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UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"

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26-30 September, 2011
Miyajima-island, Hiroshima

Phenomenology of the Squeezed Hadronic Correlations at RHIC Energies

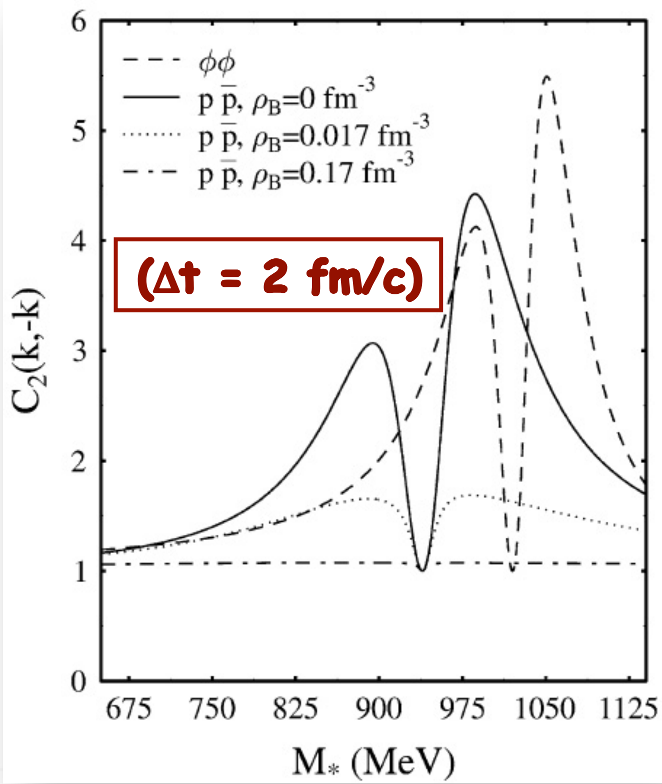
Sandra S. Padula

Danuce M. Dudek & Otávio Socolowiski, Jr.

About a decade ago…

- 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, Csörgő & Gyulassy, P.R.L. 83 (1999) 4013]

- Shortly after → similar BBC shown to exist among fermion-antifermion pairs with medium modified masses [Panda, Csörgő, Hama, Krein & SSP, P. L. B512 (2001) 49]



→ **Properties:**

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

Outline

– Brief review on squeezed correlations

– The effects of time emission parametrization on squeezing: instantaneous, Lorentzian & Lévy distributions

– Predictions of the model

– Comparison with first preliminary data (PHENIX, WPCF 2009)

Full Correlation Function ($\pi^0\pi^0$, $\phi\phi$)

$$\langle a^\dagger_{k_1} a^\dagger_{k_2} a_{k_1} a_{k_2} \rangle = \langle a^\dagger_{k_1} a_{k_1} \rangle \langle a^\dagger_{k_2} a_{k_2} \rangle \pm \langle a^\dagger_{k_1} a_{k_2} \rangle \langle a^\dagger_{k_2} a_{k_1} \rangle$$

NOTATION

$$N_1(\vec{k}_i) = \omega_{k_1} \frac{d^3N}{d^3k} = G_c(\vec{k}_i, \vec{k}_i) \equiv G_c(i,i) = \omega_{k_1} \langle a^\dagger_{k_i} a_{k_i} \rangle$$ **(Spectra)**

$$G_c(\vec{k}_1, \vec{k}_2) \equiv G_c(1,2) = \sqrt{\omega_{k_1} \omega_{k_2}} \langle a^\dagger_{k_1} a_{k_2} \rangle$$ **(Chaotic amplitude → HBT)**

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$$C_2(\vec{k}_1,\vec{k}_2) = 1 + \frac{|G_c(1,2)|^2}{G_c(1,1)G_c(2,2)} + \frac{|G_s(1,2)|^2}{G_c(1,1)G_c(2,2)}$$

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$$m_* = m - \delta m \rightarrow m_*^2(|\vec{k}|) = m^2 - \delta M^2(|\vec{k}|)$$

$$\Omega_k^2 = m_*^2 + \vec{k}^2 = \omega_k^2 - \delta M^2$$

Bogolyubov transformation

$$\begin{cases} a^\dagger_k = c^*_k b^\dagger_k + s_{-k} b_{-k} \\ a_k = c_k b_k + s^*_{-k} b^\dagger_{-k} \end{cases}$$

$$f_k = \tfrac{1}{2}\ln(\omega_k / \Omega_k)$$ ↔ **Squeezing parameter**

$$c_k = \cosh[f_k] \qquad s_k = \sinh[f_k]$$

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limit of no-squeezing: $\Omega_k \to \omega_k$
$\Rightarrow f_k \to 0 \Rightarrow s_k \to 0 \wedge c_k \to 1$

