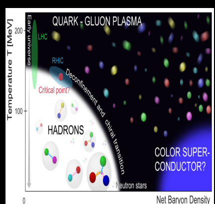
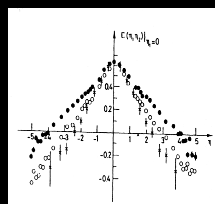
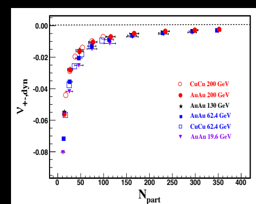
Wayne State University
College of Liberal Arts & Sciences
Department of Physics and Astronomy

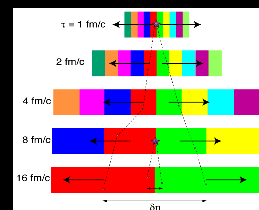
The Multiple Facets of Correlation Functions

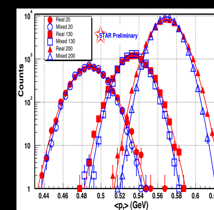
Kolkata, India, Jan 2014

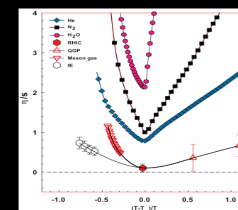












Professor Claude A Pruneau
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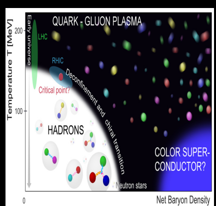

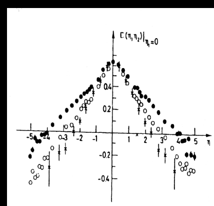

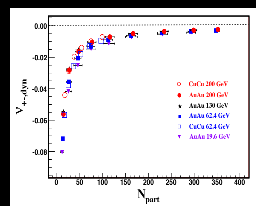

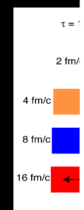

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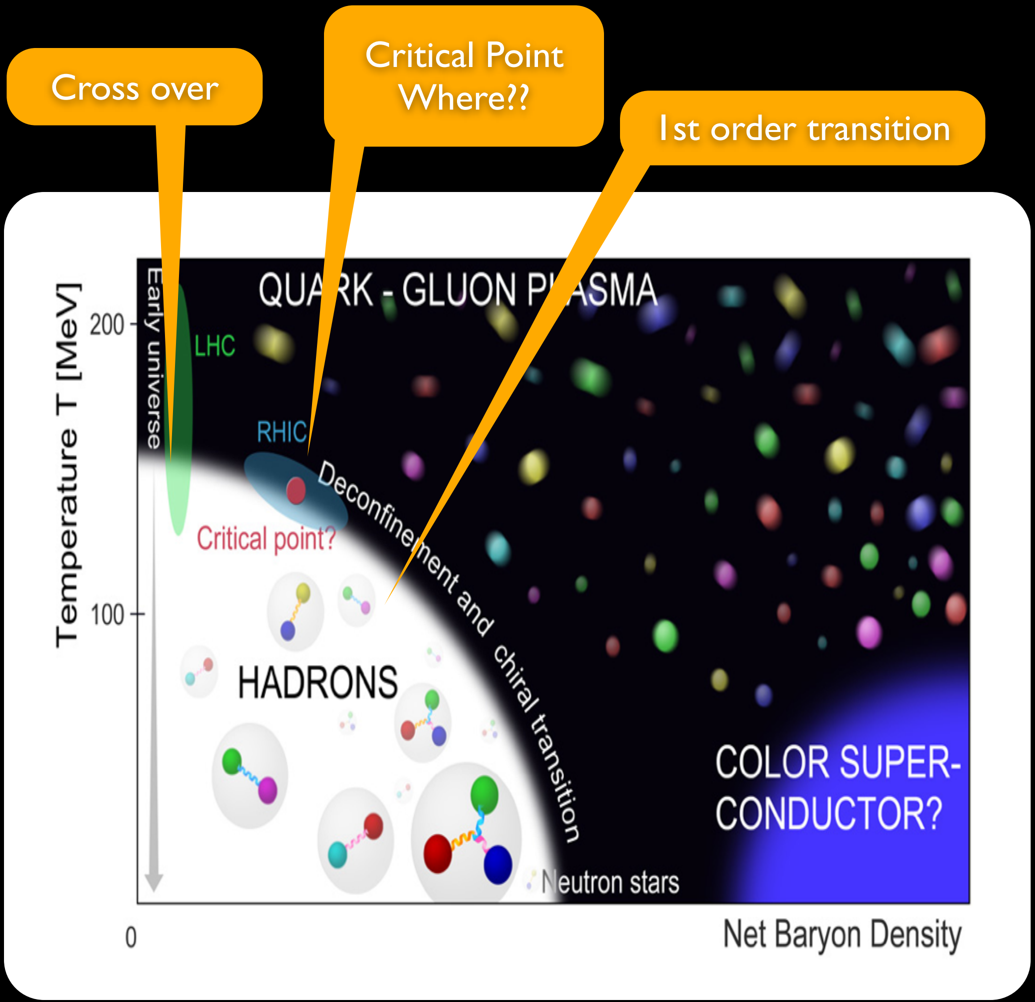
Motivations



Schematic QCD Phase Diagram

Deconfinement:

- Quark Degrees of Freedom
- Suppression of Net Charge Fluctuations
- Parton Energy Loss (Gluon Radiation)
- J/ψ Suppression (Debye Screenning)
- Conical Emission

Critical Point (CP):

- Location unclear!
- Scan phase boundary
- "Divergence" of correlation length ξ near CP
- "Divergence" of pT fluctuations near CP
- Increase Strangeness Production & Fluctuations.

Equation of State (EoS):

- Viscosity
- Heat Capacity
- Flow
- Initial State

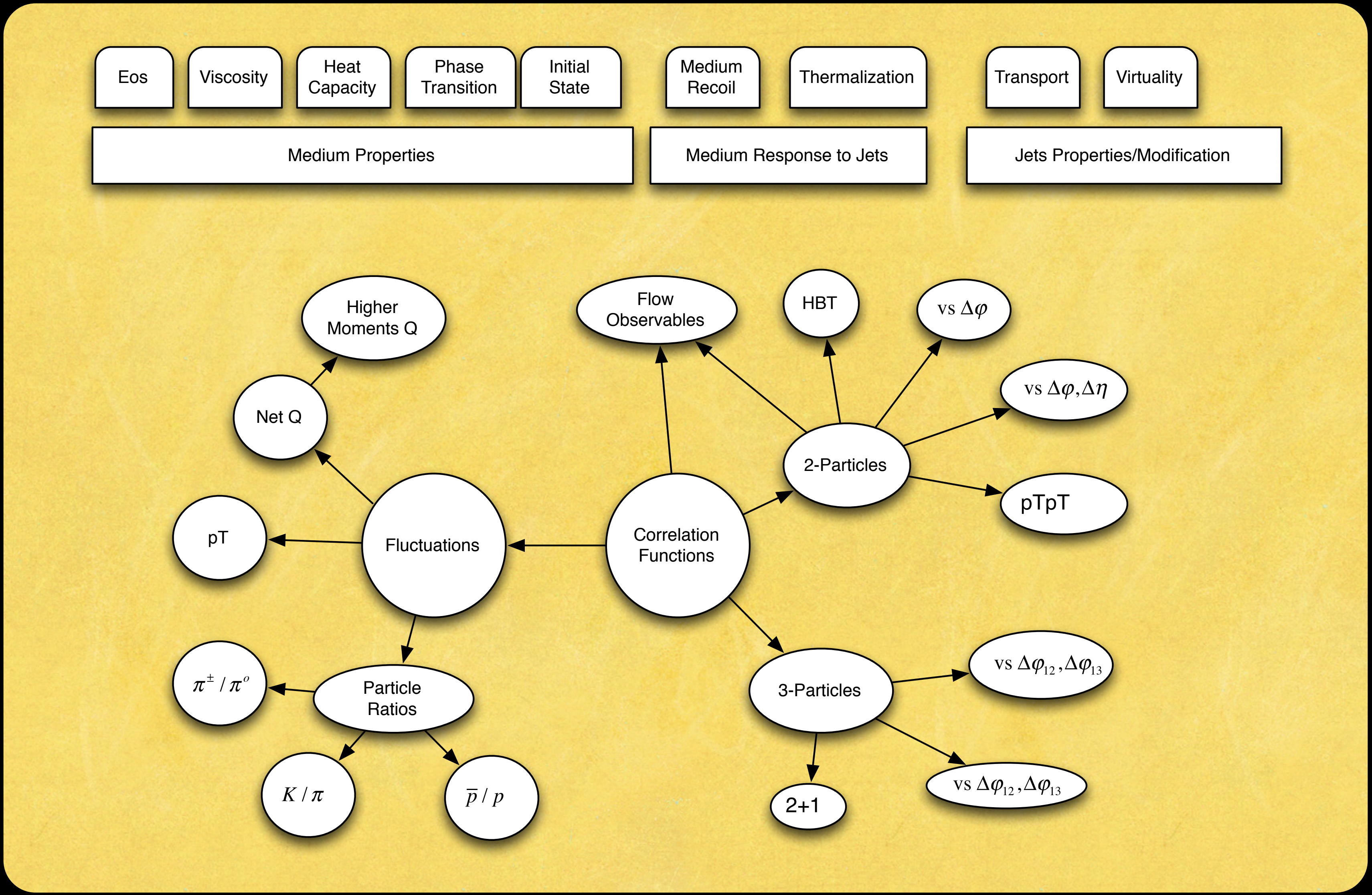
New State of Matter

- DCCs

New Phenomena

- Conical Emission
- Chiral Magnetic Effect

The Multi-facets of Correlations



Deconfinement: Suppression of Net Charge Fluctuations

Koch, Jeon, *et al.*, Asaka *et al.*, Heiselberg *et al.*, and several others:

Expect reduced net charge fluctuation variance in the presence of a QGP.

$$N_{ch} = N_+ + N_-$$

$$Q = N_+ - N_-$$

$$R = \frac{N_+}{N_-}$$

$$\omega_Q = \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle}$$

$$D \equiv \langle N_{ch} \rangle \langle \delta R^2 \rangle = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle} = 4\omega_Q$$

Scenario	ω_Q	D
Free Particles	1	4
Resonance Gas	~0.7	~2.8
QGP	<0.25	<1
QGP+Coalescence		3.3

Dilution of Fluctuations in expanding medium due to diffusion of particles

E.V. Shuryak, M.A. Stephanov, Phys. Rev. C 63, 064903 (2001)

M.A. Aziz, S. Gavin, Phys. Rev. C 70, 034905 (2004).

Collision dynamics

S. Jeon, V. Koch, Phys. Rev. Lett. 85, 2076 (2000).

Radial flow

S. Voloshin, Phys. Lett. B632, 490 (2006).

Resonance decays, final state interactions

J. Zaranek, Phys. Rev. C66 024905 (2002).

The "Conflict" and The Resolution (QM 2004)

Definitions: $Q = N_+ - N_-$ $N_{CH} = N_+ + N_-$ $Variance: \langle \delta X^2 \rangle = \langle X^2 \rangle - \langle X \rangle^2$

Theoretical Prediction: $R = \frac{\langle N_+ \rangle}{\langle N_- \rangle}$ $D \equiv \langle N_{ch} \rangle \langle \delta R^2 \rangle = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{CH} \rangle}$

NA49: $\overline{z^2} = 4\frac{\langle N_+ \rangle \langle N_- \rangle}{\langle N_{CH}{}^2 \rangle}$ $Z = Q - \frac{\langle Q \rangle}{\langle N_{CH} \rangle} N_{CH}$ $\Phi_q = \sqrt{\frac{\langle Z^2 \rangle}{\langle N_{CH} \rangle}} - \sqrt{\overline{z^2}}$

Weak Evidence for finite dynamic net charge fluctuations

PHENIX: $v(Q) \equiv \langle \delta Q^2 \rangle / \langle N_{CH} \rangle$ $D = 4v(Q)$

PHENIX (130 GeV): PRL. 89 (2002) 082301.

STAR: $\nu_{+-,dyn} = \nu_{+-} - \nu_{+-,stat}$ $D \approx 4 + \langle N_+ + N_- \rangle \nu_{+-,dyn}$

Clear Evidence for finite dynamic net charge fluctuations but not for deconfinement

STAR (130 GeV) PRC68, 044905 (2003).

$$\nu_{+-} = \left\langle \left(\frac{N_+}{\langle N_+ \rangle} - \frac{N_-}{\langle N_- \rangle} \right)^2 \right\rangle$$

Poisson Limit →

$$\nu_{+-,stat} = \frac{1}{\langle N_+ \rangle} + \frac{1}{\langle N_- \rangle}$$

Dynamic Fluctuations →

$$\nu_{+-,dyn} = \nu_{+-} - \nu_{+-,stat}$$

Observables Related →

$$\Phi_q \approx \frac{\langle N_+ \rangle^{3/2} \langle N_- \rangle^{3/2}}{\langle N_{CH} \rangle^2} \nu_{+-,dyn}$$

$$v(Q) \approx 1 + \frac{\langle N_+ + N_- \rangle}{4} \nu_{+-,dyn}$$

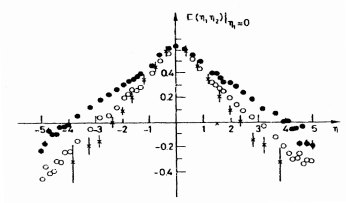
Integral Two-Particle Correlation Measure →

$$\nu_{+-,dyn} = \frac{\langle N_+(N_+-1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_--1) \rangle}{\langle N_- \rangle^2} - 2\frac{\langle N_+ N_- \rangle}{\langle N_+ \rangle \langle N_- \rangle}$$

$$\nu_{+-,dyn} = R_{++} + R_{--} - 2R_{+-}$$

C.P., S.G., S.V., PRC 66, 44904 (2002)
S. Mrowczynski, PRC C66, 024904 (2002).
J. Nystrand, et al., PRC 68, 034902 (2003).

Dynamical Fluctuations and Correlations



FNAL and ISR data.

1-body density $\rho_{1,\alpha}(\eta_\alpha) = \frac{dN}{d\eta_\alpha}$

2-body density $\rho_{2,\alpha\beta}(\eta_\alpha, \eta_\beta) = \frac{d^2N}{d\eta_\alpha d\eta_\beta}$

Differential Correlation

$$C_{\alpha\beta}(\eta_\alpha, \eta_\beta) = \rho_{\alpha\beta}(\eta_\alpha, \eta_\beta) - \rho_\alpha(\eta_\alpha)\rho_\alpha(\eta_\beta)$$

$$R_{\alpha\beta}(\eta_\alpha, \eta_\beta) = \frac{\rho_{\alpha\beta}(\eta_\alpha, \eta_\beta)}{\rho_\alpha(\eta_\alpha)\rho_\beta(\eta_\beta)} - 1$$

Robust Observable

Integral Correlation Fluctuations

$$R_{\alpha\beta}(\eta_\alpha, \eta_\beta) = \frac{\int \rho_{\alpha\beta}(\eta_\alpha, \eta_\beta) d\eta_\alpha d\eta_\beta}{\int \rho_\alpha(\eta_\alpha) d\eta_\alpha \otimes \int \rho_\beta(\eta_\beta) d\eta_\beta} - 1$$

Robust Observable

Net Charge Fluctuations

$$\nu_{+-,dyn} = R_{++} + R_{--} - 2R_{+-}$$

Charge Balance Function

$$B(\Delta\eta) = \frac{N_{+-}}{N_-} + \frac{N_{-+}}{N_+} - \frac{N_{--}}{N_-} - \frac{N_{++}}{N_+}$$

K/Pi Fluctuations (etc)

$$\nu_{K\pi} = \frac{\langle N_\pi (N_\pi - 1)\rangle}{\langle N_\pi \rangle^2} + \frac{\langle N_K (N_K - 1)\rangle}{\langle N_K \rangle^2} - 2\frac{\langle N_{K\pi}\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

Extensions to pT fluctuations, higher moments, and multi-particle correlation functions.

Dynamical Fluctuations Properties

Independent of volume fluctuations

$$\nu_{+-,dyn} = R_{++} + R_{--} - 2R_{+-}$$

Independent Particle Production

$$\nu_{+-,dyn} = 0$$

Superposition of "p-p"

$$\langle N(b)\rangle \upsilon_{+-,dyn}(b) = \text{constant}$$

$$\left\langle \frac{dN}{dy} \right\rangle_{AA} \upsilon_{AA,dyn} = \left\langle \frac{dN}{dy} \right\rangle_{pp} \upsilon_{pp,dyn}$$

Robust Observable
(Independent of efficiency)

$$R_{aa} = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2} = \frac{\varepsilon^2\langle N^2\rangle + \varepsilon(1-\varepsilon)\langle N\rangle - \varepsilon\langle N\rangle}{\varepsilon^2\langle N\rangle^2} = \frac{\langle N(N-1)\rangle}{\langle N\rangle^2}$$

Charge Conservation

$$\nu_{+-,dyn} = -\frac{2}{\langle N_+\rangle_{4\pi}} \approx -\frac{4}{\langle N\rangle_{4\pi}}$$

Perfect $N_+ = N_-$ correlation

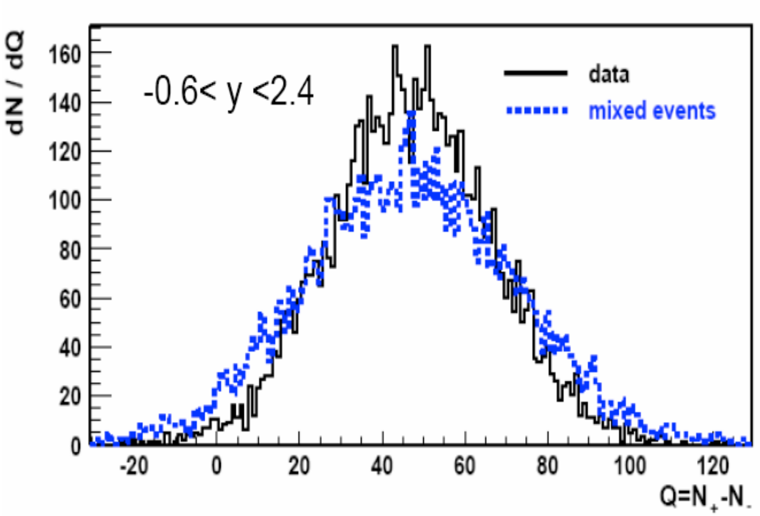
$$\nu_{+-,dyn} = -4/\langle N\rangle_\eta$$

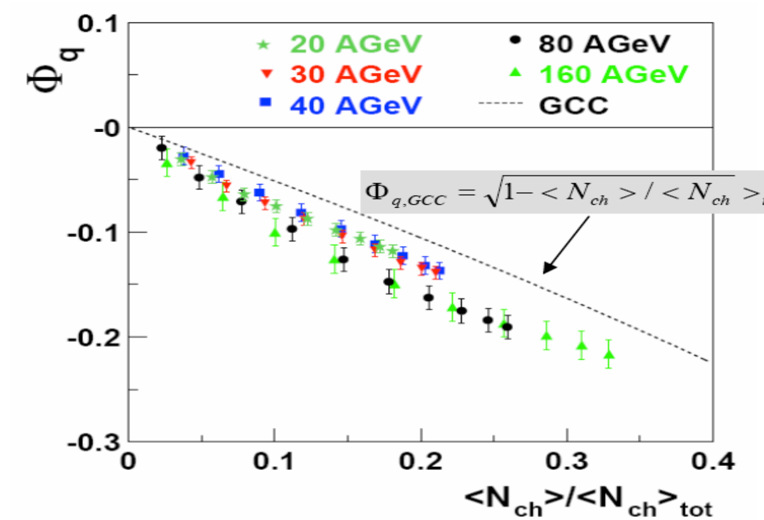
First Measurement

$$\Phi_q = \sqrt{\frac{< Z^2 >}{< N >}} - \sqrt{\overline{z^2}}$$

$$z = q - \overline{q} \qquad Z = \sum_{i=1}^{N} (q_i - \overline{q})$$

Central Pb+Pb collisions 158A GeV



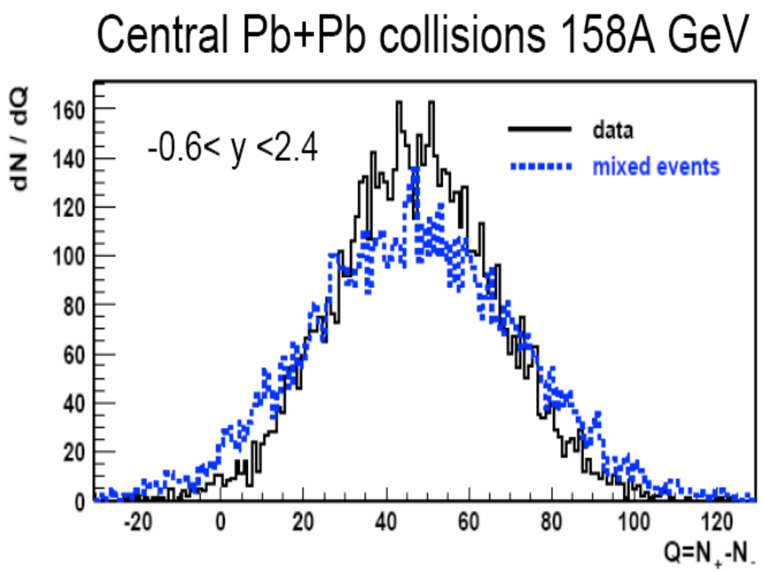


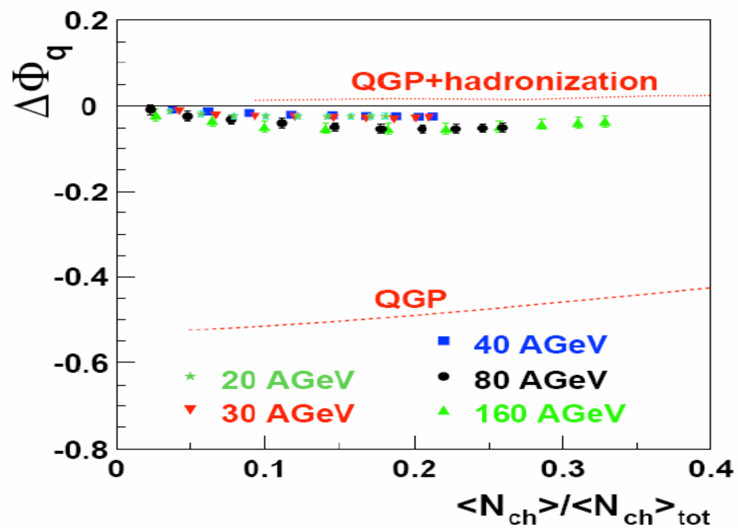
- Weak Evidence for dynamical correlations
- But NO Evidence for QGP Formation

First Measurement

$$\Phi_q = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{\overline{z^2}}$$

$$z = q - \bar{q} \qquad Z = \sum_{i=1}^{N} (q_i - \bar{q})$$





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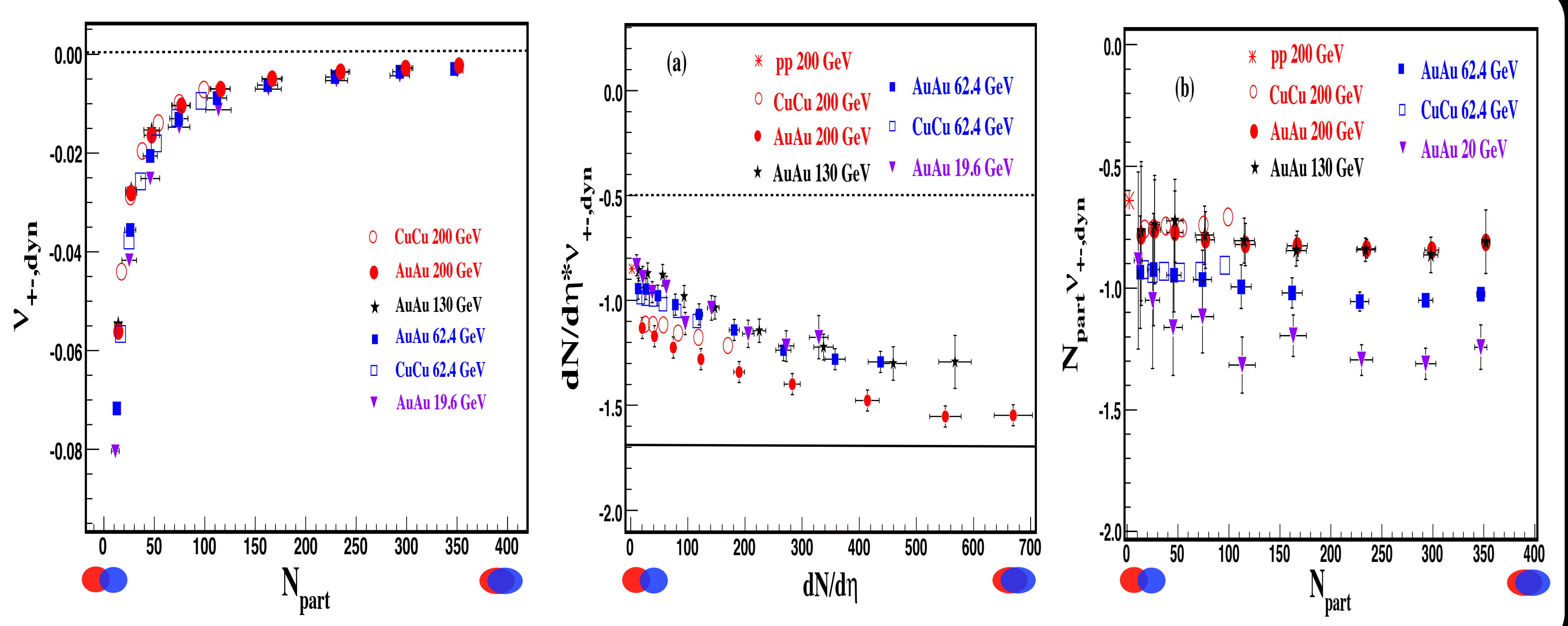
Net Charge Dynamical Fluctuations

