FIAS

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

H-QM Helmholtz Research School Quark Matter Studies

Fluctuations and Correlations in Nucleus-Nucleus Collisions within Transport Approaches

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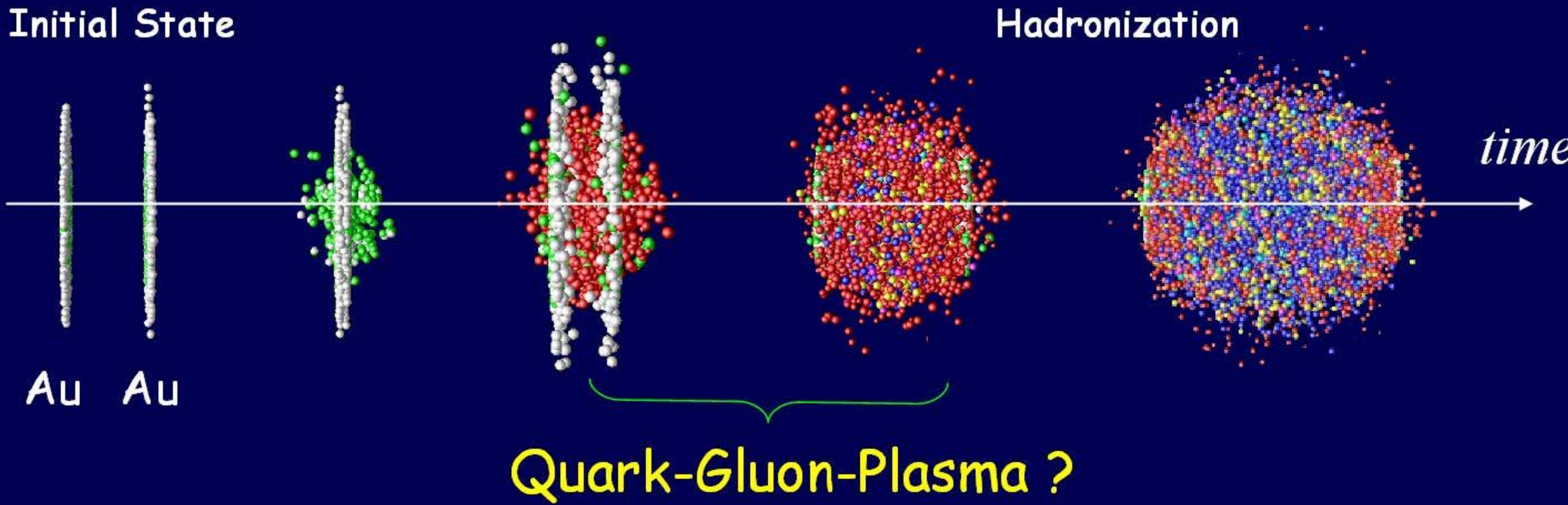
May 28, 2010

‘Little Bangs‘ in the Laboratory



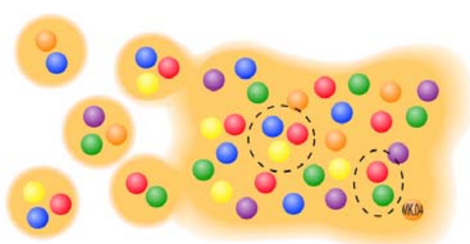
hadron degrees of freedom → quarks and gluons → hadron degrees of freedom

How can we proove that an equilibrium QGP has been created in central Au+Au collisions ?!

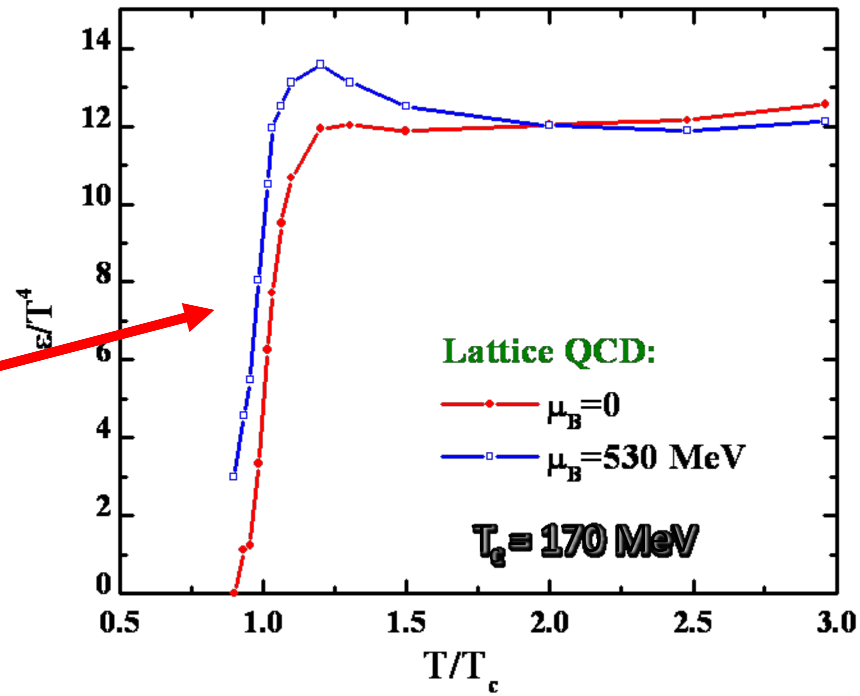
The QGP in Lattice QCD

Quantum Cromo Dynamics (fundamental theory of quark-gluon interactions):
predicts strong increase of the energy density ε at critical temperature T_C ~170 MeV

$\Rightarrow$ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~1 GeV/fm^3



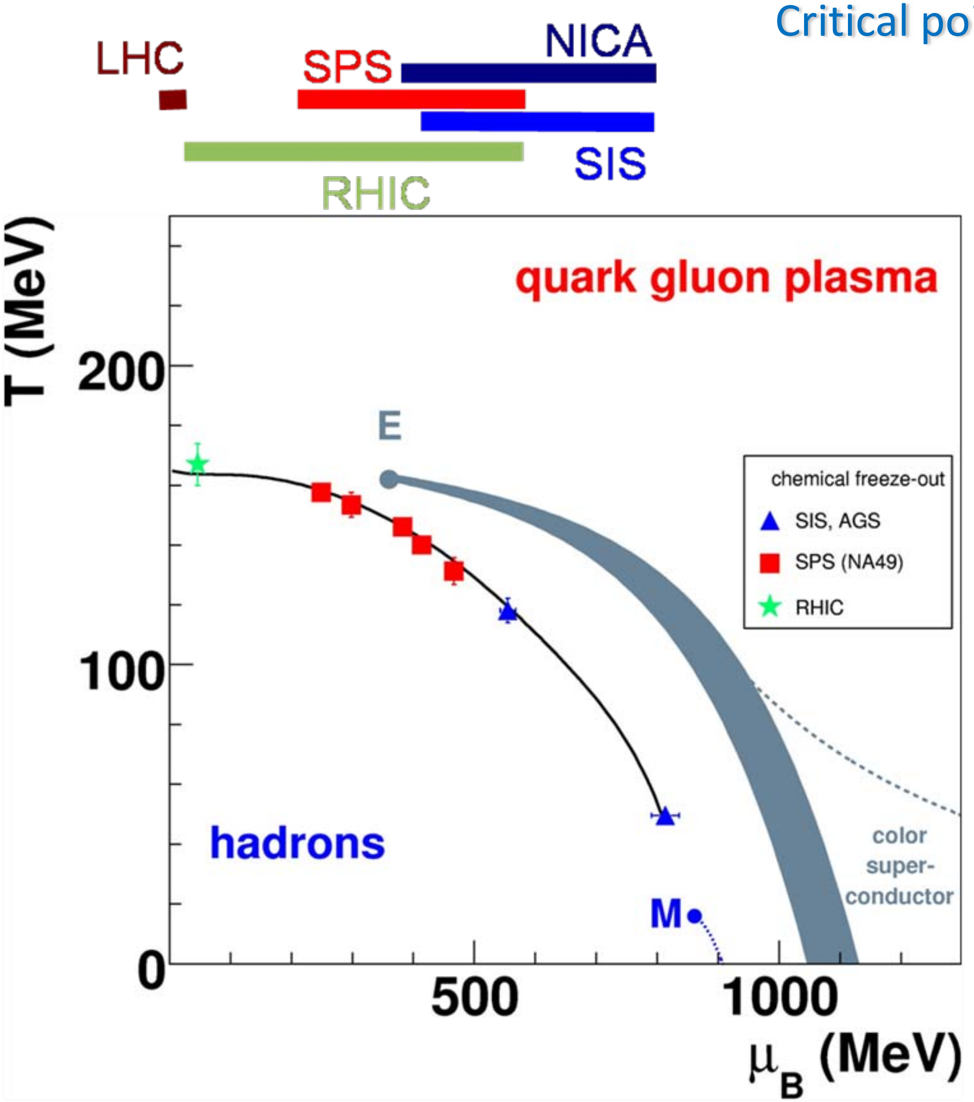
Lattice QCD:
energy density versus temperature



Z. Fodor et al., PLB 568 (2003) 73

Critical conditions - ε_C ~1 GeV/fm^3 , T_C ~170 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 AGeV

The Phase Diagram of QCD

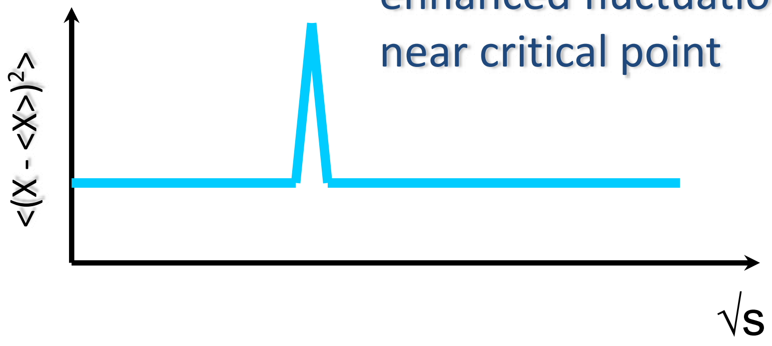


Critical point: Fodor and Katz, JHEP 0404, 050 (2004)

One of the goal for experiment:

