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

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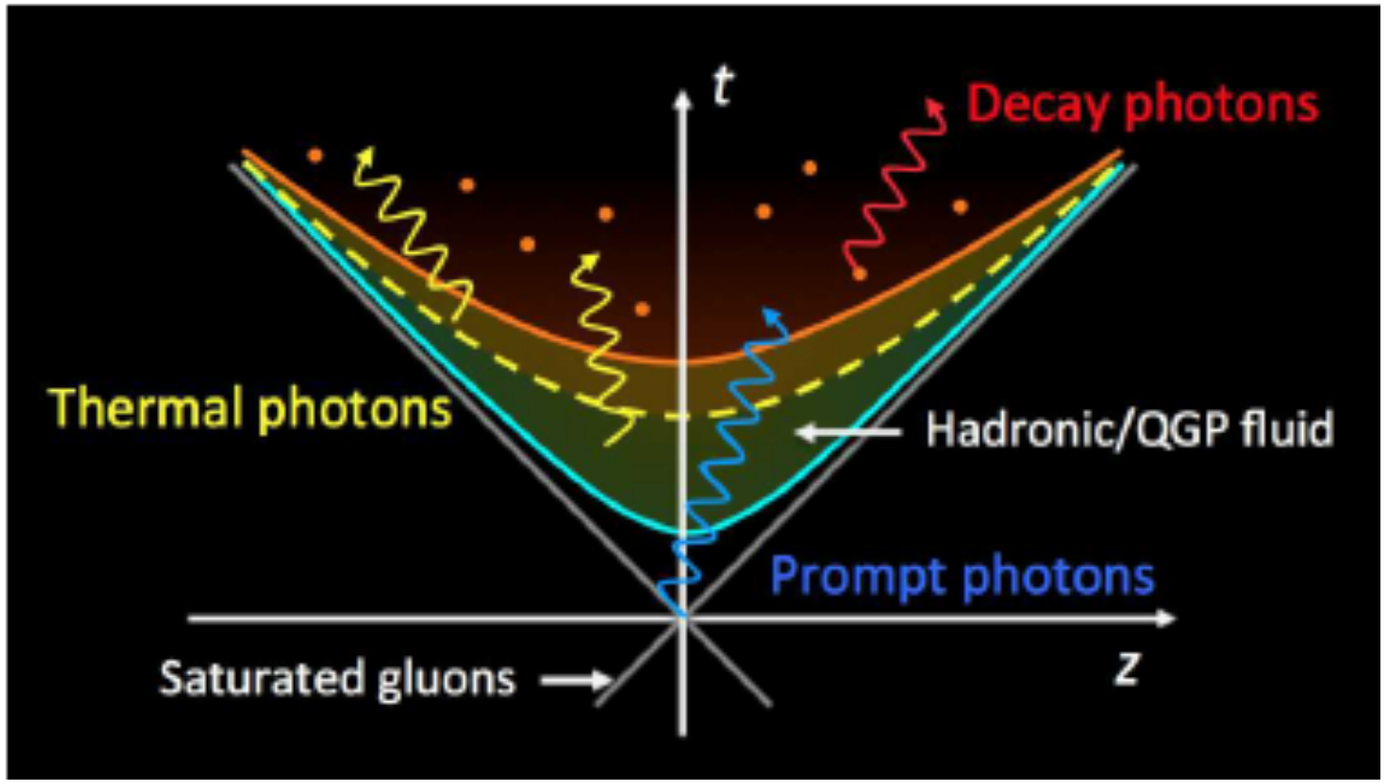
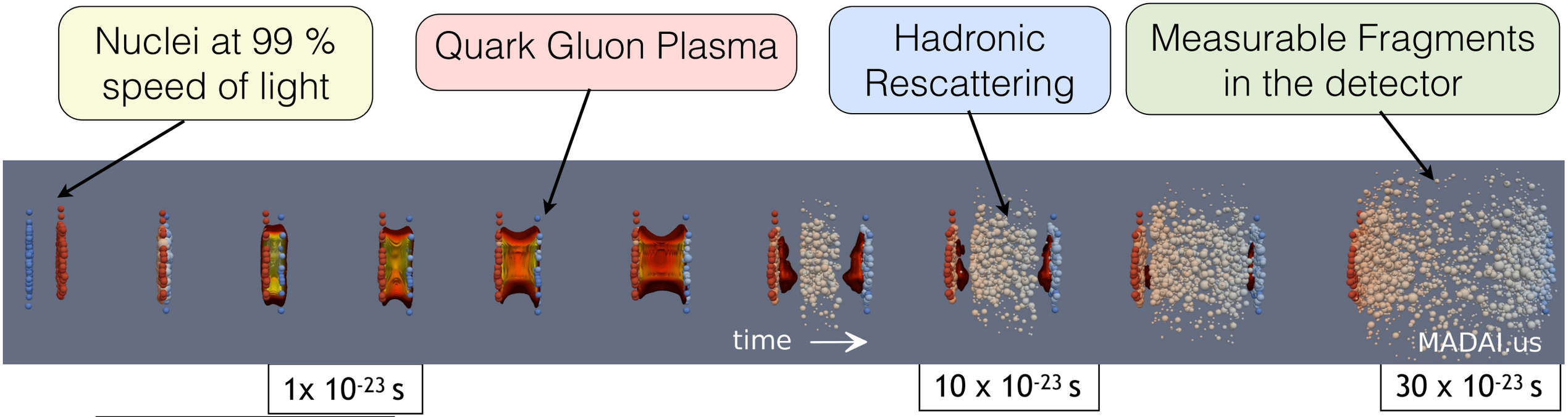
Photon Sources