Au- Au vs centrality, vs beam energy

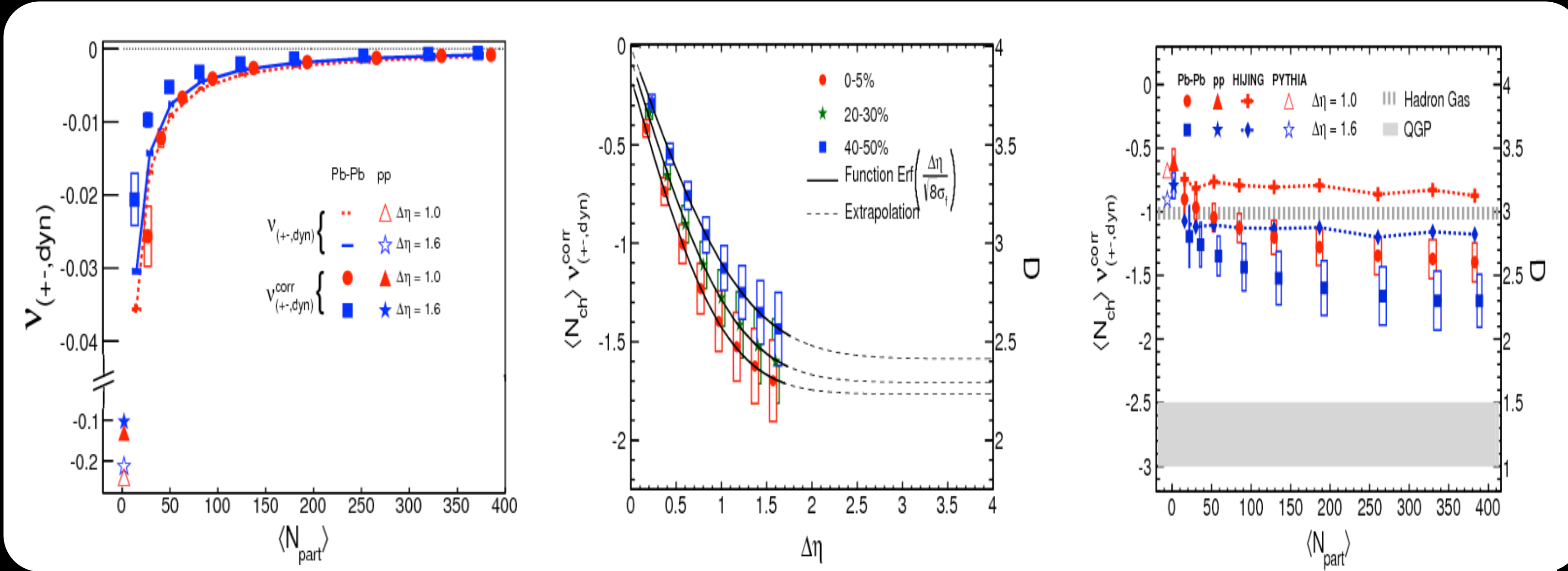
STAR TPC: |η|<0.5; 0.2 < pt < 5.0 GeV/c



C.P., M. Sharma
STAR, PRC 79 (2009) 024906

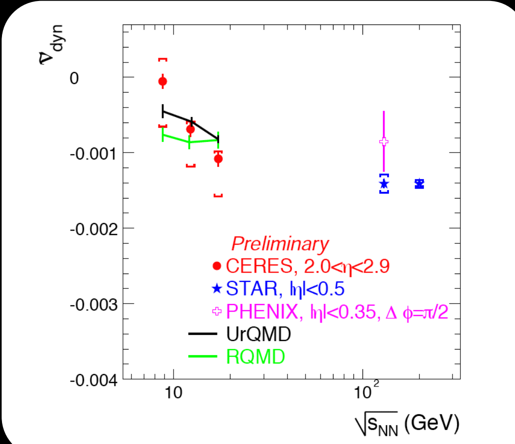
- Evidence for dynamic fluctuations
- Non trivial centrality dependence
- BUT No deconfinement signal

Net Charge Dynamical Fluctuations: ALICE

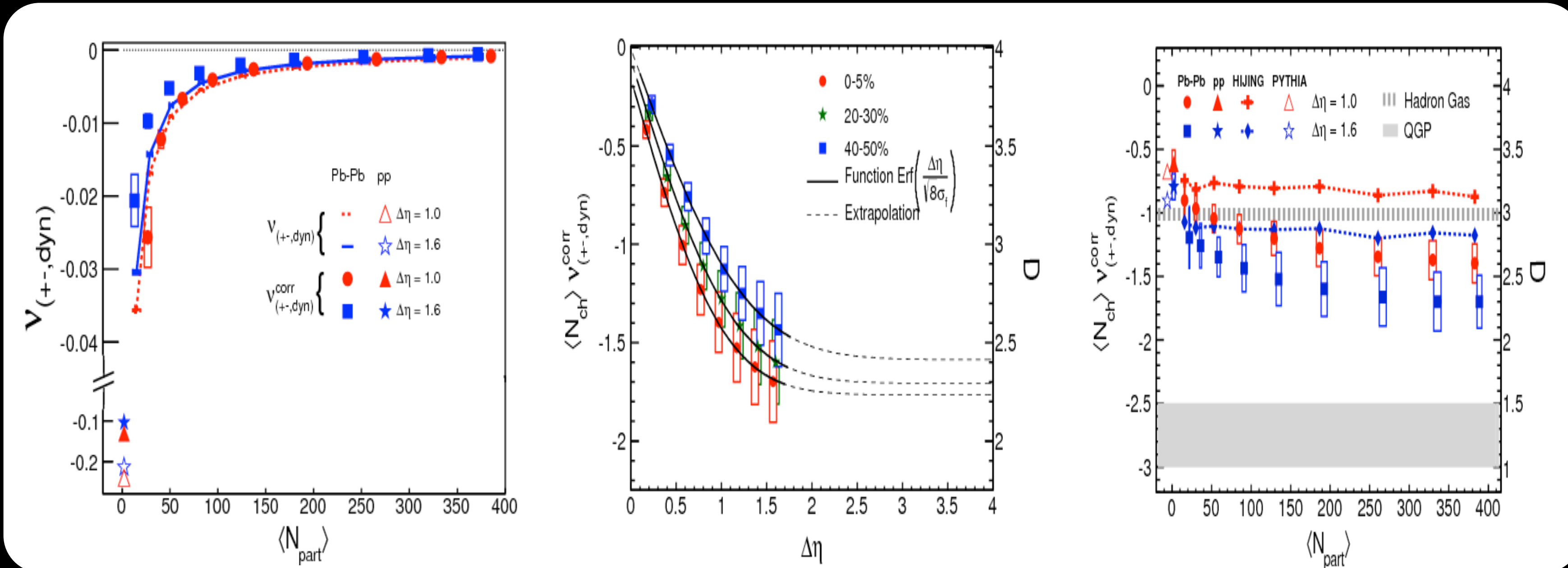


ALICE, Phys.Rev.Lett. 110 (2013) 152301

- Fluctuations suppressed w.r.t. RHIC
- Cannot be explained by radial flow alone
- Clear tendency towards QGP Prediction
- Origin in QGP Phase (?)



Net Charge Dynamical Fluctuations: ALICE



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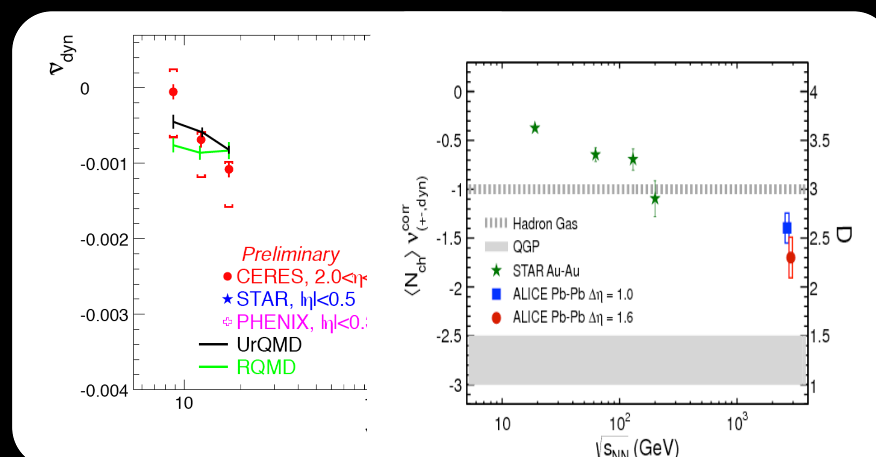
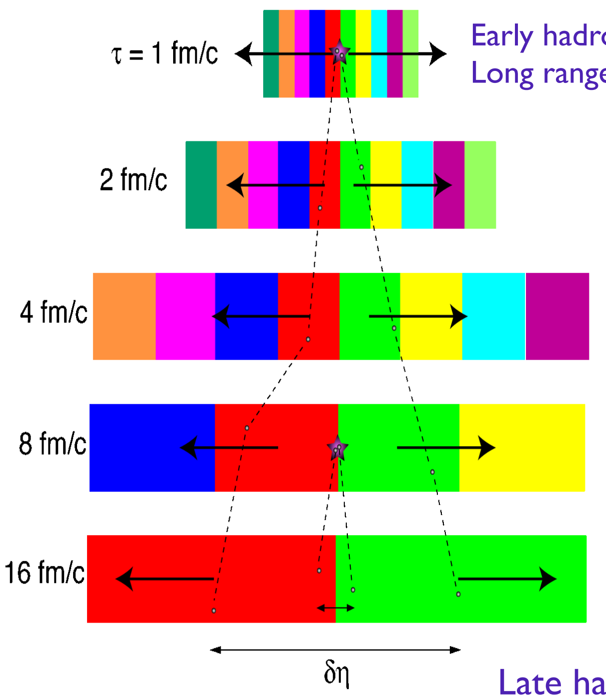


Charge Balance Function

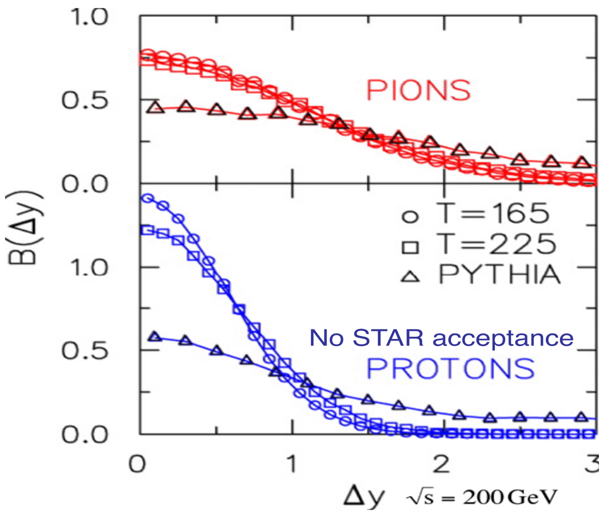
Bass, Danielewicz, and Pratt, PRL **85**, 2689 (2000)

Deconfinement:

Delayed Hadronization → Narrowing of Balance Function



Early hadronization:
Long range correlations



$$B(\Delta\eta)=\frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta)}{N_{-}}+\frac{N_{-+}(\Delta\eta)}{N_{+}}-\frac{N_{--}(\Delta\eta)}{N_{-}}-\frac{N_{++}(\Delta\eta)}{N_{+}}\right\}$$

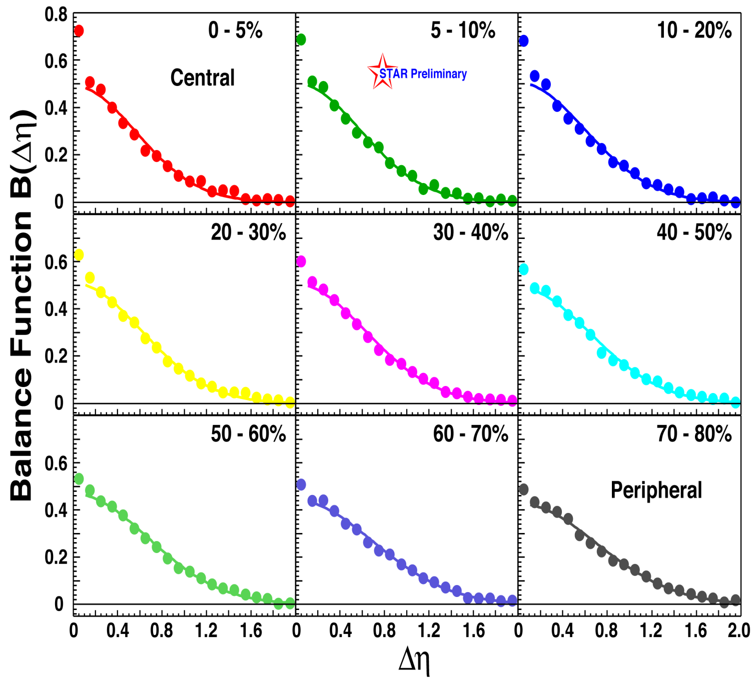
Late hadronization:
Short range correlations

$$\sigma_{\delta y}^2=\sigma_{\delta\eta}^2+\sigma_{thermal}^2$$

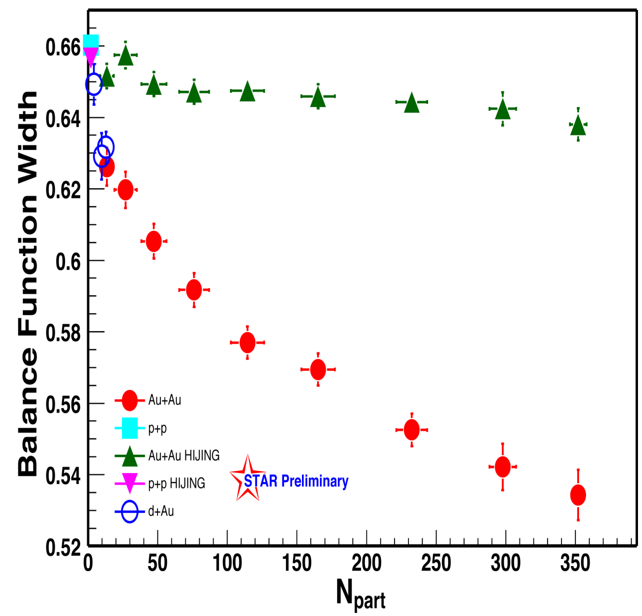
Charge Balance Function

STAR, PRL **90** (2003) 172301

Au + Au sqrt(s_{NN}) = 130 GeV



$$B(\Delta\eta)=\frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta)}{N_{-}}+\frac{N_{-+}(\Delta\eta)}{N_{+}}-\frac{N_{--}(\Delta\eta)}{N_{-}}-\frac{N_{++}(\Delta\eta)}{N_{+}}\right\}$$

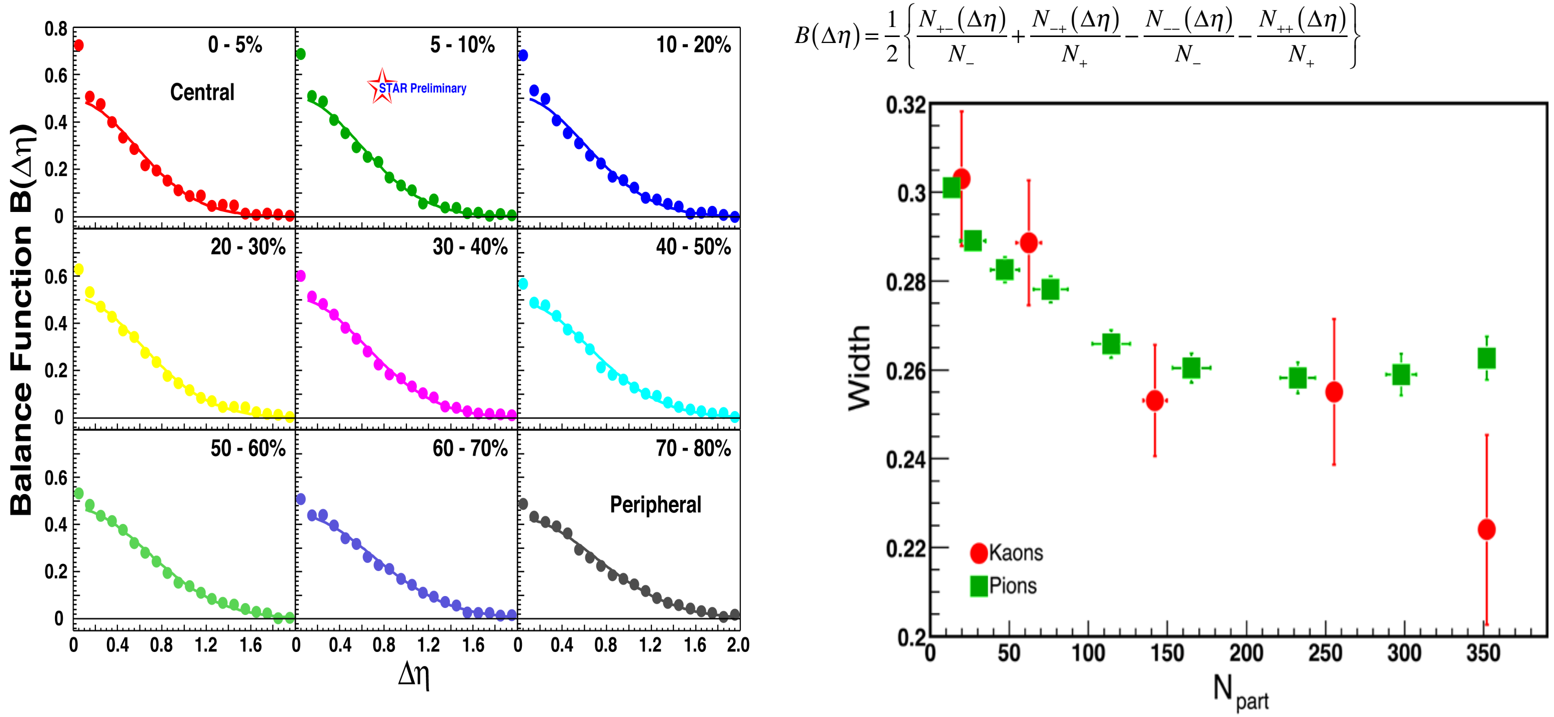


- Narrowing of Balance Function
- Observed for all charges, pions, and kaons
- Also observed at 200 GeV
- Consistent w/ Delayed Hadronization

Charge Balance Function

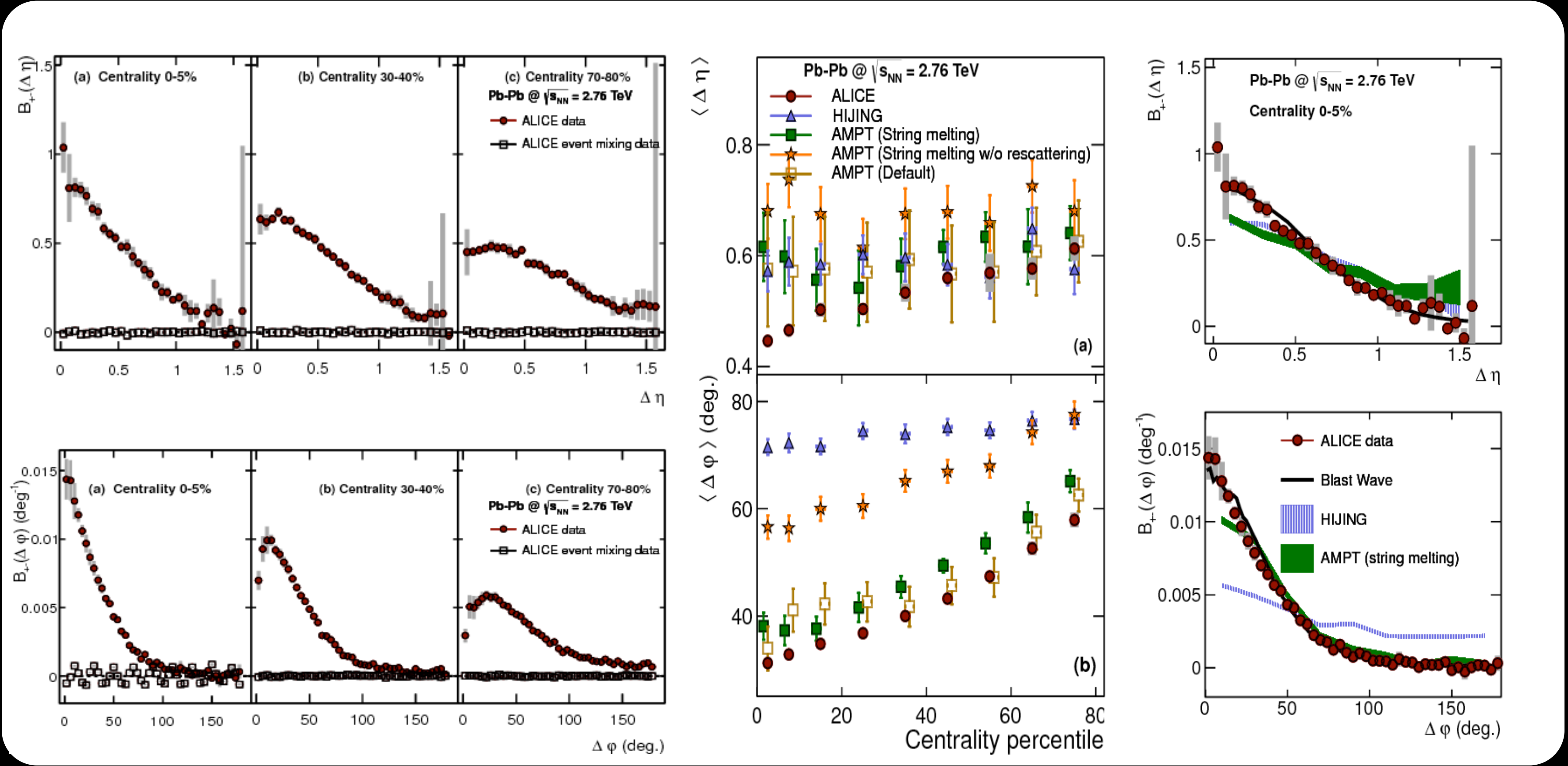
STAR, PRL **90** (2003) 172301

Au + Au sqrt(s_{NN}) = 130 GeV



- Narrowing of Balance Function
- Observed for all charges, pions, and kaons
- Also observed at 200 GeV
- Consistent w/ Delayed Hadronization

Charge Balance Function
Pb-Pb @ 2.76 TeV



ALICE, Phys. Lett. B 723 (2013) 267-279

- Narrowing of Balance Function Observed for all charges,
- Consistent w/ Delayed Hadronization, production of a deconfined phase of matter

Higher Moments

- Static, infinite medium: Correlation length ξ diverges near CP
- Related to moments of net charge, net baryon number, and net strangeness
  - M. A. Stephanov et al., Phys. Rev. D 60, 114028 (1999).
- Finite size and finite lifetime suppress ξ but it might be as large as 2-3 fm in heavy-ion collisions.
  - B. Berdnikov et al., Phys. Rev. D 61, 105017 (2000).
  - M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009);
  - K. Rajagopal and M. A. Stephanov, private comm. 2009.
  - M. Asakawa et al., Phys. Rev. Lett. 103, 262301 (2009).

$$\sigma^2 = \left\langle \Delta N^2 \right\rangle \propto \xi^2$$
$$\left\langle \Delta N^3 \right\rangle \propto \xi^{4.5}$$
$$\left\langle \Delta N^4 \right\rangle \propto \xi^7$$

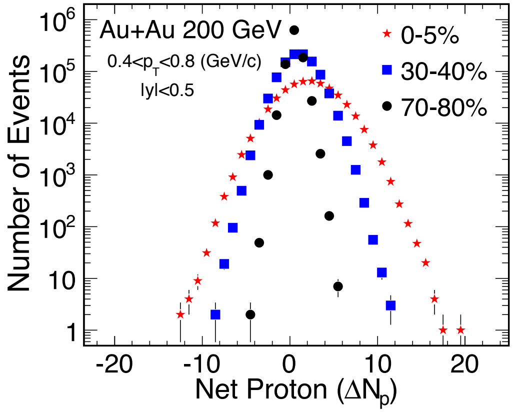
→

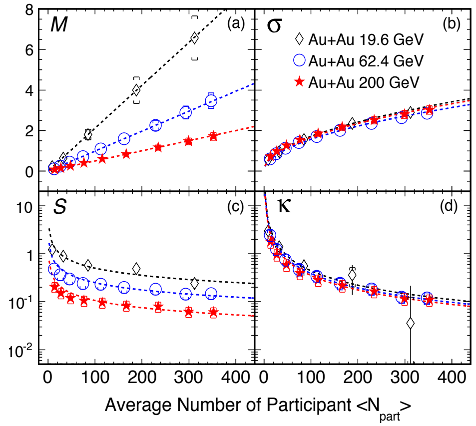
$$S = \gamma_1 = \frac{\left\langle \Delta N^3 \right\rangle}{\sigma^3} \propto \frac{\xi^{4.5}}{\xi^3} = \xi^{1.5}$$
$$\kappa = \gamma_2 = \frac{\left\langle \Delta N^4 \right\rangle}{\sigma^4} - 3 \propto \frac{\xi^7}{\xi^4} = \xi^3$$

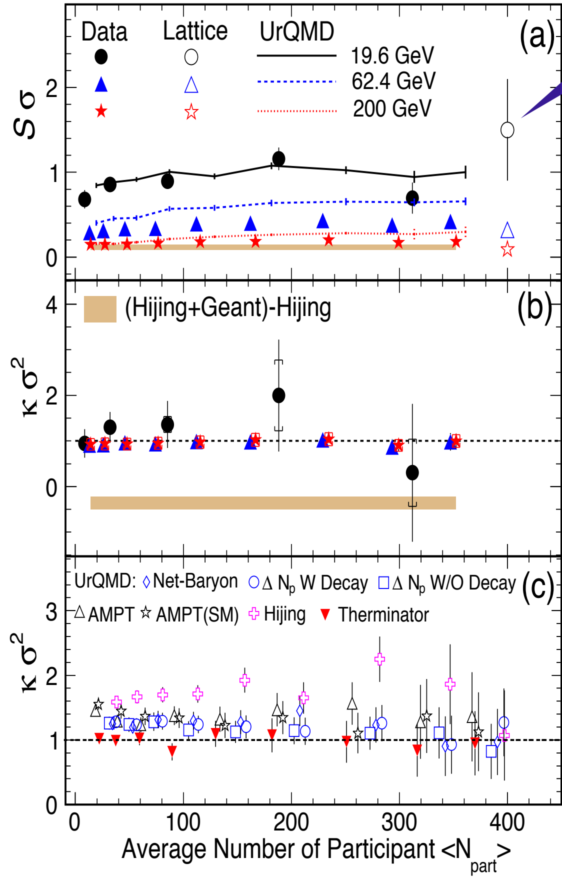
Measurements of excess skewness and kurtosis

- Lattice Calculations: Moments of net-baryon related to baryon number susceptibilities $\chi_B = \frac{\left\langle (\Delta N_B)^2 \right\rangle}{VT}$
- $\kappa\sigma^2$ ~ ratio of fourth order, $\chi_B^{(4)}$, to second order $\chi_B^{(2)}$, large deviation from unity near CP.

