PHENIX Measurements of Beam Energy Dependence of Direct Photon Emission

Axel Drees, Hard Probes 2018, October, Aix-Les-Bains, France

- Introduction
- The Thermal Photon Puzzle
- New Results: Universal Scaling
- Outlook and Summary

HARD PROBES 2018

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Thermal Photon Emission from a Heavy Ion Collisions

Relativistic Heavy-Ion Collisions

T=300-170 MeV

T=170-110 MeV
Experimental Issue: Isolate Thermal Radiation

\[ \gamma, \gamma^* \text{ from A+A} \]

**Direct**

**Non-thermal**

**Thermal**

**Pre-equilibrium**

**“Prompt” hard scattering**

**Quark-Gluon Plasma**

**Hadron Gas**

**Hadron Decays**

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

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

Need to subtract decay and prompt contributions with high accuracy

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Photon Measurements with PHENIX

$e^+e^-$ identification
E/p and RICH

Photons, neutral pion
$\gamma, \pi^0 \rightarrow \gamma \gamma$
Calorimeter

Photons
$\gamma \rightarrow e^+e^-$
$\lim_{m_{ee} \rightarrow 0} (\gamma^* \rightarrow e^+e^-)$

magnetic field & tracking detectors
Direct Photons p+p and Au+Au at $\sqrt{s_{NN}} = 200$ GeV

Direct photon yield well established
- pp consistent with pQCD
- AuAu follows $N_{coll}$ scaled
- pp above 3-4 GeV
- Significant excess below 3 GeV in AuAu
- Excess has nearly exponential shape with $T_{eff} \sim 240$ MeV


First thermal photon measurement: $T_{ini} > 240$ MeV > $T_c$

(Need to consider exploding source!)
Anisotropic Emission of Direct Photons

Anisotropic emission of direct photon with large $v_2$ and $v_3$
Many model calculations and consideration*:

- More traditional, large contribution from hadron gas
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)

- New early contributions
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions

- New effects at phase boundary
  - Extended emission
  - Emission at hadronization

*list not complete
New Insight: Vary System Size and Geometry


- Vary size & geometry through changing collision system, $\sqrt{s}$, centrality
- Measure system size via event multiplicity or $\frac{dN_{ch}}{d\eta}$ or similar
  - $\frac{dN_{ch}}{d\eta}$ is an experimental observable
  - at fixed $\sqrt{s}$ $\frac{dN_{ch}}{d\eta} \sim N_{part} \sim$ Volume
  - Varying $\sqrt{s}$ $\frac{dN_{ch}}{d\eta} \sim$ energy density x Volume
- Available for direct $\gamma$ analysis in PHENIX
  - 200 GeV: Au+Au, Cu+Au, Cu+Cu, $^3$He+Au, d+Au, p+Au, p+p
  - 200 – 62.4 – 39 GeV: Au+Au

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New Experimental Data from Different Systems

- **New PHENIX data**
  - Vary collision energy: Au+Au at 39 and 62.4 GeV
  - Vary system size: Cu+Cu at 200 GeV
  - Small systems p+Au at 200 GeV (N.Novitzky’s talk)

**Low $p_T$ direct photons in all systems**
Compare System Size for Different $\sqrt{s}$

- Characterize system size with multiplicity density:
  \[
  \frac{dN_{ch}}{d\eta}
  \]

- Compare system size and number of collisions: Empirical scaling relation across $\sqrt{s}$:
  - Connects system size and hard scattering

\[
N_{coll} = \frac{1}{SY(\sqrt{s_{NN}})} \times \left( \frac{dN_{ch}}{d\eta} \right)^\alpha
\]

$\alpha \approx 5/4$

PHENIX: arXiv:1804.04181

What is the origin of this scaling?
Comparison of Different Collision Systems

\[ \frac{d^2N}{dp_T^2 dy} = (dN_{ch}/dn)_{ch}^{1.25} \]

\[ \frac{dN_{ch}}{dn} \]

Similar low \( p_T \) photon yield when scaled with \( \frac{dN_{ch}}{dn}^{5/4} \) independent of energy, centrality, or system size


PHENIX: arXiv:1804.04181
Integrated Low $p_T$ Photon Yield

PHENIX: arXiv:1804.04181

Universal scaling behavior!
Source of photons must be similar!