Finite system expanding with non-relat. flow

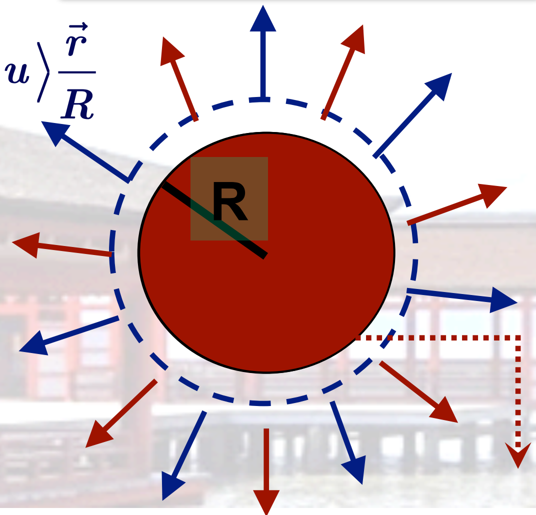
— Non-relativistic flow

— Neglecting flow effects on squeezing parameter $f_{i,j}$

— Simplest finite squeezing vol. profile → analytical calculations: 3-D Gaussian → circular cross-sectional area of radius R

$$\approx \exp[-\vec{r}^2 \,/\, (2R^2)]$$

$$\vec{v} = \langle u \rangle \frac{\vec{r}}{R}$$



Region where mass-shift is non-vanishing

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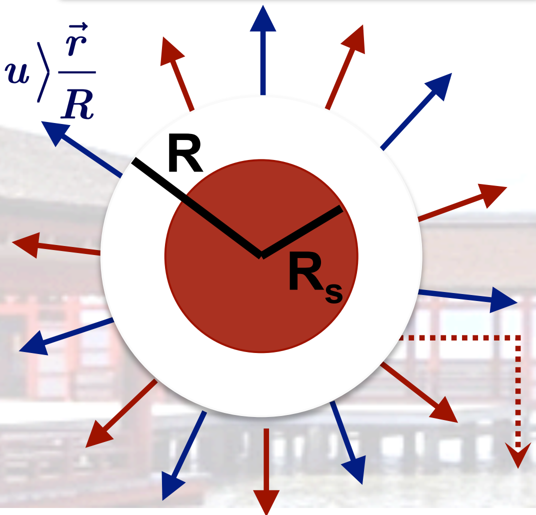

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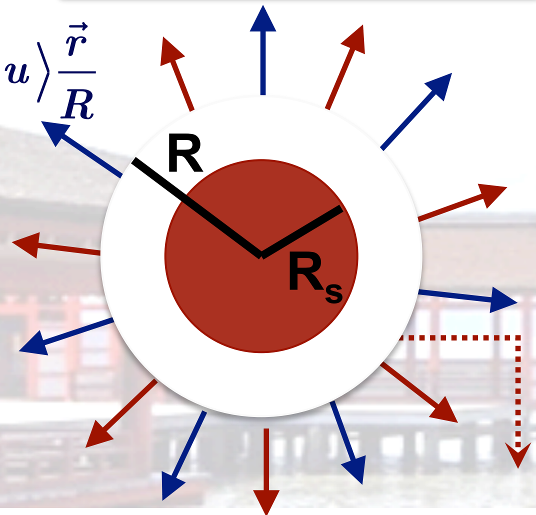

Region where mass-shift is non-vanishing

Freeze-out

$$\tilde{F}(\Delta\tau) = \int dt \, E_{i,j} \, F(\tau_f) \, e^{-iE_{i,j}(\tau-\tau_0)} \, d\tau_f$$

— **Sudden freeze-out** [$\delta(\tau-\tau_0)$]

$$\tilde{F}(\Delta\tau) = E_{i,j} e^{-2iE_{i,j}\cdot\tau_0}$$

— **Lorentzian distrib.** [$\theta(\tau-\tau_0) e^{-(\tau-\tau_0)/\Delta\tau} / \Delta\tau$]
(finite emission)

$$\tilde{F}(\Delta\tau) = \frac{E_{i,j}}{[1+(E_{i,j}\Delta\tau)^2]}$$

— **Lévy-type distrib.** **(fits of PHENIX correlat.)**

$$\tilde{F}(\Delta\tau) = E_{i,j} \exp\{-[\Delta\tau(\omega_1+\omega_2)]^\alpha\}$$

Finite system expanding with non-relat. flow

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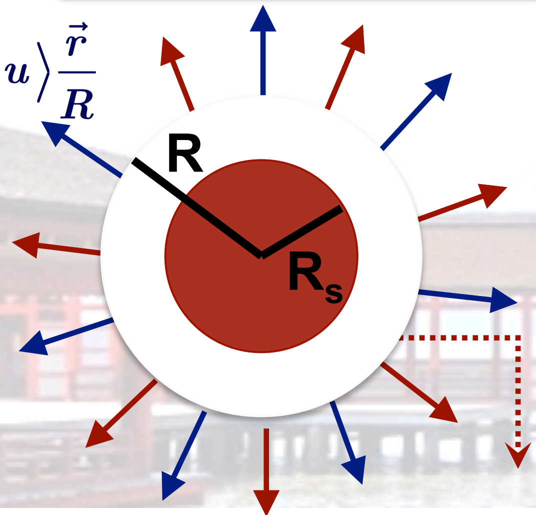

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$$n_{i,j}(x) \sim \exp\left[-\left(K^{\mu}_{i,j} u_\mu - \mu(x)\right) / T(x)\right]$$

Hydro parameterization → $\frac{\mu(x)}{T(x)} = \frac{\mu_0}{T(x)} - \frac{\vec{r}^2}{2R^2}$

