Azimuthally sensitive photon HBT interferometry – a difficult, but very interesting measurement*

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E. Frodermann and U. Heinz, arXiv:0907.1292 [nucl-th] (PRC, in press)

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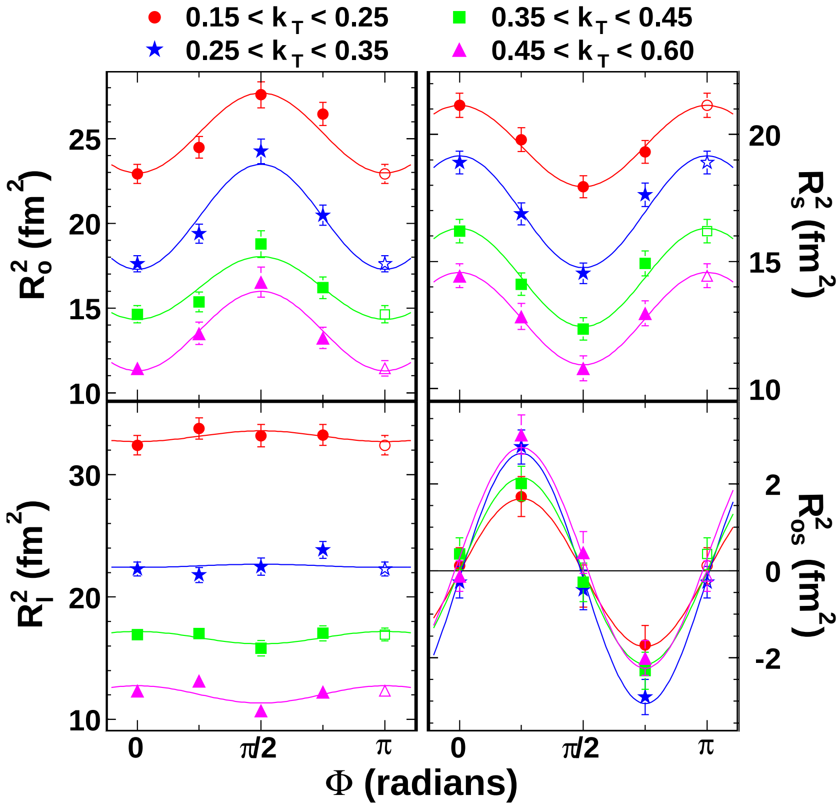
Pion azimuthal HBT oscillations measure freeze-out eccentricity

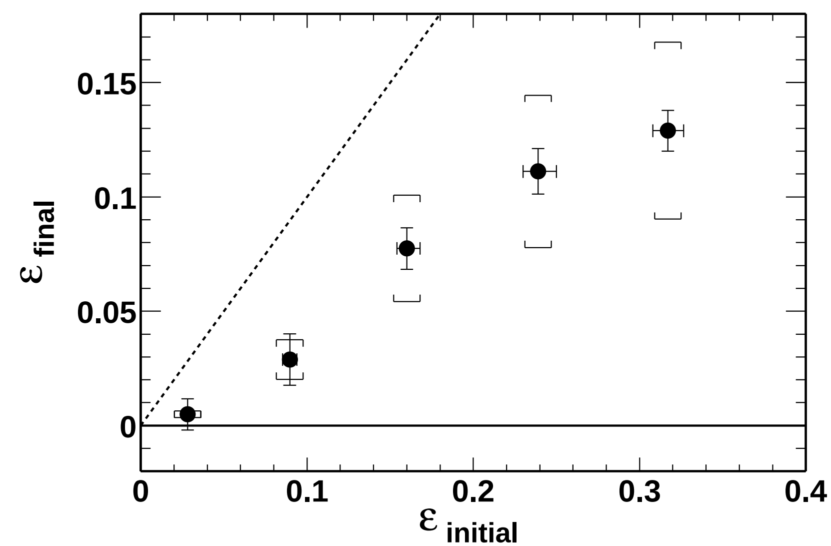
J. Adams et al. (STAR Collaboration), PRL 93 (2004) 012301

Azimuthally oscillating HBT radii



Freeze-out eccentricity

extracted a la Retiere & Lisa, PRC 70 (2004) 044907

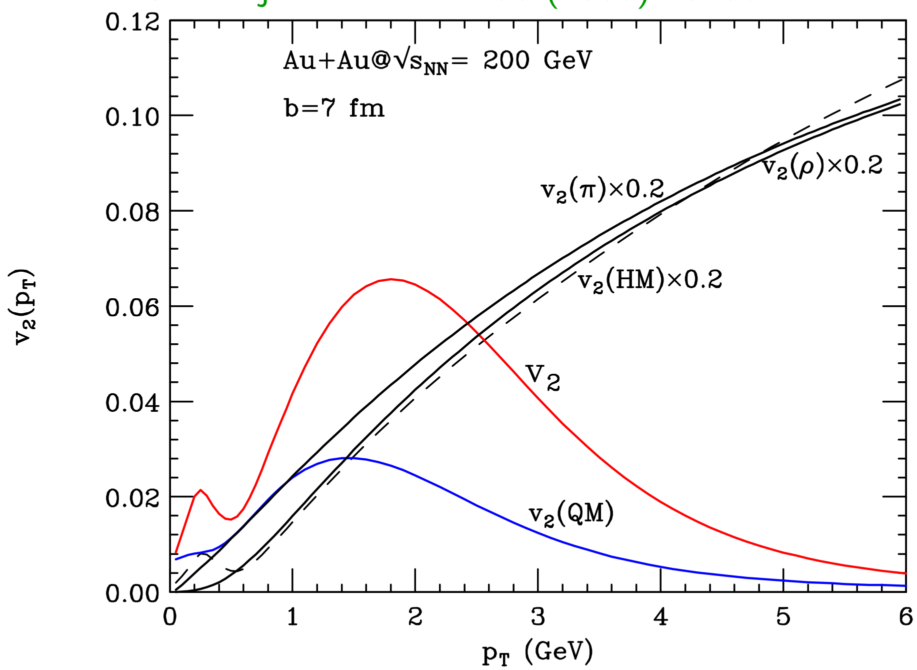


- On average (as probed by low-momentum pions) source loses about half its initial eccentricity until pion freeze-out.
- This is roughly consistent with ideal hydrodynamic predictions: Heinz & Kolb, PLB 542 (2002) 216
- Can we do better and test whether hydro correctly predicts the *evolution* of the source eccentricity?

Photon elliptic flow tracks early flow evolution

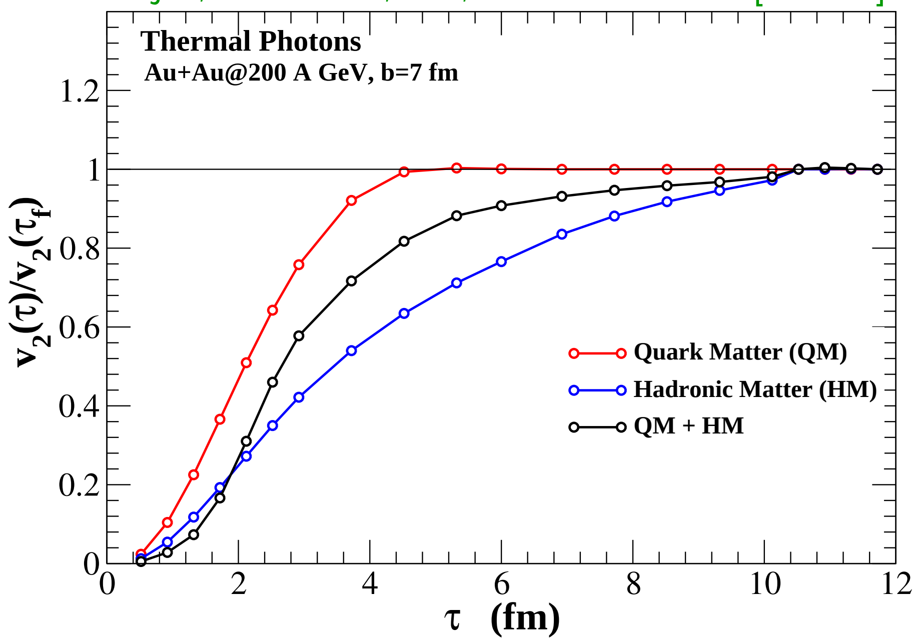
Differential photon v_2

Chatterjee et al. PRL 96 (2006) 202302



Evolution of p_T-integrated v_2

Chatterjee, Srivastava, UH, arXiv:0901.3270 [nucl-th]