N_{coll} x pQCD and N_{coll} x p+p follow same scaling at 0.1 of yield
Integrated Photon Yield $p_T > 5$ GeV/c

**PHENIX: arXiv:1804.04181**

$A+A/p+p \rightarrow \gamma_{\text{dir}} + X$

- $\text{Pb+Pb}, \sqrt{s_{NN}} = 2760$ GeV
- $\text{Au+Au}, \sqrt{s_{NN}} = 200$ GeV
- $p+p, \sqrt{s} = 200$ GeV
- $p+p, \sqrt{s} = 62.4$ GeV

$\alpha = 1.25$

**Au+Au at 200 GeV**
consistent with $N_{coll} \times p+p$ and $N_{coll} + pQCD$

**Pb+Pb**
same scaling but 30% above $N_{coll} \times pQCD$ p+p

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**NA38/NA50 Dimuon Enhancement**

- Intermediate mass dimuon enhancement
  - Discovered by NA38/NA50
  - Originally interpreted as charm enhancement
  - Established as thermal dimuons from QGP by NA60 using vertex detectors

**Graphical Data**

- NA50 Pb-Pb 158 GeV
- Central collisions

**Enhancement of open charm**

- E : Enhancement of open charm

**Graph**

- Data points for various centrality classes and collision energies.
The NA38/NA50 dimuon enhancement is a significant result in high-energy physics. It was discovered by NA38/NA50 and originally interpreted as a charm enhancement. However, it was later established as a thermal dimuons from the quark-gluon plasma (QGP) by NA60 using vertex detectors.

**Intermediate mass dimuon enhancement**
- Discovered by NA38/NA50
- Originally interpreted as charm enhancement
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**NA38/NA50 Dimuon Enhancement**

**E : Enhancement of open charm**

The NA35/NA50 dimuon excess is consistent with $N_{\text{part}}^{1.25}$ scaling.
Integrated Low $p_T$ Photon Yield

$\gamma_{dir} + X$

- $A+A/p+p \rightarrow \gamma_{dir} + X$
- $\text{Pb+Pb}, \sqrt{s_{NN}} = 2760 \text{ GeV}$
- $\text{Au+Au}, \sqrt{s_{NN}} = 200 \text{ GeV}$
- $\text{Au+Au}, \sqrt{s_{NN}} = 62.4 \text{ GeV}$
- $\text{Au+Au}, \sqrt{s_{NN}} = 39 \text{ GeV}$
- $\text{Cu+Cu}, \sqrt{s_{NN}} = 200 \text{ GeV}$
- $p+p, \sqrt{s} = 200 \text{ GeV}$

$N_{coll}$ scaled prompt photons

- $p+p$ fit, $\sqrt{s} = 200 \text{ GeV}$
- $pQCD$, $\sqrt{s} = 2760 \text{ GeV}$
- $pQCD$, $\sqrt{s} = 200 \text{ GeV}$
- $pQCD$, $\sqrt{s} = 62 \text{ GeV}$

PHENIX: arXiv:1804.04181
First Results From p/d-Au Collisions

Onset of low $p_T$ excess radiation at $\frac{dN_{ch}}{d\eta} \sim 10$?
Outlook

- **Small system data sets**
  - p-Au, $^3$He-Au, d-Au
  - “engineer” collision geometry
  - Search for onset of QGP

- **High statistics large systems**
  - Au-Au, Cu-Au
  - More precise measurements
  - New insights into thermal photon puzzle

More results for PHENIX yet to come
Summary

- Thermal photon puzzle in Au+Au at 200 GeV unresolved
  - Large photon yield
  - Large azimuthal anisotropy
  - Difficult for theoretical models to reconcile

