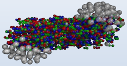

Direct Photons in Heavy-Ion Collisions from Microscopic Transport Theory and Fluid Dynamics

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The UrQMD-Group

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Sponsors

Deutsche Telekom Stiftung

H-QM Helmholtz Research School Quark Matter Studies

FIAS Frankfurt Institute for Advanced Studies

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Interactions with photons

Photons are the gauge bosons of electromagnetic interactions.

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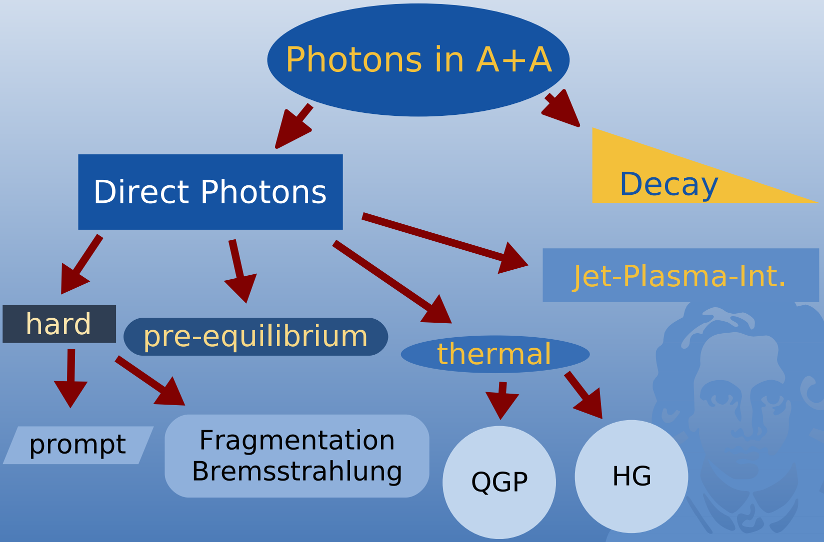
Disadvantage

Low production cross section

Photon Sources in A+A



Direct Photon Experiments in Heavy-Ion Physics

- Helios, WA 80, CERES (SPS) [1] — upper limits
- WA 93 (SPS) and STAR (RHIC) — no results (yet)
- WA 98[2] — first measurements at SPS
- PHENIX[3] (RHIC) — various results

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[1] Helios: Z. Phys. C **46**, 369 (1990); WA 80: Z. Phys. C **51**, 1 (1991); PRL **76**, 3506 (1996); CERES: Z. Phys. C **71**, 571 (1996)

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- Photons from hadronic decays make $\sim$ 97 % of all photons
- Uncertainties in hadron yield significantly change direct photon yield
- Also, photon sample is contaminated by neutral hadrons

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$p_\perp$ – time hierachy

Theoretical challenge:

Find out what stages contribute most / how much to photon yield!

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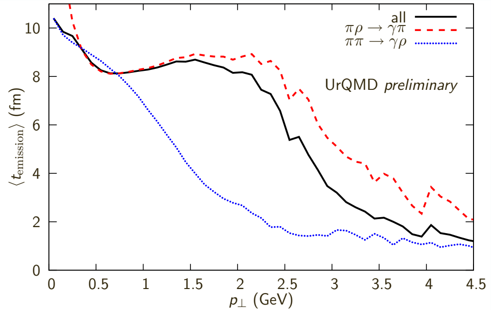
Simple picture: Hard photons are emitted early, soft photons late:
From Heisenberg principle: $\langle t_{\mathrm{emission}} \rangle \sim 1/p_\perp$.



True for $\pi\pi \to \gamma\rho$; **not true** for $\pi\rho \to \gamma\pi$, because ρ's are created at later stages

Existing models

- High $p_\perp$: yields calculated by NLO-pQCD[4]. Important at RHIC- and LHC-energies!