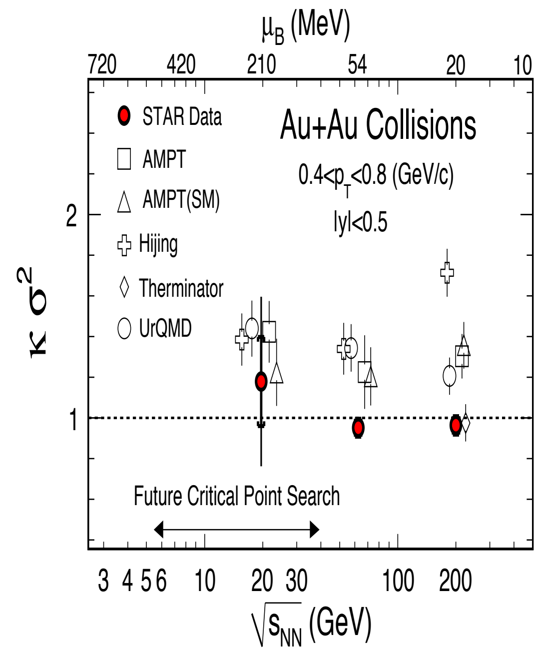
Higher Moments of Net Proton Fluctuations







w/ critical point



STAR, Phys. Rev. Lett. **105** (2010) 22302

S. Ejiri, et al., PRD, 78 (2008) 074507
M.A. Stephanov, Prog. Th. Phys. Suppl. 153 (2004) 139
Z. Fodor, S.D. Katz, JHEP 0404 (2004) 50.
R.V. Gavai, S. Gupta,
N.R. Sahoo, et al., Phys.Rev. C87 (2013) 044906
RBC-Bielefeld, Nucl.Phys. A830 (2009) 705C-708C

Interesting Data! But ....
Need better precision, extended energy range

Higher Moments: Cautionary Notes

- Efficiency Dependencies
  - and similarly for higher order terms...

$$\frac{Var[n]}{\langle n\rangle^2} = \frac{\langle n^2\rangle - \langle n\rangle^2}{\langle n\rangle^2} = \frac{\langle N(N-1)\rangle}{\langle N\rangle^2} - 1 + \frac{1}{\varepsilon\langle N\rangle}$$

- Suggests the use of ratios of factorial moments instead of skewness or kurtosis
- e.g.

$$\frac{\langle N(N-1)\rangle}{\langle N\rangle^2} \qquad \frac{\langle N(N-1)(N-2)\rangle}{\langle N\rangle^3} \qquad \frac{\langle N(N-1)(N-2)\rangle}{\langle N(N-1)\rangle^{3/2}} \qquad \frac{\langle N(N-1)(N-2)(N-3)\rangle}{\langle N(N-1)\rangle^2}$$

- A - A collisions likely to behave as a superposition of sources
- Implies Dilution Effects (Superposition of m sources):

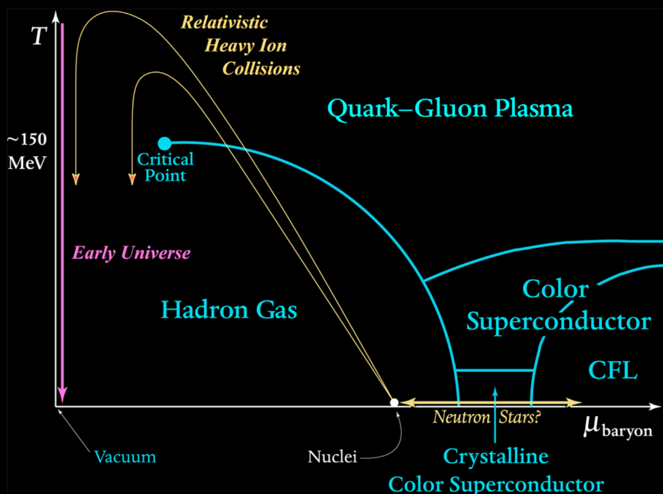
$$\rho_1^{(m)} = \langle m\rangle \rho_1^{(1)}$$
$$\rho_2^{(m)} = \langle m\rangle \rho_2^{(1)} + \langle m(m-1)\rangle \rho_1^{(1)}\rho_1^{(1)}$$
$$\rho_3^{(m)} = \langle m\rangle \rho_3^{(1)} + \langle m(m-1)\rangle \rho_2^{(1)}\rho_1^{(1)} + \langle m(m-1)(m-2)\rangle \rho_1^{(1)}\rho_1^{(1)}\rho_1^{(1)}$$
$$\rho_4^{(m)} = \langle m\rangle \rho_4^{(1)} + \langle m(m-1)\rangle \rho_3^{(1)}\rho_1^{(1)} + \langle m(m-1)\rangle \rho_2^{(1)}\rho_2^{(1)} + \langle m(m-1)(m-2)\rangle \rho_2^{(1)}\rho_1^{(1)}\rho_1^{(1)} + \langle m(m-1)(m-2)(m-3)\rangle \rho_1^{(1)}\rho_1^{(1)}\rho_1^{(1)}\rho_1^{(1)}$$

- "Signal" $\frac{\rho_4^{(m)}}{\left(\rho_1^{(m)}\right)^4} \propto \frac{1}{\langle m\rangle^3} \frac{\rho_4^{(1)}}{\left(\rho_1^{(1)}\right)^4}$

- Suggests the use of 3rd and 4th order cumulants...

K/π Fluctuations

Observation of enhanced Kaon to Pion yield at sqrt(s) ~7 GeV/u

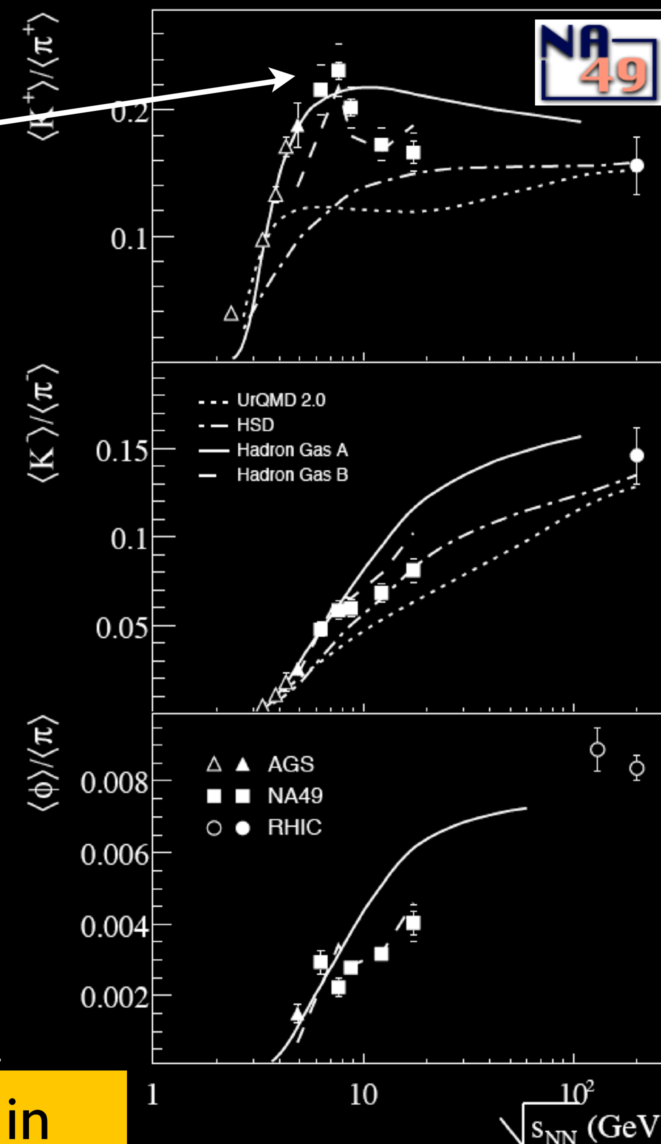


Production of strangeness may be related to the onset of deconfinement

"Event-by-event fluctuations of particle ratios related to the hadro-chemical composition of the particle source could provide a direct probe of the existence and nature of the phase transition."

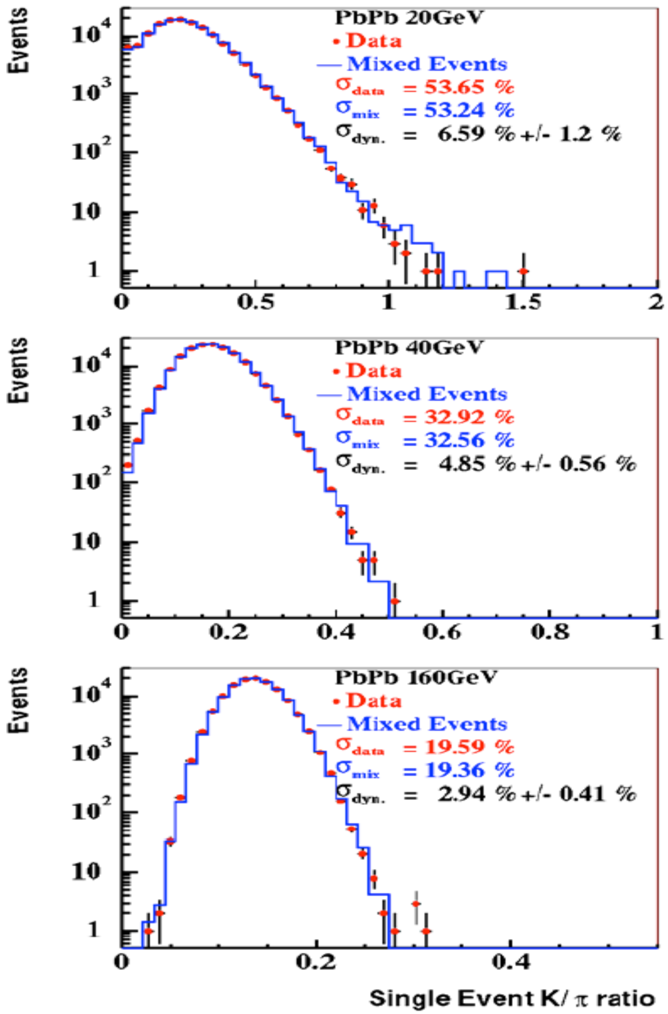
R. Stock, Nature 337 (1989) 319.

Seek evidence for abnormal fluctuations in the relative K to π yields



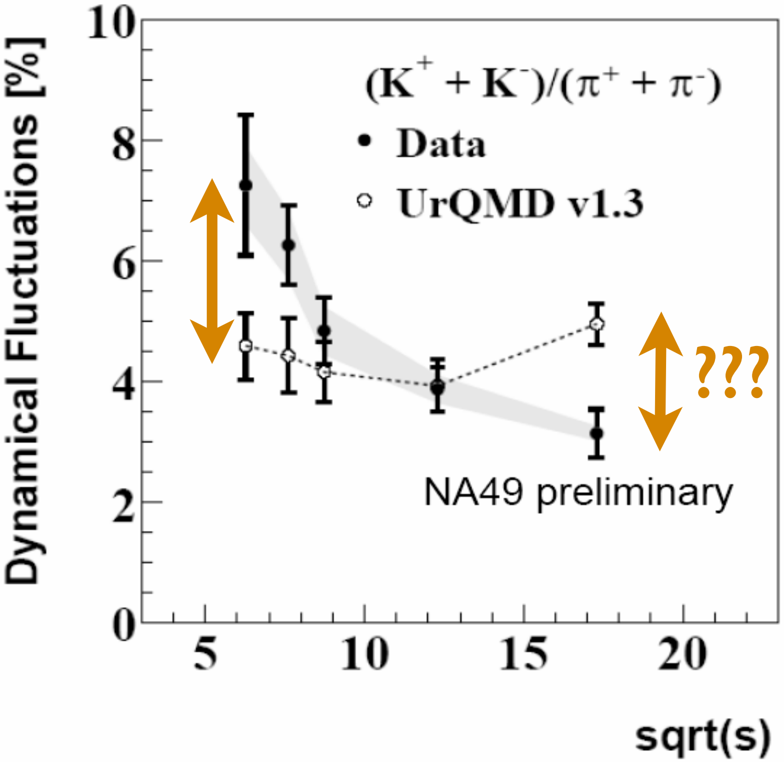
C. Blume (NA49), hep-ph/0505137

K/π Fluctuations



Pion and kaon yields obtained e-by-e from a maximum Likelihood Fit for each event

$$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$$

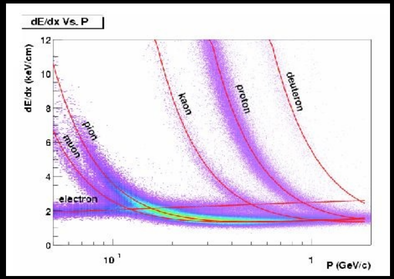


P. Seyboth for NA49 @ Hirschegg, 16-22/1/05.

K/π Fluctuations

STAR, Phys. Rev. Lett. 103, 092301 (2009)

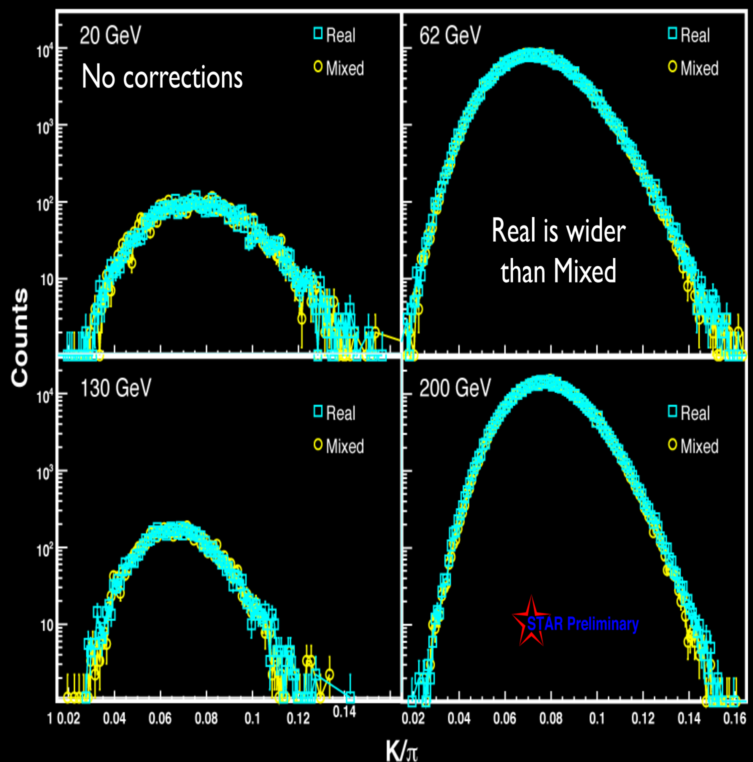
- PID based on TPC dE/dx:
- Measurements:
  - E-by-E Kaon to Pion yields ratio
  - Measure integral correlations

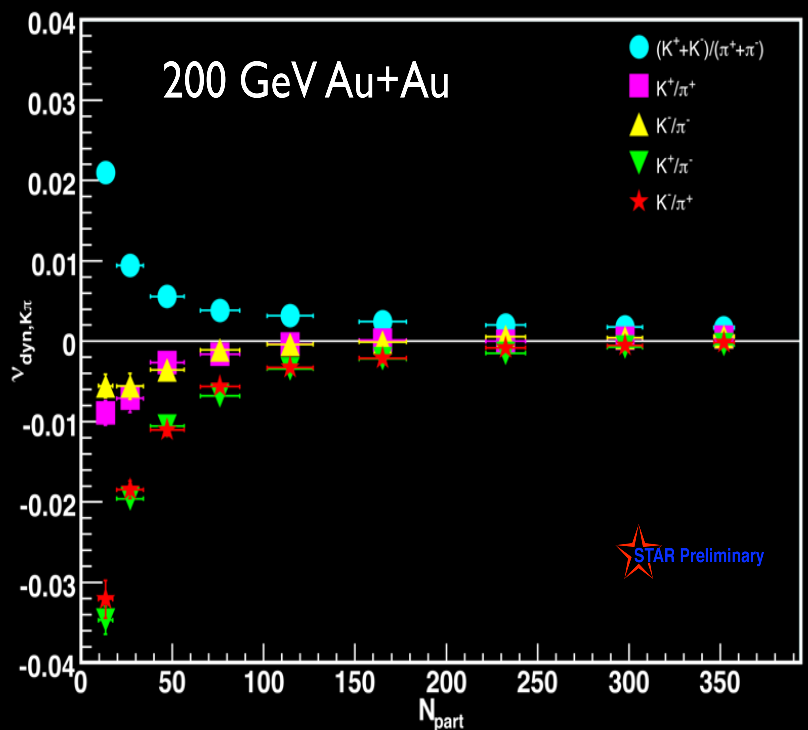


M. Anderson et al. NIMA499 (2003)

$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$

$$\nu_{K\pi} = \frac{\langle N_\pi (N_\pi - 1)\rangle}{\langle N_\pi \rangle^2} + \frac{\langle N_K (N_K - 1)\rangle}{\langle N_K \rangle^2} - 2\frac{\langle N_{K\pi}\rangle}{\langle N_K \rangle \langle N_\pi \rangle}$$

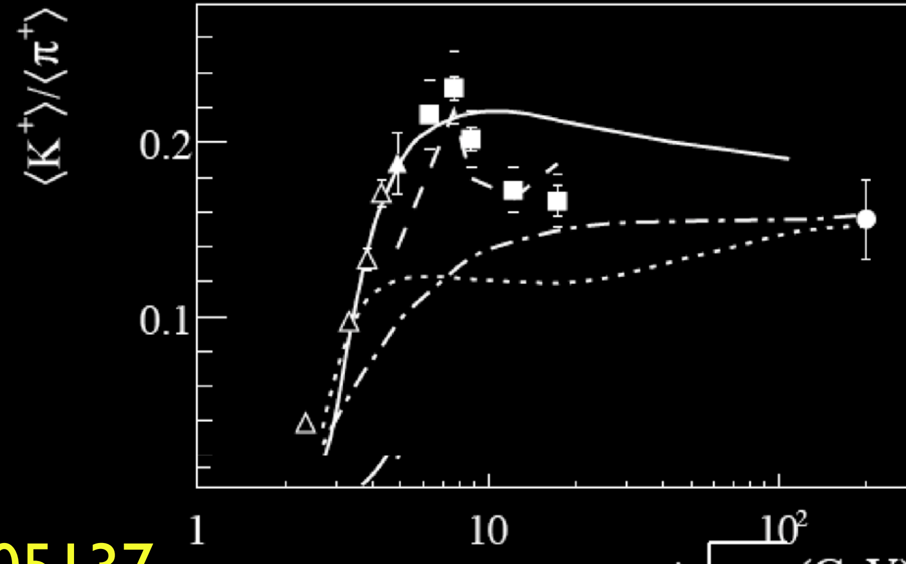


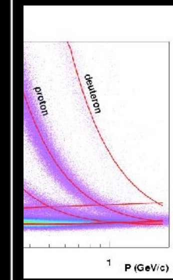


K/π Fluctuation

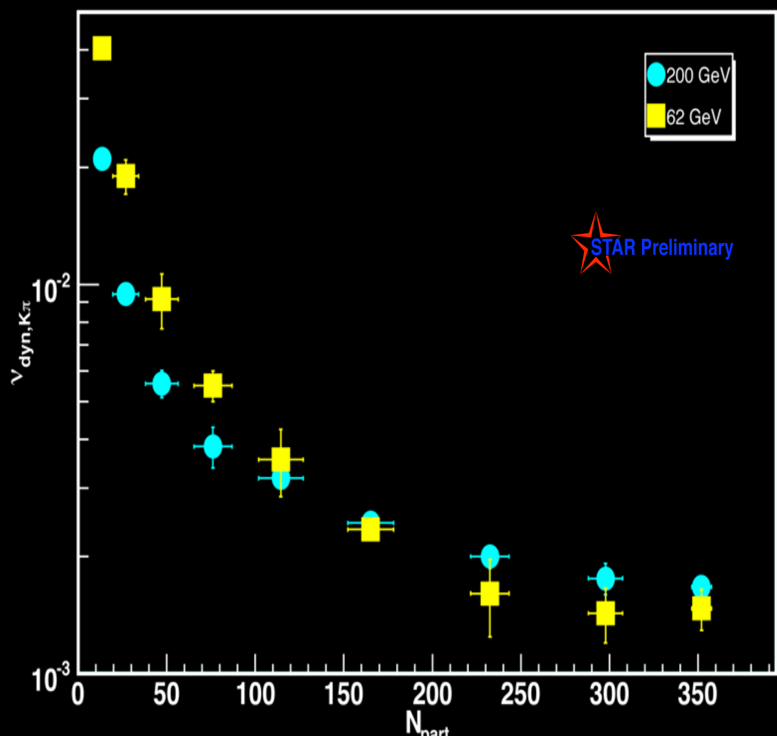
STAR, Phys. Rev. Lett. 103, 092301 (2009)

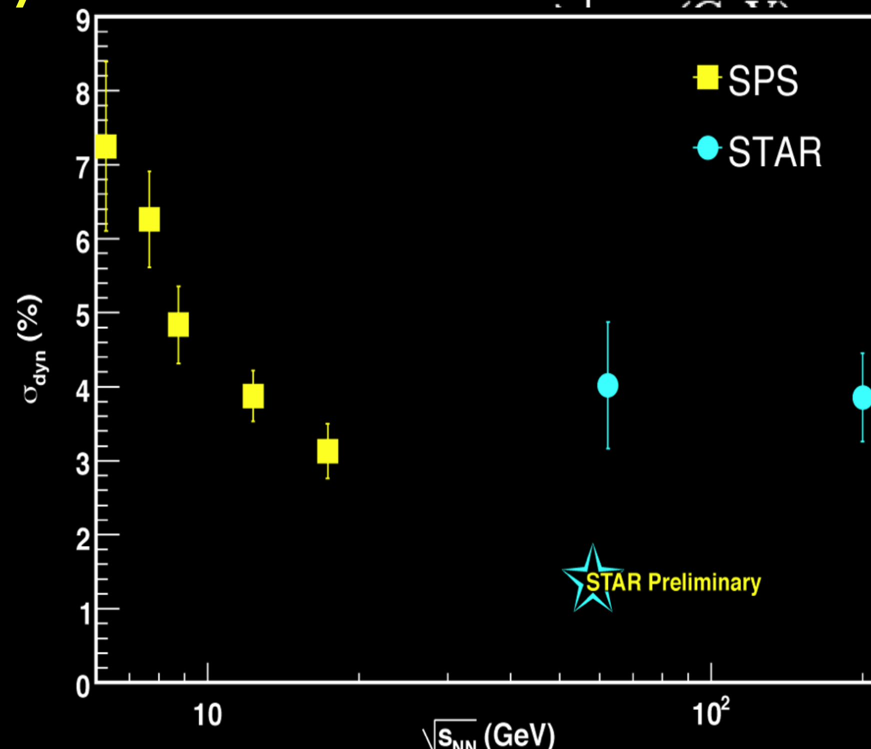
- PID based on TPC dE/dx:
- Measurements:
  - E-by-E Kaon to Pion yields ra
  - Measure integral correlations





