Thermal photon measurements with the future MPD experiment at NICA

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Outline

- Heavy ion collisions at NICA
- Motivation for thermal photons study in heavy-ion collisions
- Photon conversion method
- Feasibility studies for thermal photons measurement in the MPD
- Conclusions and outlook
Heavy ion collisions at NICA

- A mega-science project NICA, Dubna, JINR
- Modernization of existing Nuclotron facility
- Parameters:
  - relativistic ions up to Au, $\sqrt{s_{NN}} = 4$-11 GeV
  - polarized p and d, $\sqrt{s_{NN}} = 27$ GeV (for p)
  - luminosity $10^{27}$ cm$^{-2}$s$^{-1}$
- Working experiment: BM@N (fixed target)
- Experiments under construction: MPD, SPD (collider)
- Study of the phase diagram in the region of high baryonic density and intermediate temperatures
- Extension of modern heavy-ion programs at RHIC and the LHC to lower energies
Thermal radiation in heavy ion collisions

- Photons leave the medium without interaction
- Black body radiation: inverse slope proportional to $T_{\text{eff}}$

Thermal photons from QGP
- Annihilation
- Compton Scattering

Thermal photons from hadron gas

Naïve: Hot medium Large yield

Warm medium Moderate yield
Photon spectra at RHIC and LHC

**PHENIX (AuAu @ 200 GeV)**

\[ T_{\text{eff}} = 239 \pm 25 \text{ (stat)} \pm 7 \text{ (syst)} \text{ MeV} \]


**ALICE (PbPb @ 2760 GeV)**

\[ T_{\text{eff}} = 297 \pm 12 \text{ (stat)} \pm 41 \text{ (syst)} \text{ MeV} \]

Effective temperature vs energy

\[ T_{\text{eff}} \text{ vs. collision energy} \]

- **PHENIX** $\sqrt{s_{\text{NN}}} = 200 \text{ GeV, 0-94%}
  
  Fit range $p_T \in [1.0 \text{ GeV}, 5.0 \text{ GeV}]
  
  Cu+Cu \ T_{\text{eff}} = 288 \pm 49 \pm 50 \text{ MeV/c}

- **ALICE** $\sqrt{s_{\text{NN}}} = 2760 \text{ GeV, 0-20%}
  
  Fit range $p_T \in [0.9 \text{ GeV}, 2.1 \text{ GeV}]
  
  Pb+Pb \ T_{\text{eff}} = 297 \pm 12 \pm 41 \text{ MeV/c}


- **PHENIX** $\sqrt{s_{\text{NN}}} = 62.4 \text{ GeV, 0-86%}
  
  Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  
  Au+Au \ T_{\text{eff}} = 211 \pm 24 \pm 44 \text{ MeV/c}


- **PHENIX** $\sqrt{s_{\text{NN}}} = 39 \text{ GeV, 0-86%}
  
  Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  
  Au+Au \ T_{\text{eff}} = 177 \pm 31 \pm 68 \text{ MeV/c}

**PHENIX preliminary**


2760 GeV Pb+Pb: $\gamma_{\text{prompt}}$ subtracted

200 GeV Au+Au: $\gamma_{\text{prompt}}$ subtracted

200 GeV Cu+Cu: $\gamma_{\text{prompt}}$ subtracted

62.4 GeV Au+Au: $\gamma_{\text{prompt}}$ unsubtracted

39 GeV Au+Au: $\gamma_{\text{prompt}}$ unsubtracted
Challenge: decay photons

Inclusive photon spectra are dominated by decay photons

\[ R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \]

Relative contributions of different hadrons to the total decay photon spectrum as a function of the decay photon transverse momentum.

Photon reconstruction: two methods

- Electromagnetic calorimeters
  - Efficient at $p_T > 2$ GeV/c
  - Hardware trigger capabilities

- Photon conversion $\gamma \rightarrow e^+e^-$ in the material
  - $P = 1 - \exp(-7/9 \times X_0)$
  - Efficient at $0.5 < p_T < 4$ GeV/c
  - Much better resolution at low $p_T$
MPD experiment at NICA

- CMS Energy: 4-11 GeV
- Design luminosity: $10^{27} \text{ cm}^{-1} \text{ s}^{-1}$
- Stage 1: TPC, TOF, ECAL, FHCal, FFD
- Stage 2: + ITS + EndCap
Photon conversion centers

Main conversion structures in Stage 1:
• Beam pipe: 0.3% $X_0$
• Inner TPC barrel structures: 2.4% $X_0$

Future:
• Inner tracking system
• Dedicated photon converter (cylindrical metal pipe) under investigation
Conversion reconstruction efficiency

- Studied with MPDROOT Stage 1 setup
- Using MpdParticle to build secondary vertices
- Cuts optimized to maximize signal significance
- Contribution of (non-gamma) background < 10-20%
  - can be further improved with tighter cuts

**Typical cuts on electrons:**
- $|\eta|<1$
- $p_T > 50$ MeV/c
- at least 20 hits in TPC
- +/-4σ electron PID in TPC/TOF

**Typical cuts on ee pair:**
- Small DCA ($\chi^2 < 10$)
- Vertex R > 10 cm
- Direction to vertex:
  - $\theta < \exp(-2.777-2.798\times p_T) + 0.0175$
  - $m_{ee} < 22.6 + 17.4\times p_T$
  - ee plane orientation wrt B: $\Psi_{Pair} < 0.1$ rad
UrQMD and PHSD predictions at NICA energies

