Particle-antiparticle back-to-back correlation measurement in 200 GeV Au+Au collisions

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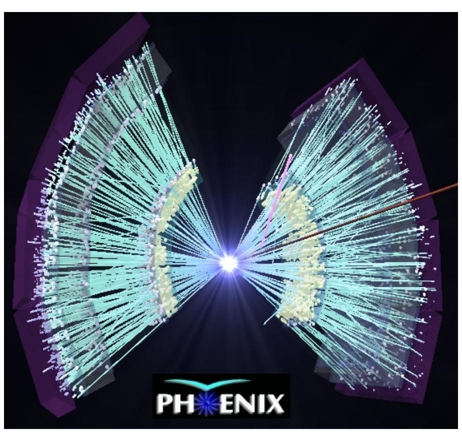

Zimányi 2009 Winter
School on Heavy Ion Physics

Outline

- Summary of motivation: Mass modification & squeezing
  - **- In-medium mass modification: mean-field models & chiral symmetry restoration**
  - **- Two-mode Bogoliubov transformations, squeezed correlations**
- Experimental details
  - **- The PHENIX detector system: capabilities**
  - **- Analysis procedure: new methods in the measurement**
- Result, discussion
  - **- Measured back-to-back correlation functions**
  - **- Systematic checks**
  - **- Possible physical implications**
  - **- Future tasks**

Motivation

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Expectation:

- In-medium mass modification of hadrons lead to soft particle-antiparticle back-to-back correlations

M. Asakawa, T. Csörgő, M. Gyulassy, Phys. Rev. Lett. 83, 4013-4016, (1999)

S. S. Padula, T. Csörgő, Braz. J. Phys. 37, 949-962, (2007)

- New type of quantum mechanical correlations, different from:

- HBT <-> back-to-back

- Jet-jet correlations <-> soft phenomenon, not from hard scattering

Practical distinction: only between particles and antiparticles

Predicted signal is sensitive to:

- mass modification (prerequisite), thus freeze-out characteristics of the matter in heavy-ion collisions, phase transition ...

- freeze-out & collective dynamics: detailed simulations show dependence on flow, system size, etc. Importantly: freeze-out time & distribution

Background

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- Signal presence possibility in relativistic heavy ion collisions
  - **- At RHIC: hadronization process: 1st order phase transition is not probable (based on azimuthally sensitive HBT measurements), a crossover-type of transition is favoured by lattice calculations -> thermalized medium with hadron content is probable**
- Possible sources of particle mass modifications:
  - **- In many (most) mean-field models of hadronic medium, a mass modification is generated by hadronic interactions if thermalized**
  - **- Chiral symmetry restoration: possible in-medium mass drop of η' mesons**
    - - HBT measurements support this scenario in 200 GeV Au+Au collisions:
    - *R. Vértesi, T. Csörgő, J. Sziklai, arXiv:0905.2803 [nucl-th]*
  - **- Presence of hadronic medium during freeze-out process is thus a plausible assumption in 200 GeV heavy-ion collisions: can cause in-medium mass modification for any hadrons**

Theoretical introduction

Thermalization in a medium:

- Two-mode „squeezing" transformation of creation & annihilation operators $a_{\mathbf{p}}^{(+)\dagger}$, $a_{\mathbf{p}}^{(+)}$: for normal mass, $b_{\mathbf{p}}^{(+)\dagger}$, $b_{\mathbf{p}}^{(+)}$: for in-medium modified mass, (+): particles, (-): antiparticles

- If a boson's in-medium mass is different from nominal value:

$$b_{\mathbf{p}}^{(+)} = \cosh r_p a_{\mathbf{p}}^{(+)} - \sinh r_p a_{-\mathbf{p}}^{(-)\dagger} \qquad b_{\mathbf{p}}^{(-)} = \cosh r_p a_{\mathbf{p}}^{(-)} - \sinh r_p a_{\mathbf{p}}^{(+)\dagger}$$

$$b_{\mathbf{p}}^{(+)\dagger} = -\sinh r_p a_{-\mathbf{p}}^{(-)} + \cosh r_p a_{\mathbf{p}}^{(+)\dagger} \qquad b_{\mathbf{p}}^{(-)\dagger} = -\sinh r_p a_{\mathbf{p}}^{(+)} + \cosh r_p a_{\mathbf{p}}^{(-)\dagger}$$