Locate the critical point using fluctuation measurements

QCD predicts enhanced fluctuations near critical point



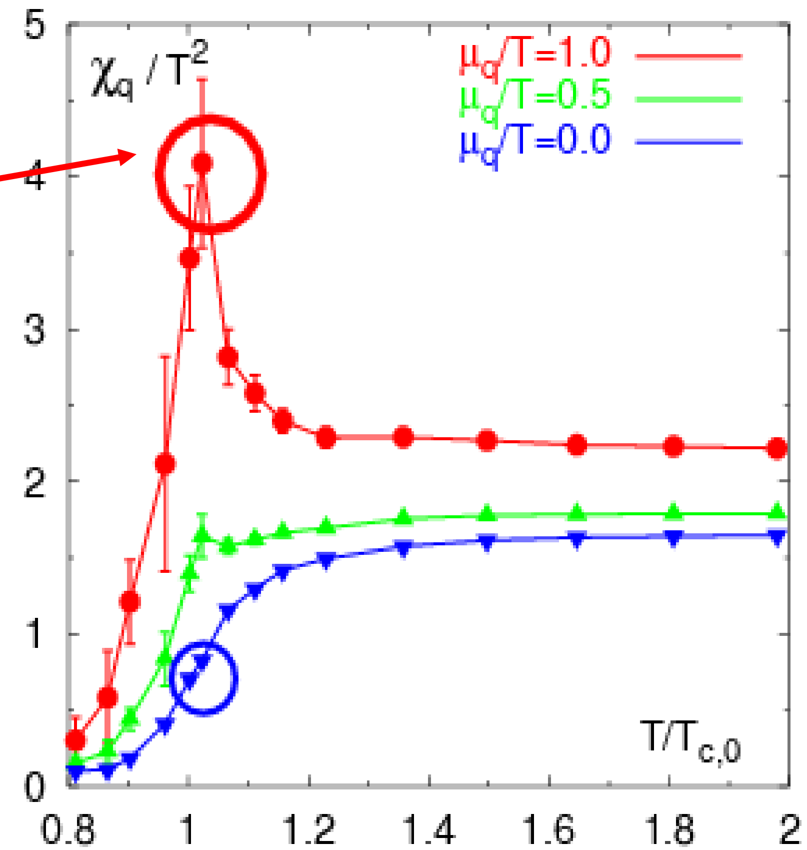
Lattice QCD: Critical Point

Allton et al., Phys. Rev. D68, 014507 (2003)

Fluctuations of the quark number density (susceptibility) at $\mu_q > 0$

$$\frac{\chi_q}{T^2} = \left[\frac{\partial^2}{\partial(\mu_q/T)^2}\frac{P}{T^4}\right]_{T_{fixed}}$$

Lattice QCD predictions:
χ_q (quark number density fluctuations) will diverge at critical chiral point =>



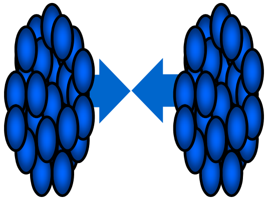
Experimental observations – look for

- baryon number fluctuations
- charge number fluctuations
- multiplicity fluctuations
- particle ratio fluctuations (K/π, p/π)
- mean p_T fluctuations
- 2 particle correlations
- ...

"Background" Fluctuations

Many factors lead to the "background" fluctuations that can mask the signal of the critical point and therefore have to be carefully studied and accounted for:

- limited size of colliding system
- fluctuations of initial condition of heavy-ion collisions
- event-by-event fluctuations of the collision geometry
- experimental acceptance
- statistical fluctuations
- …



In order to understand the "background" fluctuations we apply models, where no phase transition is implemented

- wounded nucleon model
- statistical model of hadron-resonance gas
- transport models HSD and UrQMD
- …

Basic Concept of HSD Transport Approaches

HSD – Hadron-String-Dynamics transport approach

Ehehalt, Cassing, Nucl.Phys. A602 (1996) 449;
Cassing, Bratkovskaya, Phys. Rep.308 (1999) 65.

- the phase-space density f_i follows the transport equations

$$\left(\frac{\partial}{\partial t}+\left(\nabla_{\vec{p}}H\right)\nabla_{\vec{r}}-\left(\nabla_{\vec{r}}H\right)\nabla_{\vec{p}}\right)f_i(\vec{r},\vec{p},t)=I_{coll}(f_1,f_2,\ldots,f_M)$$

with collision terms I_{coll} describing:

- elastic and inelastic hadronic reactions:

  baryon-baryon, meson-baryon, meson-meson

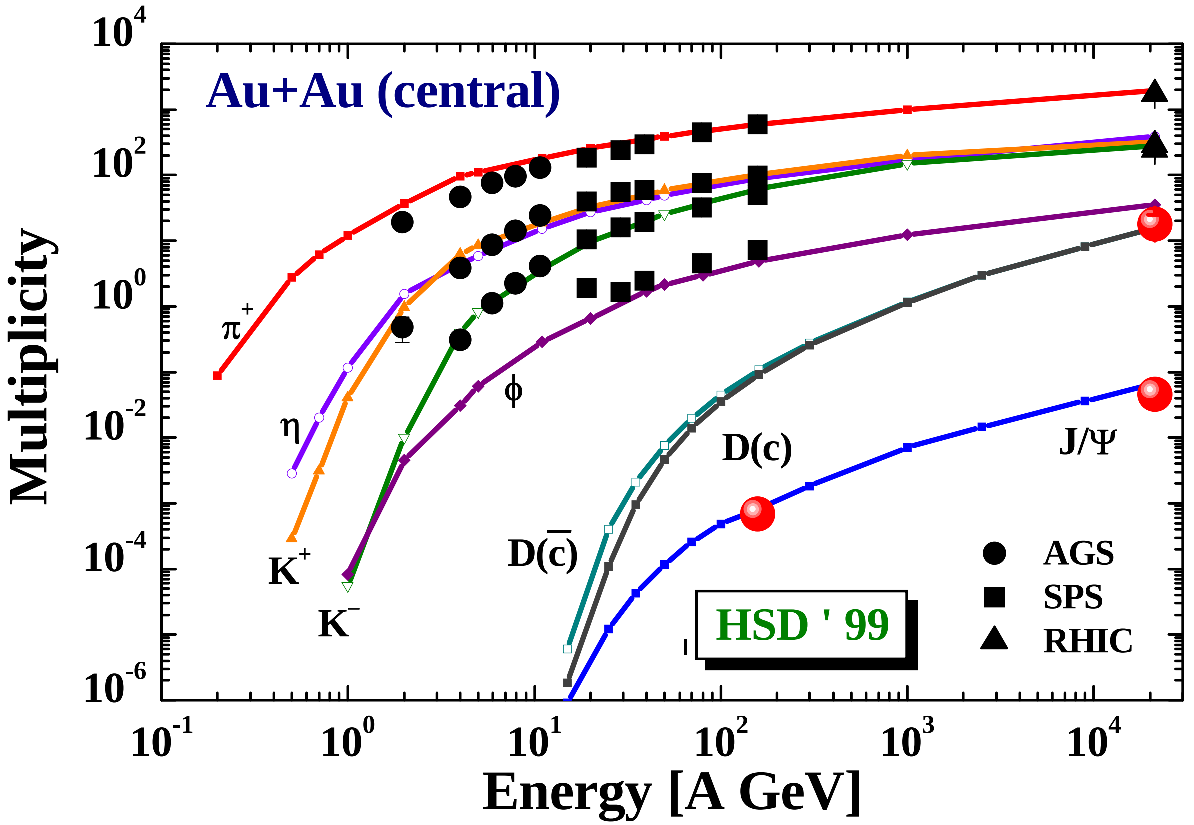
- formation and decay of baryonic and mesonic resonances
- string formation and decay

  (for inclusive particle production: BB -> X , mB -> X, X =many particles)

- implementation of detailed balance on the level of 1<->2 and 2<->2 reactions (+ 2<->n multi-particle reactions in HSD !)
- no explicit phase transition from hadronic to partonic degrees of freedom (implemented in PHSD: Cassing, Bratkovskaya Phys. Rev. C78 (2008) 034919)

HSD – a microscopic model for heavy-ion reactions

- very good description of particle production in pp, pA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (~20 TeV) energies

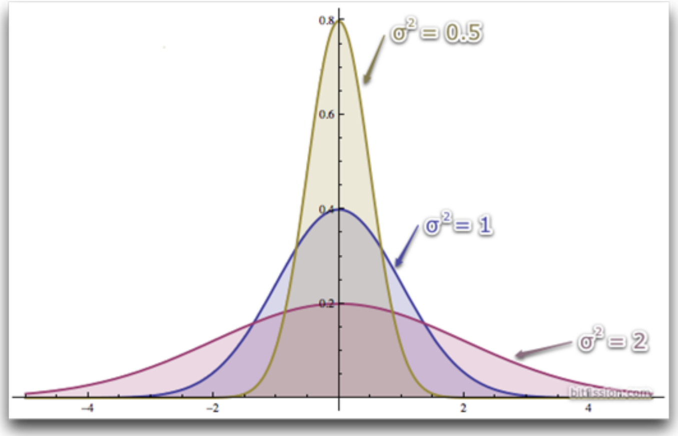


Beyond the Average Quantities: Fluctuations and Correlations

While average values of distributions can coincide, the higher moments of distributions can be different

$$\langle X^n \rangle \equiv \sum_X X^n P(X)$$

(where X – is an observable e.g. multiplicity)



One can construct measures to study fluctuations and correlations:

- Multiplicity fluctuations in some acceptance (charge, strangeness, etc.)

$$\omega = \frac{\langle (\Delta N)^2 \rangle}{\langle N \rangle} = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

- Ratio fluctuations in the acceptance (ratio of different species)

