Workshop on Hard and Dense Matter
In the RHIC and LHC Era
SEARCH FOR SQUEEZED-PAIR CORRELATIONS AT RHIC

Sandra S. Padula
IFT-UNESP, Brazil

O. Socolowski Jr., M. I. Nagy & T. Csörgő
(UNESP, Brazil & MTA KFKI RMKI, Hungary)
Motivation & Brief Introduction

- Usually medium modifications of hadron masses ↔ effects on dilepton yields and spectra

- Hadron mass shifts (interactions in a dense medium) → vanish on the freeze-out surface → expected no effects on HBT

- However, medium-modified hadrons → induce quantum mechanical correlations ↔ two-mode squeezed states of the asymptotic ones, which are therefore observable (R. Weiner)

- Late 90’s: Back-to-Back Correlations (BBC) among boson-antiboson pairs → shown to exist if the masses of the particles were modified in a hot and dense medium [Asakawa, Csörge” & Gyulassy, P.R.L. 83 (1999) 4013]

Similarities

- Properties:
  - Similar formalism for both bosonic (bBBC) and fermionic (fBBC) Back-to-Back Correlations
  - Similar (and unlimited) intensity of fBBC and bBBC
  - Expected to appear for $p_T \leq 1 - 2$ GeV/$c$

Fig. 1. Back-to-back correlations of proton–anti-proton pairs and $\phi$-meson pairs, for $T = 140$ MeV, $\Delta t = 2$ fm/$c$ and $|k| = 800$ MeV/$c$. 
Outline

• Brief review and previous results (infinite systems)

• Focus on finite expanding system, non-relativistic approach
  
  illustration: $\phi \phi$ BBC pairs

• How to search for squeezed BBC pairs in experiments
  
  suitable variables

• Modified-mass effects and squeezing on BBC and HBT correlations

• Summary and conclusions
Full Correlation Function ($\pi^0\pi^0$ or $\phi\phi$)

\[
\langle a_{k_1}^\dagger a_{k_2}^\dagger a_{k_1} a_{k_2} \rangle = \langle a_{k_1}^\dagger a_{k_1} \rangle \langle a_{k_2}^\dagger a_{k_2} \rangle \pm \langle a_{k_1}^\dagger a_{k_1} \rangle \langle a_{k_2}^\dagger a_{k_2} \rangle + \langle a_{k_1}^\dagger a_{k_2}^\dagger \rangle \langle a_{k_1} a_{k_2} \rangle
\]

\[
N_1(\vec{k}_i) = \omega_{k_1} \frac{d^3N}{d^3k} = G_c(\vec{k}_i, \vec{k}_i) \equiv G_c(i, i) = \omega_{k_1} \langle a_{k_1}^\dagger a_{k_1} \rangle
\]

\[
G_c(\vec{k}_1, \vec{k}_2) \equiv G_c(1, 2) = \sqrt{\omega_{k_1} \omega_{k_2}} \langle a_{k_1}^\dagger a_{k_2} \rangle
\]

\[
G_s(\vec{k}_1, \vec{k}_2) \equiv G_s(1, 2) = \sqrt{\omega_{k_1} \omega_{k_2}} \langle a_{k_1} a_{k_2} \rangle
\]

\[
C_2(\vec{k}_1, \vec{k}_2) = 1 \pm \frac{|G_c(1, 2)|^2}{G_c(1, 1) G_c(2, 2)} + \frac{|G_s(1, 2)|^2}{G_c(1, 1) G_c(2, 2)}
\]
In-medium & asymptotic operators

− $a_k (a_k^\dagger) \rightarrow$ annihilation (creation) operator of the asymptotic quanta with 4-momentum $p^\mu$;

− $b_k (b_k^\dagger) \rightarrow$ in-medium annihilation (creation) operator

($a$-quanta $\rightarrow$ observed; $b$-quanta $\rightarrow$ thermalized in medium)

They are related by the Bogoliubov transformation:

\[
\begin{align*}
  a_k^\dagger &= c_k^* b_k^\dagger + s_{-k} b_{-k} \\
  a_k &= c_k b_k + s_{-k}^* b_{-k}^\dagger
\end{align*}
\]

; \quad c_k = \cosh[f_k] ; \quad s_k = \sinh[f_k]

\[
  f_k = \frac{1}{2} \ln(\omega_k / \Omega_k)
\]

$\rightarrow$ squeezing parameter (Bogoliubov transformation is equivalent to a squeezing operation)
Formalism (bosons)

