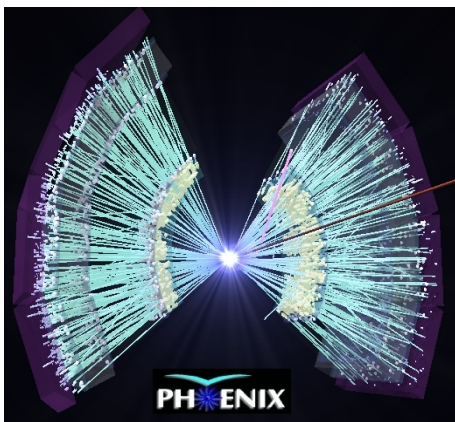


Particle-antiparticle back-to-back correlation measurement in 200 GeV Au+Au collisions

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V. Workshop on Particle
Correlations and Femtoscopy
14-17 October, 2009, CERN



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**

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 \leftrightarrow back-to-back

- Jet-jet correlations \leftrightarrow 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**

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

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:**

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

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

- **„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**

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

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

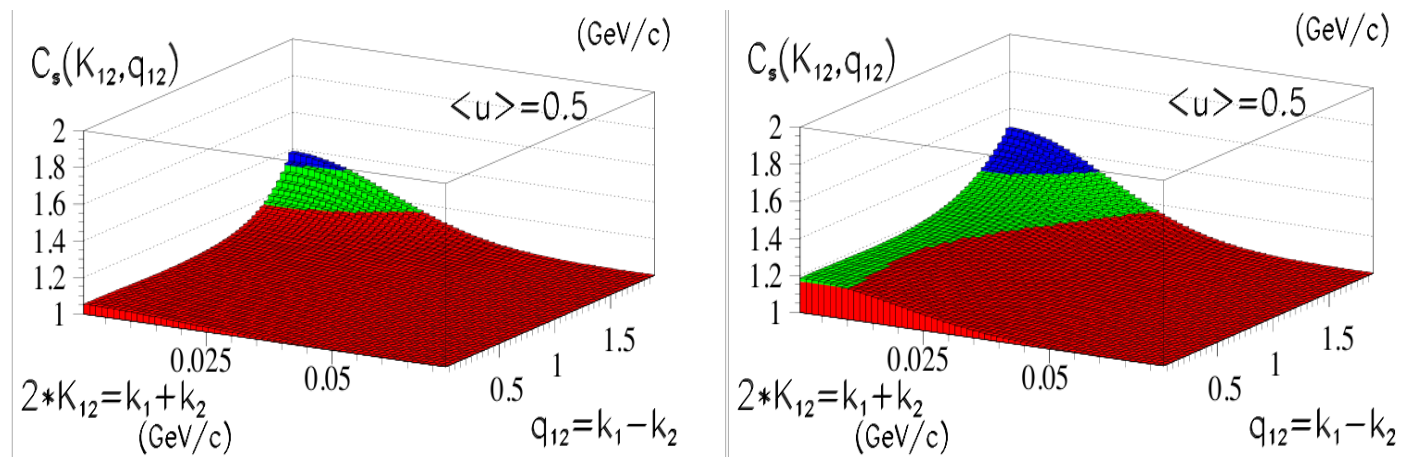
- **Squeezed state with definite momentum: superposition of „normal" states with opposite momenta**

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)

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:

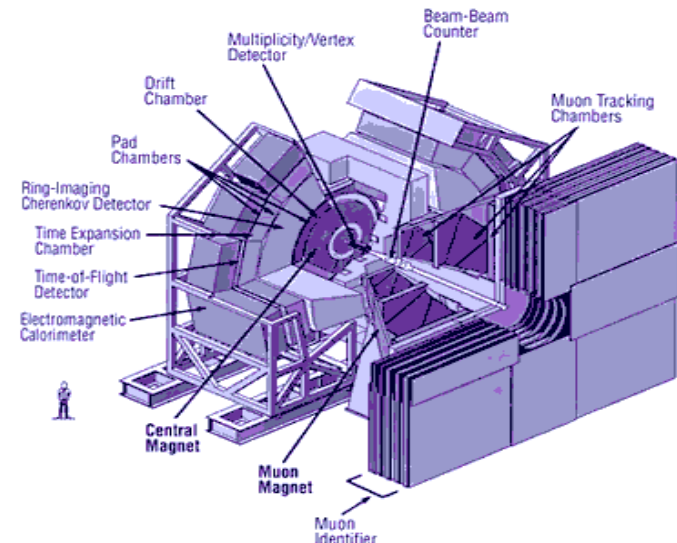
$$\tilde{F}(\omega) = \int dt F(t) \exp(-i\omega t)$$