- „Squeezing parameter" related to mass modification: $r_p = \frac{1}{2} \ln \frac{\omega_p}{\Omega_p}$

- Thermal distribution in medium is in terms of the „squeezed" states

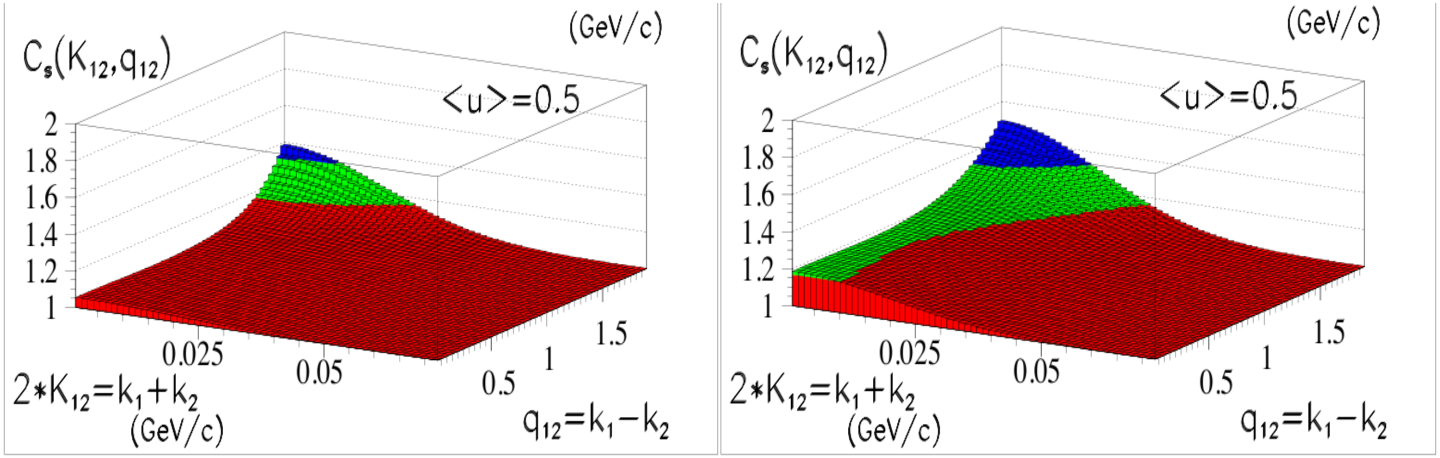
$$\mathcal{H}_0 = \int \mathrm{d}\mathbf{p}\, \omega_{\mathbf{p}} \left\{ a_{\mathbf{p}}^{(+)\dagger} a_{\mathbf{p}}^{(+)} + a_{\mathbf{p}}^{(-)\dagger} a_{\mathbf{p}}^{(-)} + \dots \right\}$$: Non-mass-modified Hamiltonian

$$\mathcal{H}_1 = \int \mathrm{d}\mathbf{p}\, \Omega_{\mathbf{p}} \left\{ b_{\mathbf{p}}^{(+)\dagger} b_{\mathbf{p}}^{(+)} + b_{\mathbf{p}}^{(-)\dagger} b_{\mathbf{p}}^{(-)} + \dots \right\}$$: Mass-modified Hamiltonian

- Squeezed state with definite momentum: superposition of „normal" states with opposite momenta