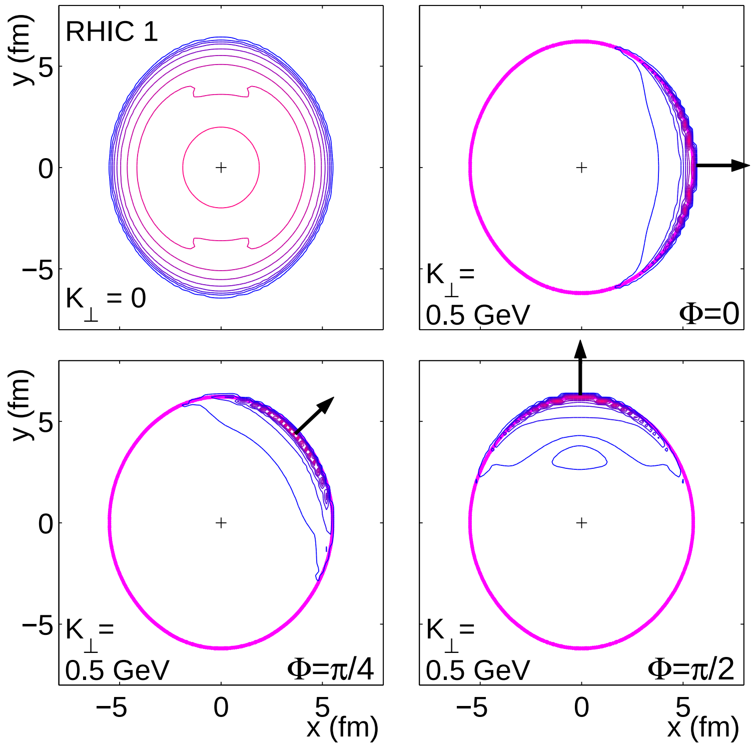
- Time evolution of total p_T-integrated photon v_2 tracks closely that of the QGP phase.
- At high p_T, photon v_2 is dominated by QGP radiation, and $v_2(p_T)$ tracks time evolution of photon v_2 (larger $p_T \leftrightarrow$ earlier times)

Question: Can one follow in parallel the evolution of the fireball eccentricity in configuration space, through azimuthal photon HBT interferometry?

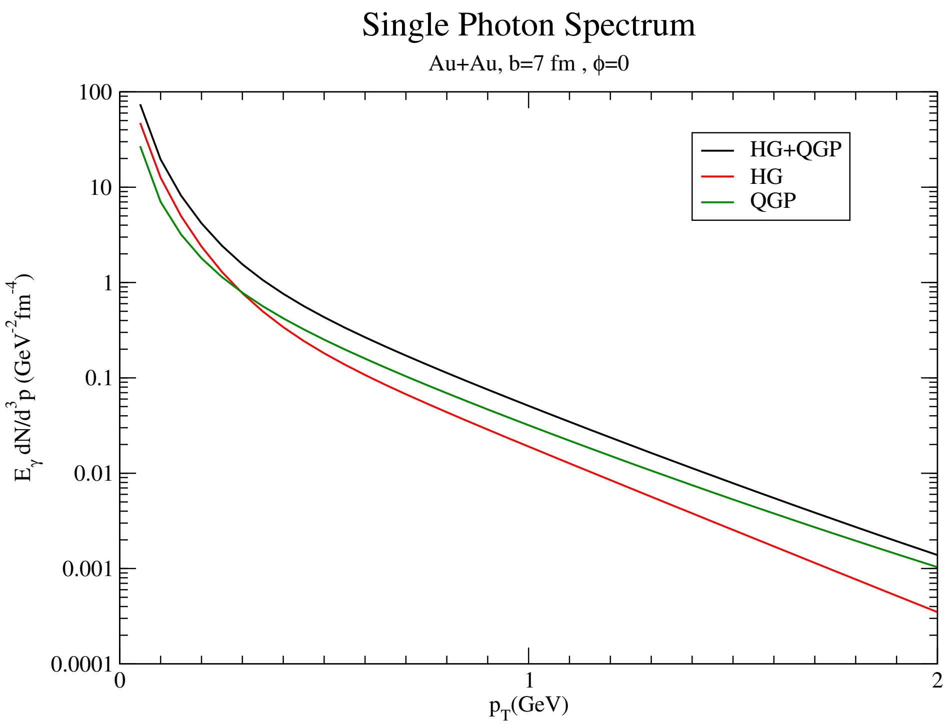
Problem: Pion studies suggest that to measure eccentricity of entire fireball must use low-K_T pion pairs (Retiere & Lisa), but to study QGP photons we need $K_T > 1$ GeV!

Pion emission function at $K_T = 0$ and 0.5 GeV

Heinz & Kolb, PLB 542 (2002) 216



Frodermann, PhD thesis (2008)