[4] E.g. Aurenche, Fontannaz *et. al*, PRD **73**, 094007 (2006)

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- Hydrodynamics: naturally implement phase transition (QGP $\leftrightarrow$ HG): e.g. Turbide, Liu , Vitev, Haglin[5]
- Transport: Study non-equilibrium effects and effects from dilute system: e.g. Dumitru, Huovinen, Li, Bratkovskaya[6]

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[6] Dumitru, Bleicher, Bass, Spieles, Neise, Stöcker and Greiner, PRC **57**, 3271 (1998); Huovinen, Belkacem, Ellis and Kapusta, PRC **66**, 014903 (2002); Li, Brown, Gale and Ko, arXiv:nucl-th/9712048; Bratkovskaya and Cassing, NPA **619**, 413 (1997); Bratkovskaya, Kiselev and Sharkov, arXiv:0806.3465 [nucl.th]

Unknown processes in transport models

- Branching ratios of many processes not known, e.g. $a_1 \longrightarrow \gamma\pi$. PDG says:

a_1(1260) DECAY MODES	Fraction (Γ_i/Γ)
$(\rho\pi)_{S-\text{wave}}$	seen
$(\rho\pi)_{D-\text{wave}}$	seen
$(\rho(1450)\pi)_{S-\text{wave}}$	seen
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$\sigma\pi$	seen
$f_0(980)\pi$	not seen
$f_0(1370)\pi$	seen
$f_2(1270)\pi$	seen
$K\bar{K}^*(892)+$ c.c.	seen
$\pi\gamma$	seen

- What do you make of it? HSD: Take data from Zielinski[a], which shows odd behaviour;
  this work: take calculations from Xiong[b]. Difference $\sim$ factor 2.5
  — may make a big difference!

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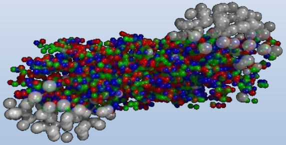
- Which channels are implemented? Bremsstrahlung? Hadronic decays?

- Hadronic decays are **not** in data! But: Do we believe that?

[a] Zielinski *et al.*, PRL **52**, 1195 (1984)

[b] Xiong, Shuryak and Brown, PRD **46**, 3798 (1992)

UrQMD



UrQMD

Ultra-**R**elativistic **Q**uantum **M**olecular **D**ynamics

- Non-equilibrium transport model
- Hadrons and resonances up to $m = 2.2$ GeV
- String excitation and fragmentation
- Cross sections are parametrized via AQM or calculated by detailed balance
- pQCD hard scattering at high energies
- Generates full space-time dynamics of hadrons and strings

UrQMD+Hydro

- Non-equilibrium initial conditions from UrQMD
- Switching to ideal relativistic one-fluid hydrodynamics when the nuclei have passed each other
- Hydro evolution with hadronic Equation of State that includes all particles from UrQMD; **no phase transition**
- Isochronous freeze-out when $\epsilon < 730\ \text{MeV/fm}^3$ ($\approx 5\epsilon_0$) in all cells
- Rescatterings and decays with hadronic cascade (UrQMD)
- See also **arXiv:0806.1695 [nucl-th]**

Photons from the model

Currently implemented channels in **Cascade**-part[7]:

$$\begin{aligned} \pi^{\pm} + \pi^{\mp} &\rightarrow \gamma + \rho^{0}, & \pi^{\pm} + \pi^{0} &\rightarrow \gamma + \rho^{\pm}, \\ \pi^{\pm} + \rho^{0} &\rightarrow \gamma + \pi^{\pm}, & \pi^{\pm} + \rho^{\mp} &\rightarrow \gamma + \pi^{0}, \\ \pi^{0} + \rho^{\pm} &\rightarrow \gamma + \pi^{\pm}, & \pi^{\pm} + \pi^{\mp} &\rightarrow \gamma + \eta, \\ \pi^{\pm} + \eta &\rightarrow \gamma + \pi^{\pm}, & \pi^{\pm} + \pi^{\mp} &\rightarrow \gamma + \gamma, \end{aligned}$$

