H-QM Helmholtz Research School Quark Matter Studies

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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

Bjørn Bäuchle, Marcus Bleicher

The UrQMD-Group

Institut für Theoretische Physik, Goethe-Universität, Frankfurt am Main

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Collaborators

The UrQMD-Group

Marcus Bleicher, Horst Stöcker, Gerhard Burau,
Stephane Häussler, Qingfeng Li, Michael Mitrovski, Elvira Santini,
Bjørn Bäuchle, Hannah Petersen, Jan Steinheimer, Sascha Vogel,
Gunnar Gräf, Katharina Schmidt, Timo Spielmann

For the hydro code

Dirk Rischke

Sponsors

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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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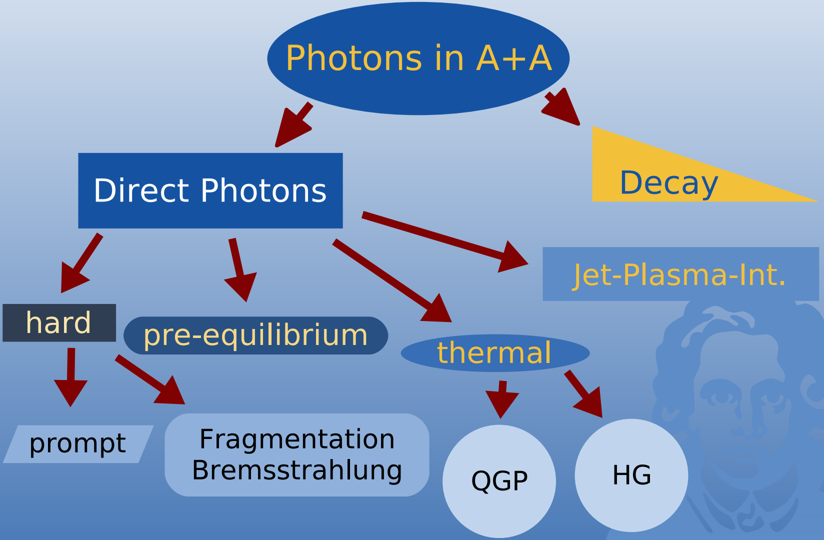
Disadvantage

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

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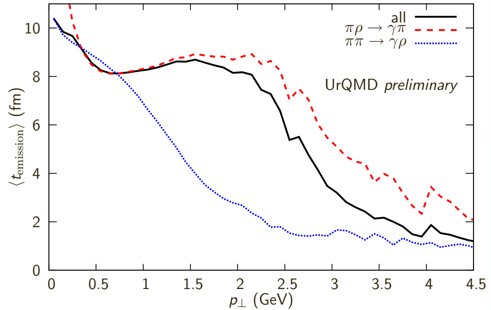
Simple picture: Hard photons are emitted early, soft photons late:
From Heisenberg principle: $\langle t_{\mathrm{emission}} \rangle \sim 1/p_\perp$.



True for $\pi\pi \longrightarrow \gamma\rho$; **not true** for $\pi\rho \longrightarrow \gamma\pi$, 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
$(\rho(1450)\pi)_{D-\text{wave}}$	seen
$\sigma\pi$	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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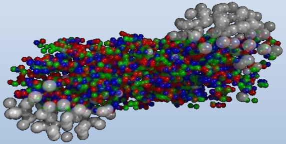
- Which channels are implemented? Bremsstrahlung? Hadronic decays?

- 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 $\epsilon < 730 \;\; \mathrm{MeV/fm}^3$ ($\approx 5\epsilon_0$) 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]:

$$
\begin{array}{llllll}
\pi^\pm + \pi^\mp \to \gamma + \rho^0, & \qquad \pi^\pm + \pi^0 \to \gamma + \rho^\pm, \\
\pi^\pm + \rho^0 \to \gamma + \pi^\pm, & \qquad \pi^\pm + \rho^\mp \to \gamma + \pi^0, \\
\pi^0 + \rho^\pm \to \gamma + \pi^\pm, & \qquad \pi^\pm + \pi^\mp \to \gamma + \eta, \\
\pi^\pm + \eta \to \gamma + \pi^\pm, & \qquad \pi^\pm + \pi^\mp \to \gamma + \gamma,
\end{array}
$$