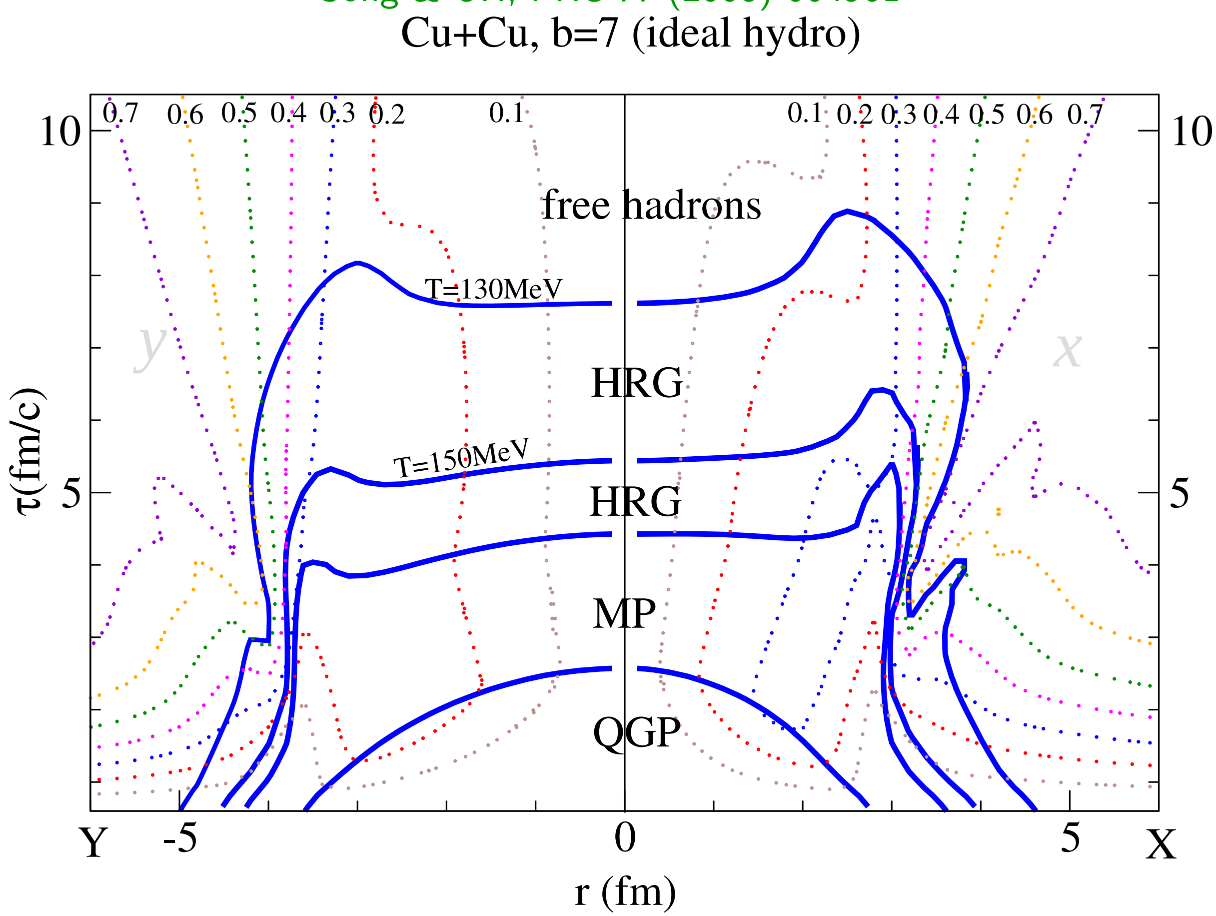


Is this the end of a nice idea? No!

Pions are emitted from the surface, photons from the volume!

Constant temperature surfaces from ideal hydro

Song & UH, PRC 77 (2008) 064901



We'll see that surface vs. volume emission makes all the difference!

HBT formalism for photons (I)

The photon spectrum and 2-photon correlation function

$$C(\boldsymbol{p}_a,\boldsymbol{p}_b) \quad = \quad \frac{E_a E_b \frac{dN}{d^3p_a d^3p_b}}{E_a \frac{dN}{d^3p_a} E_b \frac{dN}{d^3p_b}}$$

can be expressed through the photon emission function $S(x,\boldsymbol{K})$ as

$$\begin{aligned}
E\frac{dN}{d^3p} &= \int d^4x\, S(x,\boldsymbol{p})\,, \\
C(\boldsymbol{q},\boldsymbol{K}) &= 1 \pm \frac{1}{g_s}\frac{\left|\int d^4x\, S(x,\boldsymbol{K})\, e^{i\,q\cdot x}\right|^2}{\int d^4x\, S\left(x,\boldsymbol{K}{+}\frac{\boldsymbol{q}}{2}\right) \int d^4y\, S\left(y,\boldsymbol{K}\,K{-}\frac{\boldsymbol{q}}{2}\right)} \\
&= 1 \pm \frac{1}{g_s} D(\boldsymbol{q},\boldsymbol{K}) \left|\frac{\int d^4x\, S(x,\boldsymbol{K})\, e^{i\,q\cdot x}}{\int d^4x\, S(x,\boldsymbol{K})}\right|^2,
\end{aligned}$$

where $g_s{=}2$ for photons and

$$D(\boldsymbol{q},\boldsymbol{K}) \quad = \quad \frac{\left|\int d^4x\, S(x,\boldsymbol{K})\right|^2}{\int d^4x\, S(x,\boldsymbol{K}{+}\frac{\boldsymbol{q}}{2}) \int d^4x\, S(x,\boldsymbol{K}{-}\frac{\boldsymbol{q}}{2})}$$

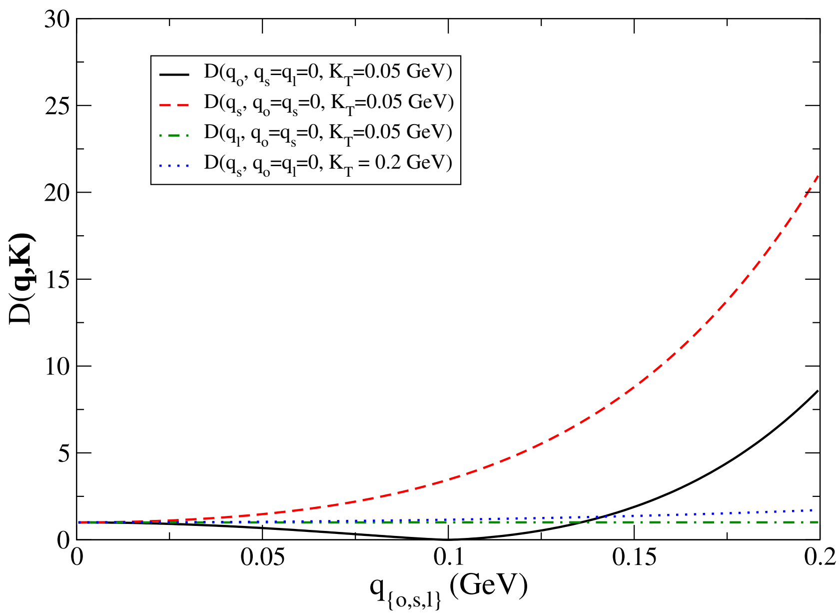
is the “smoothness correction factor”.

HBT formalism for photons (II)

Smoothness approximation:

$$D(\boldsymbol{q},\boldsymbol{K}) \to 1$$

Breaks down at small K:



Less of a problem for pions due to finite rest mass.

On-shell approximation:

$$K^0 = (E_a{+}E_b)/2 \approx E_K \Longrightarrow \beta \equiv \frac{\boldsymbol{K}}{K^0} \approx \frac{\boldsymbol{v}_{\rm pair}}{c}$$

But

$$K^0 \quad \approx \quad \begin{cases} E_K \left(1 + \frac{1}{2}(1 - \cos^2\theta_{qK})\left(\frac{q}{2E_K}\right)^2\right) \\ \approx E_K \quad \text{for} \quad 2E_K \gg q \\ \frac{q}{2}\left(1 + \frac{1}{2}(1 - \cos^2\theta_{qK})\left(\frac{2K}{q}\right)^2\right) \\ \approx \frac{q}{2} \quad \text{for} \quad m=0,\ 2K \ll q \end{cases}$$

So for $K \ll q/2$, $\beta \to \frac{2\boldsymbol{K}}{\boldsymbol{q}} \neq \frac{\boldsymbol{v}_{\rm pair}}{c}$ and $\beta = \beta(\boldsymbol{K},\boldsymbol{q})$ in general!

For massless photons, both approximations break down for small $K \lesssim 1/R_{\rm source}$!

