Photon HBT correlations from a quark-gluon plasma (& polarized photons)

Andreas Ipp

Technische Universität Wien

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Outline

● Photon production from anisotropic QGP

● Polarized photons

● Yoctosecond photon pulses

● HBT correlations

   AI, Keitel, Evers, Phys. Rev. Lett. 103, 152301 (2009)
Anisotropies in QGP

Azimuthal anisotropy

In transverse plane of non-central collisions, leads to elliptic flow, $v_2$

Polar anisotropy

$p_L < p_T$

before isotropization
Photon production in the QGP

Photon production rate:

\[ E \frac{dR_{\text{soft}}}{d^3q} = \frac{1}{2(2\pi)^3} \epsilon^\mu \epsilon^{\nu*} \text{Im} \Pi_{\mu\nu}^R(q) \]

\[ q \sim T \]

\[ \Pi_{\mu\nu}(q) = p + p + \ldots \]

“Hard” contributions: \( T \sim p \geq k_c \)

“Soft” contributions: \( gT \sim p \leq k_c \)

Compton scattering:

\[ \alpha_s \sim 0.3 \]

\[ \alpha \sim \frac{1}{137}. \]

Quark-quark annihilation:

need to use dressed propagators

Final result independent of intermediate cutoff \( k_c \sim \sqrt{gT} \)

Hard contributions

Photon production rate:

\[ 2E \frac{dR_i}{d^3q} = N \int \frac{f_q(p_1)d^3p_1}{2E_1(2\pi)^3} \frac{f_q(p_2)d^3p_2}{2E_2(2\pi)^3} \frac{(1+f_g(p_3))d^3p_3}{2E_3(2\pi)^3} \delta^{(4)}(p_1+p_2-p_3-p_4) |M_i|^2 \]

Quark-quark annihilation:

\[ iM(q(p_1)\bar{q}(p_2)\to g(p_3)\gamma(p_4)) = \left( \bar{\nu}^{j,s'}_\gamma(p_2) [iQ\epsilon^\mu] \epsilon^\mu_\gamma(p) \right) \frac{i(\gamma^\alpha q_1^\alpha+m)}{q_1^2-m^2} \left( \epsilon^{f}_\nu(p_3) [i\gamma^\nu t^f_{ji}] \epsilon^{i,s}_\gamma(p_1) \right) \]

+ crossed process

Square the matrix element:

\[ |M|^2 = (iM)^\dagger (iM) \]

average / sum over quark spins:

\[ \frac{1}{2} \sum_{s=1,2} u^s_d(p_1) \bar{u}^{s'}_{d'}(p_1) = \frac{1}{2} [\gamma^\mu p_1^\mu+m]_{dd'} \]

color trace:

\[ \frac{1}{3} \sum_{i=1,2,3} \frac{1}{3} \sum_{j=1,2,3} \sum_{f=1..8} t^f_{ij} t^f_{ji} = \frac{4}{9} \]

Ward identity for gluons / photons:

\[ \sum_{\text{polarizations}} \epsilon^*_\mu(p) \epsilon_\nu(p) \to -g_{\mu\nu} \]

for Compton scattering:

replace \( p_3 \to -p_3, p_2 \to -p_2 \)

overall minus: antiquark \( \leftrightarrow \) quark
High energy Compton scattering

\[ p = (\omega, \omega \sin \theta, 0, \omega \cos \theta) \]
\[ p_3 = (\omega_3, 0, 0, \omega_3) \]
\[ p_1 = (E_1, 0, 0, -\omega_1) \]
\[ p_2 = (E_2, p_2) \]

polarization vectors:
\[ \epsilon = \epsilon_1 \cos \varphi + \epsilon_2 \sin \varphi \]
with
\[ \epsilon_1 = (0, \cos \theta, 0, -\sin \theta) \]
\[ \epsilon_2 = (0, 0, 1, 0) \]

Klein-Nishina formula at high energies:

\[
\frac{d\sigma}{d(\cos \theta)} = \frac{Q^2 e^2 g^2}{192 \pi m^2} \left( \frac{\omega}{\omega_3} \right)^2 \frac{E_1}{(E_1 + \omega_1)^2} \left[ \frac{\omega (E_1 + \omega_1 \cos \theta)}{\omega_3 (E_1 + \omega_1)} + \frac{\omega_3 (E_1 + \omega_1)}{\omega (E_1 + \omega_1 \cos \theta)} - \frac{2m^2 \sin^2 \theta \cos^2 \varphi}{(E_1 + \omega_1 \cos \theta)^2} \right]
\]