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

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

$$
\begin{array}{ll}
\pi + \pi \to \gamma + \rho, & \qquad \pi + \rho \to \gamma + \pi^{(10)}, \\
\pi + K^* \to \gamma + K, & \qquad \pi + K \to \gamma + K^*, \\
\rho + K \to \gamma + K, & \qquad K + K^* \to \gamma + \pi
\end{array}
$$

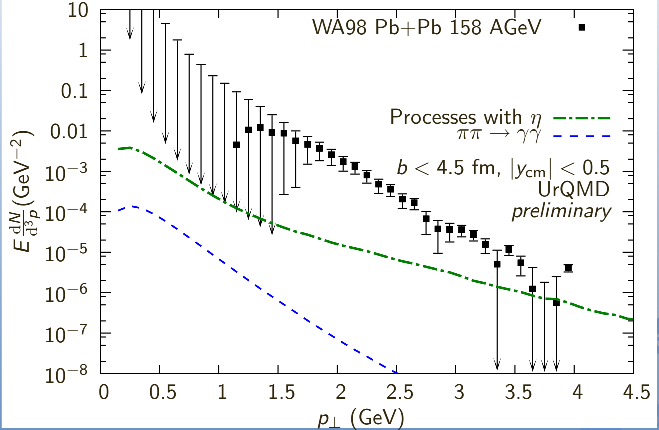
[7] Cross-sections taken from Kapusta, Lichard and Seibert, PRD **44** (1991) 2774

[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 $\pi + \rho \to a_1 \to \gamma + \pi$

$p_\perp$-spectra from pure cascade



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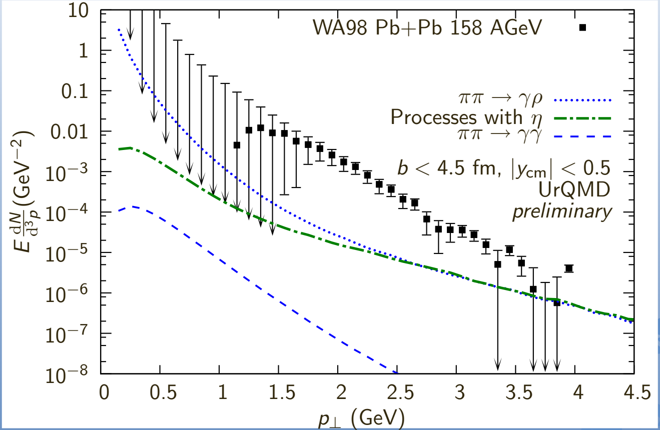

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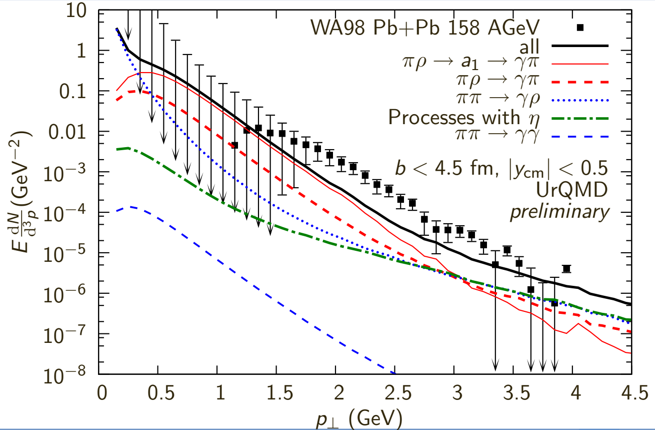
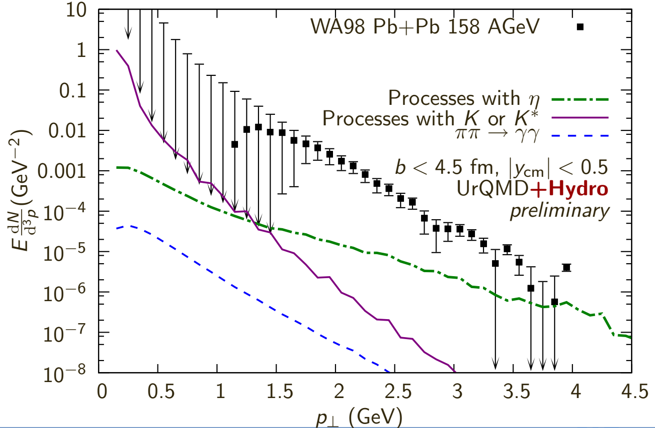