IMA499 (2003)





K/π Fluctuation

STAR, Phys. Rev. Lett. 103, 092301 (2009)

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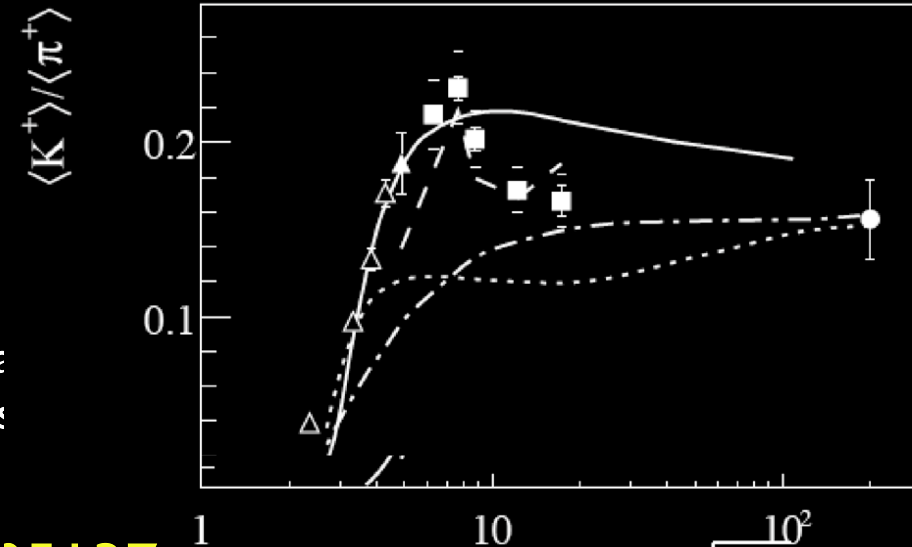
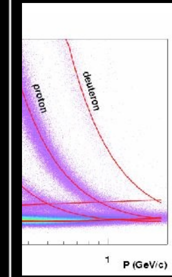
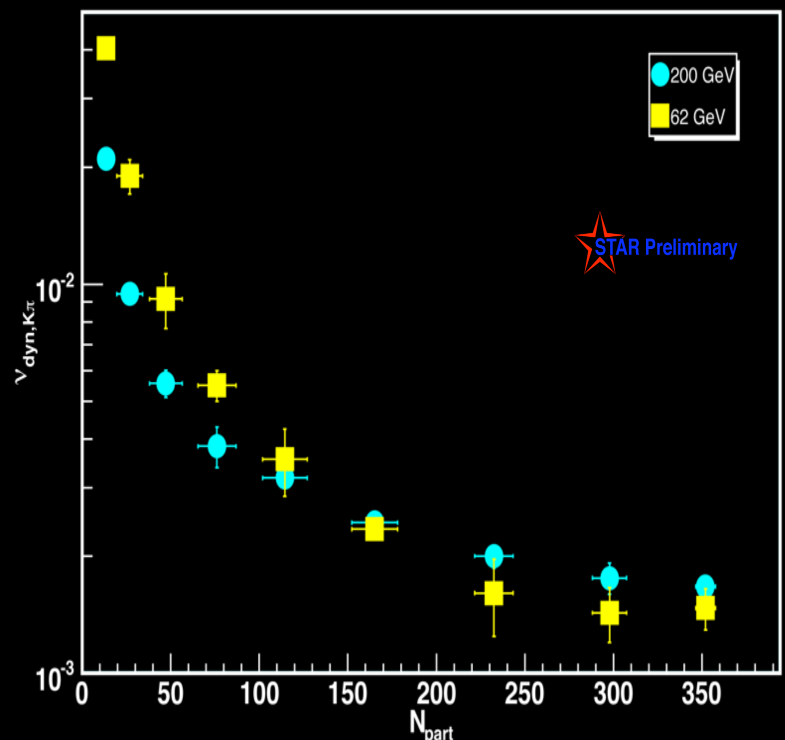
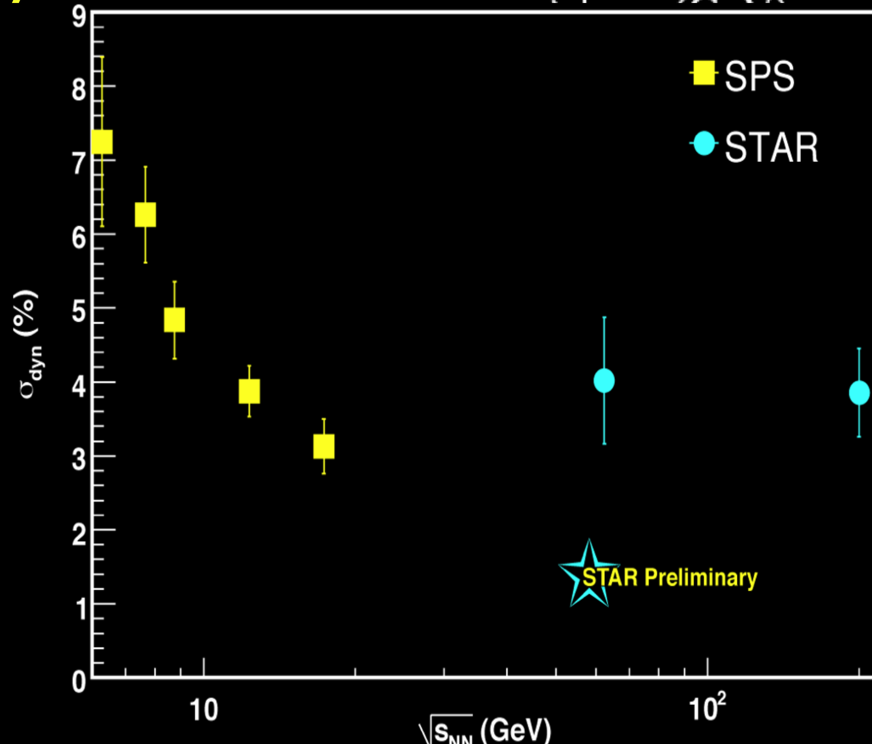




IMA499 (2003)





K/π Fluctuation

STAR, Phys. Rev. Lett. 103, 092301 (2009)

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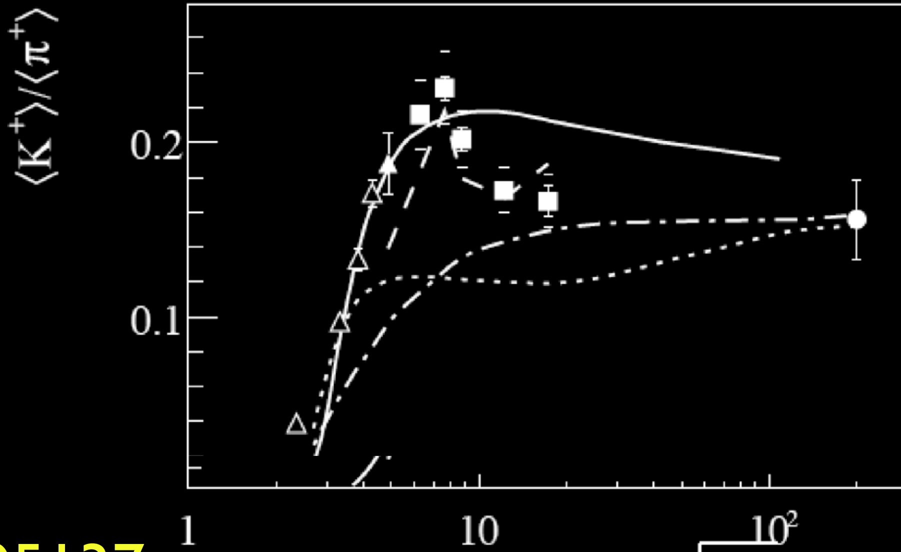
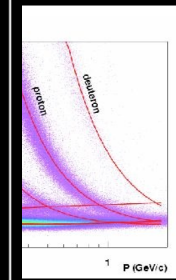
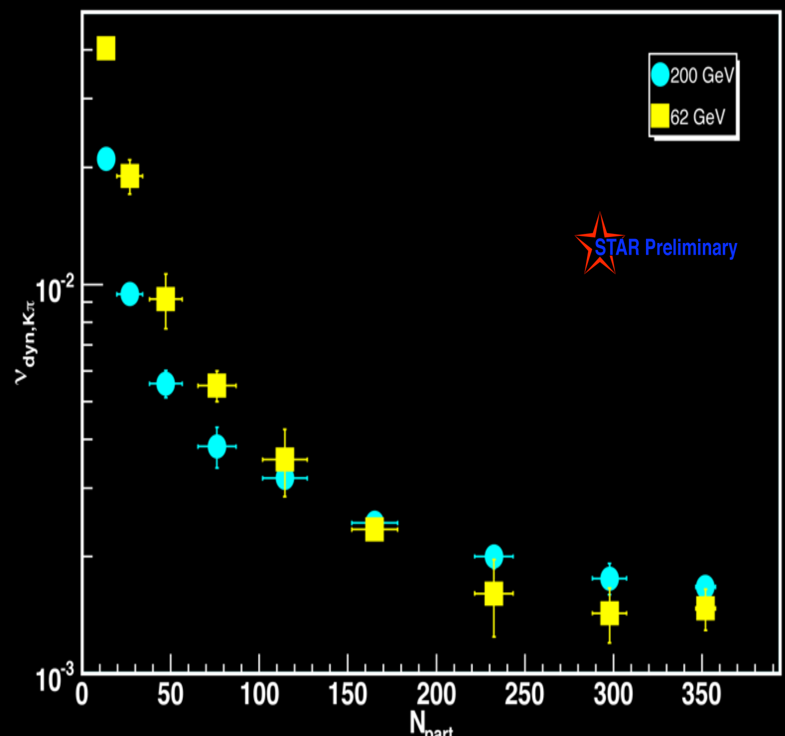
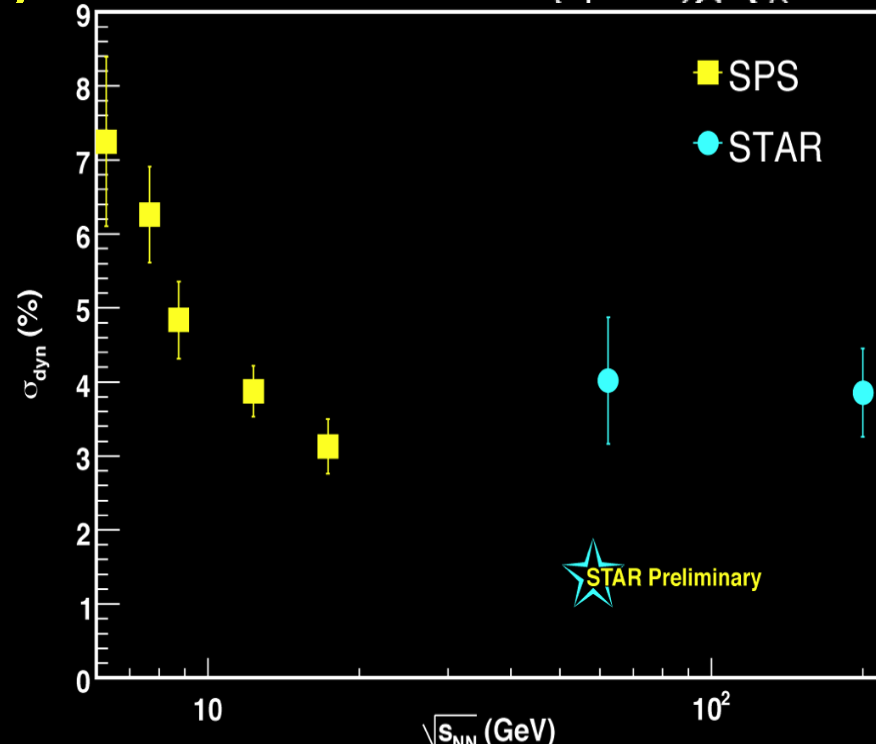


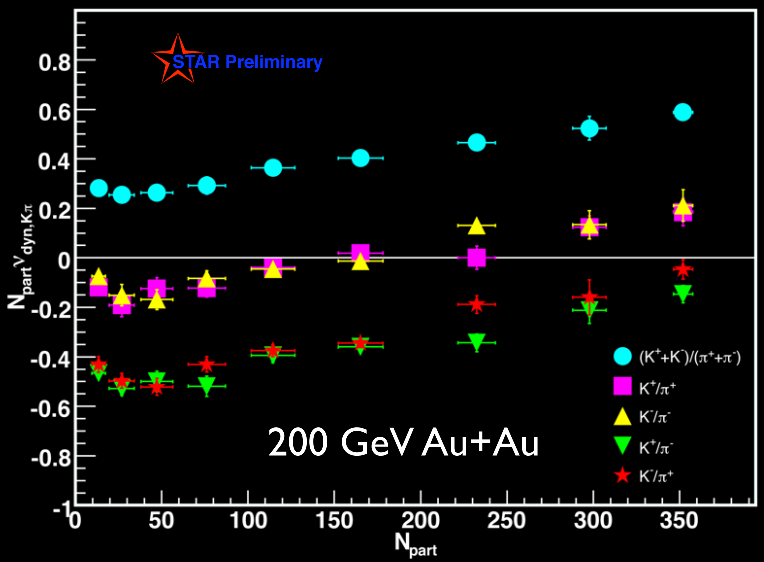


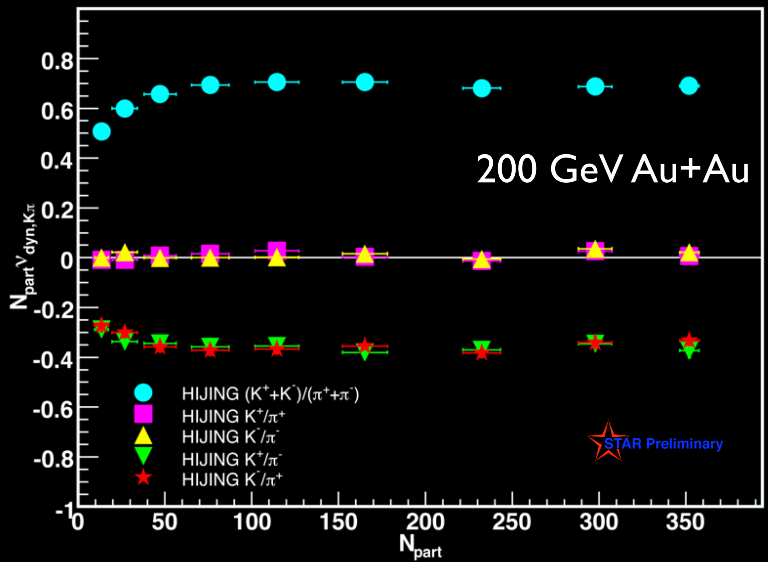
IMA499 (2003)

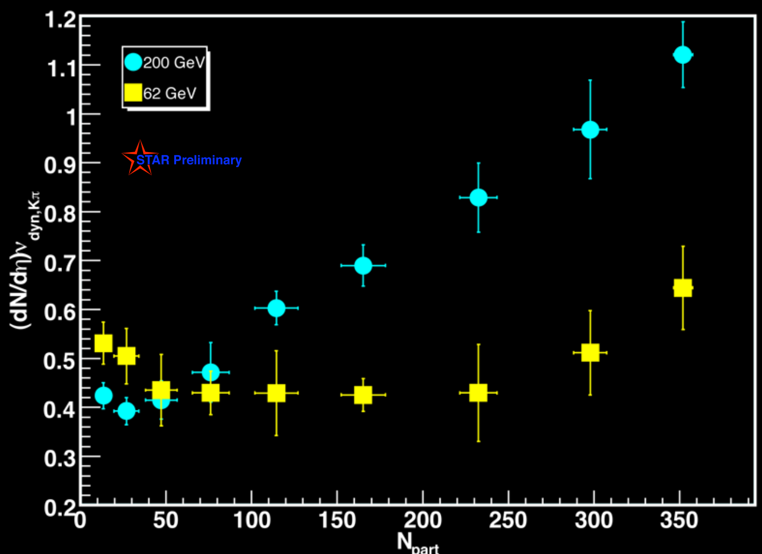




K/π Fluctuations







- Resonance decays (feed down) complicate the interpretation of k/pi fluctuations results.
- Nonetheless, "medium" effects are clearly observed.
- Provide good testing grounds for particle production models.

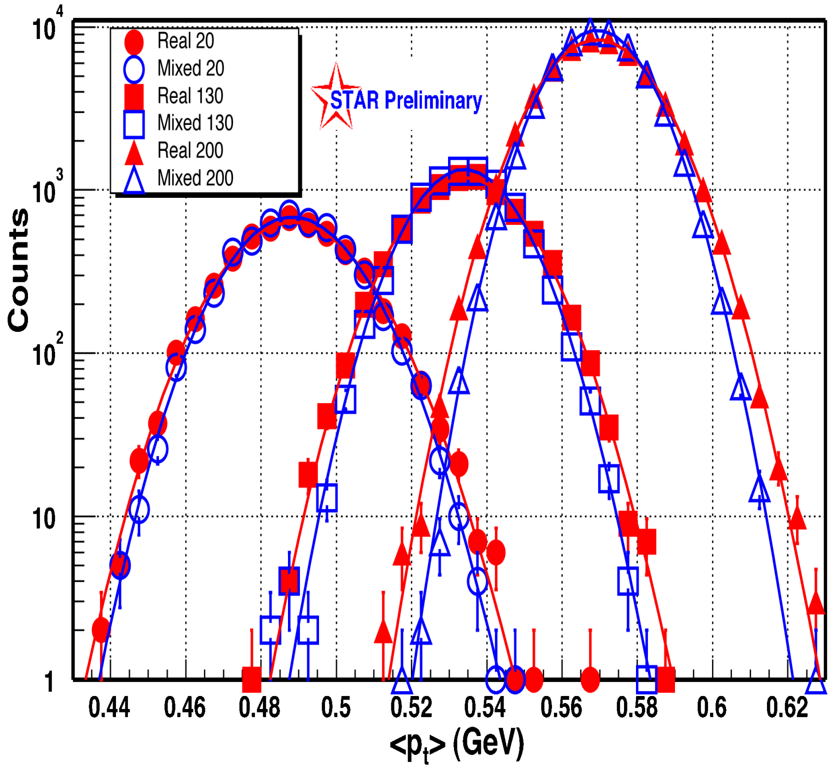
STAR, Phys. Rev. Lett. 103, 092301 (2009)

Pt Fluctuations

- Probe of phase instabilities near QCD phase boundary
  - H. Heiselberg, Phys. Rep. 351 (2001) 161
  - M. Stephanov et al. PRL 81 (1998) 4816; PRD 60 (1999) 114028.
- Onset of thermalization
  - S. Gavin, PRL 92 (2004) 162301.
- Main Measurements
  - NA49, Phys. Lett B459 (1999) 679.
  - CERES, Nucl. Phys. A727 (2003) 97.
  - STAR, PRC 71 (2005) 064906.
  - PHENIX, PRL 93 (2004) 092301.
  - ALICE (analysis in progress?)

pT Fluctuations

- Au - Au Collisions



0 - 5 % central ; $|\eta| < 1.0$

<pT> measured e-by-e

Real is wider than mixed

$$\langle\langle p_t\rangle\rangle = \sum_{i=1}^{N_{event}} \langle p_t\rangle_i / N_{event}$$

$$\langle \Delta p_{t,i}\Delta p_{t,j}\rangle = \frac{1}{N_{event}} \sum_{i=1}^{N} \sum_{j=1,i\neq j}^{N} \frac{\left(p_{t,i} - \langle\langle p_t\rangle\rangle\right)\left(p_{t,j} - \langle\langle p_t\rangle\rangle\right)}{N(N-1)}$$

N_{event} = number of events

$\langle p_t\rangle_i$ = average p_t for i^{th} event

N = number of tracks for i^{th} event

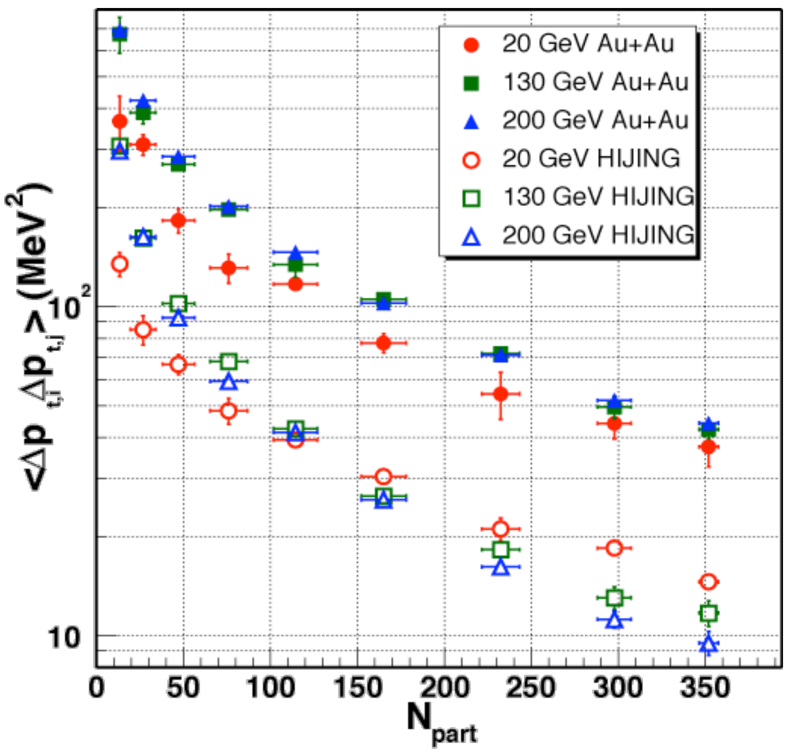
$p_{t,i}$ = p_t for i^{th} track in event

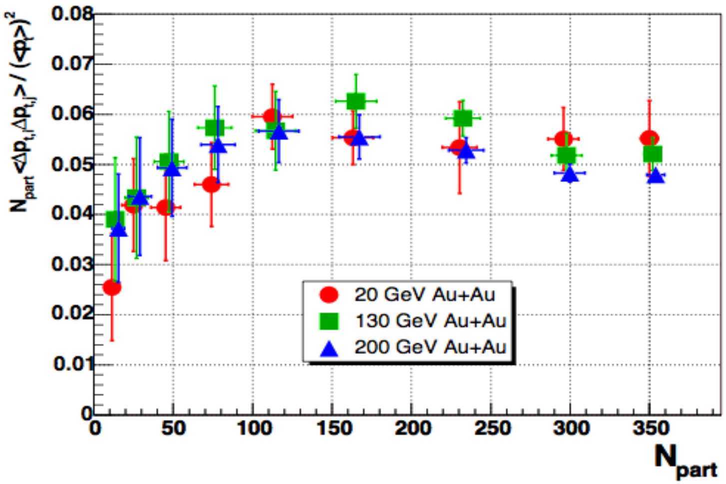
Equivalent to...

