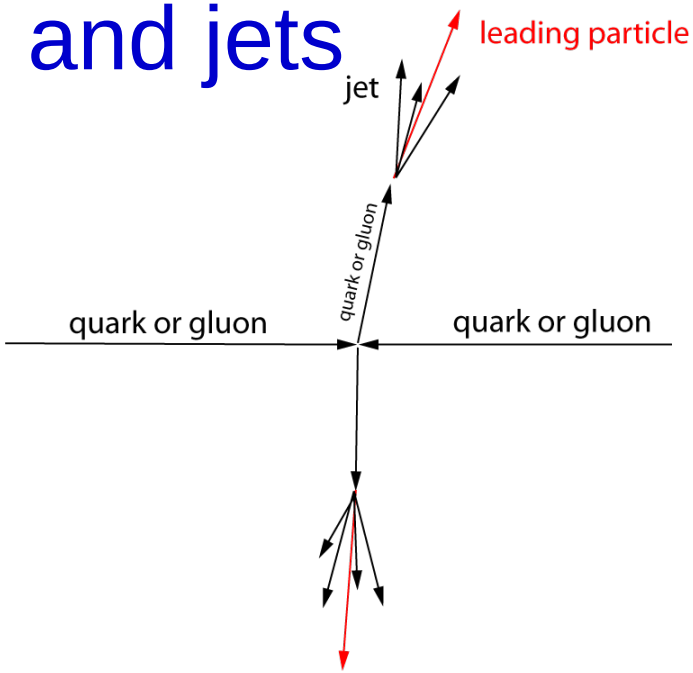
  … *a bit of history and new emerging concepts*
- Correlations with identified trigger particles
- Correlations at forward rapidities in d+Au collisions

  … probing the initial conditions
- γ-hadron correlations
- Summary

Probing QCD matter with high-p_T particles and jets

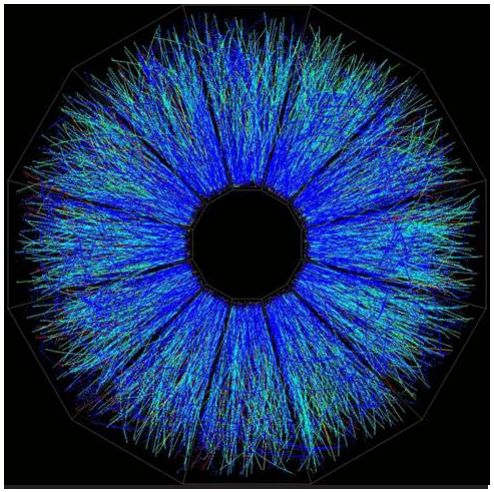
p+p

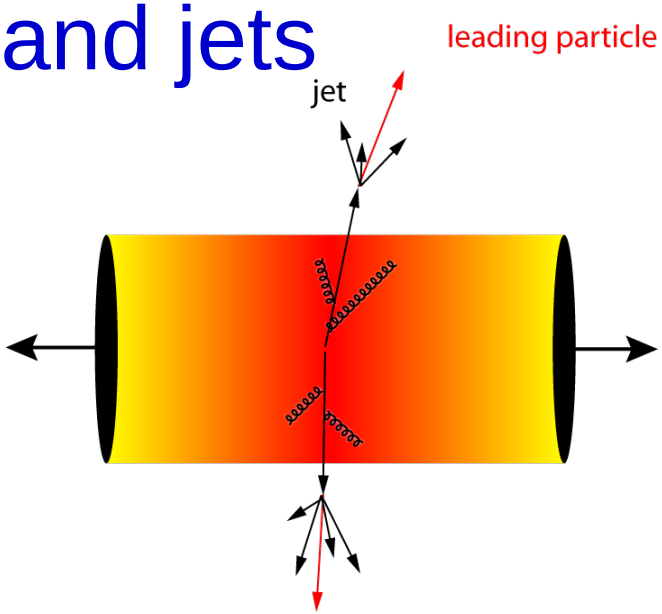




Probing QCD matter with high-p_T particles and jets

Au+Au





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

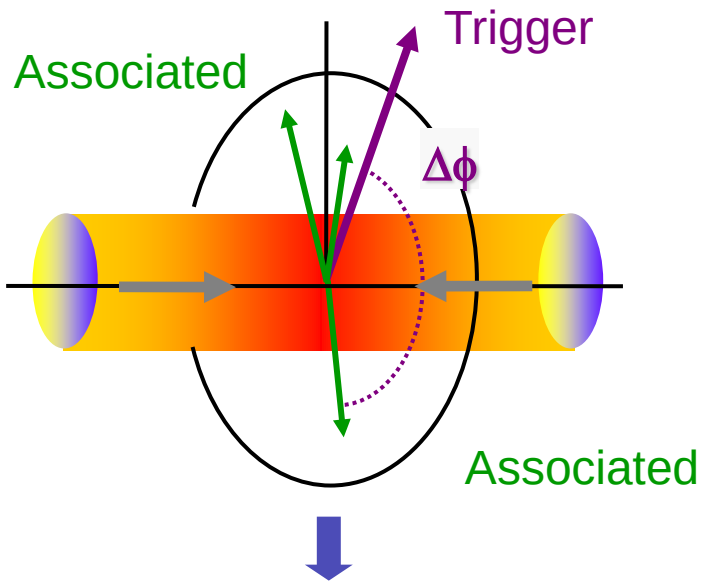
Are they similar to p+p or modified by the medium?

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

} this talk

- jets (γ-jets)
- jet-hadron correlations

“Jet-like” correlations: the method

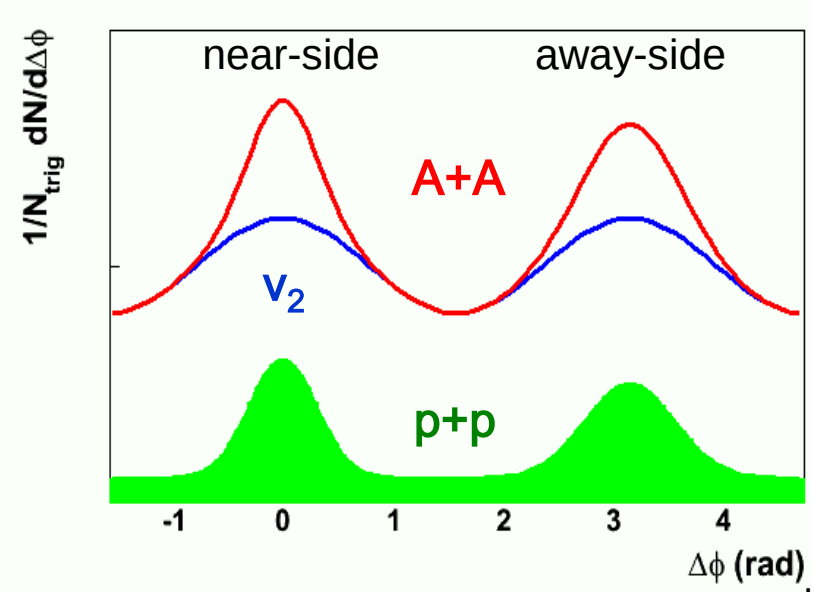


Azimuthal correlations of high-p_T particles suggested to study jet and its interaction with medium on a statistical basis.

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

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

$$R_{AA} \longrightarrow I_{AA} = \frac{D_{AA}(z_T, p_T^{\mathrm{trig}})}{D_{pp}(z_T, p_T^{\mathrm{trig}})} \qquad z_T = p_{T,assoc}/p_{T,trig}$$



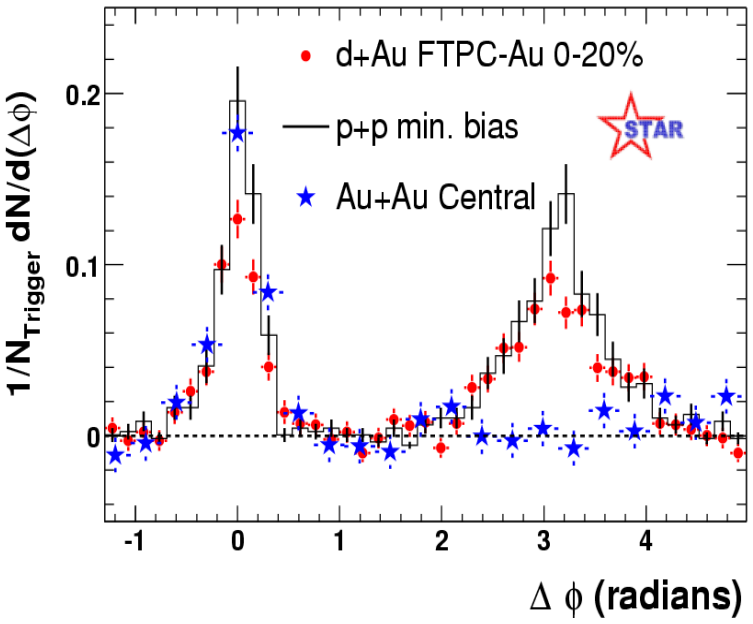
- A+A collisions: subtraction of v_2 needed

Contributions of higher Fourier harmonics v_n?
… From slide 19 …

Run 2: Jet-like correlations at intermediate p_T

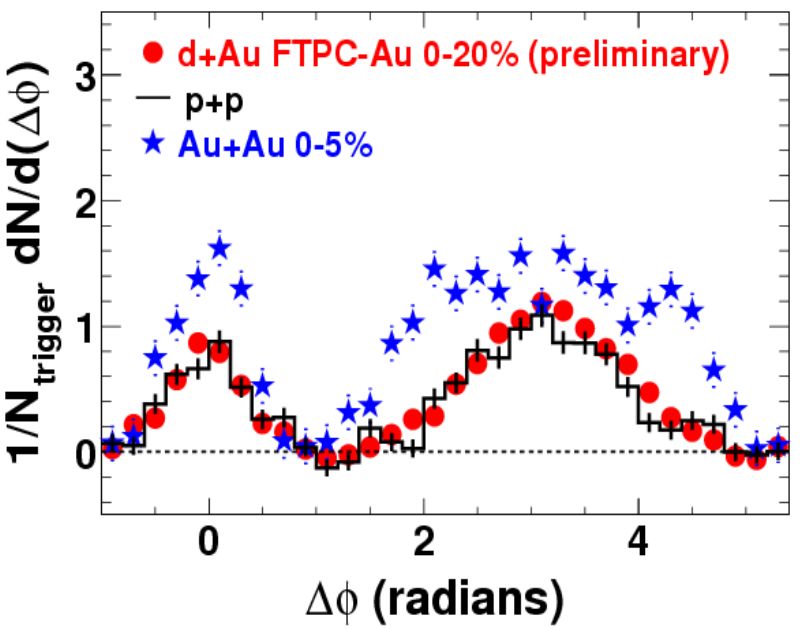
4 <p_T(trig)<6 GeV/c,

2 GeV/c <p_T(assoc)<p_T(trig)



STAR, Phys Rev Lett 91 (2004) 072304

0.15 < p_T(assoc) < 4 GeV/c



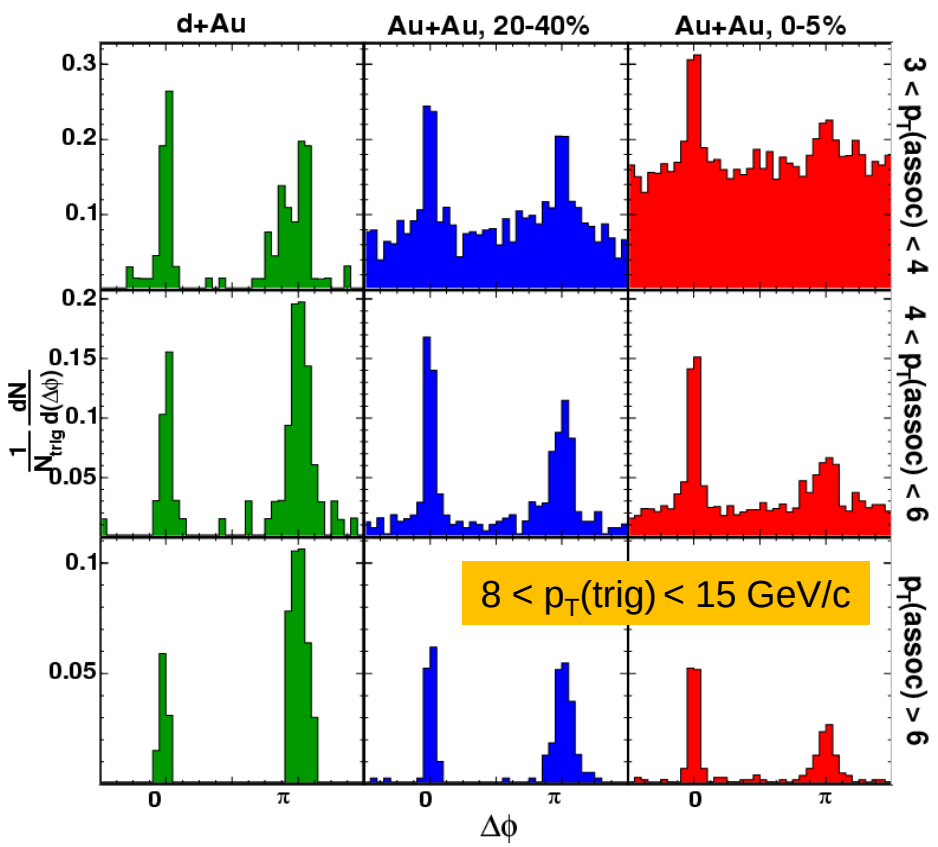
STAR, Phys. Rev. Lett. 95 (2005) 152301

Central Au+Au collisions at 200 GeV:

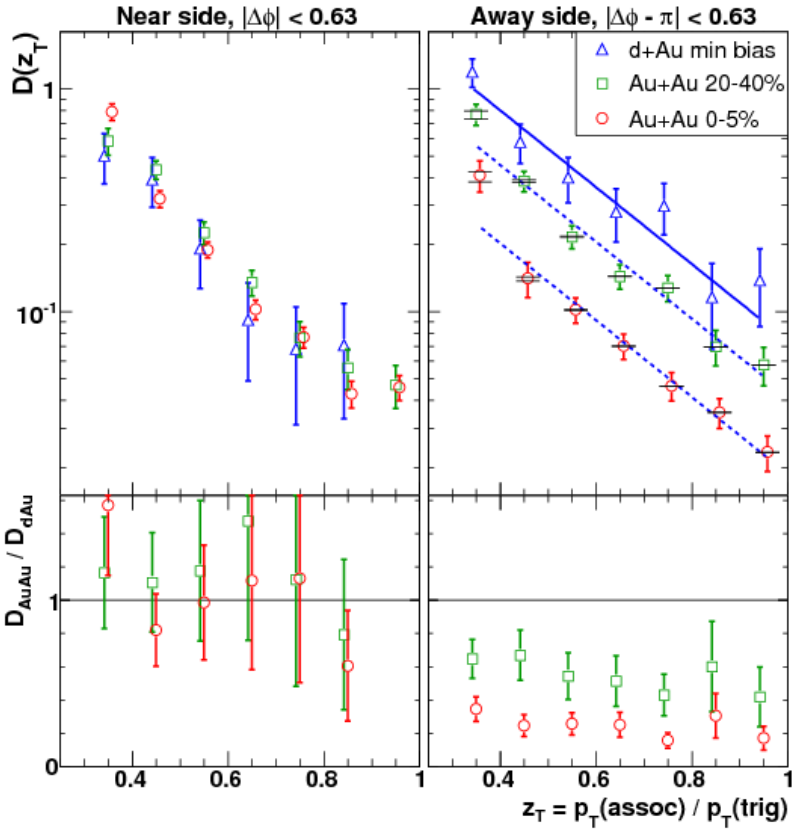
- intermediate p_T: disappearance of away-side correlations, but d+Au and p+p correlations are similar -> jet suppression is a final state effect
- lowering p_T threshold: resurrects correlated yield at away side
  - near/away-side yields are enhanced and away-side peak modified relative to p+p/d+Au

Run 4 : 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 from Run 4 (more statistics):

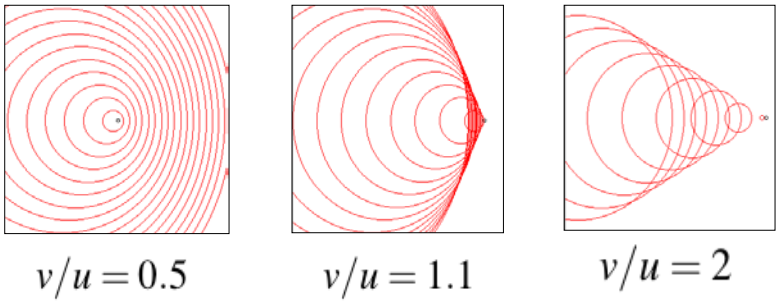
- near side yield: no suppression
- away-side yield is suppressed: $R_{AA} \sim I_{AA}$
- suppression without angular broadening or medium modification

seeing those partons that fragment in vacuum?