- PHENIX discovered universal scaling of low $p_T$ direct $\gamma$ yield with $\frac{dN_{ch}}{d\eta}^{5/4}$
  - Independent of centrality and $\sqrt{s}$ from 39 GeV to 2760 GeV beam energy
  - Holds down to system size of $\frac{dN_{ch}}{d\eta} \sim 20$
  - At fixed $\sqrt{s}$ equivalent to $N_{coll}$ scaling at low $p_T$ and high $p_T$
  - Scaled A+A yield is a factor of 10 larger than expected from p+p

- PHENIX data from p+A and d+Au
  - Indicates rapid transition onset of direct photon excess around $\frac{dN_{ch}}{d\eta} \sim 5$ to 20

- More PHENIX data varying size and geometry to be finalized/analyzed
  - Small systems: p+Au, d+Au, $^3$He+Au
  - Large systems: Au+Au and Cu+Au
Backup
Thermal Radiation from Hot & Dense Matter

Black Body Radiation
- Real or virtual photons
- Sensitive to temperature & density
  - Boltzmann dist. with avg. inv. slope $\propto T$,
  - Photon flux $\propto T^4$
- Space-time evolution of matter
  - matter expands
  - $\Rightarrow$ temperature drops
  - $\Rightarrow$ Doppler shift

Microscopic view of thermal radiation

QGP:

hadron gas:

Emission rate depends on density squared integrated over space-time evolution

High yield $\Rightarrow$ high $T$ $\Rightarrow$ early emission
Large Doppler shift $\Rightarrow$ late emission
Different pQCD calculations in good agreement
STAR Au+Au 200 GeV  PHENIX Au+Au 200 GeV

\[ \sqrt{s_{NN}} = 200 \text{ GeV}: \]
- Au+Au, 0-20%
- Au+Au, 20-40%
- Au+Au, 40-60%
- Au+Au, 60-80%
- p+p, \sqrt{s} = 200 \text{ GeV}
- p+p fit, \sqrt{s} = 200 \text{ GeV}
- pQCD, \sqrt{s} = 200 \text{ GeV}

\[ \sqrt{s_{NN}} = 200 \text{ GeV}: \]
- Au+Au, 0-20%
- Au+Au, 20-40%
- Au+Au, 40-60%
- \text{p+p, } \sqrt{s} = 200 \text{ GeV}
- \text{p+p fit, } \sqrt{s} = 200 \text{ GeV}
- \text{pQCD, } \sqrt{s} = 200 \text{ GeV}

\[ \text{Pb+Pb, } \sqrt{s_{NN}} = 2760 \text{ GeV, 0-20%}: \]
- Au+Au, \sqrt{s_{NN}} = 200 \text{ GeV, 0-20%}
- Au+Au, \sqrt{s_{NN}} = 62.4 \text{ GeV, 0-20%}
- Cu+Cu, \sqrt{s_{NN}} = 200 \text{ GeV, 0-40%}
- \text{pQCD, } \sqrt{s} = 2760 \text{ GeV}
- \text{pQCD, } \sqrt{s} = 200 \text{ GeV}

\[ \text{pQCD, } \sqrt{s} = 200 \text{ GeV} \]

**STAR Au+Au direct photons close to p+p considering assumed } \eta \text{ yield lower than used by PHENIX**
Comparing STAR and PHNEIX

\[ A+A/p+p \rightarrow \gamma_{\text{dir}} + X \]

- Pb+Pb, \( \sqrt{s_{\text{NN}}} = 2760 \text{ GeV} \)
- Au+Au, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)
- Au+Au, \( \sqrt{s_{\text{NN}}} = 62.4 \text{ GeV} \)
- Au+Au, \( \sqrt{s_{\text{NN}}} = 39 \text{ GeV} \)
- Cu+Cu, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)
- p+p, \( \sqrt{s} = 200 \text{ GeV} \)
- Au+Au, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) (STAR)

\[ N_{\text{coll}} \text{ scaled prompt photons} \]

- p+p fit, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)
- pQCD, \( \sqrt{s_{\text{NN}}} = 2760 \text{ GeV} \)
- pQCD, \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)
- pQCD, \( \sqrt{s_{\text{NN}}} = 62.4 \text{ GeV} \)