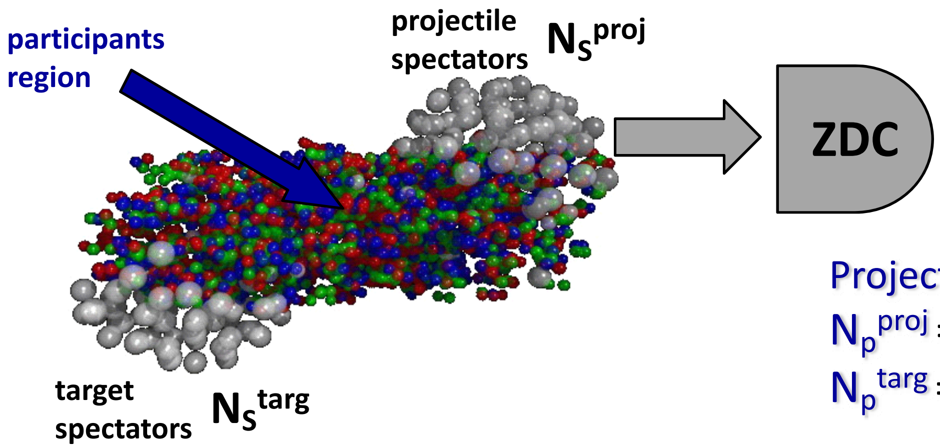
$$\sigma_{dyn}, \quad \nu, \quad etc.$$

- Correlations between different species in the acceptance

$$\rho_{AB} \equiv \frac{\langle \Delta N_A \Delta N_B \rangle}{\left[\langle (\Delta N_A)^2 \rangle \langle (\Delta N_B)^2 \rangle \right]^{1/2}}$$

- Correlations between multiplicities in different acceptance intervals
- Skewness and kurtosis

Geometry of a collision



Projectile/target participants:

$N_p^{proj} = A - N_s^{proj}$

$N_p^{targ} = A - N_s^{targ}$

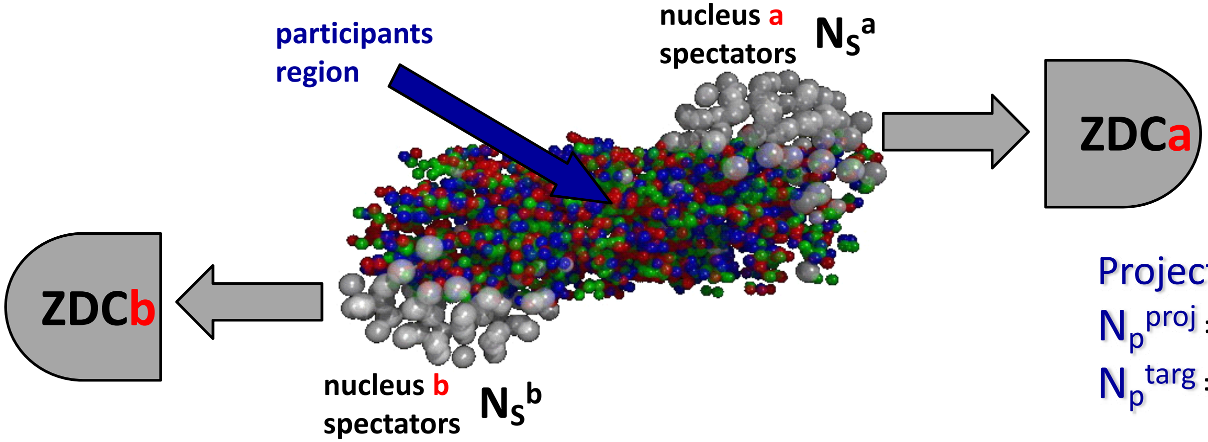
Fixed-target experiment (NA49, NA61, WA98)

- Projectile spectators can be measured precisely
- Centrality can be fixed by participants number
- Acceptance differs with energy

Collider type experiment (STAR, PHENIX)

- Spectators are fixed from both nuclei, but only neutrons (not p and fragments)
- Centrality determines in different ways (multiplicity, veto&TPC, E_T, etc.)
- The same acceptance for all energies

Geometry of a collision



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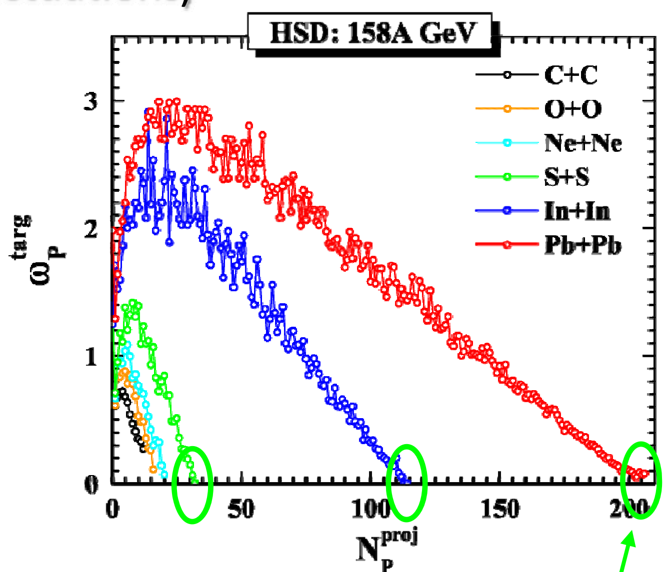
- **The same acceptance for all energies**

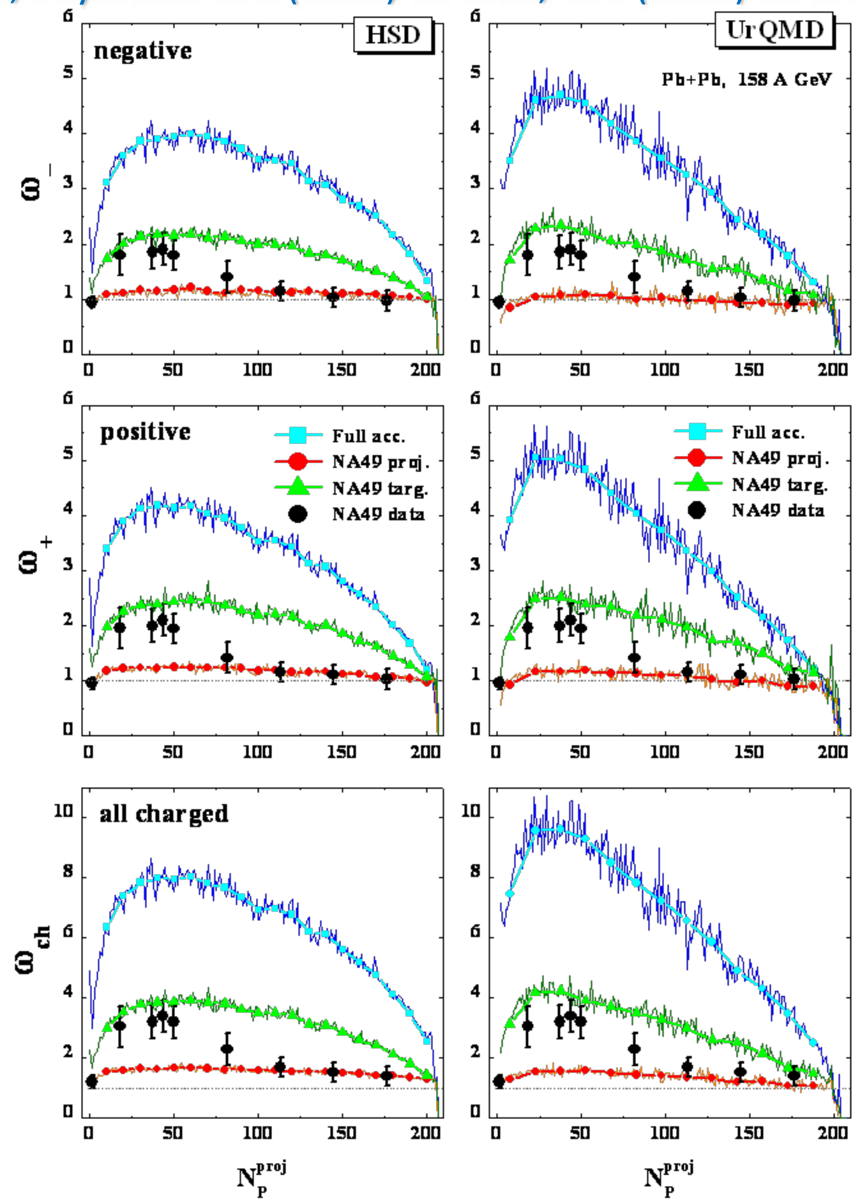
Fluctuations in the number of participants

VK, Haussler, Gorenstein, Bratkovskaya, Bleicher, Stoecker, Phys. Rev. C73 (2006) 034902; C78 (2008) 024906

- Even with fixed number of projectile participants N_p^{proj} the full number of participants N_p can fluctuate due to participant fluctuation in the target N_p^{targ}.
- Participants number fluctuations reflect in the observable fluctuations (e. g. multiplicity fluctuations)



To get rid of the fluctuations in the participant number one needs to consider only the most central collisions!