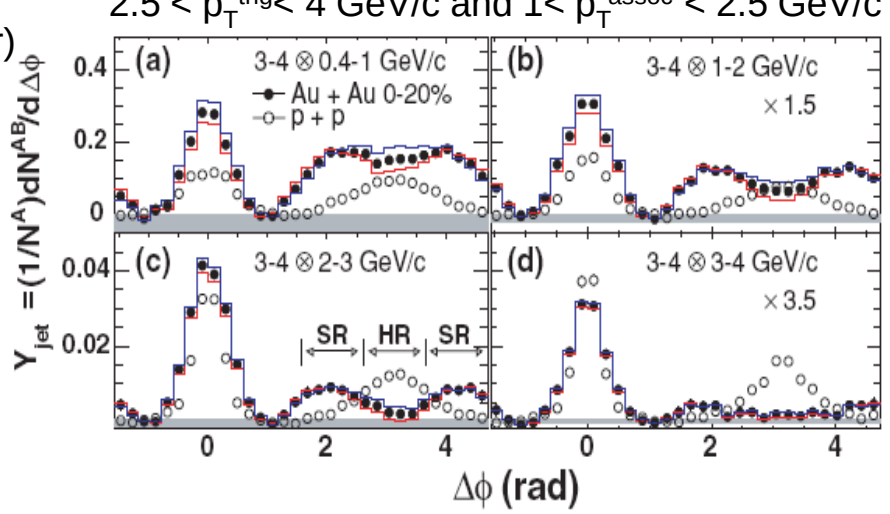
Conical emission in A+A collisions?

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

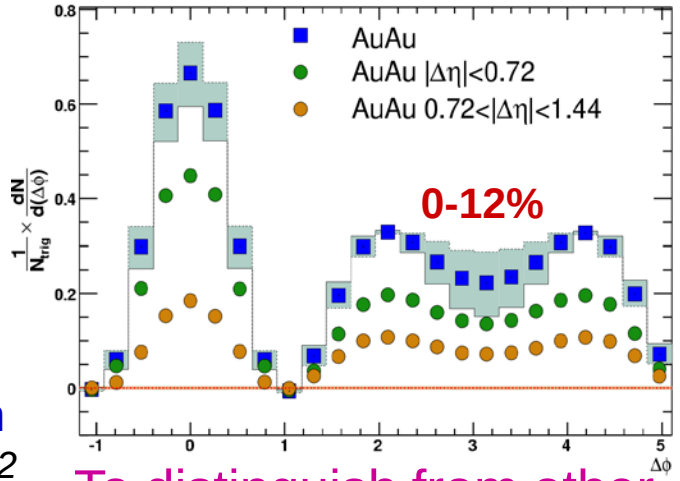
- a supersonic parton creates shock waves:
  - hydrodynamics
    Stöcker et al., NPA750 (2005) 121
    Casalderrey-Solana et al., NPA774 (2006) 577
    Renk, Ruppert, PRC73 (2006) 011901
  - colored plasma
    Ruppert, Mueller, PLB618 (2005) 123
  - AdS/CFT
    Gubser, Pufu, Yarom, PRL100, (2008) 012301



- Čerenkov gluon radiation by a superluminal parton
  Dremin, NPA750 (2006) 233; Koch et. al., PRL96 (2006) 172302
- deflected jets
  Armesto , Salgado, Wiedemann, PRL 93, (2004) 242301



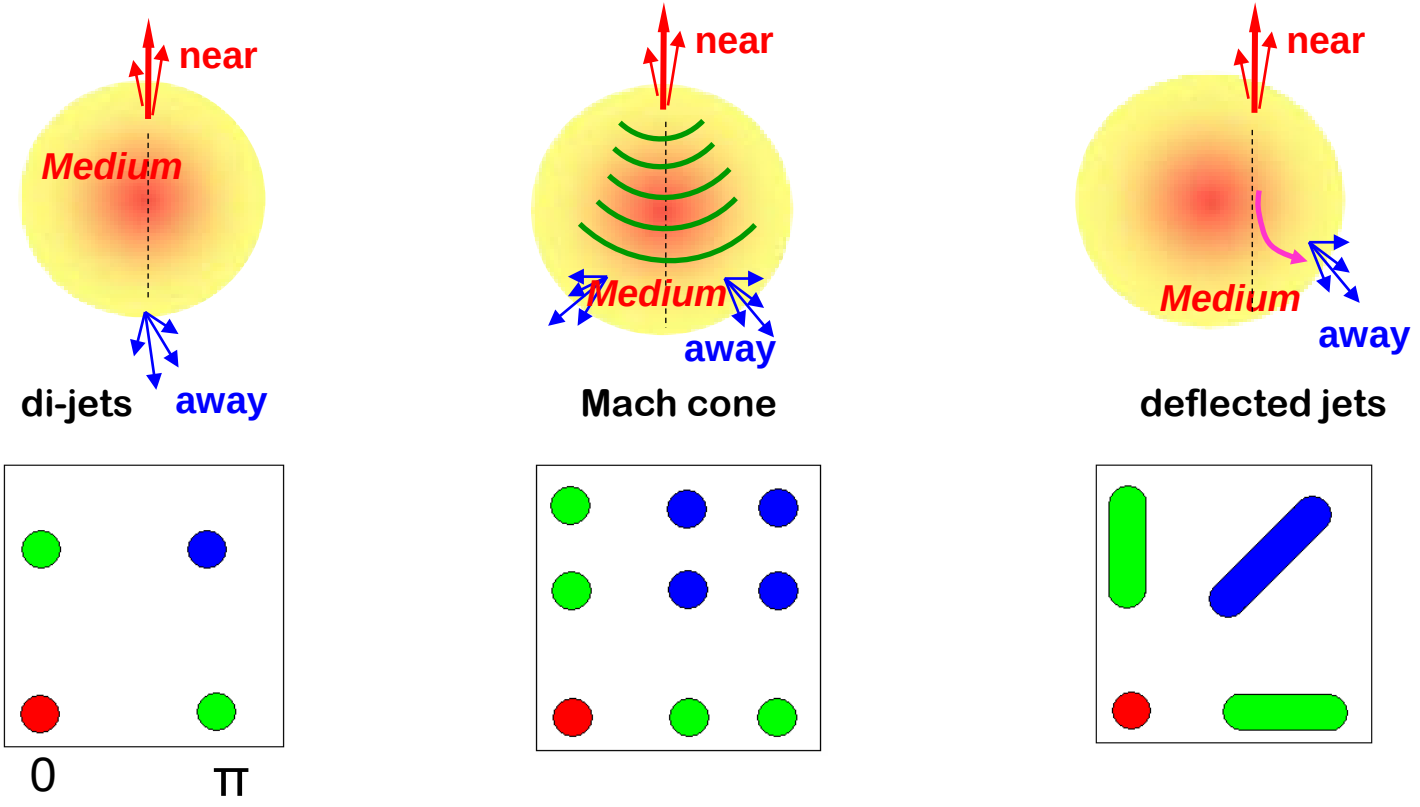
PHENIX, PRC 77, 011901(R) (2008)



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

To distinguish from other mechanisms 3-particle correlation studies needed

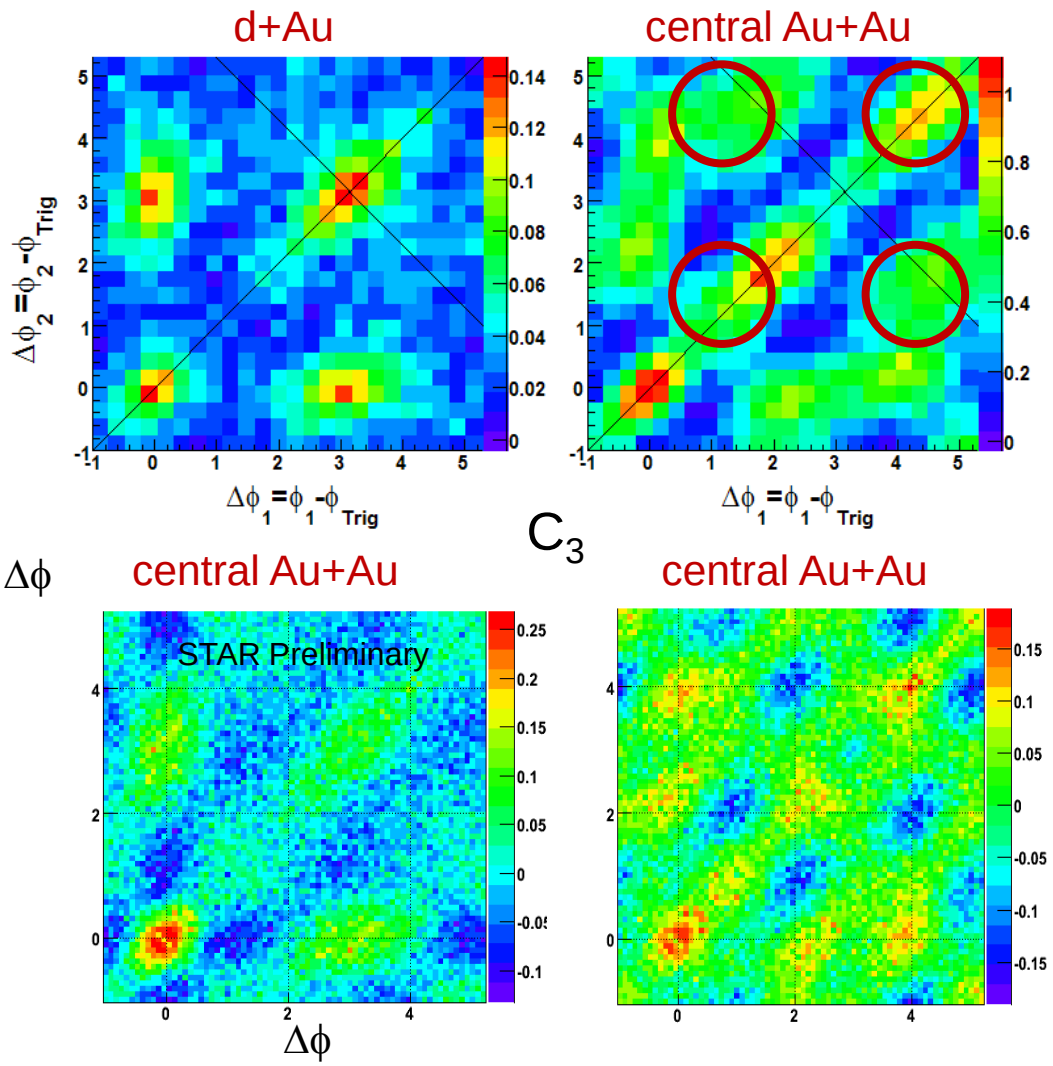
$\Delta\phi$–$\Delta\phi$ correlations



courtesy to J. Ulery

Cartoons of 3-particle $\Delta\phi$ correlations
(1 trigger + 2 associated particles)

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



Subtraction of $v_2v_2v_4$ terms using $v_2 = 0.06$

Subtraction of $v_2v_2v_4$ term using $v_2 = 0.12$

Note: large and complicated backgrounds!

Jet+flow background method:

STAR, PRL102, 052302 (2009)

- model dependent
- evidence for conical emission

Cumulant method:

- model independent

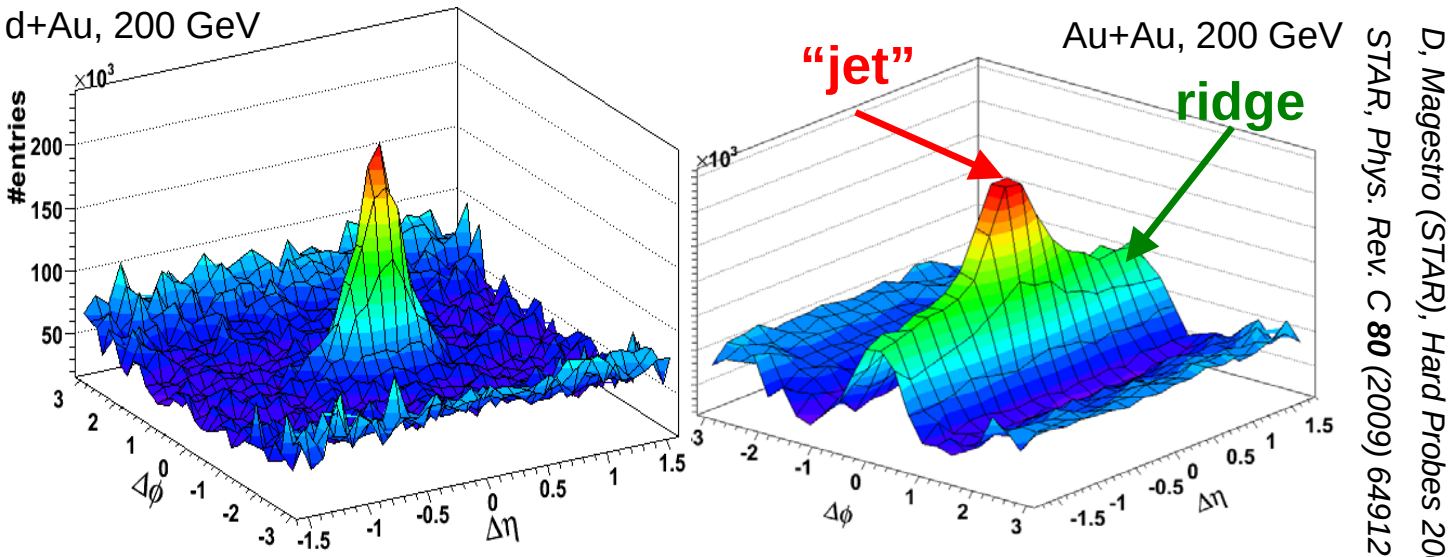
C. Pruneau (STAR),J.Phys.G34 (667),2007;
C. Pruneau, PRC 74 (2006) 064910

- strength and shape of away-side structures depend on magnitude of v_2 and v_4 coefficients
- improved analysis with rotated EP shows conical structures

• Momentum conservation effects estimated to be small for p_T^{trig}~3-4 GeV/*c*

A closer look at the near-side peak …

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



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

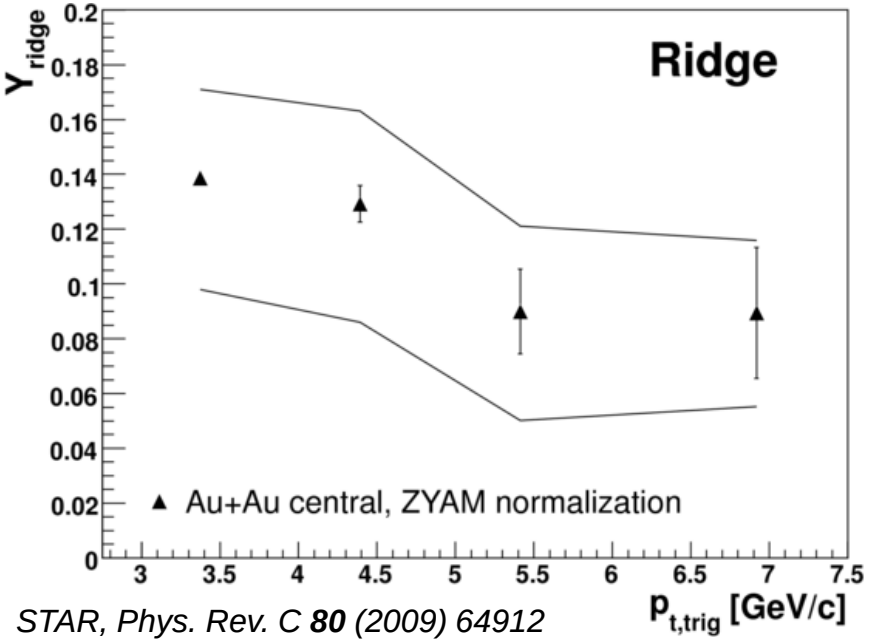
- this structure is not present in p+p or d+Au collisions

