





Enhancement of photon momentum anisotropies during the late stages of relativistic heavy-ion collisions

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Photon Sources

Photons are messengers from all stages of the reaction



- All sources have to be treated properly in a full theory calculation
- Entering the precision era for heavy-ion physics, the same approach should describe multiple observables
- Here: Investigation of late non-equilibrium stage

Hybrid Approach



- Photon emission has been treated as thermal emission from the hydrodynamic evolution
 e.g. J.-F. Paquet et al, PRC 93 (2016)
- Hadronic observables require a hadron cascade afterburner
- This work: Comparison of equilibrium and non-equilibrium emission from hadronic stage

Simulating Many Accelerated Strongly-Interacting Hadrons

- Hadronic transport approach:
 - Includes > 150 mesons and baryons
 - Based on relativistic Boltzmann equation

$$p^{\mu}\partial_{\mu}f_i(x,p) + m_i F^{\alpha}\partial^p_{\alpha}f_i(x,p) = C^i_{\text{coll}}$$



https://smash-transport.github.io

J. Weil, HP (now Elfner) et al, PRC 94 (2016)

- Open source code: C++, Git, Python Analysis, HepMC and RIVET
- Already used by HADES, CBM, JETSCAPE, BEST and individuals

Energy density [GeV/fm³] 0.2 0.4 0.25 0.5 0.75 0.5 0.75 0.5 0.75 0.6 12.0 fm/c 12.0 fm/c 13.0 fm/c 10.0 fm/c10

SMASH-vHLLE Hybrid Approach

- Modular hybrid approach for intermediate and high energy heavy-ion collisions
- Open source and public

https://github.com/smashtransport/smash-vhlle-hybrid

 Here: Simplified setting for qualitative study

A. Schäfer et al., arXiv: 2112.08724 Weil et al.: PRC 94 (2016) DOI: 10.5281/zenodo.3484711 Huovinen et al.: Eur. Phys. J A 48 (2012) Karpenko et al.: PRC 91, 064901 (2015) Karpenko et al.: Comput. Phys. Commun. 185 (2014)

SMASH

- Hadronic transport approach
- Initial conditions

VHLLE

- 3+1 D viscous hydrodynamics (event-by-event)
- Cornelius routine for hypersurface

smash-hadron-sampler

- Cooper-Frye sampler
- Particlization of fluid elements

SMASH

- Hadronic transport approach
- Evolution of hadronic rescattering

MUSIC+SMASH

- Averaged initial conditions from Trento
- MUSIC as ideal hydrodynamic evolution
- SMASH for hadronic rescattering and decays
- Different settings:
 - Run hydro to T=150 MeV and switch to transport
 - Run hydro for photons to T=120 MeV
- Simplified setup avoids additional complications, e.g. viscous corrections during hydrodynamic evolution
- Hadronic production cross-sections calculated from effective field theory
 Turbide et al.: Int.J.Mod.Phys. A19 (2004)
- Consistency with thermal rates in MUSIC is crucial
- Thanks to A. Schäfer, O. Garcia-Montero, J.-F. Paquet, C. Gale

A. Schäfer et al., PRC 105 (2022)

Hadronic Photon Production

- Pions most abundant species, therefore the most important processes for afterburner at high beam energies
 - $-2 \leftrightarrow 2$ scatterings $\pi \rho \rightarrow \pi \gamma$
 - Bremsstrahlung $\pi\pi \to \pi\pi\gamma$

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Turbide et al.: Int.J.Mod.Phys. A19 (2004)

https://github.com/smashtransport/phoxtrot



Microscopic box calculations match thermal rates

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Comparison of Rates

 In a thermal system, SMASH photon rates coincide with the ones used in MUSIC



- Bremsstrahlung dominates low transverse momentum
- Scatterings take over at higher transverse momentum
- Hadronic decays are neglected

A. Schäfer et al., PRC 105 (2022)

Hadronic Observables

 MUSIC+SMASH hybrid describes hadronic spectra and elliptic flow reasonably well
 A. Schäfer et al., PRC 105 (2022)



Unified approach to describe multiple observables

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Photon Yields

 Hadronic thermal emission is much smaller than the one from the hot and dense stage



 Non-equilibrium photons similar to equilibrium yields in MUSIC

Elliptic Flow from Hadronic Stage



- Elliptic flow of photons from hadronic stage is larger in nonequilibrium SMASH evolution
- All channels behave similarly
- Larger v₂ from hypersurface is preserved

Elliptic Flow from SMASH

Photon elliptic flow is weighted average



 Bremsstrahlung dominates again at low pt and scatterings at higher pt

Time Evolution

Development of elliptic flow of late stage photons over time



- Photon anisotropy is dominated by Bremsstrahlung photons at all times
- Peak at maximum emission from Cooper-Frye hypersurface

Full Result

Photon yields are not affected much by late stage



 Elliptic flow receives significant extra contribution below transverse momentum of 1 GeV from non-equilibrium evolution

Summary

- Included photons from non-equilibrium hadronic rescattering in a hybrid approach
- Unified description for hadronic and electromagnetic observables
- Qualitative study in a simplified approach based on MUSIC and SMASH
- Bremsstrahlung dominates low transverse momentum emission and scatterings at higher transverse momentum
- Photon yields are not affected by non-equilibrium evolution
- Elliptic flow receives a significant extra contribution when photons are emitted out of equilibrium
- More Bremsstrahlung channels important for further studies
- Addition of prompt photons and viscous effects important for a future comparison to experimental data

How to Use SMASH?

- Visit the webpage to find publications and link to SMASH-2.2 results <u>https://smash-transport.github.io</u>
- Download the code at <u>https://github.com/smash-transport/smash</u>

SMASH-2.2 has HepMC and RIVET

16

- Checkout the Analysis Suite at <u>https://github.com/smash-transport/smash-analysis</u>
- Find user guide and documentation at <u>https://github.com/smash-transport/smash/releases</u>
- Animations and Visualization Tutorial under <u>https://smash-transport.github.io/movies.html</u>

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