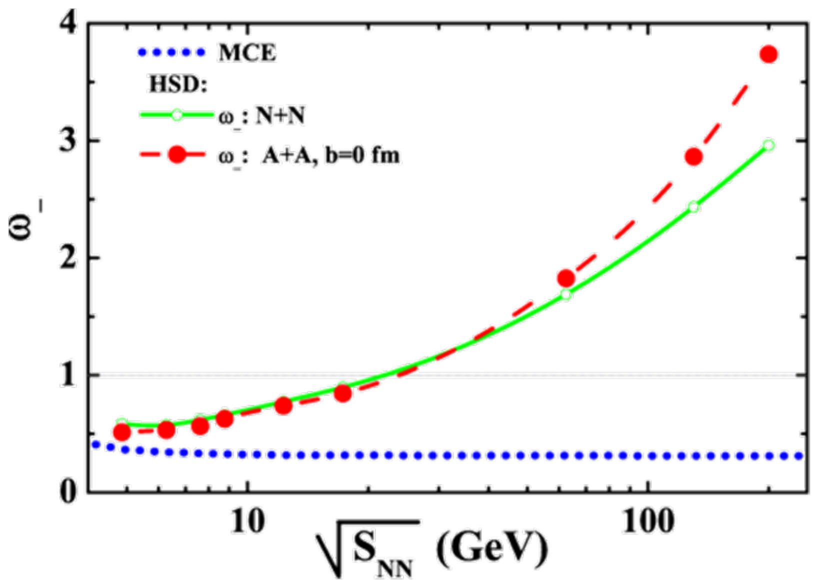


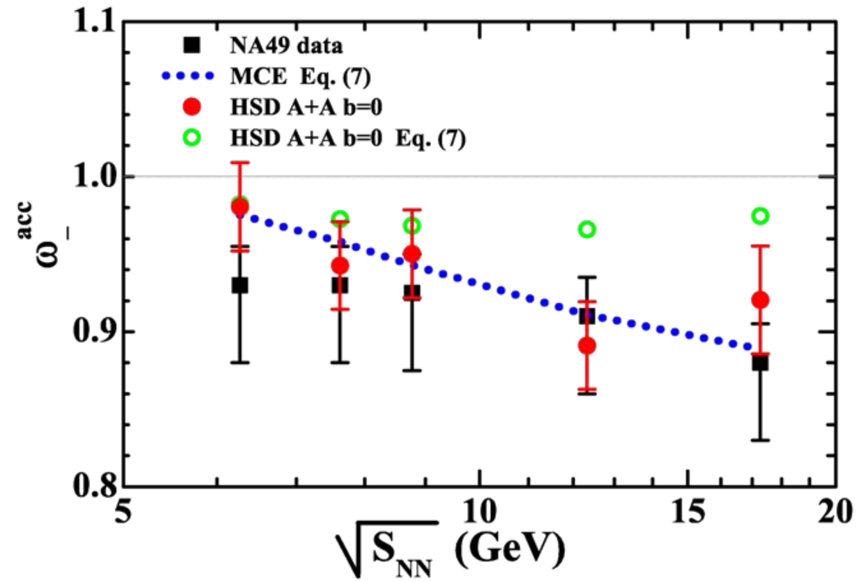
Excitation Function of Multiplicity Fluctuations in N+N and central A+A

VK, Gorenstein, Bratkovskaya, Phys. Lett. B 651, 114 (2007)

• Fluctuations in p+p and central A+A are very close within HSD.

• Statistical model shows very small and energy independent fluctuations and contradicts to the transport calculations where ω reaches significant values for large energies.



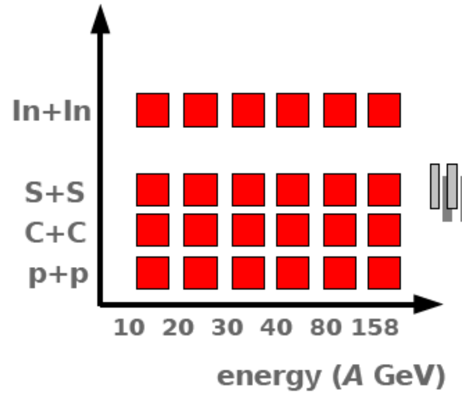


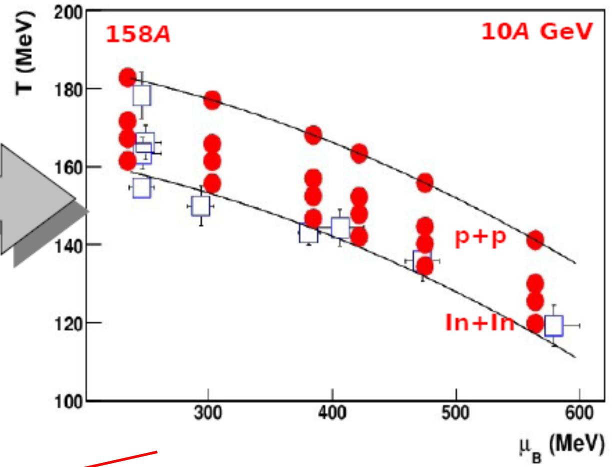
• NA49 cannot clearly distinguish between statistical and transport models because of small acceptance and small differences between the model predictions in this range of energy !

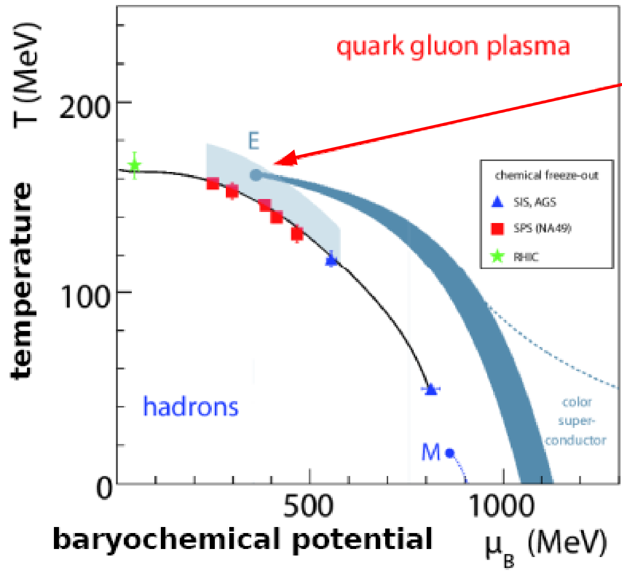
SM: Begun at al, PRC, 044903 (2006)

Fluctuations Program of NA61/SHINE Collaboration

NA61/SHINE Collaboration provides a comprehensive energy and system size scan of phase diagram at the CERN SPS







The critical point should lead to an increase of multiplicity fluctuations in two dimensional plane (energy)-(system size) or equivalently (temperature)-(baryo-chemical potential)

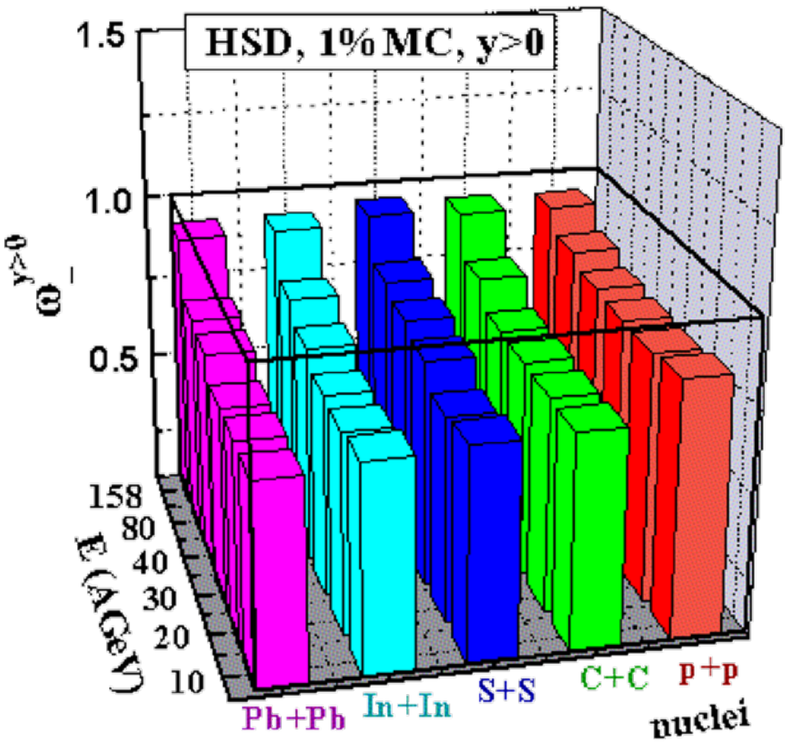
Gazdzicki, PoS CPOD2006:016

Fluctuations and CP: Stephanov, Rajagopal, Shuryak, Phys. Rev. D 60, 114028
Freeze-out points: Becattini et al., Phys. Rev. C 73, 044905

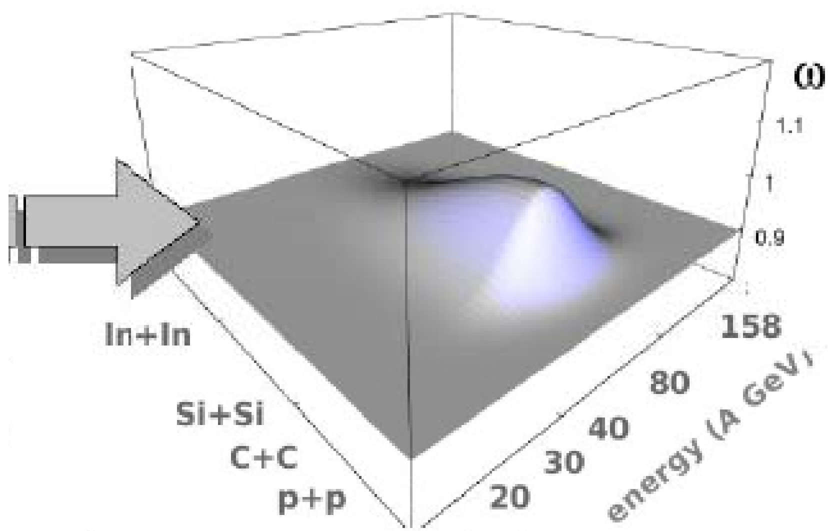
Multiplicity Fluctuations in HSD: 1%MC

VK, Lungwitz, Gorenstein, Bratkovskaya, Phys. Rev. C78 (2008) 024906

rapidity y>0



- Multiplicity fluctuations for 1%MC practically do not depend on atomic mass for y>0 and only slightly grow with increasing collision energy.

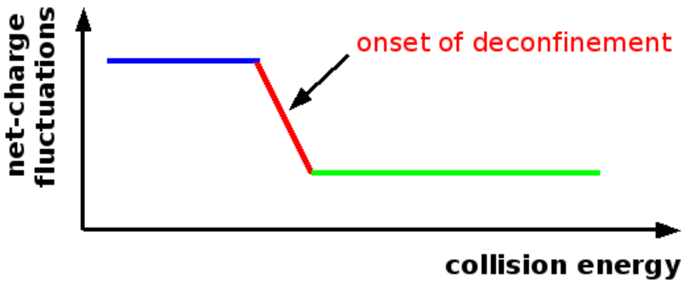


Gazdzicki, PoS CPOD2006:016

- HSD shows a plateau on the top of which the SHINE Collaboration expects to find increasing multiplicity fluctuations as a "signal" for the critical point.