- Dominant contribution from $\pi + \rho \to \gamma + \pi$ (incl. a_1)
- Hard $\pi + \pi$-scatterings make power-law tail at high $p_\perp$

$p_\perp$-spectra from hybrid-model



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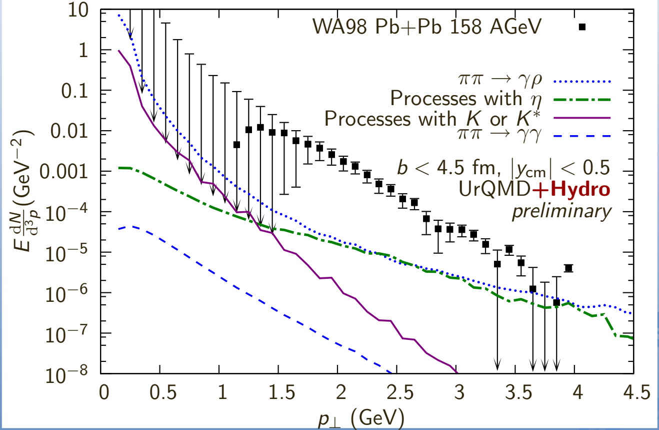
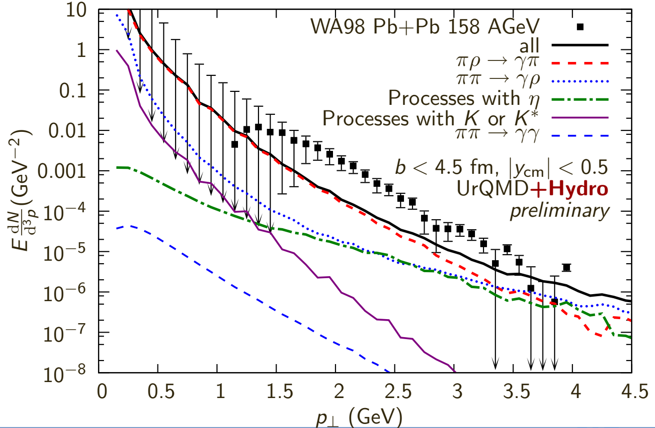
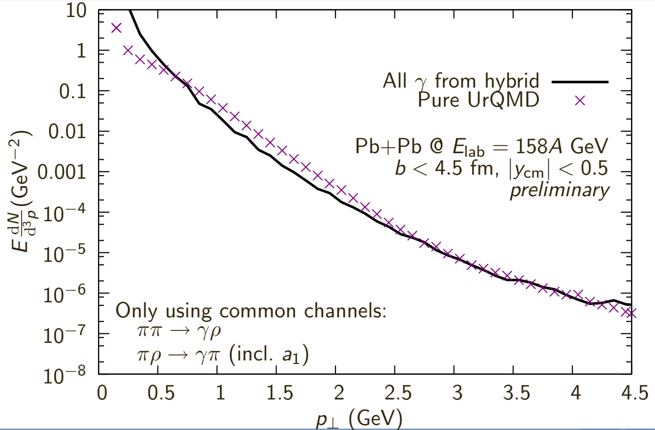