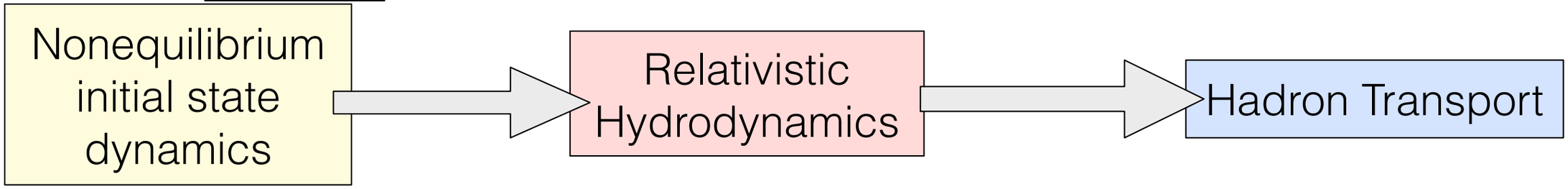
- Photons are messengers from all stages of the reaction



- 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

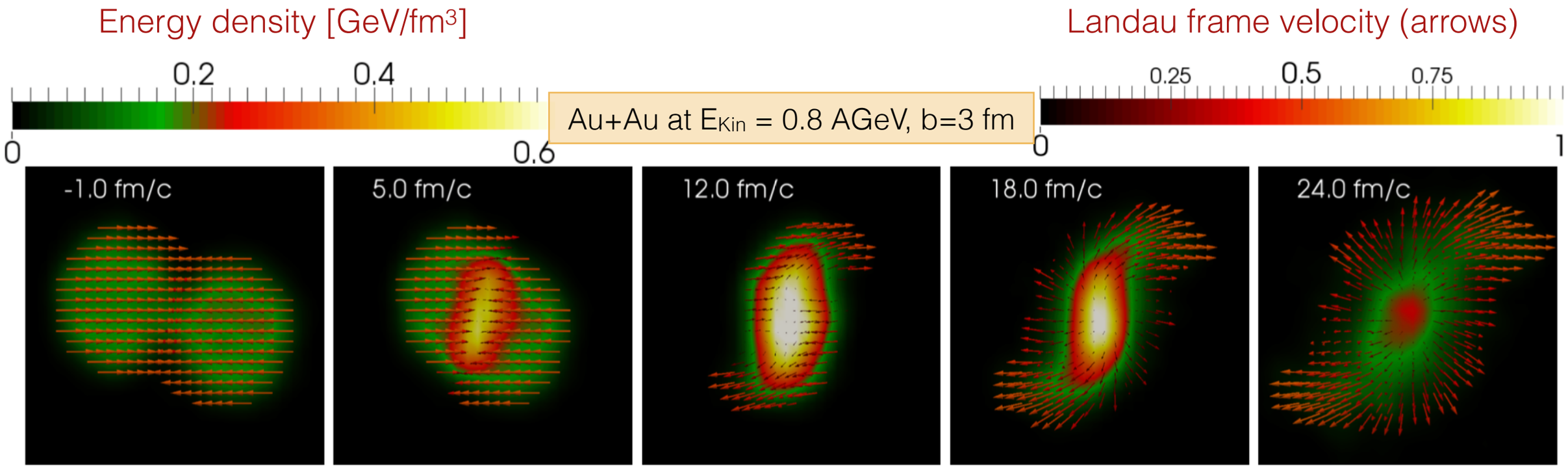
- Hadronic transport approach:
  - Includes > 150 mesons and baryons
  - Based on relativistic Boltzmann equation

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

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



SMASH-vHLLE Hybrid Approach

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

https://github.com/smash-transport/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