Gaussian sources

For a source that has Gaussian shape in x-space:

$$C_{\rm smooth}(\boldsymbol{q},\boldsymbol{K}) = 1 + \lambda(\boldsymbol{K})\, \exp\left[-\sum_{i,j=o,s,l} q_i\, q_j\, \mathcal{R}^2_{ij}(\boldsymbol{K})\right],$$

where the width parameters ("HBT radii") $\mathcal{R}_{ij}$ can be obtained from the space-time variances of the source $S(x,\boldsymbol{K})$ as

$$\mathcal{R}^2_{ij}(\boldsymbol{K}) = \langle(\tilde{x}_i - \beta_i\tilde{t})(\tilde{x}_j - \beta_j\tilde{t})\rangle$$

With the on-shell approximation, these variances depend only on $\boldsymbol{K}$.
For low-K_T photons, $\mathcal{R}^2_{ij} \to \mathcal{R}^2_{ij}(\boldsymbol{q},\boldsymbol{K})$, and the Gaussian exponent becomes ($Y{=}0$)

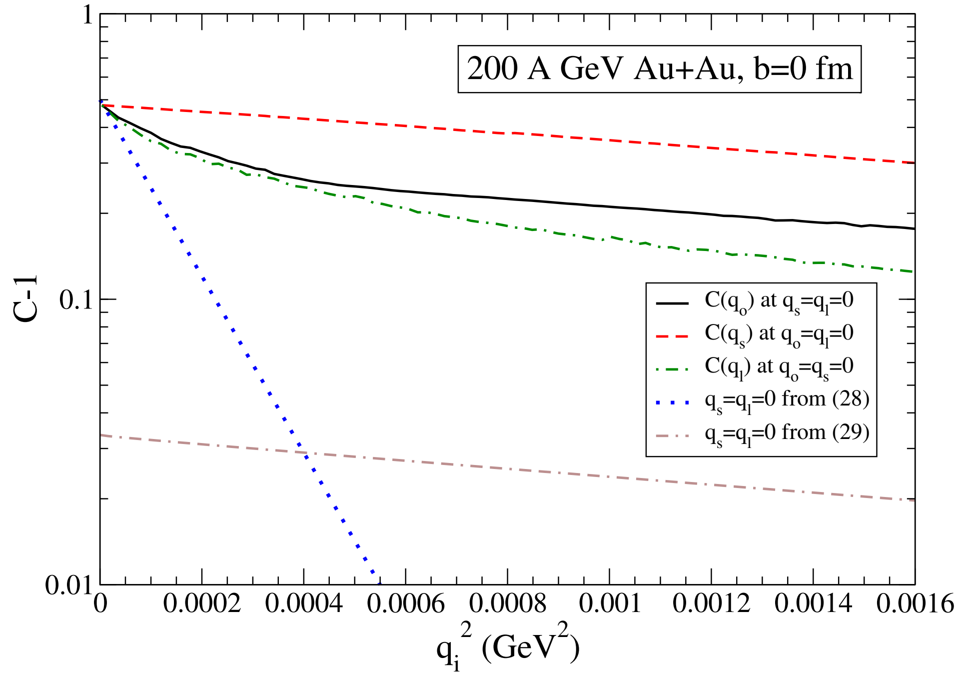
$$\sum_{ij} q_i q_j \langle(\tilde{x}_i{-}\beta_i(q)\tilde{t})(\tilde{x}_j{-}\beta_j(q)\tilde{t})\rangle = \begin{cases} q_s^2\langle\tilde{x}_s^2\rangle, & q_o{=}q_l{=}0, \\ q_o^2\left(\langle\tilde{x}_o^2\rangle - 2\langle\tilde{x}_o\tilde{t}\rangle + \langle\tilde{t}^2\rangle\right), & q_s{=}q_l{=}0, \\ q_l^2\langle\tilde{x}_l^2\rangle, & q_o{=}q_s{=}0, \end{cases} \quad (q{\ll}2K) \tag{28}$$

$$\sum_{ij} q_i q_j \langle(\tilde{x}_i{-}\beta_i(q)\tilde{t})(\tilde{x}_j{-}\beta_j(q)\tilde{t})\rangle = \begin{cases} q_s^2\langle\tilde{x}_s^2\rangle, & q_o{=}q_l{=}0, \\ q_o^2\langle\tilde{x}_o^2\rangle - 4K_\perp|q_o|\langle\tilde{x}_o\tilde{t}\rangle + 4K_\perp^2\langle\tilde{t}^2\rangle, & q_s{=}q_l{=}0, \\ q_l^2\langle\tilde{x}_l^2\rangle, & q_o{=}q_s{=}0. \end{cases} \quad (q{\gg}2K) \tag{29}$$

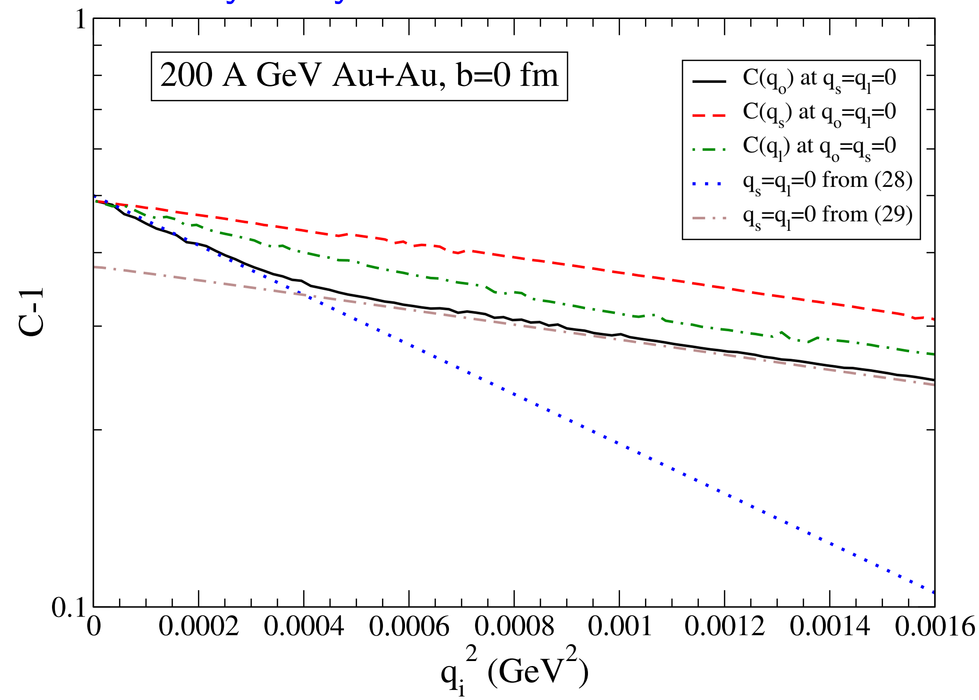
For $q{\gg}2K$, the outward correlator does **not** depend on the emission duration!