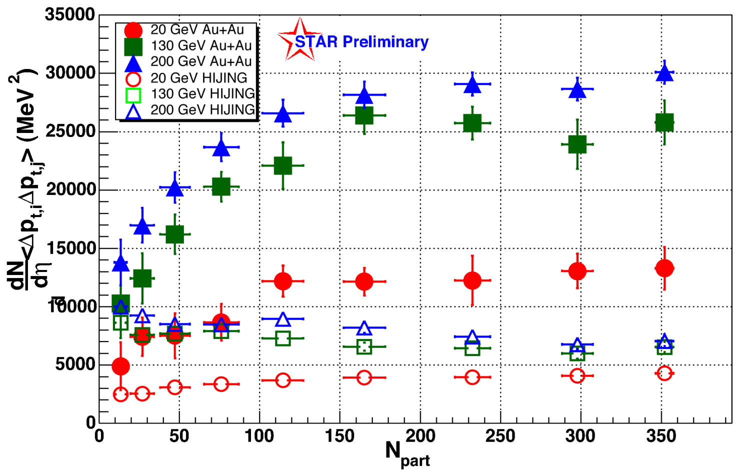
$$\langle \Delta p_T \Delta p_T\rangle = \frac{\int \rho_2 \Delta p_{T,1} \Delta p_{T,2}\, dp_{T,1}\, dp_{T,2}}{\int \rho_2\, dp_{T,1}\, dp_{T,2}}$$

pT Fluctuations

Au - Au Collisions





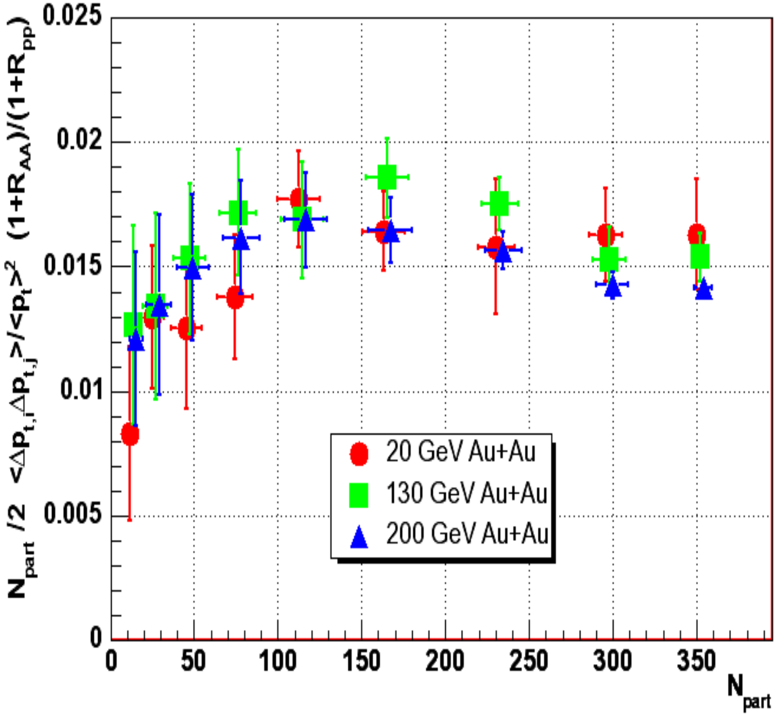


- Dynamic pT Correlations
- Approx $1/N_{part}$ dependence
- $1/dN/d\eta$ scaling violation
- Modest dependence on beam energy.
- Dramatic Disagreement w/ HIJING

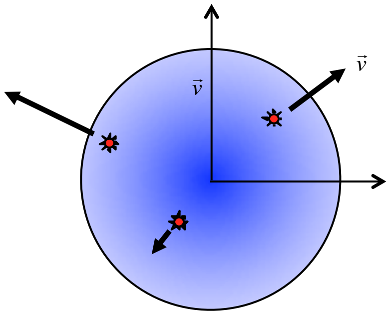
pT Fluctuations

Au - Au Collisions

Scaling Behavior

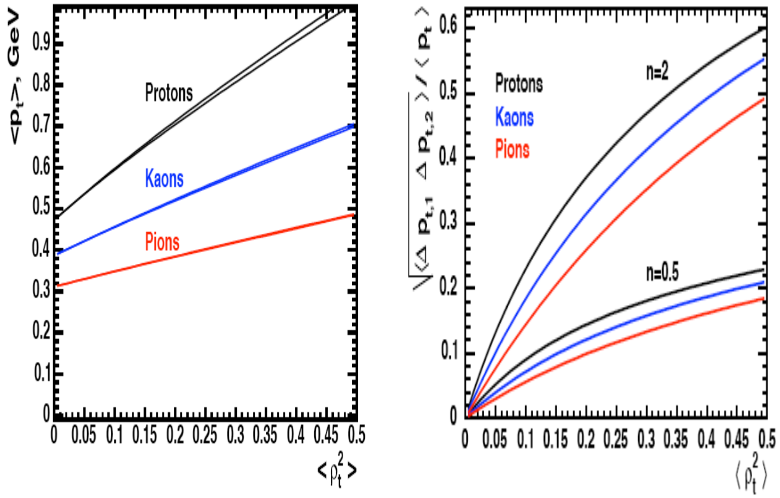


S. Voloshin, nucl-th/0312065



"blast wave" Model

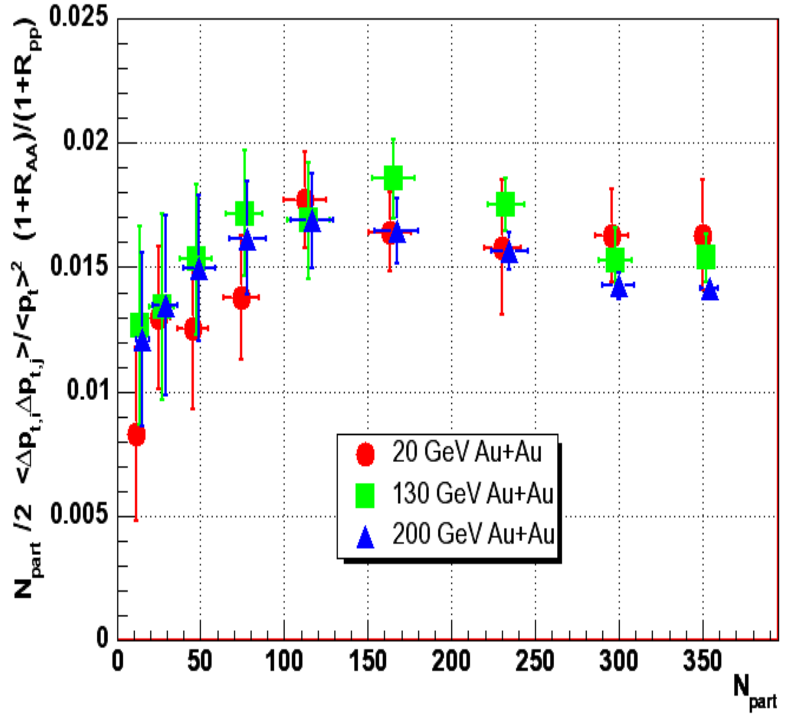
$$v \propto r^n$$



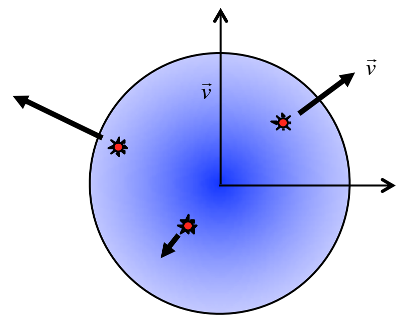
pT Fluctuations

Au - Au Collisions

Scaling Behavior



S. Voloshin, nucl-th/0312065



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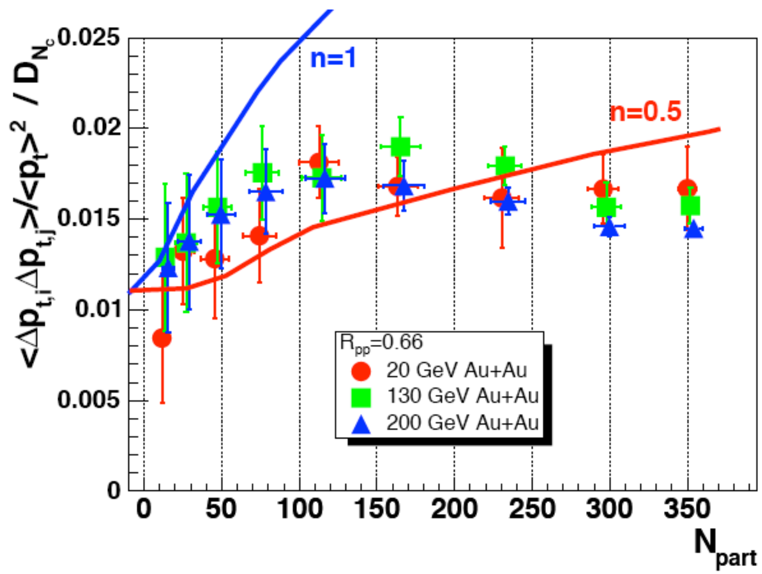
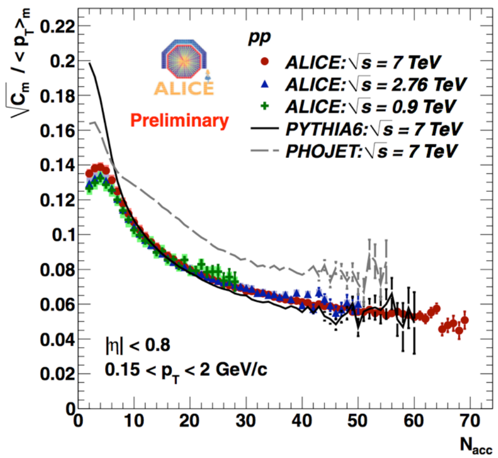
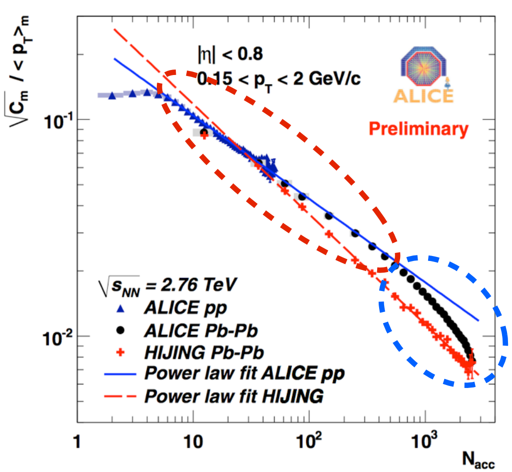
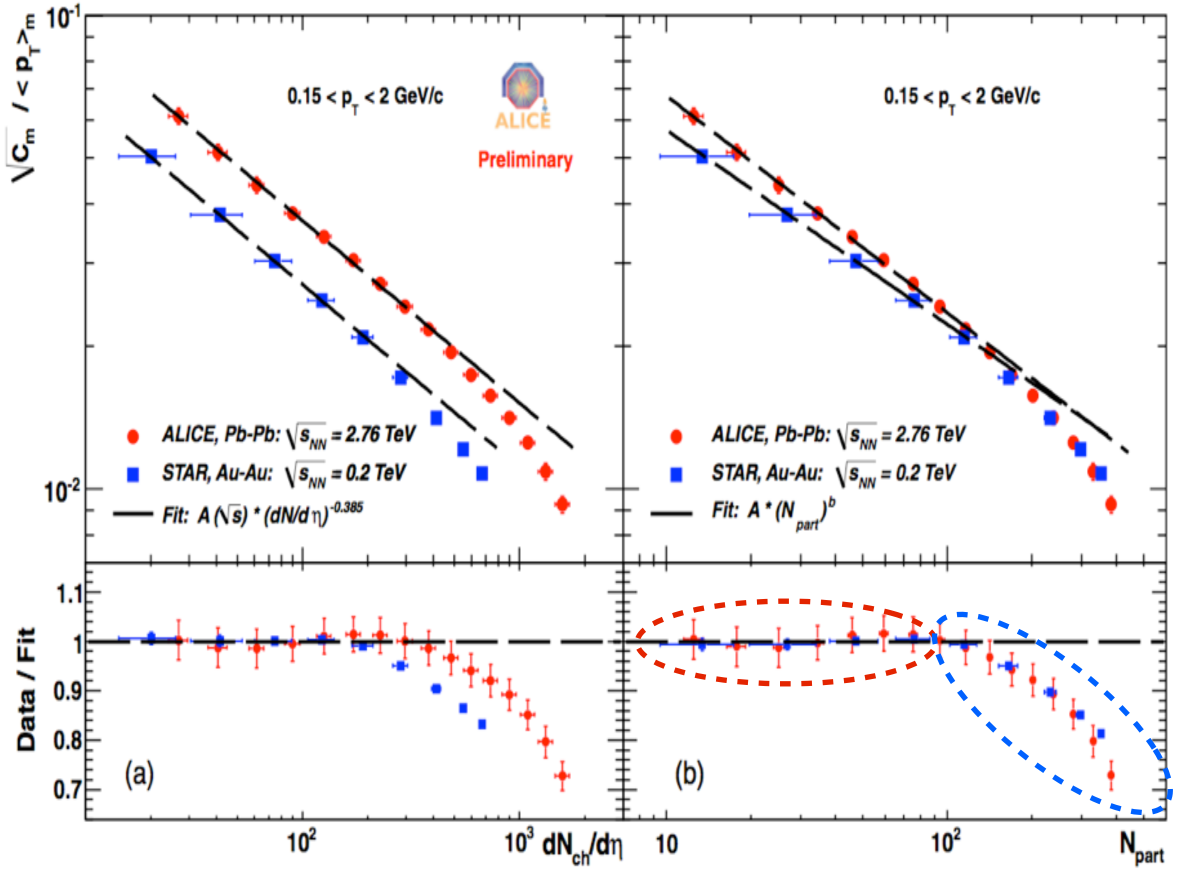


pT Fluctuations (ALICE)



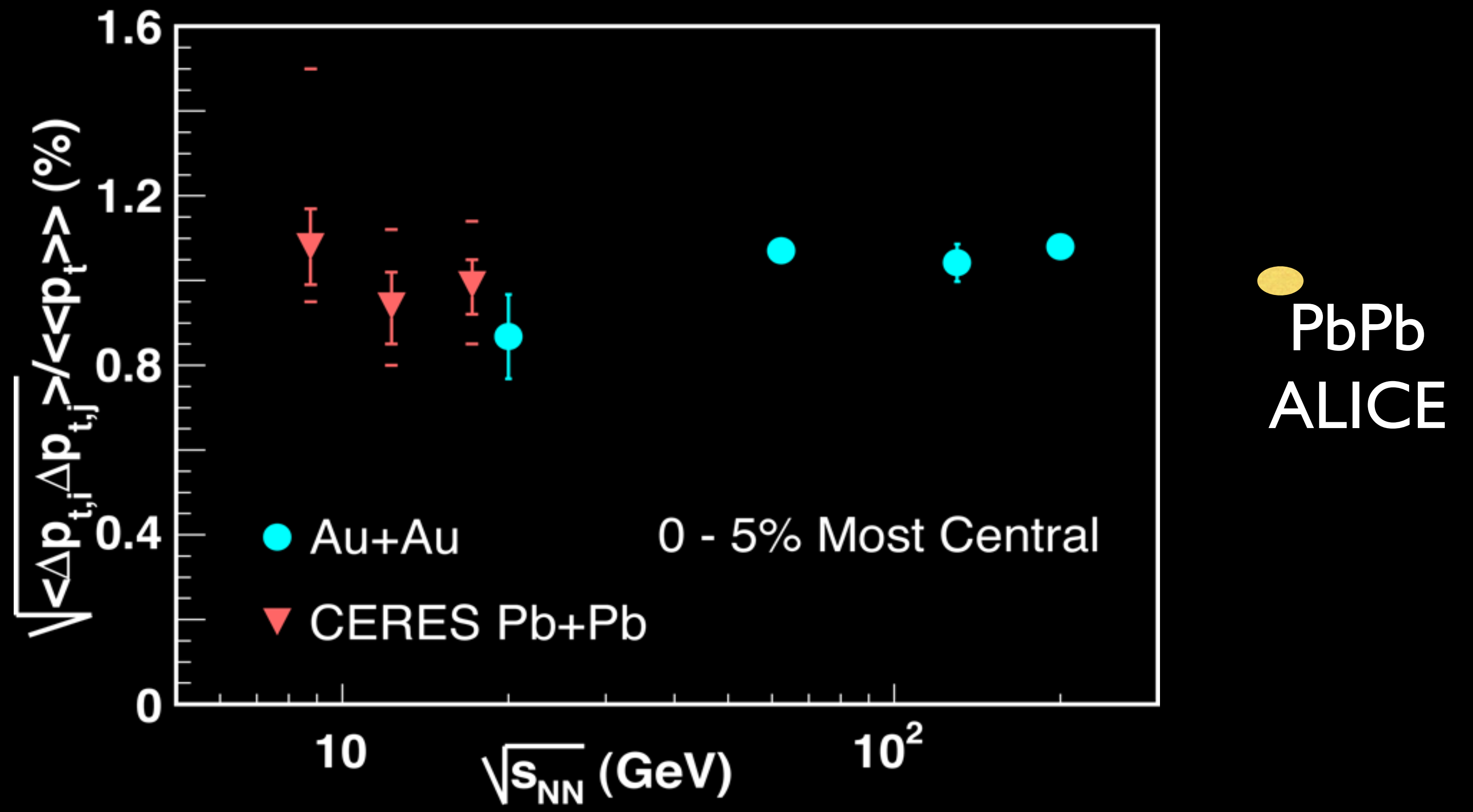




J. Phys. G, Nucl. Part Phys. 38 (2011) 124095

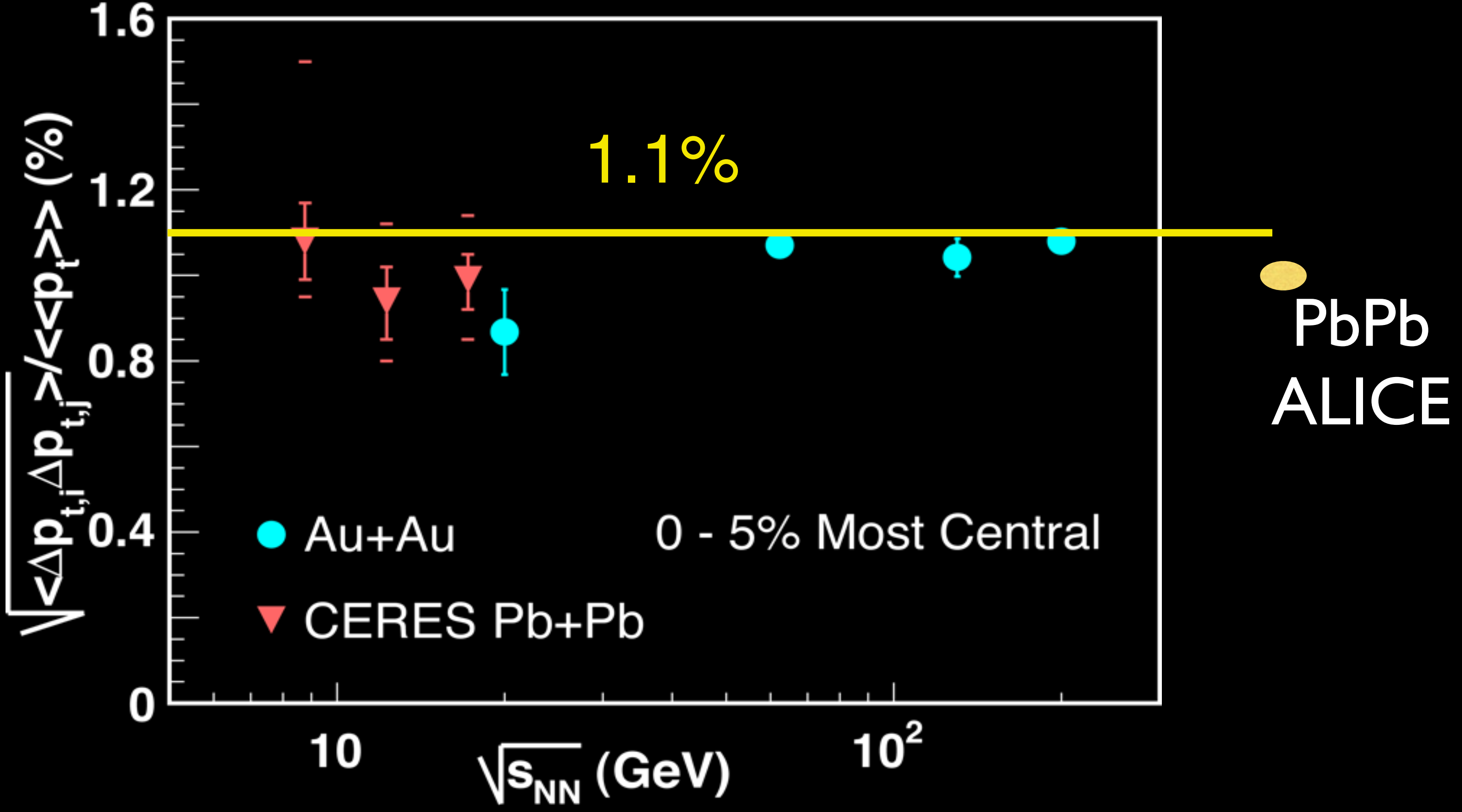
- Dependence on beam energy
- AA scales as pp below N_{part} ~ 100
- Substantial "medium" effects for N_{part} > 100

$(\langle \Delta p_{t,i} \Delta p_{t,j} \rangle)^{1/2} / \langle\langle p_t \rangle\rangle$



No smoking gun!

$(\langle \Delta p_{t,i} \Delta p_{t,j} \rangle)^{1/2} / \langle\langle p_t \rangle\rangle$



No smoking gun!

The Mach Cone "Puzzle"

R_{AA} ~ 0.2 implies large energy/momentum loss.

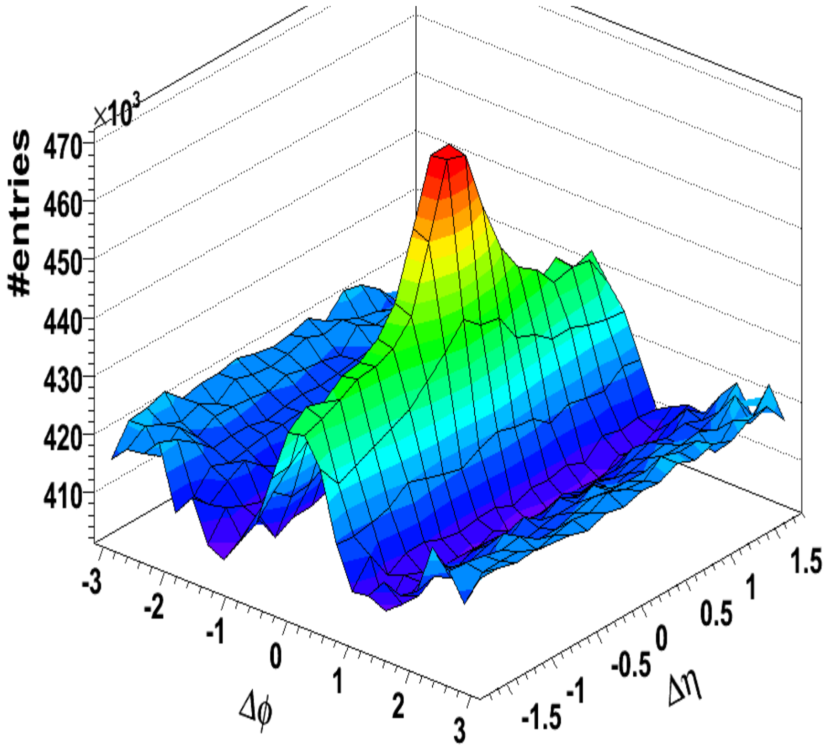
Where is the energy/momentum going?

- Mach Cone Emission?
- Medium recoil?

The Ridge and the Dip

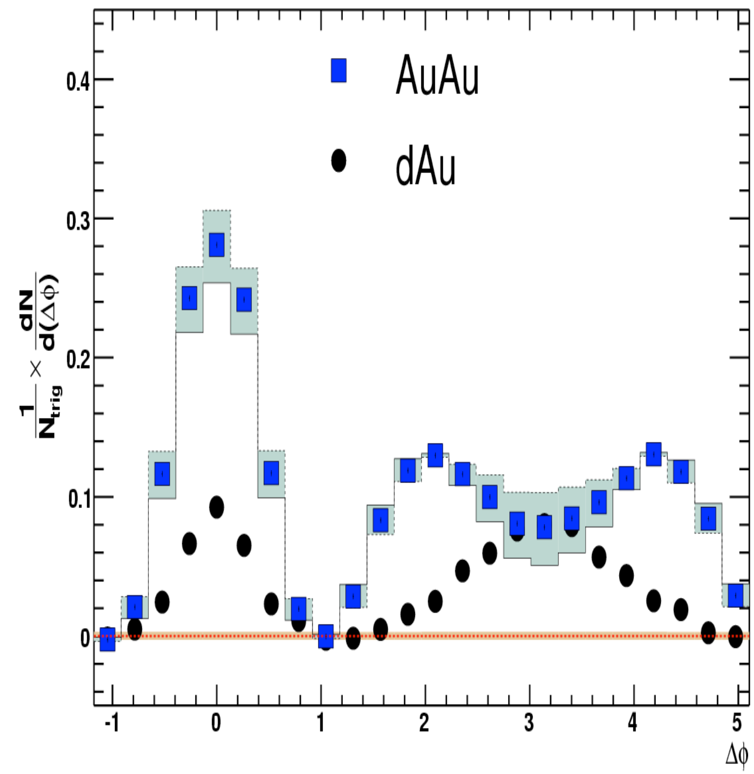
Au+Au 0-10% STAR

3<pt,trigger<4 GeV; pt,assoc.>2 GeV



Jörn Putschke, et al., STAR, Quark Matter 2006

pT,trig = 3.0-4.0 GeV/c; pT,asso = 1.0-2.5 GeV/c



Mark Horner , et al., STAR, Quark Matter 2006

Near-Side Ridge

Away-Side Dip

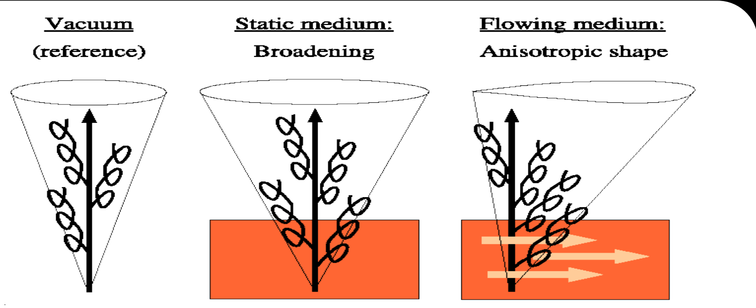
Theoretical Scenarios: Ridge & Dip (2006)

Ridge

Parton radiation (Armesto etal)
- Radiates energy before fragmenting and couples to the longitudinal flow
- Gluon bremsstrahlung of hard-scattered parton
- Parton shifted to lower p_t
- Radiated gluon contributes to broadening
- Near-side jet also looses energy (finite pathlength)!

