Direct Photon Production from Heavy Ion Collisions

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The UrQMD Group (http://urqmd.org)
based on PRC 81 (2010) 044904
and ongoing work

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Sponsors
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HIC for FAIR
Helmholtz International Center
H-QM
Helmholtz Research School Quark Matter Studies
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research
Introduction

Model

Photon Spectra at SPS

Results for FAIR

Results for RHIC

Summary & Outlook
Why Heavy Ion Collisions?

History of the Universe

Hot nuclear matter present until $\approx 1 \, \mu$s after Big Bang

Direct observation of Big Bang only until $\approx 300\,\text{ka}$ after BB
Why Heavy Ion Collisions?

History of the Universe

Hot nuclear matter present until $\approx 1 \mu s$ after Big Bang

Direct observation of Big Bang only until $\approx 300 ka$ after BB

No Problem:
Recreate parts of Big Bang in the lab!
Why Heavy Ion Collisions?

- Collective behaviour of QCD-Matter
- Explore Phase Diagram
Why Heavy Ion Collisions?

- Collective behaviour of QCD-Matter
- Explore Phase Diagram:
  - Critical Point
  - Deconfinement
  - Chiral Restauration
- Get there by smashing nuclei!
Why direct photons?

- Interesting scattering in fireball
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- Hadronic decay products...
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- ...rescatter. Information lost.
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- Photons do not rescatter → keep information!
Why direct photons?

- Interesting scattering in fireball
- Hadronic decay products...
- ...rescatter. Information lost.
- Photons do not rescatter \(\rightarrow\) keep information!
- Plenty uninteresting photon sources
Photon Sources in A+A

- Direct Photons
  - hard
  - pre-equilibrium
  - prompt

- Photons in A+A
  - Decay
  - Jet-Plasma-Int.

- Fragmentation Bremsstrahlung
- QGP
- HG
Direct Photon Experiments

- 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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\(^2\) PRL 85, 3595 (2000)

\(^3\) e.g. PRL 94, 232301 (2005)
Direct Photon Experiments

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- Photons from hadronic decays make \(\sim 97\%\) of all photons
- Uncertainties in hadron yield significantly change direct photon yield
- EM-Calorimeters expensive, coverage therefore usually small


\(^2\) PRL 85, 3595 (2000)

\(^3\) e.g. PRL 94, 232301 (2005)
Theory: Underlying Models

**pQCD** Good for high $p_\perp$, good for $pp$. In $AA$, nuclear effects can be parametrized\(^4\). Important at RHIC- and LHC-energies, what about SPS?

**Hydro** Good for thermalized systems, phase transitions. Input: Parametrized Rates $E \frac{dN}{d^3p d4x} (p, T, \mu)$ Application: numerical challenge\(^5\)!

**Transport** Good for not-too-dense systems. Input: Cross-sections $\frac{d\sigma}{dt} (s, t, \rho)$ Application: straight-forward\(^6\)

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\(^4\) E.g. Aureanche, Fontannaz *et. al*, PRD 73, 094007 (2006)


Theory: Unknown processes

- Branching ratios of many processes not known, e.g. $a_1 \rightarrow \gamma \pi$. PDG says "seen".

What of it? Data from Zielinski\(^7\) show odd behaviour; this work: take calculations from Xiong\(^8\). Difference $\sim$ factor 2.5 — may make a big difference!

\(^7\)Zielinski et al., PRL 52, 1195 (1984)
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- Which channels are implemented? Bremsstrahlung? Hadronic decays?

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- Which channels are implemented? Bremsstrahlung? Hadronic decays?
- Hadronic decays are not in data! But: Do we believe that?

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UrQMD

Ultra-Relativistic Quantum Molecular Dynamics

- Classical propagation of hadrons
- QM scattering cross-sections
- Cross-sections fitted to data or calculated via detailed balance or parametrized via additive quark model
- All hadrons from PDG up to \( m = 2.2 \) GeV
- Full microscopic collision history available
- Version 3.3 out now! Go to http://urqmd.org/
UrQMD+Hydro (new in u3.3)

- High-density part of evolution optionally substituted by ideal hydrodynamics
- Macroscopic description
- Microscopic initial state from transport (UrQMD) mapped to densities and flow velocities
- Hydro propagation with variable Equation of State
- Back to transport when $\epsilon < 5\epsilon_0$ in all cells...
  - ...separately for all $z$ (gradual)
  - ...in complete system (isochronous)
- Rescatterings and decays with UrQMD
- See also Petersen et al. Phys. Rev. C 78 (2008) 044901
Equations of State