Photon correlator at (very) small pair momentum $K_T = 0.01$ GeV

Hydrodynamic photon source

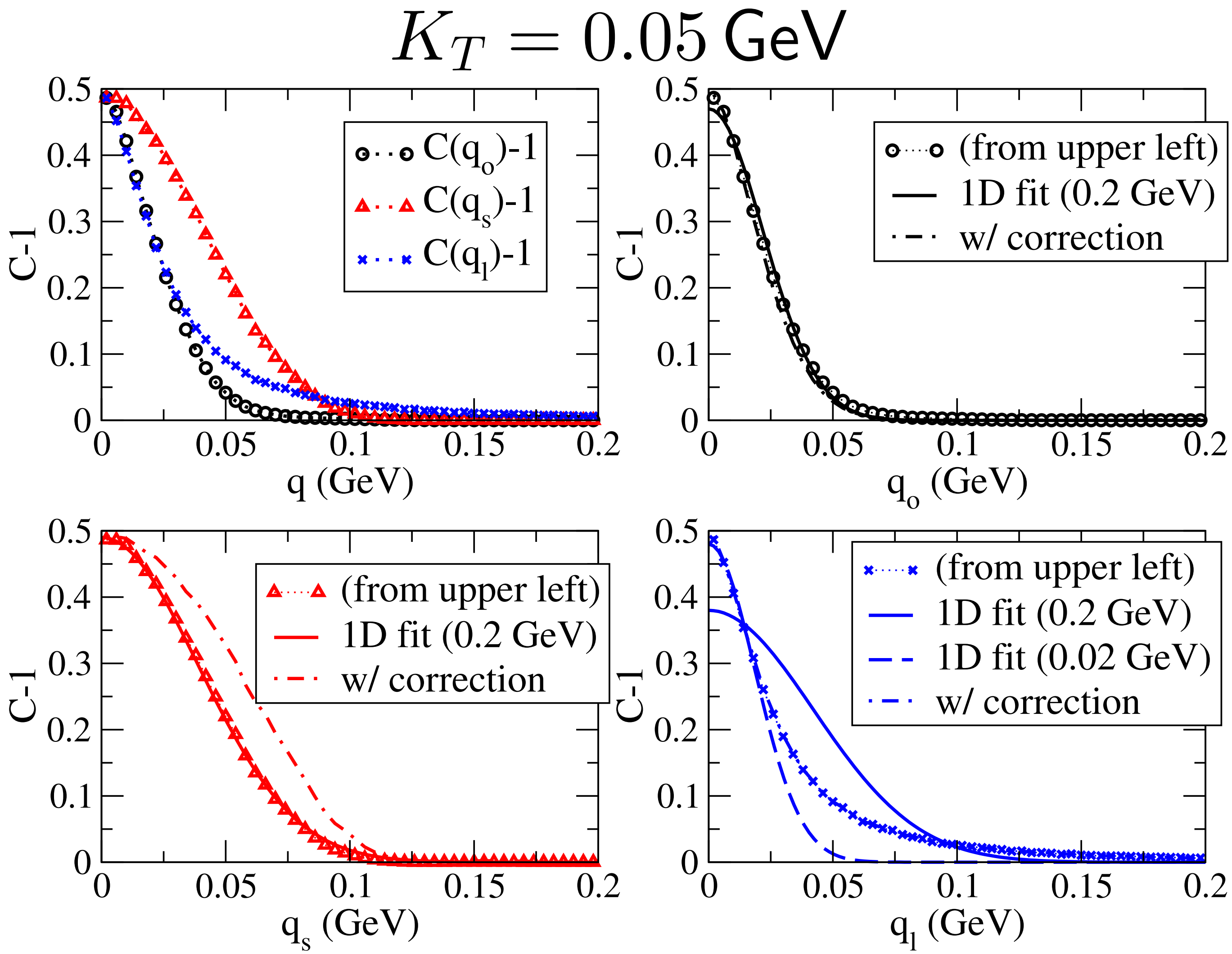


Hydrodynamic source $\times e^{-\eta^2}$



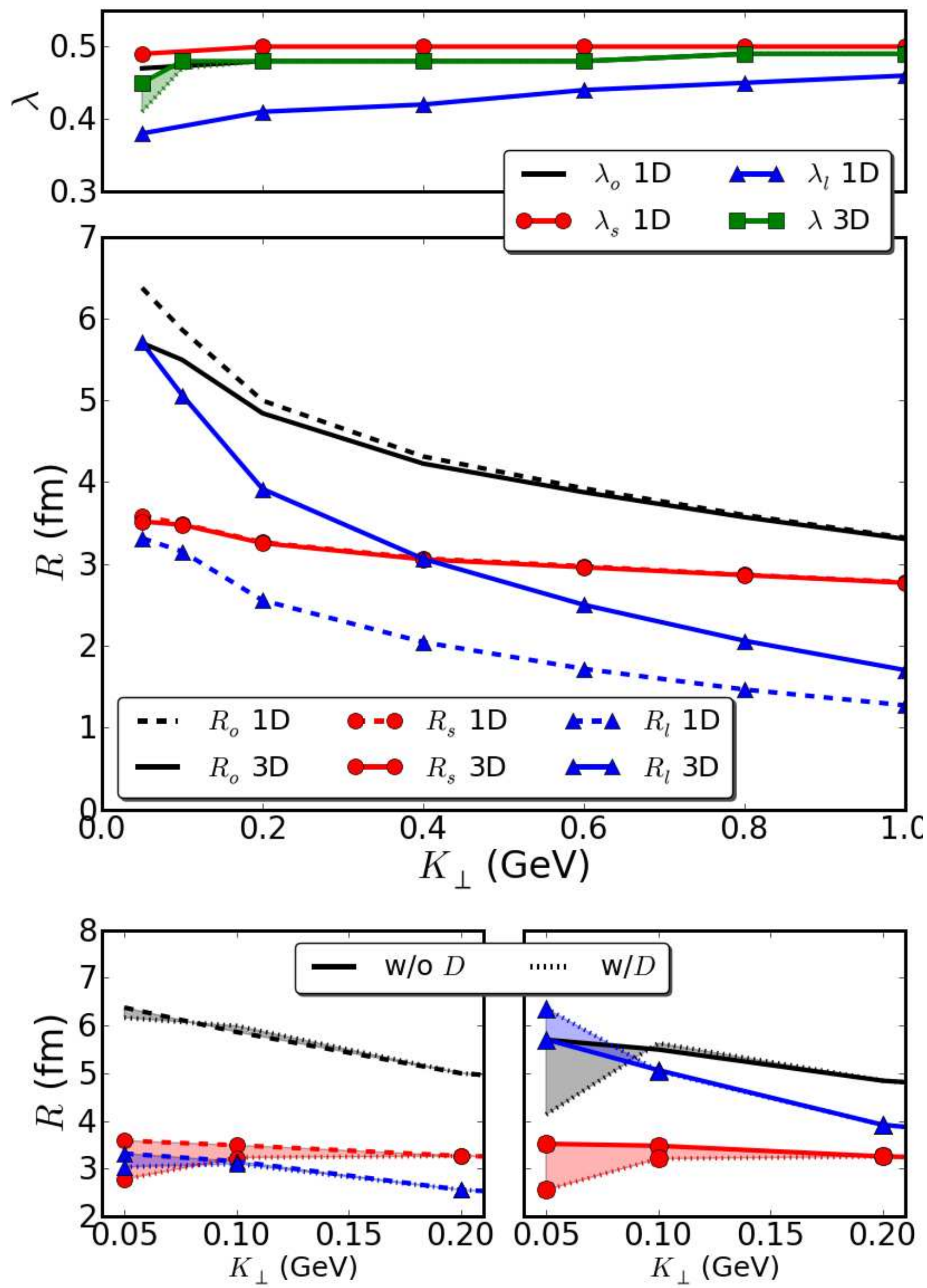
- Blue dotted line: analytic expression in terms of variances for $q \ll 2K$
- Brown dash-dotted dotted line: analytic expression in terms of variances for $q \gg 2K$
- The analytic expressions work well for the hydro source with Gaussian rapidity cutoff at $\Delta\eta_s = 1/\sqrt{2}$.
- They fail for the full (2+1)-d hydro source because for $K_T \to 0$ the photon emission function becomes exactly boost-invariant, with $\langle \tilde{t}^2 \rangle$ and $\langle \tilde{z}^2 \rangle \to \infty$.
- For $q \gg 2K$ the slopes of the outward and sideward correlators agree, i.e. $\langle \tilde{x}_o^2 \rangle = \langle \tilde{x}_s^2 \rangle$ as necessary for an azimuthally symmetric source at $b = 0$.
- Longitudinal correlator is non-Gaussian, due to boost-invariant expansion
- Smoothness correction $D(\boldsymbol{q}, \boldsymbol{K})$ introduces additional non-Gaussian features in the transverse directions
- **$\Rightarrow$ No shortcuts! Must compute full correlator and extract HBT radii from Gaussian fits.**

Photon correlations from central Au-Au collisions at RHIC (I)