Medium heating + Parton recombination
(Chiu & Hwa Phys. Rev. C72:034903,2005)
- Recombination of thermal partons only indirectly affected by hard scattering → not part of the jet

Radial flow + trigger bias
- S.A. Voloshin, Nucl. Phys. A749, 287 (2005))
- C. Pruneau, et al, Nucl.Phys. A802 (2008) 107-121.

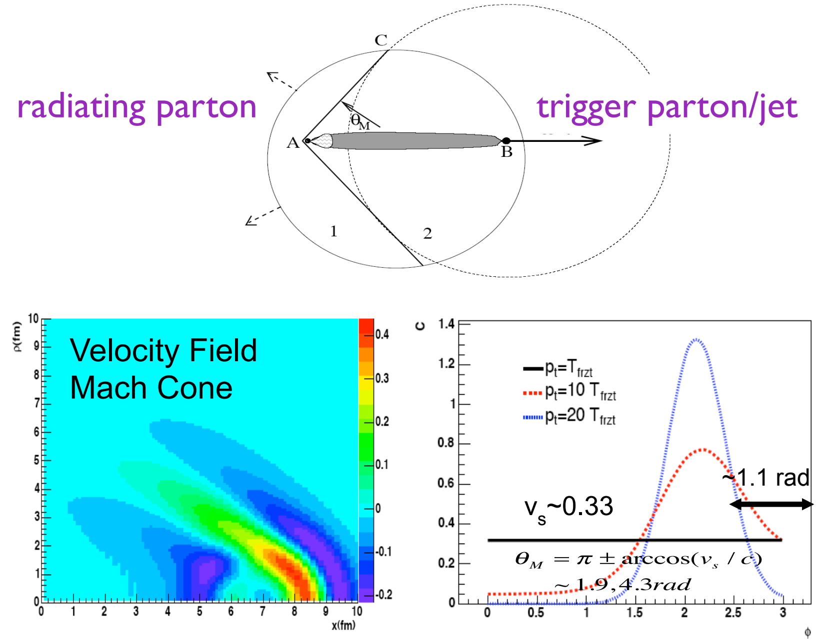


Armesto et al, PRL 93 (2004), nucl-ex/0405301

Dip

Mach Cone Concept/Calculations
- Stoecker, Casalderry-Solana et al, Muller et al.; Ruppert et al., …
- Cherenkov Radiation
  Majumder, Koch, & Wang; Vitev

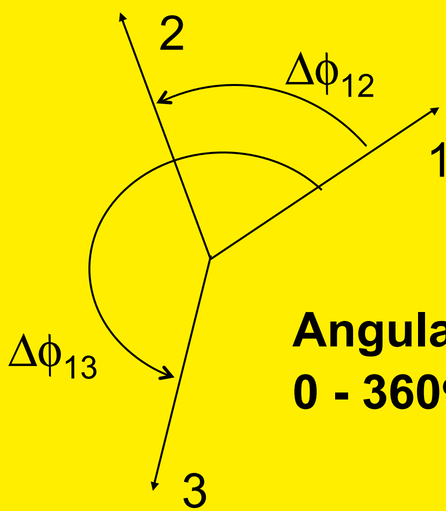
Jet Deflection (Flow)
- Fries; Armesto et al.; Hwa



Mach Cone & Deflection Kinematical Signatures

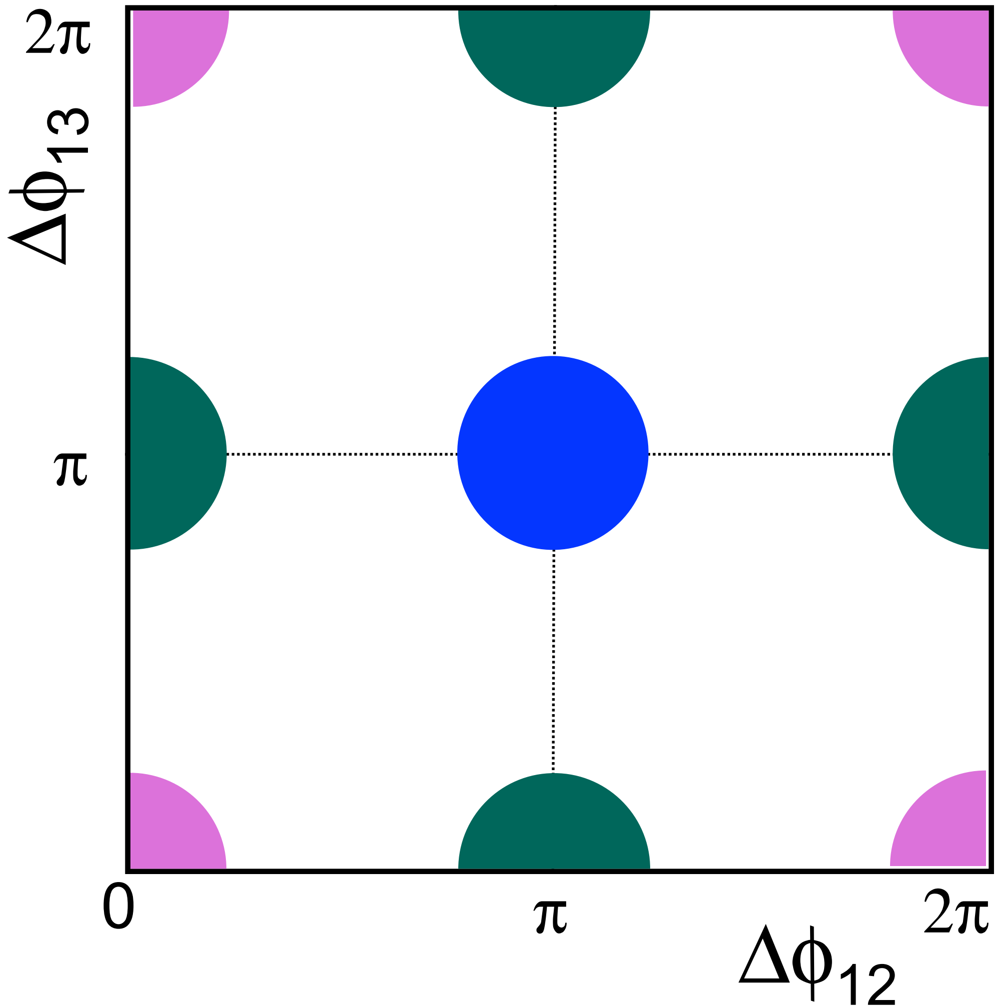
Back-to-back Jets “in vacuum”

Relative Angles Definition



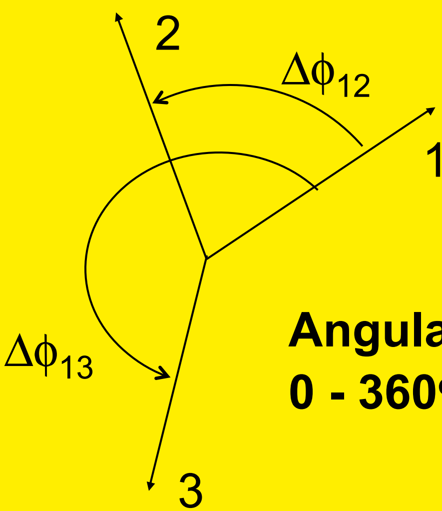
Angular Range
0 - 360°

1: 3 < pt < 4 GeV/c (Jet Tag)
2,3: 1 < pt < 2 GeV/c,



Mach Cone & Deflection Kinematical Signatures

Away-side broadening



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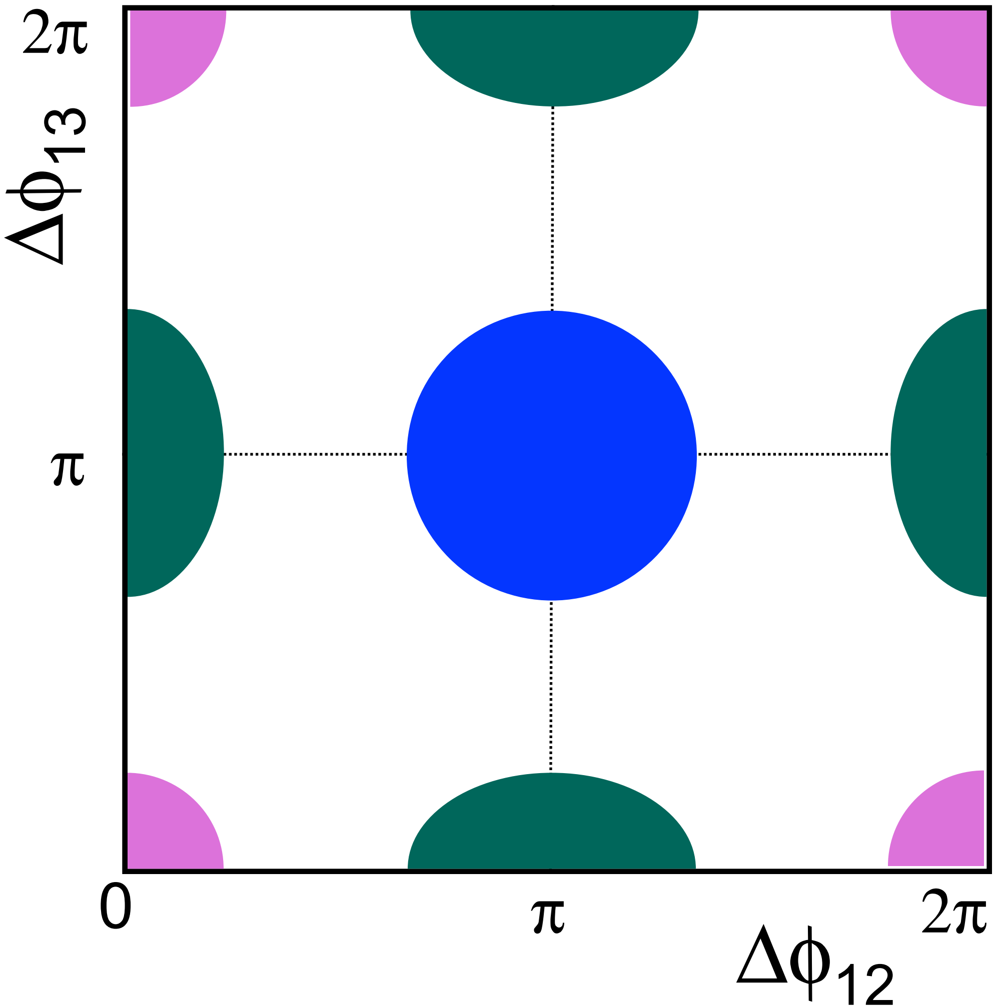
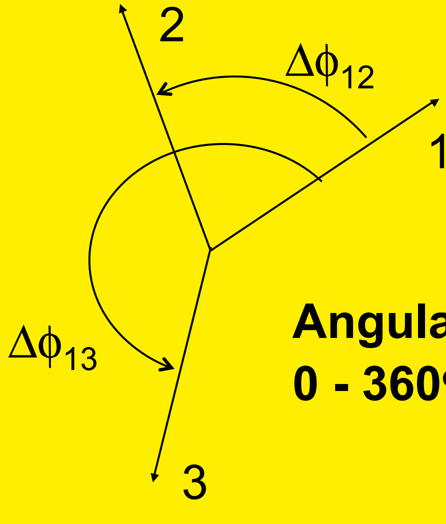
2,3: 1 < pt < 2 GeV/c,



Mach Cone & Deflection Kinematical Signatures

Relative Angles Definition



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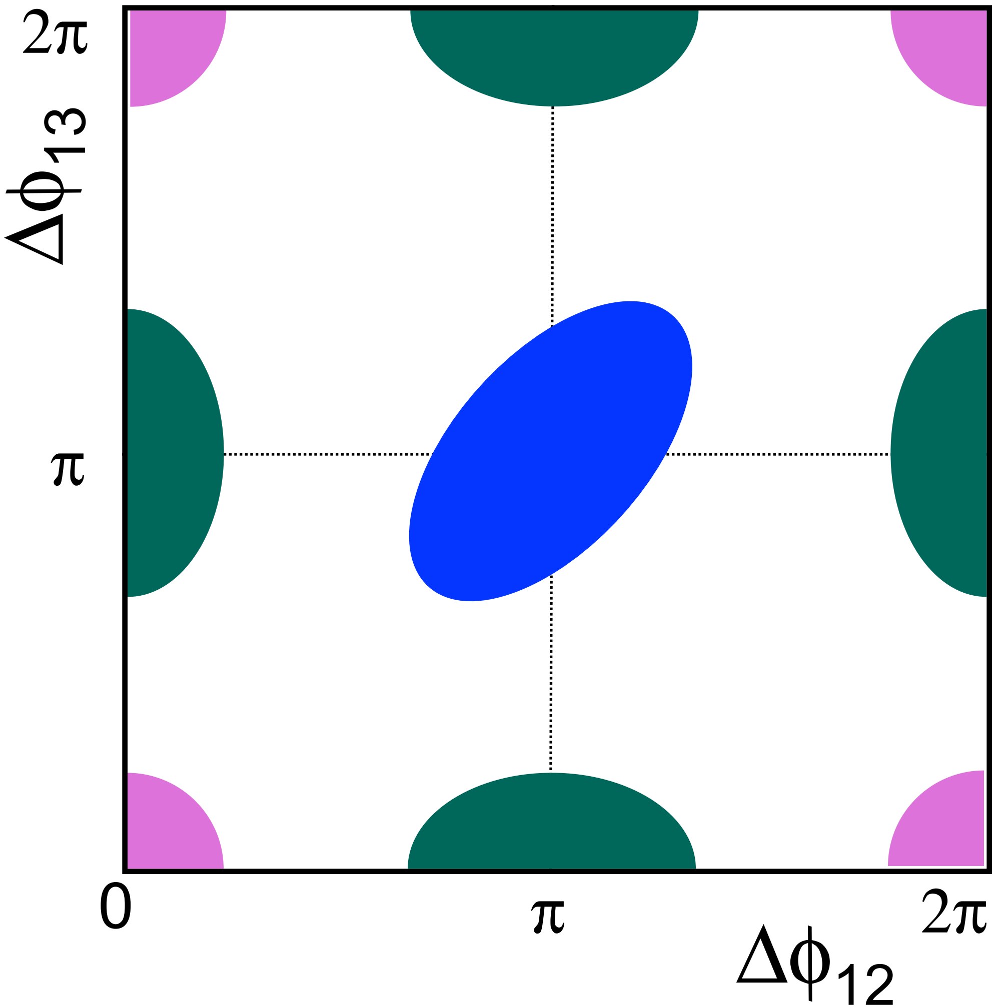
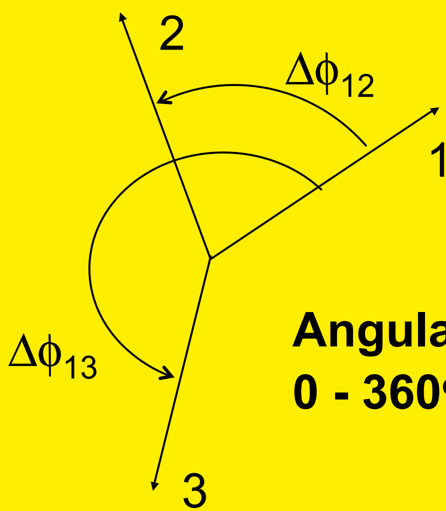
2,3: 1 < pt < 2 GeV/c,

Away-side deflection & flow



Mach Cone & Deflection Kinematical Signatures

Relative Angles Definition



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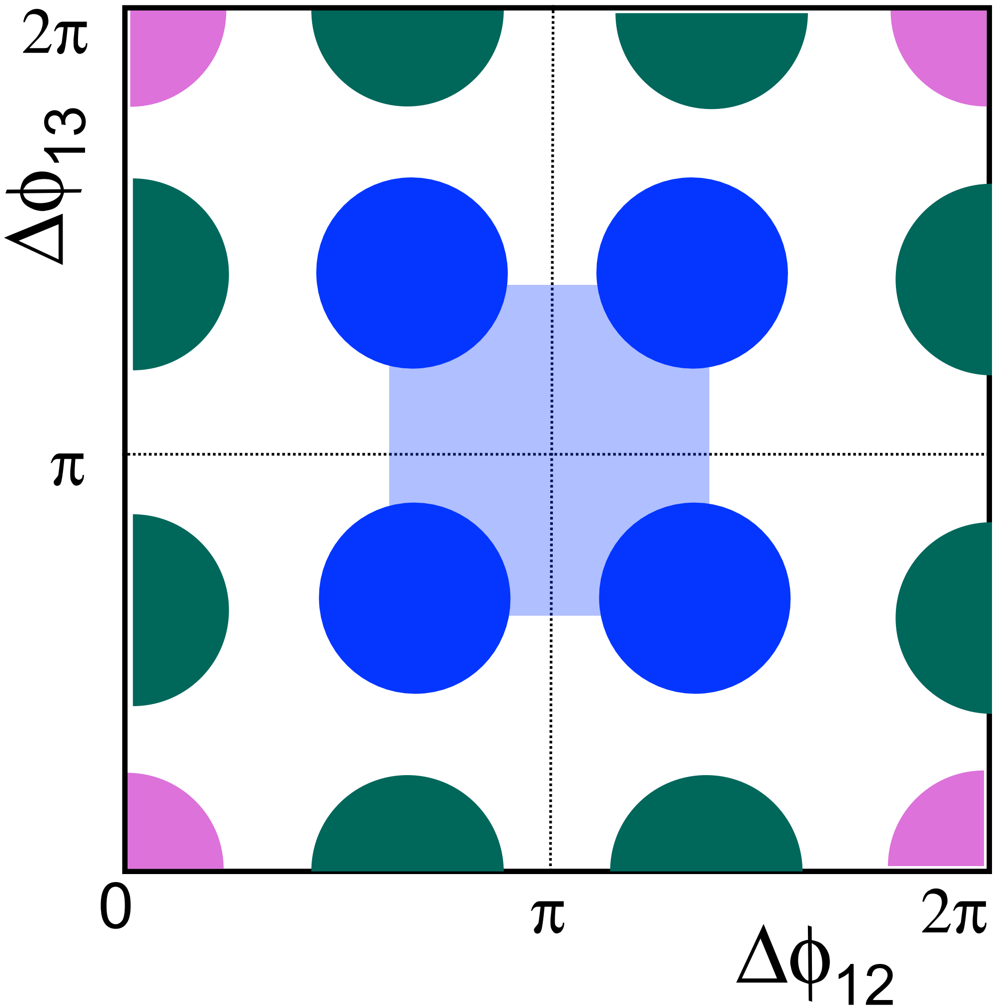
Mach Cone



Measurement of 3-Particle Cumulant

- Jet tag (trigger) : $3 < p_t < 4$, or 20 GeV/c, $|\eta|<1$
- Associates: $1 < p_t < 2$ GeV/c, $|\eta|<1$

C.P., **J.Phys. G34 (2007) S667-S670**

Measurement of 3-Particle Cumulant

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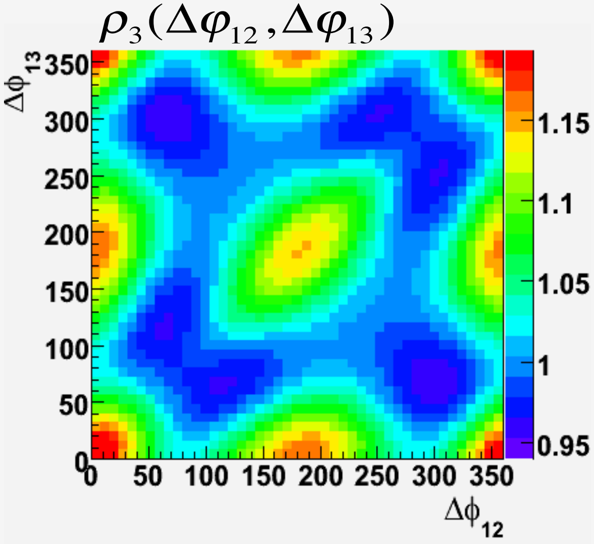

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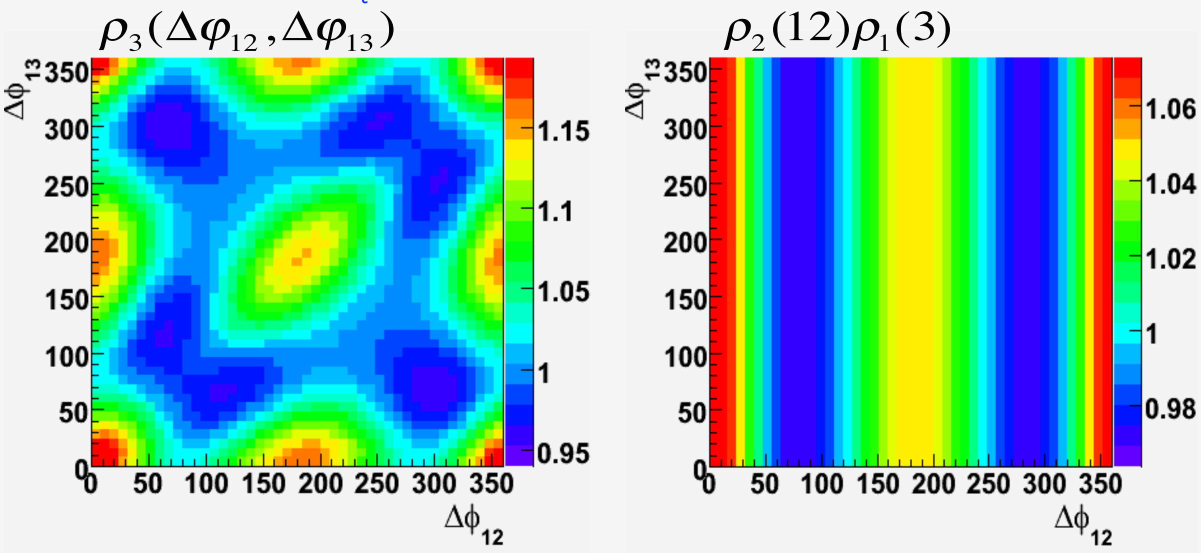

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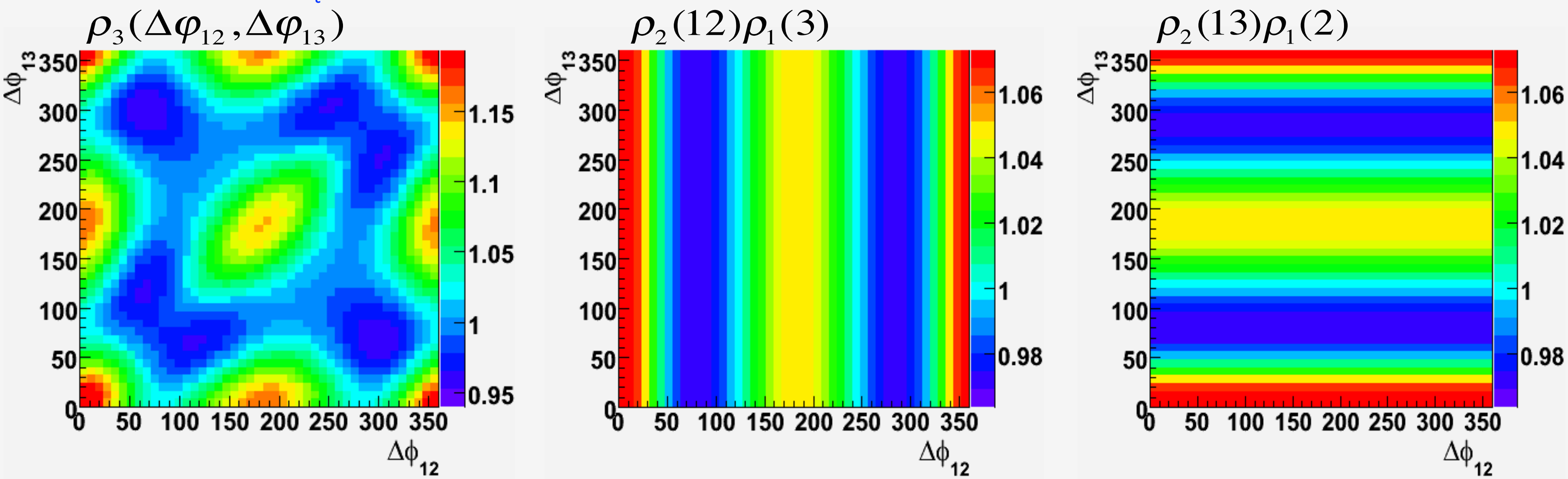