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

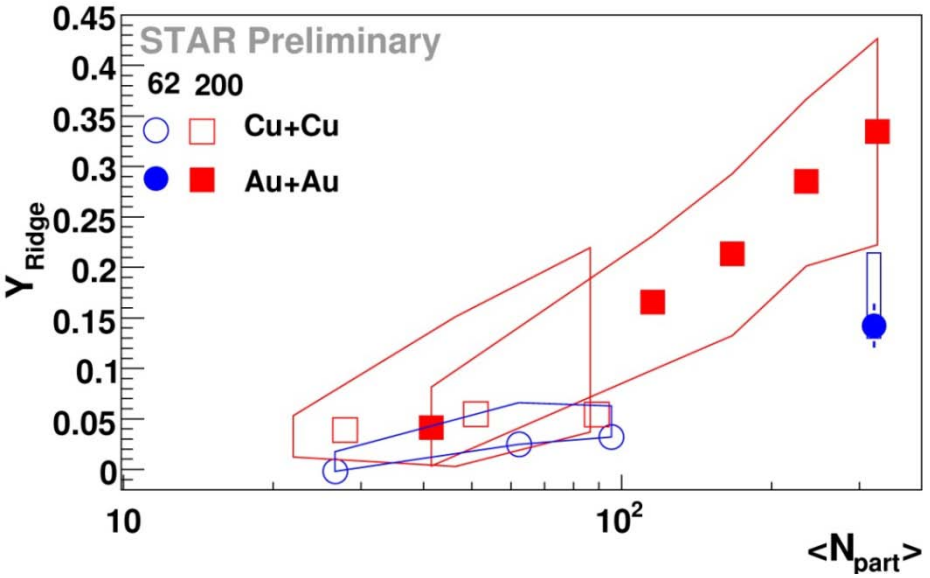
Initial state fluctuations and hydrodynamic flow?
glasma flux tubes,
participant fluctuations (triangular flow) …

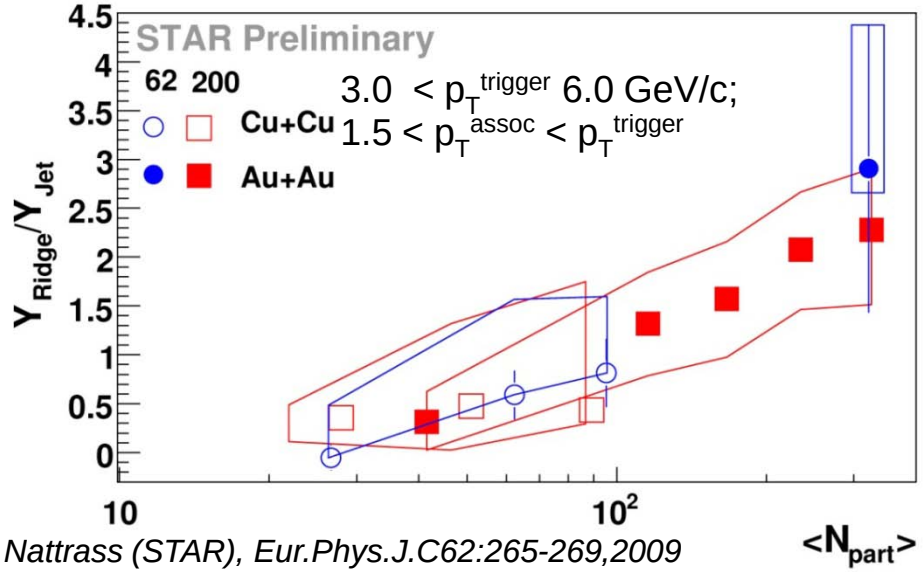
See talk by C. Y. Wong on ridge models

What is the near-side ridge?



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





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

Ridge yield:

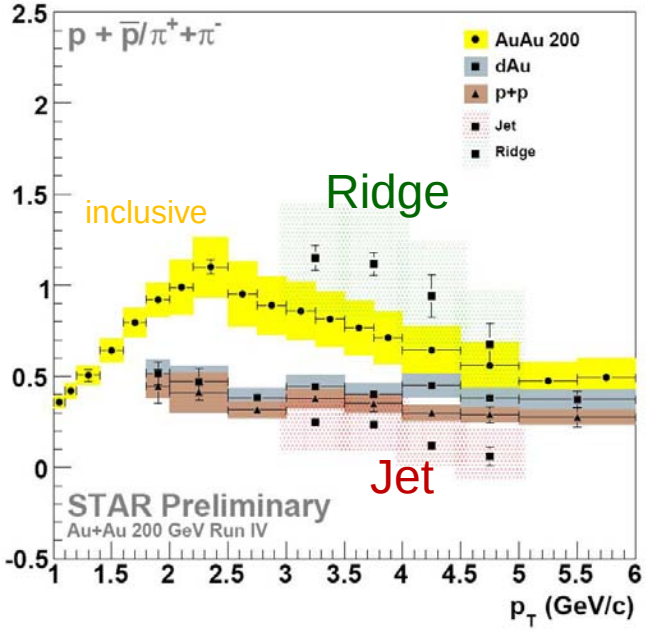
- persists to p_T trigger ~ 7 GeV/c
  → higher statistics needed to confirm this observation
- increases with N_{part}

BUT

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

Medium modified jet?

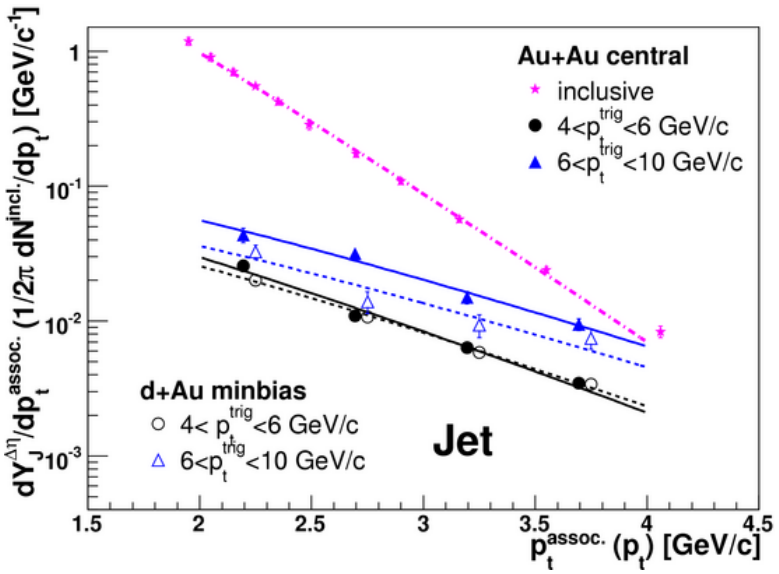
Ridge properties: bulk-like

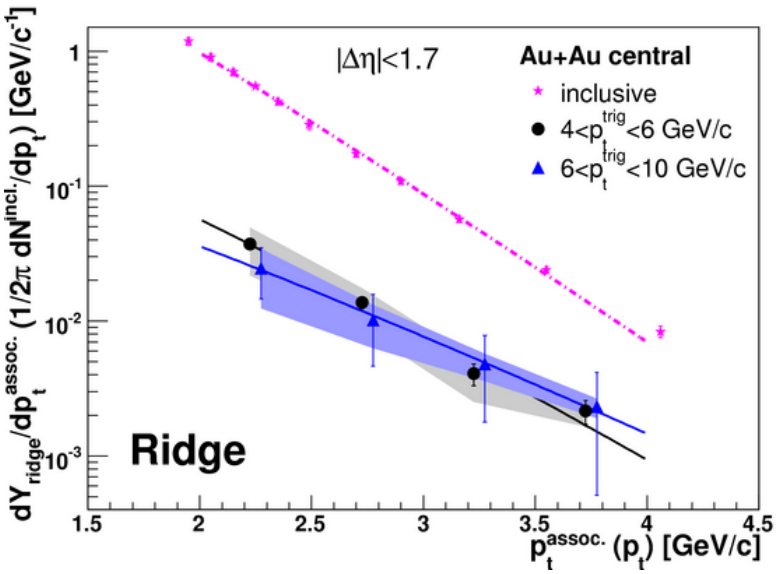


Ridge yield:

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

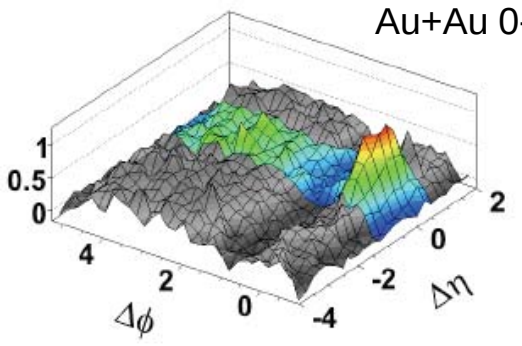
Medium modified by jet?

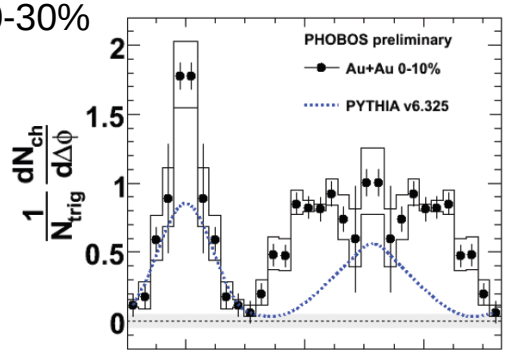


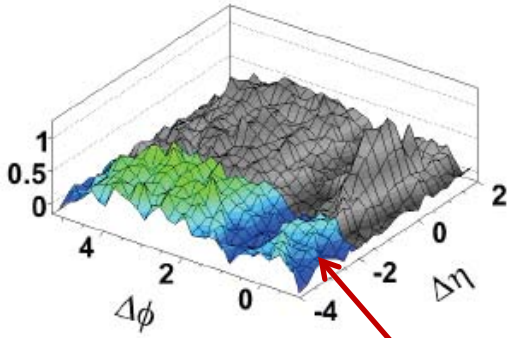


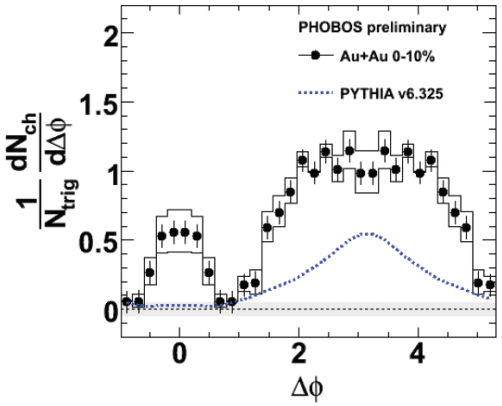
STAR, Phys. Rev. C **80** *(2009) 64912*

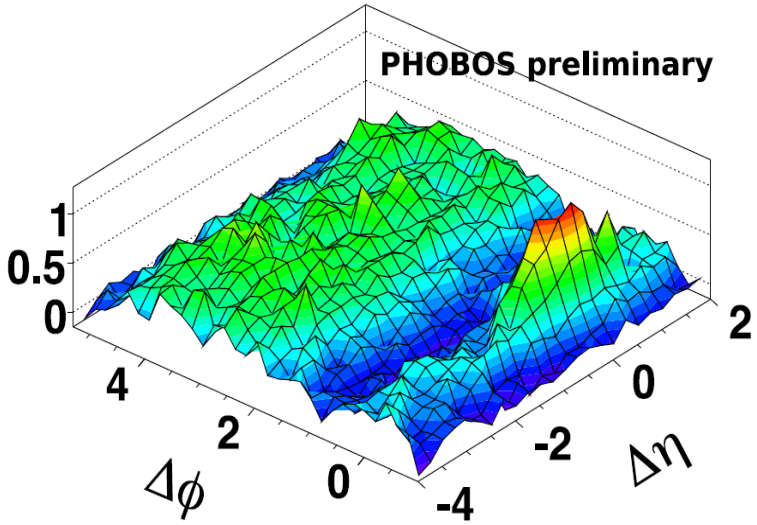
Ridge at forward rapidity at RHIC





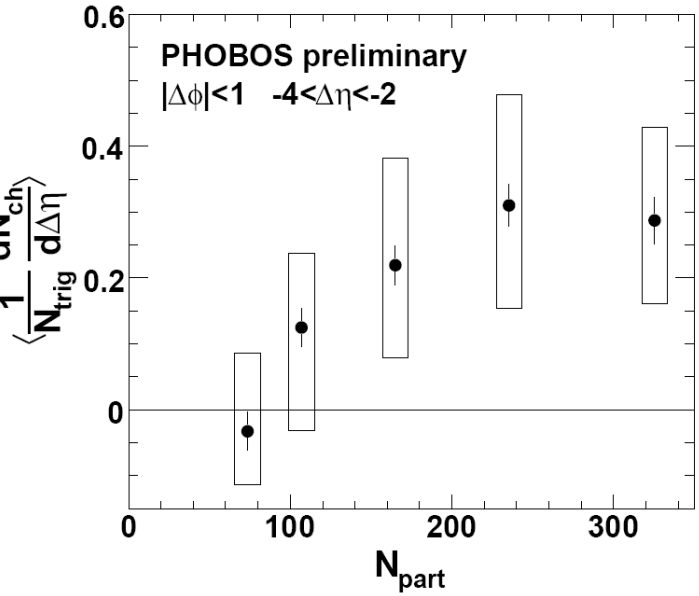






$p_T^{trig} > 2.5$ GeV/c
$p_T^{assoc} > 20$ MeV/c

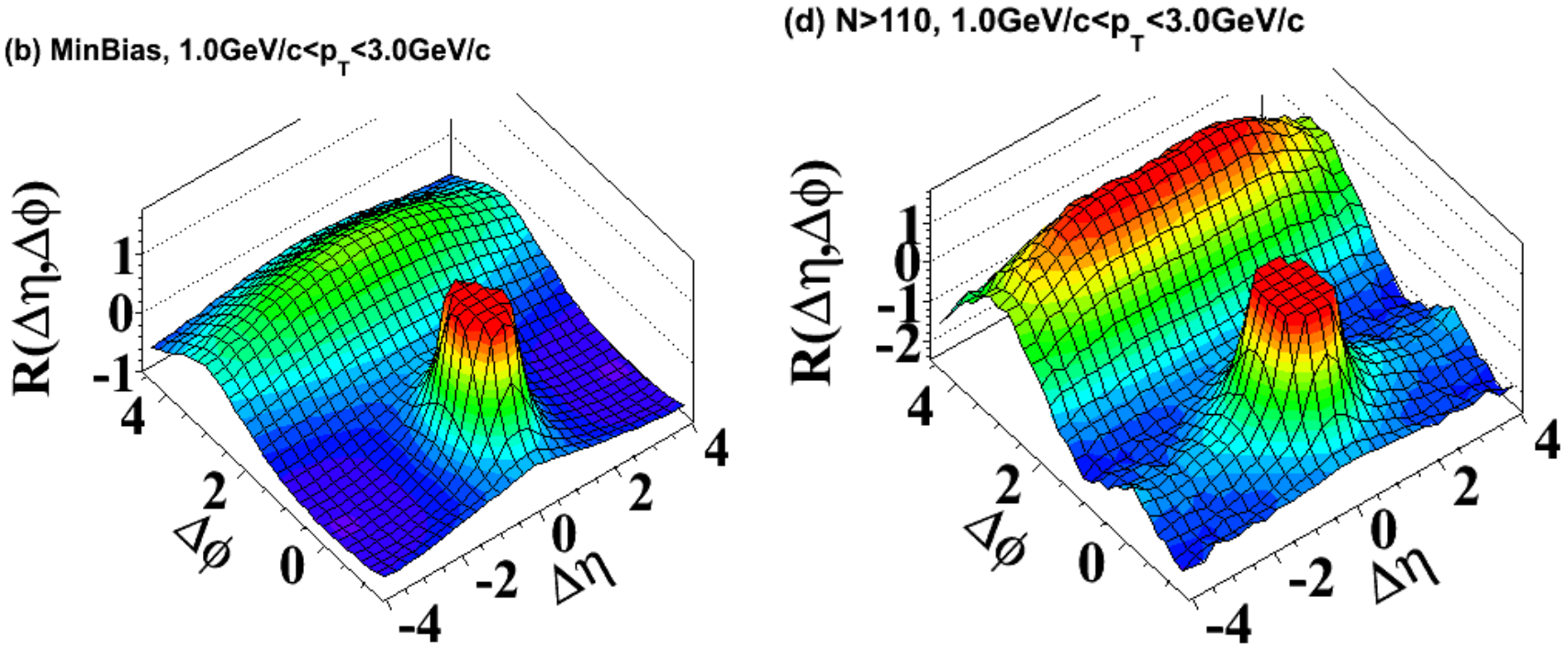
N_{part} dependence of ridge yield at $-4 < \Delta\eta < -2$:
decreases with decreasing N_{part} and vanishes around $N_{part} \sim 80$