A. Schäfer et al., PRC 105 (2022)

- 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

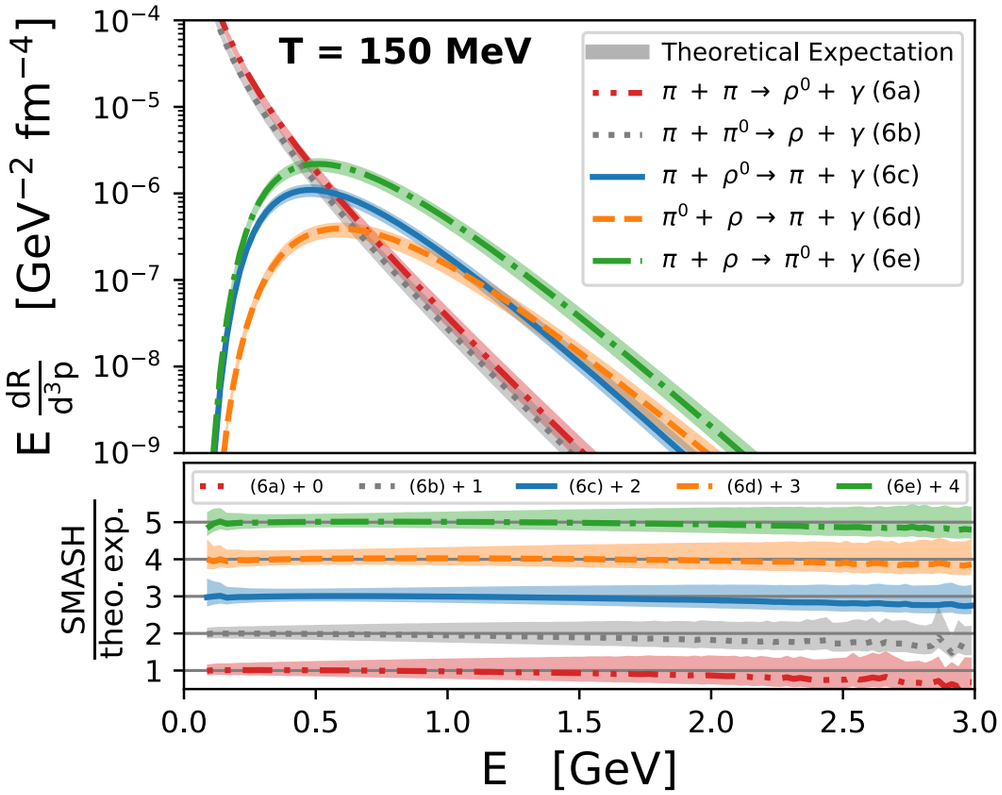
Hadronic Photon Production

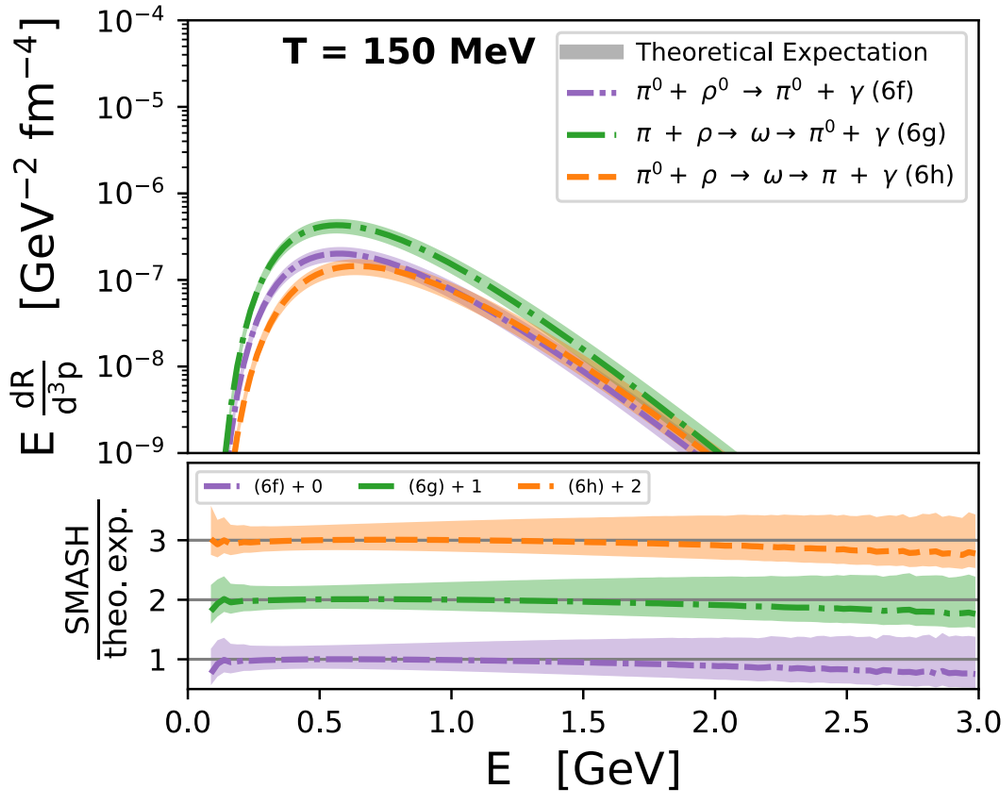
- Pions most abundant species, therefore the most important processes for afterburner at high beam energies
  - $2 \leftrightarrow 2$ scatterings $\pi\rho \rightarrow \pi\gamma$
  - Bremsstrahlung $\pi\pi \rightarrow \pi\pi\gamma$