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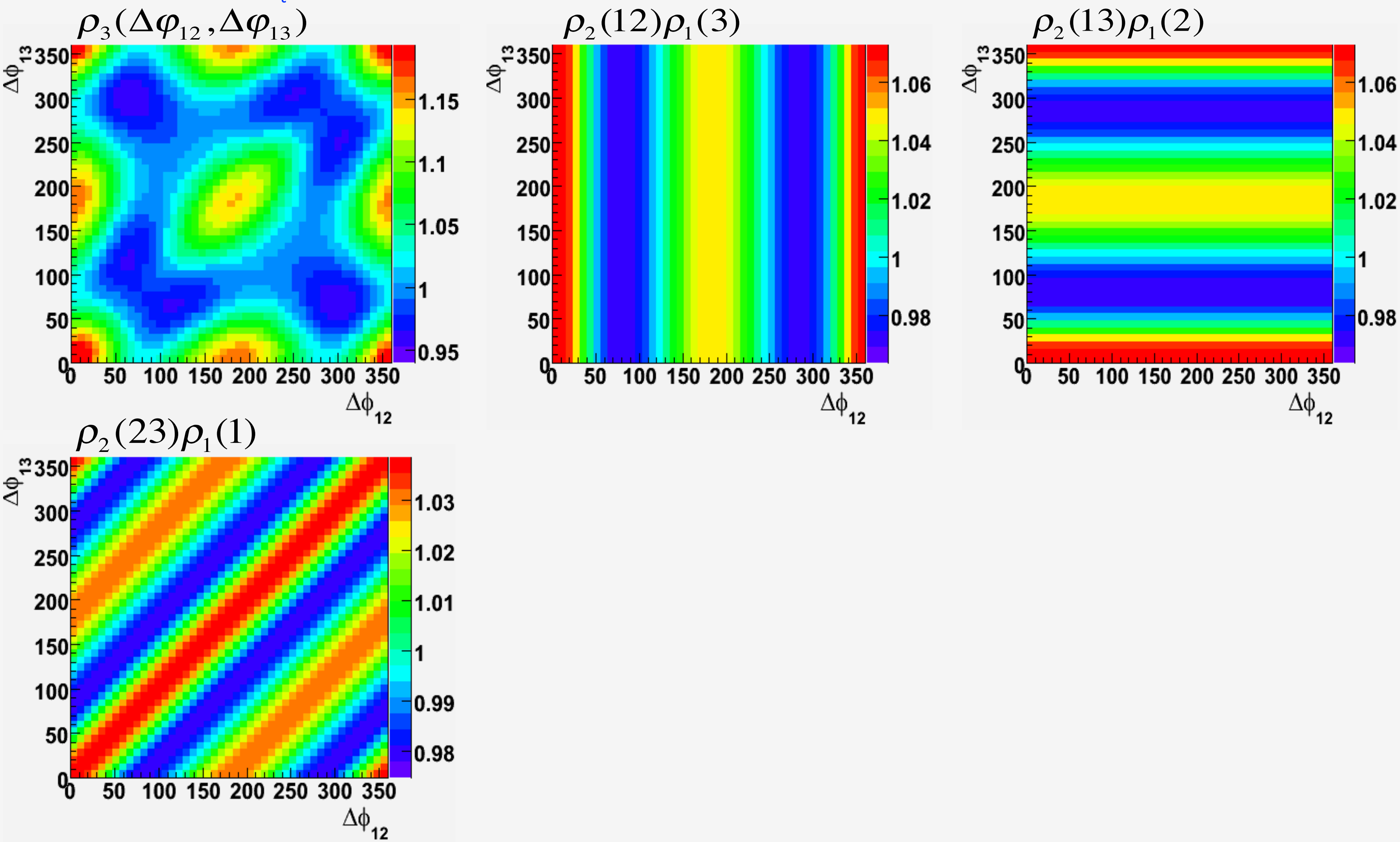

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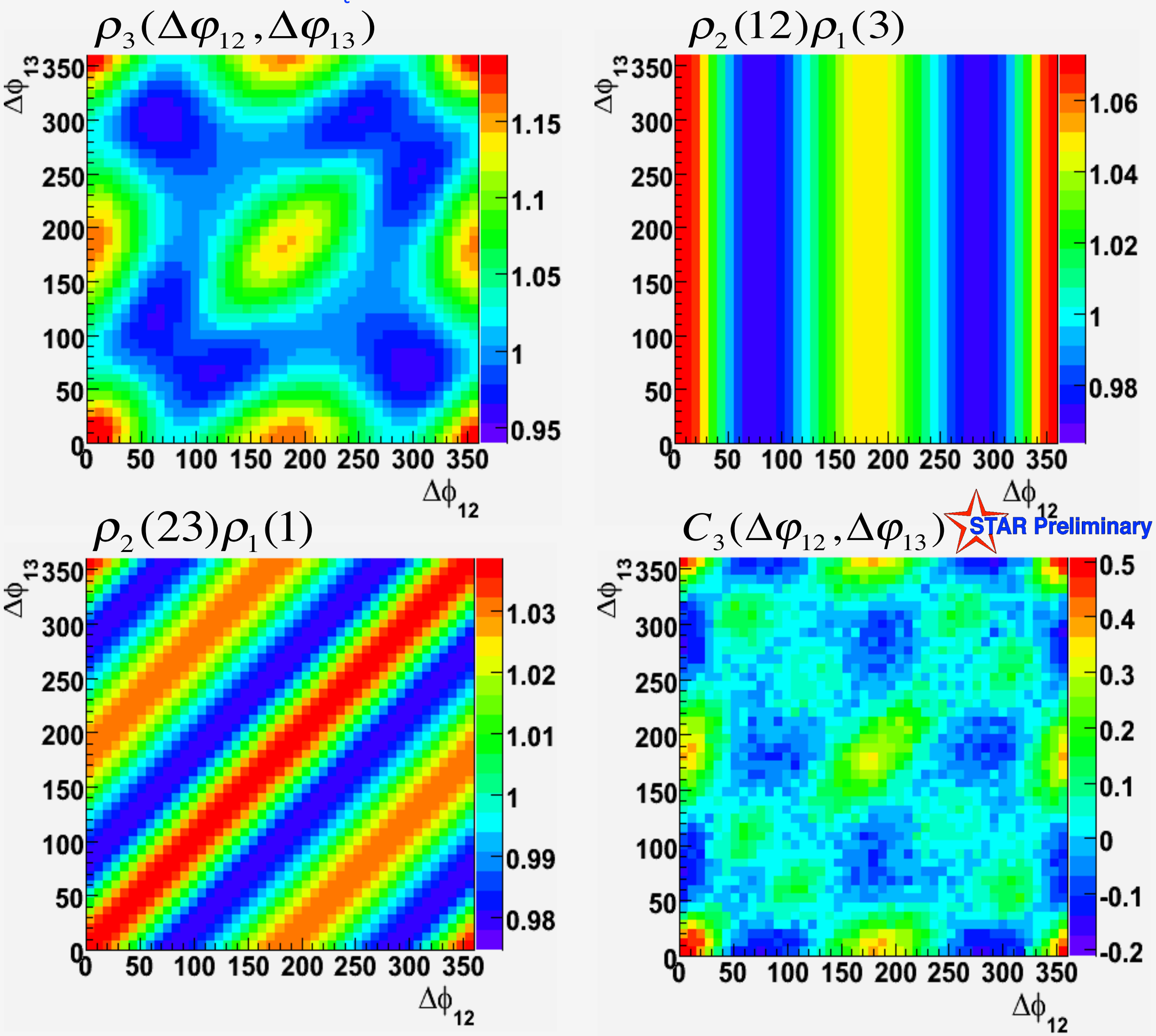
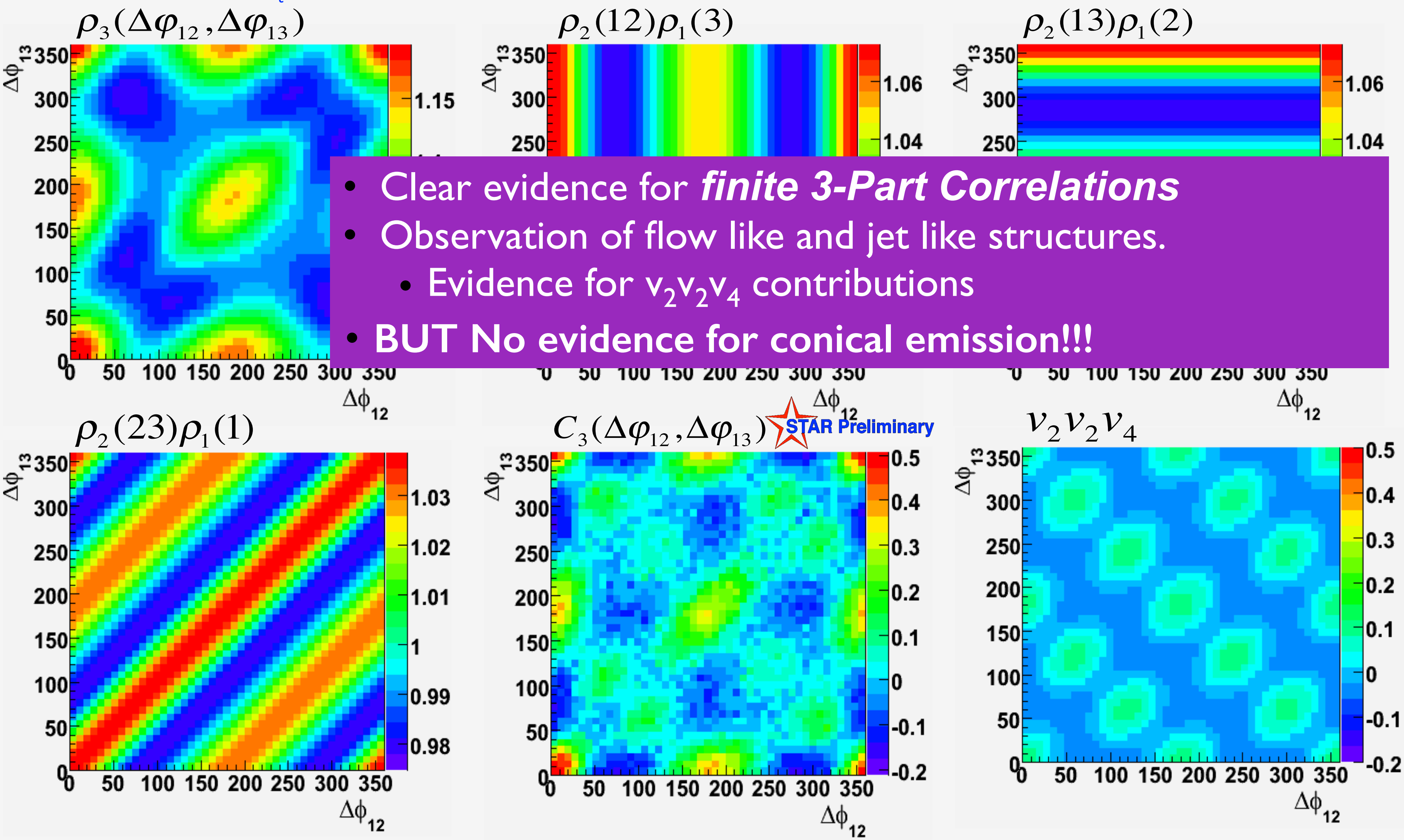


C.P., **J.Phys. G34 (2007) S667-S670**

Measurement of 3-Particle Cumulant

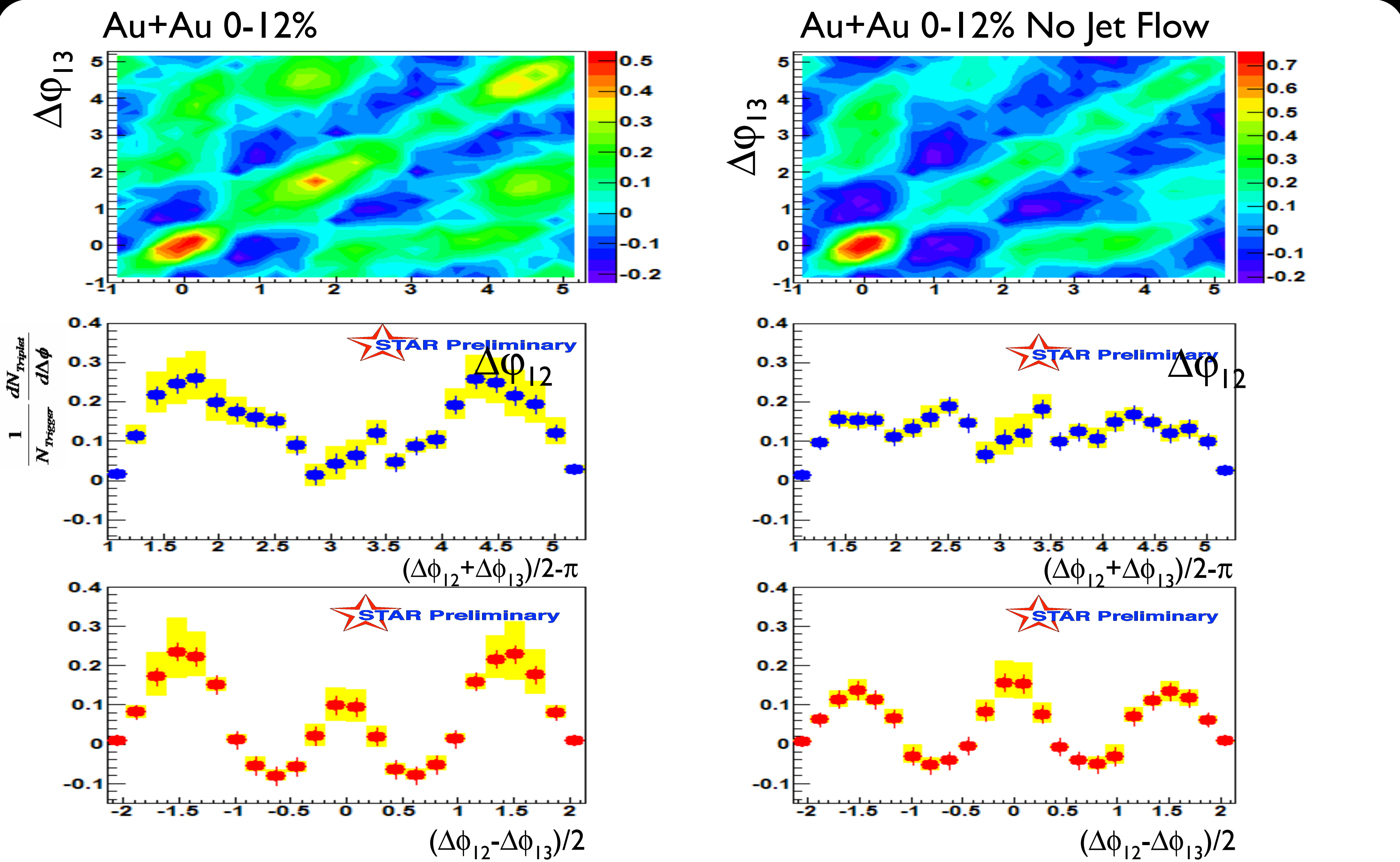
- Jet tag (trigger) : $3 < p_t < 4$, or 20 GeV/c, $|\eta|<1$
- Associates: $1 < p_t < 2$ GeV/c, $|\eta|<1$



- Clear evidence for ***finite 3-Part Correlations***
- Observation of flow like and jet like structures.
  - Evidence for $v_2v_2v_4$ contributions
- **BUT No evidence for conical emission!!!**

C.P., **J.Phys. G34 (2007) S667-S670**

Two-Component Model Analysis

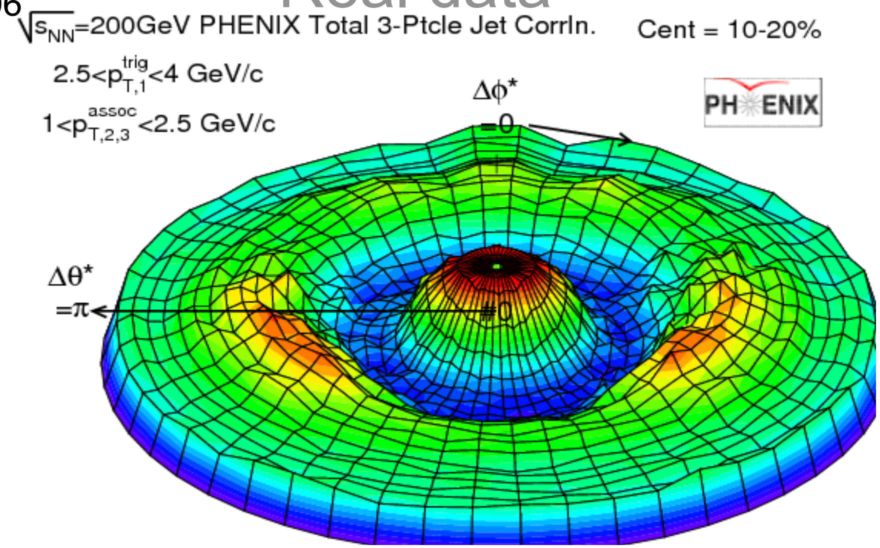


STAR, Phys.Rev.Lett. 102 (2009) 052302

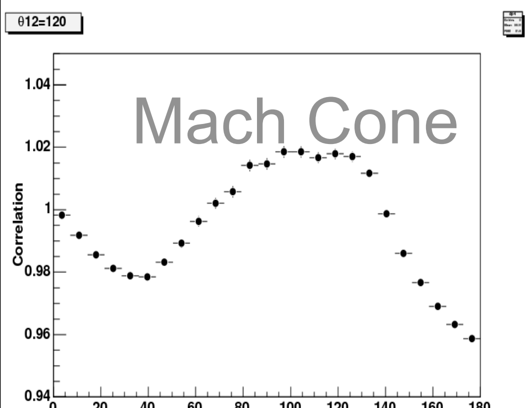
Three particle correlation

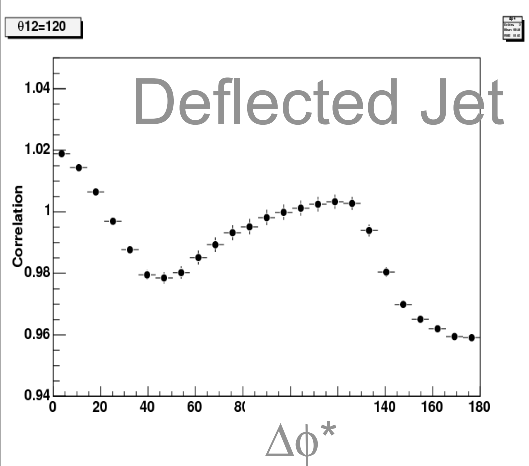
Chun Zhang, et al. PHENIX, QM06

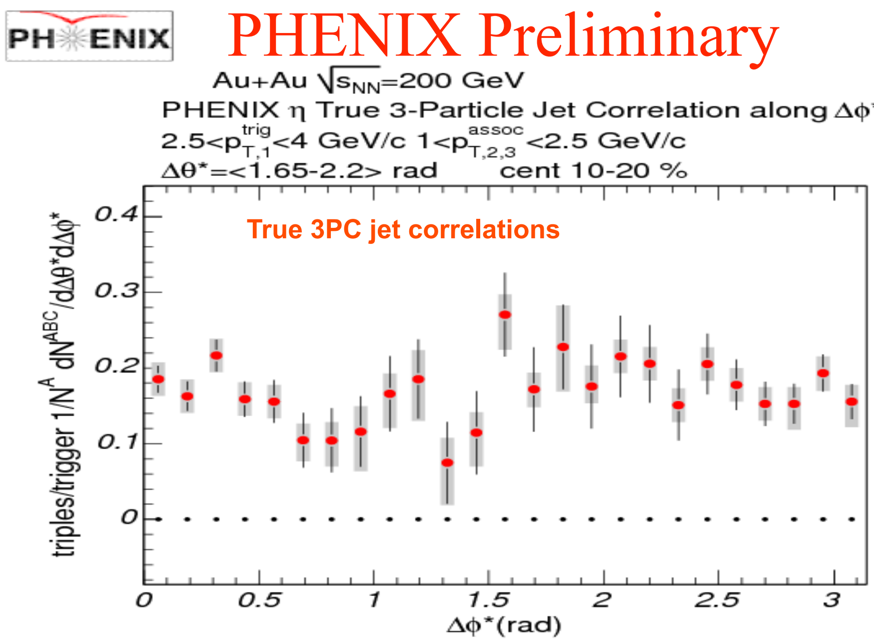
Real data



PHENIX simulation



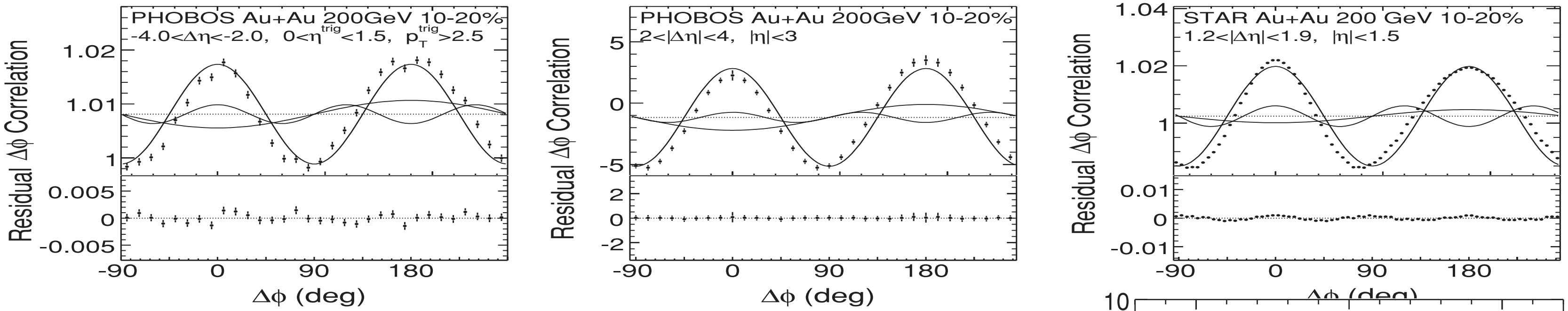


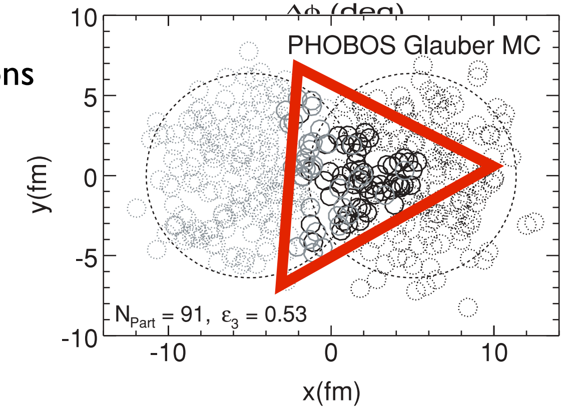


Data is consistent with the presence of a Mach Cone away-side jet but does not rule out small contributions from other topologies.

Paradigm Shift…

B. Alver & G. Roland, PRC 81, 054905 (2010)





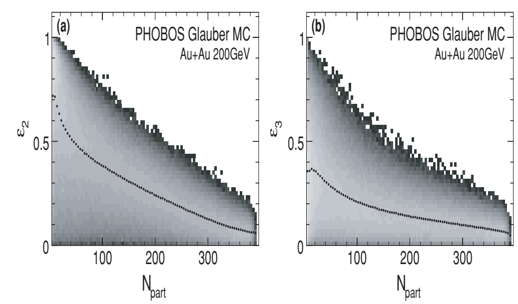
Collision-geometry fluctuations and triangular flow in heavy-ion collisions

- Underlying Assumptions
- Initial Collisions Produce Long Range Correlations
- Fast Thermalization >>> Medium
- Hydrodynamic Evolution
- *Spatial Anisotropy >>> Momentum Anisotropy*
- Finite System Has **Non-zero Odd Spatial Eccentricities**

Consequences:

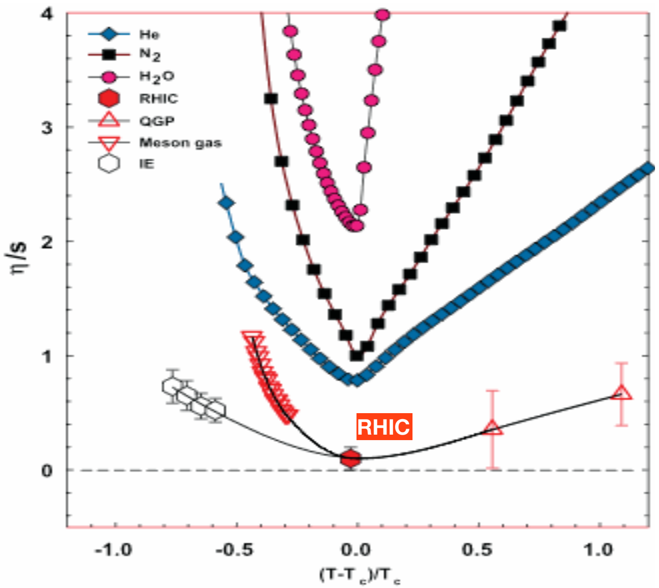
- **Initial Geometry Fluctuations Produce Odd Harmonics**
- **Produces an away-side dip**

- **SIMPLE EXPLANATIONS ARE THE BEST!!!!**
  - **Most people lost interest in conical emission!**
  - **But it might still exist…**
  - **There are ways to fish it out if it is there...**



Is the sQGP a Perfect Fluid?