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

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

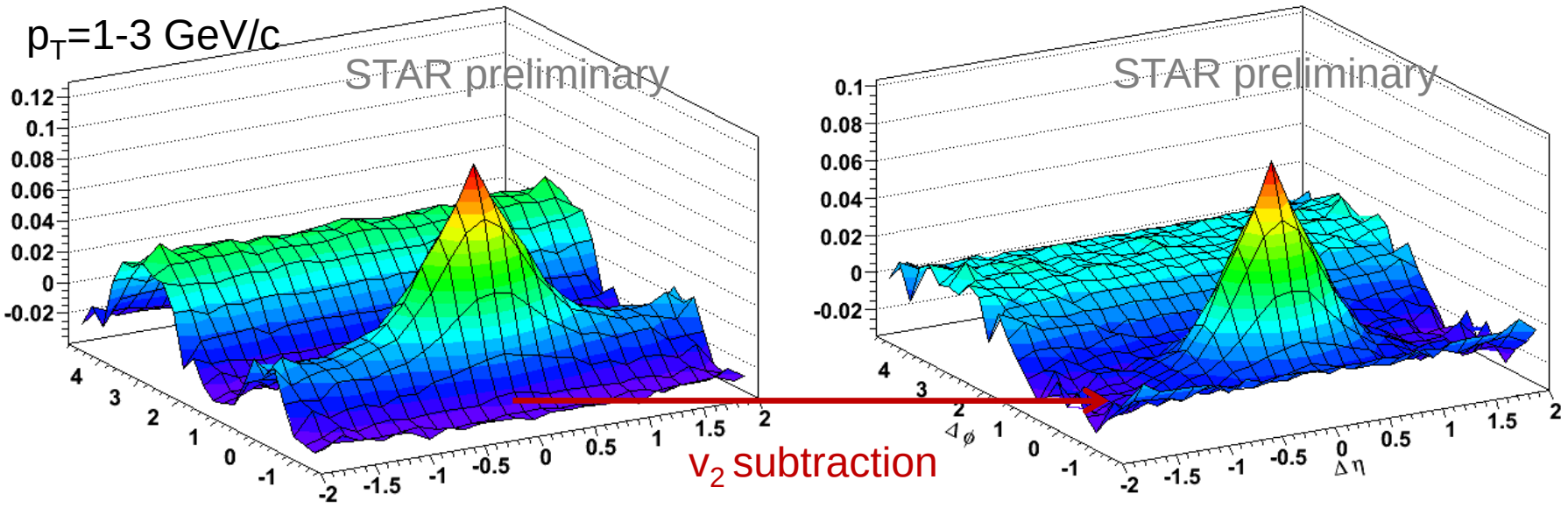
Intermediate p_T=1-3 GeV/c



Large multiplicity p+p collisions at 7 TeV:
pronounced long-range pseudorapidity structure at small $\Delta\phi$ and at intermediate p_T observed by CMS.

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 7 TeV is mainly dominated by elliptic flow.

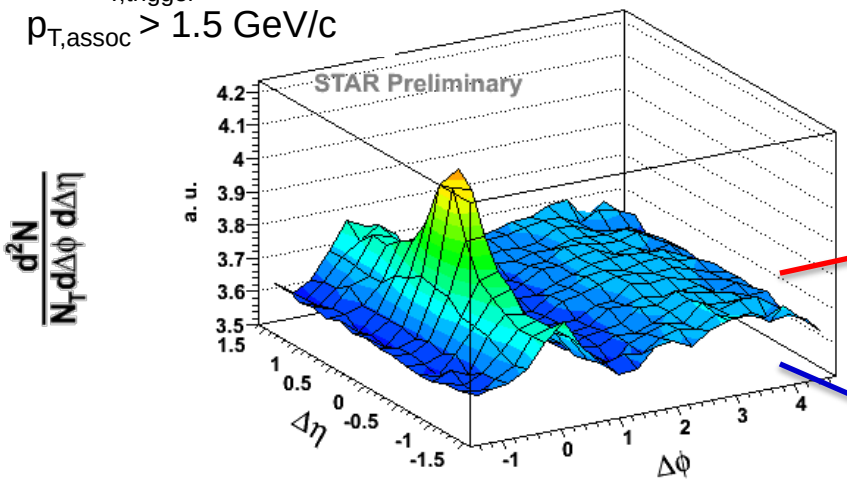
Leading PID triggered di-hadron correlations

h-h correlation

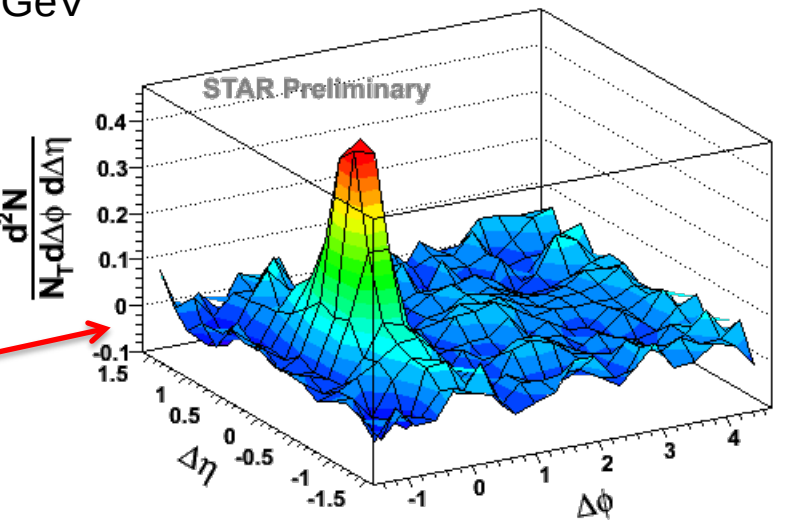
0-10% centrality Au+Au, 200 GeV

$4 < p_{T,trigger} < 6$ GeV/c

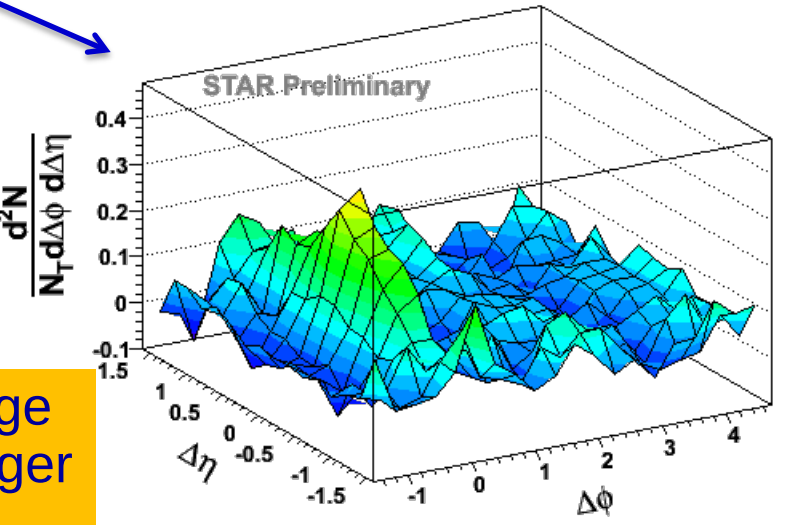
$p_{T,assoc} > 1.5$ GeV/c



π trigger



(p +K) trigger



- PID on a statistical basis
  (TPC: relativistic dE/dx rise)
- v_2 subtraction:
  $v_2(K^0)$ used for mesons (π, K)
  v_2 (Λ) used for protons

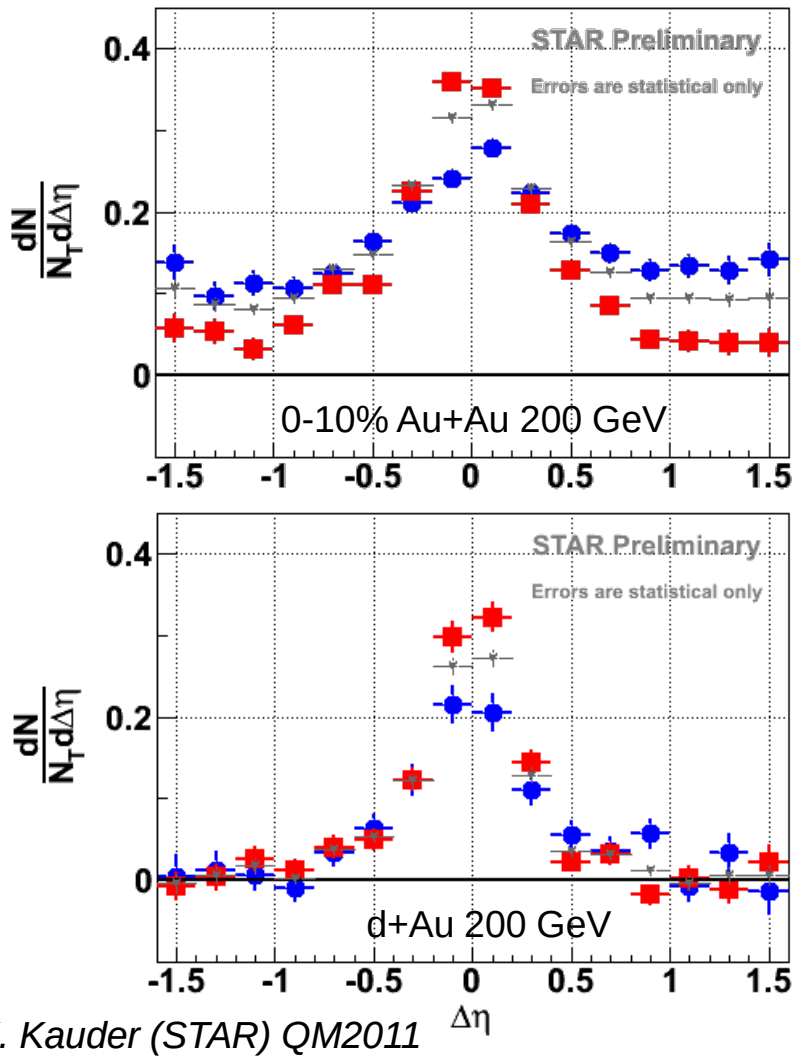
*STAR, PRC **77** (2008) 54901*

Jet-like correlation and ridge at near side depend on trigger particle type.

K. Kauder (STAR) QM2011

PID triggered correlations: $\Delta\eta$ projection

$4 < p_{T,trigger} < 6$ GeV/c, $p_{T,assoc.} > 1.5$ GeV/c, $|\Delta\phi|<0.73$



K. Kauder (STAR) QM2011

Trigger:
- π
- (p +K)
- h

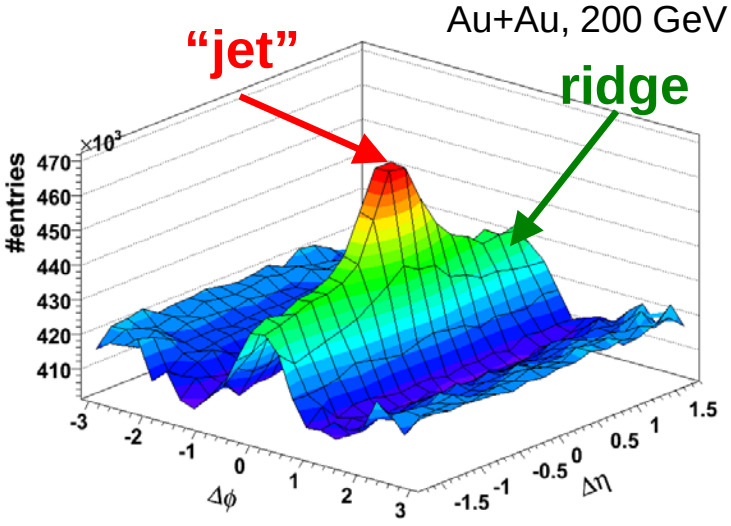
Trigger	d+Au Jet-like yield		Au+Au Jet-like yield		Ridge yield per unit $\Delta\eta$	
π	**0.19**	**0.01**	**0.22**	**0.01**	**0.057**	**0.005**
p +K	**0.14**	**0.02**	**0.12**	**0.01**	**0.118**	**0.007**
h	0.168	0.007	0.173	0.005	0.097	0.003

jet-like yield: larger for π triggers than for p+K triggers in both d+Au and Au+Au.

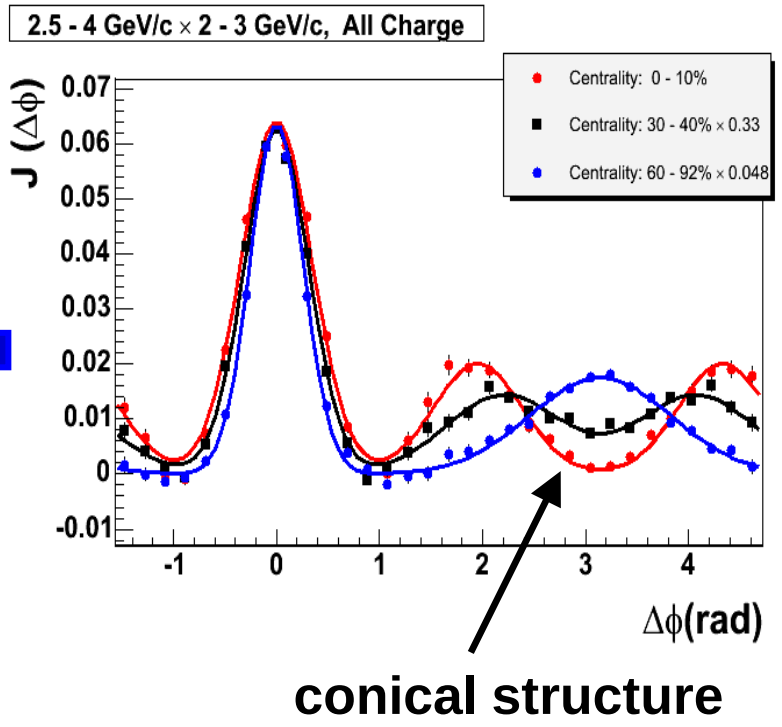
ridge yield: smaller for π triggers than p+K triggers.

Can we explain the near-side ridge and away-side conical structure by one physics scenario?

STAR



PHENIX



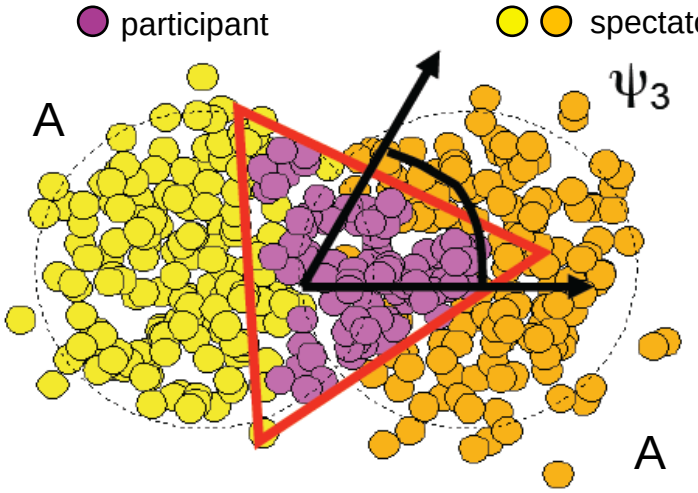
Triangular flow v_3

- Fourier decomposition of particle distribution relative to reaction plane:

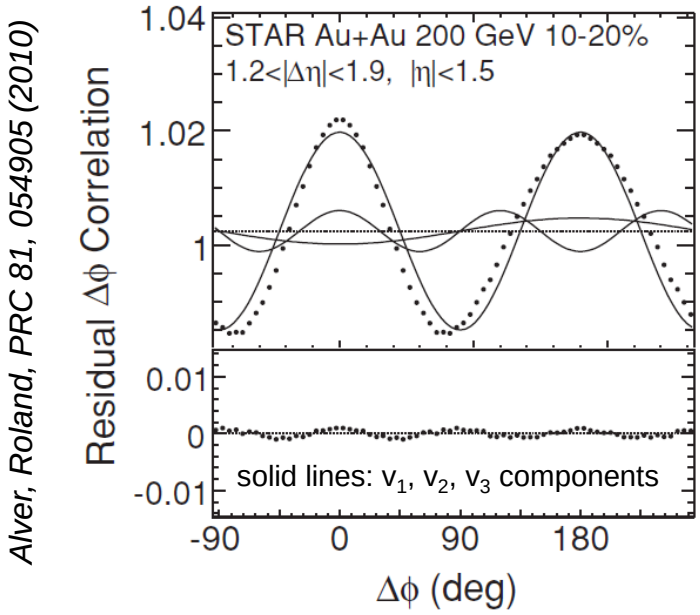
$$\frac{dN}{d(\varphi - \Psi_R)} = A\left[1 + \sum_n 2v_n \cos(n(\varphi - \Psi_R))\right]$$

- symmetric system: odd v_n coefficients = 0
- initial state fluctuations, hotspots …
  → odd v_n coefficients are ≠ 0!