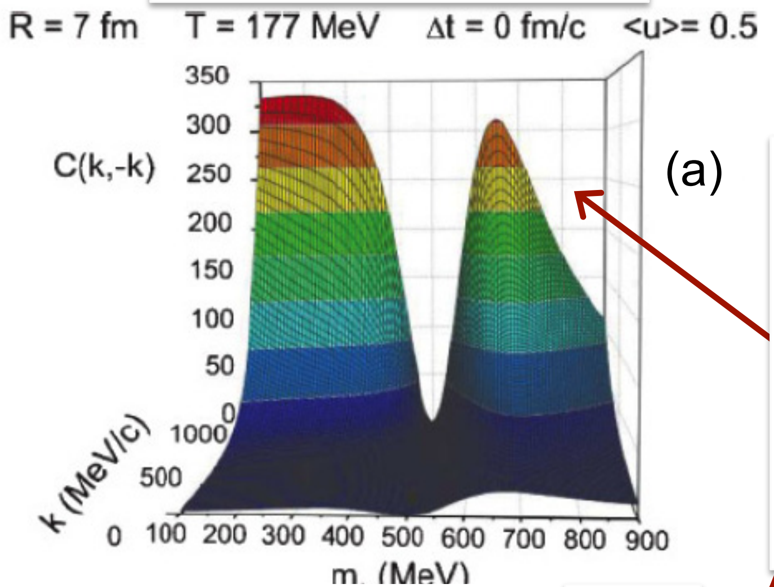
$$u^\mu = \gamma(1,\vec{v}) \quad ; \quad \vec{v} = \langle u \rangle \frac{\vec{r}}{R}$$

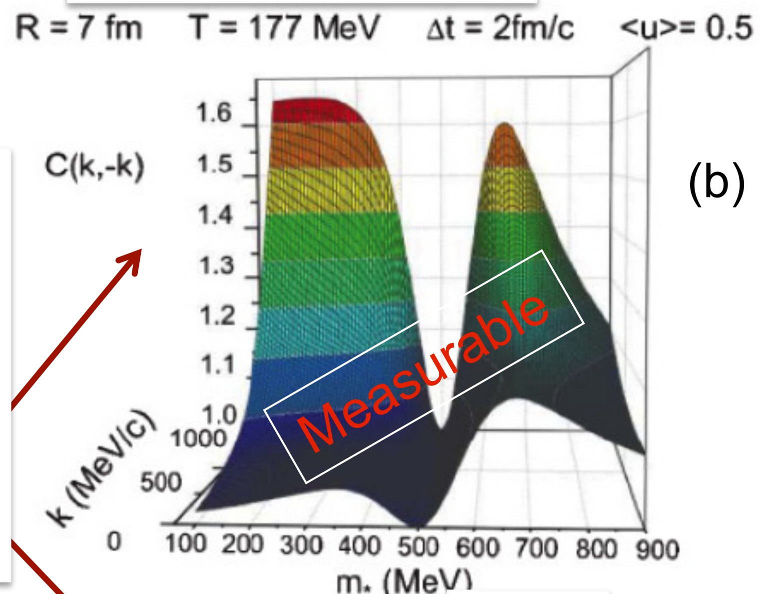
$$\gamma = (1-\vec{v}^2)^{-1/2} \approx 1 + \tfrac{1}{2}\vec{v}^2 \quad [\mathcal{O}(v^2)]$$

K^+K^- BBC pairs → m_* scan

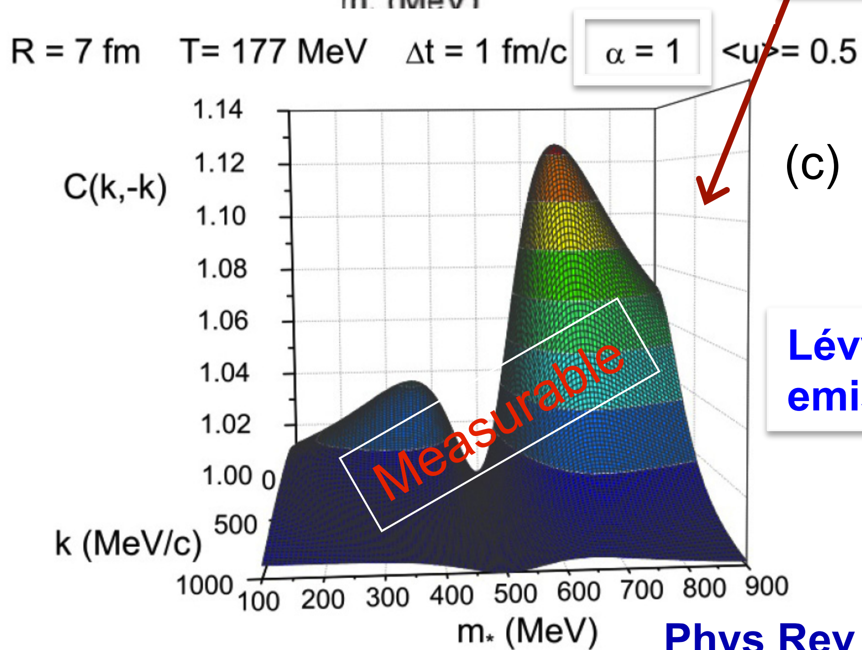
Instant time emission

Lorentzian time distr.