High-energy limit: \( E_1 \approx \omega_1, m^2 \to 0 \)

- dominant (divergent) contribution at \( \theta \approx \pi \) (backward scattering)
- similar for annihilation diagram
  (no polarization from hard contribution in this limit)
Anisotropic QGP

Isotropic plasma:
- Processes with different orientation average out
- No net polarization

Anisotropic plasma:
- Preferred direction given by momentum anisotropy
- Also photon obtains preferred polarization orientation
Massive quarks

$r$: Compton contribution; $r_{\text{tot}}$: Total contribution;

Anisotropy parameter $\xi = \xi_0 (\tau_0 / \tau)^\alpha$


→ talk by Gordon Baym
Observe polarized photons

Polarization of the Cosmic Microwave Background (ESA / Planck 2015)

Mantis shrimp  Octopus  Bee  Dung beetle  Real 3D

Trento, Dec 4, 2015  Andreas Ipp
Photon production rate:

\[ E \frac{d R_{\text{soft}}}{d^3 q} = \frac{1}{2(2\pi)^3} \epsilon^\mu \epsilon^{\nu*} \text{Im} \Pi_{\mu \nu}^R(q) \]

Photon polarization tensor in “realtime formalism”:

\[ \text{Im} \Pi_{R,\mu \nu}^R(q) = -i \Pi_{12}^{\mu \nu} \equiv -e_q e^2 N_c \int \frac{d^4 p}{(2\pi)^4} \text{Tr} \left[ \gamma^\mu S_{12}^*(P) \gamma^\nu S_{21}(P-Q) + \gamma^\mu S_{12}(P) \gamma^\nu S_{21}^*(P-Q) \right] \]

with dressed fermionic propagators

\[ S_{12/21}^*(P) = S_{\text{ret}}^*(P) \Sigma_{12/21}(P) S_{\text{adv}}^*(P) \]

and Schwinger-Dyson relations:

\[ (S_{\text{ret}}^*)^{-1}(P) = S_{\text{ret}}^{-1}(P) - \Sigma_{\text{ret}}(P) \]

\[ (S_{\text{adv}}^*)^{-1}(P) = S_{\text{adv}}^{-1}(P) - \Sigma_{\text{adv}}(P) \]

which can be calculated in “Hard Loop” approximation
Soft contributions

Photon production rate:

\[ E \frac{dR_{\text{soft}}}{d^3q} = \frac{1}{2(2\pi)^3} \epsilon^\mu \epsilon^{\nu*} \text{Im} \Pi^{R}_{\mu\nu}(q) \]

result for unpolarized photon:

\[ g_{\mu\nu} \text{Im} \Pi^{R,\mu\nu}(q) = -i e_q^2 e^2 N_c \frac{4f_q(q)}{q} \int \frac{d^3p}{(2\pi)^3} Q_\alpha [S^*_{\text{ret}}(P) - S^*_{\text{adv}}(P)] \bigg|_{p_0 = p \cdot \hat{q}} \]

result for polarized photon:

\[ \epsilon^\mu \epsilon^{\nu*} \text{Im} \Pi^{R}_{\mu\nu}(q) = -i e_q^2 e^2 N_c \frac{2f_q(q)}{q} \int \frac{d^3p}{(2\pi)^3} \times \left[ -(\epsilon \cdot \epsilon^*) Q_\alpha + (\epsilon \cdot Q) \epsilon^*_\alpha + (\epsilon^* \cdot Q) \epsilon_\alpha \right] [S^*_{\text{ret}}(P) - S^*_{\text{adv}}(P)] \bigg|_{p_0 = p \cdot \hat{q}} \]

\[ = -1 \]
\[ = 0 \]
\[ = 0 \]

no polarization effect
Photon polarization

Stokes parameters

<table>
<thead>
<tr>
<th>100% Q</th>
<th>100% U</th>
<th>100% V</th>
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<tbody>
<tr>
<td>+Q</td>
<td>+U</td>
<td>+V</td>
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<td>Q &gt; 0; U = 0; V = 0</td>
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<td>-Q</td>
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(Virtual photons: also longitudinal polarization)

Gonodactylus smithii

(C) Wikipedia: Waveplate
Quark polarization projectors

How to include quark polarization in the calculation?

\[ u^s(q)\bar{u}^s(q) = (\gamma_\alpha q^\alpha + m) \frac{1+ p_s \gamma^5 \gamma_\beta s^\beta}{2} \]

Polarization axis \( s \) is defined in rest frame of \( q \) with \( s \cdot q = 0 \).