- UrQMD and PHSD generators: good agreement in neutral meson cross sections
Neutral meson reconstruction

- Using 20M minimum bias URQMD events
- Pion signal is clearly visible in a wide $p_T$ range
- Statistics not enough to study eta reconstruction
Neutral meson reconstruction efficiency

- Embedding technique used to study reconstruction efficiency vs $p_T$
- 700 000 min. bias UrQMD events @ 11 GeV
- 500 $\pi^0 + 500 \eta$ embedded with flat $p_T$ distribution
- Neutral meson reconstruction efficiency $\sim 10^{-4}$
- $\pi^0$ peak is significantly narrower with conversion method compared to ECAL

\[\pi^0 \rightarrow \gamma \gamma \rightarrow (e^+e^-)(e^+e^-)\]

\[\eta \rightarrow \gamma \gamma \rightarrow (e^+e^-)(e^+e^-)\]
Corrected $\pi^0$ spectra

Efficiency-corrected spectra are extrapolated down to 0 $p_T$:
- Tsallis function
- Two-component model (Bylinkin, Rostovtsev)
- Hagedorn function

The obtained fits can be used to calculate photon spectra from $\pi^0$ decays

Extrapolation uncertainties are significant only at low photon $p_T < 0.3$ GeV/c
The integrated direct photon yield:

- scales as \((dN_{ch}/d\eta)^{1.25}\) in a wide range of multiplicities/collision energies
- the scaling is violated in small collision systems / small multiplicities \((dN_{ch}/d\eta < 20)\)
- AA yield is a factor of ~10 larger than the \(N_{coll}\)-scaled yield in pp

Assuming this scaling still holds at lower energies, we can expect universal multiplicity scaling for

- (0-60)\% centralities at 11 GeV
- (0-40)\% centralities at 4 GeV

No reliable predictions for photons in UrQMD/PHSD -> using data driven method
Universal scaling of $p_T$-differential direct photon yields at moderate $p_T$ is observed at RHIC/LHC.

It can be used to predict $p_T$ spectra of direct photons at NICA energies for $p_T > 0.6$ GeV/c.

Switch to thermal spectrum at $p_T < 0.6$ GeV/c: $dN/dp_T \sim p_T \exp(-p_T/T)$.

Using conservative effective temperature $T = 150$ MeV (see e.g. *PRC* 93 (2016) 054901).
Reconstructed direct photon spectra can be obtained from predicted direct photon yields multiplied by the photon reconstruction efficiency.

\[ \text{Reconstructed } p_T (\text{GeV/c}) \]

\[ \text{Efficiency} \]

\[ \frac{1}{N_{\text{ev}}} \frac{dN}{dp_T} (\text{GeV/c})^{-1} \]

- Au-Au, direct photons, \(|\eta|<1\)
  - \( \sqrt{s_{\text{NN}}} = 11 \text{ GeV, } 0\text{-}20\% \)
  - \( \sqrt{s_{\text{NN}}} = 11 \text{ GeV, } 20\text{-}40\% \)
  - \( \sqrt{s_{\text{NN}}} = 11 \text{ GeV, } 40\text{-}60\% \)
  - \( \sqrt{s_{\text{NN}}} = 4 \text{ GeV, } 0\text{-}20\% \)
  - \( \sqrt{s_{\text{NN}}} = 4 \text{ GeV, } 20\text{-}40\% \)
Inclusive photon spectra and $R_\gamma$ ratio

Inclusive photon spectrum was simulated as a sum of direct and decay photon spectra

$$R_\gamma = \frac{\gamma_{inc}}{\gamma_{decay}} = \frac{\gamma_{inc}/\pi^0}{\gamma_{decay}/\pi^0_{param}}$$

Excess over 1 shows the fraction of direct photons

- Systematic uncertainties on $R_\gamma$ can be reduced to ~5%
- Conclusion: direct photon yields can be extracted with good accuracy down to low $p_T$

$$\gamma_{direct} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{inc}$$
Conclusions and outlook

- Photons are valuable probes of dense hadronic matter produced in heavy ion collisions
- Photon conversion method is a powerful tool to measure photon and neutral meson spectra
- Reconstruction of thermal photon yields looks promising at MPD
- Next:
  - Evaluate perspectives of thermal photon flow measurements
  - Feasibility studies on the dedicated converter and Stage 2 setup
BACKUP
Electron PID

TPC dE/dx: 0.2 - 0.5 GeV/c

TOF: $p_T < 0.3$ GeV/c

Selecting tracks in +/-4σ around the mean value:
Optimization of electron pair selection cuts
Fit functions for pt distributions

- Two-component model (Bylinkin, Rostovtsev):
  \[ E \frac{d^3\sigma}{dp^3} = A_e \exp \left( \frac{M - \sqrt{p_T^2 + M^2}}{T_e} \right) + A \left( 1 + \frac{p_T^2}{n_{br} T^2} \right)^{-n_{br}} \]

- Hagedorn fit:
  \[ \frac{dN}{dy dp_T} = p_T A \left( \exp \left( -a \times p_T - |b| p_T^2 \right) + \frac{p_T}{p_0} \right)^{-n} \]

- Tsallis fit:
  \[ E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi} \frac{d\sigma}{dy} \frac{(n-1)(n-2)}{(nT)^2} \left( 1 + \frac{m_T}{nT} \right)^{-n} \]