Predictions for possible signal

- So the decay of the mass-modifying volume would lead to particle-antiparticle *back-to-back* correlation
  - **- In principle, strength is unlimited from above: clear difference from HBT**
  - **- Collective dynamics smears the signal**
  - **- Experimentally: measure correlation, $C_{BB}(K)$ in terms of $K \equiv |\mathbf{k}_1 + \mathbf{k}_2|$**
- Many calculations done for ϕ mesons, recently some for kaons
  - **- Examples for kaons:**



S. S. Padula, D. M. Dudek, O. Socolowski, Jr., Acta Phys. Polon. B40, 1225-1230, (2009)

Potential discovery channels

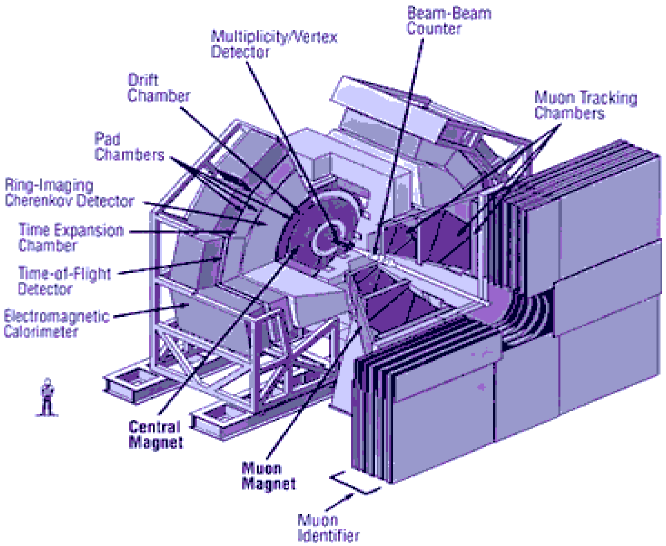
- Φ meson: ruled out by statistics in 200 GeV Au+Au collisions, for now
- Other important ingredient: signal is suppressed due to finite emission times (i.e. non-instantaneous production of final hadrons)
  - **- Suppression factor depending on energy:** $|\tilde{F}(\omega_{\mathbf{k}} + \omega_{-\mathbf{k}})|^2$
- Fourier-transform of freeze-out distribution makes one worry:

$$\tilde{F}(\omega) = \int dt F(t) \exp(-i\omega t)$$

  - **- For a typical exponential decay, it is Lorentz-type (power-law suppression)**
    - **- for $\Delta t \sim$1-2fm/c: signal can survive suppression -> discovery channel would be intermediate momentum pions, kaons, protons**
  - **- For non-exponential (e.g. Gaussian, Levy-type) freeze-out distribution: suppression is „worse" than *exponential;* huge (uncertain) suppression**
    - **- Only possible discovery channel is (very) low momentum pions (kaons, protons are excluded), but: resonance contamination ...**