Charge fluctuations

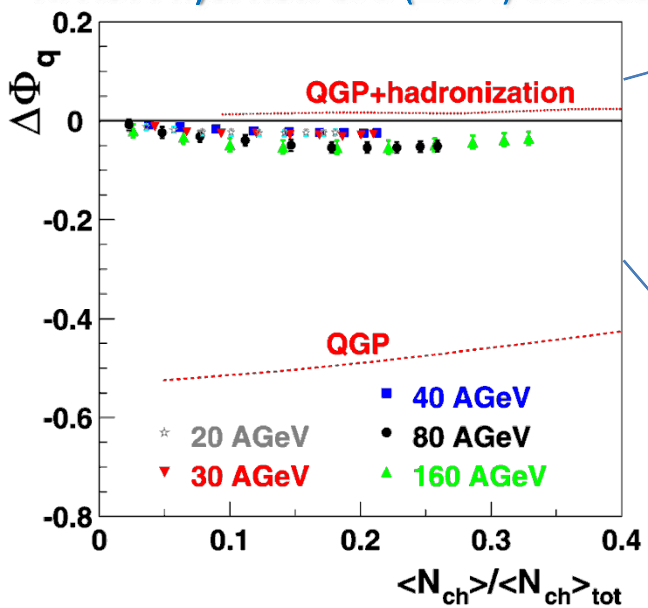
sensitive to the EoS at the early stage of the collision and to its changes in the deconfinement phase transition region



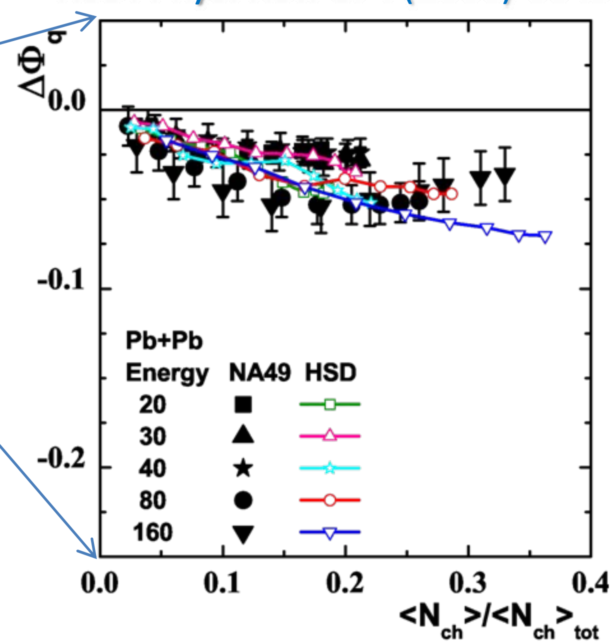
Jeon, Koch, PRL85 (2000) 2076
Asakawa, Heinz, Muller PRL85 (2000) 2072

net-charge fluctuations are smaller in QGP than in a hadron gas

NA49: Phys. Rev. C70 (2004) 064903



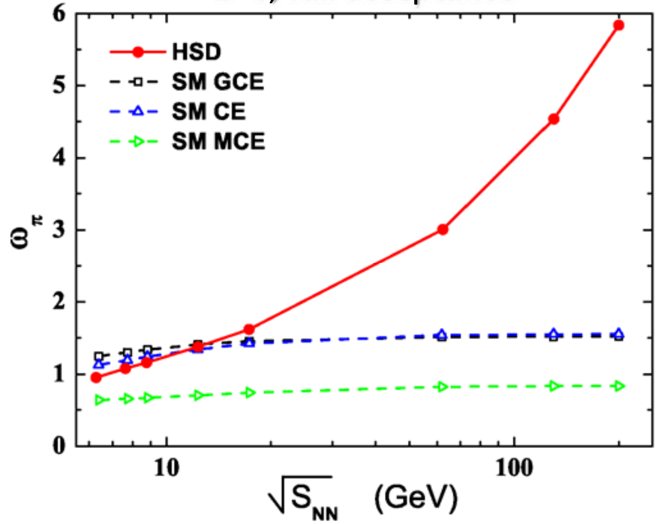
HSD: Phys. Rev. C74 (2006) 064911

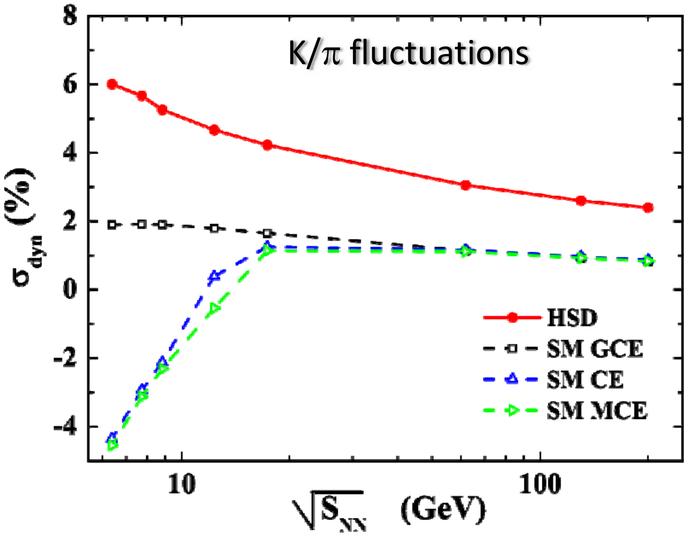


The decay of resonances strongly modifies the initial QGP fluctuations!

Statistical and HSD Model Results for Ratio Fluctuations

Gorenstein, Hauer, VK, Bratkovskaya, Phys. Rev. C 79(2009) 024907





Difference in SM and the transport model predictions for ω increases with energy!

For ratio fluctuations the measure

$$\sigma^2 \equiv \frac{\langle \Delta (N_A/N_B)^2 \rangle}{\langle N_A/N_B \rangle^2}$$

is used. In assumption $|\Delta N_A| \ll \langle N_A \rangle, \quad |\Delta N_B| \ll \langle N_B \rangle$ it can be rewritten as:

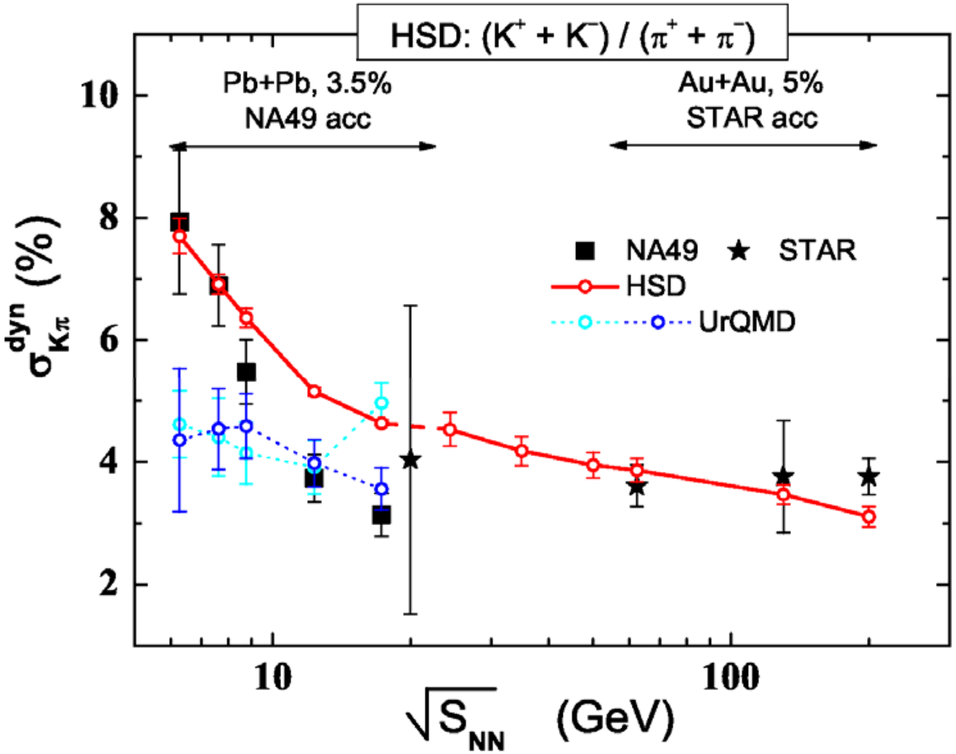
$$\sigma^2 \cong \frac{\omega_A}{\langle N_A \rangle} + \frac{\omega_B}{\langle N_B \rangle} - 2\rho_{AB} \left[\frac{\omega_A \omega_B}{\langle N_A \rangle \langle N_B \rangle} \right]^{1/2}$$

After subtraction of σ for mixed events one gets:

$$\sigma_{dyn} \equiv \pm |\sigma^2 - \sigma^2_{mix}|^{1/2} \times 100\%$$

- For σ_{dyn} SM and HSD differ for small energies in contrast to ω!

K/π Ratio Fluctuations: Transport vs Data



- Exp. data show a plateau from top SPS up to RHIC energies and an increase towards lower SPS energies.