$$\pi + \rho \rightarrow a_1 \rightarrow \gamma + \pi^{8}$$

Currently implemented rates in **Hydro**-part[9]

$$\begin{aligned} \pi + \pi &\rightarrow \gamma + \rho, & \pi + \rho &\rightarrow \gamma + \pi^{(10)}, \\ \pi + K^{*} &\rightarrow \gamma + K, & \pi + K &\rightarrow \gamma + K^{*}, \\ \rho + K &\rightarrow \gamma + K, & K + K^{*} &\rightarrow \gamma + \pi \end{aligned}$$

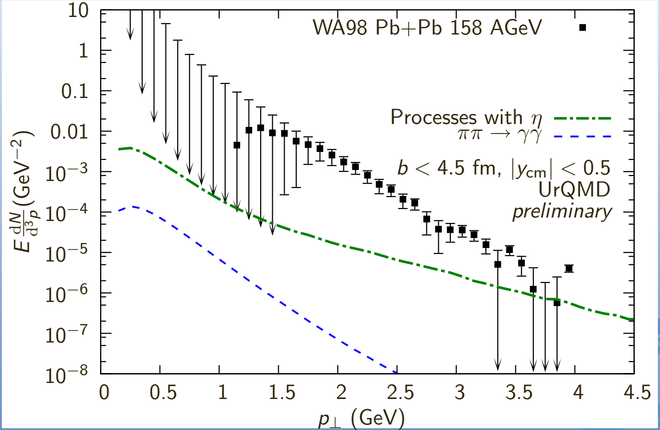
[7] Cross-sections taken from Kapusta, Lichard and Seibert, PRD **44** (1991) 2774

[8] This cross-section from Xiong, Shuryak and Brown, PRD **46**, 3798 (1992)

[9] Parametrizations taken from Turbide, Rapp and Gale, PRC **69**, 014903 (2004)

[10] Includes $\pi + \rho \rightarrow a_1 \rightarrow \gamma + \pi$

$p_\perp$-spectra from pure cascade



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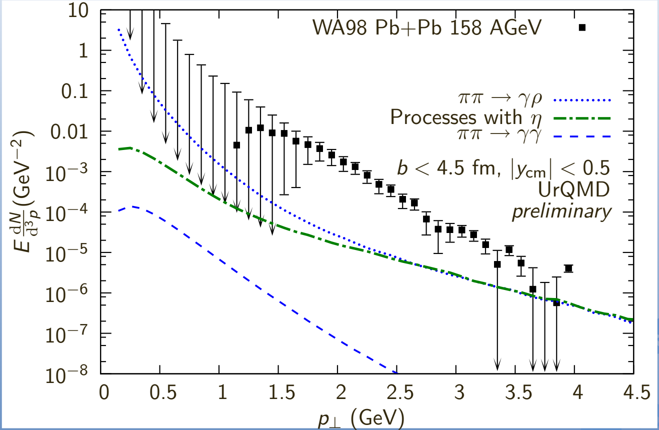