- Superfluid Helium
- Ultra Cold Gasses (few nK)

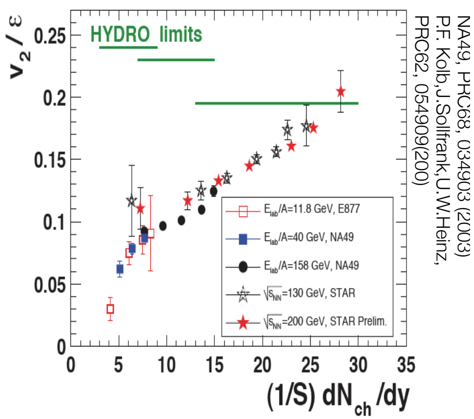


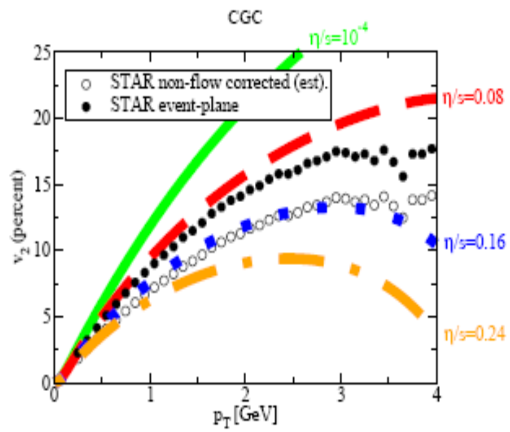
Conjectured low bound of shear viscosity/entropy:

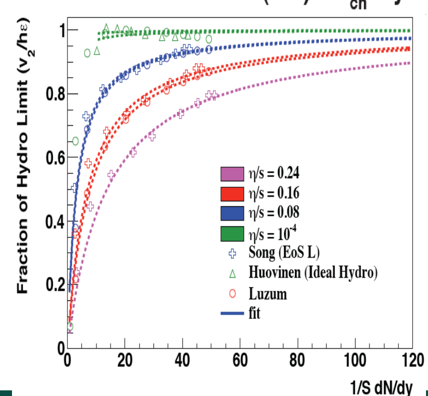
Supersymmetric Yang Mill Theory (Ads/CFT duality Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

- Quark Gluon Plasma
  T~200 MeV~10^{12} K
  Temperature of early universe at ~1 micro-sec







M. Luzum & P. Romatschke, 0804.4015; 0901.4588

H. Song & U. Heinz 0805.1756v2

P. Huovinen

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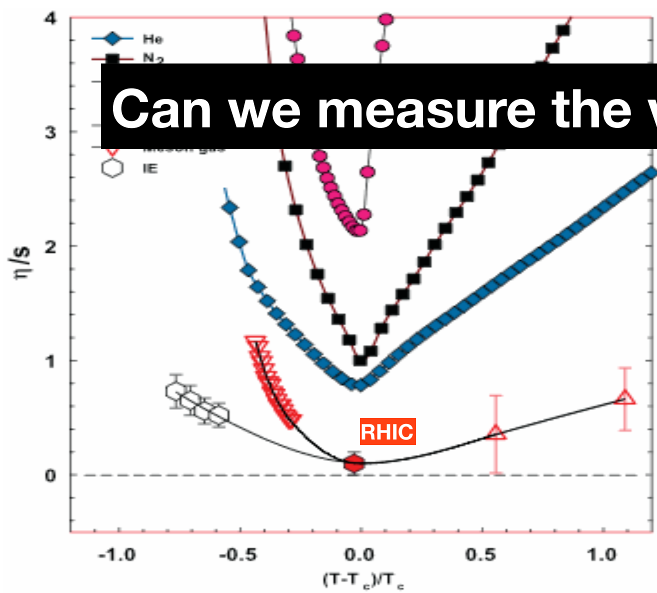

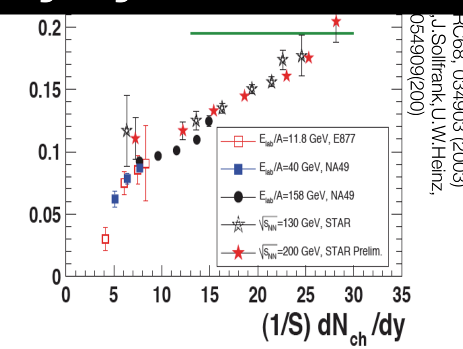

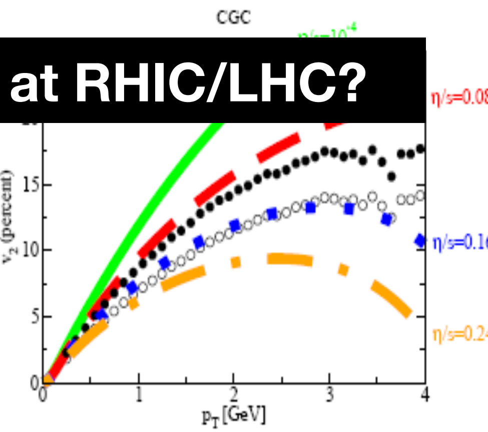

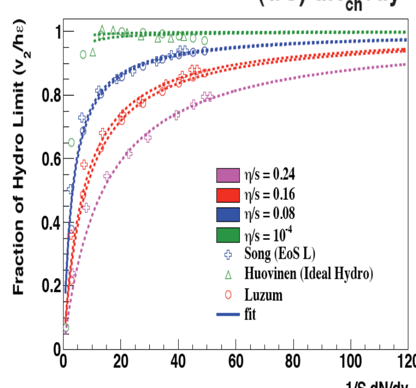

M. Luzum & P. Romatschke, 0804.4015; 0901.4588

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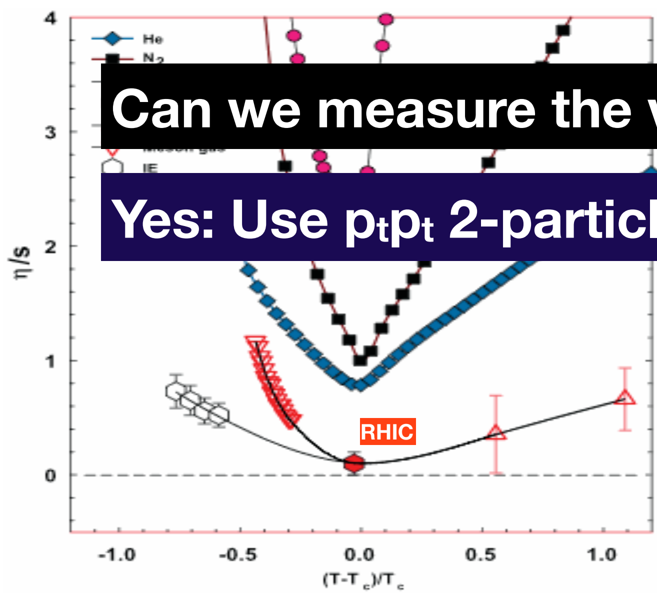
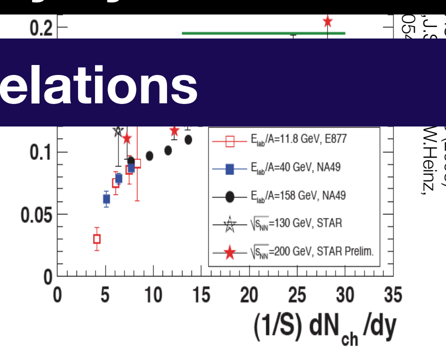
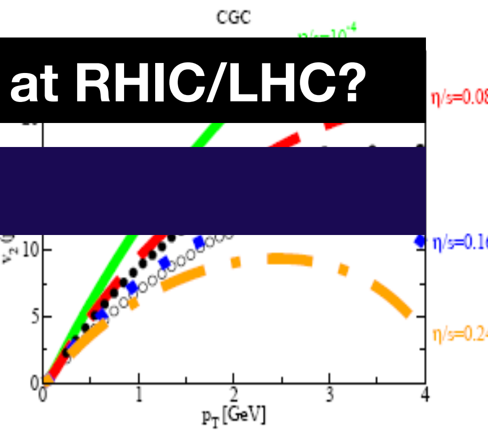


Can we measure the viscosity by other means at RHIC/LHC?

Yes: Use $p_t p_t$ 2-particle correlations





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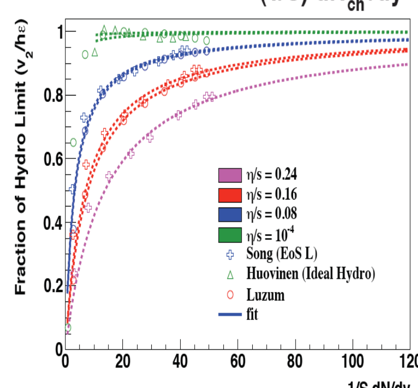


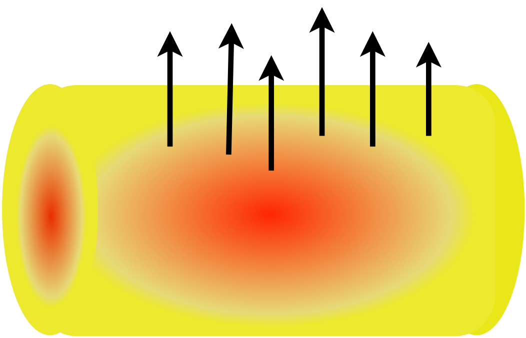
M. Luzum & P. Romatschke, 0804.4015; 0901.4588

H. Song & U. Heinz 0805.1756v2

P. Huovinen

Measurement of viscosity based on p_t p_t Correlations

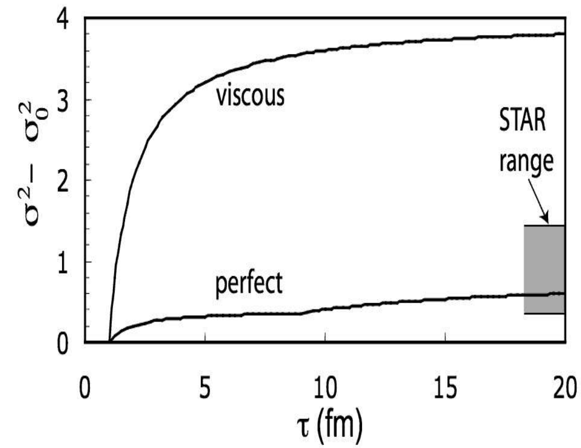
Gavin and Abdel-Aziz, nucl-th/0606061 (2006)

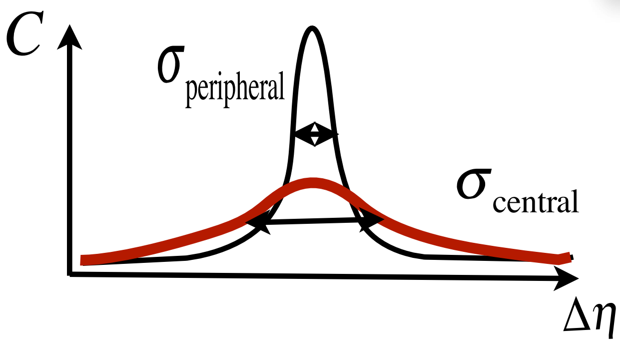


NEAR SIDE: Fluid Cells Viscous Drag damps their relative motion and broadens correlations

$$C(\Delta\eta) = \langle p_{t,1} p_{t,2} \rangle - \langle p_t \rangle^2$$

$$\nu = \frac{\eta}{T_c s}$$





$$\sigma^2 = \sigma_o^2 + 2\Delta V(\tau_f)$$

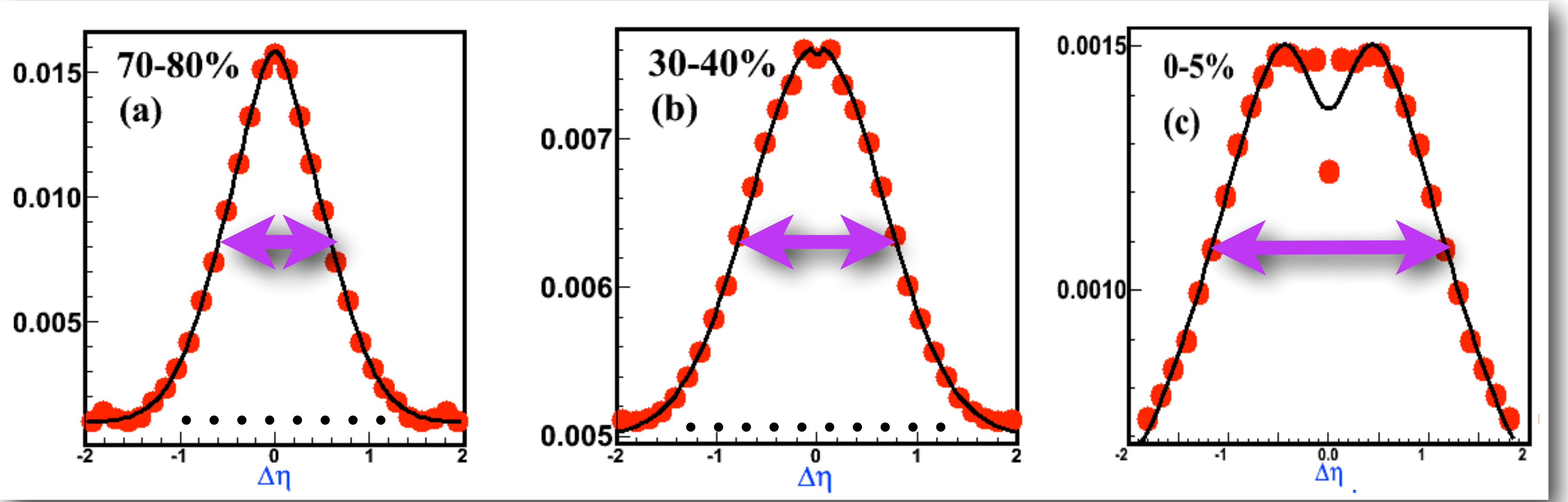
$$\Delta V(\tau) \equiv \left\langle (\eta - \langle\eta\rangle)^2 \right\rangle = \frac{2\nu}{\tau_o}\left(1 - \frac{\tau_o}{\tau}\right)$$

Experimental Observable

$$C(\Delta\eta, \Delta\varphi) = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{j\neq i=1}^{n_2} p_{t,i} p_{t,j} \right\rangle}{\langle n_1 \rangle \langle n_2 \rangle} - \langle p_{t,1} \rangle \langle p_{t,2} \rangle$$

Results: $C\left(\Delta\eta, |\Delta\varphi| < 1\right)$

NEAR SIDE: Fluid Cells Viscous Drag damps their relative motion and broadens correlations



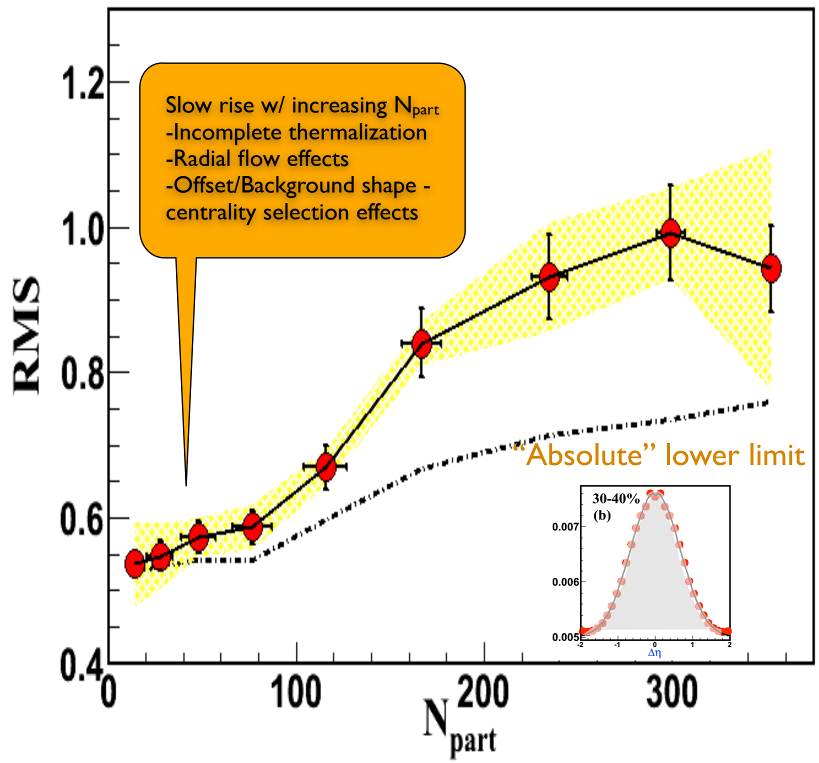
- Correlation Function is not Gaussian
- Characterize width as RMS of the distribution above "pedestal"
- Determine pedestal (offset) based on fit of the line shape

$$b + a_n \exp(-\Delta\eta / 2\sigma_n^2) + a_w \exp(-\Delta\eta / 2\sigma_w^2)$$

- Subtract offset; Set $\Delta\eta = 0$ point equal to neighboring points in 0-5%; Calculate RMS from data, but include $|\Delta\eta| > 2$ extrapolation from fit.

Results: $C\left(\Delta\eta, |\Delta\varphi| < 1\right)$

M. Sharma et al.



Phys.Lett. B704 (2011) 467-473

- Values obtained by this method consistent w/ values obtained by flow measurements
- Similar analysis needed at LHC.

Interpretation based on Gavin and Abdel-Aziz, Phys.Rev.Lett. 97 (2006) 162302; nucl-th/0606061 (2006)

Viscous broadening: $\sigma^2_{viscous} = \frac{4\nu}{\tau_o}\left(1 - \frac{\tau_o}{\tau}\right)$ $\quad \nu = \frac{\eta}{T_c s}$

Measured broadening: $\Delta\sigma^2 \simeq \sigma^2_{viscous} = 0.58 \pm 0.28$

Assume Temperature: $T_c = 170\ \text{MeV}$

Formation Time (th. syst.): $\tau_o = 1^{+0.5}_{-0.4}$

Freeze-out Time (central): $\tau = 10 - 20\ \text{fm/c}$

Range defines theory systematic errors

Shear Viscosity/Entropy:

$$\eta/s = 0.14 \pm 0.02(\text{stat}) \pm 0.06(\text{meas syst.})$$
$$\pm 0.14(\text{theory syst.})$$

Shear Viscosity/Entropy - Upper limit:

$$\eta/s^{\max} = 0.2 + 0.14(\text{theory syst.})$$

In agreement w/ estimates from flow measurements

pTpT Correlations

'Number' Correlations

$$R_2(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\rho_1(\eta_1,\varphi_1)\rho_1(\eta_2,\varphi_2)}-1$$

pTpT Correlations

$$\left\langle \Delta p_{t,1}\Delta p_{t,2}\right\rangle(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{\int_{accept}\rho_2(\eta_1,\varphi_1,p_{t,2}\eta_2,\varphi_2,p_{t,2})\Delta p_{t,1}\Delta p_{t,2}\,dp_{t,1}\,dp_{t,2}}{\int_{accept}\rho_2(\eta_1,\varphi_1,p_{t,2}\eta_2,\varphi_2,p_{t,2})\,dp_{t,1}\,dp_{t,2}}$$

measured as:

$$\left\langle \Delta p_{t,1}\Delta p_{t,2}\right\rangle(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{\sum_{events}\sum_{accept}\Delta p_{t,1}\Delta p_{t,2}}{\sum_{events}n_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}$$

$$\Delta p_T = p_T-\left\langle p_T\right\rangle$$

Flow Only (corr w.r.t reaction plane):

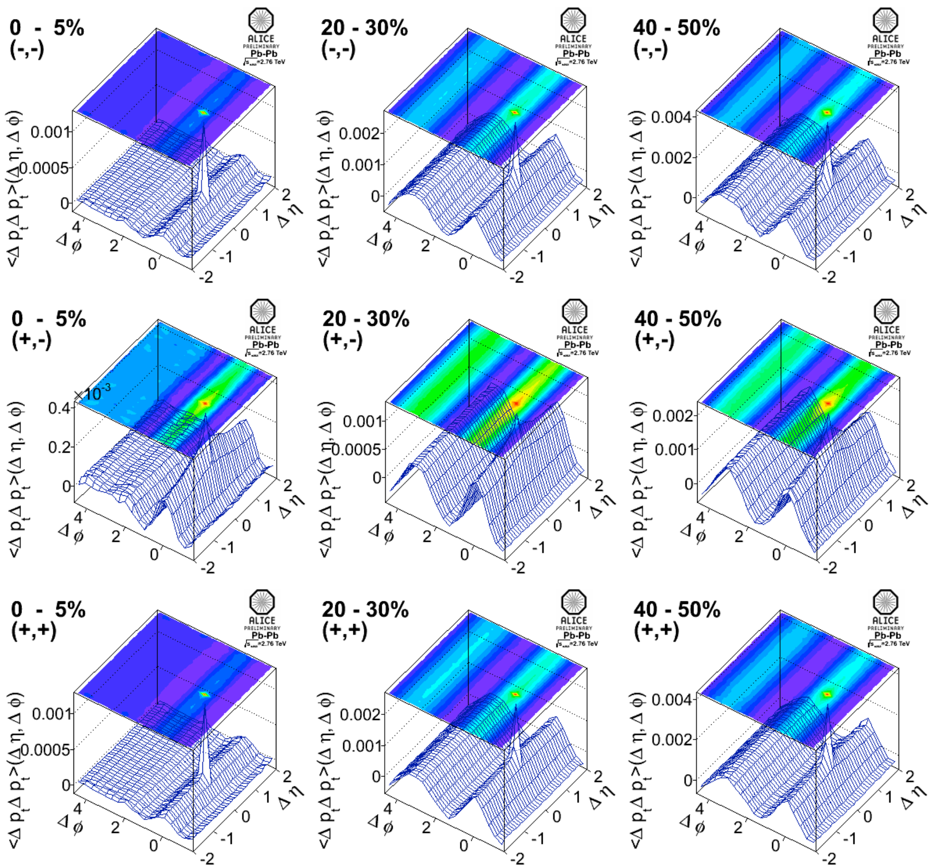
$$\left\langle \Delta p_t\Delta p_t\right\rangle(\eta_1,\eta_2,\Delta\phi)=\frac{2\sum_n\left(v_n^p(\eta_1)-\left\langle p_t\right\rangle(\eta_1)v_n(\eta_1)\right)\left(v_n^p(\eta_2)-\left\langle p_t\right\rangle(\eta_2)v_n(\eta_1)\right)\cos(n\Delta\phi)}{1+2\sum_n v_n(\eta_1)v_n(\eta_1)\cos(n\Delta\phi)}$$

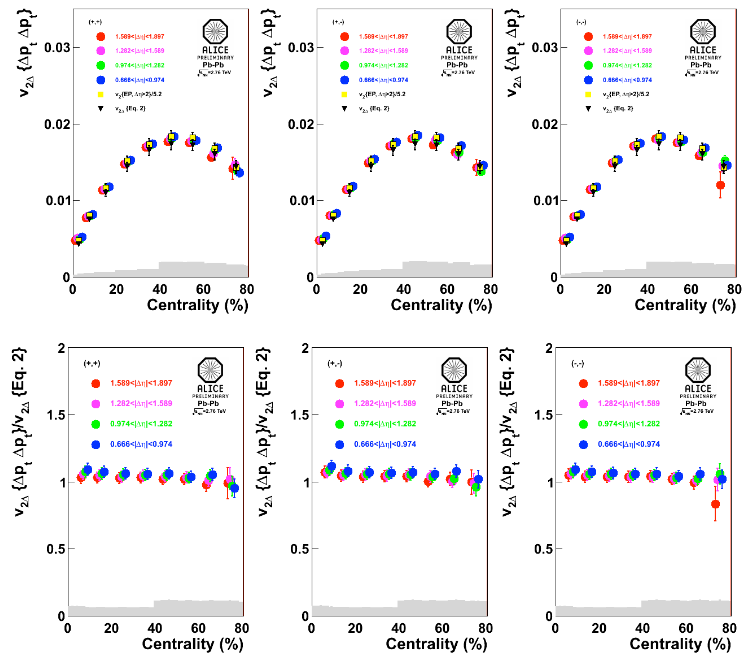
$$v_n(\eta) = \frac{1}{P_n(\eta)}\int P_n(\eta,p)v_n(\eta,p)dp$$ Regular Flow Coefficients

$$v_n^{p_t}(\eta) = \frac{1}{P_n(\eta)}\int P_n(\eta,p)v_n(\eta,p)p\,dp$$ pT weighted Flow Coefficients

Simple Prediction: $$v_n^{\Delta p_t\Delta p_t}\simeq v_n^{p_t}-\left\langle p_t\right\rangle v_n$$

pTpT Correlations



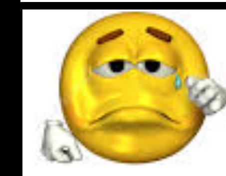
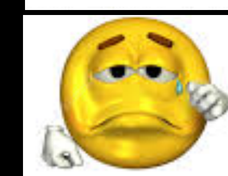


- Similar results for higher harmonics
- Factorization
- Scaling (Flow Model)

$$v_n^{\Delta p_t \Delta p_t} \simeq v_n^{p_t} - \langle p_t \rangle v_n$$

P. Pujahari + C.P.

Summary (Score Card)

Measurement	Conclusion(s)/Outcome	
Net Charge Fluctuations	Tendency towards suppression expected from QGP but suppression not fully realized.	
Balance Function	Narrowing observed in central collisions Consistent with delayed hadronization.	
Net Charge Higher Moments	Increased expected not observable Inconclusive because of background?	
Kaon/Pion Fluctuations	Insufficient data at low beam energy	
pT Fluctuations	Scaled Correlations suppressed not enhanced.	
Ridge/Dip	No Mach Cone: Rise of Triangularity But where is the medium recoil?	

Summary (Score Card cont'd)

Measurement	Conclusion(s)/Outcome	
Correlations Longitudinal Broadening	Estimate of viscosity consistent w/ flow results	
DptDpt Correlations	Further evidence for flow & factorization	

Epilog:

- Good (Not excellent) score card!
- A + A collisions are mesoscopic systems: Collision dynamics dominates - must be accounted for before one considers system wide fluctuations.
- Correlation/Fluctuation Observables have nonetheless as a very powerful discovery tool.