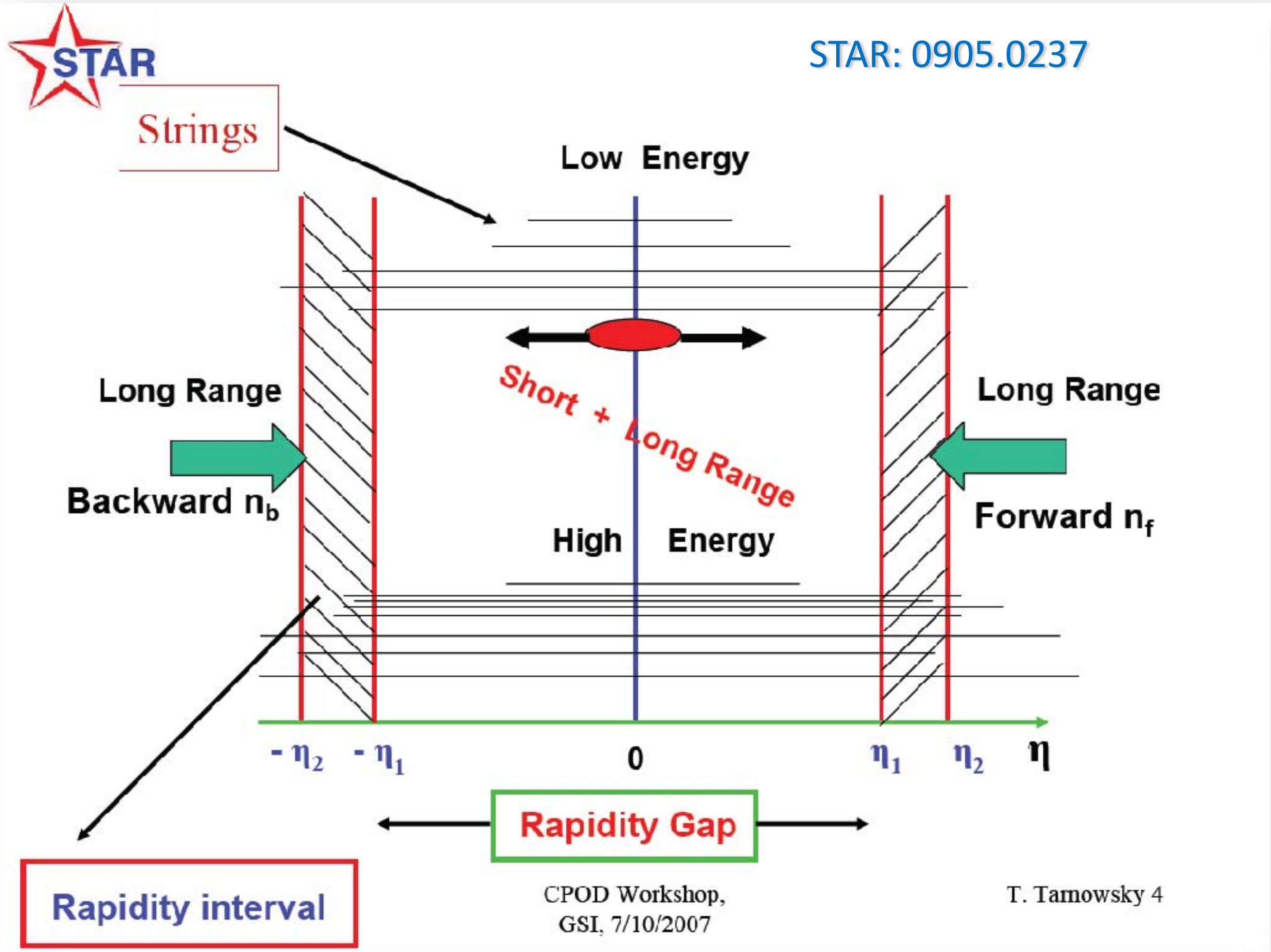
evidence for a critical point at low SPS energies ?

- But the HSD results shows the same behavior.

- K/π ratio fluctuations are driven by hadronic sources. No evidence for a critical point in the K/π ratio ?

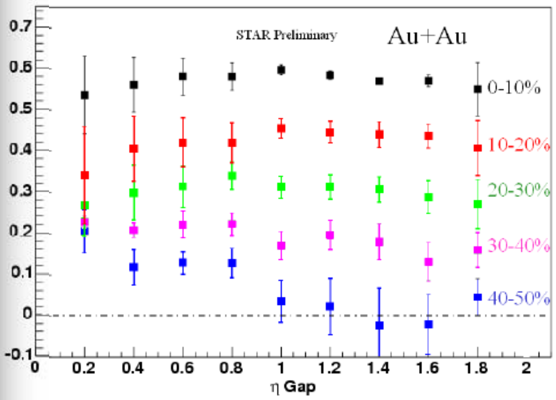
HSD: Phys. Rev. C 79 (2009) 024907
UrQMD: J. Phys. G 30 (2004) S1381, PoS CFRNC2006,017
NA49: 0808.1237
STAR: 0901.1795

Forward-Backward Correlations in Nucleus-Nucleus Collisions: Baseline Contributions from Geometrical Fluctuations?



$$\rho_{fb} \equiv \frac{\langle \Delta N_f \cdot \Delta N_b \rangle^{\eta gap}}{\sqrt{\langle (\Delta N_f)^2 \rangle^{\eta gap} \ \langle (\Delta N_b)^2 \rangle^{\eta gap}}}$$

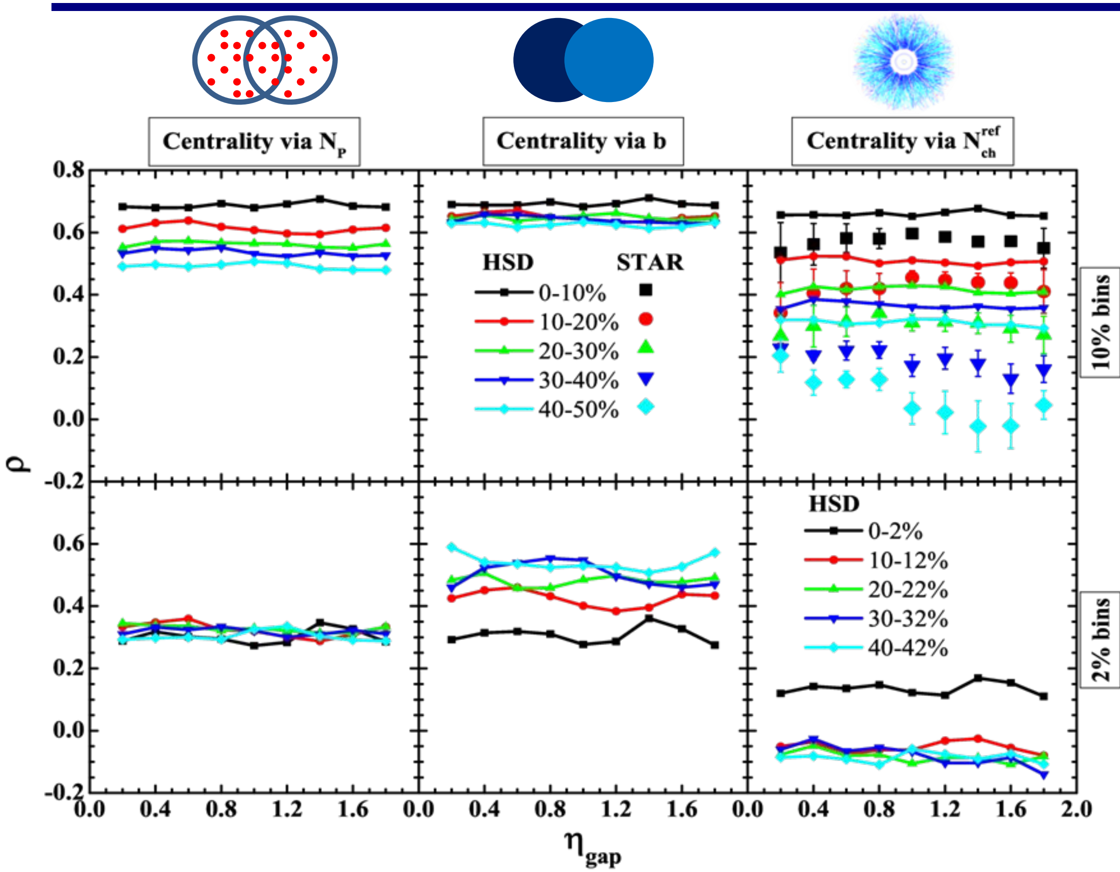
Au+Au √s = 200 GeV



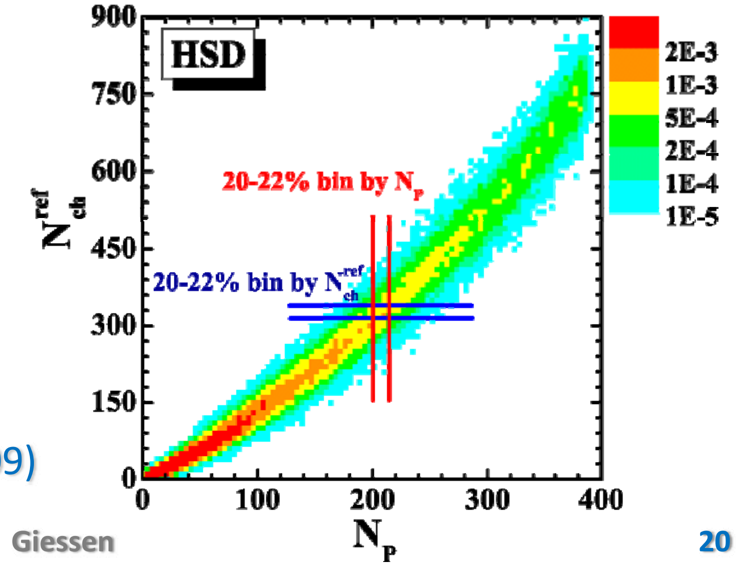
STAR:
More central collision -> higher correlations.

Interpretation:
- Dual Partonic Model?
- CGC?
- Geometrical fluctuations?

Forward-Backward Correlations: Au+Au 200 GeV



- Correlation coefficient strongly depends on centrality definition.
- When decreasing the width of centrality bins the FB correlation becomes weaker.



- Different centrality definitions lead to different event samples in the same centrality class. This is crucial for small centrality bins!

VK, Hauer, Torrieri, Gorenstein, Bratkovskaya, Phys.Rev.C79 (2009)

Summary

- The systematic study of fluctuations and correlations in microscopic transport approaches has been performed as a function of centrality, energy, experimental acceptance and system size. The results can be used as a baseline for the experimental and theoretical study of deconfinement and the critical point.

- The fluctuations in the number of target participants – for fixed projectile participants - strongly influence all observable fluctuations.

- Statistical and transport models show different results in central A+A collisions for multiplicity fluctuations versus energy. To distinguish between models new measurements at higher energies and with larger acceptance are needed!

- Transport models show a smooth energy and atomic number dependence for the multiplicity fluctuations. Thus, the hadron-string model (without explicit phase transition!) demonstrates that the expected enhanced fluctuations - attributed to the critical point and phase transition - can be observed experimentally on top of a monotonic and smooth 'background'.

- HSD results for the K/π ratio fluctuations show that it grows at low SPS energies, the same as in the data! The results of transport models for K/p and p/π ratio fluctuations do not fully reproduce experimental data and are inconclusive.