**Hadron Gas**
- Includes all particles from UrQMD
- no phase transition

**Bag Model**
- MIT Bag Model
- First Order Phase Transition at $T_C = 170$ MeV

**Chiral Model**
- Chirally restored phase
- First Order PT, Cross-over and CEP
### Photons from the model

#### Both models

\[ \pi + \pi \rightarrow \gamma + \rho, \quad \pi + \rho \rightarrow \gamma + \pi \]

#### Only Cascade


\[ \pi + \pi \rightarrow \gamma + \eta, \quad \pi + \eta \rightarrow \gamma + \pi, \quad \pi + \pi \rightarrow \gamma + \gamma \]

Cross-sections known, applied to every scattering

#### Only Hydro


\[ \pi + K^* \rightarrow \gamma + K, \quad \pi + K \rightarrow \gamma + K^*, \]
\[ \rho + K \rightarrow \gamma + K, \quad K + K^* \rightarrow \gamma + \pi \]

Thermal rates known, applied to every cell
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 appropriate weight

\[ N = \frac{d\sigma_{\gamma}}{dt} \Delta t / \sigma_{\text{tot}} \Rightarrow \text{less events calculated, better statistics} \]

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 \( N = \int \frac{d^3p}{E} \Delta V \Delta t \ E \frac{dR}{d^3p} \)) is created.
Check: Rates from Transport

\[
\frac{1}{2\pi} \frac{dR}{d\tau} \left[ \text{GeV}^{-2} \text{fm}^{-4} \right]
\]

- **Box-calculations (UrQMD)**: \( \bullet \)
- **Hydro-rates (Turbide et al.)**: \(-\)

\[\pi\pi \rightarrow \gamma\rho\]
\[\pi\rho \rightarrow \gamma\pi\]

\( T = 150 \text{ MeV} \)

Box: \( V = (20 \text{ fm})^3 \), \( \pi/\rho/a_1\)-gas

\( E \) [GeV]
Stages: HG-EoS

- Hard photons only from before hydro-evolution
- Similar yield in hybrid and cascade mode!
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- Hard photons only from before hydro-evolution
- Similar yield in hybrid and cascade mode!

\[ \text{Pb+Pb @ } E_{\text{lab}} = 158A \text{ GeV} \]
\[ b < 4.5 \text{ fm, } |y_{\text{cm}}| < 0.5 \] (preliminary)

Only using common channels:
\[ \pi\pi \rightarrow \gamma\rho \]
\[ \pi\rho \rightarrow \gamma\pi \text{ (incl. } a_1) \]

\( p_\perp \) (GeV)
Stages: HG-EoS

Hard photons only from before hydro-evolution

Similar yield in hybrid and cascade mode!
Stages: HG-EoS

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Stages: HG-EoS

- Hard photons only from before hydro-evolution
- Similar yield in hybrid and cascade mode!
Stages: Cascade

- Complete cascade
- Initial stage
- Intermediate stage
- Final stage

UrQMD

\[ \text{Pb+Pb 158 AGeV} \]
\[ b < 4.5 \text{ fm}, |y_{c.m.}| < 0.5 \]

Split by time
Stages: BM-EoS

Hybrid, Bagmodel EoS
Pb+Pb 158 AGeV

$b < 4.5 \text{ fm, } |y_{c.m.}| < 0.5$

$E \frac{dN}{d^3p}$ vs. $p_{\perp}$ [GeV$^{-2}$]

Complete hybrid
Initial stage
Intermediate stage
Final stage

Hydro enhanced!
Different EoS vs. data

All models undershoot data, but **no pQCD here!**
Diff. EoS, pQCD vs. data

Very good agreement for all three models
Photon Sources: Cascade

\[ E \frac{dN}{d^3p} (\text{GeV}^{-2}) \]

\[ p_\perp (\text{GeV}) \]

\[ b < 4.5 \text{ fm}, |y_{cm}| < 0.5 \]

\[ \eta \rightarrow \pi \pi \rightarrow \gamma \gamma \]

\[ \text{UrQMD preliminary} \]
Photon Sources: Cascade

\[ E \frac{dN}{d^3p} \text{(GeV}^{-2}) \]

\[ p_\perp \text{(GeV)} \]

\[ \text{WA98 Pb+Pb 158 AGeV} \]

\[ \pi\pi \rightarrow \gamma\rho \]

\[ \text{Processes with } \eta \]

\[ \pi\pi \rightarrow \gamma\gamma \]

\[ b < 4.5 \text{ fm, } |y_{cm}| < 0.5 \]

\[ \text{UrQMD preliminary} \]
Photon Sources: Cascade

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

Processes with $\eta$
Processes with $K$ or $K^*$

$\pi\pi \rightarrow \gamma\gamma$

$b < 4.5$ fm, $|y_{cm}| < 0.5$

UrQMD $+$ Hydro

Preliminary
Photon Sources: Hybrid

![Graph showing photon spectra and processes]