Problem in limit \( m \to 0 \).

\[
\begin{align*}
\tilde{p} &= (m, 0) \to p = (E, p), \\
\tilde{s} &= (0, s) \to s = \left( \frac{p \cdot s}{m}, \frac{E - m}{m} \frac{p (p \cdot s)}{p^2} + s \right)
\end{align*}
\]

Separation into longitudinal polarization (helicity) and transverse polarization:

\[
\begin{align*}
\tilde{u}^s(q)\tilde{\bar{u}}^s(q) &\to \gamma_\alpha q^\alpha \frac{1+ p^\parallel \gamma^5 + p^\perp \gamma^5 \gamma_\beta s^\beta}{2} \\
&\equiv \mathcal{P}(q) \quad \text{(polarization projector)}
\end{align*}
\]

A priori momentum dependent quantities: \( p^\parallel(q), p^\perp(q), s(q) \).
With spin-polarized quarks

\[ |M_c|^2 = -\frac{\epsilon^2 g^2}{6} \left( \frac{s}{u} + \frac{u}{s} \right) \]

(for \( m \to 0 \))

decompose spin in rest frame:

\[ s = p^\parallel \hat{q} + p^\perp \hat{s}^\perp \]

describe polarization through density matrix:

\[ \rho_{\pm} \rightarrow \gamma_\alpha q^\alpha \frac{1 + p^\parallel \gamma^5 + p^\perp \gamma^5 \gamma_\beta S^\beta}{2} \]

\[ |M_c|^2 = -\frac{\epsilon^2 g^2}{12} \left( 1 + p^\parallel (q_1) p^\parallel (q_2) \right) \left( \frac{s}{u} + \frac{u}{s} \right) \]

\[ + \left( p^\parallel (q_1) + p^\parallel (q_2) \right) \left( \frac{s}{u} - \frac{u}{s} \right) i \det |\epsilon \epsilon^* \hat{q}| \]

\[ + 4 p^\perp (q_1) p^\perp (q_2) \left[ (q \cdot \hat{s}_1)(q \cdot \hat{s}_2) \left( \frac{1}{u} + \frac{1}{s} \right) \right. \]

\[ - \frac{\hat{s}_1 \cdot \hat{s}_2}{2} \left( \frac{q \cdot \hat{s}_1}{u} \right) \left( \frac{q \cdot \hat{s}_2}{s} \right) + \frac{(q \cdot \hat{s}_2)(q_2 \cdot \hat{s}_1)}{s} \]
Integrate hard contributions

Assumption: global spin direction \( \hat{s} = \hat{y} \)

\[
E \frac{dR_c}{d^3 q} = 20\pi \int_\delta f^{F}_\xi (q_1) f^{B}_\xi (q_3) \left| M^S_c \right|^2 - f^{F}_\xi (q_2) \left| M^c_c \right|^2, \]

Compton

\[
E \frac{dR_a}{d^3 q} = \frac{320\pi}{3} \int_\delta f^{F}_\xi (q_1) f^{F}_\xi (q_2) \left( 1 + f^{B}_\xi (q_3) \right) \left| M^a_c \right|^2. \]

Annihilation

Bose enhancement

\[
\int_\delta \equiv \frac{d^3 q_1}{2E_1} \frac{d^3 q_2}{2E_2} \frac{d^3 q_3}{2E_3} \delta^{(4)}(q_1 + q_2 - q_3 - q) \]

Pauli blocking
Soft contributions

\[ \Pi_{\mu\nu}(q) = \ldots \]

