Direct Photons in Heavy-Ion Collisions

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Journal Club on heavy-ion collisions

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PHENIX papers discussed

- Measurement of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

  arXiv:1205.5759v1 [nucl-ex]

- Enhanced production of direct photons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and implications for the initial temperature

  arXiv:0804.4168v2 [nucl-ex]

Photons in heavy-ion collisions

- direct photons
    - prompt photons from hard scattering of partons $p_T^\gamma > 4$ GeV
    - parton-medium interactions $p_T^\gamma > 4$ GeV
    - photons from scattering of thermalized particles $p_T^\gamma < 4$ GeV
- decay photons

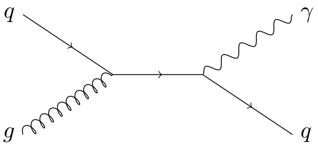


Figure 1 : $q + g \rightarrow q + \gamma$

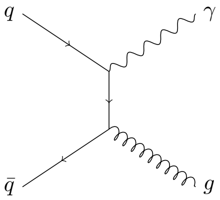


Figure 2 : $q + \bar{q} \rightarrow g + \gamma$

Influences on direct photon production

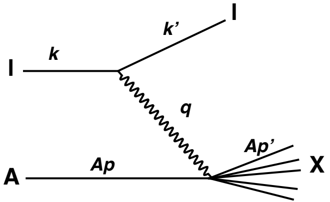
- modification of direct photon yield in Au+Au compared to p+p
- due to initial state of colliding nuclei:
  - shadowing or anti-shadowing
  - isospin effect
- final state effects due to QGP:
  - suppression of fragmentation photons due to parton energy loss
  - scattering of hard and thermal partons

Shadowing and anti-shadowing

Deep inelastic lepton-nucleon scattering:

$$l(k) + A(Ap) \to l(k') + A(Ap')$$

$$q = k - k' \,, x = \frac{-q^2}{2 \cdot pq} = \frac{Q^2}{2 \cdot pq}$$



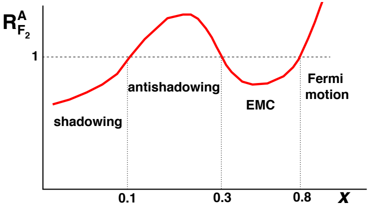
Nucleon structure function:

$$F_2(x, Q^2) = x \cdot \sum_f z_f^2 (q_f(x) + \bar{q}_f(x))$$

Nuclear ratio $R^A_{F_2}(x, Q^2)$ for structure function F_2:

$$R^A_{F_2}(x, Q^2) = \frac{F_2^A(x, Q^2)}{A \cdot F_2^{\text{nucleon}}(x, Q^2)}$$

where A is the nuclear mass number



Isospin effect

strong interaction: p, n are different states of the same particle

$$p = |I = \frac{1}{2}, I_3 = +\frac{1}{2}\rangle \;\;,\;\; n = |I = \frac{1}{2}, I_3 = -\frac{1}{2}\rangle$$

consider two scattering processes:

$$(1)\;\; p + p \rightarrow d + \pi^+$$
$$(2)\;\; p + n \rightarrow d + \pi^0$$

with interaction of the form $V = \alpha\, \vec{I}^{(i)} \cdot \vec{I}^{(j)}$, we know:

$$\sigma \propto |\mathcal{M}|^2 \;\;,\;\; \mathcal{M} = \langle \text{final}|V|\text{initial}\rangle$$

with Wigner-Eckart theorem:

$$\frac{\sigma_{(1)}}{\sigma_{(2)}} = 2$$

$\rightarrow$ cross section depends on scattering process, suppresses direct photon production in A+A compared to scaled p+p rates

Nuclear modification factor

yield in $A + A$ for hard processes is expected to be equal to $p + p$ cross-sections, scaled by:

$$\langle T_{AA} \rangle = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{pp}^{\text{inel}}}$$