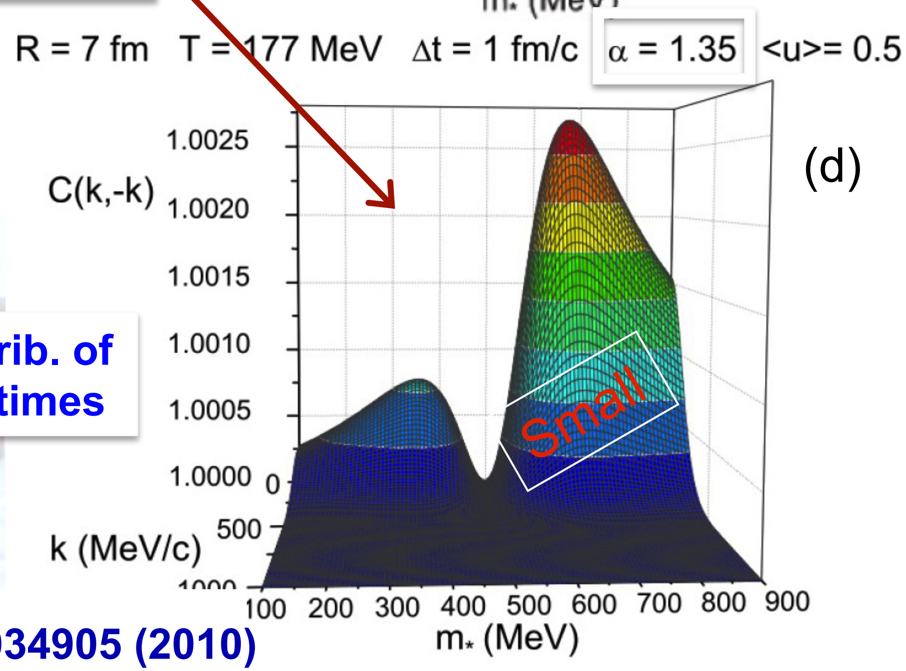




Maximal values for each (m_*,$|k|$), i.e., for strict back-to-back pairs [~ equiv. HBT intercept of correlation function]



Lévy distrib. of emission times



Phys Rev C82, 034905 (2010)

For the experimental search

m_* scan $\Rightarrow$

- Necessary → to determine maximum values of squeezed correlation function

$$C_s(m_*, \vec{k}_1 = -\vec{k}_2 = \vec{k})$$

- m_* → in-medium, not measurable
- Momenta → measurable with finite precision

$$\left|\vec{k}_1\right| - \left|\vec{k}_2\right| \leq \Delta\vec{k} \neq 0$$

Two main steps:

1) Rewrite theoretical $C_s(k_1,k_2)$ 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 maximal for

$$\vec{k}_1 = -\vec{k}_2 = \vec{k}$$

i.e., for $\vec{K}_{12} = 0$ → study for different values of q

2) Combine particle-antiparticle pair

→ Theory: generate (k_1,k_2)-simulation

→ Experiment: combine pairs $(Same$ event$)/(Mixed$ event$)$

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$$|\vec{k}_1| - |\vec{k}_2| \leq \Delta\vec{k} \neq 0$$

- Relativistic extension (M. Nagy)

$$Q_{back} = (\omega_1 - \omega_2, \vec{k}_1 + \vec{k}_2) = (q^0_{12}, 2\vec{K}_{12})$$

$$Q^2_{bbc} = -Q^2_{back} \approx (2\vec{K}_{12})^2$$

Non-relativistic limit

Two main steps:

1) Rewrite theoretical $C_s(k_1,k_2)$ in terms of K and q:

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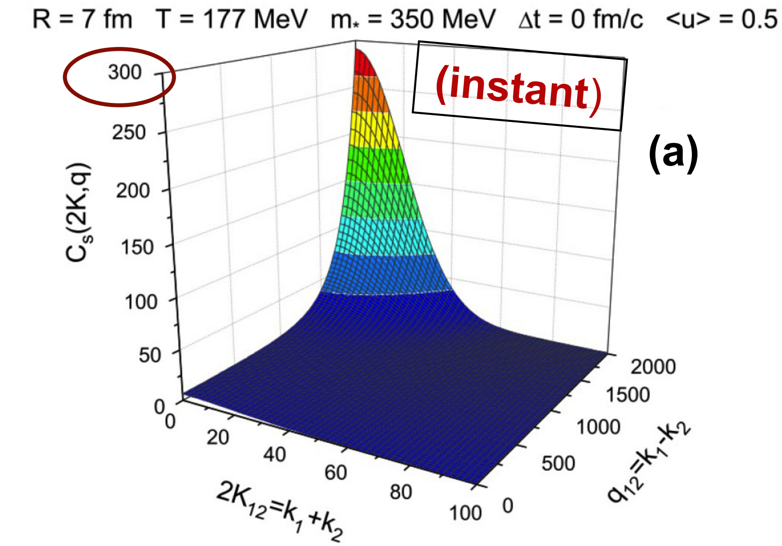
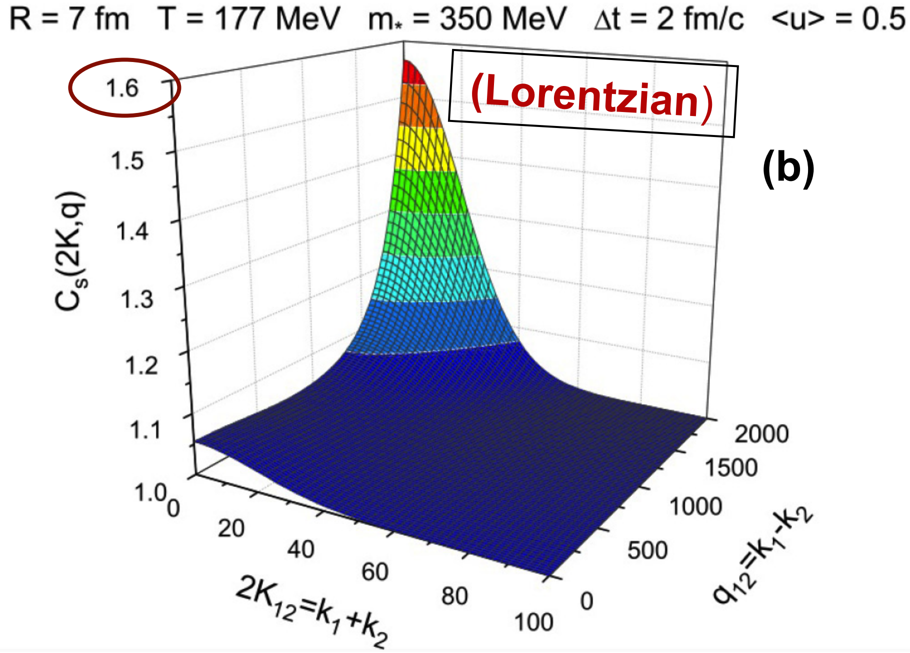
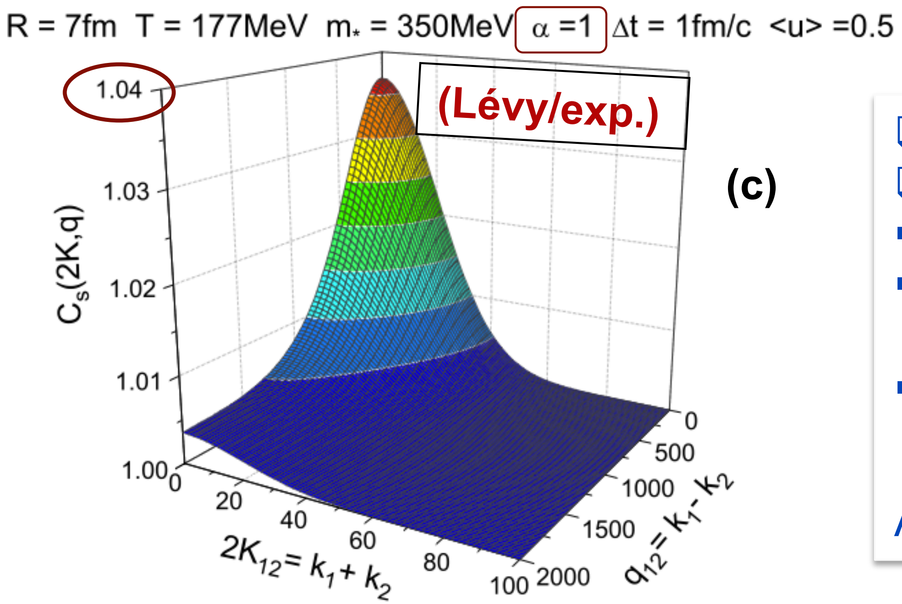
Squeezed correlations of K^+K^- pair: predictions

Choose first maximum of $C_s(k_1,k_2)$ in $(m_*, \vec{k}_1 = -\vec{k}_2 = \vec{k})$ plane ↔ $m_* = 350$MeV