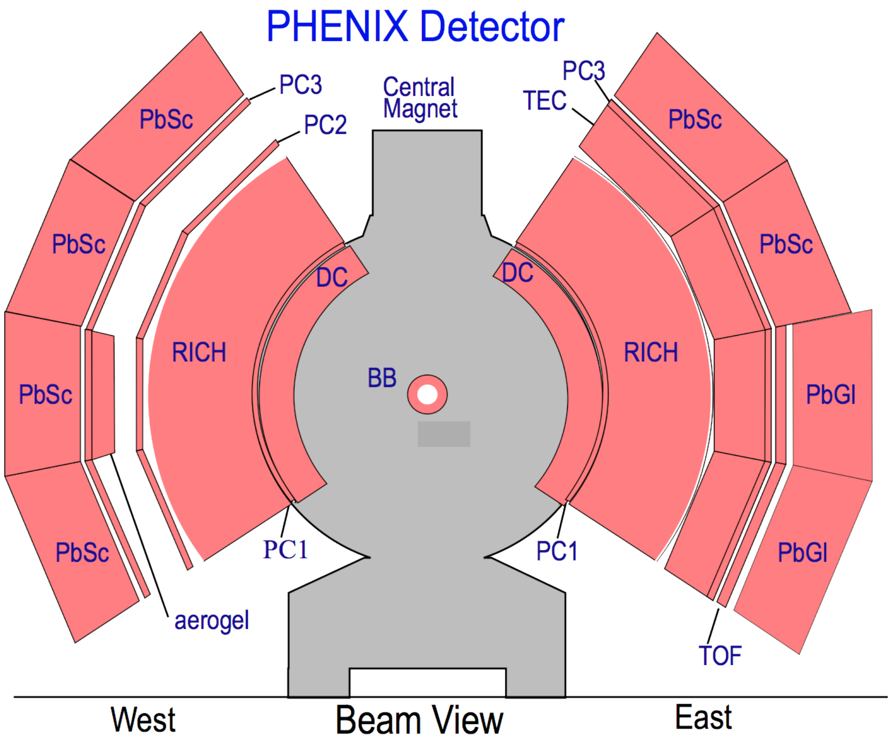
Experiment

- RHIC: unique opportunity to study extreme temperature & pressure nuclear matter
- PHENIX:
  - **- Philosophy: good particle identification (PID) capabilities for broad range of momentum, for photons, hadrons, electrons, muons, ... sacrifice acceptance**
  - **- The present analysis strongly relies on PID, thus PHENIX has excellent potential...**



Experimental setup

PHENIX in 2004:



Reasons for 2004 data:

- **Computational needs for calibration**
- **Less background at lower momentum**

Used subsystems:

- **Beam-to-Beam Counter: trigger, vertex & centrality (with Zero Degree Calorimeter)**
- **Drift Chamber & Pad Chambers: track reconstruction & verification**
- **Time of Flight & PbSc calorimeter: timing -> charged hadron PID at p_T=0.15-1.2 GeV (low p_T PID explored in PHENIX for the first time)**