- Strong non-Gaussian features in q_l direction $\Longrightarrow$ restrict longitudinal fit range to $q_l < 0.02$ GeV in 3-D Gaussian fit, in order to avoid contamination of transverse fit radii in azimuthal analysis at $b \neq 0$.
- Strong effect from smoothness correction factor in sideward direction

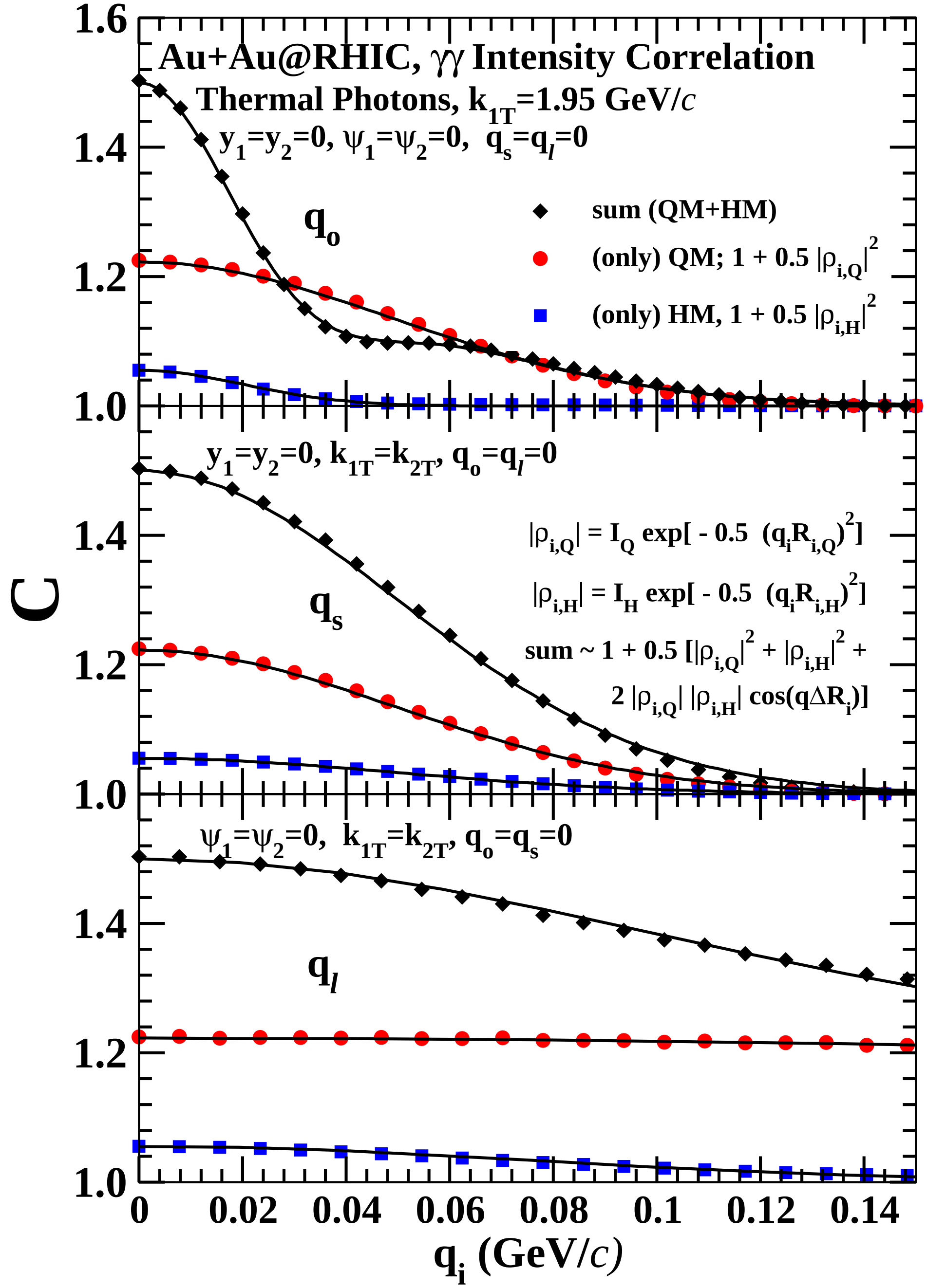
Photon correlations from central Au-Au collisions at RHIC (II)



- Dashed: 1-D Gaussian fit radii
- Solid: 3-D Gaussian fit radii
- Dotted: includes smoothness correction $D(\boldsymbol{q}, \boldsymbol{K})$
  (strong effects for small K_T, but negligible above $K_T = 0.1$ GeV)
- Large difference between R_o and R_s (black and red curves) at all K_T, from emission duration
- Huge non-Gaussian effects in R_l (blue curves)

Photon correlations from central Au-Au collisions at RHIC (III)

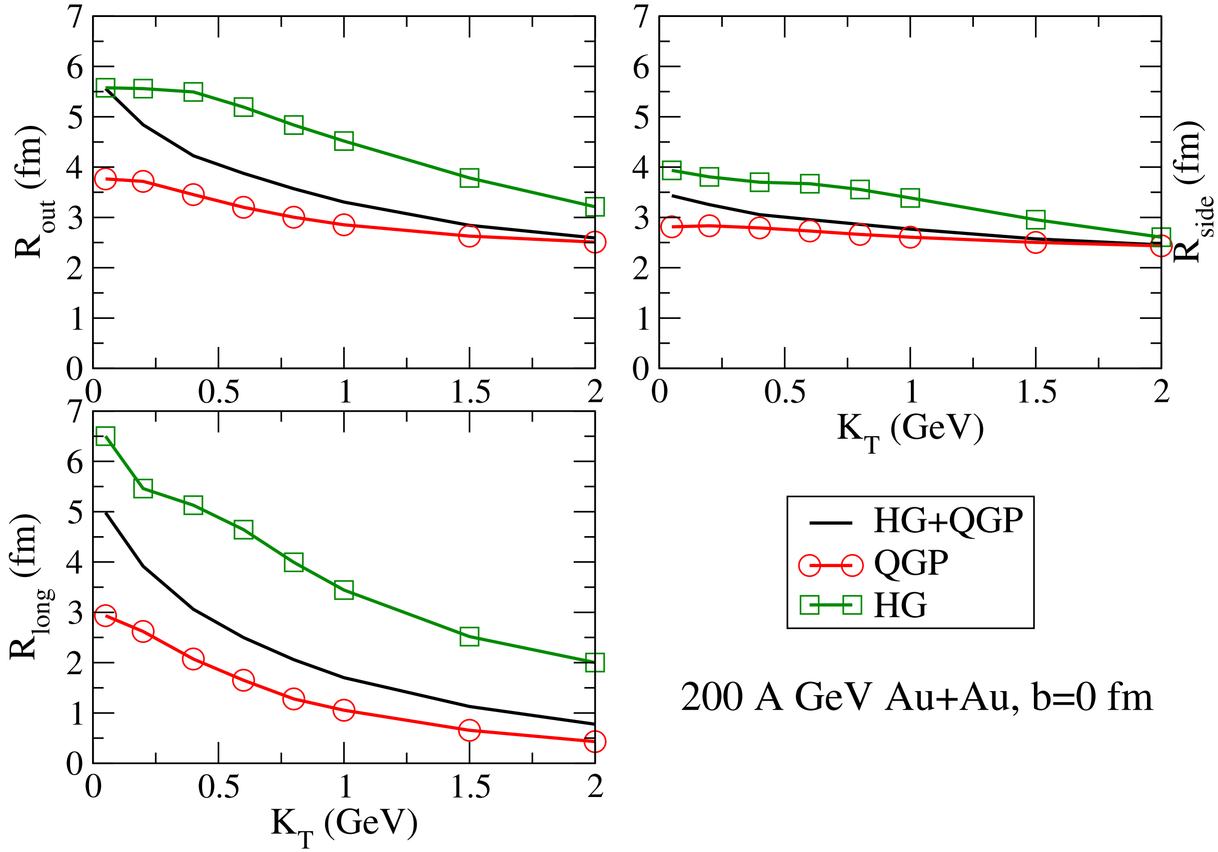
Srivastava & Chatterjee, arXiv:0907.1360 [nucl-th]



Interfering QGP and HG sources!?