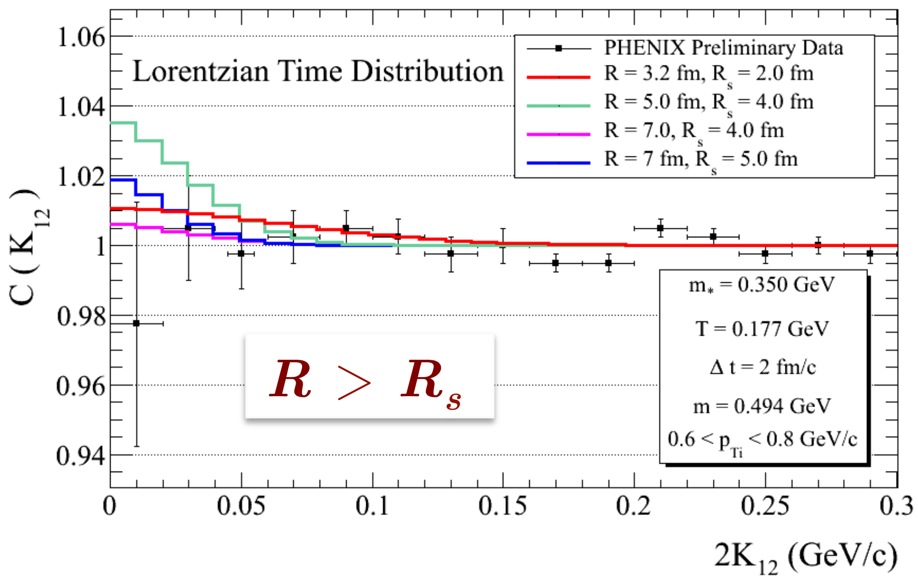


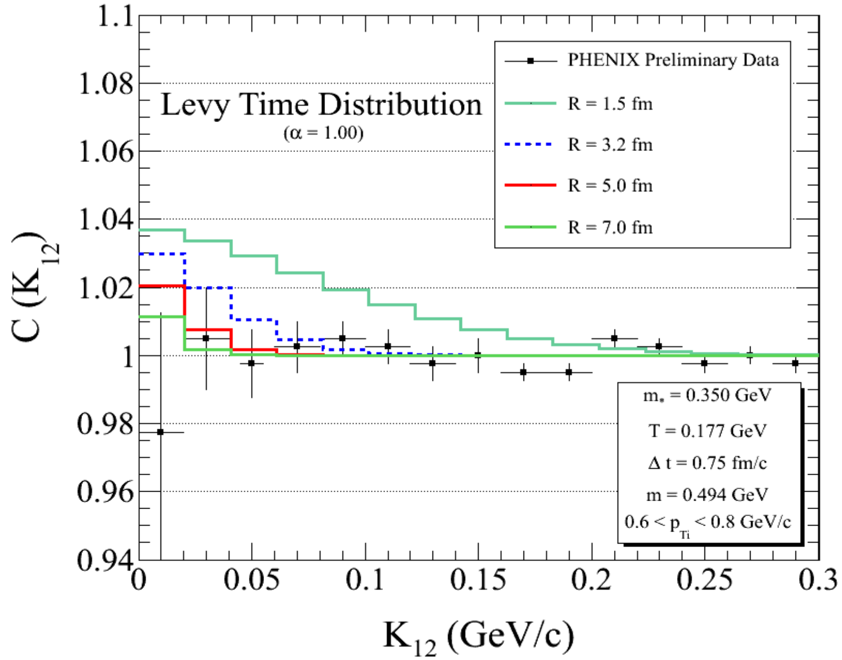


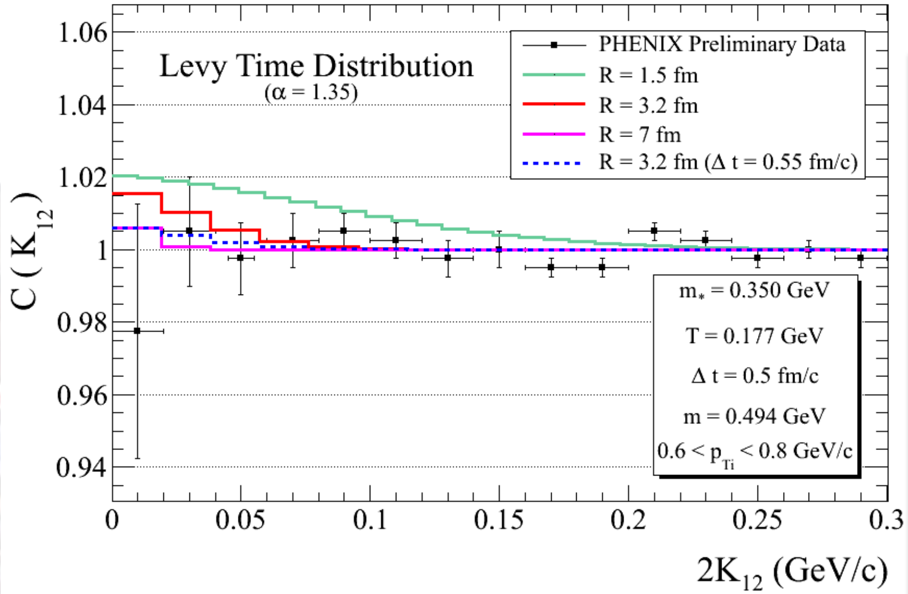
- ❑ Time emission distribution → unknown
- ❑ Possibilities:
- ▪ Instant emission (delta function)
- ▪ Lorentzian emission → reduces signal by ~20 times
- ▪ Lévy ($\alpha = 1$ ↔ exponential emission) → reduces signal by ~ factor of 300 (but measurable)

All above predictions ↔ expanding systems

Comparison to preliminary data







Partial conclusions

- Evidence of mass modification → may be inconclusive, but not negative!
- Time emission distribution:
  - If **Lorentzian** → mass modification occuring in smaller part of the system
  - If **Lévy** distribution (either w/ $\alpha_{Levy} = 1$ (exponential) or $\alpha_{Levy} = 1.35$ → mass modified all over the system