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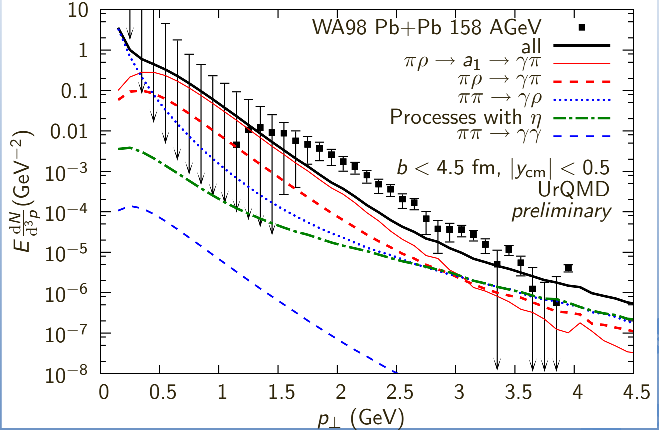
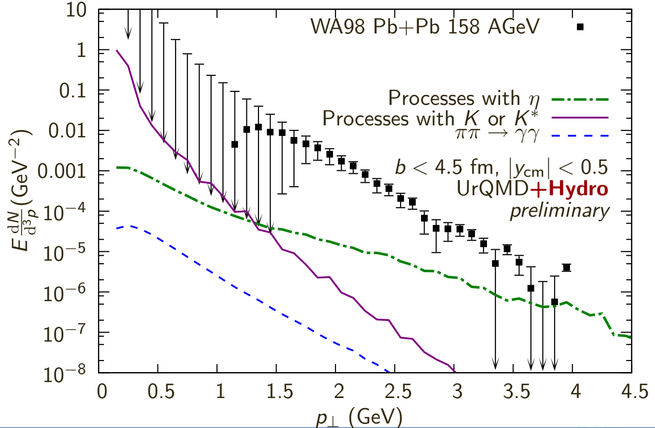


- Dominant contribution from $\pi + \rho \to \gamma + \pi$ (incl. a_1)
- Hard $\pi + \pi$-scatterings make power-law tail at high $p_\perp$

$p_\perp$-spectra from hybrid-model



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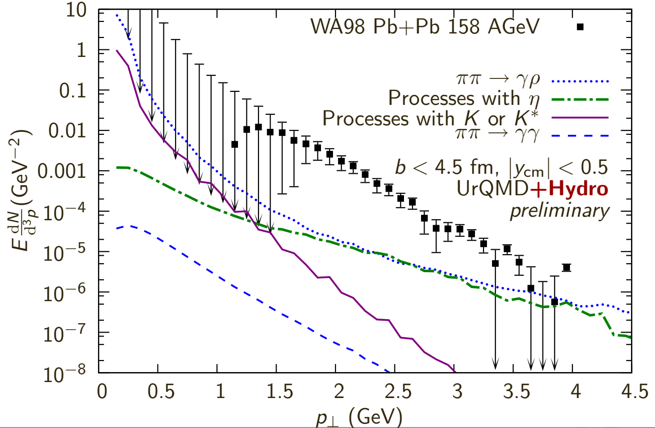

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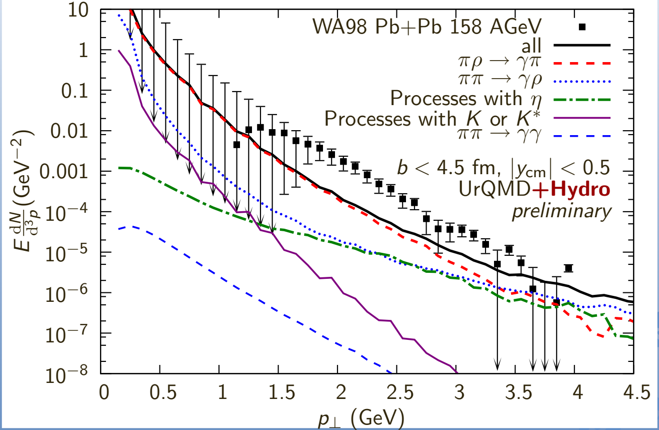
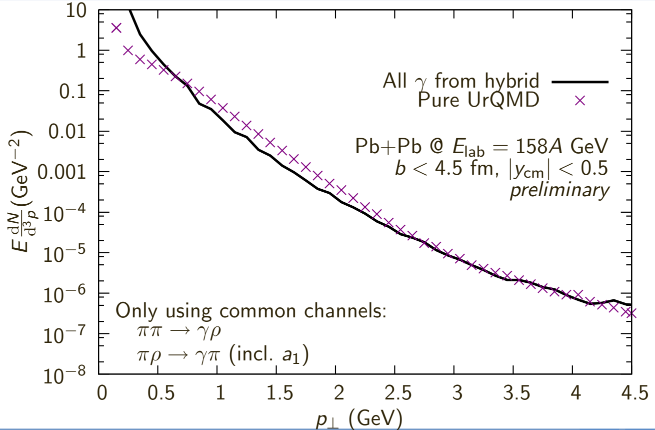


- Also, dominant contribution from $\pi + \rho \rightarrow \gamma + \pi$
- Very similar yield as in cascade mode!