Nuclear effects are quantified by the nuclear modification function:

$$R_{AA}(p_T) = \frac{\left(1/N_{AA}^{\text{evt}}\right) \cdot d^2N_{AA}/dp_T dy}{\langle T_{AA} \rangle \cdot d^2\sigma_{pp}/dp_T dy}$$

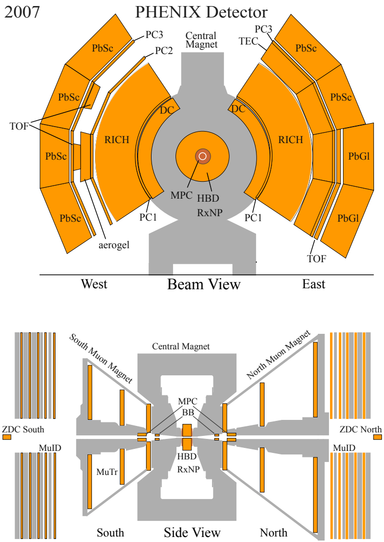
where $d^2\sigma_{pp}/dp_T dy$ is the measured $p + p$ cross section for direct photons

Measurement of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

arXiv:1205.5759v1 [nucl-ex]

Direct photon analysis

- direct photons ($p_T > 4$ GeV) in Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- analysis used 1.03×10^9 MB events
- photons reconstructed in PbSc + PbGl
- centrality from correlations between number of charged particles in
  - Beam-Beam Counters at $3.0 < |\eta| < 3.5$
  - zero-degree calorimeter



Direct photon analysis

- hight p_T: minimum opening angle between photons from π^0 decay decreases
- EMCal showers begin to merge
- decay photons can not be distinguished or energy is incorrectly shared
- starts at $p_T \approx 10$ GeV/c (16 GeV/c) for PbSc (PbGl)
- affects 50 % of all π^0 decays at $p_T \approx 16$ GeV/c (24 GeV/c) for PbSc (PbGl)
- significant effect for PbSc, negligible for PbGl

Direct photon analysis

PbGl:

- $\approx 10 - 15\%$ contamination of photon candidates with charged particles
- associate photon candidates with charged hits in pad chamber (PC3)
- merged clusters removed by PID cuts
- spectra corrected for acceptance and reconstruction efficiency
- simulation to exclude decay photons:

$$R_\gamma = \frac{\left(\gamma_{\mathrm{incl}}/\pi^0\right)_{\mathrm{data}}}{\left(\gamma_{\mathrm{dec}}/\pi^0\right)_{\mathrm{MC}}} \rightarrow \gamma_{\mathrm{dir}} = \gamma_{\mathrm{incl}} - \gamma_{\mathrm{dec}} = \left(1 - R_\gamma^{-1}\right) \cdot \gamma_{\mathrm{incl}}$$

Direct photon analysis

PbSc:

- photon candidates corrected for electrons, charged hadrons and neutrons
- fraction determined with GEANT detector simulation
- hight p_T: calorimeter response to single photons and correlated decay photons different $\rightarrow$ Problem: correction of raw inclusive spectrum
- raw distrubtion of decay photons calculated with GEANT simulation and subtracted
- subtraction gives raw direct photons $\rightarrow$ corrected for acceptance and efficiency
- R_γ calculated with MC from PbGl analysis: $R_\gamma = \frac{\gamma_{\text{dir}}^{\text{data}} + \gamma_{\text{dec}}^{\text{MC}}}{\gamma_{\text{dec}}^{\text{MC}}}$

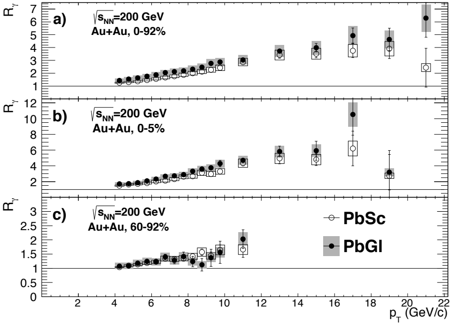
Systematic uncertainties

Systematic uncertainties of direct photon yield in % for PbGl (PbSc) in Au+Au MB events