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

https://github.com/smash-transport/phoxtrot

A. Schäfer et al, PRD 99 (2019)

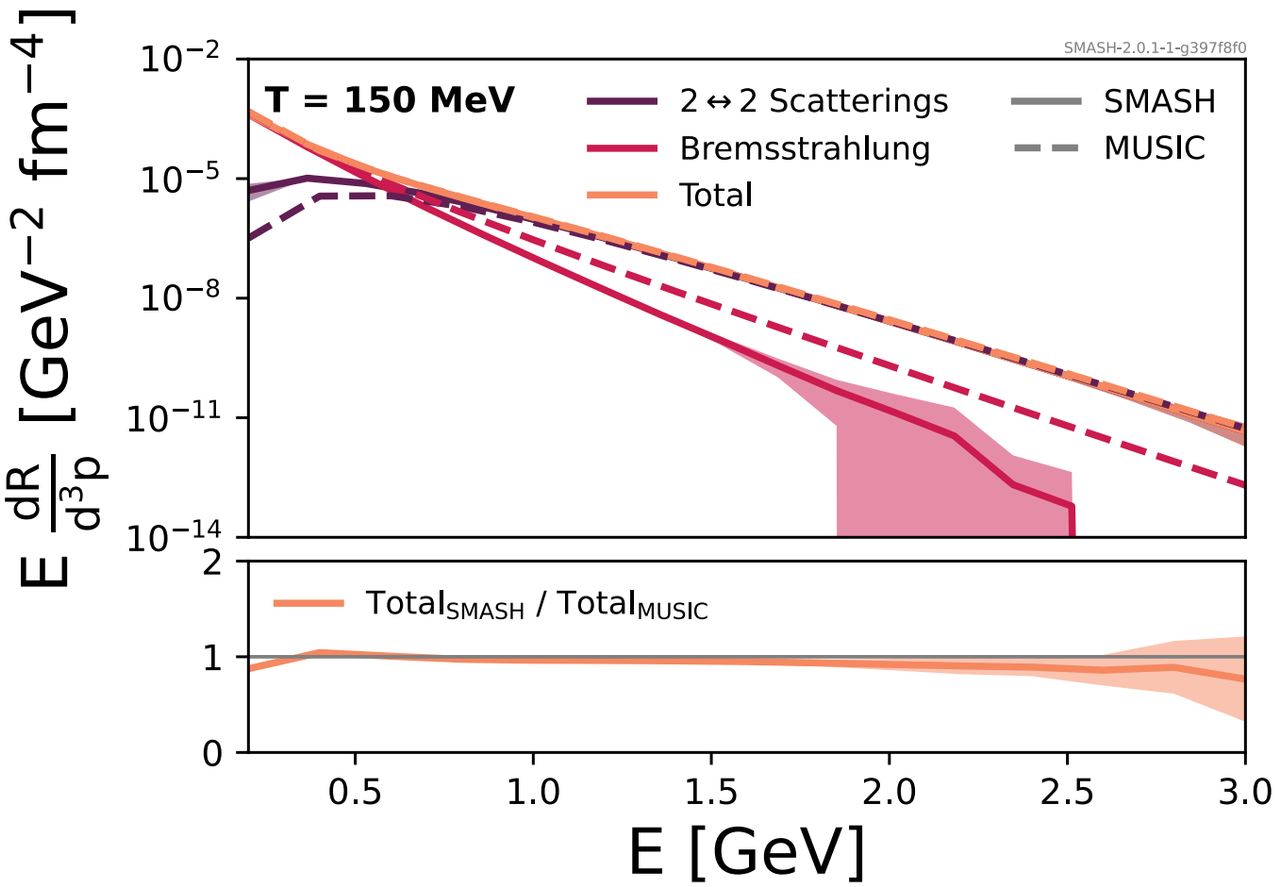




- Microscopic box calculations match thermal rates

Comparison of Rates

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



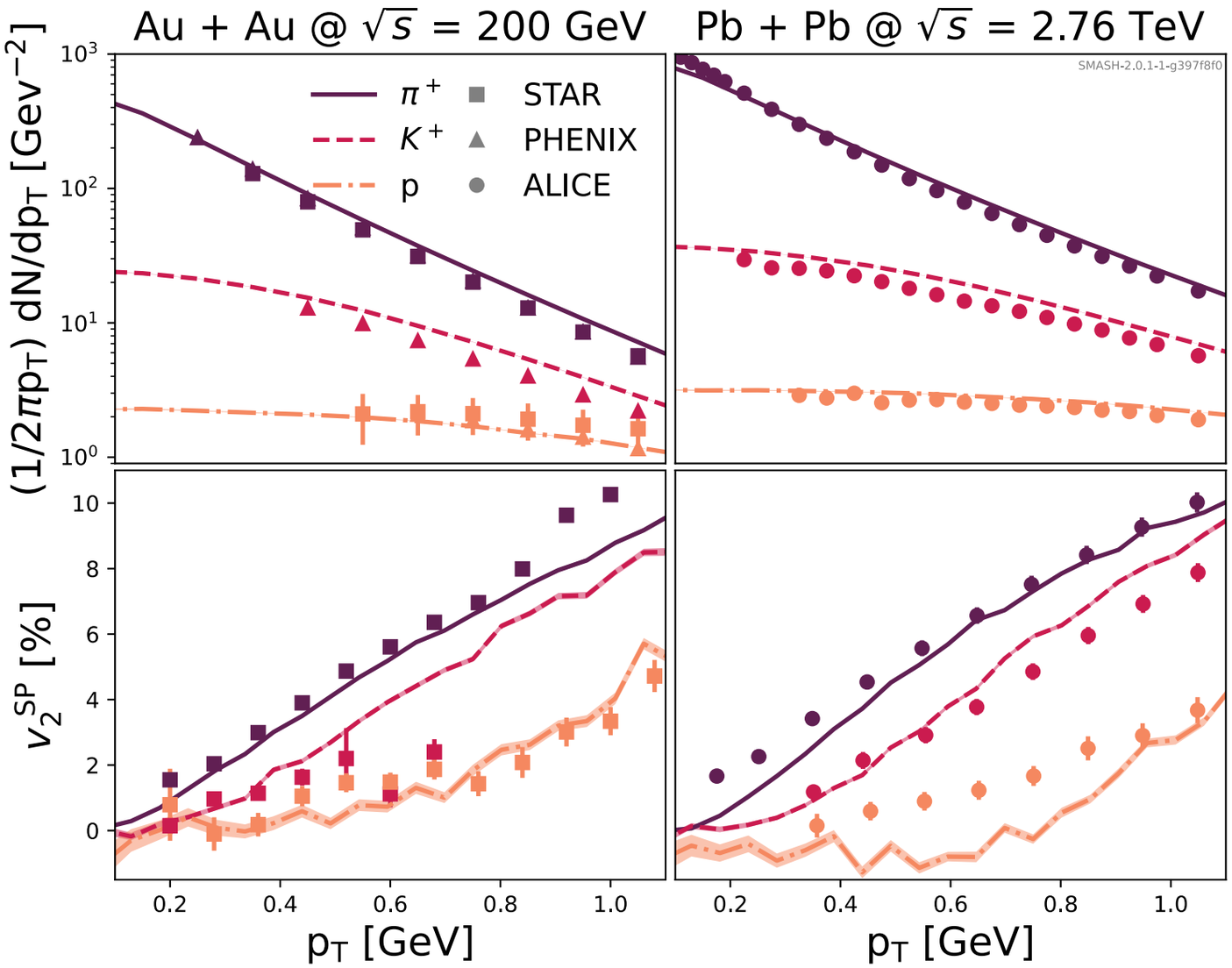
- Bremsstrahlung dominates low transverse momentum
- Scatterings take over at higher transverse momentum
- Hadronic decays are neglected

A. Schäfer et al., PRC 105 (2022)

Hadronic Observables

- MUSIC+SMASH hybrid describes hadronic spectra and elliptic flow reasonably well

