Introduction

Radiation due to a single point charge

Radiation due to two point charges

Elliptic flow due to radiation

Summary

Classical fields, Unruh radiation and heavy ions

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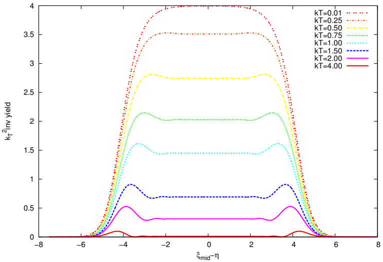
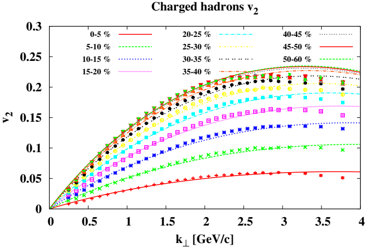


- Photon rapidity spectra of a single point charge

- Elliptic flow: fits for experimental data



Outline

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Hydrodynamics in heavy ion collisions

- Fermi: thermodynamics for high-energy collisions
- Landau: particle production after expansion
- Several new models since then

Bjorken model

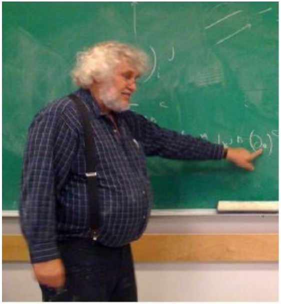
- fast thermalization
- expansion: 1D, y = η
- plateau in rapidity spectrum

↔

Landau model

- fast thermalization
- longitudinal + transversal expansion
- bell shapes in rapidity spectrum

Unruh effect



Unruh effect

A relativistic observer with constant acceleration sees blackbody radiation, non accelerating: monocromatic plane wave. Interpretation: Relativistic Doppler-effect.

- No heath bath
- No Brownian-motion

- Planck spectrum

Unruh temperature

proportional to the accelaration (g) :

$$kT = \frac{\hbar g}{2\pi c}$$

Unruh effect

Radiation and Doppler effect

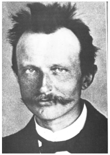
Moving observer sees different plane wave: Doppler effect, if there is accelaration radiation can be interpreted due to the Doppler shift.

$$I(\Omega) \propto |\int e^{i\int \omega\sqrt{\frac{1-v(\tau)}{1+v(\tau)}}d\tau-\Omega\tau}d\tau|^2 \propto |\int e^{ic\omega z/g} z^{-i\Omega c/g-1} dz|^2$$

- $z = e^{-\xi}$
- ξ : rapidity
- $a_i = (sinh\xi, cosh\xi)\frac{d\xi}{d\tau}$
- $a_i a^i = -g^2$

Planck spectra

$$I(\Omega) = \frac{1}{e^{2\pi c\Omega/g}-1}$$



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Linear accelaration

An accelarating point charge radiates, it can be interpreted as emission of photons.

T.S Biro Z. Szendi, Zs. Schram (1401.1987 –> EPJ A 2014)

Number of photons: $$d^3N = \frac{d^3k}{2k_0(2\pi)^3} \sum |\epsilon \cdot J(k)|^2$$

- J(k):source term $J^i(k) = q \int e^{ik \cdot x(\tau)} \, u^i(\tau) \, d\tau,$
- modified source: $\epsilon \cdot J(k) = q \int\limits_{\tau_1}^{\tau_2} e^{ik \cdot x(\tau)} \, \frac{d}{d\tau} \left(\frac{\epsilon \cdot u}{k \cdot u} \right) \, d\tau$
- $k_i = k_\perp \, (\cosh \eta, \sinh \eta, \cos \psi, \sin \psi)$

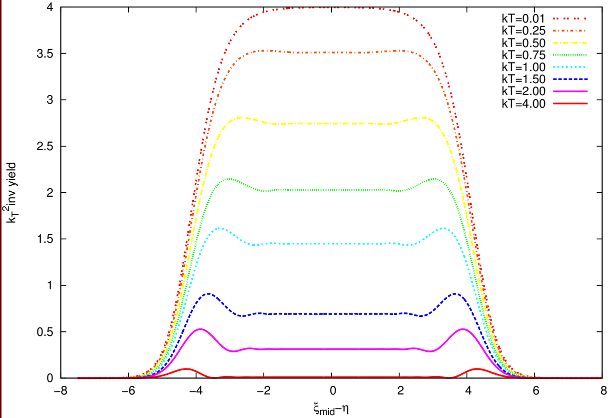
Photon distribution

$$k_\perp^2 \, \frac{dN}{k_\perp dk_\perp d\eta} = 2\alpha_e \left| \int\limits_{v_1}^{v_2} e^{i\ell k_\perp \gamma v} dv \right|^2$$

Photon distr. for large k:

$$\frac{d^2N}{k_\perp dk_\perp d\eta} = N_0 \, e^{-\hbar c k_\perp / k_B T}$$

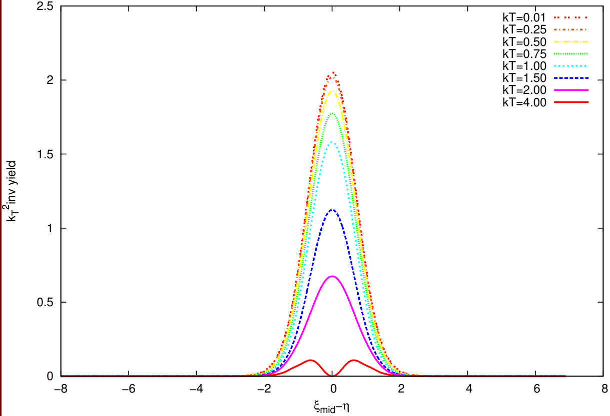
$$T = \frac{\hbar c}{2 k_B \ell} = \pi \, T_{Unruh}$$



T.S Biro Z. Szendi, Zs. Schram (1401.1987 –> EPJ A 2014)

- longer decelaration time
- plateau
- $lk_\perp > 0.5?$

Semiclassical photon-rapidity spectra II.

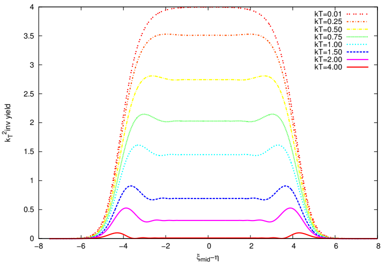


T.S Biro Z. Szendi, Zs. Schram (1401.1987 –> EPJ A 2014)

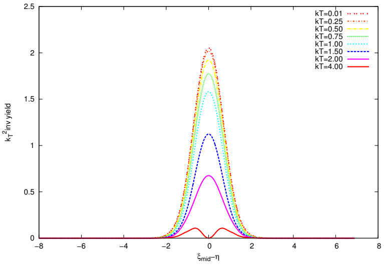
- short deceleration time
- $g = 1$
- bell shape

Bjorken and Landau - a comparison

Bjorken



Landau



short time acc.
plateau

⟷

long time acc.
bell shape

shift: $g\tau = \pi$

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A dipole-like structure

Two point like sources

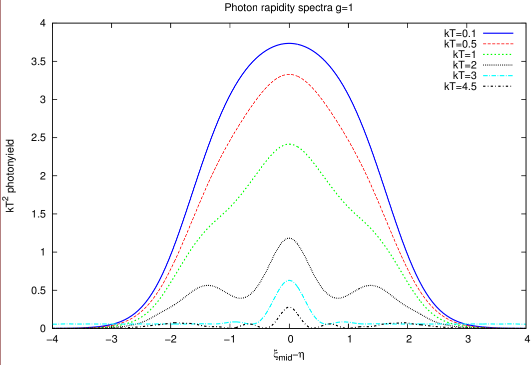
Two point charges moving in opposite directions on parallel paths. The yield is: $Y \propto \left| A_1 e^{ik_\perp \frac{d}{2}\cos(\alpha-\psi)} + A_2 e^{-ik_\perp \frac{d}{2}\cos(\alpha-\psi)} \right|^2$

- A_i: amplitudes
- α : detector angle
- ψ : angle of the event
- d : distance

After expending the square:

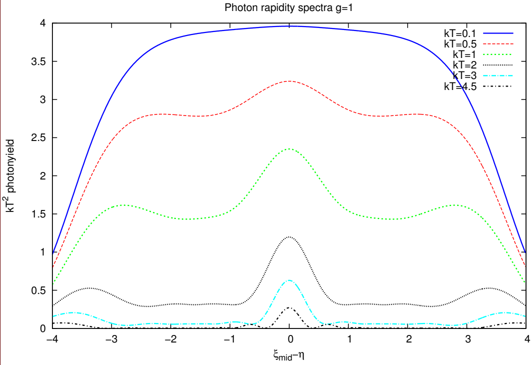
$$Y \propto |A_1|^2 + |A_2|^2 + A_1 A_2^* \, e^{ik_\perp \frac{d}{2} cos(\alpha-\psi)} + A_1^* A_2 \, e^{-ik_\perp \frac{d}{2} cos(\alpha-\psi)}$$

Photon rapidity spectra for point charges



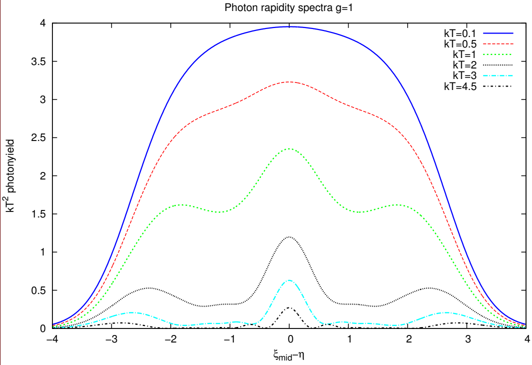
- short deceleration time
- $g = 1$
- phase: 0
- bell shape
- interference patterns

Photon rapidity spectra for point charges II.



- long deceleration time
- $g = 1$
- phase: 0
- bell shape
- interference patterns

Photon rapidity spectra for limit



- short deceleration time
- $g = 1$
- phase: 0
- bell shape

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Flow coefficients

Two point like sources

Two point charges moving in opposite directions on parallel paths. The yield is: $Y \propto \left| A_1 e^{ik_\perp \frac{d}{2}\cos(\alpha-\psi)} + A_2 e^{-ik_\perp \frac{d}{2}\cos(\alpha-\psi)} \right|^2$

Flow coefficients

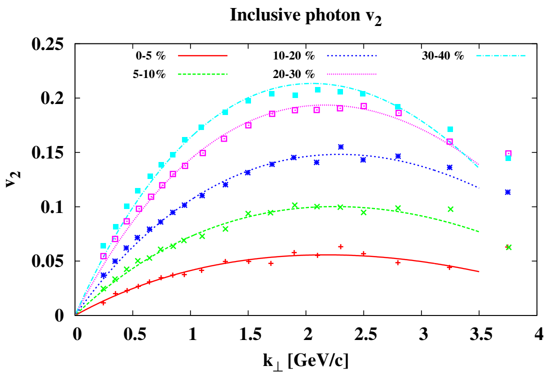
Flow coefficients are the relative amplitudes of $\cos(n\theta)$ terms to the zeroth order term.

v_n

$$v_n = \frac{2R_n J_n(k_\perp d)}{|A_1|^2 + |A_2|^2 + R_0 J_0(k_\perp d)}$$

- J_n : Bessel functions (first kind)
- $R_n := 2\Re e\left(i^n A_1 A_2^*\right) = 2\,|A_1|\,|A_2|\,\cos\left(\delta + n\frac{\pi}{2}\right)$
- δ : phase factor

Fits to inclusive photons (ALICE)

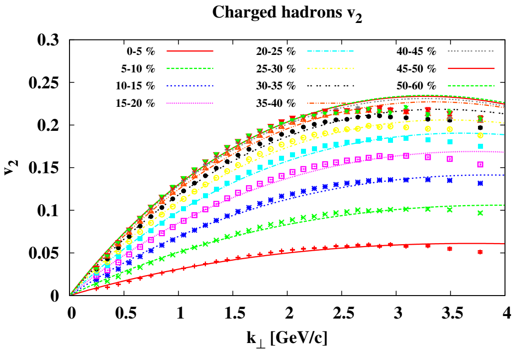


- Pb-Pb collissions
- several centrality classes
- $\sqrt{s_{NN}} = 2.76 TeV$

Figure: v_2 for inclusive photons

J. Phys. Conf. Ser. 446, 012028 (2013), M.Horvath, Z.Schram, T.S. Biro EPJA 51 7 (2015) 75

Comparison to hadron data



- Au-Au collisions
- $\sqrt{s_{NN}} = 200GeV$
- $\gamma \approx 1$
- d = 0.07 [fm]

Figure: Fits for hadron data from PHENIX

Phys. Rev. Lett. 105, 062301 (2010), arXiv:1003.5586v2, M.Horvath, Z.Schram, T.S. Biro EPJA 51 7 (2015) 75

Summarizing the fit parameters

Summarizing the results from the fits:

- d is stable → $d \approx 0.07 - 0.1$ [fm]
- γ is stable → $\gamma \approx 1$
- fits for different centrality → $c : 0 - 60\%$
- comes close to data → hadron, photon

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Radiation-single point charge

- no initial conditions
- no fluctuations
- charge: linear trajectory
- Landau, Bjorken like behaviour

Hydro, thermo

- initial conditions
- fluctuations
- p-p elliptic flow?
- heath bath?

Radiation-Two charges

- Dipole like sturcture
- v_2 calculations
- Fits to experimental data
- (Illusory) flow without hydro

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Flow coefficients

Flow coefficients are the relative amplitudes of $\cos(n\theta)$ terms to the zeroth order term.

Using the Jacobi-Anger formula:

$$e^{ix\cos\Theta} = J_0(x) + 2\sum_{n=1}^{\infty} i^n J_n(x)\cos(n\Theta).$$

v_n

$$v_n = \frac{2R_n\, J_n(k_\perp d)}{|A_1|^2 + |A_2|^2 + R_0\, J_0(k_\perp d)}$$

- J_n : Bessel functions (first kind)
- $R_n := 2\Re e\left(i^n A_1 A_2^*\right) = 2\,|A_1|\,|A_2|\,\cos\left(\delta + n\frac{\pi}{2}\right)$
- δ : phase factor

Azimuthal anisotrophy for n= 2, v_2

For n = 2 the flow coefficient becomes:

$$v_2 = \frac{-2\,\varepsilon\, J_2(k_\perp d)\, cos(\delta)}{1+\varepsilon\, J_0(k_\perp d)\, cos(\delta)}$$

with $\varepsilon = \frac{2\,|A_1|\,|A_2|}{|A_1|^2+|A_2|^2} \leq 1$

If the following parametrization is made:

- $A_1 = e^{i\delta_0}$
- γ: ratio of the amplitudes
- $A_2 = e^{i(\delta_0+\delta)}$
- d : dipole size

The flow coefficient, v_2 becomes:

Final v_2

$$v_2 = \frac{-J_2(k_\perp d)\cos\delta}{\frac{1+\gamma^2}{2\gamma}+J_0(k_\perp d)\cos\delta}$$

Amplitudes for the dipole

Two sources in the opposite direction:

- velocity from c to 0 - first charge
- second: velocity: from c to above 0 - second charge

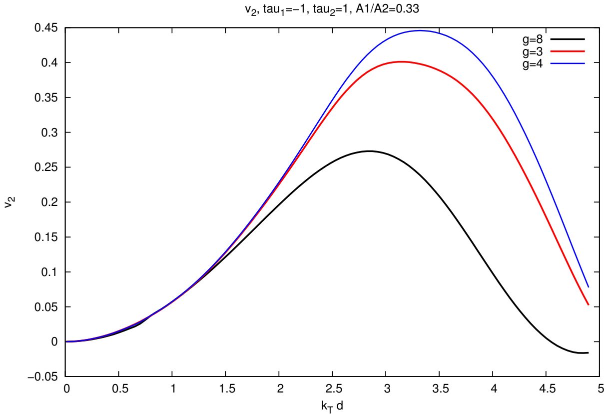
$$A_1 = \int_{-\infty}^{0} \mathrm{d}v \frac{e^{iv\Delta}}{(1+v^2)^{\frac{3}{2}}} = \frac{\Delta}{2}\left(2K_1(\Delta) + i\pi\left(K_1(\Delta) - L_{-1}(\Delta)\right)\right)$$

$$A_2 = \int_{\infty}^{v_2} \mathrm{d}v \frac{e^{iv\Delta}}{(1+v^2)^{\frac{3}{2}}} = -A_1^* + \int_{0}^{v_2} \mathrm{d}v \frac{e^{iv\Delta}}{(1+v^2)^{\frac{3}{2}}},$$

where the parameters are:

- K_n Bessel functions
- $\Delta = \frac{k_\perp}{g}$

Numerical results for v_2



- $g = 4$
- $g = 3$
- $g = 8$

v_2 from two radiating point charges with:

- different accelarating times — assymetric tau
- no averaging — given A_1/A_2

v_2 analytically

Analytically averaging over the phase factor results in:

Averaged v_2

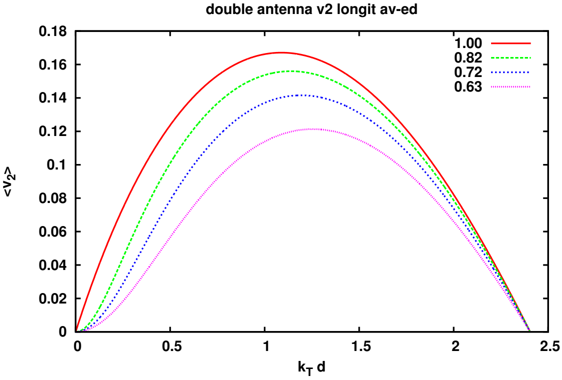
$$\langle v_2 \rangle = \frac{J_2(dk_\perp)}{J_0(dk_\perp)} \left(\frac{1}{\sqrt{1 - \frac{4\gamma^2}{(1+\gamma^2)^2} J_0^2(dk_\perp)}} - 1 \right)$$

- leading term: from dipole
- geometric factor: F

v_2

$$\langle v_2 \rangle_{fit} = F \cdot \langle v_2 \rangle (dk_\perp, \gamma)$$

Analytical results for averaged v_2



- $F = 1$
- Only the dipole term exists
- lines: different aplitude ratios

Figure: Analytical results for averaged v_2

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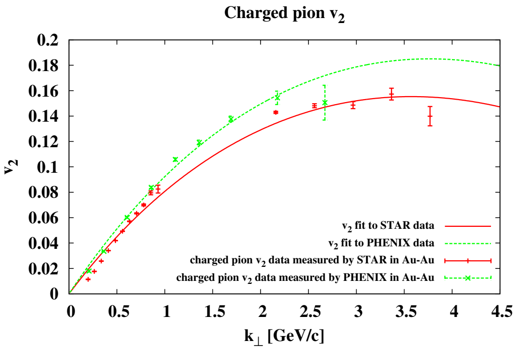

- Au-Au collisions
- $\sqrt{s_{NN}}$ = 62 GeV / 200 GeV
- $\gamma \approx 1$
- $d = 0.06[fm]$

Figure: v_2 of charged pions, data is from STAR (red) and PHENIX (green)

Phys. Rev. C 75, 054906 (2007)
Phys. Rev. Lett. 91, 182301 (2003)

The model

After Fourier expansion the yield can be written:

$$Y = Y_0 + Y_2\, F\, cos(2\varphi) \qquad \text{with F: } \frac{A^2-B^2}{A^2+B^2}$$

How to attach this ellipse to the collisions?

- nuclei disks with radius R
- intersection: ellipse
  - F = $\frac{b}{2R}$
- b: impact parameter
- subhadronic dipoles

Dipoles can be ordered parallel or perpendicular to the reaction plane, but F remains the same!