- Infinite medium

\[ H = H_0 - \frac{1}{2} \int d\vec{x} \ d\vec{y} \ \phi(\vec{x}) \delta M^2(\vec{x} - \vec{y}) \phi(\vec{y}) \]

\[ H_0 = \frac{1}{2} \int d\vec{x} \ (\dot{\phi}^2 + | \nabla \phi |^2 + m^2 \phi^2) \]

- Scalar field \( \phi(x) \rightarrow \) quasi-particles propagating with momentum-dependent medium-modified effective mass, \( m_* \), related to the vacuum mass, \( m \), by

\[ m_*^2(|k|) = m^2 - \delta M^2(|k|) \]

- Consequently:

\[ \Omega_k \rightarrow \text{frequency of the in-medium mode with momentum } \vec{k} \]

\[ \Omega_k^2 = m_*^2 + \vec{k}^2 = \omega_k^2 - \delta M^2(|k|) \]
### bBBC & fBBC - formalism summary

#### Bosonic BBC

<table>
<thead>
<tr>
<th>$c_k = \cosh[f_k]$</th>
<th>$s_k = \sinh[f_k]$</th>
</tr>
</thead>
</table>

\[
\begin{align*}
  a_k^\dagger &= c_k \ b_k^\dagger + s_{-k} \ b_{-k} \\
  a_k &= c_k \ b_k + s_k^* \ b_k^\dagger
\end{align*}
\]

\[
\begin{align*}
  f_k &\equiv r_k^{ACG} = \frac{1}{2} \log \left( \frac{\omega_k}{\Omega_k} \right) \\
  \omega_k^2 &= m^2 + \vec{k}^2 \\
  \Omega_k^2 &= \omega_k^2 - \delta M^2(|k|) \\
  m^*_k &= m^2 - \delta M^2(|k|)
\end{align*}
\]

#### Fermionic BBC

<table>
<thead>
<tr>
<th>$c_k = \cos[f_k]$</th>
<th>$s_k = \sin[f_k]$</th>
</tr>
</thead>
</table>

\[
\begin{align*}
  a_{\lambda,k}^\dagger &= \begin{pmatrix} c_k & \frac{f_k}{|f_k|} s_k A \end{pmatrix} \begin{pmatrix} b_{\lambda,k} \\
    -\frac{f_k^*}{|f_k|} s_k^* A^\dagger \ & c_k^* \end{pmatrix}
\end{align*}
\]

\[
A = [\chi_{\lambda}^\dagger (\sigma.\hat{k}) \tilde{\chi}_{\lambda'} ; \ A^\dagger = [\tilde{\chi}_{\lambda'}^\dagger (\sigma.\hat{k})^\dagger \chi_{\lambda}]
\]

\[
\tilde{\chi}_{\lambda'} = -i\sigma^2 \chi_{\lambda'} ; \ \hat{k} = \frac{k}{|k|}
\]

is a Pauli spinor

\[
\tan(2f_k) = -\frac{|k| \Delta M(k)}{\omega_k^2 - \Delta M(k)M}
\]

\[
m^*_k = m - \Delta M(k) \\
\omega_k^2 = m^2 + \vec{k}^2 \ ; \ \Omega_k^2 = m^*_k + \vec{k}^2
\]
Finite expanding systems

- Does the BBC survive
  - Finite medium (volume $V$) ?
  - Flow ?

- Squeezed correlations were shown
  - to survive both (more realistic) conditions, still with sizeable strength
  - non-relativistic treatment with flow-independent squeezing parameter $\phi$ squeezed correlations


... brief reminder of main results follows →

Answer is YES!
Formalism for treating finite expanding systems

- For a hydrodynamical ensemble $\Rightarrow$ amplitudes can be written as
  \[ \text{[Makhlin & Sinyukov, N.P. A566 (1994) 598c]} \]

\[
G_c(1,2) = \frac{1}{(2\pi)^3} \int d^4\sigma_\mu(x) K_{1,2}^\mu e^{i q_{1,2} \cdot x} \left[ c_{1,2} \right] \left[ n_{1,2} + s_{-1,-2} \right] \left( n_{-1,-2} + 1 \right)
\]

\[
G_s(1,2) = \frac{1}{(2\pi)^3} \int d^4\sigma_\mu(x) K_{1,2}^\mu e^{i 2 K_{1,2} \cdot x} \left[ s_{-1,2} c_{2,-1} n_{-1,2} + c_{1,-2} s_{-2,1} \right] \left( n_{1,-2} + 1 \right)
\]

\[ 2 * K_{i,j}^\mu = (k_i + k_j) \]

\[ q_{i,j}^\mu = (k_i - k_j) \]
Expanding non-relativistic finite system

- For large mass $m$ and small mass shifts $[ (m_* - m) / m \ll m ]$
  \rightarrow \text{flow effects on squeezing parameter } f_{i,j} \text{ are negligible:}

  \[ c_{i,j} \text{ and } s_{i,j} \rightarrow \text{flow independent} \]