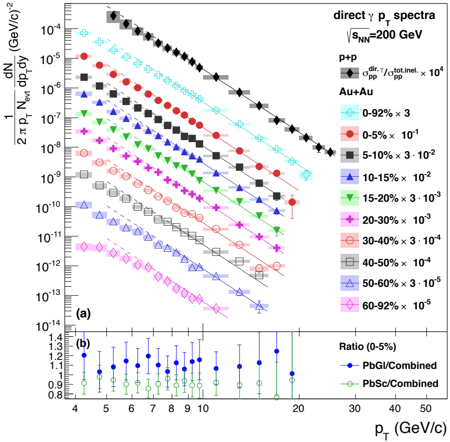
Error type / p_T	4.75 GeV/c	9.25 GeV/c	15 GeV/c
Background corrections	9.1 (5.2)	5.7 (2.5)	5.1 (2.2)
Yield corrections	11.9 (10.5)	8.3 (9.4)	7.9 (11.2)
Energy scale	7.9 (6.8)	6.8 (7.0)	6.8 (7.0)
Decay γ simulation	12.5 (7.2)	5.2 (4.3)	3.8 (3.7)
Total Systematic	21.0 (13.9)	13.2 (12.7)	12.3 (13.9)

Systematic uncertainties for both calorimeters are uncorrelated due to different analysis

Results

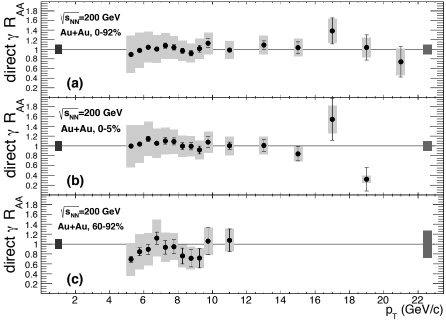


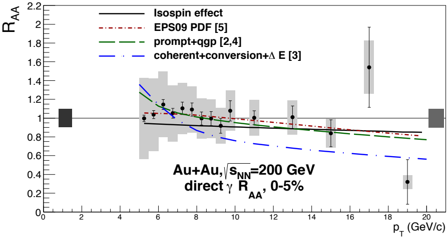
- excess above unity indicates presence of direct photons
- increases with centrality due to suppression of π^0
- corrected results agree within errors
- can be combined using: $w = {}^{1}/_{\sigma^2_{\text{total}}}$



- direct photon spectra
- lines indicate a T_{AA} scaled power law $\left({}^{A}/_{p_T}\right)^n$ fit for p+p

Results





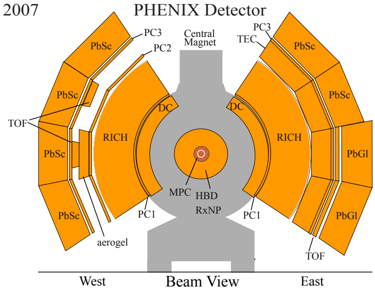
- R_{AA} is within errors consistent with unity for all centrality selections
- data is consistent with IS effects: Isospin and EPS09 PDF (includes isospin corrections) curve
- FS effects due to QGP are balancing
- scenario: production of direct photons in hard scattering
- high p_T photons traverse matter unaffected

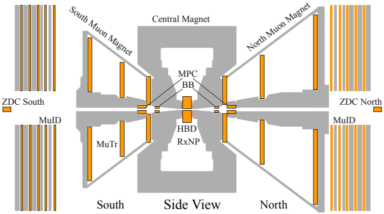
Enhanced production of direct photons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and implications for the initial temperature

arXiv:0804.4168v2 [nucl-ex]