- Srivastava & Chatterjee see interference structure in outward correlator (black line) at $K_T \gtrsim 2\,$GeV, from time-separated (by about $12\,\mathrm{fm}/c$) early QGP (red) and late HG (blue) emission sources.
- Needs well-separated sources! Requires large K_T to reduce thermal smearing.
- Uses different hydro model than our work.
- Have so far been unable to reproduce this feature with our hydro.
- **Very interesting if true!**

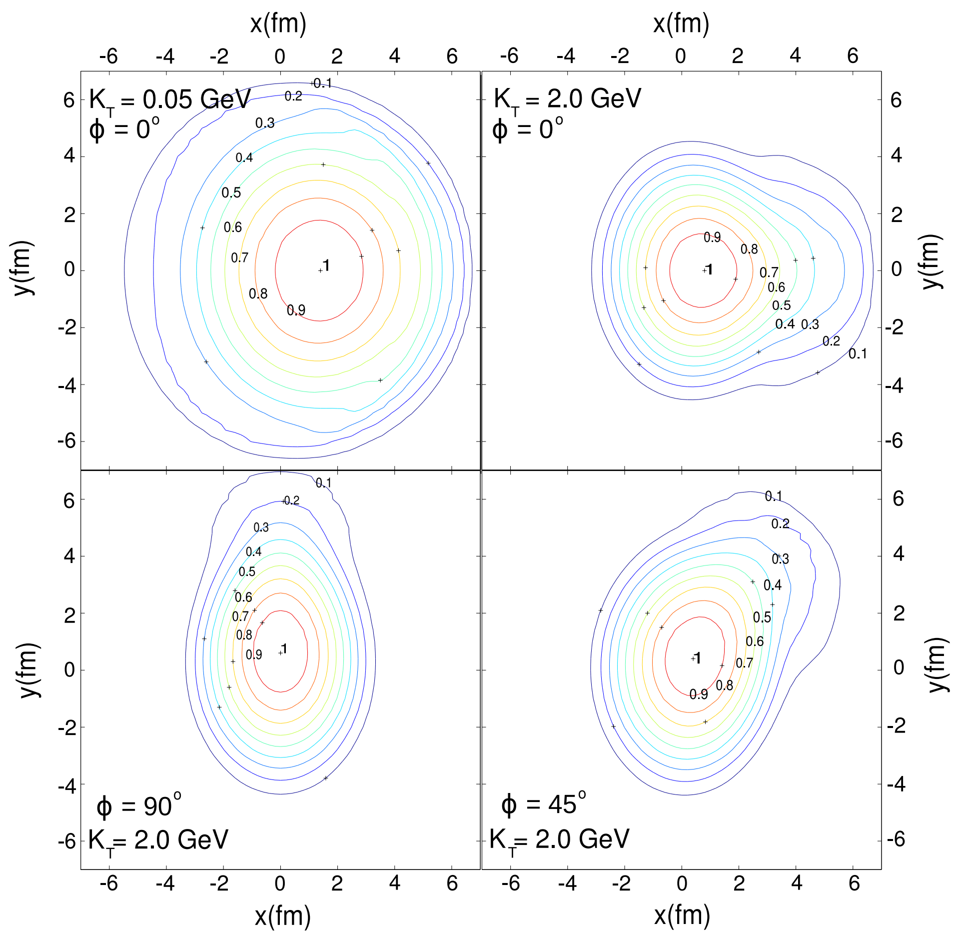
Separating QGP and HG photon sources



- QGP source is smaller and features smaller HBT radii than HG source, in all three directions
- For $K_T > 2$ GeV, HBT radii from total source agree with those from QGP source $\Longrightarrow$ hadronic photons negligible at $K_T > 2$ GeV
- At low K_T, total source shows larger emission duration effects than either QGP or HG source alone (not surprisingly)

Photon emission functions from non-central Au-Au collisions

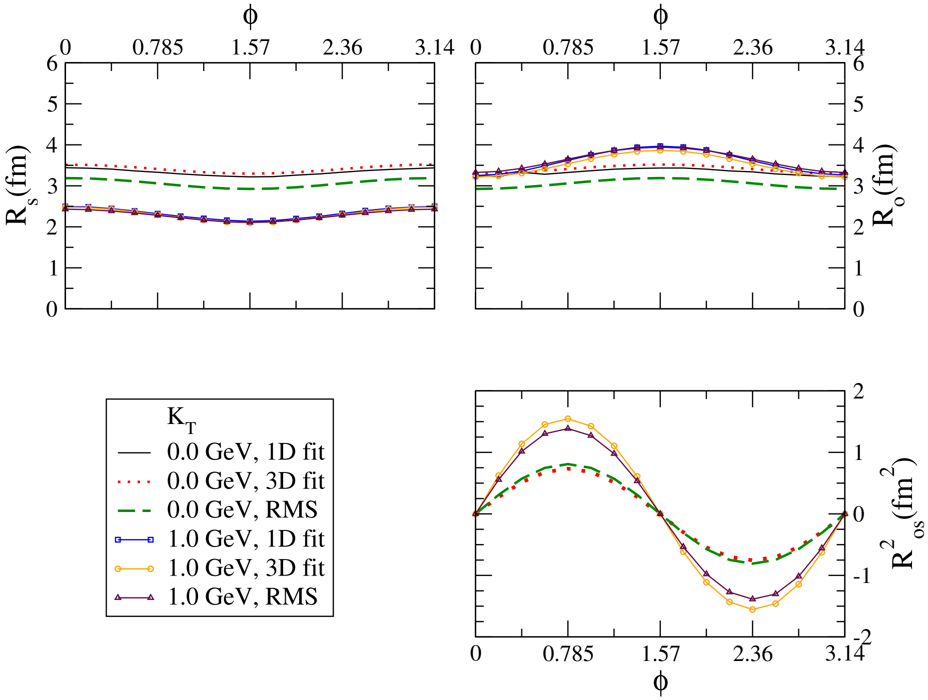
Quite different from pion emission functions!