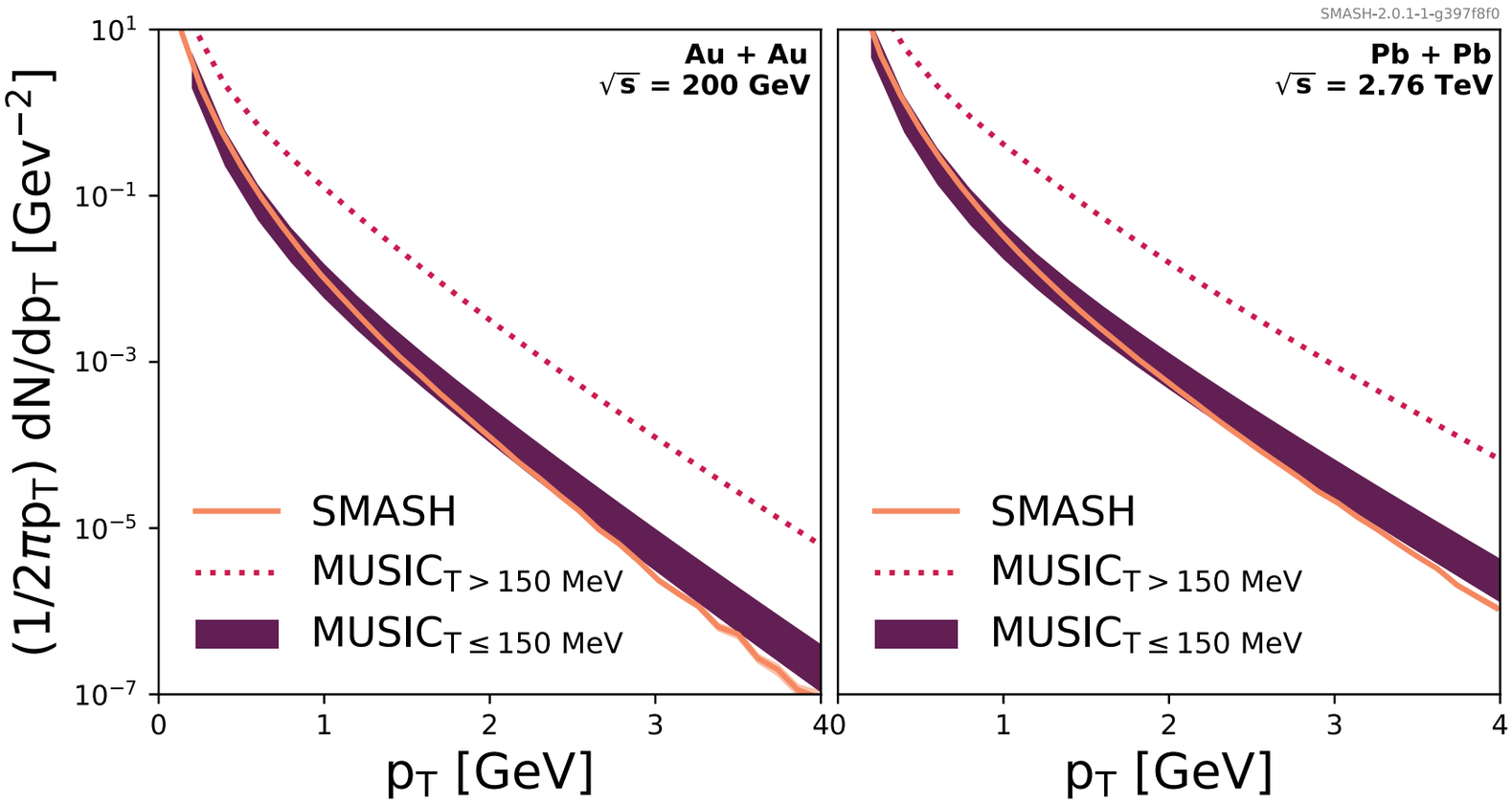
A. Schäfer et al., PRC 105 (2022)



- Unified approach to describe multiple observables

Photon Yields

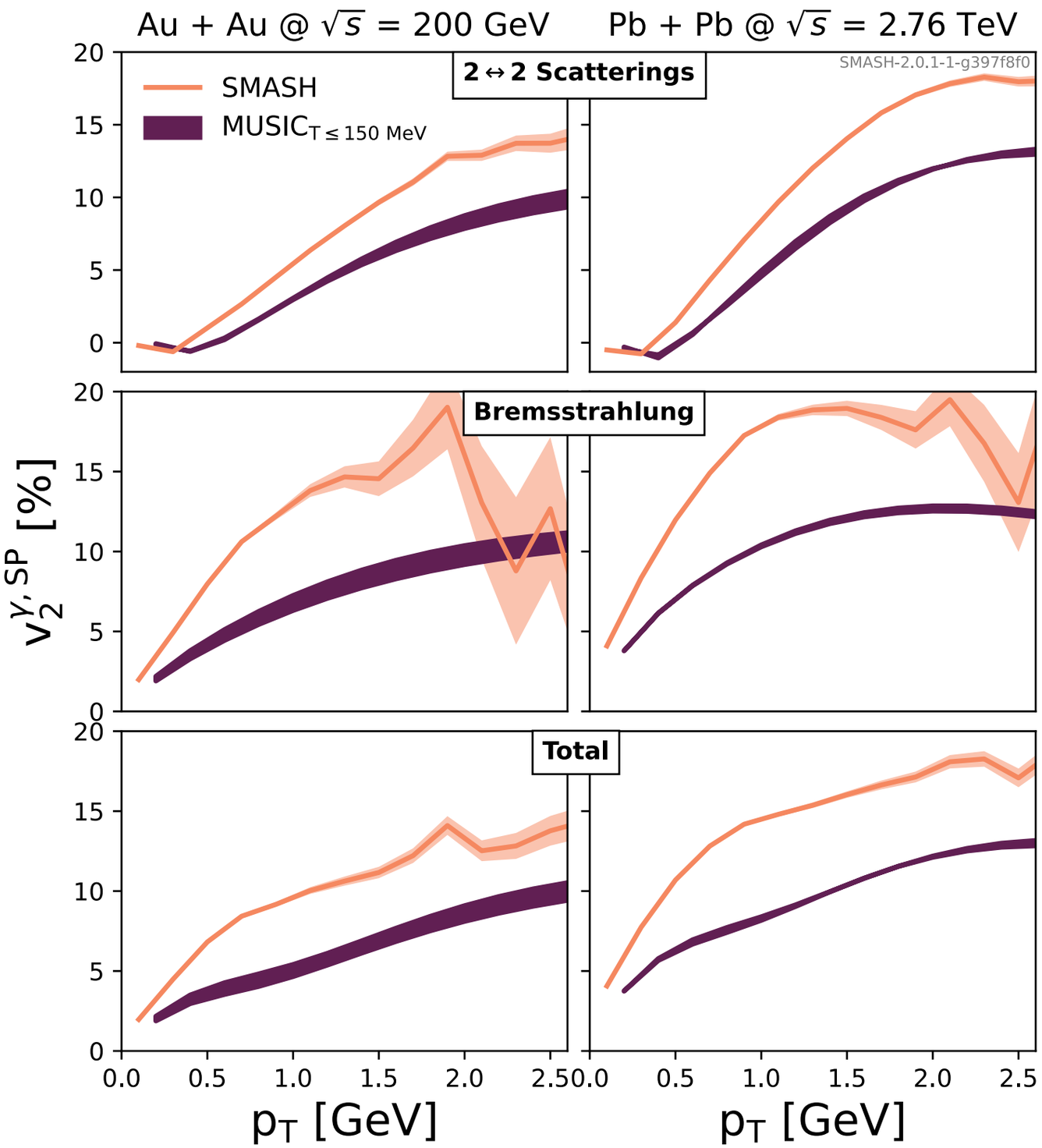
- Hadronic thermal emission is much smaller than the one from the hot and dense stage