- Finite volume $V$
  - $s_{i,i} = 0$ outside mass-shift region ($\Delta M = 0$)

- Simplest $V$ profile \rightarrow analytical calculations:

Cross-sectional area \rightarrow Gaussian

\[ \approx \exp[-\bar{r}^2 / (2R^2)] \]

Region where mass-shift is non-vanishing


**Additional hypotheses**

- \( n_{i,j} \rightarrow \) Boltzmann limit of Bose-Einstein distribution:

\[
 n_{i,j}(x) \sim \exp \left[ - \left( \frac{K_{i,j}^{\mu} u_{\mu} - \mu(x)}{T(x)} \right) \right]
\]

Hydro parameterization \( \rightarrow \)

\[
 \frac{\mu(x)}{T(x)} = \frac{\mu_0}{T(x)} - \frac{\vec{r}^2}{2R^2}
\]

- Freeze-out:

**Sudden freeze-out** \( \rightarrow \)

\[
 \int dt \; E_{i,j} e^{-2iE_{i,j} \cdot \tau} \delta(\tau - \tau_0) \; d\tau_f = E_{i,j} e^{-2iE_{i,j} \cdot \tau_0}
\]

**Finite emission interval** \( \rightarrow \)

\[
 \int dt \; E_{i,j} F(\tau_f) e^{-iE_{i,j}(\tau - \tau_0)} \; d\tau_f = \frac{E_{i,j}}{[1 + (E_{i,j} \Delta \tau)^2]}
\]

\[
 F(\tau) = \frac{\theta(\tau - \tau_0)}{\Delta \tau} e^{-(\tau - \tau_0)/\Delta \tau}
\]

\[
 u^{\mu} = \gamma(1, \vec{v}) \quad ; \quad \vec{v} = \langle u \rangle \frac{\vec{r}}{R}
\]

\[
 \gamma = (1 - \vec{v}^2)^{-\frac{1}{2}} \approx 1 + \frac{1}{2} \vec{v}^2 \quad [\mathcal{O}(v^2)]
\]
Summary of the previous results

• Previous results showed:
  – $C_s(k, -k)$ survives both
    • Finite emission times ($\Delta t = 2\text{fm}/c$)
    • Moderate flow (could enhance signal at small $k$)
  – However, only the behavior of the maximum value of $C_s(k, -k)$ vs. $m_*$ vs. $k$ was studied before (not useful for looking for the signal)

• Which would be the basic signal to be searched for? $\Rightarrow$ better look for different values of $k_1, k_2$, i.e., $C_s(k_1, k_2)$
Squeezed Correlation vs. $k_1$ & $k_2$

$G_s(k_1, k_2) = \frac{E_{1,2}}{(2\pi)^{3/2}} c_{12} s_{12} \left\{ R^3 \exp\left( -\frac{R^2(k_1 + k_2)^2}{2} \right) + 2 n_0 R_*^3 \exp\left( -\frac{(k_1 - k_2)^2}{8m*T} \right) \right\} \times \exp\left[ -\frac{im\langle u \rangle R}{2m*T_*} - \frac{1}{8m*T_*} - \frac{R_*^2}{2} \right] (k_1 + k_2)^2$

Remember: $2 \tilde{K} = k_1 + k_2$, $\tilde{q} = k_1 - k_2$

$C_s(\tilde{k}_1, \tilde{k}_2) = 1 + \frac{|G_s(1,2)|^2}{G_c(1,1)G_c(2,2)}$

$R_* = R \sqrt{\frac{T}{T_*}}$

$T_* = (T + \frac{m^2}{m_* \langle u \rangle^2})$

$G_c(k_i) = \frac{E_{i,i}}{(2\pi)^{3/2}} \left\{ |s_{ii}|^2 R^3 + n_0 \* R_*^3 \left( |c_{ii}|^2 + |s_{ii}|^2 \right) \exp\left( -\frac{k_i^2}{2m*T_*} \right) \right\}$