- Processes with $\pi \pi \rightarrow \gamma \rho$
- Processes with $\eta$
- Processes with $K$ or $K^*$
- $\pi \pi \rightarrow \gamma \gamma$

$b < 4.5 \text{ fm, } |y_{cm}| < 0.5$

UrQMD + Hydro
preliminary
Photon Sources: Hybrid

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

- High energies: UrQMD excites strings
- String ends (Quarks or Diquarks) have lower $\times$-sect
- What if they are excluded from $\gamma$-production?

![Graph comparing photon spectra at SPS]

- **UrQMD w/o string ends**
- **UrQMD with string ends**
- **pQCD-photons (Gale)**
- **pQCD-photons (Turbide et al.)**

**Legend:**
- **Pb+Pb 158 AGeV**
- $b < 4.5$ fm, $|y_{c.m.}| < 0.5$
\( \rho \) on mass peak

- Scattering with incoming \( \rho \):
  \[ m_\rho^2 = p^\mu p_\mu \]
  from UrQMD

- Scattering
  \[ \rightarrow \gamma \rho : m_\rho = 770 \text{ MeV?} \]

- Maybe \( m_\rho \) distributed acc. to
  Breit-Wigner

\[ \pi^\pm \pi^\mp \rightarrow \gamma \rho^0 \times 10 \]

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

\[ \pi^\pm \pi^\mp \rightarrow \gamma \rho^0 \]
Flattening at high $p_\perp$

Flattening at high $p_\perp$ corresponds to earlier emission times
Flattening at high $p_{\perp}$ corresponds to earlier emission times
A closer look at high $p_\perp$-photons

\[ \frac{dN}{d\sqrt{s}} (\text{GeV}^{-1}) \]

\[ \frac{E}{dN_{d\sqrt{s}} (\text{GeV}^{-2})} \]

\[ E_{dN_p (\text{GeV}^4)} \]

\[ p_\perp \]

\[ \sqrt{s_{\text{coll}}} \]

\[ \gamma \]
A closer look at high $p_\perp$-photons

- Most photons at high $p_\perp$ come from high-$\sqrt{s}$-collisions
- Hadronic treatment questionable
Emission times

- Initial flash
- bulk emission later
- very long tail at intermediate $p_{\perp}$

\[ \langle t_{\text{emission}} \rangle \text{[fm]} \]

\[ p_{\perp} \text{[GeV]} \]

\[ b < 4.5 \text{ fm} \]

\[ |y_{c.m.}| < 0.5 \]

\[ \text{Pb+Pb @ 158 AGeV} \]

\[ \pi \rho \rightarrow \gamma \pi \]

\[ \pi \pi \rightarrow \gamma \rho \]

\[ \pi \pi \rightarrow \gamma \gamma \]

\[ \text{Processes with } \eta \text{ and } \pi \pi \rightarrow \gamma \gamma \]

\[ \langle t_1 \rangle, \langle t_2 \rangle, \langle t_3 \rangle \]

\[ dN \text{[10}^{-3} \text{ fm}^{-1}] \]

\[ t \text{[fm]} \]

\[ p_{\perp} = 1 - 1.5 \text{ GeV} \]

\[ p_{\perp} = 2 - 2.5 \text{ GeV} \]

\[ p_{\perp} = 3 - 3.5 \text{ GeV} \]

Only $\pi \rho \rightarrow \gamma \pi$
Future: FAIR

Same picture at FAIR:

*Hadronic models* similar, *Bag Model* enhanced.