- Non-equilibrium photons similar to equilibrium yields in MUSIC

A. Schäfer et al., PRC 105 (2022)

Elliptic Flow from Hadronic Stage

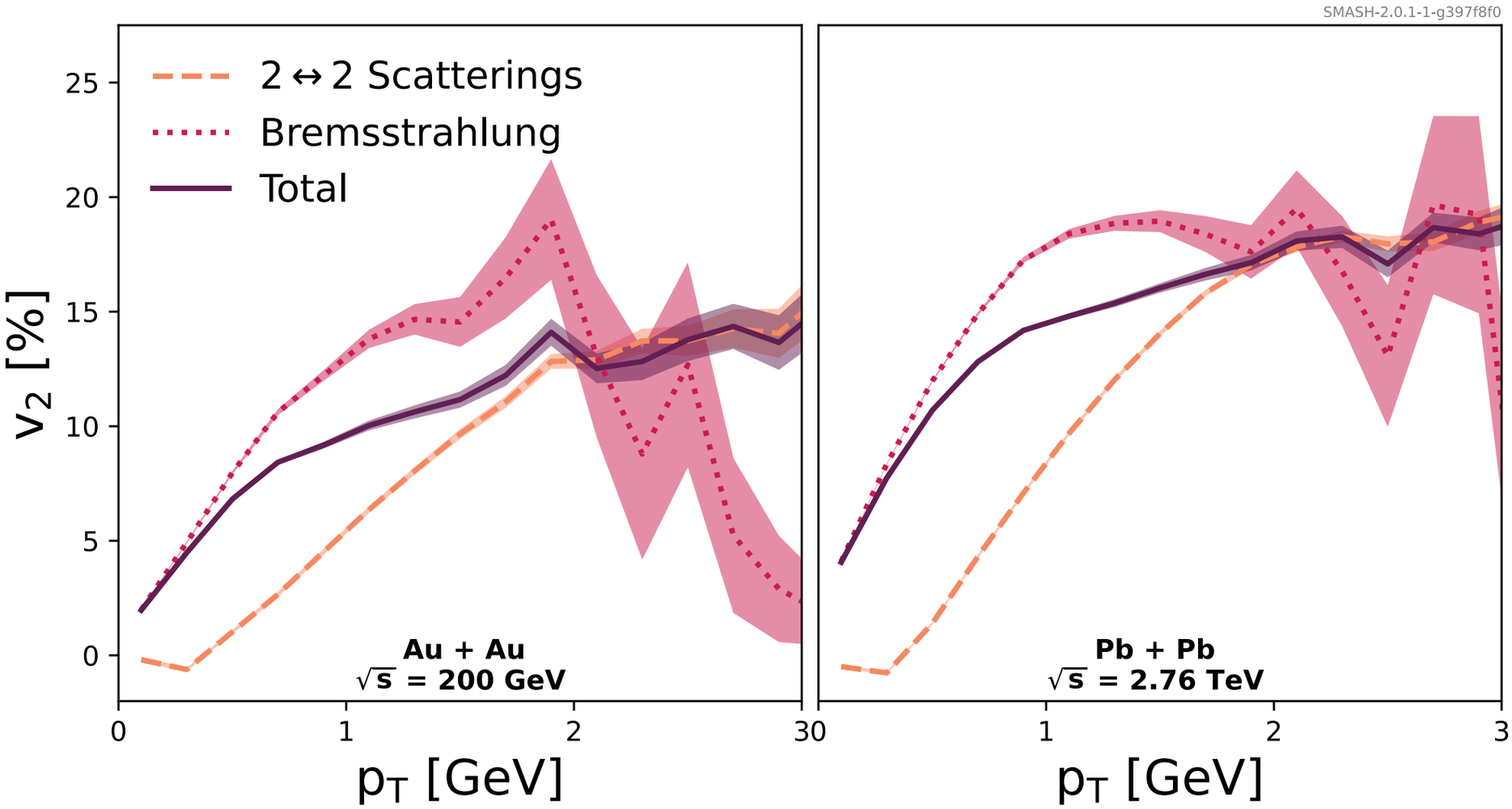


- Elliptic flow of photons from hadronic stage is larger in non-equilibrium SMASH evolution
- All channels behave similarly
- Larger v_2 from hypersurface is preserved