First experimental search for hadronic squeezed states

- At the WPCF 2009 → Martón Nagy showed
  - PHENIX *Preliminary* data

$$C_s(k_1,k_2) \text{ vs. } (|k_1+k_2|,|k_1-k_2|)$$

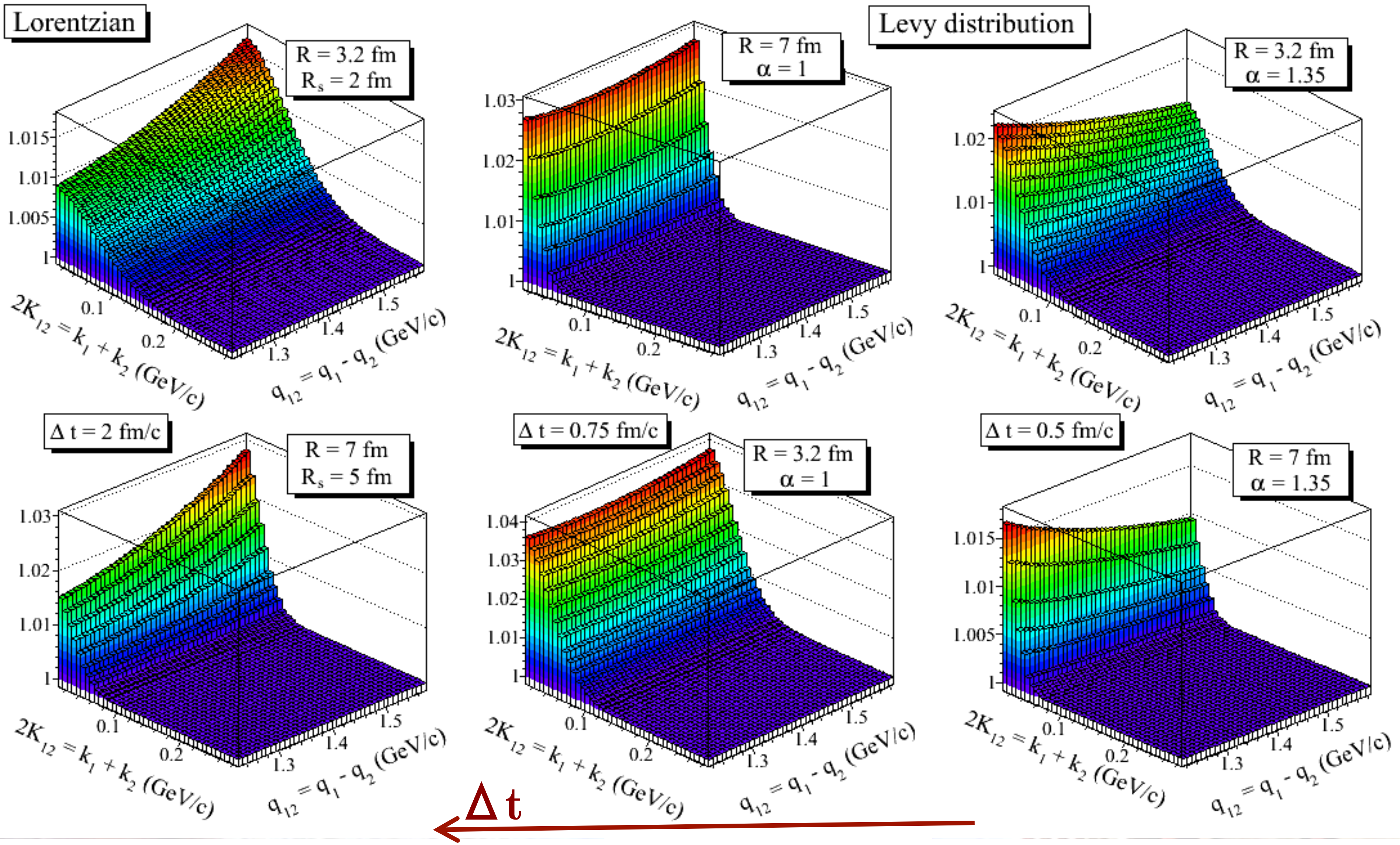
- K^+K^-, $p\bar{p}$ and $\pi^+\pi^-$.

  (compatible with our model for bosons)

- How do the results compare with our model?

2-D $C_s(K_{12}, q_{12})$ → disentangle scenarios

$m_* = 0.350$ GeV, $T = 0.177$ GeV, $\langle u \rangle = 0.5$, $m = 0.494$ GeV



Comments & Conclusions

– 1 **Considering K^+K^- squeezed correlations**

- Focused on the role of the time emission interval
  - Lorentzian time factors → strongly suppresses squeezing signal
  - Lévy time factor → reduces the intensity even more drastically:
    - » α **=1**; $\Delta\tau$ **=1fm/c** → intensity still measurable
    - » α **=1.35**; $\Delta\tau$ **=1fm/c** → too small
- However, a priori, emission process is unknown

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– 2 Comparison with PHENIX preliminary data

- – Results inconclusive but do not exclude the signal so far:
  - » Lorentzian in time → compatible w/ squeezing all over $R_s < R$
  - » Lévy distrib. → compatible w/ squeezing over R
- – Higher statistics required → perhaps we already have the signal:
  - » $C_s(k_1+k_2, k_1-k_2)$ vs. (k_1+k_2, k_1-k_2) → enhances differences