$2 \tilde{K} = k_1 + k_2$
Suitable variables

• Two main possibilities:

1. Combining particle-antiparticle pairs \((k_1, k_2)\) → theory ↔ simulation

2. Rewriting \(C_s(k_1, k_2)\) in terms of \(K\) and \(q\):
   - \(2 * \vec{K}_{i,j} = (\vec{k}_i + \vec{k}_j)\)  \(\vec{q}_{i,j} = (\vec{k}_i - \vec{k}_j)\)
   - The effect is maximum for \(i.e., \vec{K} = 0\) → study for different values of \(q\)
Relativistic extension of

\[ 2 * \vec{K}_{i,j} = (\vec{k}_i + \vec{k}_j) \]

- If we define (suggested by M. Nagy)
  \[ Q_{inv}^{back} = (\omega_1 - \omega_2, \vec{k}_1 + \vec{k}_2) = (q_{12}^0, 2\vec{K}_{12}) \]
  - Where
  \[ 2K^\mu = [(k_1^0 + k_2^0), (\vec{k}_1 + \vec{k}_2)] ; \quad q^\mu = [(k_1^0 - k_2^0), (\vec{k}_i - \vec{k}_j)] \]
  - However, even better: define a new variable, such as
    \[ Q_{bbc}^2 = - (Q_{inv}^{back})^2 = 4(\omega_1 \omega_2 - K^\mu K_\mu) \]
    - Then, its non-relativ. limit (\( \omega_i = \sqrt{m^2 + \vec{k}_i^2} \approx m + \frac{\vec{k}_i^2}{2m} \)) is
      \[ Q_{bbc}^2 \approx (2\vec{K}_{12})^2 \]
$C_s$ $(K_{12}, q_{12})$ vs. $(2*K_{12})$ vs $q_{12}$ - no flow

Time reduction factor:

$$\frac{E_{i,j}}{1 + (E_{i,j} \Delta \tau)^2}$$

R=7 fm, $m_s=1$GeV, $\Delta t=0$, $T=0.14$GeV

$<u>=0$

$C(2K,q)$

$R=7$ fm, $m_s=1$GeV, $\Delta t=2$ fm/c, $T=0.14$GeV

$<u>=0$

$C(2K,q)$
Effect of radial flow @ RHIC ($<u> \sim 0.5$)

**Diagram 1:**

**Diagram 2:**
\[ C_{sq}(K_{12}, q_{12}) \text{ vs. } K_{12} \text{ vs. } q_{12} - \text{flow effects} \]

- Flow clearly has an effect:
  - For \(<u>=0 \Rightarrow C_s \) decreases fast for increasing \(q_{12}\);
  - \(<u>=0.5 \Rightarrow C_s \) decreases more slowly
  - Flow **enhances** and **extends** the signal to broader region \((K_{12}, q_{12})\)
Simulation: $C_s(k_1,k_2)$ - preliminary

- Squeezed Correlation as function of $2*K_{12}$:
  - $\Delta t = 2 \text{ fm/c}$
  - $T = 140 \text{ MeV}$
  - $R = 7 \text{ fm/c}$
  - $m*$
Bose-Einstein Correlations

• The complete correlation function of \(\phi\)'s have an identical-particle term \((\phi \phi)\), reflecting their Bose-Einstein nature.

• In certain regions of the \((\vec{K}_{12}, \vec{q}_{12})\) Bose-Einstein correlation dominates.

• Would the mass-shift have any effect in the \(\phi\)-\(\phi\) identical particle correlation? A: YES! (although weaker than in the particle-antiparticle case)
HBT correlation function

• Effects of squeezing on the Chaotic (HBT) Correlation Function

\[ G_c(k_1, k_2) = \frac{E_{1,2}}{(2\pi)^{3/2}} \left[ R^3 |s_{12}|^2 \exp \left(-\frac{R^2(k_1 - k_2)^2}{2} \right) + n_0 R^3 \left| c_{12} \right|^2 + |s_{12}|^2 \right] \exp \left(-\frac{(k_1 + k_2)^2}{8m_* T^*} \right) \times \exp \left[-\frac{im \langle u \rangle R}{2m_* T^*} \left(k_1^2 - k_2^2\right)\right] \exp \left[-\left(\frac{1}{8m_* T^*} + \frac{R^2}{2}\right)(k_1 - k_2)^2\right] \]

\[ \Theta \quad 2^* \bar{K} \cdot \bar{q} \]

\[ \bar{q} = \bar{k}_1 - \bar{k}_2 \]