Participant triangularity



$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$



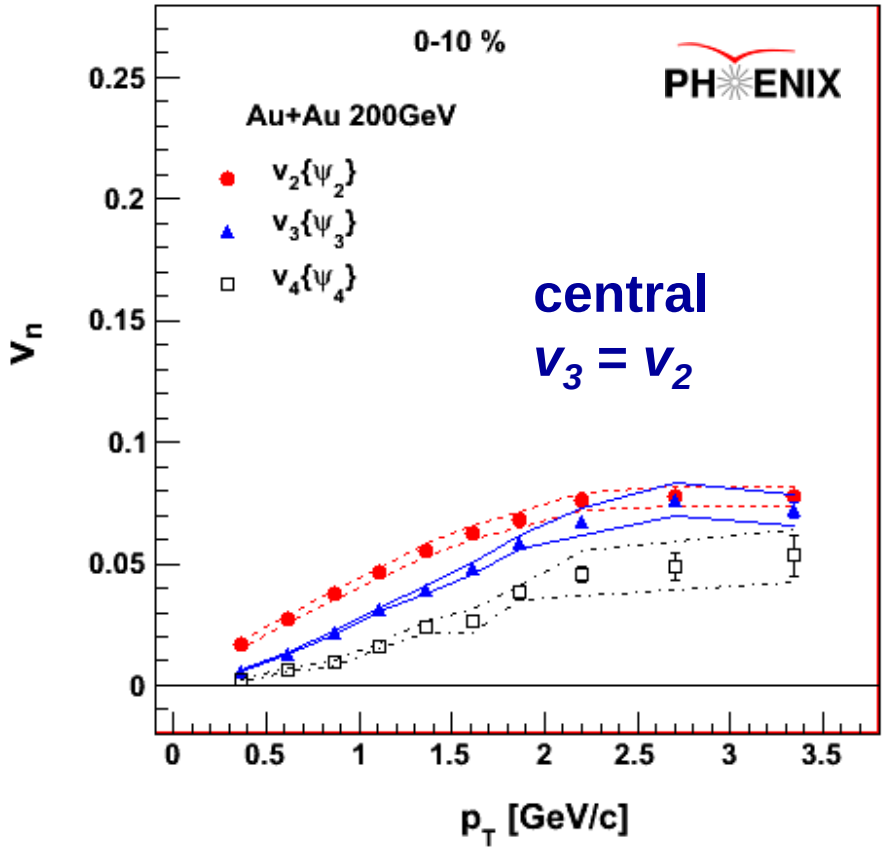
Alver, Roland, PRC 81, 054905 (2010)

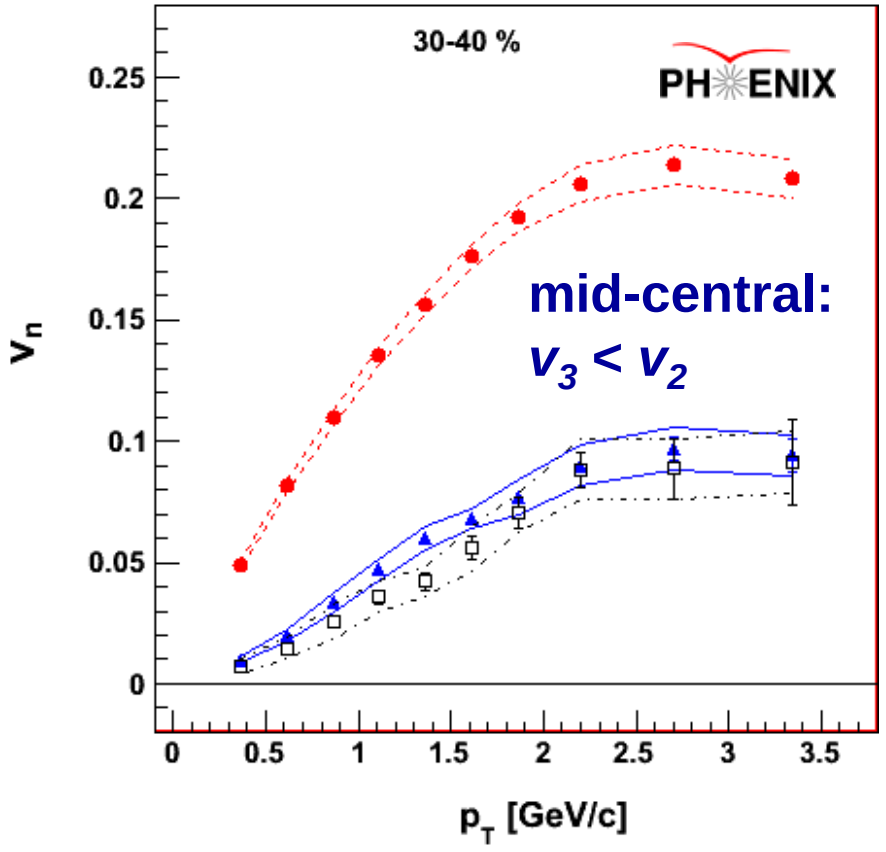
Mishra, Mohapatra, Saumia, Srivastava, PRC77, 064902 (2008)
Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010
Alver, Roland, PRC 81, 054905 (2010)
Takahashi et al., PRL 103 , 242301 (2009)
Petersen, Qin, Bass, Mueller, PRC 82, 041901(R) (2010)
Alver, Gombeaud,Luzum, Ollitrault, PRC 82, 034913 (2010)
Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100, 022303 (2010)
Holopainen, Niemi, Eskola, PRC83, 034901 (2011)
Schenke, Jeon, Gale, PRL 106, 042301 (2011)
Qiu, Heinz, arXiv:1104.0650

… and many others …

v_2 vs v_3 in Au+Au collisions

PHENIX, arXiv:1105.3928, S. Esumi , R. Lacey (PHENIX) QM2011

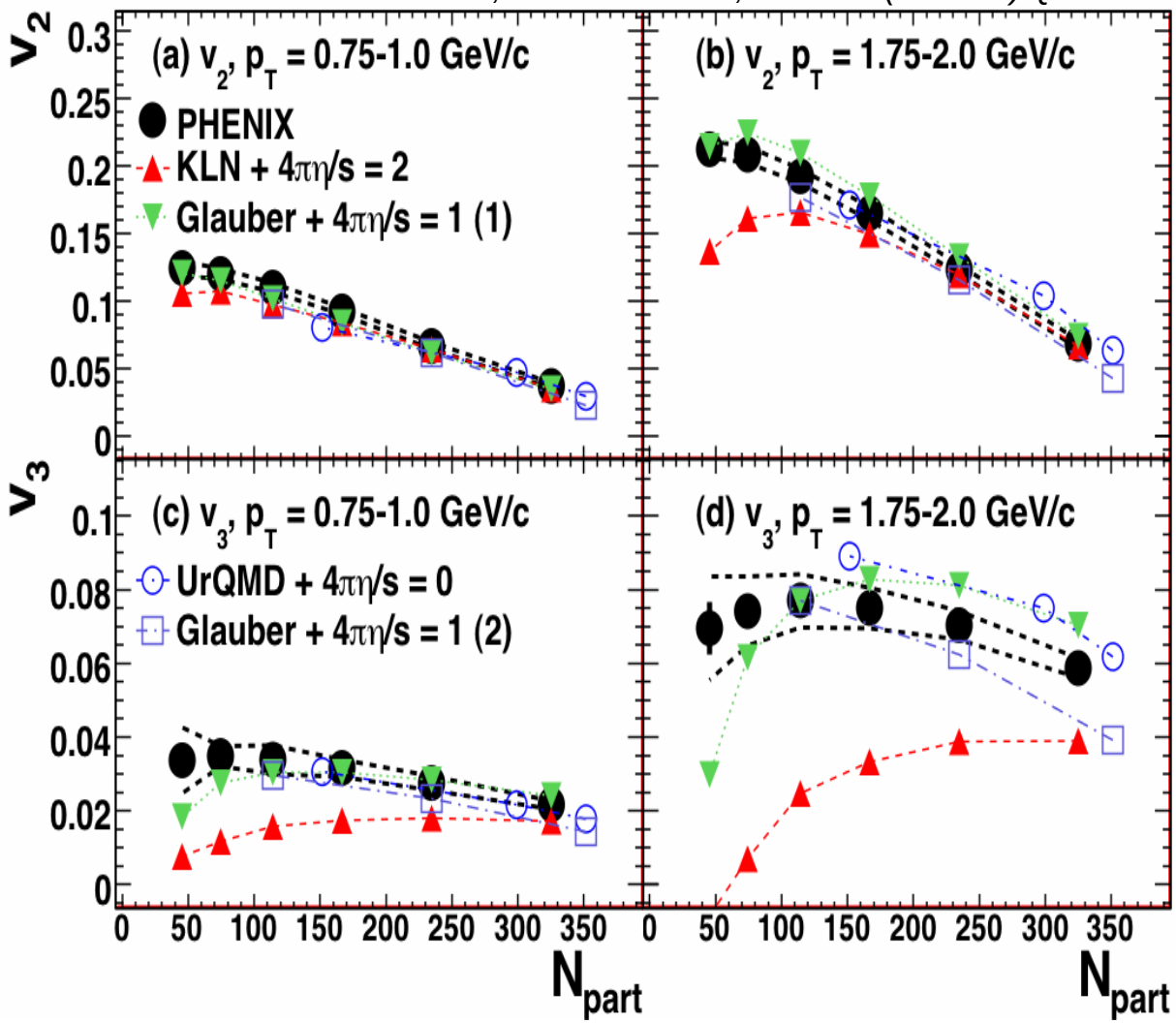


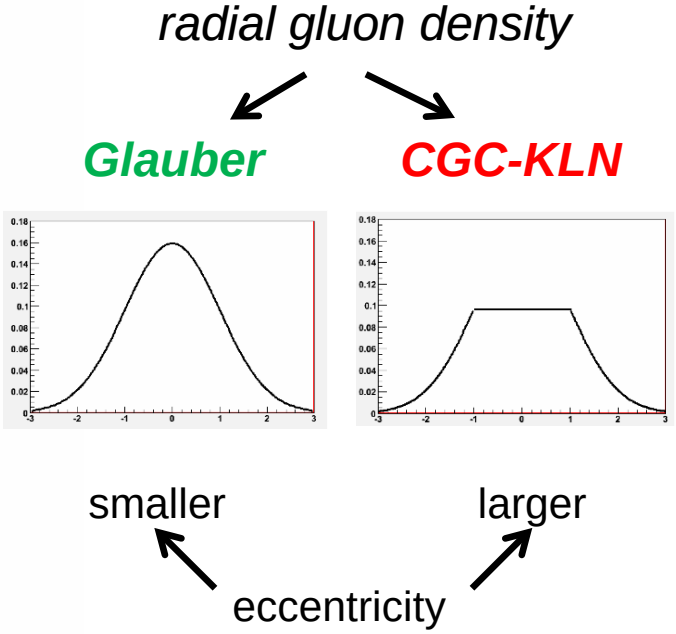


Weak centrality dependence of v_3 observed
→ points toward fluctuations origin of v_3.

Centrality dependence of v_2 and v_3

PHENIX, arXiv:1105.3928, S. Esumi (PHENIX) QM2011





v_3 can provide constraints on the hydro-model:

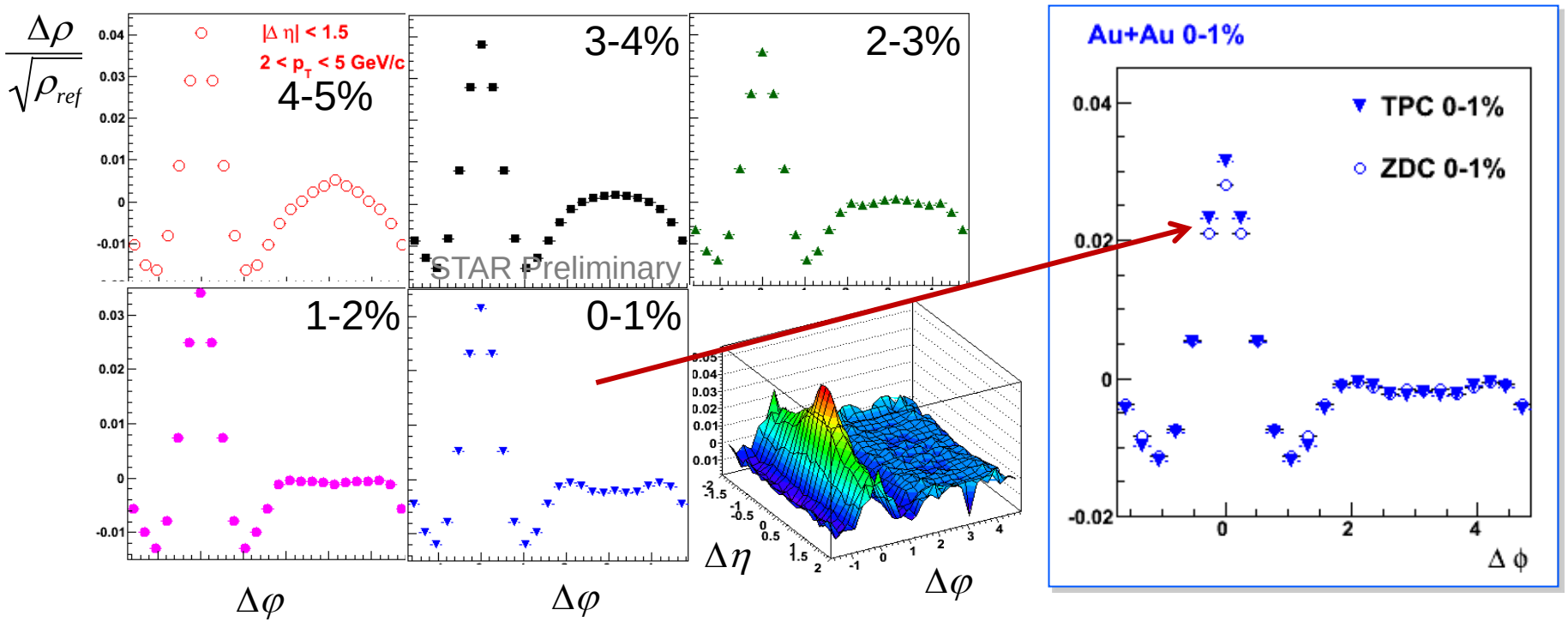
Data favor Glauber initial state with $\eta/s = 1/4\pi$.

B. Alver et. al., Phys. Rev. C82, 034913(2010).
B. Schenke et. al., Phys. Rev. Lett. 106, 042301(2011).
H. Petersen et. al., Phys. Rev. C82, 041901(2010).

Evidence for v_3 from correlations

v_3 is largest at intermediate p_T and for central collisions where the overlap geometry is most symmetric.