A. Schäfer et al., PRC 105 (2022)

Elliptic Flow from SMASH

- Photon elliptic flow is weighted average

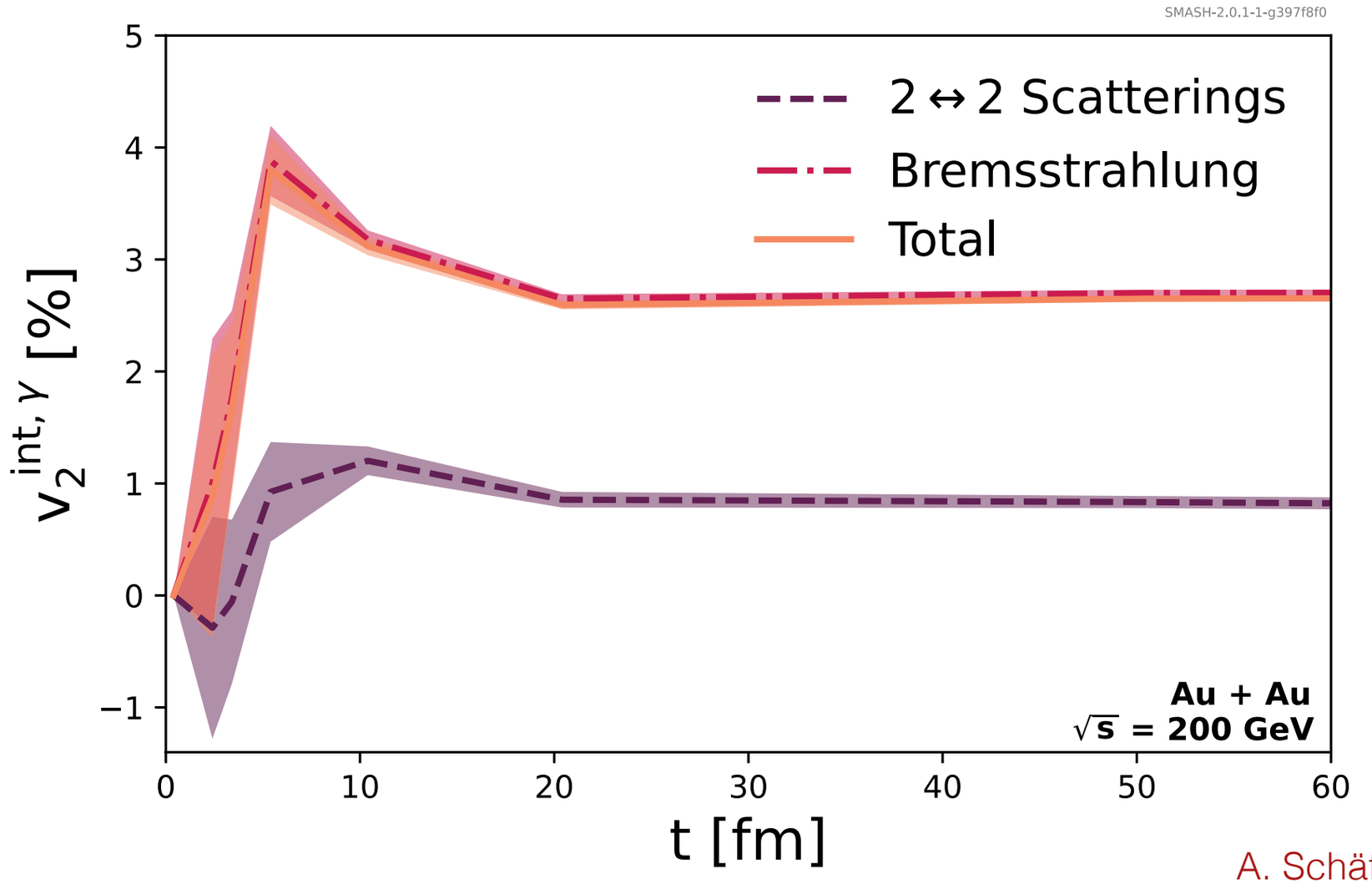


- Bremsstrahlung dominates again at low pt and scatterings at higher pt

A. Schäfer et al., PRC 105 (2022)

Time Evolution

- Development of elliptic flow of late stage photons over time

