Photon Production in a Hadronic Transport Approach

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Outline

• Introduction and motivation
• Photon production: a simple mesonic system
• Direct photons in SMASH
• Photon production in equilibrium
• Summary
• Outlook
Probing the QCD phase diagram

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Photon Production in a Hadronic Transport Approach (Niklas Ehlert)

- photons
  - background
  - decay photons
  - direct photons
    - prompt photons
    - thermal photons
    - bremsstrahlung
Direct photons

- theoretical predictions undershoot measured spectrum and flow
- maybe not dominated by early hot QGP?

A. Adare et al. [PHENIX Collaboration], arXiv:1509.07758 [nucl-ex].
Photons from a hadron gas

\[ \mathcal{L} = |D_\mu \Phi|^2 - m_\pi^2 |\Phi|^2 - \frac{1}{4} \rho_{\mu\nu}\rho^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ |D_\mu \Phi|^2 = (\partial_\mu \Phi^\dagger + ie A_\mu \Phi^\dagger + ig_\rho \rho_\mu \Phi^\dagger)(\partial^\mu \Phi - ie A^\mu \Phi - ig_\rho \rho^\mu \Phi) \]

\[ = -ie[\partial_\mu \Phi^\dagger A^\mu \Phi + \Phi^\dagger A^\mu \partial_\mu \Phi] - ig_\rho[\partial_\mu \Phi^\dagger \rho^\mu \Phi + \Phi^\dagger \rho^\mu \partial_\mu \Phi] \]

\[ + e^2 A_\mu A^\mu \Phi^\dagger \Phi + g_\rho^2 \rho_\mu \rho^\mu \Phi^\dagger \Phi + 2eg_\rho A_\mu \Phi^\dagger \rho^\mu \Phi \]

- simple hadron resonance gas
- only pi-, rho- and eta-mesons
- evaluated via Scalar Field Theory

[KAP91]
Deriving cross sections from scalar field theory

example: \[ \pi^\pm + \pi^\mp \rightarrow \rho^0 + \gamma \]

\[
\sigma(\pi^\pm + \pi^\mp \rightarrow \rho^0 + \gamma) = \frac{\alpha g_\rho^2}{4s|p_{c.m.}|^2} \left\{ 2\Delta t - \Delta m^2 \left[ \frac{m_{\pi}^2 \Delta t}{\tilde{t}_1 \tilde{t}_2} - \frac{m_{\pi}^2 \Delta u}{\tilde{u}_1 \tilde{u}_2} + \frac{s - 2m_{\pi}^2}{s - m_{\rho}^2} \ln \left( \frac{\tilde{t}_2 \tilde{u}_1}{\tilde{t}_1 \tilde{u}_2} \right) \right] \right\}
\]
Total cross section comparison

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Mass dependence of initial rho cross sections

\[ \pi^0 + \rho^+ \rightarrow \pi^+ + \gamma \]

\[ \sqrt{s} \text{ [GeV]} \]

\[ \sigma \text{ [mb]} \]

- \( m_\rho = 300 \text{ MeV} \)
- \( m_\rho = 400 \text{ MeV} \)
- \( m_\rho = 776 \text{ MeV} \) (pole mass)
- \( m_\rho = 900 \text{ MeV} \)
Width dependence of final rho cross sections

\[ A(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - M_0^2)^2 + m^2 \Gamma^2(m)} \]

\[ \pi^+ \pi^0 \rightarrow \rho^+ + \gamma \text{ SMASH} \]
\[ \pi^+ \pi^- \rightarrow \rho_0^+ + \gamma \text{ UrQMD} \]
\[ \pi^+ \pi^- \rightarrow \rho^0 + \gamma \text{ SMASH} \]
\[ \pi^+ \pi^- \rightarrow \rho^- + \gamma \text{ UrQMD} \]
In the following:

• box simulations with pions, rhos and etas
• thermal and chemical equilibrium
• box sizes: $10^3$ to $40^3$ fm$^3$
• temperature: 100 to 200 MeV
Perturbative photon production

1. check for collisions: \( d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \)
2. determine \( \sqrt{s} \) and \( p_{cm} \)
3. sample outgoing mass, find limits for Mandelstam \( t \) from effective masses
4. sample \( t \) according to \( \frac{d\sigma}{dt}(s, t) \) and calculate \( \theta \)
5. get \( \phi \) from uniform distribution
6. include weighting factor:

\[
R = \frac{\sigma_\gamma}{\sigma_{\text{tot}}}
\]

\[
\Delta R(s, t) = \frac{\frac{d\sigma_\gamma}{dt}(s, t) \Delta t}{\sigma_{\text{tot}}(s)}
\]