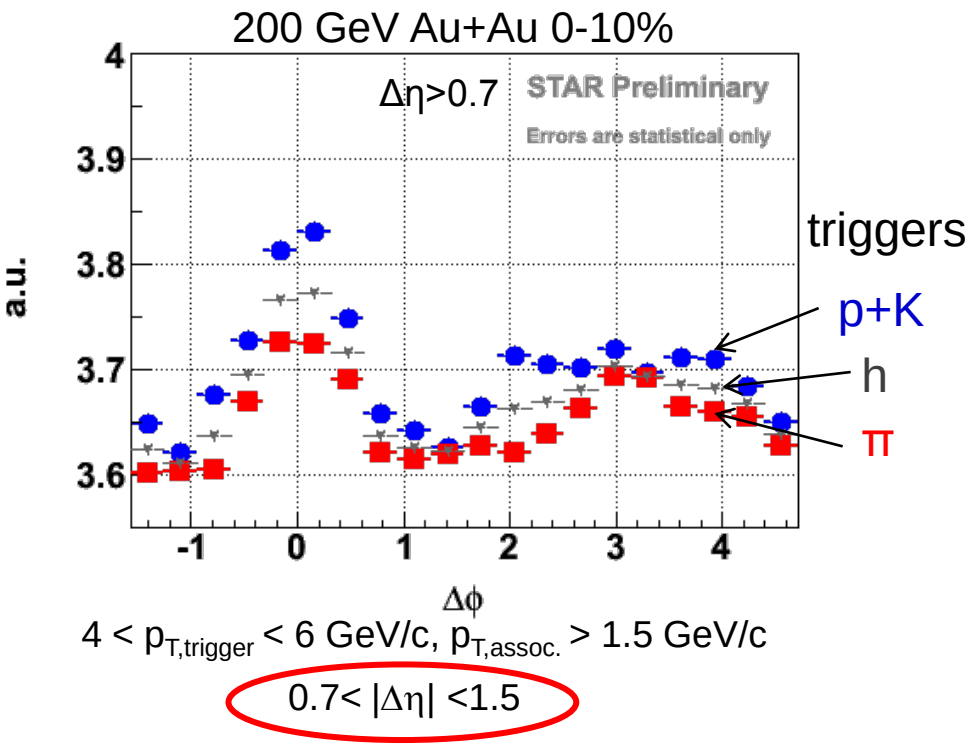
STAR: P. Sorensen (talk), C. de Silva (poster) QM2011



0-1% centrality: n=3 double hump is present on the away-side without v_2 subtraction.

Correlations with identified particles

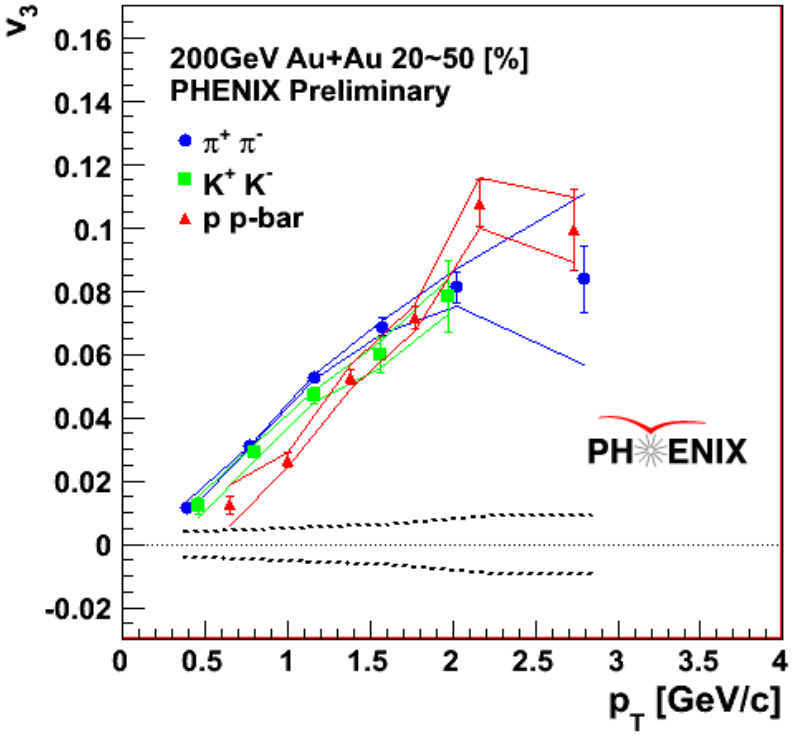
K. Kauder (STAR) QM2011



$4 < p_{T,trigger} < 6$ GeV/c, $p_{T,assoc.} > 1.5$ GeV/c

$0.7 < |\Delta\eta| < 1.5$

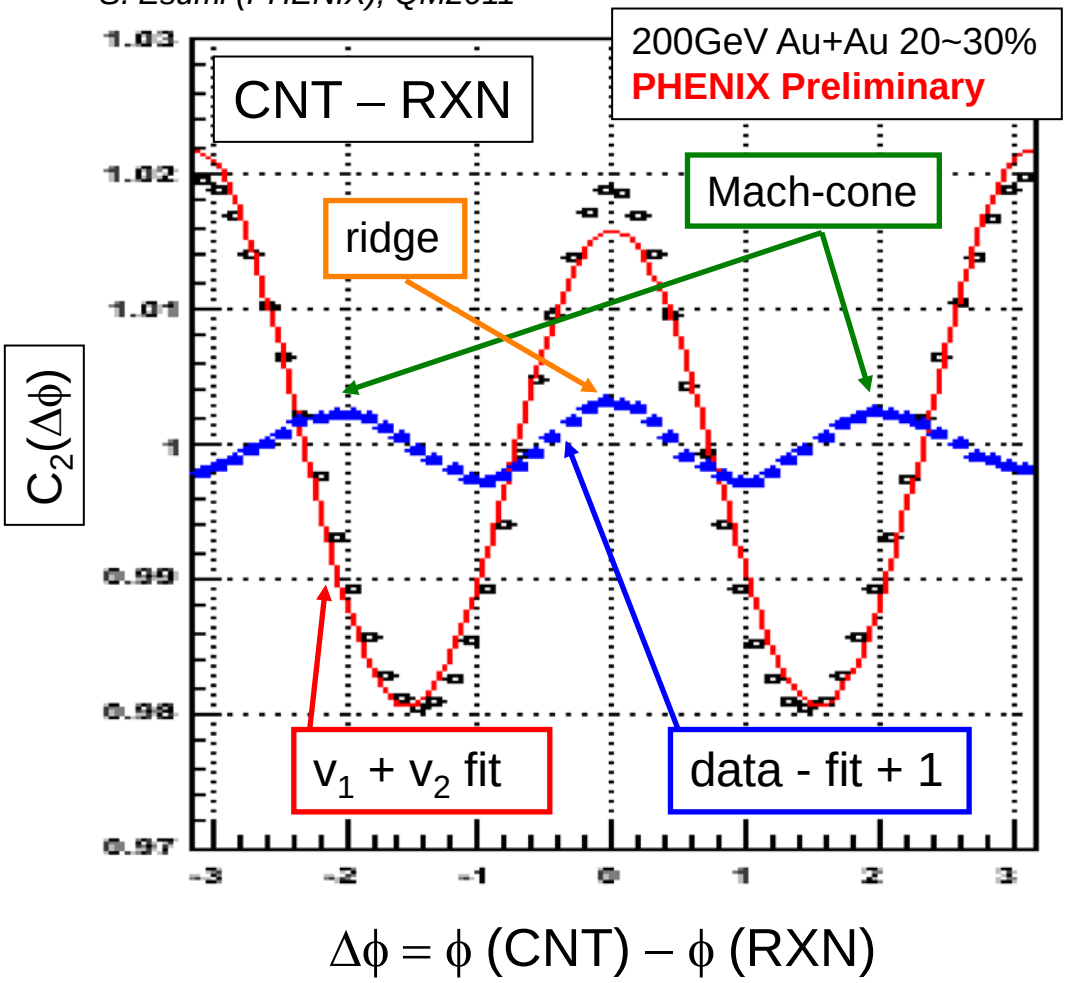
S. Esumi (PHENIX) QM2011



- double-hump away-side structure for non-pion triggers at large $\Delta\eta$ (no bkg. subtraction)
- need PID measurements of v_3 at intermediate p_T

Di-hadron correlations: central - forward η

S. Esumi (PHENIX), QM2011



$\Delta\phi = \phi\,(\mathrm{CNT}) - \phi\,(\mathrm{RXN})$

Reaction plane detector RXN:
$|\eta|$=1.0~2.8

Central tracking arm:
$|\eta|$<0.35
charged hadrons: p_T=2-4(GeV/c)

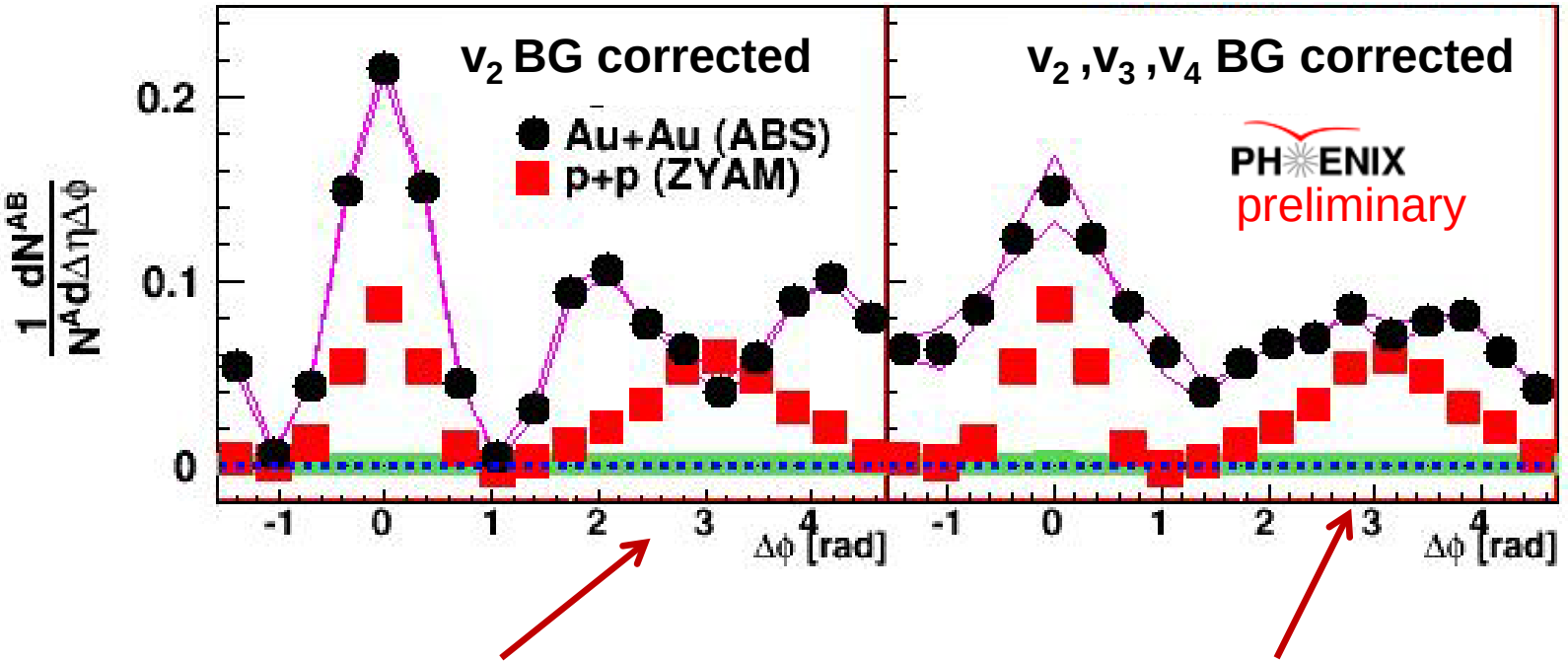
- another way to extract v_n without using Φ_n

Clear v_3 in long range $\Delta\phi$ correlation observed.

v_3 and the conical structure

200GeV Au+Au, 0-20%

PHENIX: S. Esumi, R. Lacey, QM2011



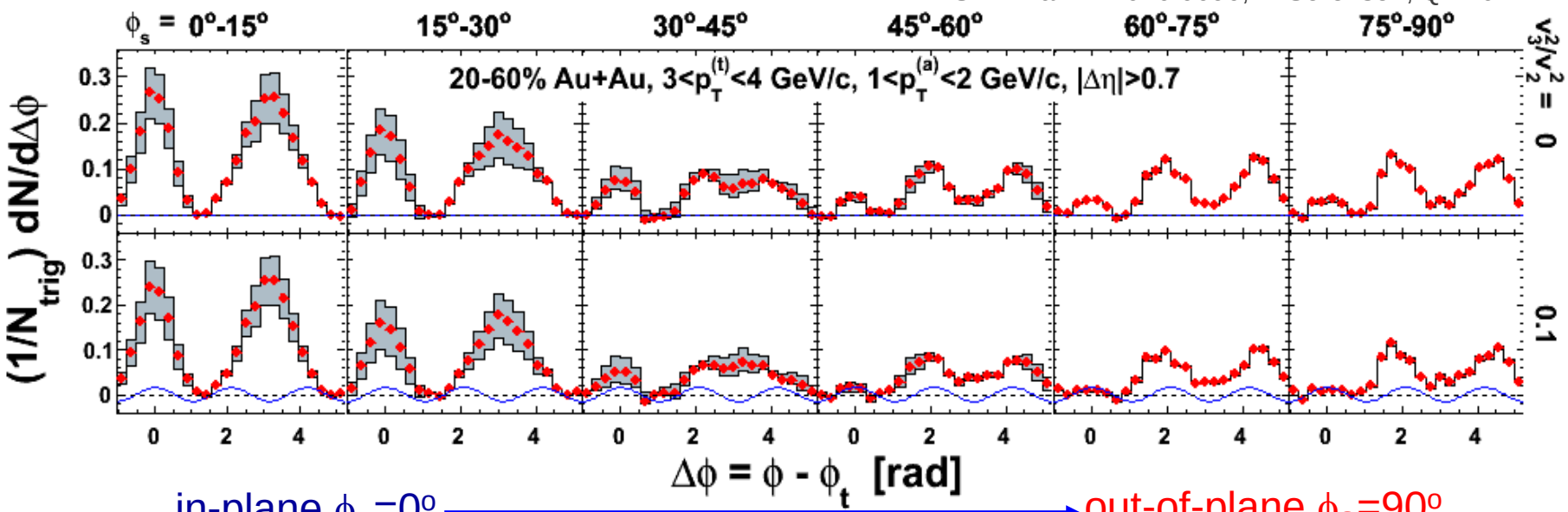
v_2 subtraction → double-hump structure on away side

v_2, v_3, v_4 subtracted
→ double-hump structure disappeared
→ away-side peak still broadened

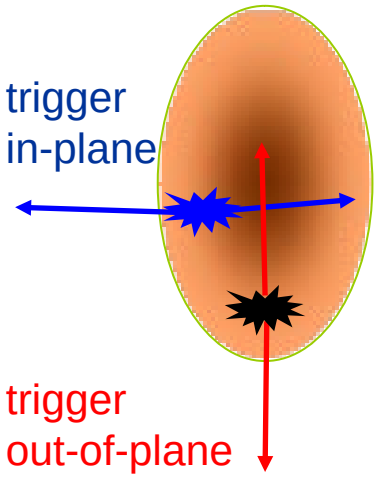
We need precision measurements to see what is left for "jet-medium" modification.

Di-hadron correlations relative to event plane

STAR: arXiv:1010.0690, P. Sorensen, QM2011



in-plane ϕ_S=0° → out-of-plane ϕ_S=90°



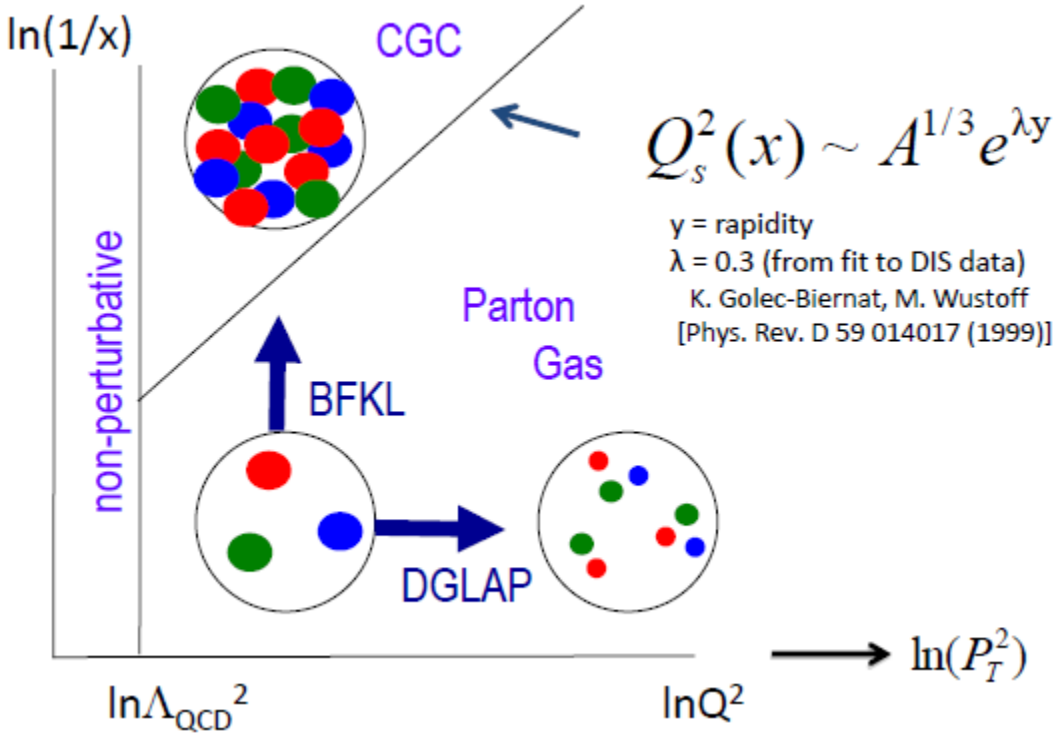
v_2(forward EP) subtracted → residual structure
→ adding v_3 does not account for all of the residual structure

Possible Δη-dependence to $\Psi_{EP,1} \cdot \Psi_{EP,2}$?
Non-flow effects ?
v_2(forward EP) underestimates v_2 at small Δη ?

