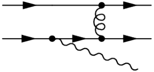
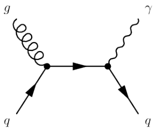
Photon production in the Quark-Gluon Plasma

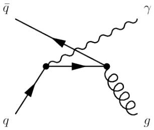
transport meeting Frankfurt 2016

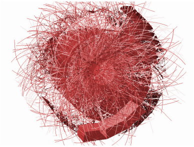
Moritz Greif

in collaboration with Kai Zhou, Florian Senzel, Hendrik van Hees, Kai Gallmeister, Alex Meistrenko, Alexander Rothkopf, Carsten Greiner, Zhe Xu









Overview

Introduction

- contributing photon sources in heavy ion collisions
- The direct photon puzzle

Photons in partonic transport

- transport approach BAMPS
- Photon emission rates in BAMPS

Results and interpretation

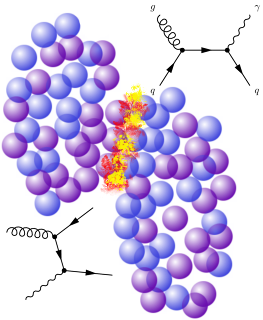
- p_T-spectra from BAMPS
- Elliptic flow from BAMPS
- high-p_T leakage effect for Jets

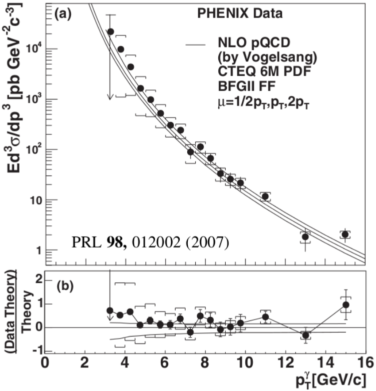
Introduction

- Contributions of different stages of the heavy ion collision
- Former attempts to describe CERN-SPS data
- Nonequilibrium contributions
- The direct photon puzzle

pQCD photons = prompt photons = initial photons

more or less under control $p_T \gtrsim 2\mathrm{GeV}$.





Klasen et al., Eur. Phys. J. C (2014) 74:3009, Owens, Rev.Mod.Phys.59,456

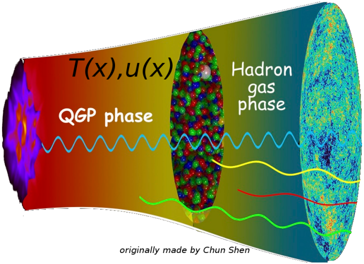
Thermal photons from QGP and hadron gas

1. Take some photon rate ($R \equiv N^\gamma$/volume/time):

   e.g. a simple elastic rate: $E\frac{\mathrm{d}R}{\mathrm{d}^3k} = C_{EM}\frac{\alpha_{EM}\alpha_s}{2\pi^2}T^2 e^{-E/T}\ln\left(\frac{2.912}{g^2}\frac{E}{T}\right)$,

2. Take some heavy ion background information $T(\vec{x},t)$, $u^\mu(\vec{x},t)$
3. Obtain the photon spectrum:

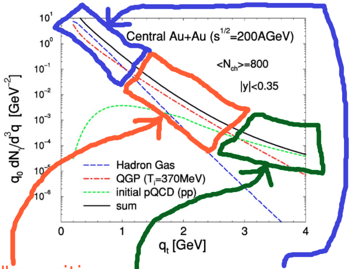
$$E\frac{\mathrm{d}N}{\mathrm{d}^3p} = \int_{\text{heavy ion collision}} \mathrm{d}^4x\, R\left(p^\mu u_\mu(\vec{x},t), T(\vec{x},t)\right)$$



Direct photon production=not from decay

Photon rate folded with fireball evolution:

PHYSICAL REVIEW C **69**, 014903 (2004)



"Window" sensitive to the QGP

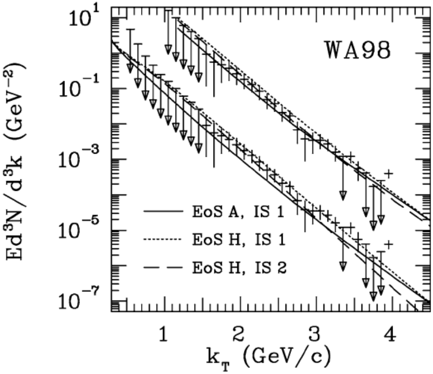
"Window" sensitive to the Hadron Gas

Dominated by prompt (initial) photons

Example: Direct photon studies in former times

- CERN SPS: WA98 - (around 1999-2004)

P. Huovinen et al. / Physics Letters B 535 (2002) 109



- Photon rate similar to today (AMY+Rapp)
- Background evolution: Bjorken, diff. EOS
- Data can not discriminate HG / QGP
- Role of QGP+pQCD photons unclear
- Elliptic flow not measured

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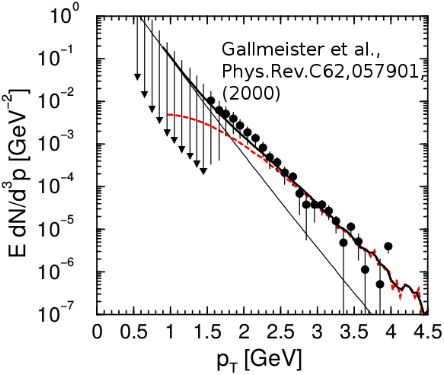

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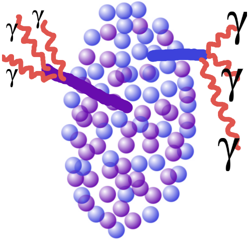
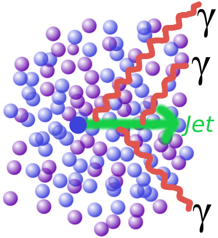
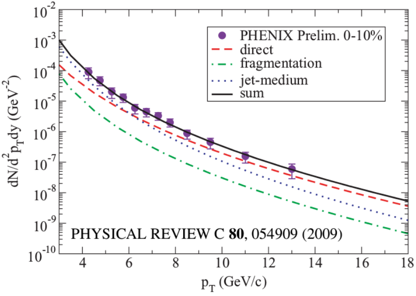
Nonequilibrium contributions from Jets







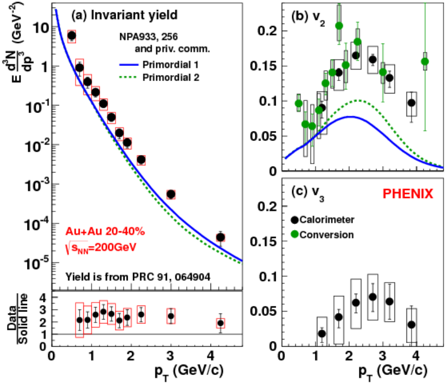
- Studies done for $p_T \sim 4 - 14$ GeV
- Requires photon fragm. functions
- Requires Jet distributions and energy loss
- Elliptic flow positive/negative
- Diff. jet-photon conversion mechanism

The direct photon puzzle

Explain theoretically yield and elliptic flow of photons

RHIC, Au+Au $\sqrt{s} = 200\mathrm{GeV}$

Fireball model:



Hees et al., NPA933, 256

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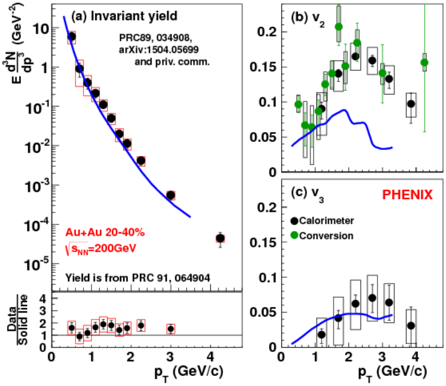
PHSD transport model:



Linnyk et al., PRC 89,034908 (2014)

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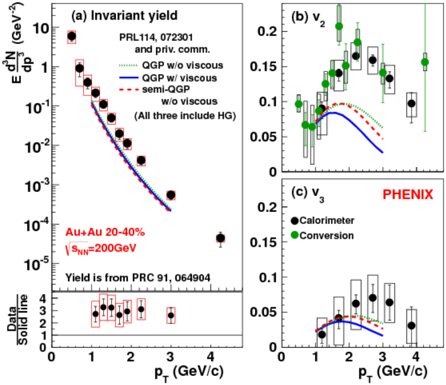
MUSIC hydrodynamics:



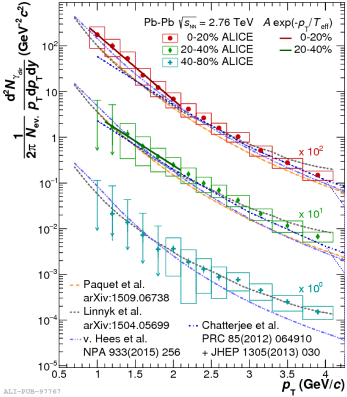
Gale at al., PRL 114, 072301 (2015)

The direct photon puzzle

Explain theoretically yield and elliptic flow of photons

LHC, Pb+Pb $\sqrt{s} = 2.76\text{TeV}$

Comparison of direct photon spectra:



ALICE collaboration, PLB 754, 235 (2016)

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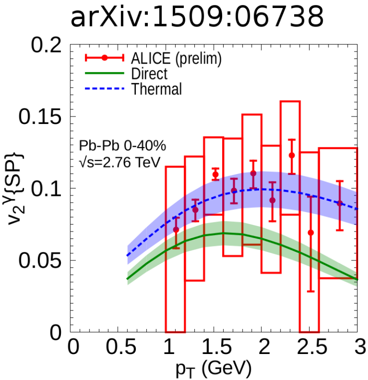

Paquet et al, arXiv:1509:06738

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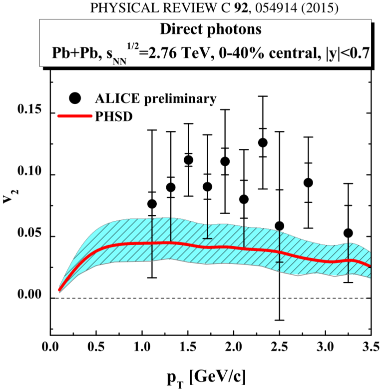
PHSD transport model:



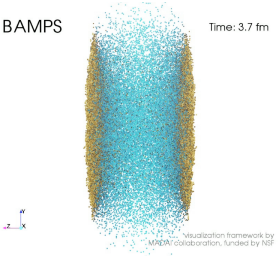
Linnyk et al., PRC 89,034908 (2014)

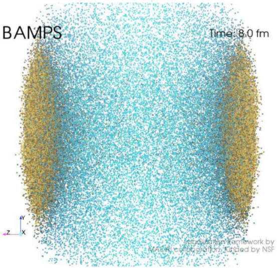
Photons in partonic transport

- BAMPS
- Lorentz invariance of produced spectra
- Photon emission rates in literature
- Photon emission rates in BAMPS
- Influence of different Debye masses

Our approach (in short): BAMPS

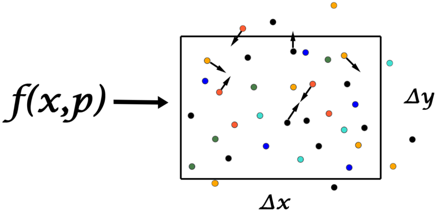
Boltzmann **A**pproach to **M**ulti **P**arton **S**catterings





$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{22}[f] + \mathcal{C}_{23}[f]$$

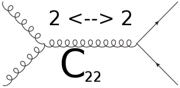
Zhe Xu & Carsten Greiner, 2005.
Phys. Rev. C 71 (2005) 064901.

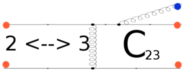


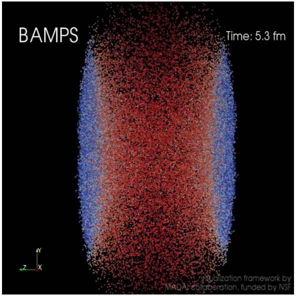
Many people have contributed to BAMPS: **...,Oliver Fochler, Jan Uphoff, Florian Senzel, MG, Kai Gallmeister, Kai Zhou + the Beijing group**

BAMPS: Boltzmann Approach To Multi-Parton Scatterings

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{22}[f] + \mathcal{C}_{23}[f]$$







Stochastic collision probability,
Total cross sections $\sigma_{22}(s)$, $\sigma_{23}(s)$,
Fully Lorentz-invariant formulation

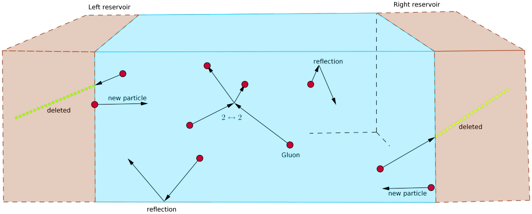
$$P_{22} = v_{rel} \frac{\sigma_{22}}{N_{test}} \frac{\Delta t}{\Delta^3 x}$$

$$P_{23} = v_{\mathrm{rel}} \frac{\sigma_{23}}{N_{test}} \frac{\Delta t}{\Delta^3 x}, \quad P_{32} = \ldots$$

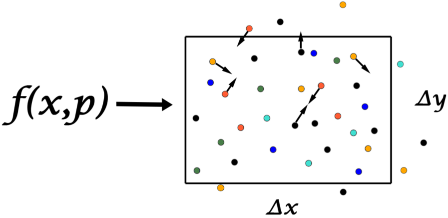
$$v_{\mathrm{rel}} = \frac{s}{2E_1 E_2}$$

Z. Xu & C. Greiner, 2005.
Phys. Rev. C 71 (2005) 064901.

BAMPS: run as a fixed box



Scattering in **cells**:



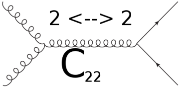
Baseline: $\frac{dN}{NE^2 dE} = \frac{1}{T^3} e^{-E/T}$

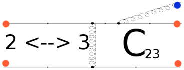
Box calculations useful:

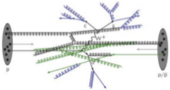
- Test and compare effect of cross sections
- Extract Rates
- Extract transport coefficients

BAMPS: expanding Heavy-Ion collision

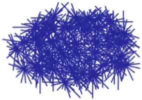
$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{22}[f] + \mathcal{C}_{23}[f]$$



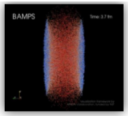




PYTHIA-Glauber

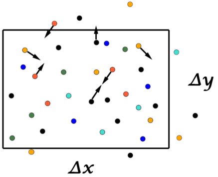


$AA = pp \times N_{\text{binary}}$



noneq. QGP

$f(x,p) \longrightarrow$



Phys. Rev. C 71 (2005) 064901

- Reproduce dE_T/dy distribution for RHIC or LHC data
- onshell massless particles $q, \bar{q}, g, \gamma$
- pQCD cross sections, radiative Gluons/Photons: LPM-suppression modelled
- Compton/Annihilation- γ-production
- Exact Bremsstrahlung $qq \longrightarrow qq\gamma$

Exact Lorentz covariant collision algorithm

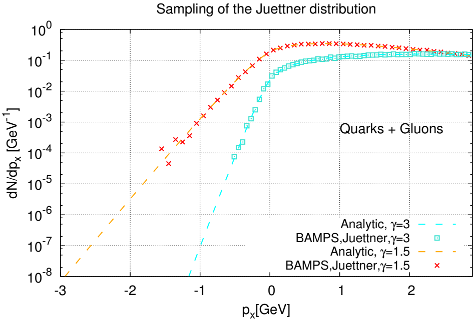
Spectrum of produced particles allright? *General* production rate:

$$p_4^0 \frac{\mathrm{d}R}{\mathrm{d}^3\vec{p}_4} = \frac{1}{2(2\pi)^3} \int \frac{\mathrm{d}^3\vec{p}_1}{2p_1^0(2\pi)^3} \int \frac{\mathrm{d}^3\vec{p}_2}{2p_2^0(2\pi)^3} \int \frac{\mathrm{d}^3\vec{p}_3}{2p_3^0(2\pi)^3} f_1 f_2 W_{\vec{p}_1\vec{p}_2\to\vec{p}_3\vec{p}_4}$$

Finally:

$$\frac{\mathrm{d}R}{\mathrm{d}^3\vec{p}} = \frac{\mathcal{N} n}{\gamma^2 E}\sigma(\gamma E - \beta_x \gamma p_x)\, e^{-\frac{(\gamma E - \beta_x\gamma p_x)}{T}}$$

- β_x : boost velocity
- $\mathcal{N}$: constant
- n : LRF density
- σ : isotropic cross section



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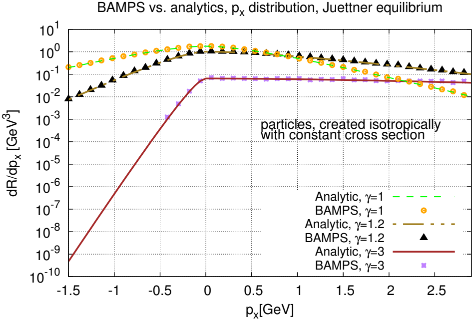

Photon emission rate

$$E_k \frac{\mathrm{d}^3 R}{\mathrm{d}^3 k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \mathrm{Im}\Pi^R_{\mu\nu}(E_k, \vec{k})$$

with finite temperature retarded photon self-energy $\Pi^R_{\mu\nu}$.

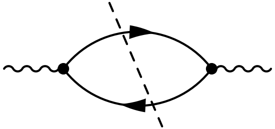

Figure : The photon self energy at one loop order, and the only possible cut. No phase space, no contribution.

Finite-temperature field theory, Kapusta,Gale, Cambridge University Press 2006

Carrington et al., PRD 67, 025021 (2003)

Wong, PRD 64, 025007 (2001)

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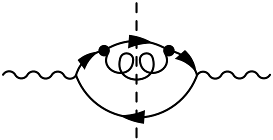

Figure : One particular contribution to the photon self energy at two loop order, and one particular cut that is possible. Accounts for squared amplitude channels.

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Carrington et al., PRD 67, 025021 (2003)

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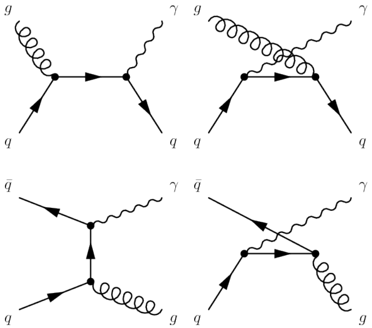

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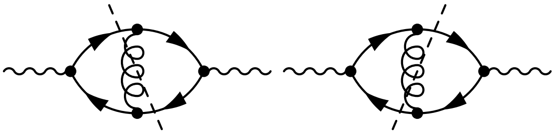

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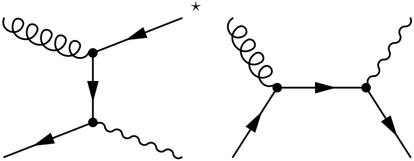

Figure : Interference contribution between s- and u-channel of the Compton scattering process.

Finite-temperature field theory, Kapusta,Gale, Cambridge University Press 2006

Carrington et al., PRD 67, 025021 (2003)

Wong, PRD 64, 025007 (2001)

Elastic photon production *rate*

Hard momentum transfers $t > t^\star$:

$$R = \mathcal{N} \int \frac{\mathrm{d}^3 p}{2E_p} \int \frac{\mathrm{d}^3 p'}{2E_{p'}} \int \frac{\mathrm{d}^3 k}{2E_k} \int \frac{\mathrm{d}^3 k'}{2E_{k'}} (2\pi)^4 \delta^{(4)}(P + P' - K - K')$$
$$\times |\mathcal{M}|^2 f(P) f(P') \left(1 \pm f(K')\right)$$

+ Soft momentum transfers $t < t^\star$ (HTL propagators and vertices):

$$E_k \frac{\mathrm{d}^3 R}{\mathrm{d}^3 k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \mathrm{Im}\Pi^R_{\mu\nu}(E_k, \vec{k})$$

The sum gives total HTL resummed finite rate:

(independent of $t^\star$)

$$E \frac{dR}{d^3 p}\bigg|_{\text{Compton+Annihilation}} = \left(\sum_i q_i^2\right) \frac{\alpha_{\text{EM}} \alpha_{\text{strong}}}{2\pi^2} T^2 e^{-E/T} \ln\left(\frac{2.912}{g_s^2} \frac{E}{T}\right)$$

Kapusta, Lichard, Seibert, Phys. Rev. D 44, 2774 (1991)

Elastic photon production *rate* in BAMPS

Two sources of lacking precision:

A) Compton and annihilation matrix elements in BAMPS

$$|\mathcal{M}|^2 = \frac{16}{3}\pi^2 \alpha \alpha_s \left(\frac{s^2 + st}{(s + m_{D,q}^2)^2} + \frac{s^2 + st}{(u - m_{D,q}^2)^2} \right)$$

$$|\mathcal{M}|^2 = \frac{128}{9}\pi^2 \alpha \alpha_s \left(\frac{tu}{(t - m_{D,q}^2)^2} + \frac{tu}{(u - m_{D,q}^2)^2} \right)$$

...instead of HTL resummed loop for $t < t^\star$.

B) Statistics in BAMPS

Pauli-Blocking/Bose-Enhancement missing- only classical statistics.

Correction of elastic photon production *rate* in BAMPS

A) Compton and annihilation matrix elements in BAMPS

Correct by $m_{D,q}^2 \longrightarrow \kappa m_{D,q}^2$.

Thermal mass for light quarks:

$$m_{D,q}^2 = g^2 C_F \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{1}{p} (f_g + f_q)$$

where $C_F = 4/3$ for QCD, and $g^2 = 4\pi\alpha_s$ is the strong coupling.

B) Statistics in BAMPS

Correct by factor C_{stat} in collision probability.

$$R \longrightarrow R = C_{\text{stat}} \mathcal{N} \int \int \int \int \ldots |\mathcal{M}|^2 f(P) f(P') \tag{1}$$

Parameters κ, C_{stat} tuned to *total* photon production rate R.

Correction of elastic photon production *rate* in BAMPS

A) Compton and annihilation matrix elements in BAMPS

Correct by $m^2_{D,q} \longrightarrow \kappa m^2_{D,q}$. $\kappa = 2.45$

Compare integrated rates with quantum statistics (zero'th moment):

- $R^\gamma_{\text{quantum, HTL}}$ from AMY (numerically integrated)
  - P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP. 0111, 057 (2001)
- $R^\gamma_{\text{quantum, Born}}$ using Shen et al. (numerically integrated)
  - C. Shen, J.-F. Paquet, U. Heinz, and C. Gale, Phys. Rev.C91, 014908, 2015

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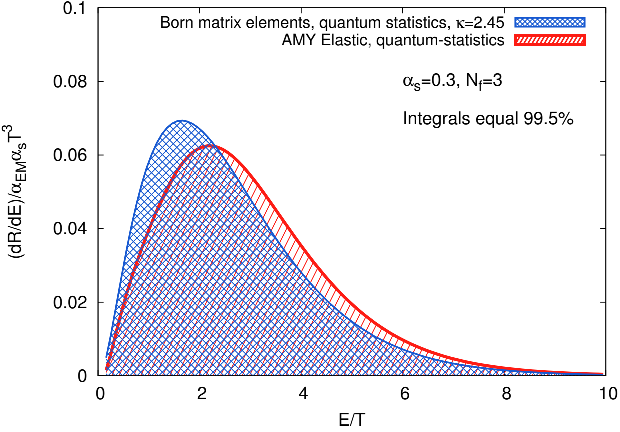

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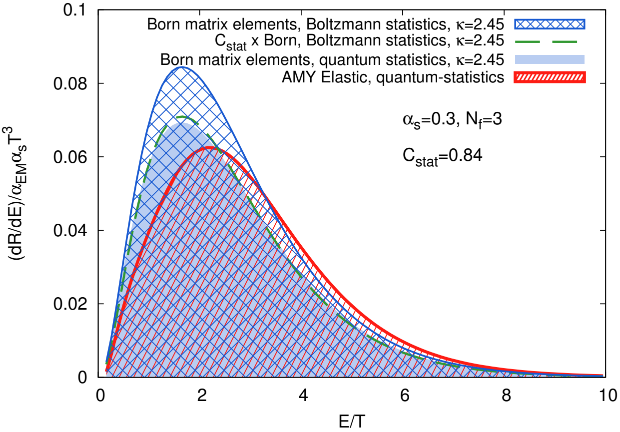
Moment	AMY/Born
0th	99.5 %
1st	112.5 %
2nd	121.9 %
3rd	128.1 %
4th	132.1 %

Table : The comparison of AMY with Born-photon rates for higher moments of the photon rate, using the fixed value of $\kappa = 2.45$.

Correction of elastic photon production *rate* in BAMPS

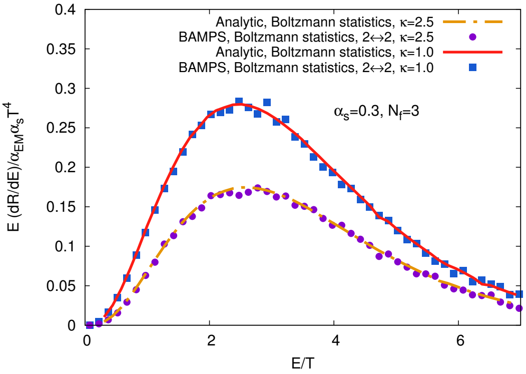
B) Statistics in BAMPS

Correct by overall factor C_{stat} in collision probability. $C_{\text{stat}} = 0.84$.



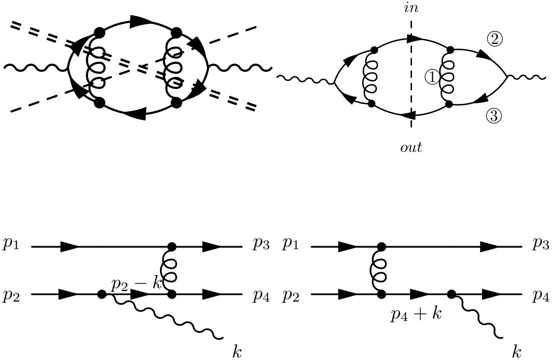
Final elastic matrix element in BAMPS:

$$|\mathcal{M}|^2_{\text{effective}} = C_{\text{stat}} \left[128 \cdot \frac{16}{3}\pi^2 \alpha\alpha_s \left(\frac{s^2+st}{(s+\kappa m^2_{D,q})^2} + \frac{s^2+st}{(u-\kappa m^2_{D,q})^2} \right) \right.$$
$$\left. + \; 24 \cdot \frac{128}{9}\pi^2 \alpha\alpha_s \left(\frac{tu}{(t-\kappa m^2_{D,q})^2} + \frac{tu}{(u-\kappa m^2_{D,q})^2} \right) \right]$$



Photon production: higher order loops

Photon rate at order $\mathcal{O}(e^2 g_s^2 T^4)$ obtained via γ-self energy.



(a) $i\mathcal{M}_a$ (b) $i\mathcal{M}_b$

Figure : The diagrams we use in BAMPS.

e.g. P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP. 0111, 057 (2001)

Photon Bremsstrahlung processes: The exact matrix element

Using the MATHEMATICA package FEYNCALC 8.2.0:

$$A \equiv 2(25) + m_{D,q}^2$$
$$B \equiv 2(45) + m_{D,q}^2$$
$$C \equiv 4(45) + m_{D,q}^2$$
$$D \equiv (35)B^2 - 2(34)A(2(25) - B - m_{D,q}^2)$$
$$E \equiv (23)A((25)C + (45)(-B - m_{D,q}^2)) + (24)A(2(34)A + (35)(A+B)) + (25)D$$
$$F \equiv (24)A(A+B) + (25)B^2$$
$$G \equiv (23)A((24)B + (45)A) + (34)F$$
$$H \equiv -2(23)B + (34)(-B - m_{D,q}^2) + (35)m_{D,q}^2$$
$$J \equiv (45)H + (24)(35)B + (25)((34)C + 2(35)(45))$$
$$\overline{|\mathcal{M}|^2} = \frac{1}{4}\frac{2}{9}Q_{EM}^2 g^4 128 \frac{A((12)J - 2(13)(24)(45)A) + (14)E + (15)G}{A^2B^2(2(24) + 2(25) - 2(45) + m_{D,g}^2)^2}$$

(we defined the scalar product of 4-vectors $(ij) \equiv p_i \cdot p_j$)

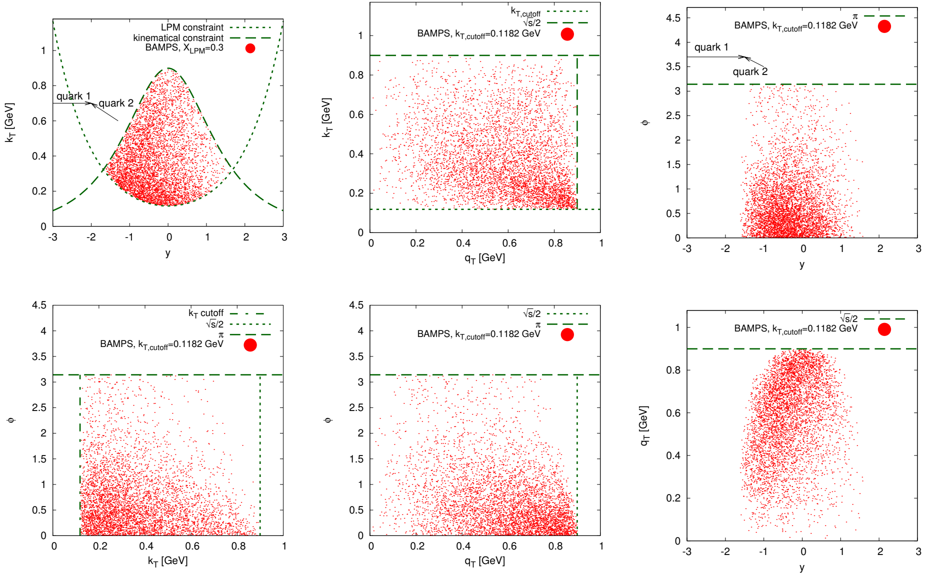
Inelastic cross section for radiated photons

Exact matrix element computed, coordinate transformation from $P_{\text{in }1}, P_{\text{in }2}, P_{\text{out }1}, P_{\text{out }2}, K \to$ integrate cross section:

$$\sigma_{23} = \frac{1}{2s} \int_{p_1'} \int_{p_2'} \int_{p_3'} \int_{p_1} \int_{p_2} \left|\mathcal{M}_{12\to 1'2'3'}\right|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_1' - p_2' - p_3')$$
$$= \frac{1}{256\pi^4 s} \int \mathrm{d}^2 q_\perp \int \mathrm{d}^2 k_\perp \int \mathrm{d}y \int \mathrm{d}\phi \left|\mathcal{M}_{12\to 1'2'3'}\right|^2 \mathcal{J}(k_\perp, q_\perp, y, \phi)$$

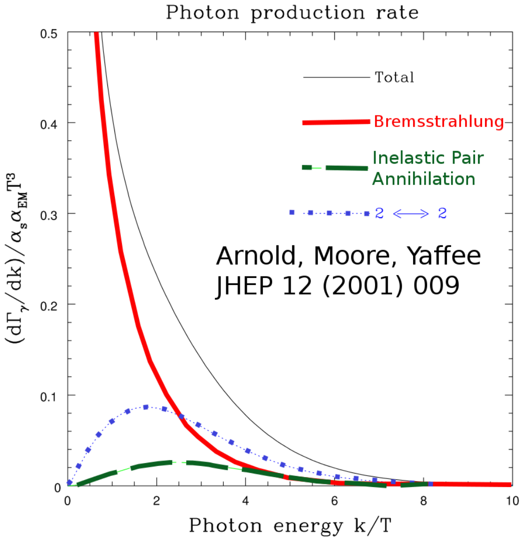
- For each particle pair in cell: compute σ_{23}
- $\left|\mathcal{M}_{12\to 1'2'3'}\right|^2 (P_{\text{in }1}, P_{\text{in }2}, k_\perp, q_\perp, y, \phi)$
- *VEGAS* integration algorithm
- If collision happens: sample outgoing momenta with *Metropolis*-algorithm according to $|\mathcal{M}|^2$
- Numerically very demanding, needs Lookup-Tables.

Numerical sampling of the outgoing photon momenta



Comparison of bremsstrahlung in BAMPS with full rate

Zero'th moment divergent, badly suited for comparison:



Comparison of bremsstrahlung in BAMPS with full rate

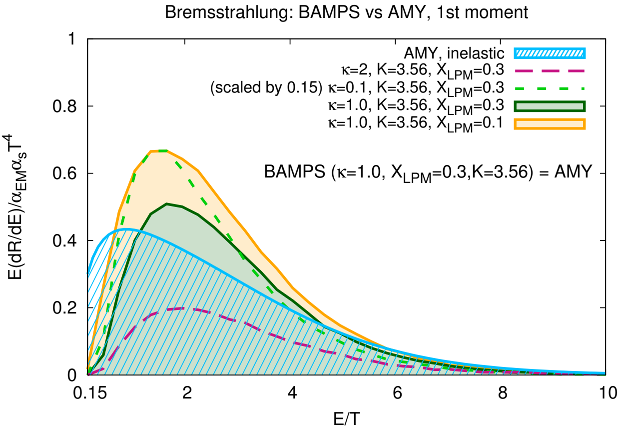


Figure : First moment of the inelastic rate from AMY compared to BAMPS. The moments are equal, if we use a factor $K_{\mathrm{inel}} = 3.5$.

Comparison of bremsstrahlung in BAMPS with full rate

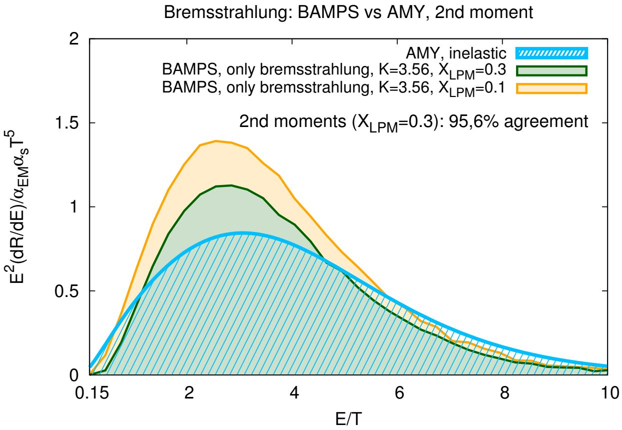
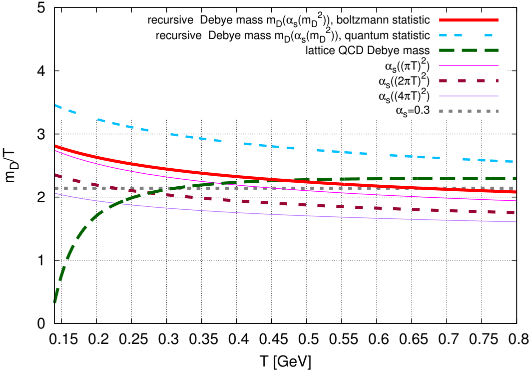


Figure : The factor $K_{\mathrm{inel}} = 3.5$ has been fixed by comparing the first moment. Then the **second** moment (shown in this plot) from BAMPS agrees within 5 % with AMY.

Debye masses: different choices



$$m_{D,q}^2 = 4\pi\alpha_s(Q^2)\frac{N_c^2-1}{2N_c}\int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{1}{E}\left(f_{\mathrm{gluon}}+f_{\mathrm{quark}}\right)$$

Debye masses: different choices

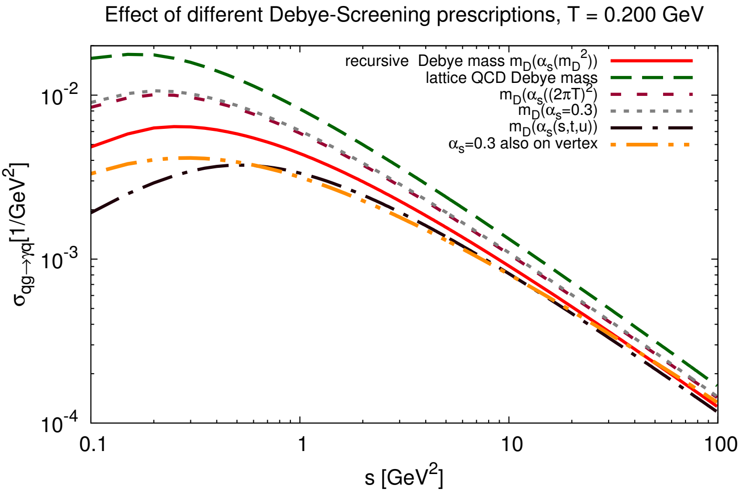
- HTL formula with fixed $\alpha_s = 0.3$ and $T = u_\mu u_\nu T^{\mu\nu}/3n$. Assumes chemical+kinetical equilibrium.
- HTL formula dynamically from BAMPS: nonequilibrium distribution functions.
  Proportional to fugacity!
- HTL formula with $\alpha_s((2\pi T)^2)$
- Lattice parametrization: drops at low T!

  see Burnier, Kaczmarek, Rothkopf, JHEP 1512 (2015) 101
- selfconsistently solved with $\alpha_s(m_D^2)$ following Andre Peshier

  see Peshier, arXiv:hep-ph/0601119

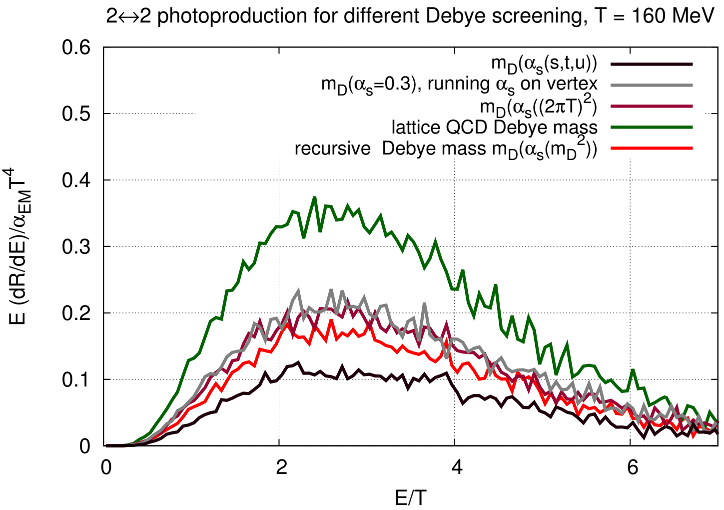
Hydro: fixed α_s in HTL resummed rates $\sim$ equilibrium HTL Debye mass

Debye mass-choices: effect on Compton cross section

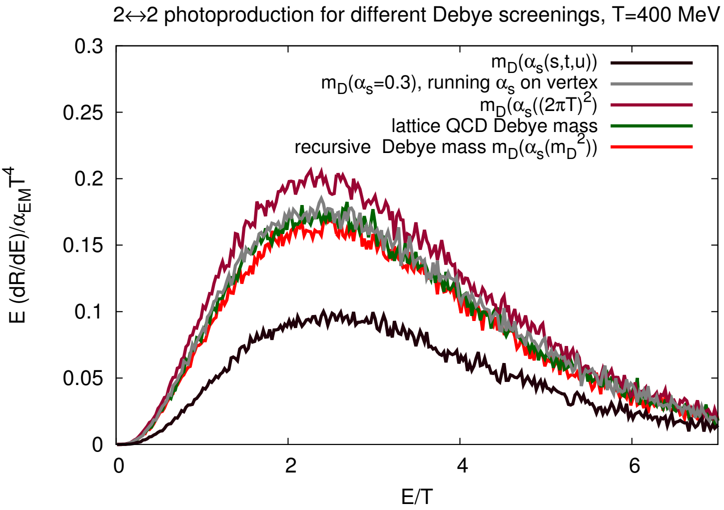


Debye mass-choices: effect on rates

$T = 160$ MeV: strong enhancement using Lattice Debye mass!



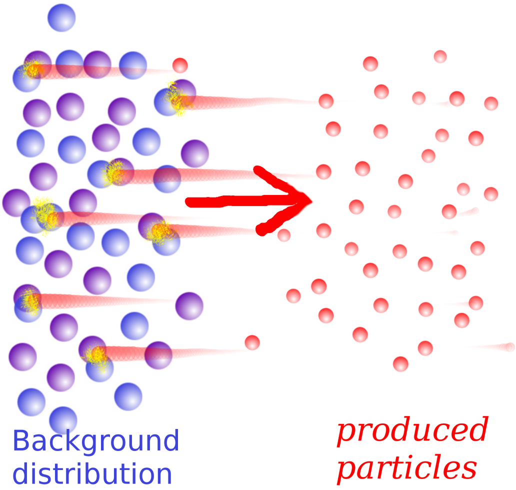
Debye mass-choices: effect on rates



Results and interpretation

- Hydrodynamic push for photons
- p_T-spectra from BAMPS
- Fugacities, Temperatures
- Elliptic flow from BAMPS
- high-p_T leakeage effect for Jets

Hydrodynamic push for produced particles



Transfer of momentum anisotropy in equilibrium

Anisotropy of quark/gluon distribution

Fix $\frac{\mathrm{d}N}{\mathrm{d}^3\vec{p}} \sim \exp(-p^\mu u_\mu / T)$ equilibrium with boost: $\gamma > 1$

Analytic: $v_2 = \int \mathrm{d}^3\vec{p}\, \frac{\mathrm{d}N}{\mathrm{d}^3\vec{p}} \left(\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}\right) / \int \mathrm{d}^3\vec{p}\, \frac{\mathrm{d}N}{\mathrm{d}^3\vec{p}}$

BAMPS: Average $\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$ over all partons

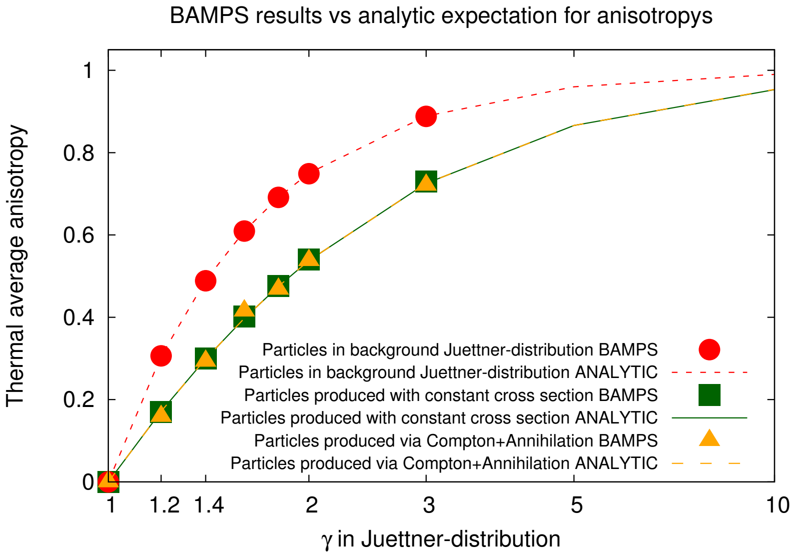
Anisotropy of produced photons

Photon production rate: $E \frac{\mathrm{d}R}{\mathrm{d}^3\vec{p}} = \text{function}(p^\mu u_\mu, T)$ same $\gamma > 1$

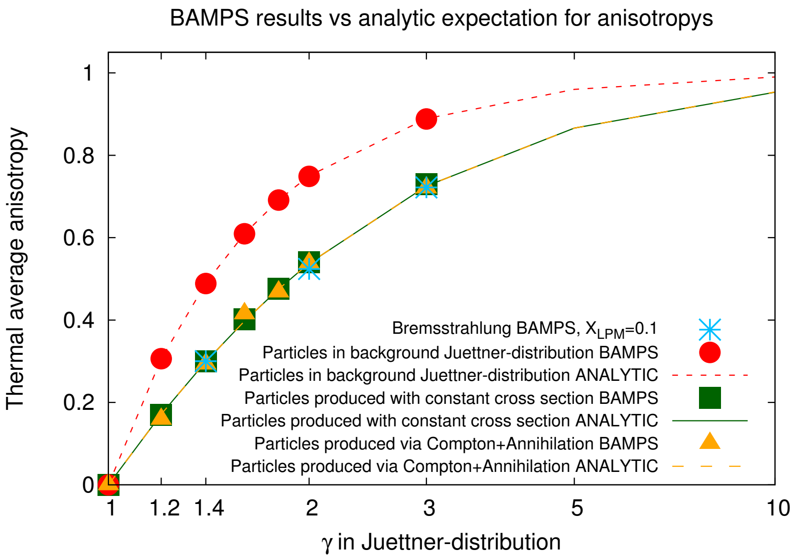
Analytic: $v_2 = \int \mathrm{d}^3\vec{p}\, \frac{\mathrm{d}R}{\mathrm{d}^3\vec{p}} \left(\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}\right) / \int \mathrm{d}^3\vec{p}\, \frac{\mathrm{d}R}{\mathrm{d}^3\vec{p}}$

BAMPS: Average $\frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$ over all photons

Transfer of momentum anisotropy in equilibrium

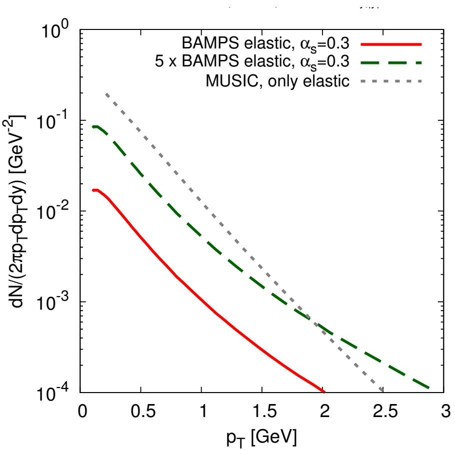


Transfer of momentum anisotropy in equilibrium



p_T-spectra of photons

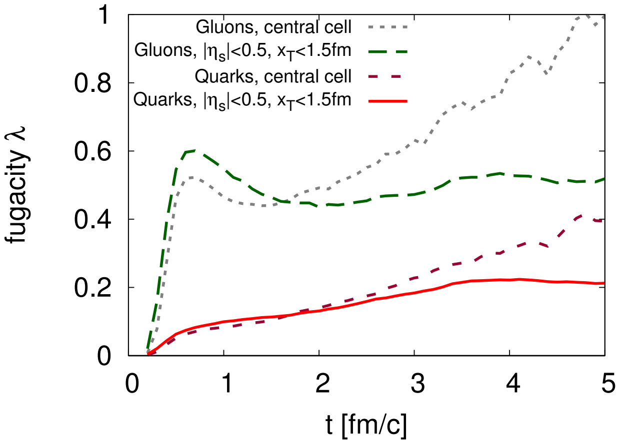
Compare results from BAMPS to 2+1D viscous hydro code *MUSIC*



see Schenke et al., Phys.Rev. C82 (2010) 014903, Paquet et al.Phys.Rev. C93 (2016), 044906

p_T-spectra of photons

Reason for 5 times lower yield: Fugacities

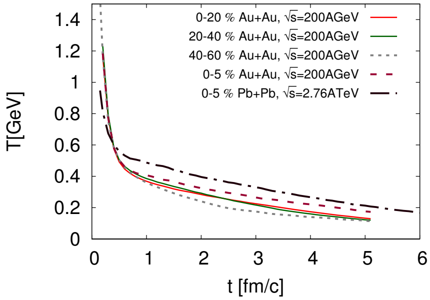


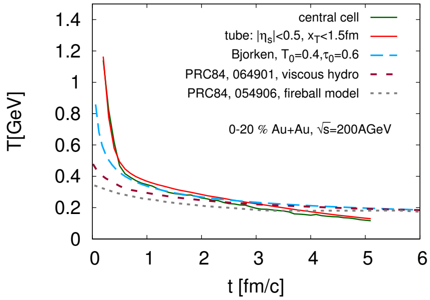
see also Monnai, Phys. Rev. C 90, 021901, (2014)

p_T-spectra of photons

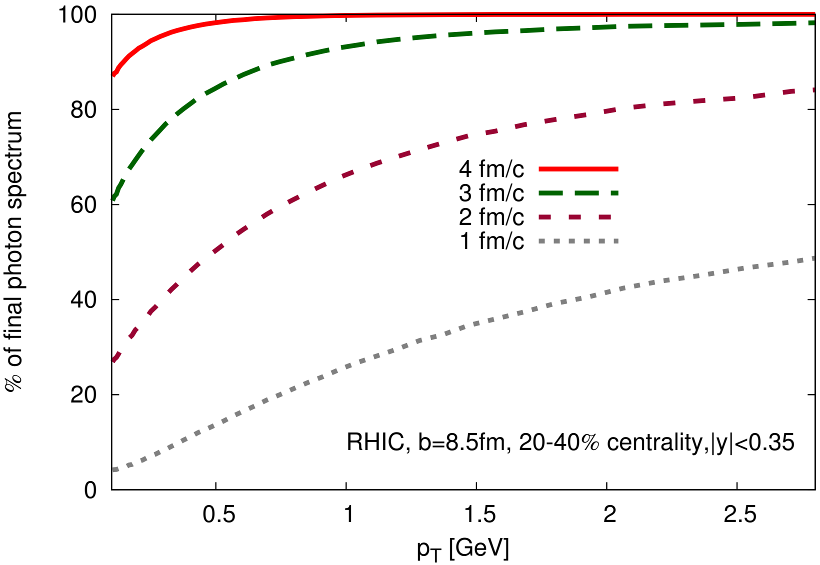
Compare results from BAMPS to 2+1D viscous hydro code *MUSIC*

Reason for shallower slope: different effective temperature in BAMPS:



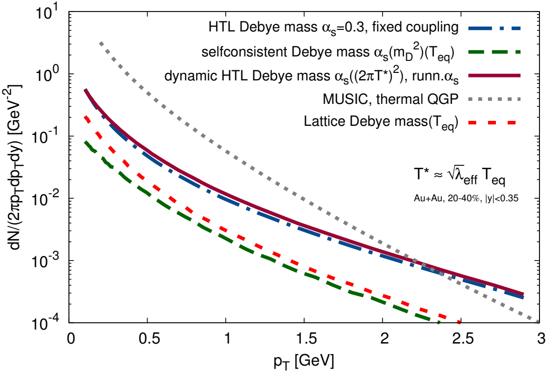


Time development of p_T spectra in QGP phase



p_T-spectra of photons

Compare different Debye-Screening prescriptions: Can be large effect!

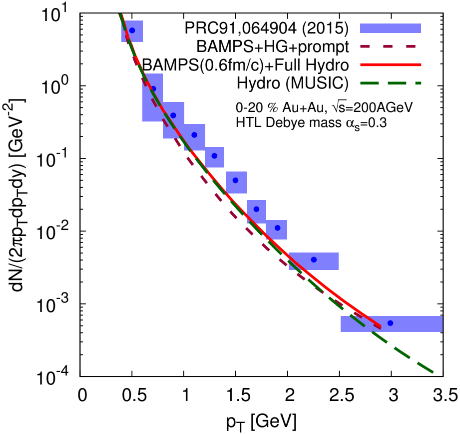


Dynamical Debye mass includes fugacity:

$$m_D^2(\text{dynamical}) \approx m_D^2|_{\text{HTL}}\left(\sqrt{\lambda_{\text{eff}}}\,T_{\text{eq}}\right) \lesssim m_D^2|_{\text{HTL}}\left(T_{\text{eq}}\right)$$

p_T-spectra of photons

Add BAMPS (only QGP) to hydro results: Schematic comparison with data tempting...



p_T-spectra of photons

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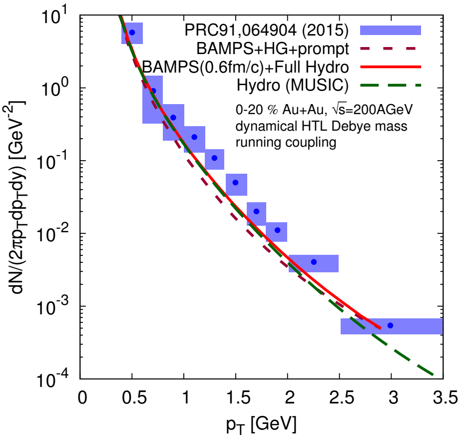
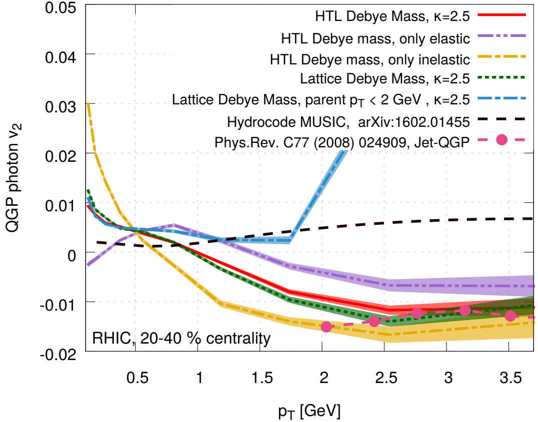


elliptic flow $v_2(p_T)$ of photons



- negative v_2 at high p_T comparable to Jet-QGP studies
- low-p_T shows hydrodynamic push
- difference elastic-inelastic to be understood

see also Turbide et al., PRL96, 032303, (2006), Qin et al., PRC80, 054909, (2009)

elliptic flow $v_2(p_T)$ of photons

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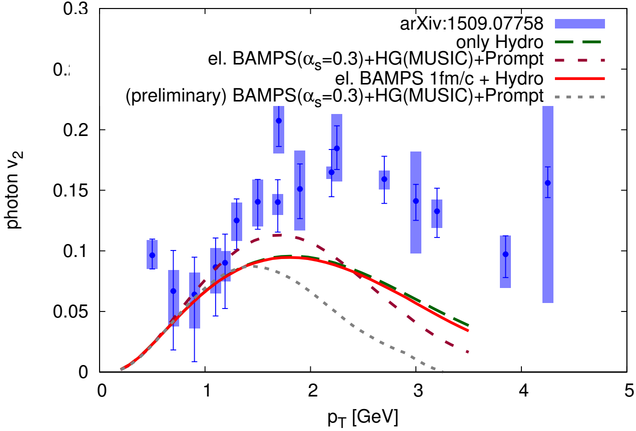
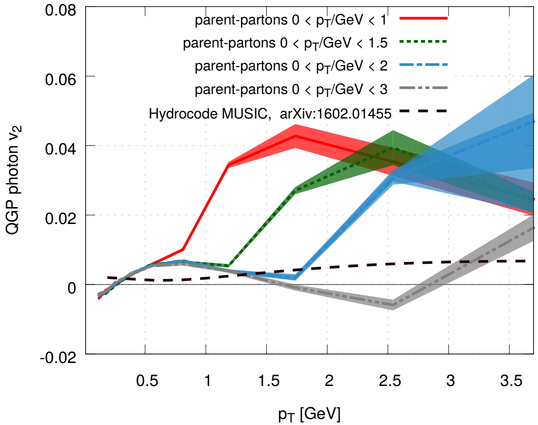
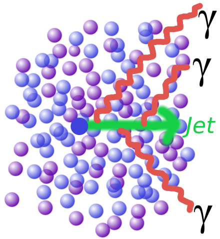


elliptic flow $v_2(p_T)$ of photons

restrict $\max(p_T^1, p_T^2) < p_T^{\mathrm{cut}}$:



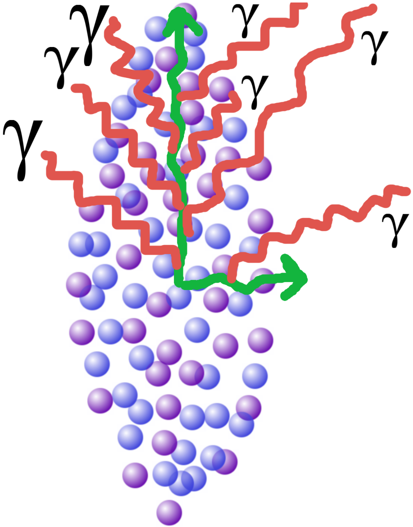


- negative flow originates from high-p_T-particles
- low-p_T from hydrodynamic push

$\Rightarrow$ verify this by box calculation

Jet-contribution: negative elliptic flow $v_2(p_T)$ of photons

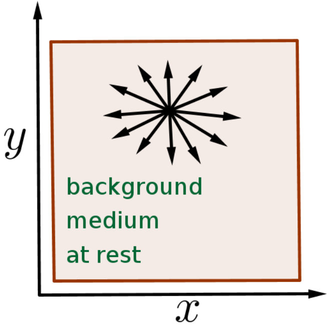
Pure geometric effect "leakage effect":



Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

Scenario A: square geometry, no flow, Jets



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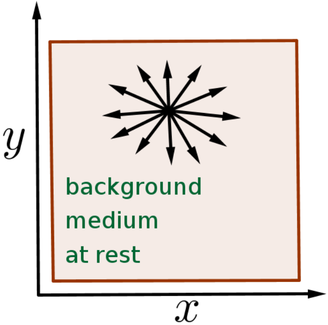
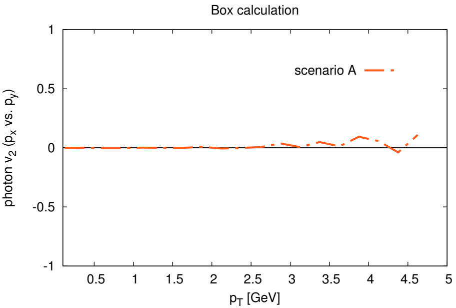
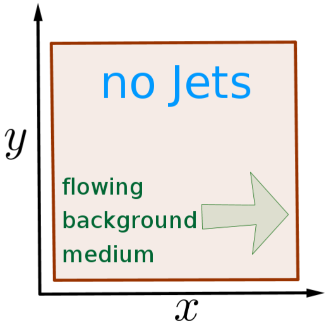




Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

Scenario B: square geometry, flow in x-direction, no Jets



Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

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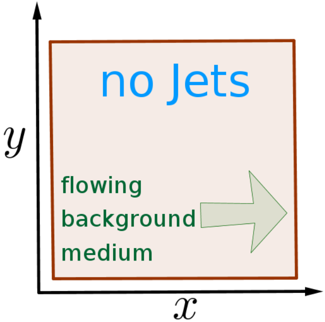
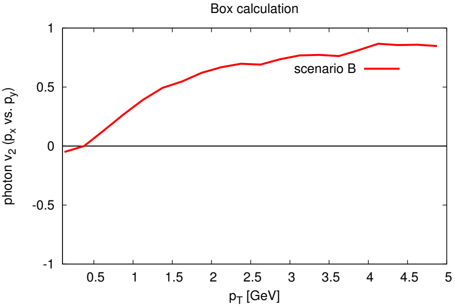
Scenario B: square geometry, flow in x-direction, no Jets

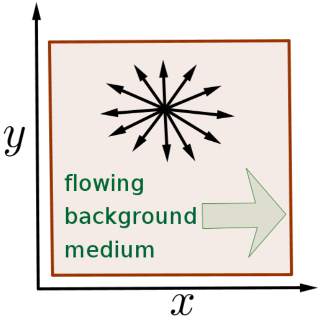




Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

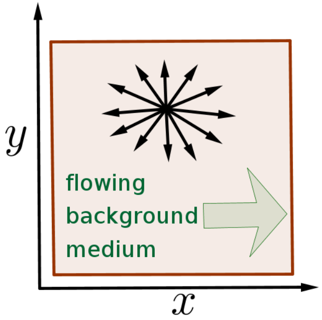
Scenario C: square geometry, flow in x-direction, Jets

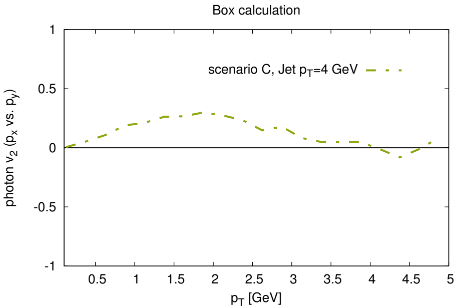


Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

<u>Scenario C: square geometry, flow in x-direction, Jets</u>

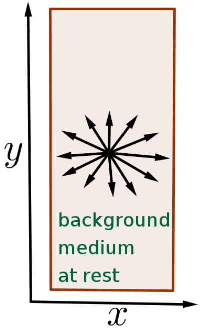




Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

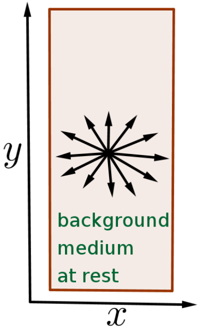
Scenario D: asymmetric geometry, no flow, Jets

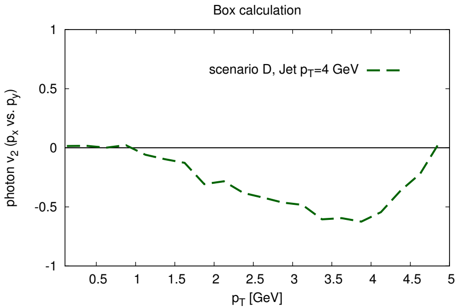


Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

Scenario D: asymmetric geometry, no flow, Jets

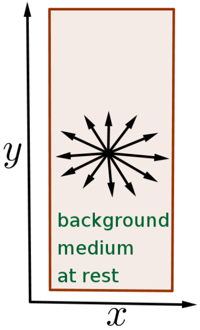


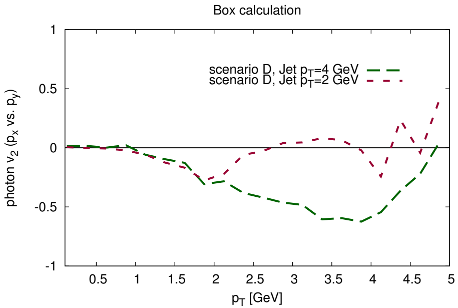


Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

Scenario D: asymmetric geometry, no flow, Jets

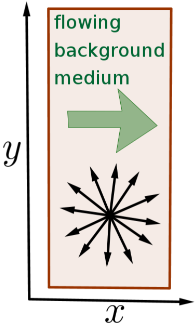




Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

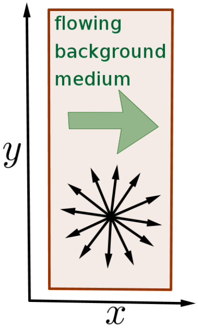
Scenario E: asymmetric geometry, flow in x-direction, Jets

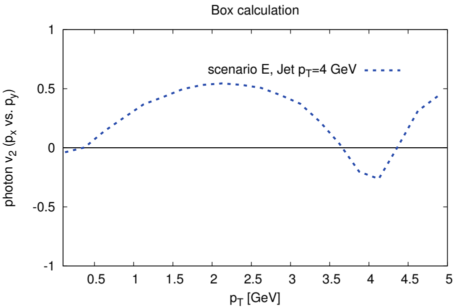


Jet-contribution: test elliptic flow $v_2(p_T)$ of photons in box

5 different scenarios A-E:

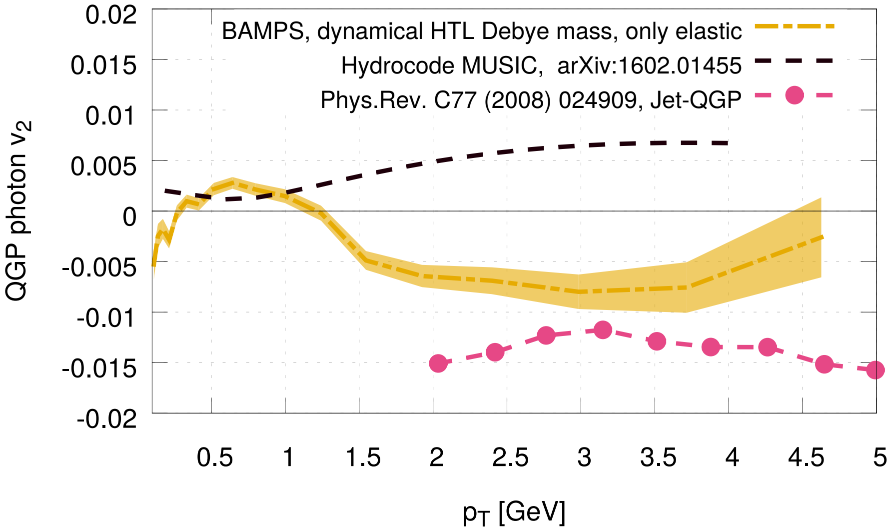
Scenario E: asymmetric geometry, flow in x-direction, Jets





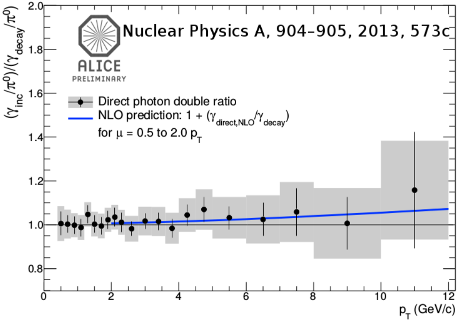
high-p_T photon v_2?

Preliminary:



Outlook

- Jet fragmentation to photons: check contribution within BAMPS
- Closer look to Jet-medium photons
- Compute ALICE and RHIC for all centralities available
- low-p_T direct photon search experimentally extremely challenging



- v_2 of $\pm 1\%$ experimentally not distinguishable

Conclusion

1) Photons puzzle

direct photon spectrum and direct photon flow not perfectly understood

2) BAMPS: $3+1d$, $N_f = 3$ transport code

Solving of the Boltzmann equation + simulates HIC with pQCD cross sections

3) QGP Photonproduction from BAMPS

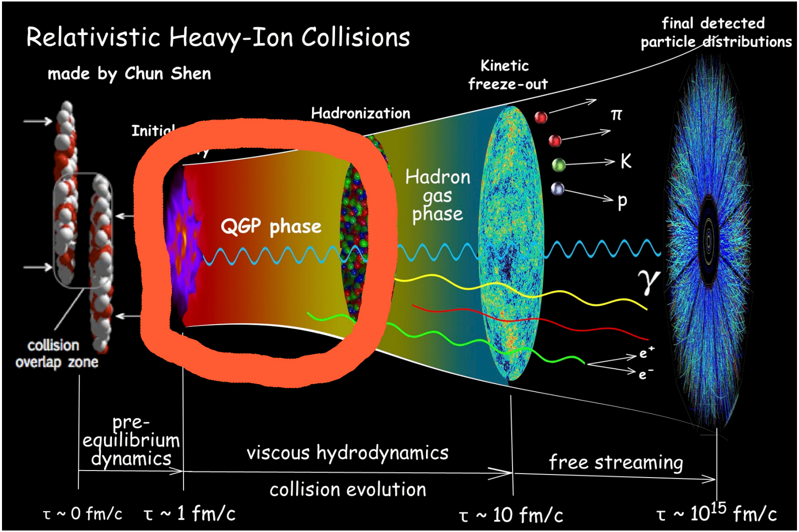
Rates compared with AMY pQCD spectra. Spectra different shape than hydro. Flow large nonequilibrium component.

A neutrino and a photon walk into a bar. And for the next 60ns the neutrino complains about how dark it is.

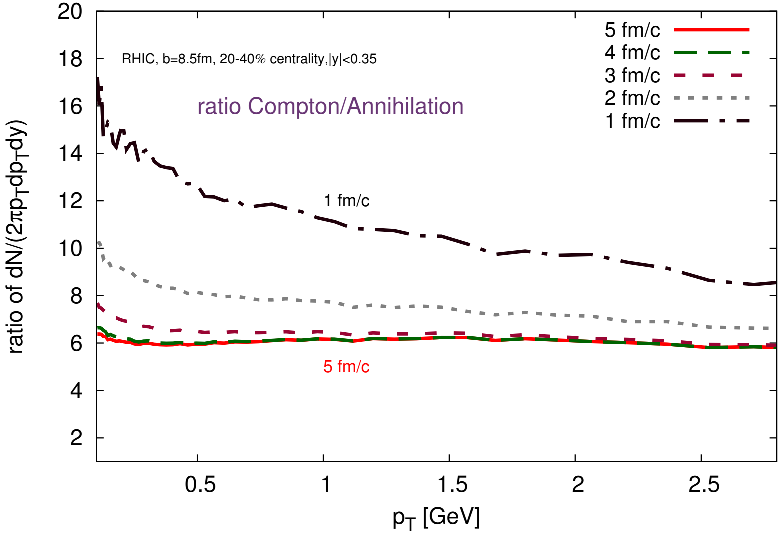
We don't allow faster than light photons in here, said the bartender. A photon walks into a bar.

APPENDIX

Photons from the QGP

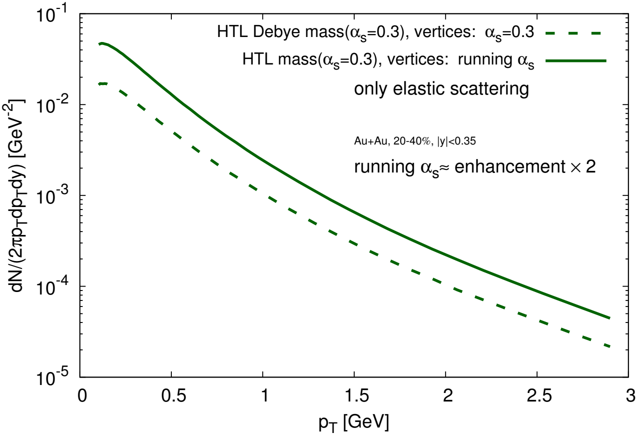


Ratio of Compton scattering versus Annihilation

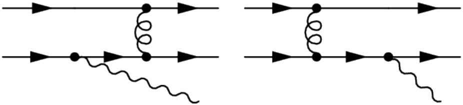


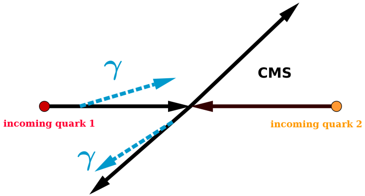
p_T-spectra of photons

Coupling at vertices running $\alpha_s(Q^2)$, scale Q^2 momentum transfer



Photon Bremsstrahlung processes: Some details





Useful coordinates for radiated photon:

Reference: incoming quark 1 $p_z > 0$

y: rapidity wrt incoming quark 1, $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

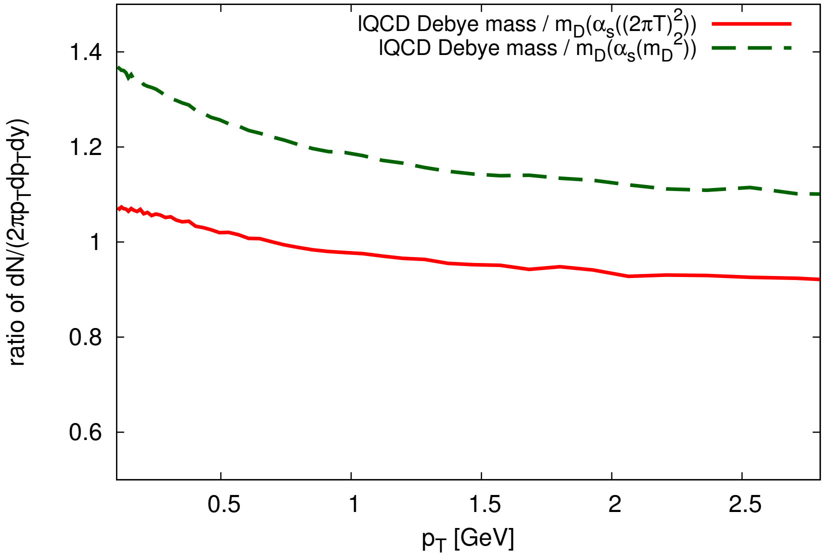
$k_\perp$: transverse momentum of photon wrt to p_z

$q_\perp$: gluon momentum transfer

φ: $\measuredangle(\vec{q}_\perp, \vec{k}_\perp)$

- We use the **exact** pQCD computation of $|\mathcal{M}_{\mathrm{brems}}|^2$ with screened quark and gluon propagators
- Inelastic pair annihilation neglected

Debye uncertainty of p_T spectra using T_{eq}

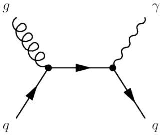


Photon production: higher order loops

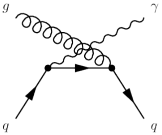
Photon rate at order $\mathcal{O}(e^2 g_s^2 T^4)$ obtained via γ-self energy.

Cutting rules give scattering matrix elements.

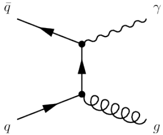
$\underline{2 \leftrightarrow 2:}$



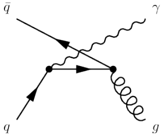
s-channel



u-channel

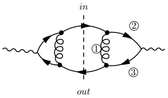


t-channel

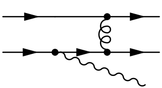


u-channel

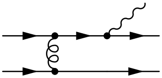
$\underline{2 \rightarrow 3:}$



Cut for $2 \rightarrow 3$



Important diagram



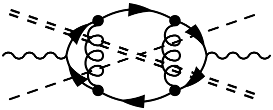
$\rightarrow$ LPM effect

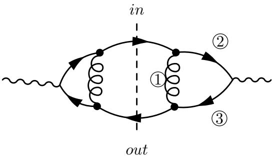
+ $3 \rightarrow 2$, $1 \leftrightarrow 4$, ... not easily feasible in transport models

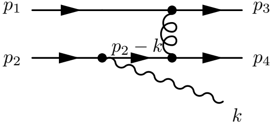
e.g. P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP. 0111, 057 (2001)

Photon production: higher order loops

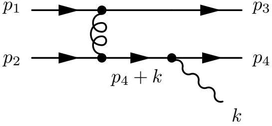
Photon rate at order $\mathcal{O}(e^2 g_s^2 T^4)$ obtained via γ-self energy.







(a) $i\mathcal{M}_a$

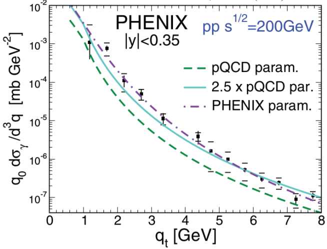


(b) $i\mathcal{M}_b$

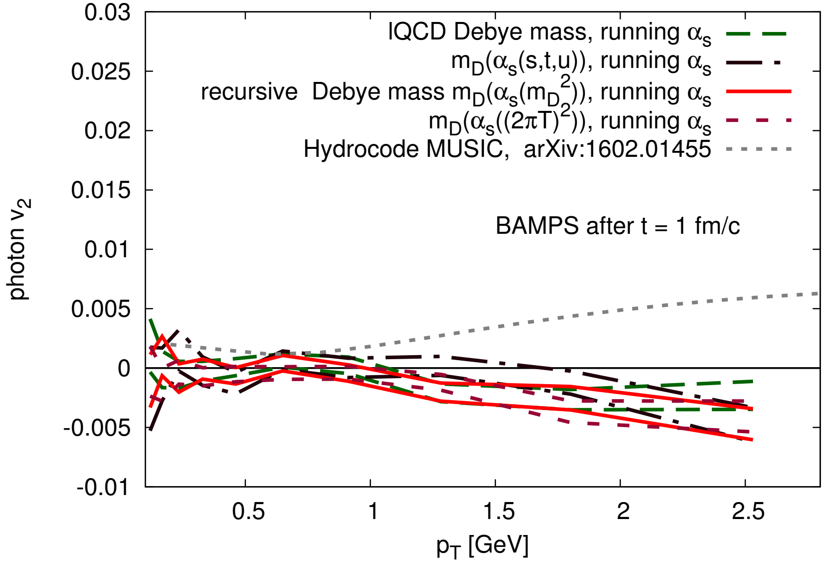
Figure : The diagrams we use in BAMPS.

e.g. P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP. 0111, 057 (2001)

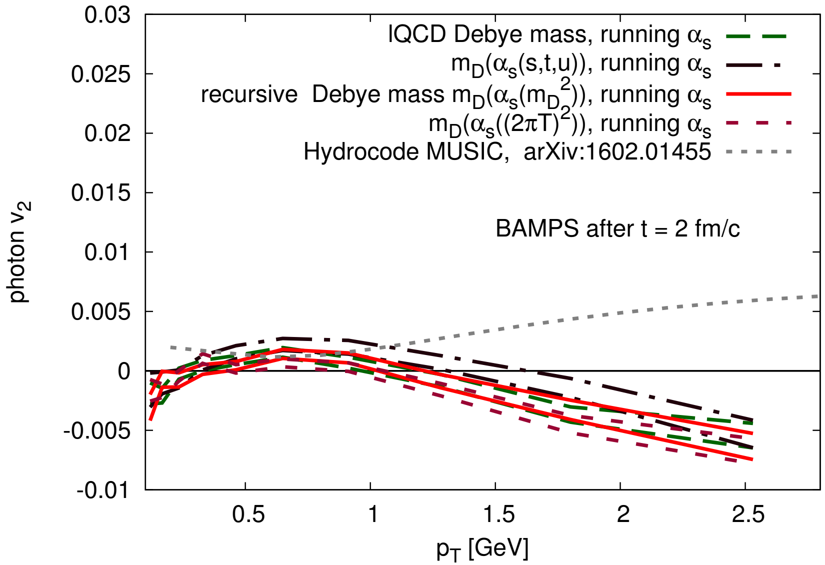
PHYSICAL REVIEW C **84**, 054906 (2011)



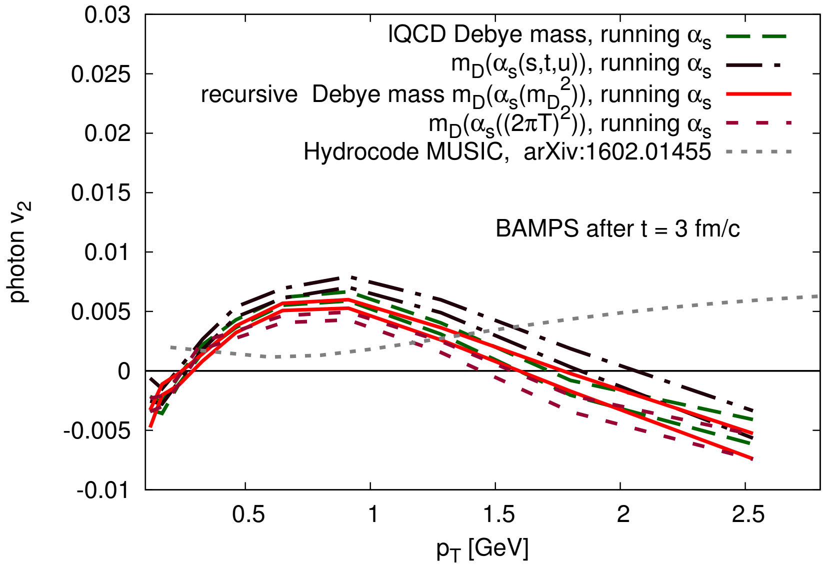
$v_2(p_T)$ in QGP phase



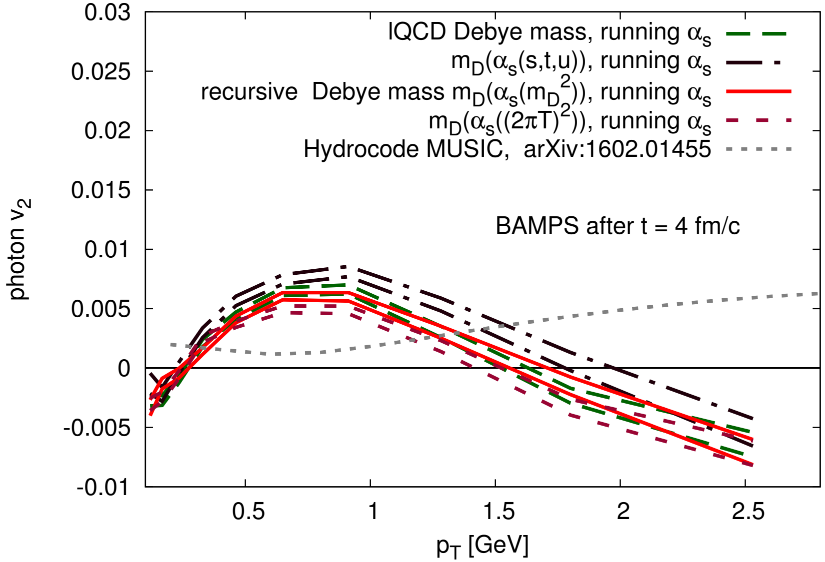
$v_2(p_T)$ in QGP phase



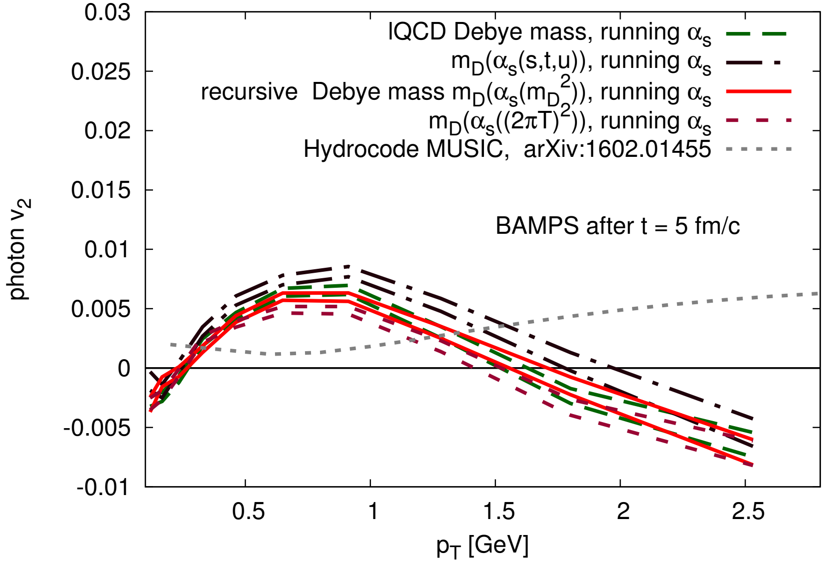
$v_2(p_T)$ in QGP phase



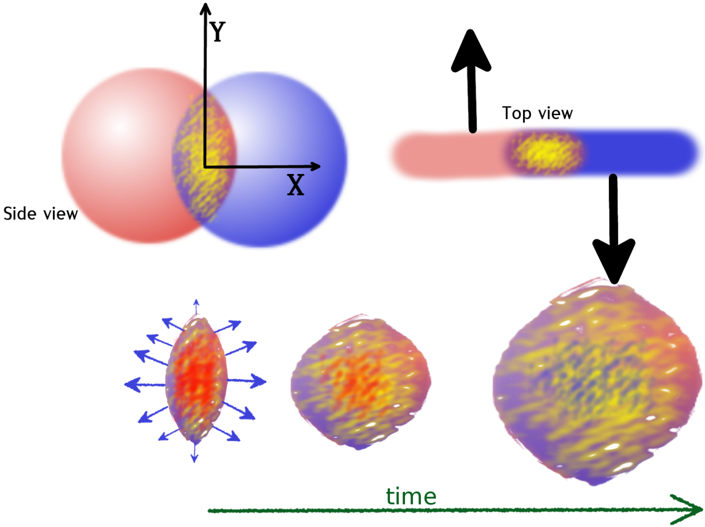
$v_2(p_T)$ in QGP phase



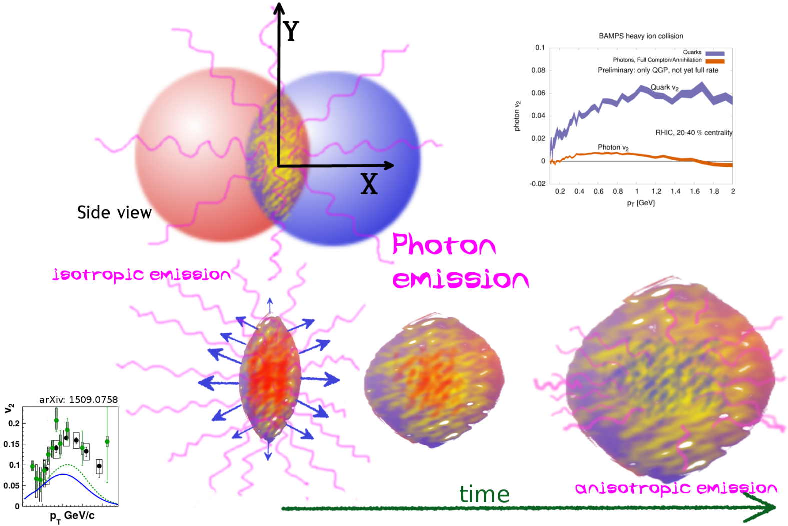
$v_2(p_T)$ in QGP phase



Elliptic flow for photons: Transfer of anisotropy from quarks to photons

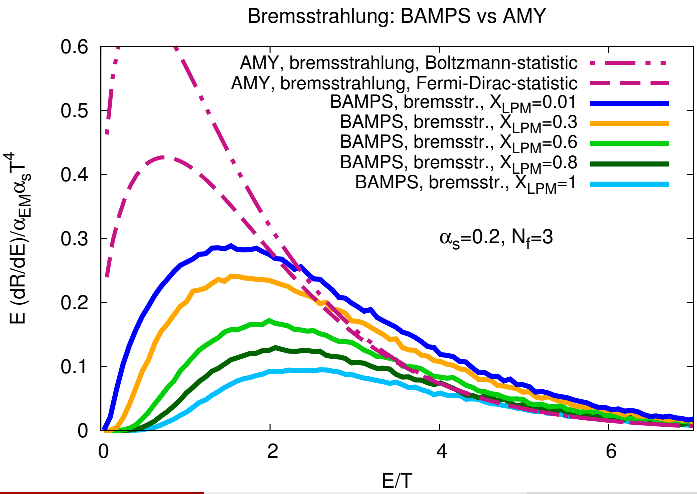


Elliptic flow for photons: Transfer of anisotropy

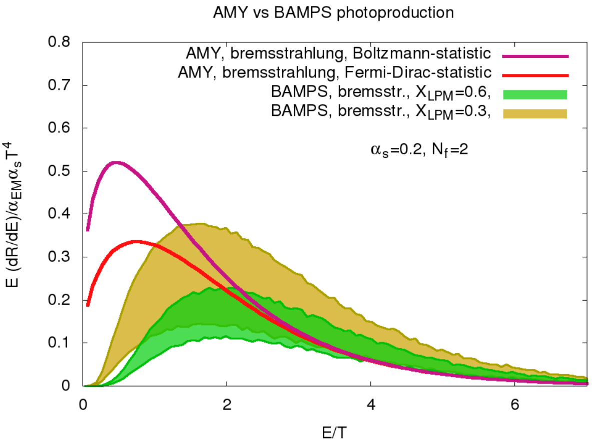


First results from BAMPS for Bremsstrahlung

Interference can only be treated phenomenologically:
$|\mathcal{M}_{23}|^2 \rightarrow |\mathcal{M}_{23}|^2\,\Theta(\lambda_{\mathrm{mfp}} - X_{\mathrm{LPM}}\tau_{\mathrm{formation}})$, we vary X_{LPM}. $\tau_{\mathrm{f}} \sim k_T^{-1}$.

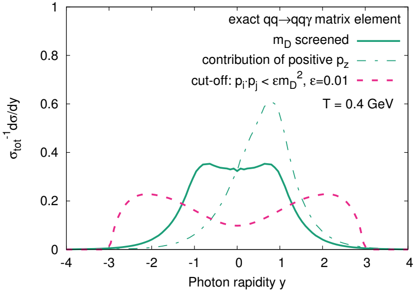


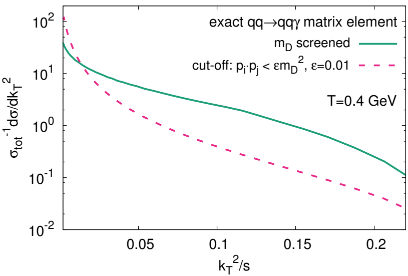
Debye-screening uncertainty for Bremsstrahlung



Band: Debye-mass $\times 2^{\pm 1}$. Future: use Debye-mass from lattice.

Differential cross sections for radiative photon emission:

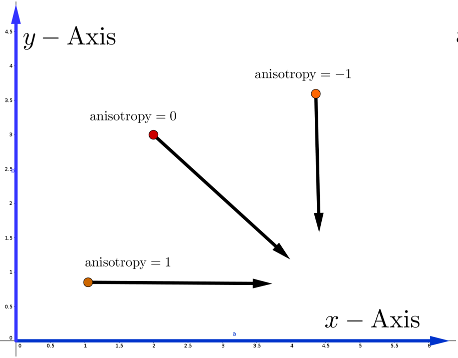




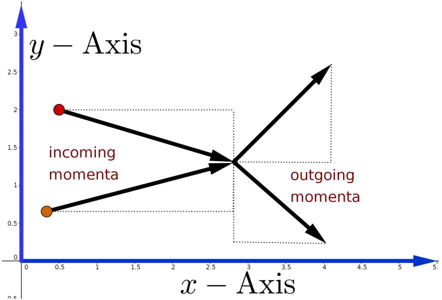
Elliptic flow in partonic transport simulations

"v_2" (rather: momentum anisotropy) can be studied per particle:

$$"v_2" = \frac{1}{N} \sum_{i=1}^{\text{all particles } N} \frac{p_{i,x}^2 - p_{i,y}^2}{p_{i,x}^2 + p_{i,y}^2} = \left\langle \frac{p_{i,x}^2 - p_{i,y}^2}{p_{i,x}^2 + p_{i,y}^2} \right\rangle_{\text{all particles}}$$



Example: anisotropy can be *lost* after collision:

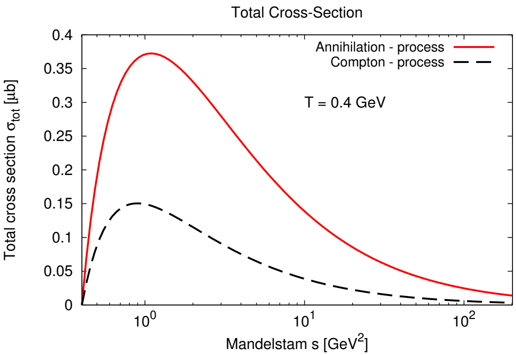


Elliptic flow in partonic transport simulations

$$"v_2" = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_{\text{all particles}}$$

Probability for collision:
s-dependent!

$$P_{22} = \sigma_{22} \frac{s}{2E_1 E_2} \frac{\Delta t}{\Delta V N_{\text{test}}}$$



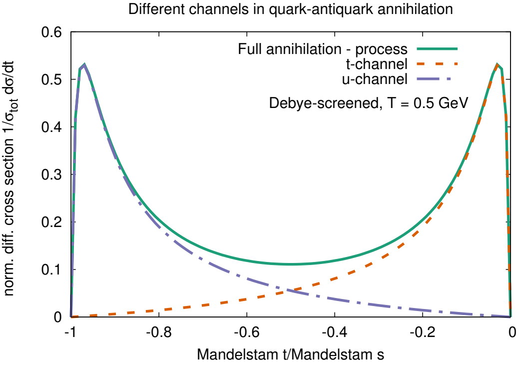
Two effects:

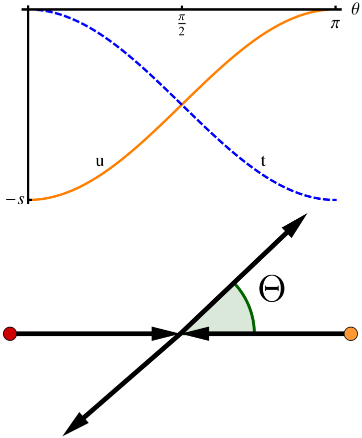
- *Total* cross section: which particles *do* collide?
- *Differential* cross section: preferred scattering angle Θ

Elliptic flow in partonic transport simulations

Specific process: **distribution** of scattering angles

Mandestam $t = -\frac{s}{2}\left(1 - \cos\Theta_{CM}\right)$





- Total cross section and v_{rel} "select" collision partners
- v_2 of final particles depends on $d\sigma/dt = |\mathcal{M}|^2/16\pi s^2$

Elliptic flow in partonic transport simulations

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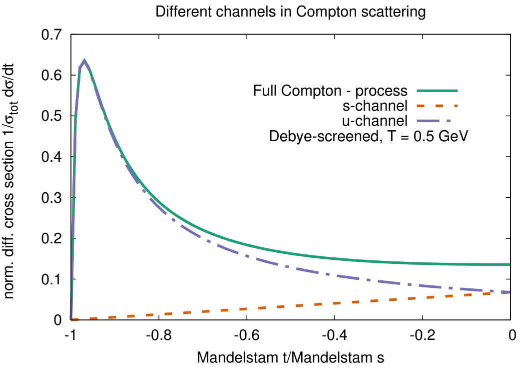

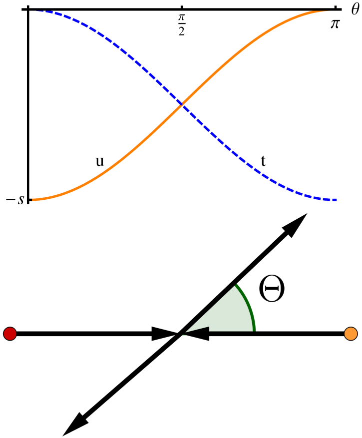

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