Photon production rate:

\[ E \frac{dR_{\text{soft}}}{d^3 q} = \frac{1 + p^\parallel(q)}{(2\pi)^3} \left| \epsilon \epsilon^* \right| \frac{5e^2 f^F_\epsilon(q)}{3|q|} \int \frac{d^3 k}{(2\pi)^3} \text{Im} q \cdot S^*_R(k) \]

with dressed fermionic propagators \( S^*_R(k) \)

which can be calculated in “Hard Loop” approximation.
Polarized photon rate

\[ \frac{E dR}{d^3q} \rho^2 [\text{fm}^{-4} \text{GeV}^{-4}] \]

for anisotropy parameter \( \xi = 0 \)

Visibility of global polarization

\[ V = \frac{\text{max} - \text{min}}{\text{max} + \text{min}} \]

\[ E/T \geq 5 \text{ corresponds to } E \geq 1\text{GeV} \]

Quark polarization \rightarrow circular photon polarization.

Global spin

Global polarization from fluid vorticity

Beccattini et al.,
Phys. Rev. C88, 034905 (2013);
arXiv:1501.04468

Theoretical prediction:

\[ P(\Lambda) \approx -0.3 \]
Liang and Wang,
PRL 94, 102301 (2005)

Measurement of \( \Lambda \) hyperons:

\[ |P(\Lambda, \Lambda)| \leq 0.02 \]
Selyuzhenkov,

\( \Lambda \) polarization may be affected by hadronization

Betz, Gyulassy, and Torrieri,
Global polarization of hyperons measured by STAR in the RHIC Beam Energy Scan:

„First clear positive signal of global polarization in heavy ion collisions!“

→ 3σ to 5σ signal for Λ’s at each energy below 39 GeV
Polarized proton beams

Polarized protons at RHIC

Transverse spin-dependent azimuthal correlations of charged pion pairs observed at STAR

arXiv:1504.00415
Chiral magnetic effect

Slide by Harmen Warringa

\[ \langle Q^2 \rangle \neq 0 \]

\[ \langle N_5^2 \rangle \neq 0 \]

\[ \langle J_z^2 \rangle > \langle J_{x,y}^2 \rangle \]

\[ \langle \Delta_\pm^2 \rangle > 0, \quad \langle \Delta_+ \Delta_- \rangle < 0 \]

→ see also talk by Ho-Ung Yee
Detect dilepton polarization

Polarization of dileptons

No polarization from dimuons
Arnaldi et al., (NA60)
PRL 102, 222301 (2009)

Kenta Shigaki @QM'14
So far no signal from dielectrons, but background needs to be subtracted properly
Detecting linear / circular polarization

in the GeV range: Si crystal acts as quarter wave plate
use coherent $e^+e^-$ pair production to detect polarization state

A. Apyan et al., NA59 Collaboration at CERN SPS.
NUHEP-EXP-2-006, 2003, hep-ex/0306041
History of light pulse duration

Nd:glass: Neodymium glass laser
CW Dye: Continuous Wave Dye laser
CPM: Colliding Pulse-Mode locked dye laser
Ti:sapphire: Titanium sapphire laser
HHG: High-Harmonic Generation
QGP: Quark Gluon Plasma

case studies: chemical and biological events
chemical reactions, femtochemistry
electron motion, attosecond science
nuclear events


Pulse duration: ns, ps, fs, as, zs, ys

- Nd:glass
- CW Dye
- CPM
- Compression
- Ti:sapphire
- HHG
- QGP
Expanding plasma

Bjorken expansion model

\[ \Delta \theta = 2 \Delta y = \frac{2d}{ct} \]

region of interest

quanta emerging from collision point at speed of light

receding nuclear pancake

J. D. Bjorken, PRD 27, 140 (1983)

Anisotropy can cause:

- **Chromo-Weibel instability**
  Mrowczynsi (1993); Romatschke, Strickland (2003); Arnold, Lenaghan, Moore (2003); ...

- **Violation of viscosity bound**
  Rebhan, Steineder (2012)

- **Yoctosecond double pulses**
  AI, Keitel, Evers (2009)
### Momentum space anisotropy

**Isotropic plasma:**

- **Gluons:** Bose-Einstein distribution
  \[
  f^B(q) = \frac{1}{e^{|q|/T} - 1}
  \]
- **Quarks:** Fermi-Dirac distribution
  \[
  f^F(q) = \frac{1}{e^{|q|/T} + 1}
  \]

**Anisotropic plasma:**

- Stretch or compress isotropic distribution along axis \( \hat{n} \):
  \[
  f_\xi(q) = f_{iso}(\sqrt{q^2 + \xi(q \cdot \hat{n})^2})
  \]

- \( \xi \): anisotropy parameter

---

Photon rate

- Photon rate as function of emission angle $\theta_q$ for various anisotropy parameters $\xi$

Model for time-evolution

Anisotropy parameter

Energy density

Isotropization time $\tau_{iso}$


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Suppression of differential photon rate can lead to double peak structure, but this still needs to be integrated over space-time.
Space-time diagram of the collision

Bjorken expansion model

J. D. Bjorken, PRD 27, 140 (1983)
Emission transverse to beam axis

Time evolution of photon emission

\[ \frac{dN}{dtd\omega d\Omega} \text{ (as}^{-1}\text{GeV}^{-1}) \]

\[ \begin{align*}
\text{(a)} & \quad p = 2 \text{ GeV} \\
& \quad b = 0 \text{ fm} \\
& \quad \theta = \pi / 2
\end{align*} \]

\[ \begin{align*}
\text{(b)} & \quad p = 3 \text{ GeV} \\
& \quad b = 0 \text{ fm} \\
& \quad \theta = \pi / 2
\end{align*} \]

Structure of peak fully dominated by geometry.
Double peak structure washed out.

AI, Keitel, Evers, PRL 103, 152301 (2009)
Non-central collisions

In order to see double peaks, one needs:

- non-central collisions (to decrease physical size of QGP)
- detector in forward direction (to increase effect of momentum anisotropy)
Intermediate angle: a double peak may appear.
(but: large model uncertainties)

Time evolution of photon emission

\[ \tau_{iso} = 2 \text{ fm/c} \]

\[ \eta = 0.88 \]

\[ \eta = 1.6 \]

AI, Keitel, Evers, PRL 103, 152301 (2009)
HBT correlation

Hanbury Brown and Twiss (1956)

HBT correlation function:

\[ C_2(k, k') = \frac{P_2(k, k')}{P_1(k)P_1(k')} \]

Two-particle inclusive distribution function:

\[ P_2(k, k') = \int d^4x d^4x' w(x, \frac{k+k'}{2})w(x', \frac{k+k'}{2}) \times \left[ 1 + \frac{1}{2} \cos(\Delta k \cdot \Delta x) \right] \]

Single-particle inclusive distribution function:

\[ P_1(k) = \int d^4x w(x, k) \]
HBT correlation measurement

Detection in forward direction:

**Forward Calorimeter (FoCal)**
(ALICE detector upgrade?)
Peitzmann, arXiv:1308.2585

Expect around $10^6$ prompt photons per year for $k_T = 1$ to 4 GeV/$c$.

Can expect few hundred photon pairs in same time frame.
Collinear configuration:
side peak appears
at large isotropization times

$$\theta = 25^\circ$$
$$\eta = 1.5$$

$$k = 4\text{GeV}/c$$
$$k_T = 1.7\text{GeV}/c$$

$$b = 10\text{fm}$$

AI, Somkuti, PRL 109, 192301 (2012).
HBT correlation measurement

Detector in forward direction:

side peak appears at large isotropization times

\[ \theta = 2^\circ \sim 8^\circ \]
\[ (\eta = 4 \sim 2.7) \]
\[ k = 25 \text{GeV/c} \]
\[ (k_T = 0.9 \sim 3.5 \text{GeV/c}) \]
\[ b = 12 \text{fm} \]

\[ \frac{C_2(\theta_{\text{rel}})}{C_2(0)} \]

\[ \tau_{\text{iso}} = \tau_0 \]
\[ \tau_{\text{iso}} = 0.5 \text{fm/c} \]
\[ \tau_{\text{iso}} = 1 \text{fm/c} \]
\[ \tau_{\text{iso}} = 1.5 \text{fm/c} \]
\[ \tau_{\text{iso}} = 2 \text{fm/c} \]
Summary

- Compton scattering may lead to linear photon polarization (mass dependent)
- Global quark polarization may lead to circular photon polarization
- Shape of HBT correlation may be sensitive to isotropization time
Open challenges

Theoretical challenges:

- Role of mass in Compton scattering?
- Soft collinear scattering (AMY formalism) in anisotropic case?
- Polarization from hadron gas?

Experimental challenges:

- Detect polarized photons

(Just a matter of competition and natural selection ...)