Study of $v_3^2\{2\}$ vs Δη → decomposition into a narrow and wide Gaussian →centrality evolution of the amplitude of the wide Gaussian follows $N_{part}\varepsilon^2_{part,n}$ for details see P. Sorensen (STAR) QM'11

Probing the initial conditions …

Low-x and Color Glass Condensate



$$Q_s^2(x) \sim A^{1/3} e^{\lambda y}$$

y = rapidity
λ = 0.3 (from fit to DIS data)
K. Golec-Biernat, M. Wustoff
[Phys. Rev. D 59 014017 (1999)]

$$x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$$

low-x = large gluon densities

→ recombination becomes important
→ necessary to include non-linear contributions to evolution

Color Glass Condensate (CGC)

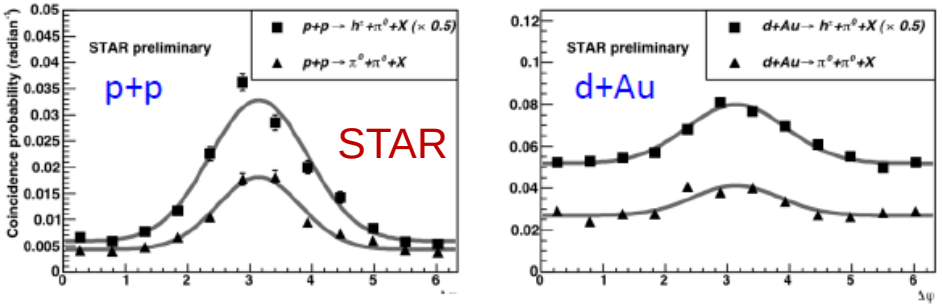
• semi-classical effective field theory to compute low-x gluons in nuclei

• predicts suppression of away-side correlations at forward rapidity ('monojets')

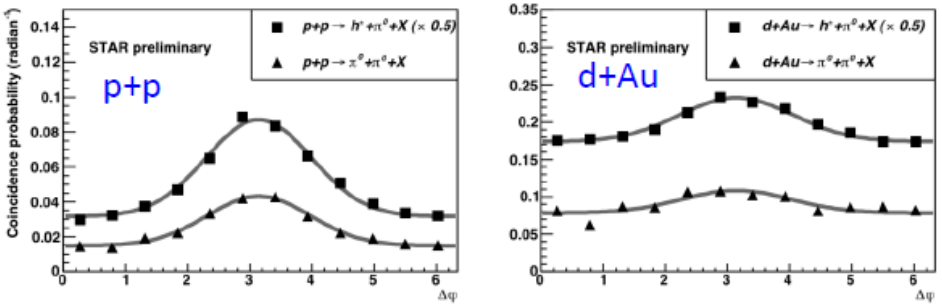
Saturation: low-x, large √s, large y, large A

Mid-forward rapidity correlations at RHIC

P_T(FMS) > 2.5 GeV/c ; 1.5 GeV/c < P_T(BEMC/TPC) < P_T(FMS)

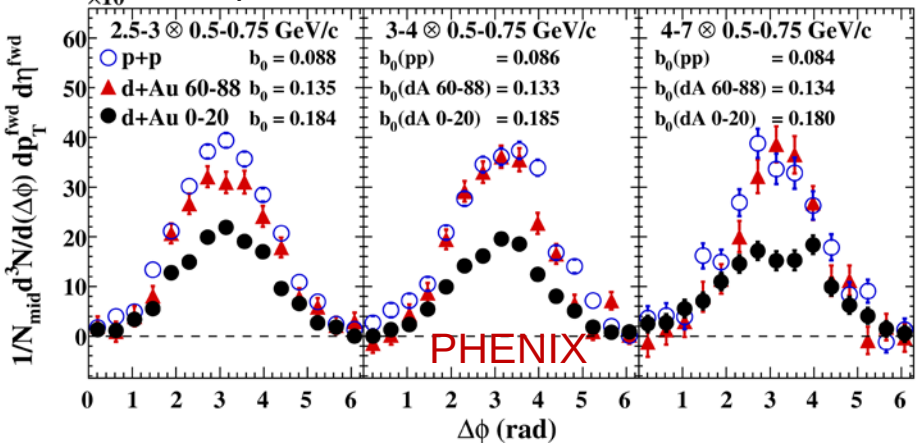


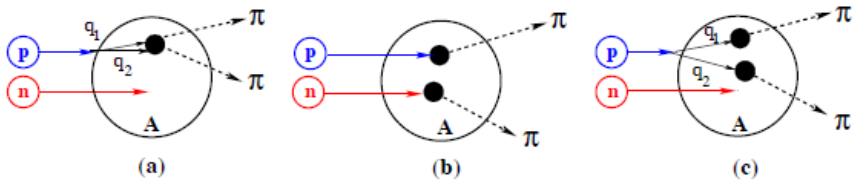
P_T(FMS) > 2.0 GeV/c ; 1.0 GeV/c < P_T(BEMC/TPC) < P_T(FMS)



E. Braidot et al. (STAR), 1102.0931

d+Au, 200 GeV π^0-π^0 *PHENIX, nucl-ex/1105.5112*

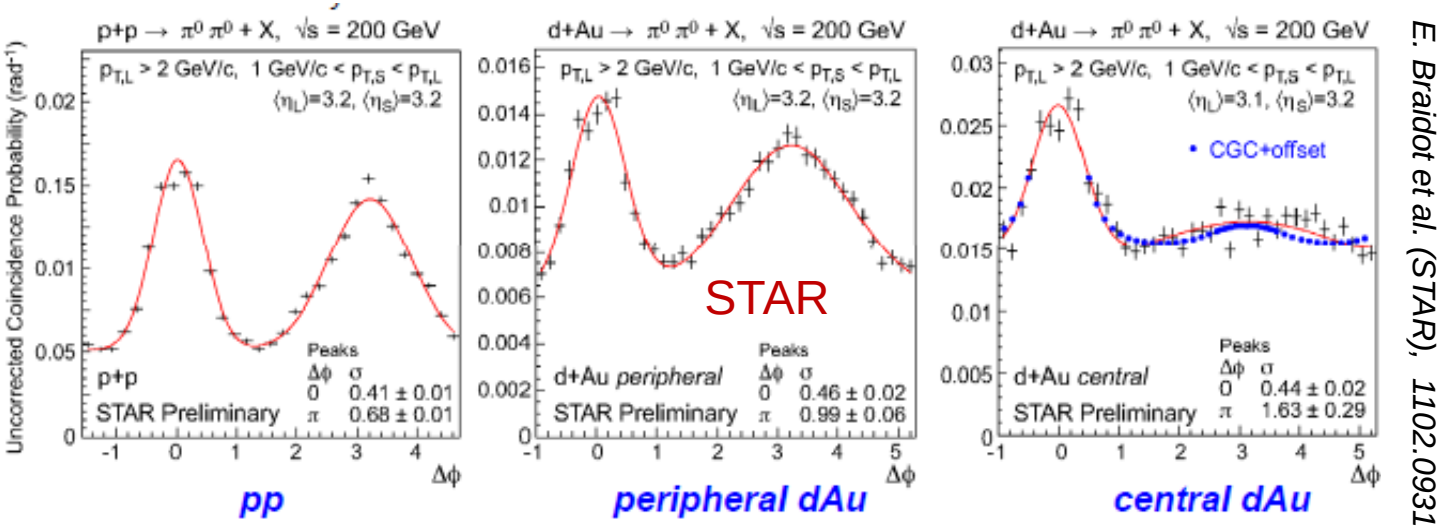




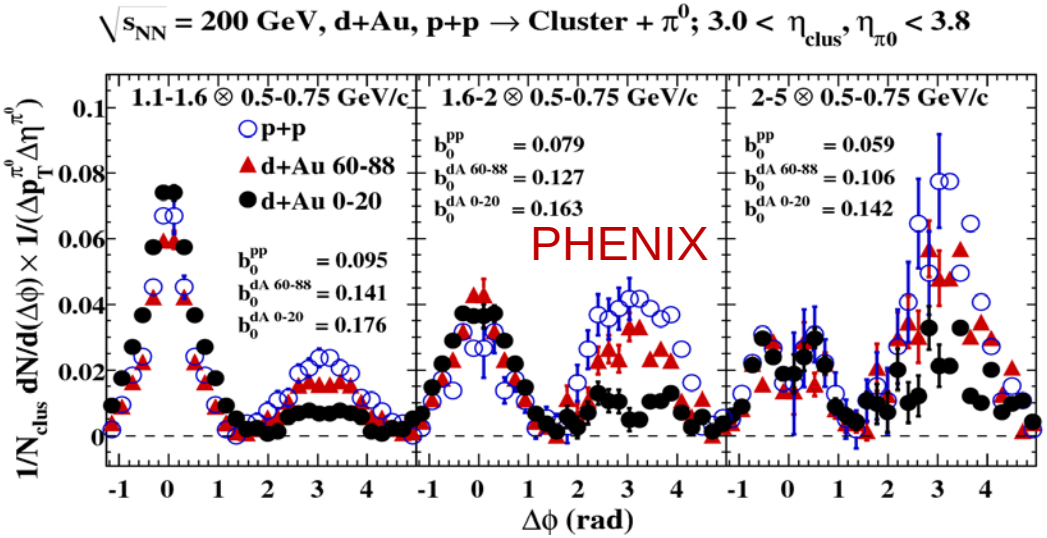
- high pedestal in d+Au: multi-parton interactions?
  Strikman, Vogelsang, PRD 83, 034029 (2011)

- no significant broadening from p+p to d+Au observed
- no hints of away-side peak disappearance

Forward-forward rapidity correlations: p+p/d+Au



E. Braidot et al. (STAR), 1102.0931

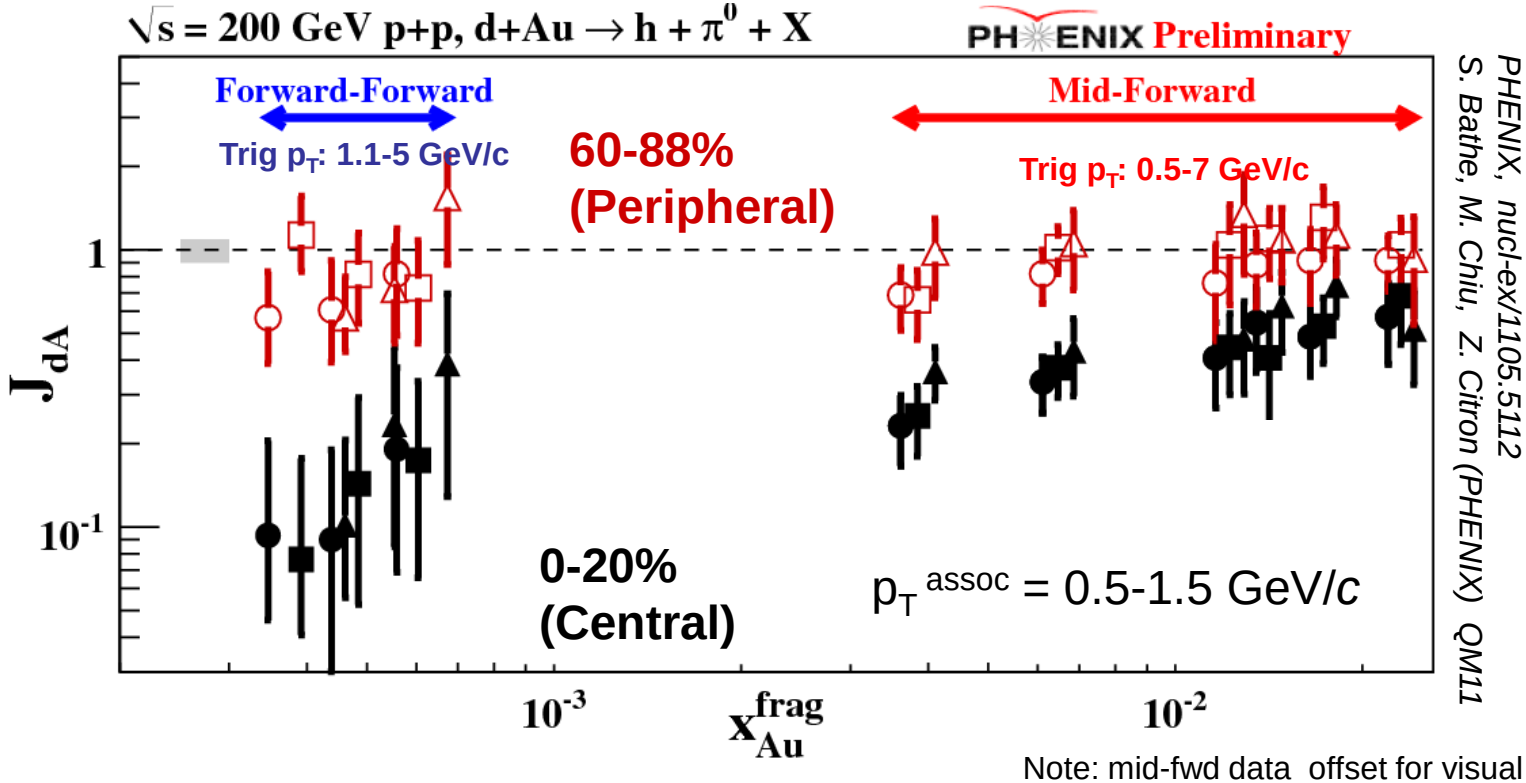


PHENIX, nucl-ex/1105.5112

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

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

x_{Au}^{frag} dependence



Note: mid-fwd data offset for visual clarity
Stat. and syst. errors added in quadrature

$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

as a function of

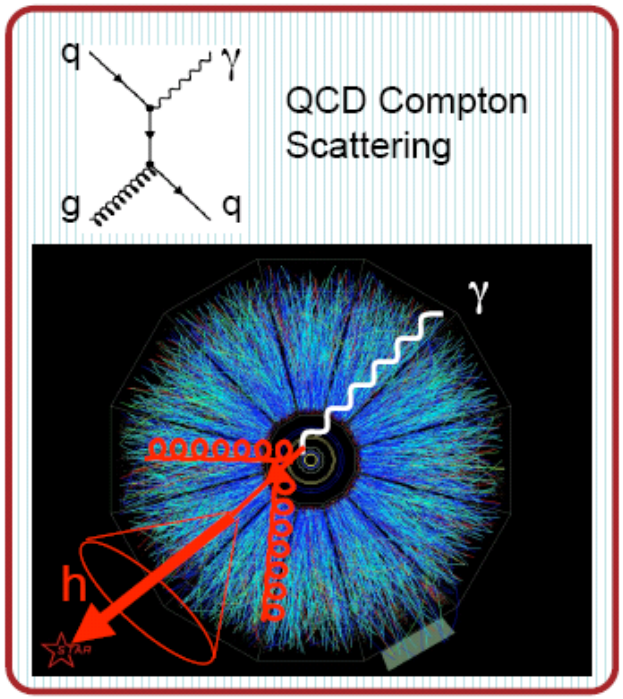
$$x_{Au}^{frag} \equiv \frac{\langle p_{T1} \rangle e^{-\langle \eta_1 \rangle} + \langle p_{T2} \rangle e^{-\langle \eta_2 \rangle}}{\sqrt{s}}$$

Di-hadron suppression at low-x qualitatively consistent with CGC

BUT: Does it prove CGC? What about shadowing, initial state energy loss, MPI?