*Chiral EoS* shows higher Temperature
Contributions @ FAIR

No surprises from channel-differential investigation
Comparison PHENIX @ RHIC vs. UrQMD

PHENIX-Data

UrQMD-calculations

Min. Bias \times 10^3

0-10\% \times 10^0

10-20\% \times 10^{-2}

20-30\% \times 10^{-4}

30-40\% \times 10^{-6}

40-50\% \times 10^{-8}

50-60\% \times 10^{-10}

60-92\% \times 10^{-12}
**PHENIX w/ HG-EoS**

![Graph showing photon spectra at SPS and RHIC results for PHENIX with HG-EoS.](image)

**Legend:**
- Pure UrQMD calculations
- Hybrid calculations
- \(\langle N_{\text{coll}} \rangle\)-scaled NLO pQCD
- Min. Bias \(\times 10^4\)
- 0-10%
Summary

► UrQMD and UrQMD+Hydro ideal for investigating photons
► Fit data at SPS, pQCD needed
► pQCD negligible at FAIR
► Hadronic Sources not sufficient at RHIC
► Hydro stage with QGP: largely enhanced emission
► $\pi\rho$ dominant (hadronic) contribution at intermediate $p_\perp$
► Exponential slope from non-thermalized system possible!
► High-$p_\perp$ from high-$\sqrt{s}$

Outlook

► Bag Model, Chiral EoS for RHIC
► Investigate Parameter $t_{\text{hydrostart}}, \varepsilon_{\text{crit}}$
► Investigate transition scenario (gradual vs. isochronous)
► Different systems: $\text{Au}+\text{Au}, \text{Cu}+\text{Cu}$ @
  $\sqrt{s_{\text{NN}}} = 130, 62.4, (200) \text{ GeV}$, $\text{U}+\text{U}$ @ $E_{\text{lab}} = 11, 30 \text{ GeV}$
Backup-Slides
Photon emission $\times$-sections

- $\pi^\pm \pi^\mp \rightarrow \gamma \rho^0$
- $\pi^\pm \pi^0 \rightarrow \gamma \rho^\pm$
- $\pi^\pm \pi^\mp \rightarrow \gamma \eta$
- $\pi^\pm \eta \rightarrow \gamma \pi^\pm$
- $\pi^\pm \pi^\mp \rightarrow \gamma \gamma$

$\sigma$ [mb] vs $\sqrt{s}$ [GeV]

$m_\rho$ Breit-Wigner

$m_\rho$ fixed

$\sqrt{s}$ [GeV]
Photon emission rates

\[ E \frac{d^3\Gamma}{d^3p} \text{ [GeV}^{-2} \text{fm}^{-4}] \]

- \( T = 170 \text{ MeV} \)
- \( \pi\pi \to \gamma\rho \times 1000 \)
- \( \pi\rho \to \gamma\pi \times 1000 \)
- \( \pi K \to \gamma K^* \)
- \( \pi K^* \to \gamma K \)
- \( \rho K \to \gamma K \times 10^{-6} \)
- \( K^* K \to \gamma \pi \times 10^{-6} \)
Previous Work with UrQMD

- Dumitru et al. (UrQMD v1.0)
- UrQMD v1.3, this work
- UrQMD v2.3, this work

The graph shows the dependence of $E dN/d^3p$ on $p_\perp$ for different versions of UrQMD. The data points are shown for $p_\perp$ ranging from 1 to 3 GeV. The lines represent the simulations and the markers represent the experimental data.
Initial Temperature Profile

![Graph showing initial temperature profile with contour lines and labels for BM-EoS and HG-EoS.](image)

- BM-EoS
- HG-EoS

Temperature values: 50, 100, 150, 200, 250

Axes:
- x [fm]
- y [fm]

Bjørn Bäuchle, FIAS
Direct Photon Production from Heavy Ion Collisions
Bergen, 28/04-10
Total cross-section in UrQMD

\[ \sigma(\pi^+\pi^- \rightarrow \text{resonance}) \]
\[ \sigma(\pi^+\pi^- \rightarrow \text{strings}) \]
\[ \sigma(\pi^+\pi^- \rightarrow \text{hard scattering}) \]
Inclusion of PYTHIA

\[ E \frac{dN}{d^3p} \] [GeV^{-2}]

with PYTHIA

without PYTHIA

UrQMD \( p + p \) 158 GeV

all charged particles
Why not PYTHIA for pQCD
Total cross-section

\[ \sigma(\pi^+\pi^- \rightarrow \text{resonance}) \]
\[ \sigma(\pi^+\pi^- \rightarrow \text{strings}) \]
\[ \sigma(\pi^+\pi^- \rightarrow \text{hard scattering}) \]
Total cross-section

\[
\sigma(\pi^+\pi^- \rightarrow \text{resonance})
\]
\[
\sigma(\pi^+\pi^- \rightarrow \text{strings})
\]
\[
\sigma(\pi^+\pi^- \rightarrow \text{hard scattering})
\]