Direct comparison of stages



- Hard photons only from before hydro-evolution $\Rightarrow$ we do not lose (many) non-equilibrium photons when switching to hydro!
- Similar yield in hybrid and cascade mode!

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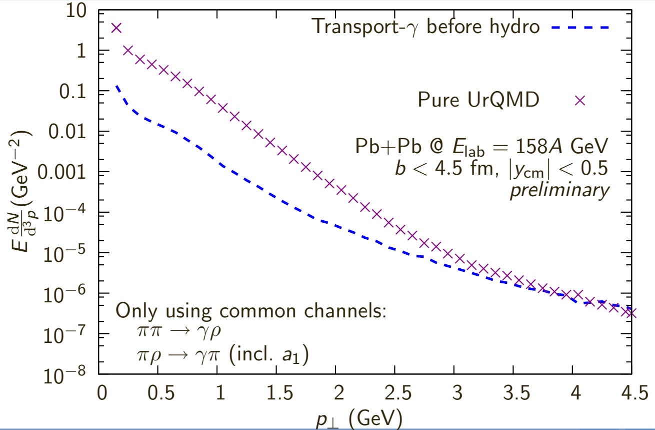

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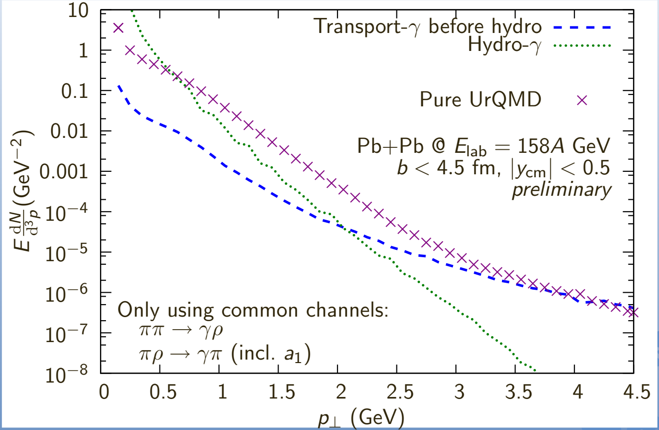

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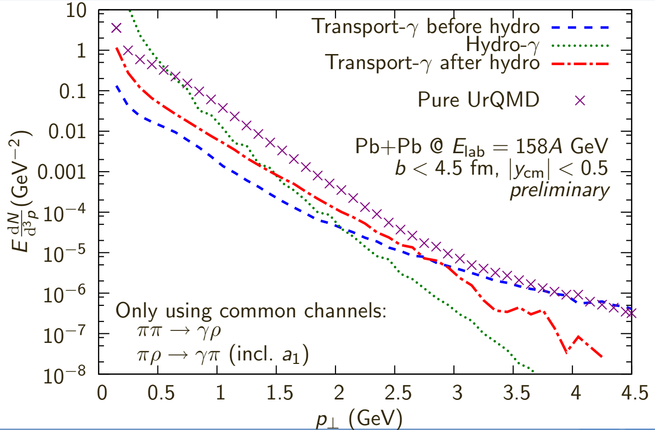