Analysis details

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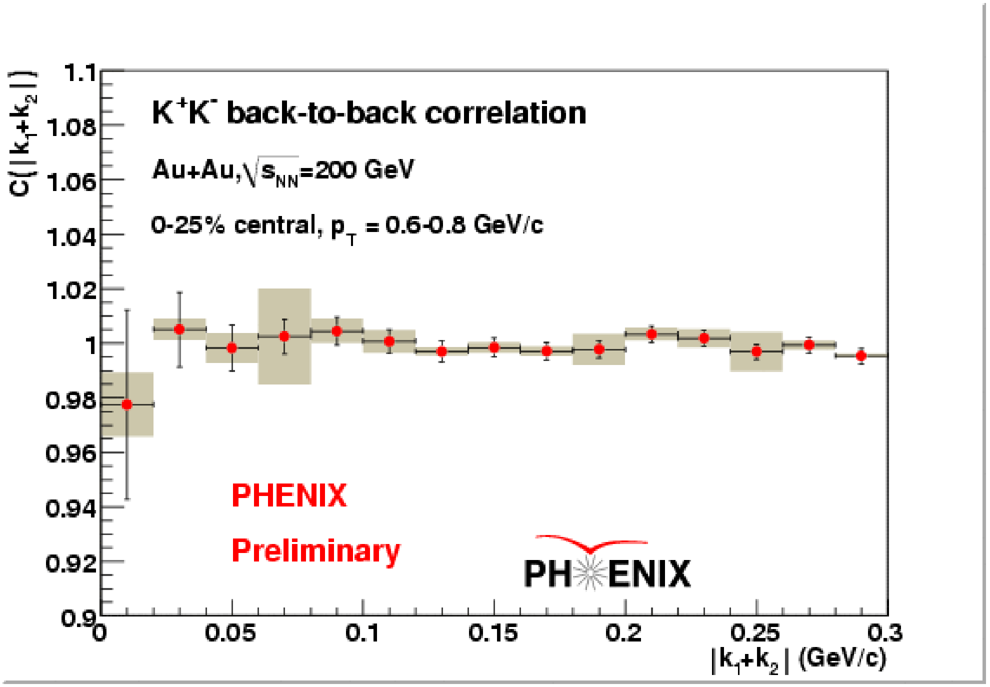
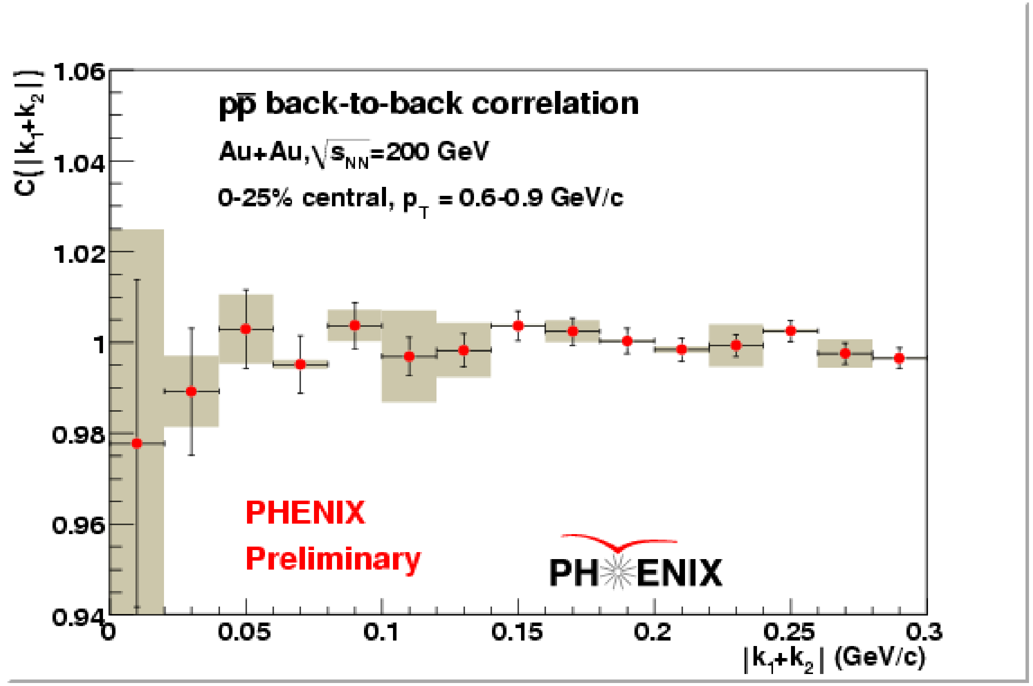
- Used momentum range nomenclature:
  - - "High" momentum: hard scattering regime
  - - "intermediate" momentum: non-perturbative, but highly relativistic domain
  - - "low" momentum regime: p_T around rest mass
- Data analysis technique not so different from HBT measurements:
  - - Track matching cuts (needed (hyper)fine tuning for reliable PID at low p_T) in PC3, PbSc and TOF; track splitting/merging cuts in DCH, PC1, PbSc/TOF
  - - Timing (m^2 spectrum) cuts for PID of pions, kaons and protons
  - - Measured: normalized actual pair distribution / mixed event pair distribution
- Results:
  - - On following slides, selected measurements are presented