- **For a typical exponential decay, it is Lorentz-type (power-law suppression)**
 - **for $\Delta t \sim 1\text{-}2\text{fm}/c$: signal can survive suppression \rightarrow 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 ...**

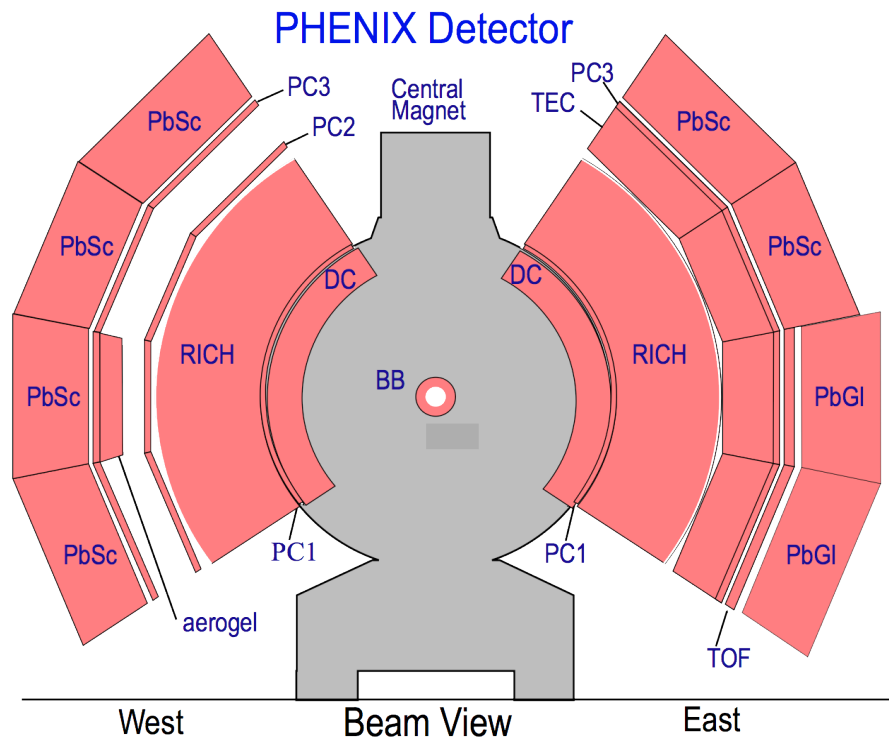
RHIC: unique opportunity to study extreme temperature & pressure nuclear matter

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...**



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)

Used momentum range nomenclature:

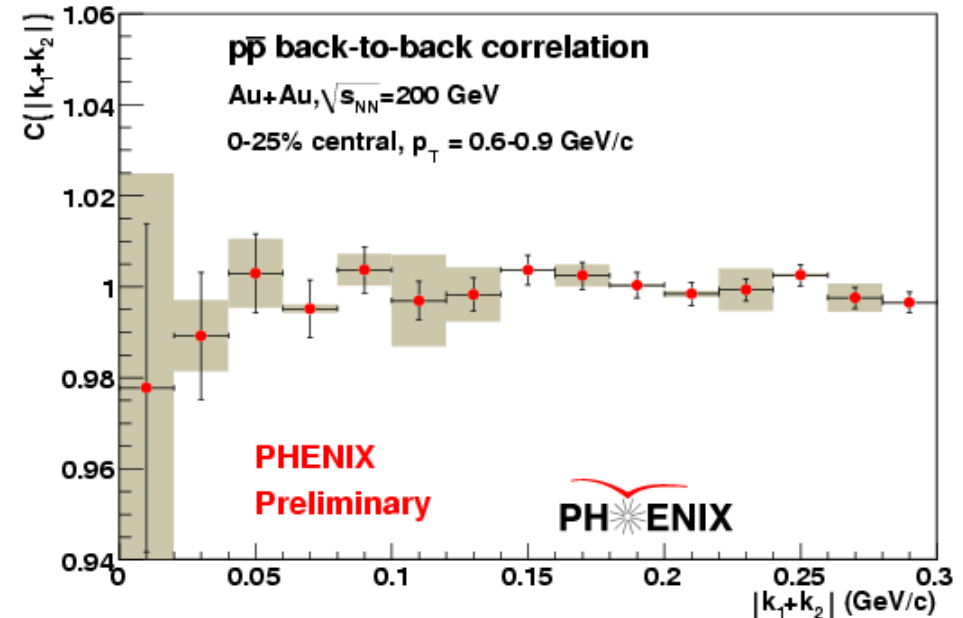
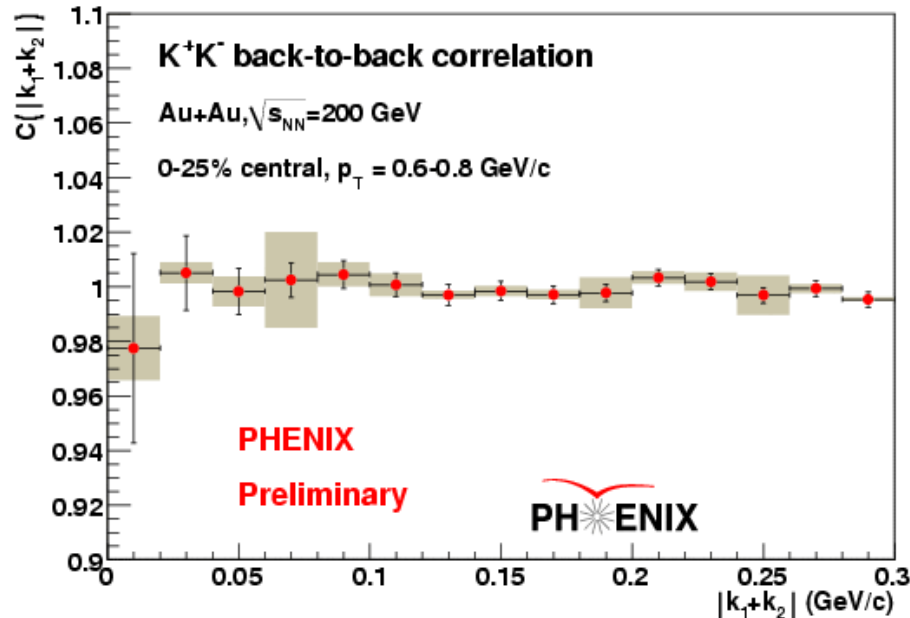
- “High” momentum: hard scattering regime
- “intermediate” momentum: non-perturbative, but highly relativistic domain
- “low” momentum regime: p_T around rest mass

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:

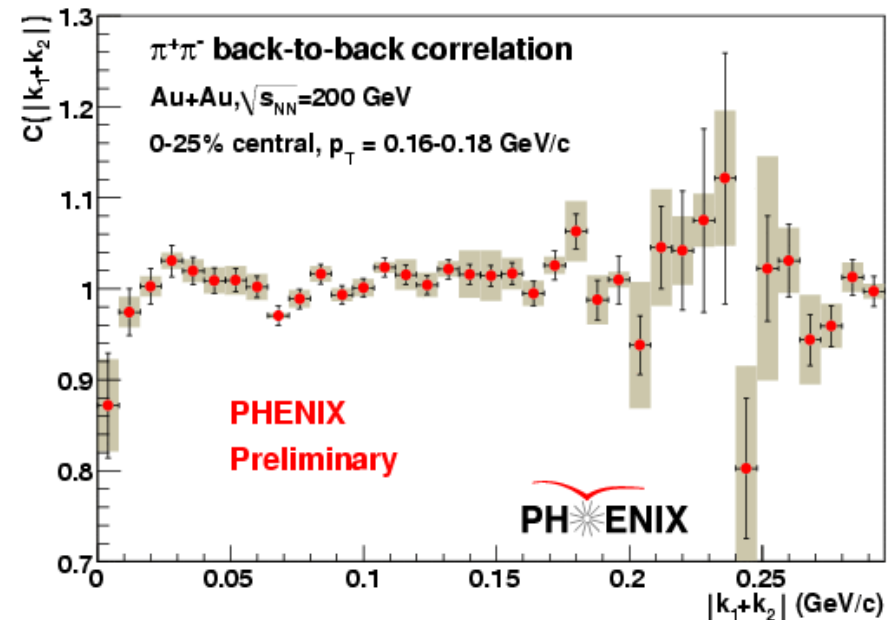
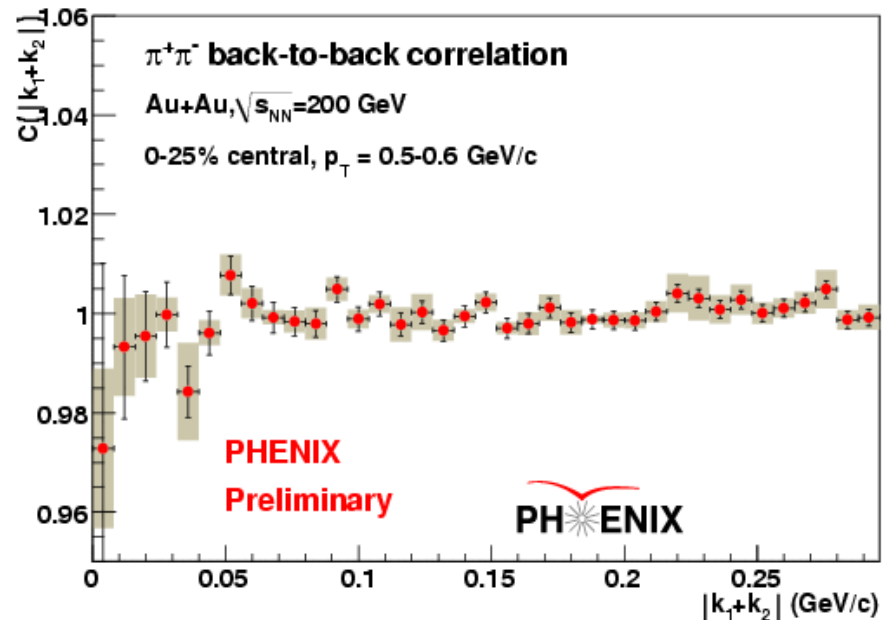
- On following slides, selected measurements are presented



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



Intermediate momentum:

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

Low momentum:

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

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**

If one assumes basic theory is right:

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

- **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 ...**

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

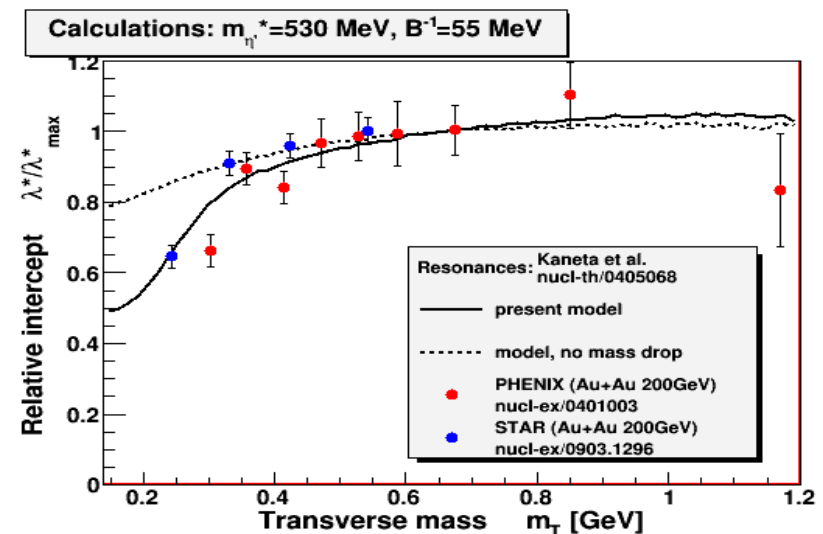
- **But then one needs to explain likely η' mass modification**

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

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!