7. boost to initial frame
Basic tests

Photon yield vs energy (70 events, 20 testparticles, Box = (20 fm)$^3$, runtime: 100 fm)
Time (in)dependence

- $\pi + \pi \rightarrow \gamma + \gamma$
- $\pi + \pi \rightarrow \rho_0 + \gamma$
- $\pi^0 + \pi \rightarrow \rho + \gamma$
- $\pi + \eta \rightarrow \pi + \gamma$
- $\pi + \pi \rightarrow \eta + \gamma$
- $\pi + \rho_0 \rightarrow \pi + \gamma$
- $\pi + \rho \rightarrow \pi^0 + \gamma$
- $\pi^0 + \rho \rightarrow \pi + \gamma$

Graphs showing $1/N_{\text{event}} \cdot dN/dt$ as a function of time $t$ [fm].
Volume (in)dependence

![Graph showing the dependence of photon production on volume]

- Volume = $(10 \text{ fm})^3$
- Volume = $(20 \text{ fm})^3$
- Volume = $(40 \text{ fm})^3$

**Graph Parameters**
- $1/N_{\text{event}} E dR/d^3p$ [GeV$^2$ fm$^{-1}$]
- $E$ [GeV]

**Legend**
- Blue circles
- Black squares

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Average photon energy vs. $\sqrt{s}$
Thermal photon rates

\[ R_i = N \int \frac{d^3p_1}{2E_1(3\pi)^3} \frac{d^3p_2}{2E_2(3\pi)^3} \frac{d^3p_3}{2E_3(3\pi)^3} \frac{d^3p}{2E(3\pi)^3} (2\pi)^4 \delta(p_1^\mu + p_2^\mu - p_3^\mu - p^\mu) |\mathcal{M}_i|^2 f_1(E_1) f_2(E_2) [1 \pm f_3(E_3)] \]

[KAP91], [TUR13]

\[ f_1(E_1) f_2(E_2) \rightarrow \exp \left( \frac{E_1 + E_2}{T} \right) \]

\[ E_1 + E_2 > E \gg T. \]

\[ \frac{d\sigma}{dt} = \frac{|\mathcal{M}_i|^2}{64|p_{cm}|^2 \pi s} \]

\[ E \frac{dR_i}{d^3p} = \frac{N}{(2\pi)^5} \frac{T}{E} e^{-E/T} \int ds \ln \left( 1 \pm e^{-E/sT} \right)^{\pm 1} |p_{cm}|^2 \sigma(s) \]
Suppression of: $\pi^\pm + \pi^\mp \rightarrow \gamma + \gamma$
Suppression of: $$\pi^\pm + \pi^\mp \rightarrow \gamma + \gamma$$
Temperature scaling

![Graph showing photon production in a hadronic transport approach for different temperatures (T = 160 MeV SMASH, T = 130 MeV SMASH, T = 100 MeV SMASH).](attachment:image.png)
Conclusion

- thermal direct photon production from a simple mesonic system has been implemented successfully in SMASH

Outlook

- add several other production channels
- calculate $p_T$-spectra for very low $p_T$
- merge with hybrid-hydro model
- calculate flow and other observables
- compare to experimental data
Thank you for your attention!
Sources

[BAU10]: Björn Bäuchle, *Direct Photons in Heavy-Ion Collisions*, PHD Thesis, Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany, September 2010


[WEIL16]: J. Weil et al., *Particle production and equilibrium properties within a new hadron transport approach for heavy-ion collisions*, arXiv:1606.06642 [nucl-th].
Photon Production in a Hadronic Transport Approach (Niklas Ehlert)
Photon yield vs energy (70 events, Box = (20 fm)$^3$)

- $T = 100$ MeV SMASH
- $T = 130$ MeV SMASH
- $T = 160$ MeV SMASH
- Kapusta param. $T = 100$ MeV
- Kapusta param. $T = 130$ MeV
- Kapusta param. $T = 160$ MeV

$1/N_{\text{event}} E \frac{dR}{d^3p} [\text{GeV}^{-2} \text{fm}^{-1}]$

$E [\text{GeV}]$

0 0.5 1 1.5 2 2.5 3 3.5
Photon rate vs energy (70 events, T = 130 MeV)

$1/N_{event} E\,dR/d^3p$ [GeV$^2$ fm$^{-4}$]

E [GeV]

Volume = (10 fm)$^3$
Volume = (20 fm)$^3$
Volume = (40 fm)$^3$
Photon yield vs $\sqrt{s}$ (70 events, 20 testparticles, Box = (40 fm)$^3$, $T = 160$ MeV, runtime: 100 fm)
Photor yield vs $\sqrt{s}$ (70 events, 10 testparticles, Box = (20 fm)$^3$, $T = 160$ MeV, runtime: 100 fm)