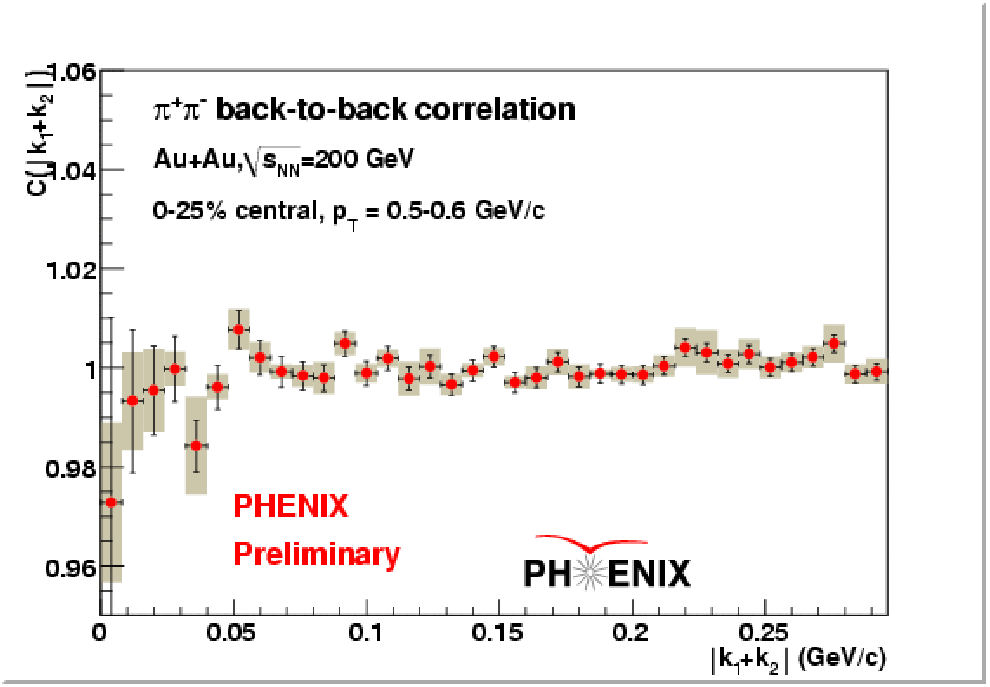
Results: kaons, protons

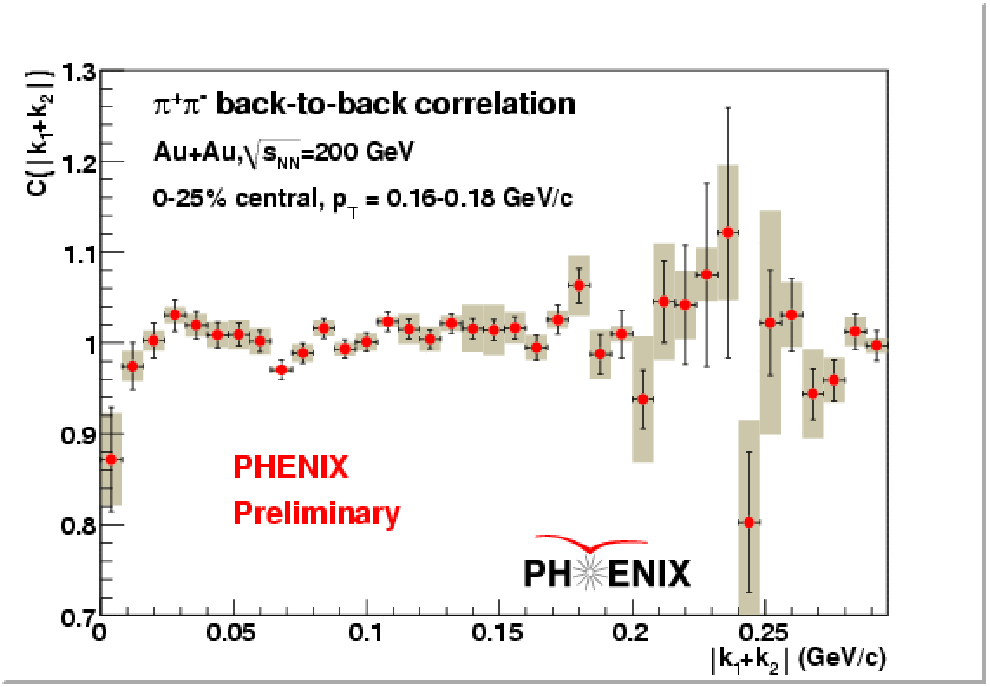




- No visible deviation from 1 is found
  - - Neither for kaons, nor for protons, using ~900M Au+Au events
  - - Shaded bars: estimated uncertainty from PID (&other) cut variations
  - - Reliable PID is possible only in intermediate momentum ranges
- Low momentum pions favored by anomalous freeze-out distribution