γ-hadron correlations

γ-hadron correlations



- a “golden probe” of parton energy loss in the medium

- precise measurement of the in-medium modification of fragmentation function

p+p, Au+Au collisions: statistical method

$$Y_{direct} = \frac{R_\gamma Y_{incl} - Y_{decay}}{R_\gamma - 1}$$

$$R_\gamma = \frac{N_{incl}}{N_{decay}}$$

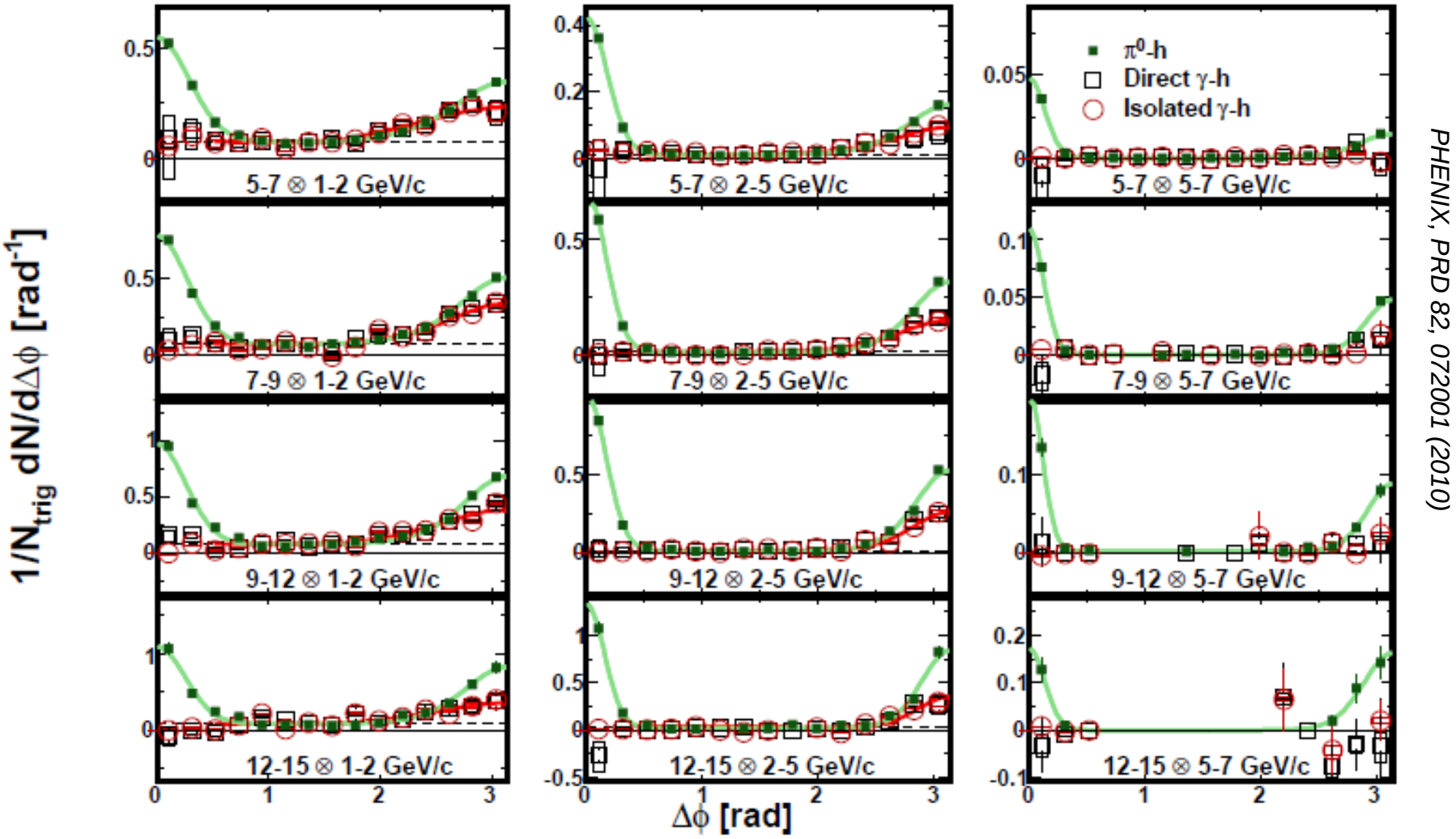
p+p collisions: isolation cut

$$E_{cone} = \sum_{\text{tracks}} p_T + \sum_{\text{clusters}} E$$

$$E_{cone} < 10\% E_\gamma$$

$$R_{cone} = 0.3$$

γ-hadron correlations in p+p: cross-check of methods



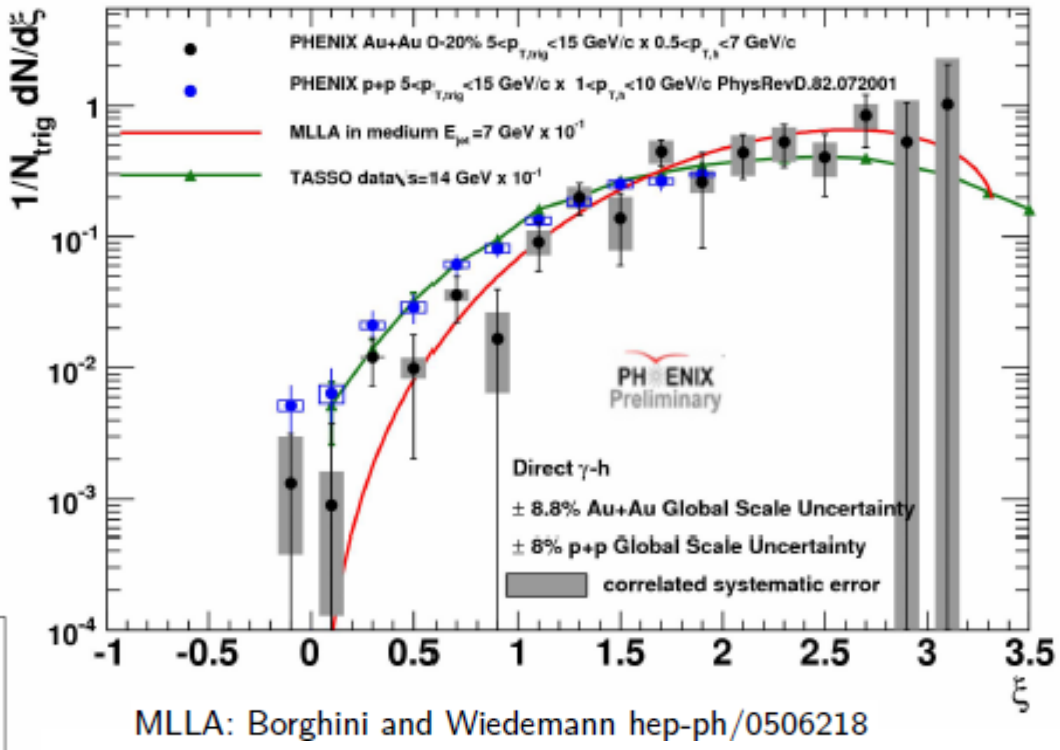
Over a wide p_T range both methods agree well. A clear away-side peak observed.

γ-hadron: fragmenation function (PHENIX)

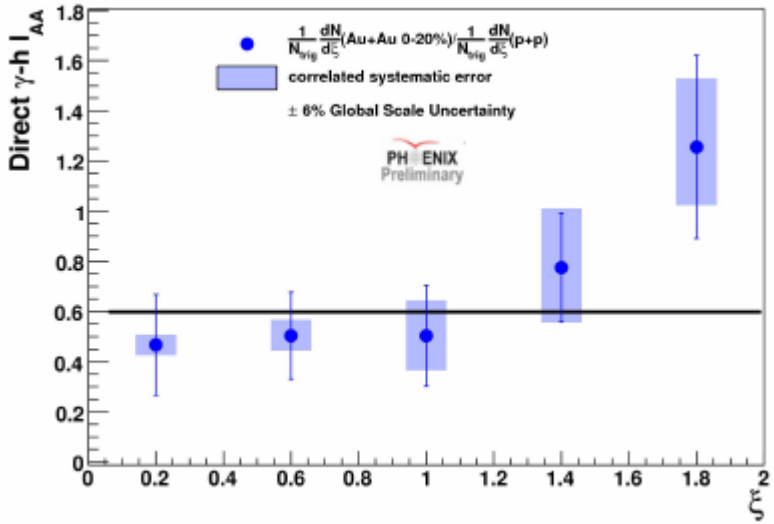
$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

FF in Au+Au collisions:

- measured down to high ξ ~3 (= low z: $p_{T,h}$ =0.5-1GeV/c)
- good agreement with MLLA



MLLA: Borghini and Wiedemann hep-ph/0506218

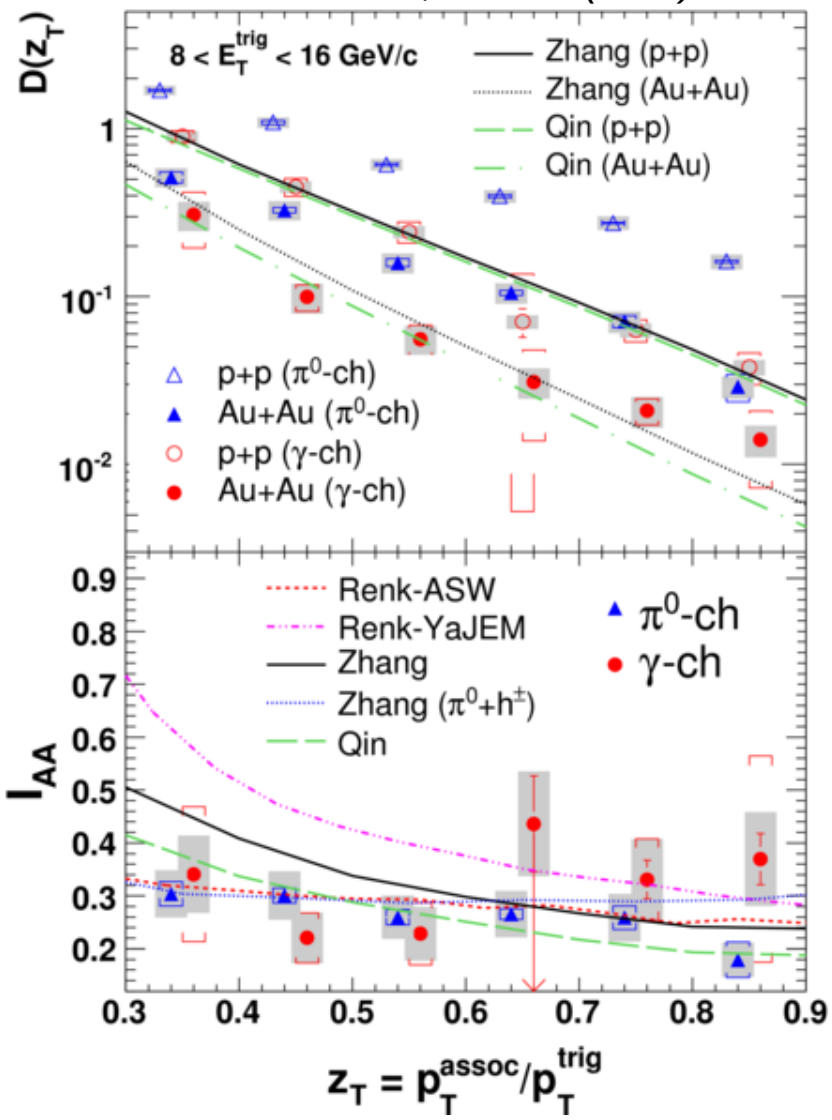


- strong suppression of I_{AA} observed
- I_{AA} (ξ) consistent with a constant

$\langle I_{AA} \rangle$ = 0.598 0.095
χ^2/NDF=4.85/4

γ-hadron: fragmenation function, I_{AA} (STAR)

STAR, PRC 82 (2010) 34909



- $D(z_T)$: π^0 –h >γ_{dir}-h

This is expected as γ_{dir} carries the total scattered constituent momentum, while π^0 only its fraction

- I_{AA}: is z_T independent and similar for π^0 –h and γ_{dir}-h

Model comparison:
Zhang (no fragm. photons),
Qin (fragm. photons included),
Renk-ASW:
describe data well

Renk-YaJEM:
- overpredicts data at small z
- lost energy redistributed through medium to very low p_T and large angles?

Summary

- Strong modification of correlation patterns in central A+A collisions at RHIC observed and described in terms of "ridge" and "conical emission" in the past 7 years.

- Recent theoretical developments and data analysis indicate presence of higher Fourier flow components (triangular flow) which is consistent with initial density fluctuation models.

- Detailed studies of correlation functions are needed to quantify the magnitude of the remaining jet-medium modification.

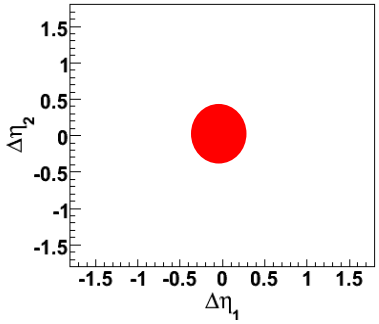
- Suppression of away-side correlation at forward rapidity observed in d+Au collisions which is qualitatively consistent with CGC. Further studies needed to evaluate contribution of other effects.

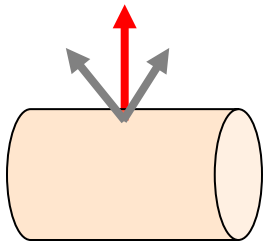
- Ongoing and future studies at RHIC with large statistics and improved PID capabilities are coming: γ-jets, heavy quarks …

Backup slides

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

1) Jet fragmentation in vacuum

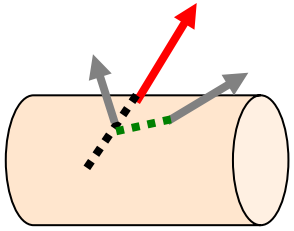


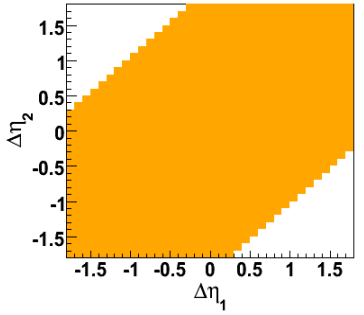


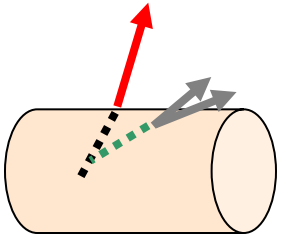
2) In medium radiated gluons diffused in η

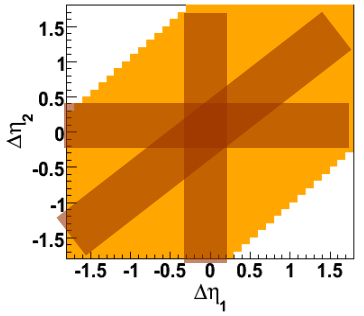
3) In medium radiated gluons collimated by longitudinal flow

4) Combination of jet fragmentation and diffused gluons





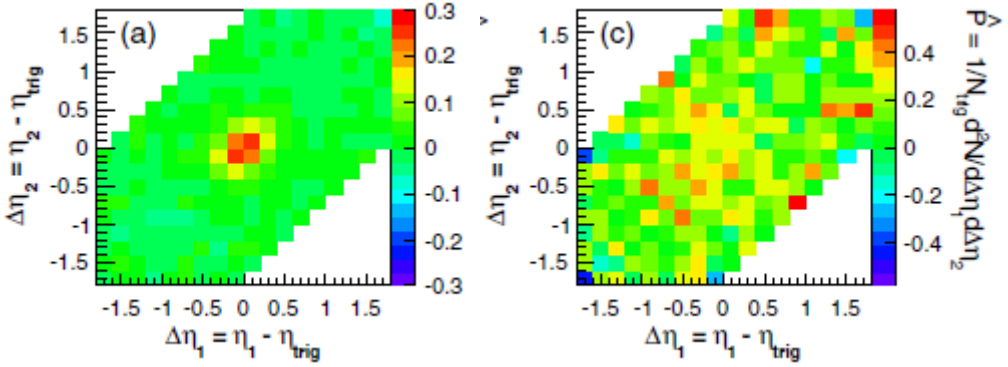




Data:

d+Au

0-12% Au+Au



STAR, PRL 105, 022301 (2010)

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

Uniform overall excess of associated particles observed at intermediate p_T

- more data needed
- studies at higher p_T^{assoc} and $p_T^{trigger}$

Note: Involves complicated background subtraction