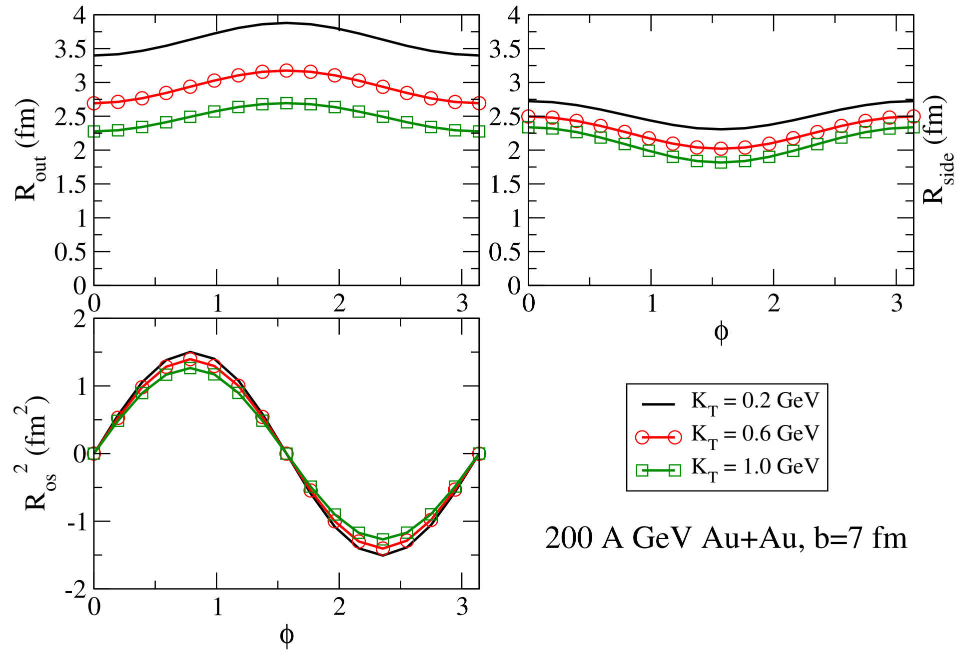
- At $K_T = 0$, emission function is centered at the origin, and azHBT measures eccentricity of time-integrated source (weighted by photon intensity towards early times)
- At small $K_T \neq 0$, emission function moves slightly outward, due to flow boost; azHBT still measures eccentricity of time-integrated source
- At large $K_T \gtrsim 2\,\text{GeV}$, emission function *moves back to the center* and becomes more focussed around the point of highest temperature; boosted HG source causes small bulge in outward direction, but this bulge is weak and doesn't much distort azHBT. azHBT measures *early* eccentricity.
- **Note:** No squeezing to the edge as for pions! At high K_T, homogeneity region (and its eccentricity) reflects entire fireball, not just some small sliver near the fireball edge!

Azimuthal oscillations of HBT radius parameters

Pions



Photons

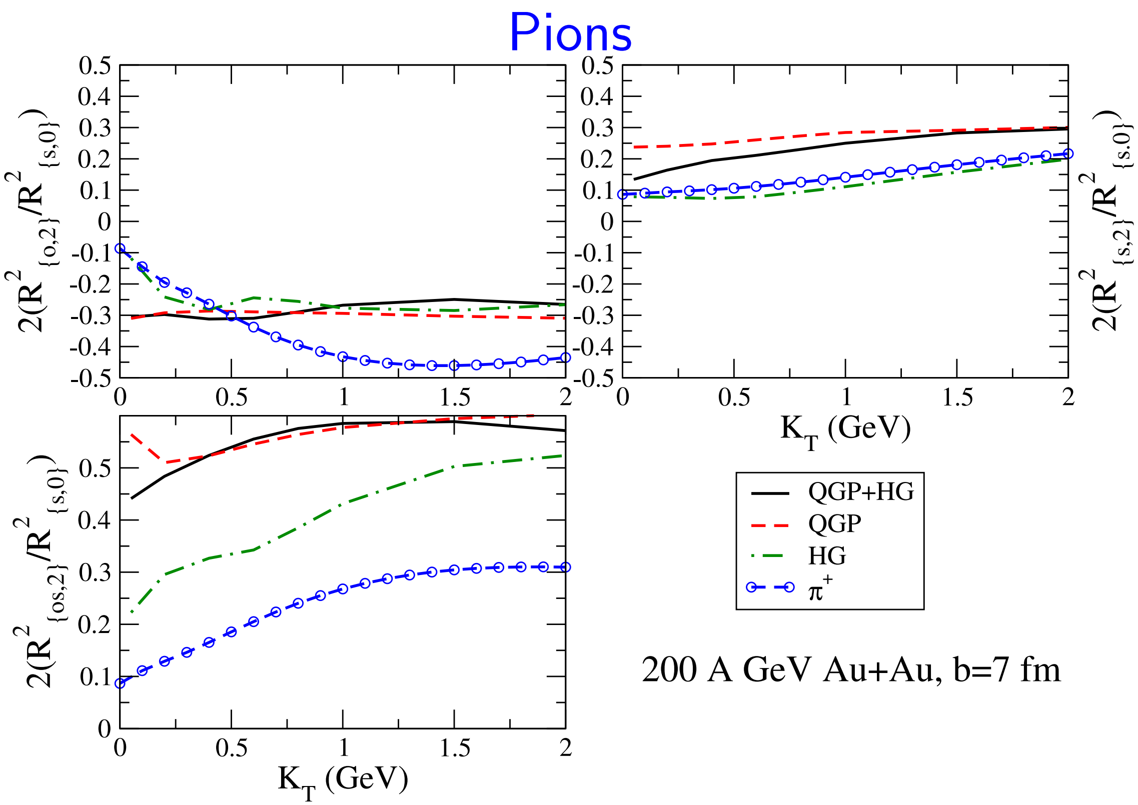


- K_T-dependence of Φ-averaged R_s smaller for photons than pions $\leftrightarrow$ less radial flow at early times
- K_T-dependence of Φ-averaged R_o larger for photons than pions $\leftrightarrow$ larger emission duration contribution for low-K_T photons
- R^2_{os} oscillation amplitude for photons almost independent of K_T and at small K_T larger than for pions
- R^2_{os} oscillation almost purely $\sin(2\Phi)$:

$$R^2_{os} = \cos(2\Phi)\langle\tilde{x}\tilde{y}\rangle + \sin(2\Phi)\frac{\langle\tilde{y}^2-\tilde{x}^2\rangle}{2} + \beta(q)\left(\langle\tilde{x}\tilde{t}\rangle \sin\Phi - \langle\tilde{y}\tilde{t}\rangle \cos\Phi\right)$$

suggests that geometric deformation dominates and is larger than for pions due to early emission.
Works even at $K_T = 0$ where single photon spectrum is dominated by HG!

Normalized azimuthal oscillation amplitudes and source eccentricity



$$2\frac{R^2_{(o,s),2}}{R^2_{s,0}} = \frac{R^2_{(o,s)}(0) - R^2_{(o,s)}(\frac{\pi}{2})}{R^2_s(0) + R^2_s(\frac{\pi}{2})},$$

$$2\frac{R^2_{os,2}}{R^2_{s,0}} = \frac{R^2_{os}(\frac{\pi}{4}) - R^2_{os}(\frac{3\pi}{4})}{R^2_s(0) + R^2_s(\frac{\pi}{2})}.$$

- Eccentricity $\epsilon_x = 2\,R^2_{s,2}/R^2_{s,0}$
- For pions this holds only in the limit $K_T \longrightarrow 0$, but for photons this works up to $K_T \sim 2\,\text{GeV}$.

$\Longrightarrow$ K_T-dependence of normalized sideward oscillation amplitude maps time-dependence of source eccentricity!

Conclusions

- Photons are emitted from the space-time volume, pions from the freeze-out surface of the fireball $\Longrightarrow$ quite different HBT characteristics
- Due to masslessness of photons, smoothness and on-shell approximation break down at low K_T, introducing non-Gaussian shape corrections $\Longrightarrow$ No shortcuts! – must compute full correlator without approximations and fit it in exactly the same way as done in experiment.
- At low $K_T < 1/R_{\rm source}$, outward correlator develops 2-slope structure that allows to separate time and geometry (i.e. spatial width in outward direction and emission duration) at a single K_T-value!
- Oscillatory structure in outward correlator at $K_T > 1{-}2$ GeV from two-source (QGP – HG) interference? (Srivastava & Chatterjee)
- At all K_T emission function is volume-dominated and tracks the fireball deformation at the corresponding average emission time.
- K_T-dependence of normalized sideward oscillation amplitude allows to track time-dependence of fireball eccentricity.
- **Photon azHBT = a window with a view!**