Results: pions





Intermediate momentum:

- **No significant deviation either (~900M Au+Au events)**

Low momentum:

- **No significant signal**
- **Some structure? (not significant)**

Discussion

- No significant signal (flat back-to-back correlation) is found for kaons & protons, and pions (in intermediate momentum range)
- Deviation from 1 not really significant in low momentum pions either

* * *

- Systematic checks:
  - **- Cut variations, kinematical ranges: some done, some others underway**
- Possible developments (beyond statistics):
  - **- Improved estimate on signal occurrence**
  - **- Pion measurement: “physical” background not really understood, especially in the low momentum range:**
    - **- Resonance (ρ, η, η', ω, etc...) decay contribution yields physical structure even if the searched correlation is not present**

Possible implications

If one assumes basic theory is right:

1.) There is a signal below the experimental detection treshold:

- **- In this case, no significant development is expected in near future**

2.) There is a mass modification, but anomalous freeze-out distribution suppresses the expected signal

- **- If really this is the case, not much can be done about it**
- **- One should search for squeezed correlations in other colliding systems or energies, or at other experiments**

3.) There is no mass modification (ie. signal absence means no “principal source”):

- **- Either there is a hadronic medium formed or not**
- **- Other measurements are needed: elliptic flow, η' mass modification ...**

Possible implications II

If there is really no mass modification of the investigated hadrons:

1.) There is a hadronic medium formed

- Unlikely (almost excludable) constraint on mean field models

2.) There is no hadronic medium formed

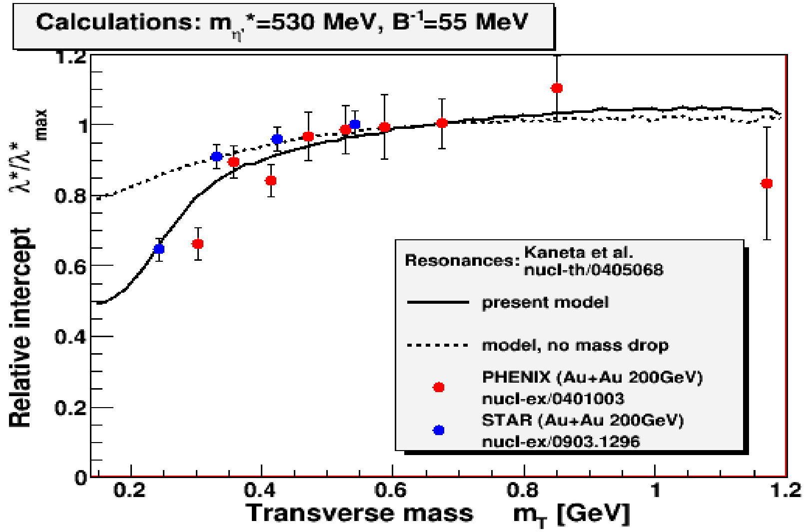
- But then one needs to explain likely η' mass modification

3.) A possible sort-out:

- chiral symmetry restoration at lower temperatures than deconfinement

- Re-confinement via supercooled state, flash-like freeze-out

- Interesting in conjunction with elliptic flow scaling data



R. Vértesi, et al., arXiv:0905.2803 [nucl-th]

Summary and outlook

- PHENIX measurement of new type of particle-antiparticle back-to-back correlation is presented and analyzed
  - **- Basic theoretical ground is well established, input theory parameters (origin of mass modification, suppression factors ...) are not clear**
- No statistically significant deviation from 1 is found for pions, kaons and protons in the investigated momentum ranges
  - **- In principle, statement could change with improved statistics**
  - **- Understanding physical backgrounds is critical**
- Measurement of other particles?
  - **- Need more data for improved measurement, or for resonances (eg. ϕ meson)**

Thank you for your attention!