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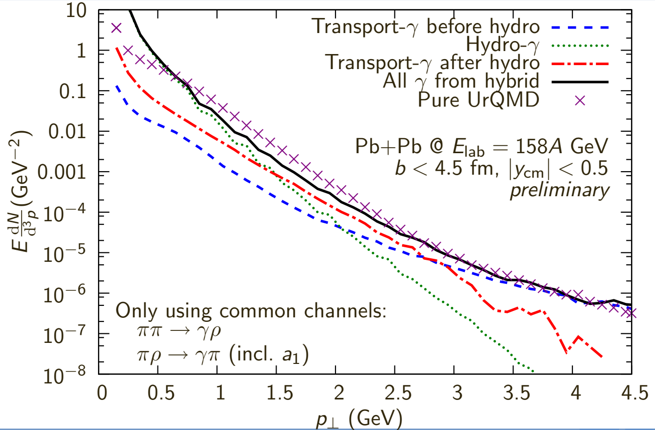

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- Similar yield in hybrid and cascade mode!

Summary

- Photons are an interesting probe and can provide unique insights to early stages.
- Some models on the market, details are controverse
- Hybrid and pure-transport model yield very similar results

Conclusions

- Photon emission independent of underlying dynamics
- (Initial-state-)non-equilibrium effects dominant from $p_\perp \sim 2$ GeV

Things to be done:

- More production channels in cascade and hydro will be implemented
- Different EoS will be compared
- Add photons from initial hard pQCD-Scatterings

Backup-Slides

Cross-Sections and Production Rates

Cascade: Photons are produced in binary collisions acc. to their cross-sections, e.g. for $\pi^{\pm}\rho^{0} \longrightarrow \gamma\pi^{\pm}$:[11]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\alpha g_\rho^2}{12 s p_{\mathrm{c.m.}}^2}\left[2 - s\frac{m_\rho^2 - 4m_\pi^2}{(s-m_\pi^2)^2} - (m_\rho^2 - 4m_\pi^2)\left(\frac{s - m_\rho^2 + m_\pi^2}{(s-m_\pi^2)(t-m_\pi^2)} + \frac{m_\pi^2}{(t-m_\pi^2)^2}\right)\right]$$

Hydro: Photons are produced at a given temperature acc. to thermal rates. E.g. for $\pi\rho \longrightarrow \gamma\pi$:[12,13]

$$E\frac{\mathrm{d}R}{\mathrm{d}^3p} = \left(\frac{\Lambda^2}{\Lambda^2 + Em_\pi}\right)^8 T^{2.8}\exp\left(\frac{-(1.461\,T^{2.3094} + 0.727)}{(2TE)^{0.86}} + (0.566\,T^{1.4094} - 0.9957)\frac{E}{T}\right) fm^{-4}\,GeV^{-2}$$

. . . and then boosted with the cell's velocity.

[11] See Kapusta, Lichard and Seibert, PRD **44** (1991) 2774

[12] See e.g. Turbide, Rapp and Gale, PRC **69**, 014903 (2004)

[13] All relevant variables given in GeV; $\Lambda = 1$ GeV.

Photons from the model

Cascade

- Emitted photons may be only a fraction of a photon
- Each collision and channel: 100 photons produced with different mandelstam t-values and appopiate weight $N = \frac{\mathrm{d}\sigma_\gamma}{\mathrm{d}t} \Delta t / \sigma_{\mathrm{tot}} \Rightarrow$ less events calculated, better statistics

Hydro

- Take care of proper Lorentz-Transformation (mind Cooper-Frye):
- Generate random $p_\mu u^\mu$ according to thermal rate, then **generate** $\vec{p}$ so that it yields desired $p_\mu u^\mu$.
- For all cells, every implemented rate: one photon-information (with weight $N = \int \frac{\mathrm{d}^3 p}{E} \Delta V \Delta t \, E \frac{\mathrm{d}R}{\mathrm{d}^3 p}$) is created.

Our Model in a nutshell

- Combination of hydrodynamics for high-density part and transport for initial- and final state
- Possibility to study impacts of
  different dynamics (hydro ⇔ transport) and
  different physics (QGP ⇔ hadron gas) by
  varying Equation of State in hydro
- No guesswork involved in initial conditions for hydro
- Possibility to clearly distinguish different channels
- Time-resolution of photon emission