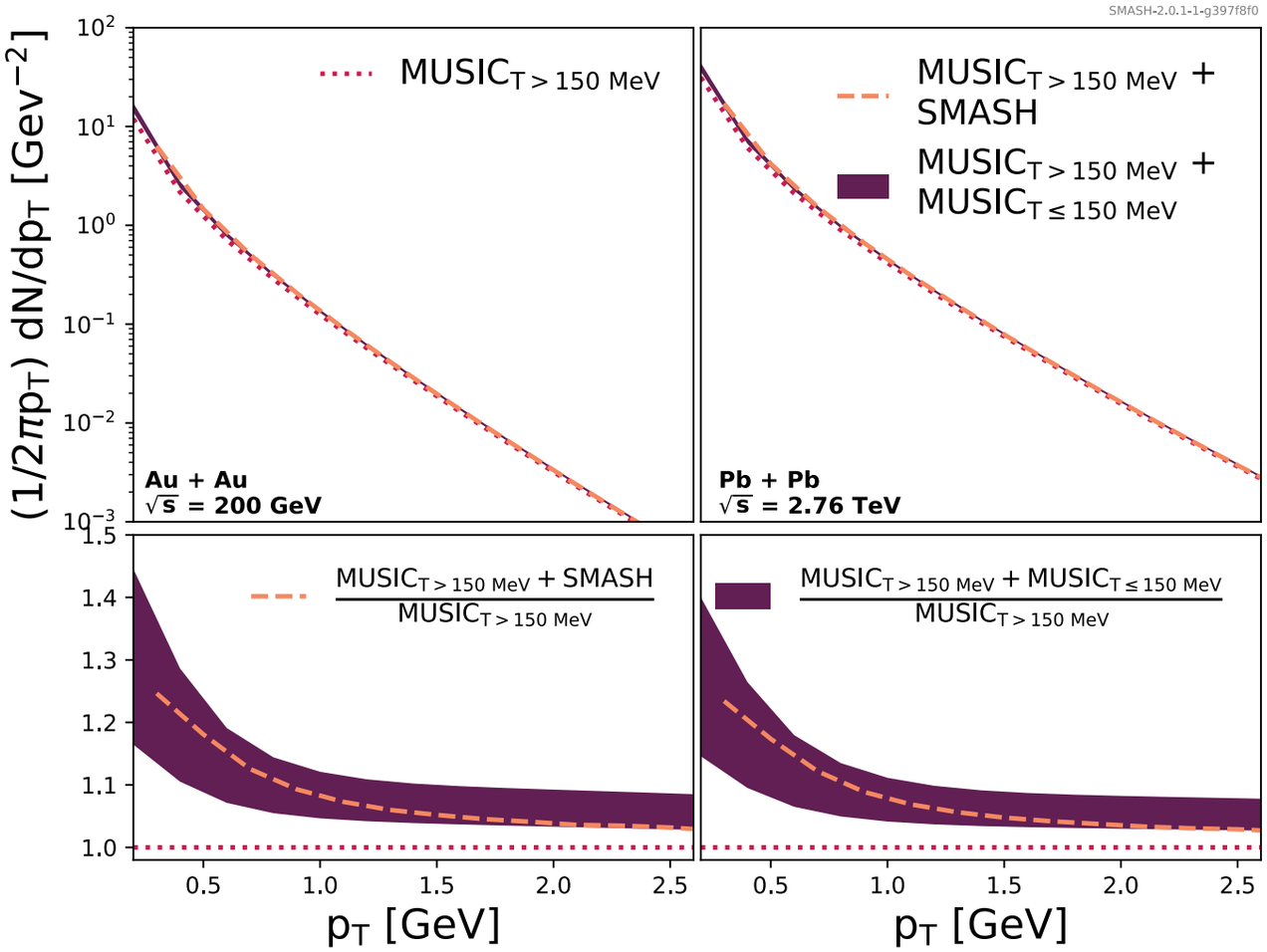


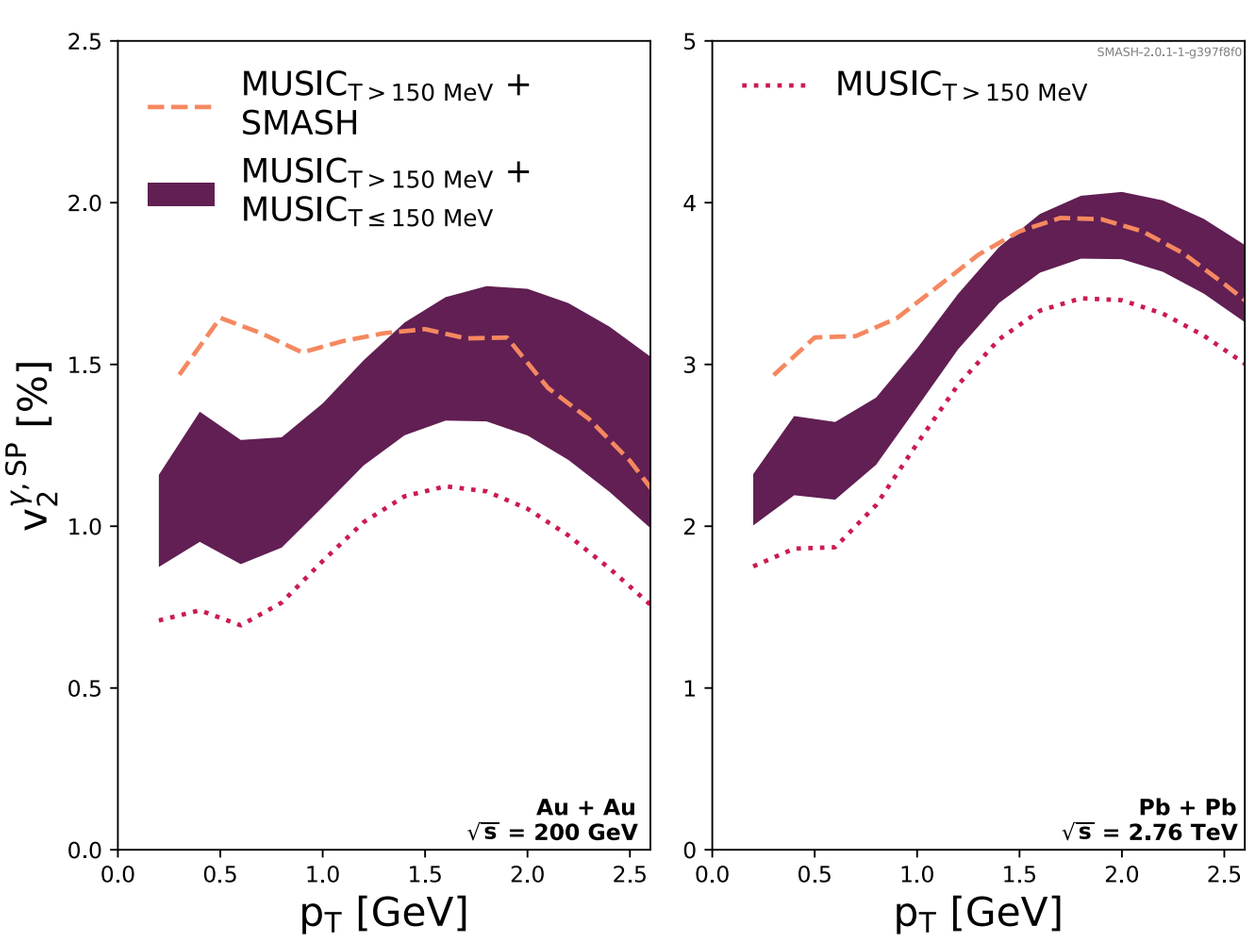
A. Schäfer et al., PRC 105 (2022)

- 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

A. Schäfer et al., PRC 105 (2022)

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

SMASH-2.2 has HepMC and RIVET