\[ 2^* \bar{K} = \bar{k}_1 + \bar{k}_2, \quad \bar{q} = \bar{k}_1 - \bar{k}_2 \]

\[ G_c(k_i) = \frac{E_{i,i}}{(2\pi)^{3/2}} \left[ R^3 |s_{ii}|^2 + n_0^* R^3 \left| c_{ii} \right|^2 + |s_{ii}|^2 \right] \exp \left(-\frac{k_i^2}{2m_* T^*} \right) \]

\[ R_* = R \sqrt{\frac{T}{T^*}} \]

\[ C_c(\bar{k}_1, \bar{k}_2) = 1 + \frac{|G_c(\bar{k}_1, \bar{k}_2)|^2}{G_c(\bar{k}_1, \bar{k}_1)G_c(\bar{k}_2, \bar{k}_2)} \]

\[ T^* = (T + \frac{m^2}{m_*} \langle u \rangle^2) \]
\( \phi \phi \)-HBT Correlations - \( \Delta t=0 \) - dependence on the average energy \( K_{12} \)

- For illustration:
  - Instant freezout (\( \Delta t=0 \))
  - No squeezing \( \rightarrow \) correlation width increases (curve broadens)

- Effects of squeezing:
  - Opposes those of flow (curves narrower)
  - effects more pronounced for increasing \( K_{12} \)
Similar to previous:

- But finite freezeout ($\Delta t=2$ fm/c)

- Slight difference even at $<u>=0$

- Same qualitative difference as for $\Delta t=0$: squeezing opposes to the flow effect, reducing the width

$\phi\phi$-HBT Correlations - $\Delta t=2$ fm/c -
dependence on the average energy $K_{12}$
Dependence on $\Theta$ - angle($\vec{K}_{12}, \vec{q}_{12}$)

- Conclusions:
  - Very small sensitivity to squeezing at $\Theta=0$ and $\langle u \rangle = 0$
  - Flow amplifies the differences $\rightarrow$ sizeable for $\langle u \rangle = 0.5$
  - No sensitivity to time for $\Theta=\pi/2$ (as expected)
  - Average over $\Theta$ $\rightarrow$ significant difference between no squeezing and squeezing on
Summary and Conclusions

• Brief review of squeezed correlations

• And of the most important results of the model (in a non-relativistic treatment of expanding finite systems)

• Suggestion of suitable variables to use in the experimental search of the BBC's:
  \[ C_s(K_{12}, q_{12}) \text{ vs. } (2^K_{12}) \text{ vs } q_{12} \] or in invariant terms:
  \[ Q_{bbc}^2 = -(Q_{inv}^{back})^2 = 4(\omega_1\omega_2 - K^\mu K_\mu) \]

• Showed some preliminary results on the expected behavior of the \[ C_s(k_1,k_2) \text{ & } C_c(k_1,k_2) \text{ vs. } (2^K_{12}) \text{ vs } q_{12} \]

  Just a detail missing: experimental discovery!

• Let's find it now! And show it at the next QM 2009!!
I gratefully acknowledge the Organizing Committee of the “Workshop on Hot and Dense Matter in the RHIC-LHC era”, as well as FAPESP, Brazil, for their partial support.
EXTRAS
Formalism (fermions)

\[ H = H_0 + H_I \quad ; \quad H_0 = \int d\vec{x} \bar{\psi}(x)(-i\gamma \cdot \vec{\nabla} + M)\psi(x) : \]
\[ \psi(x) = \frac{1}{V} \sum_{\lambda, \lambda', \vec{k}} (u_{\lambda, \vec{k}} a_{\lambda, \vec{k}} + v_{\lambda', -\vec{k}} a_{\lambda', -\vec{k}}^\dagger) e^{i\vec{k} \cdot \vec{x}} \]

\[ \langle a_{k_1}^\dagger a_{k_2}^\dagger a_{k_1} a_{k_2} \rangle = \langle a_{k_1}^\dagger a_{k_1} \rangle \langle a_{k_2}^\dagger a_{k_2} \rangle - \langle a_{k_1}^\dagger a_{k_2} \rangle \langle a_{k_2}^\dagger a_{k_1} \rangle + \langle a_{k_1}^\dagger a_{k_2}^\dagger \rangle \langle a_{k_1} a_{k_2} \rangle \]