$p_\perp$-spectra from hybrid-model



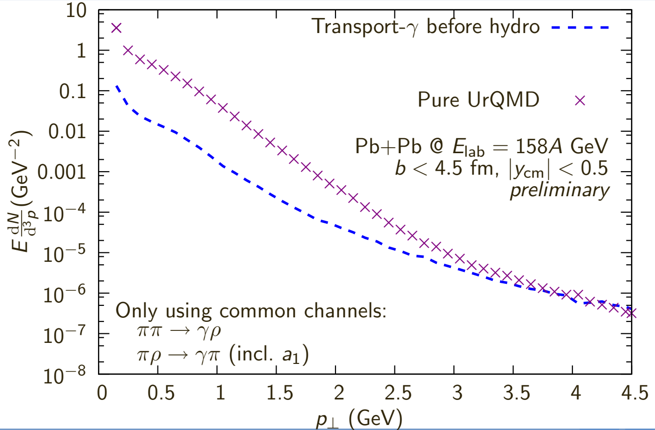
- Also, dominant contribution from $\pi + \rho \to \gamma + \pi$
- Very similar yield as in cascade mode!

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!

Direct comparison of stages



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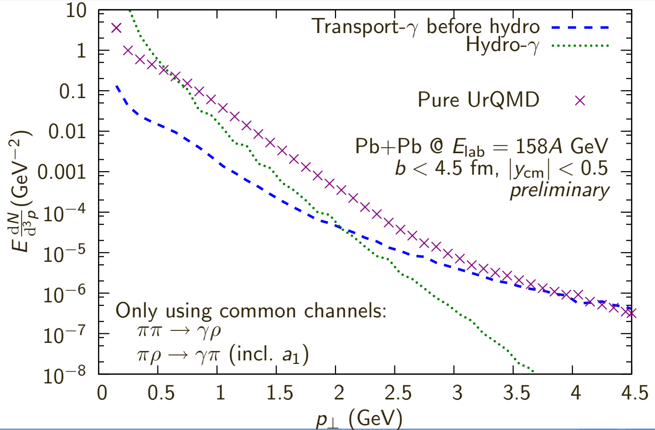

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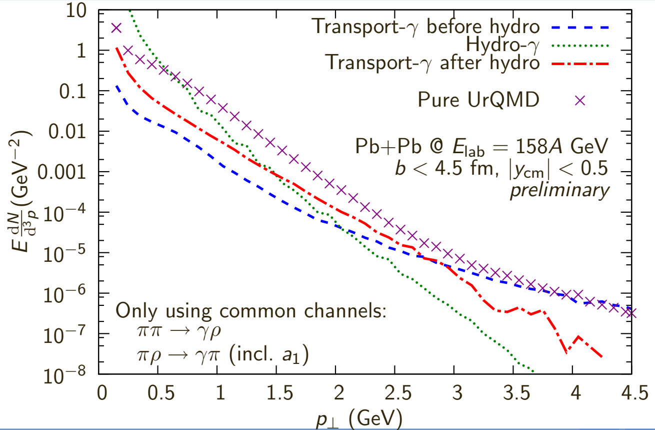

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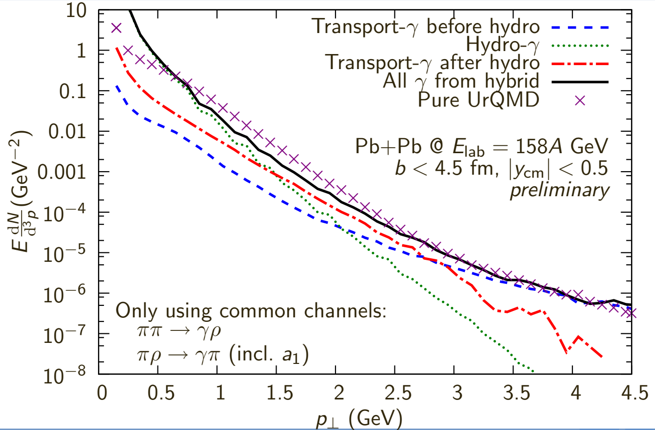

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- Similar yield in hybrid and cascade mode!

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 $\Leftrightarrow$ transport) and
  different physics (QGP $\Leftrightarrow$ 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