EXTRA SLIDES

Correlation for strict BBC pairs

$$C_s(k,-k) \sim 1+\frac{|c_0|^2\,|s_0|^2\,R^6}{|s_0|^4\,R^6} \sim 1+\frac{|c_0|^2}{|s_0|^2} \xrightarrow[\substack{s_0\to 0\\ c_0\to 1}]{m\sim m_*} \text{div.}$$

$$2 * K^{\mu}_{i,j} = (k_i + k_j)$$

$$q^{\mu}_{i,j} = (k_i - k_j)$$

$$\langle u\rangle = 0\ ;\ |k| \gg 1$$

$$k_2 = -k_1 = k$$

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

$$\left\{ |s_0|^2 R^3 + \left(|c_0|^2 + |s_0|^2 \right) \left(\frac{R^2}{(1+\frac{m^2\langle u\rangle^2}{m_* T})} \right)^{\frac{3}{2}} \exp\left(-\frac{m_*}{T} - \frac{k^2}{2m_* T} + \frac{m^2\langle u\rangle^2 k^2 / m_*^2}{(1+\frac{m^2\langle u\rangle^2}{m_* T})2T^2} \right) \right\}^{-2}$$

Squeezed Correlation vs. k_1 & k_2

$2*\vec{K}=\vec{k}_1+\vec{k}_2$ $\vec{q}=\vec{k}_1-\vec{k}_2$

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

$2*\vec{K}=\vec{k}_1+\vec{k}_2$

Remember: $2*\vec{K}=\vec{k}_1+\vec{k}_2\ ,\ \vec{q}=\vec{k}_1-\vec{k}_2$

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

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

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

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

Formalism (fermions)

$$H = H_0 + H_I \quad ; \quad H_0 = \int d\vec{x} : \bar{\psi}(x)(-i\vec{\gamma}.\vec{\nabla} + M)\psi(x):$$

$$\psi(x) = \frac{1}{V} \sum_{\lambda,\lambda',\vec{k}} (u_{\lambda,\vec{k}} a_{\lambda,\vec{k}} + v_{\lambda',-\vec{k}} a^{\dagger}_{\lambda',-\vec{k}}) e^{i\vec{k}.\vec{x}}$$

$$\langle a^{\dagger}_{k_1} a^{\dagger}_{k_2} a_{k_1} a_{k_2} \rangle = \langle a^{\dagger}_{k_1} a_{k_1} \rangle \langle a^{\dagger}_{k_2} a_{k_2} \rangle - \langle a^{\dagger}_{k_1} a_{k_2} \rangle \langle a^{\dagger}_{k_2} a_{k_1} \rangle + \langle a^{\dagger}_{k_1} a^{\dagger}_{k_2} \rangle \langle a_{k_1} a_{k_2} \rangle$$

- 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

- Σ^s → notation: $\Sigma^s(k) = \Delta M(k)$
- Σ^1 → very small → neglected
- Σ^0 → weakly-dependent on momentum → totally thermalized medium: $m_* = m - \Sigma^0$ → (results for net baryon number)
- Hamiltoniana H_1 → describes a system of quasi-particles with mass-dependent momentum $m_* = m - \Delta M(k)$

bBBC & fBBC - formalism summary

- **Bosonic BBC**

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

$$\begin{cases} a^{\dagger}_{k} = c_k b^{\dagger}_{k} + s_{-k} b_{-k} \\ a_k = c_k b_k + s^{*}_{-k} b^{\dagger}_{-k_1} \end{cases}$$

$$\begin{cases} f_k \equiv r_k^{ACG} = \frac{1}{2}\log\left(\frac{\omega_k}{\Omega_k}\right) \\ \omega_k^2 = m^2 + \vec{k}^2 \\ \Omega_k^2 = \omega_k^2 - \delta M^2(|k|) \\ m_*^2 = m^2 - \delta M^2(|k|) \end{cases}$$

- **Fermionic BBC**

$$c_k = \cos[f_k] \; ; \; s_k = \sin[f_k]$$

$$\begin{pmatrix} a_{\lambda,k} \\ \tilde{a}^{\dagger}_{\lambda',-k} \end{pmatrix} = \begin{pmatrix} c_k & \frac{f_k}{|f_k|} s_k A \\ -\frac{f_k^*}{|f_k|} s_k^* A^{\dagger} & c_k^* \end{pmatrix} \begin{pmatrix} b_{\lambda,k} \\ \tilde{b}^{\dagger}_{\lambda',-k} \end{pmatrix}$$

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

$$\begin{cases} \tilde{\chi}_{\lambda'} = -i\sigma^2\chi_{\lambda'} \; ; \; \hat{k} = \vec{k}/|\vec{k}| \\ \tan(2f_k) = -\frac{|k|\Delta M(k)}{\omega_k^2 - \Delta M(k) M} \\ m_*(k) = m - \Delta M(k) \\ \omega_k^2 = m^2 + \vec{k}^2 \; ; \; \Omega_k^2 = m_*^2 + \vec{k}^2 \end{cases}$$