- System described by quasi-particles → medium effects taken into account through self-energy function
- For spin-1/2 particles under mean fields in a many body system:
  \[ \sum_s + \gamma^0 \sum^0 + \gamma^i \sum^i \] → to be determined by detailed calculation
- \( \Sigma^s \rightarrow \) notation: \( \Sigma^s(k) = \Delta M(k) \)
- \( \Sigma^1 \rightarrow \) very small → neglected
- \( \Sigma^0 \rightarrow \) weakly-dependent on momentum → totally thermalized medium: \( \mu_\ast = \mu - \Sigma^0 \) (results for net barion number)
- Hamiltoniana \( H_1 \rightarrow \) describes a system of quasi-particles with mass-dependent momentum \( m_\ast = m - \Delta M(k) \)
Correlation for strict BBC pairs

- Momenta of the pair

\[ k_2 = -k_1 = k \]

Remember:

\[ 2 \ast K_{i,j}^\mu = (k_i + k_j) \quad ; \quad q_{i,j}^\mu = (k_i - k_j) \]

- Back-to-Back correlation function

\[
C_s(k,-k) = 1 + \left| c_0 \right| \left| s_0 \right| R^3 + 2 \left| c_0 \right|^2 \left| s_0 \right|^2 \left( \frac{R^2}{1 + \frac{m^2 \langle u \rangle^2}{m_* T}} \right)^{\frac{3}{2}} \exp \left\{ -\frac{m_*}{T} - \frac{k^2}{2m_* T} \right\} \times \left\{ \frac{R^2}{1 + \frac{m^2 \langle u \rangle^2}{m_* T}} \right\}^{\frac{3}{2}} \exp \left\{ -\frac{m_*}{T} - \frac{k^2}{2m_* T} + \frac{m^2 \langle u \rangle^2 k^2}{m_*} \left( 1 + \frac{m^2 \langle u \rangle^2}{m_* T} \right) 2T^2 \right\}^{-2}
\]
Full correlation function - 1

- Estimate for Gaussian-type momentum-dependent mass shift (by Asakawa, Csörgő and Gyulassy)

![Graph showing correlation function](image)

**FIG. 2.** Schematic illustration of the new kind of correlations for mass-shifted $\pi^0$ pairs, assuming $T = 140$ MeV, $G_c \sim \exp[-g_1^2 R_G^2/2]$, $G_s \sim \exp[-2K_1^2 R_G^2]$, with $R_G = 2$ fm. The fall of the BBC for increasing values of $|k|$ is controlled here by a momentum-dependent effective mass, $m_{\pi}^* = m_{\pi}[1 + \exp(-k^2/\Lambda_{\pi}^2)]$, with $\Lambda_{\pi} = 325$ MeV in the sudden approximation. Without the $\Lambda_{\pi}$ cutoff, the BBC would increase indefinitely as $|k| \to \infty$. 
• Expectation with the simple momentum-independent model discussed here (squeezed correlation is enhanced at large values of the individual momenta)

FIG. 2. Schematic illustration of the new kind of correlations for mass-shifted $\pi^0$ pairs, assuming $T = 140$ MeV, $G_c \sim \exp[-q_{12}^2 R_0^2/2]$, $G_s \sim \exp[-2K_{12}^2 R_0^2]$, with $R_0 = 2$ fm. The fall of the BBC for increasing values of $|k|$ is controlled here by a momentum-dependent effective mass, $m^*_\pi = m_\pi [1 + \exp(-k^2/\Lambda^2)]$, with $\Lambda_s = 325$ MeV in the sudden approximation. Without the $\Lambda_s$ cutoff, the BBC would increase indefinitely as $|k| \to \infty$. 
$C_s(K_{12}, q_{12})$ vs. $2^*K$ (vs $q$) slices

![Graphs showing $C_s(K_{12}, q_{12})$ vs. $2^*K$ for different $q$ slices.](image-url)
Brief Introduction

• Late 90’s: Back-to-Back Correlations (BBC) among boson-antiboson pairs shown to exist if the masses of the particles were modified in a hot and dense medium [Asakawa, Csörgo” & Gyulassy, P.R.L. 83 (1999) 4013].

• Shortly after similar BBC existed among fermion-antifermion pairs with medium modified masses [Panda, Csörgo”, Hama, Krein & SSP, P. L. B512 (2001) 49].

• Some properties:
  - Similar formalism for both bosonic (bBBC) and fermionic (fBBC) Back-to-Back Correlations
  - Similar (and unlimited) intensity of fBBC and bBBC
  - Expected to appear for $p_T \leq 1-2$ GeV/c
  - Non-relativistic limit: