Out-of-Equilibrium Photon Production in the Late Stages of Relativistic Heavy-Ion Collisions

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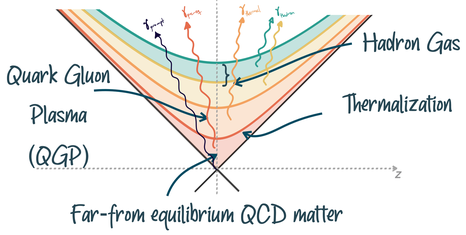
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

Motivation

- Direct photons are clean probes created throughout the collision and free of final state effects.
- Current mismatch with data ("Direct Photon Puzzle") may be fixable via inclusion of non-equilibrium effects

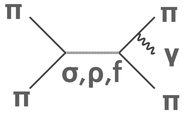
How does microscopic hadronic rescattering during the late stage affect the results?



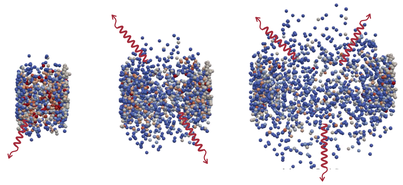
Photons from Hadronic Transport

*Slides 2-3

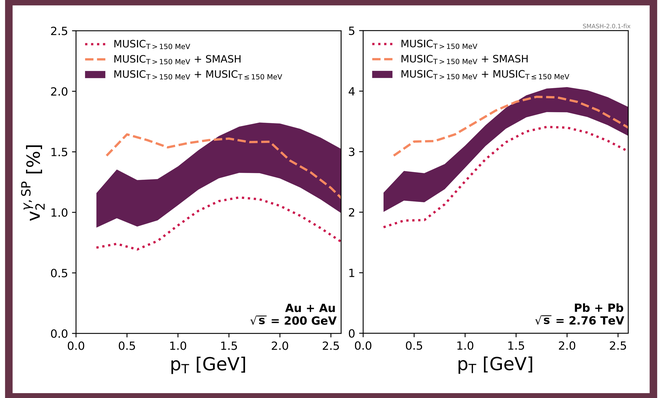
- Non-equilibrium production of photons in hadronic matter
  - Microscopic scattering and production using the SMASH transport code.
- Photons are sampled when underlying meson scattering happens
  - Perturbative production - no backreaction
- γ kinematic properties are sampled from differential cross-sections
  - Using U(1) symmetric Chiral Perturbation Theory



Main contributions: meson-bremsstrahlung and 2-to-2 scattering processes



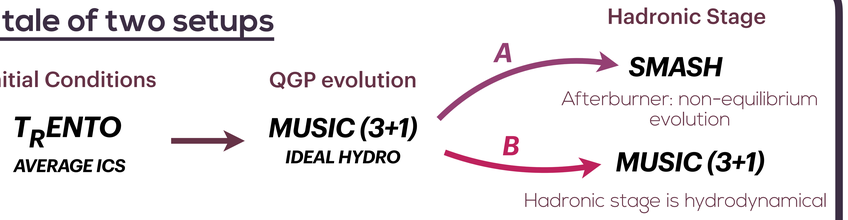
- First full hybrid calculation for photon production at high beam energies
- Late time non-equilibrium effects are significant for anisotropy generation



- Non-trivial to resolve the discrepancies in the photon observables
- Approach could be further improved by new channels (Kaon, Baryonic, ...)

Interested? Read the paper!

A tale of two setups



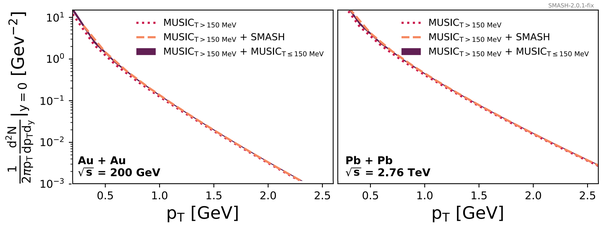
Details: Au+Au @ $\sqrt{s} = 200$ GeV + Pb+Pb @ $\sqrt{s} = 2.76$ TeV b=5 fm ~ 10-20%

Results

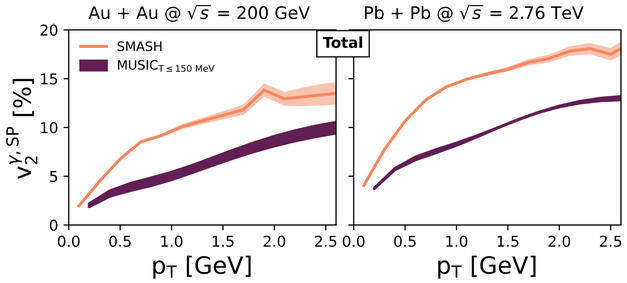
*Slides 4

Computed yield and anisotropy of photons. For v_2 we used $v_2(p_\perp) = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_\perp^2 \rangle}$

Photon anisotropies are measured relative to the hadronic event plane



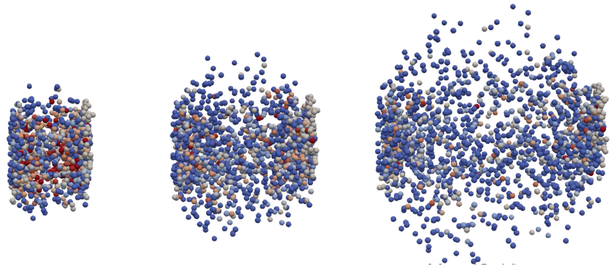
YIELDS ARE RELATIVELY UNAFFECTED



NON-EQUILIBRIUM EFFECTS ENHANCE PHOTON ANISOTROPIES

SMASH*

smash



- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- Hadronic transport approach
- Includes hadrons with masses up to ~ 2 GeV
- Particles propagate and collide on the basis of physical cross sections
- Effective solution to Boltzmann equation: $p_\mu \partial^\mu f + m\, \partial_{p_\mu}(F^\mu f)^\mu = C[f]$
- Successfully studied bulk properties, as well as dilepton and strangeness production

This work: SMASH 1.8
https://smash-transport.github.io
https://doi.org/10.5281/zenodo.3484711

Newest version-> SMASH 2.1.4

Weil *et al*, *Phys.Rev.C* 94 (2016) 5, 054905
Steinberg *et al*, *Phys.Rev.C* 99 (2019) 6, 064908
Mohs *et al*,*J.Phys.G* 47 (2020) 6, 065101
Rose *et al*, *J.Phys.G* 48 (2021) 015005
Steinberg *et al*, arXiv: 1912.09895
Staudenmeier *et al*, *Phys.Rev.C* 98 (2018) 5, 054908

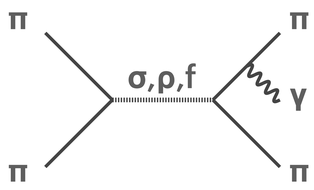
PHOTONS FROM HADRONIC TRANSPORT

Get differential and total cross section from the Chiral Lagrangian

Use $\frac{d\sigma}{dt}$ and $\frac{d\sigma}{dt}\frac{d\sigma}{dkd\theta}$ (depending on end-state kinematics) to sample the direction and momentum of photons

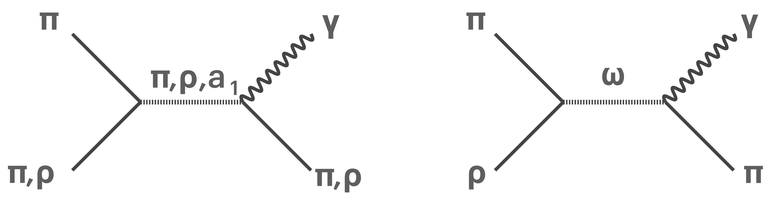
MESON BREMSSTRAHLUNG

Photon production from pion 2-to-3 process.
Mediated by σ,ρ and f resonances



2-TO-2 SCATTERINGS

Photon production from ρ/pion 2-to-2 scattering processes



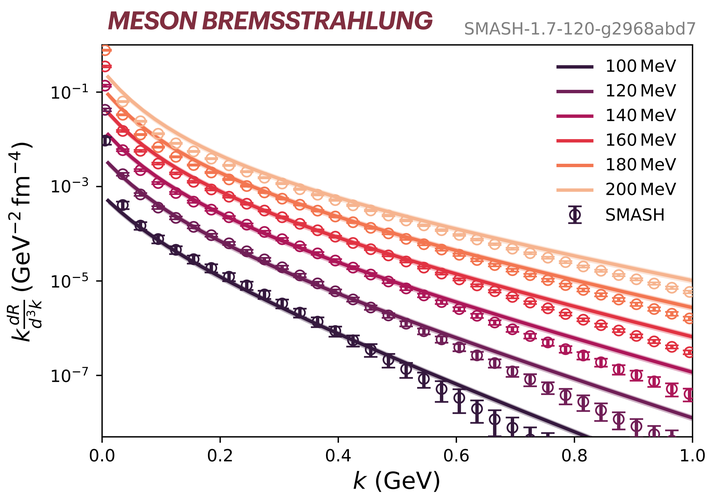
Schäfer *et al*, *Phys.Rev.D* 99 (2019) 11, 114021

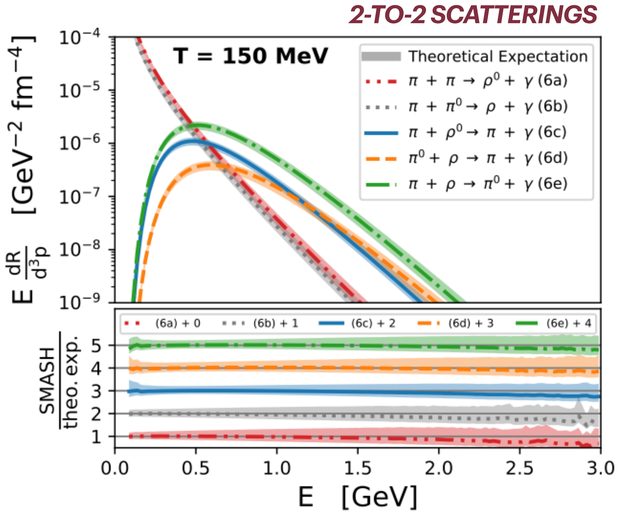
BENCHMARK: COMPARISON TO THERMAL RATES

SMASH setup: thermal matter with periodic box

Compute Thermal photon rates: 4-volume density of photons

Fair agreement to known parametrizations





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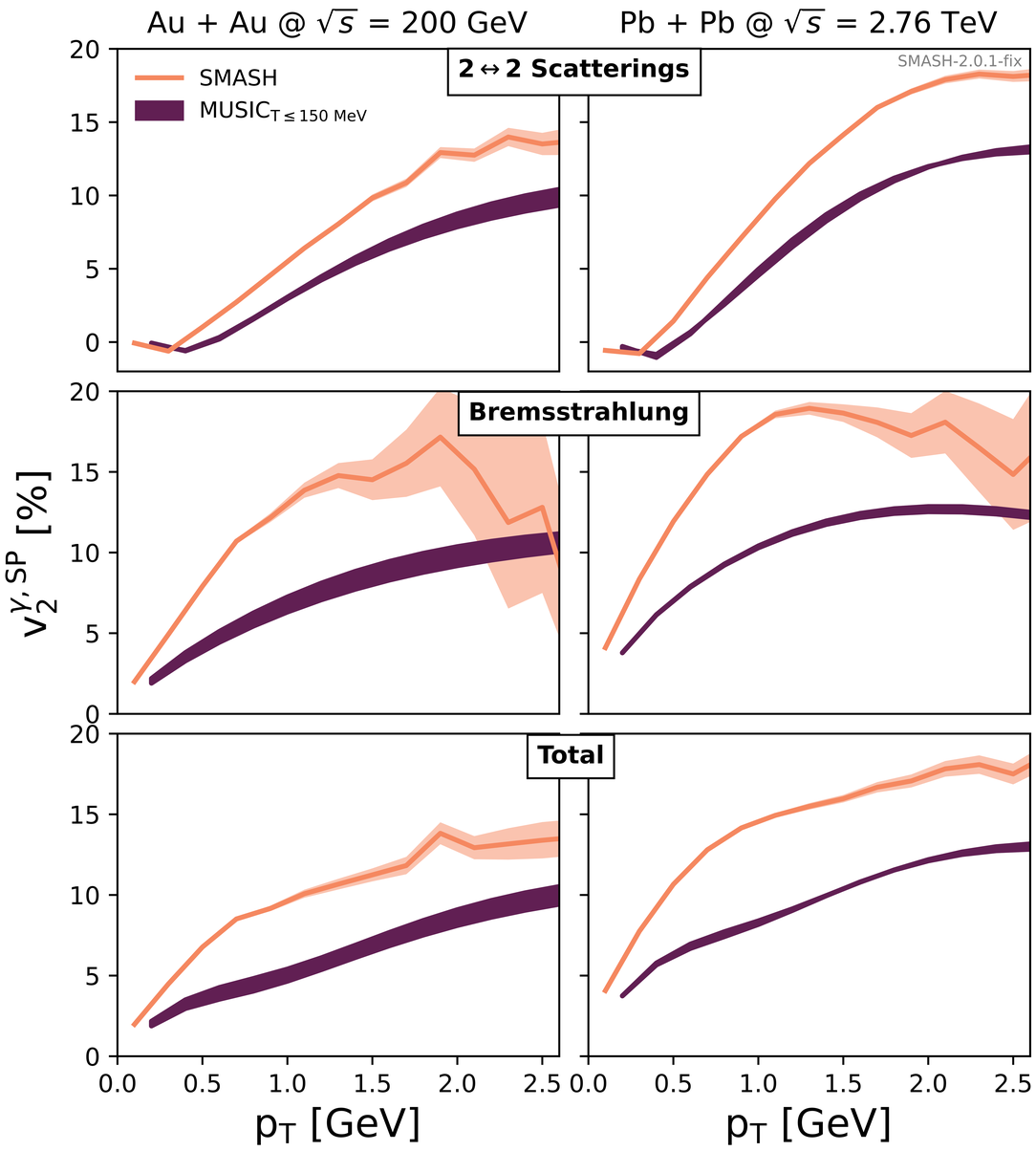


HYDRO VS. TRANSPORT

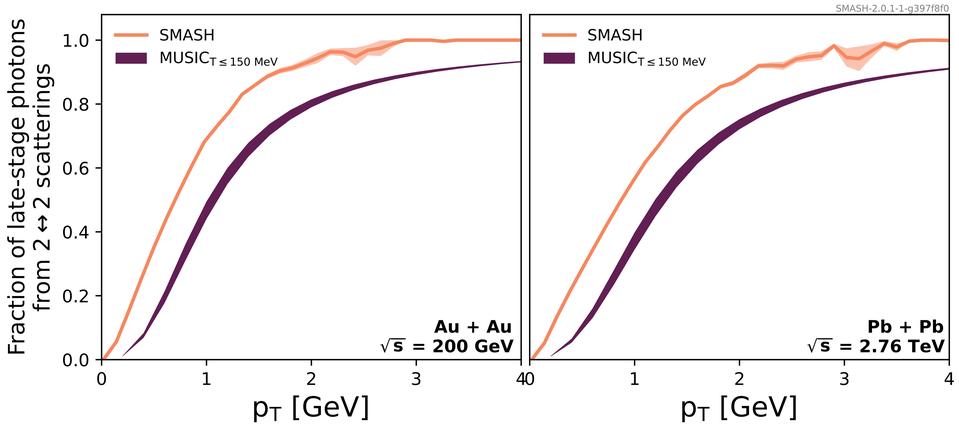
Comparison

Eq. vs Non-Eq. Effects

Photons from SMASH (transport)
vs. MUSIC (Hydro, Hadronic)

Hydro Photons produced using thermal rates:

Note: Total is a weighted average!



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