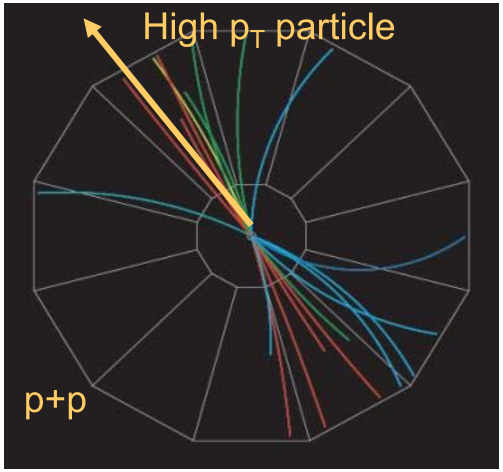
- Forward-backward correlations show a large sensitivity on the initial collisional geometry and centrality bin definition!

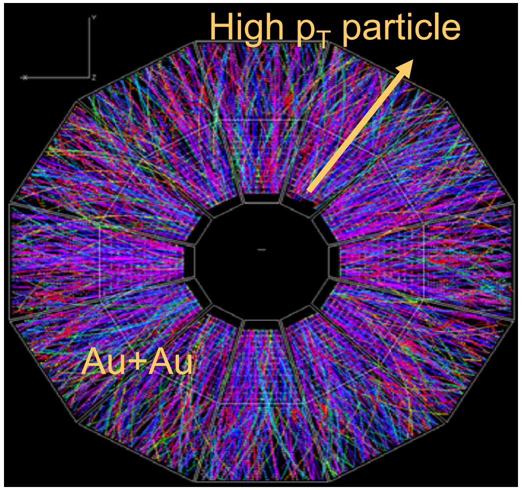
The results are published in:

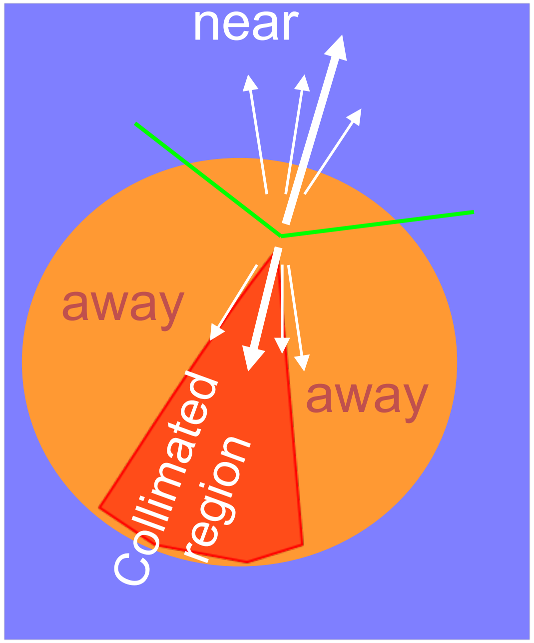
1. VK, S. Haussler, M.I. Gorenstein, E.L. Bratkovskaya, M. Bleicher and H. Stoecker. **PRC**73,034902(2006).
2. VK, M.I. Gorenstein, and E.L. Bratkovskaya. **Phys.Rev.C**76, 031901 (2007).
3. VK, M.I. Gorenstein, E.L. Bratkovskaya, and H. Stoecker. **Phys.Rev.C**74, 064911 (2006).
4. V.V. Begun, M. Gazdzicki, M.I. Gorenstein, M. Hauer, VK and B. Lungwitz. **Phys.Rev.C**76,024902(2007).
5. VK, M.I. Gorenstein, and E.L. Bratkovskaya. **Phys.Lett.B**651, 114 (2007).
6. VK, B. Lungwitz, M.I. Gorenstein, and E.L. Bratkovskaya. **Phys.Rev.C**78, 024906 (2008).
7. M.I. Gorenstein, M. Hauer, VK, and E.L. Bratkovskaya. **Phys.Rev.C**79, 024907 (2009).
8. VK, M. Hauer, M.I. Gorenstein and E.L. Bratkovskaya. **Jphys.G**36, 125106 (2009).
9. VK, M. Hauer, G. Torrieri, M.I. Gorenstein and E.L. Bratkovskaya. **Phys.Rev.C**79, 034910 (2009).
10. VK. **PoS CFRNC2006**, 010 (2006).
11. VK. **“New trends in high-energy physics”,** 207 (2007).
12. VK. **PoS CPOD07**, 021 (2007).
13. M. Hauer, V.V. Begun, M. Gazdzicki, M.I. Gorenstein, VK and B. Lungwitz. **J. Phys.G**35, 044064 (2008).
14. VK. **“Progress in High Energy Physics and Nuclear Safety”,** 139 (2008).
15. VK, M. Hauer, M.I. Gorenstein and E.L. Bratkovskaya. **PoS CPOD2009**, 030 (2009).
16. VK. **J.Phys.G** in print, arXiv: 0912.5157.
17. VK, M.I. Gorenstein, E.L. Bratkovskaya, W. Greiner. **J. Phys. G**37, 073101 (2010) review article.

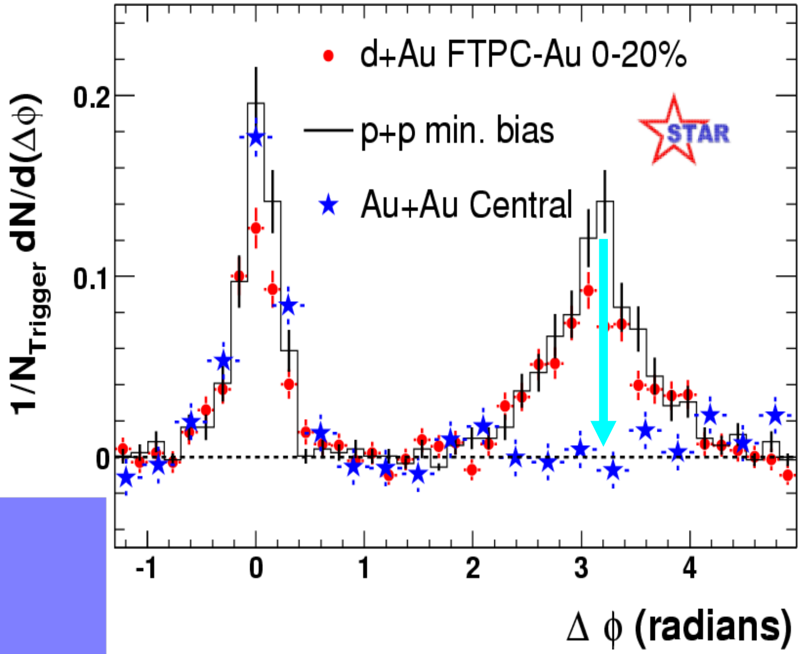
Jet quenching and angular correlations in A+A

Jet Energy Loss



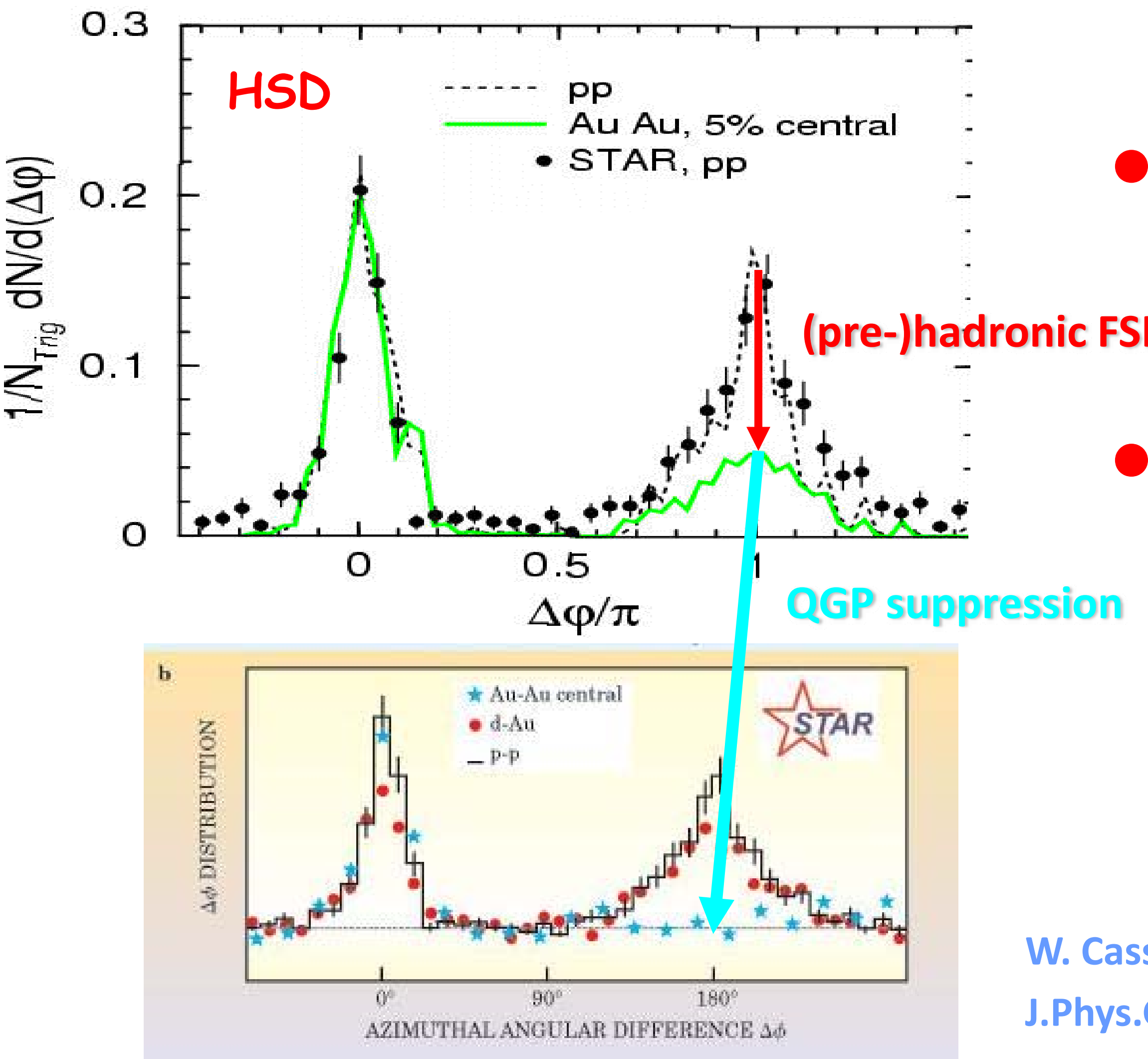






QGP suppression ?!

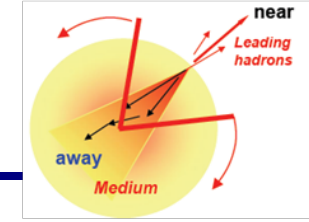
Jet suppression: dN/dφ (HSD)



- The jet angular correlations for pp are fine!
- The near-side jet angular correlation for central Au+Au is well described, but the suppression of the far-side jet is too low!

W. Cassing, K. Gallmeister and C. Greiner, J.Phys.G30 (2004) S801; NPA 748 (2005) 241

New exp. data: $\phi-\eta$ angular correlations



Intermediate p_T: near-side ridge

STAR

arXiv:0808.4096

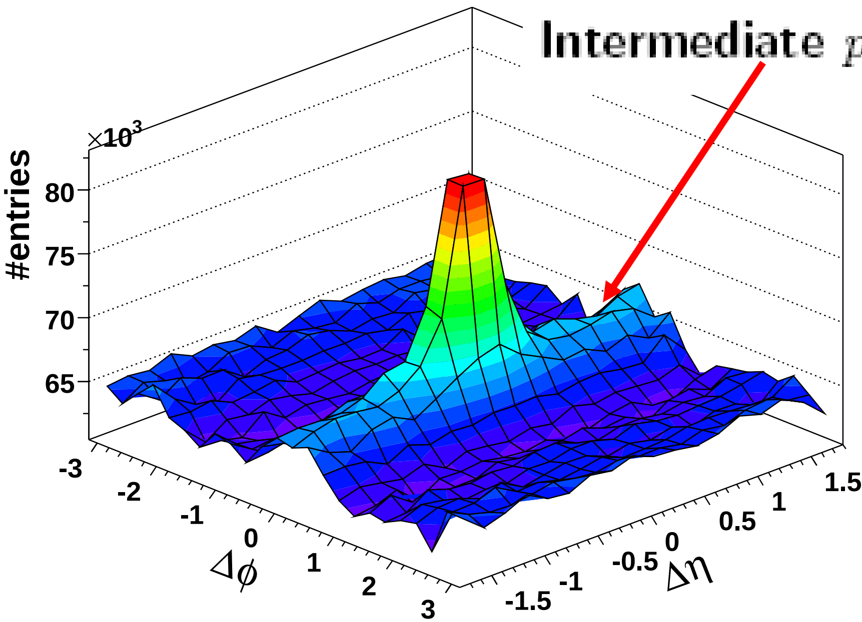


Fig. 1. (Color on-line) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/$c < p_T^{assoc} < p_T^{trig}$ in 0-12% central Au+Au collisions. Two different trigger p_T selections are shown: $3 < p_T^{trig} < 4$ GeV/c (upper panel) and $4 < p_T^{trig} < 6$ GeV/c (lower panel). No background was subtracted.

PHOBOS

arXiv:0903.2811

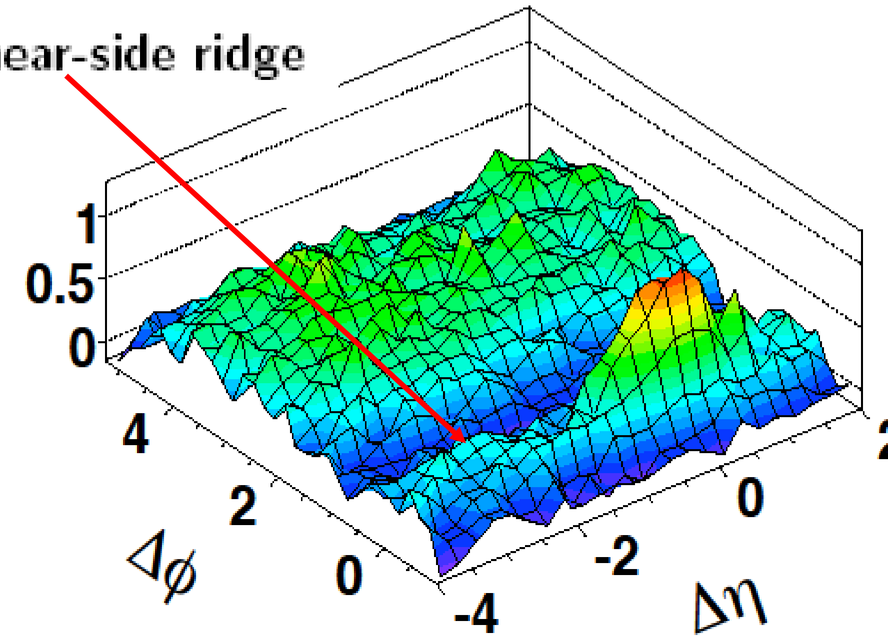
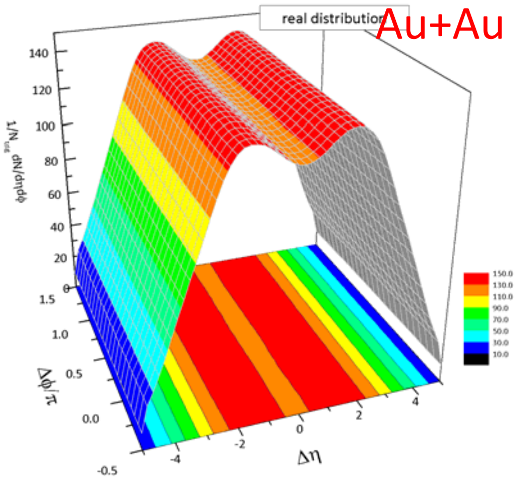


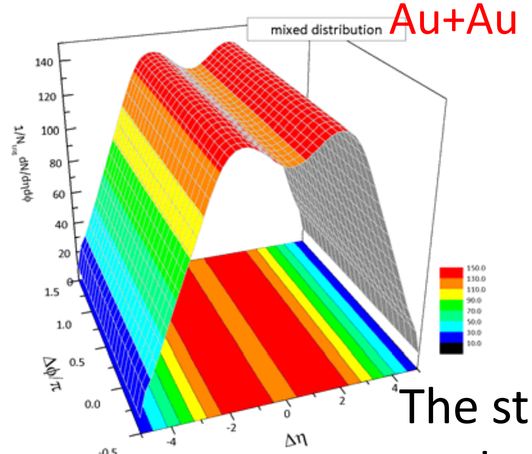
FIG. 2: (color online) Per-trigger correlated yield with $p_T^{trig} > 2.5$ GeV/c as a function of $\Delta\eta$ and $\Delta\phi$ for $\sqrt{s}$ and $\sqrt{s_{NN}}$=200 GeV (a) PYTHIA p+p and (b) PHOBOS 0-30% central Au+Au collisions. (c) Near-side yield integrated

High p_t particle correlations in HSD (preliminary)

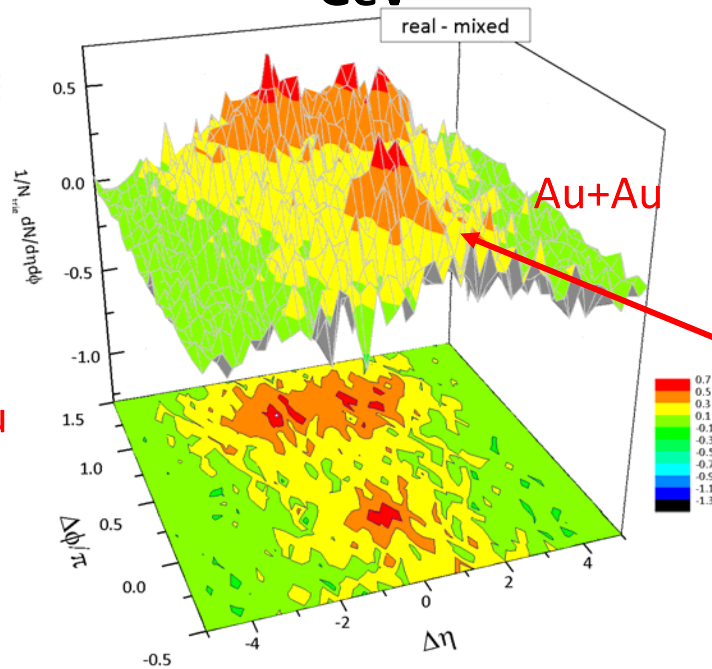
Real distribution

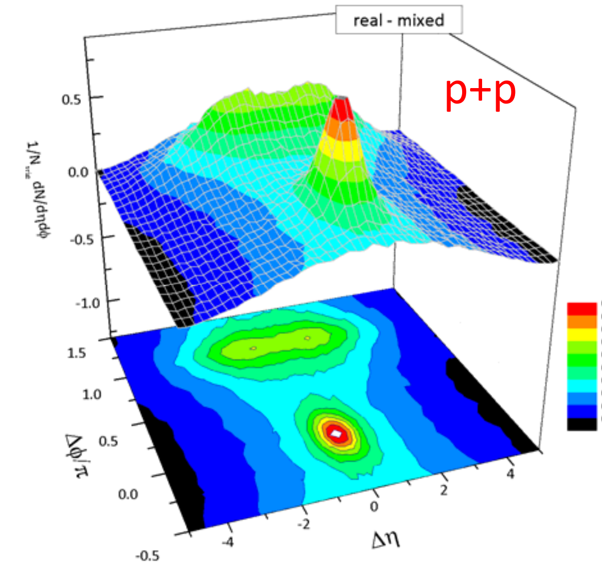


Mixed distribution

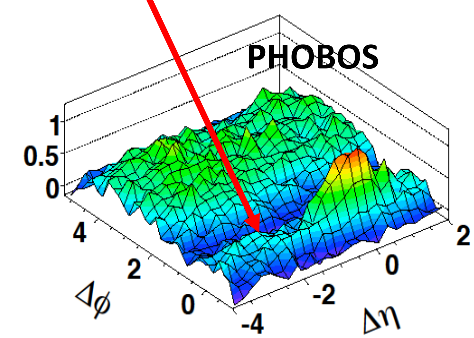


Intermediate p_T:
p_T(trig) > 2.5 GeV/c
0.02 < p_T(assoc) < 2.5 GeV





Preliminary HSD:
no near-side ridge found ?



The structure is seen in Au+Au collision only after background subtraction.