Electron-positron pair analysis

- e^+e^- pairs from internal conversion for
  - $m_{e^+e^-} < 0.3$ GeV/c^2
  - $1 < p_T < 5$ GeV/c
  - in p+p and Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- Au+Au: 1.03×10^9 MB events
- p+p: 43 nb^{-1} MB triggered and 2.25 pb^{-1} single electron triggered
- pairs measured in DC, identification via RICH and EMCal
- helium bags to reduce conversion material





Electron-positron pair analysis

any source of high energy photons can emit virtual photons
$\rightarrow$ search for low invariant mass e^+e^- pairs

$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi m_{ee}} \cdot \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \cdot \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) S dn_\gamma$$

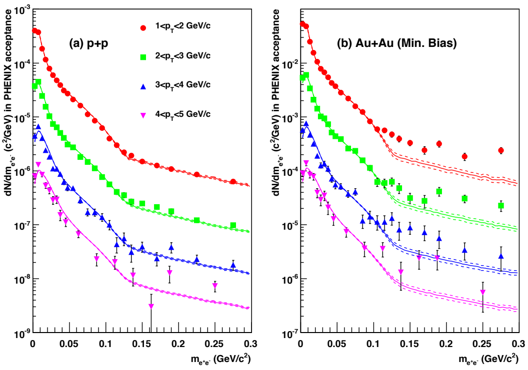
S is process dependent:

- $m_{ee} \rightarrow 0$ or $m_{ee} \ll p_T$: $S \rightarrow 1$
- for photons and e^+e^- pairs from hadron decays:
  - $S = |F(m_{ee}^2)|^2 \cdot \left(1 - \frac{m_{ee}^2}{M_h^2}\right)^3$
  - $m_{ee} > M_h$: $S = 0$
  - cutoffs exploited to separate direct and and decay photons

Electron-positron pair analysis

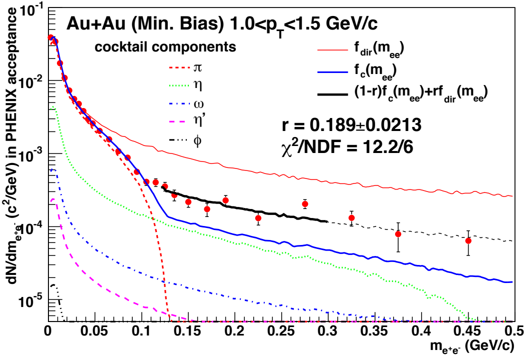
- electrons and positrons with $p_T > 0.2\ ^{\mathrm{GeV}}/_{c}$ are combined into pairs
- pairs from conversion in detector material are removed due to orientation in magnetic field
- combinatorial background from mixing events
- two sources of correlated background:
  - two e^+e^- pairs from meson decays
  - correlated hadrons decaying in two e^+e^- pairs
- correlated background determined from like-sign pair data

Results



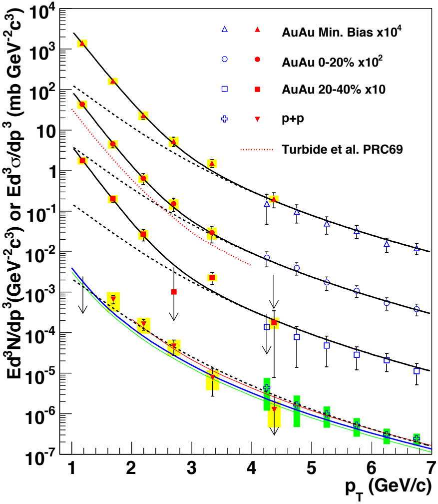
- mass spectra of e^+e^- pairs
- solid lines: "cocktail" hadron decays from MC
- "knee" corresponds to π^0 cut-off for $m_{ee} > M_{\pi^0}$
- for Au+Au: greater excess above cocktail
- possible source: internal conversion of direct photons

Results



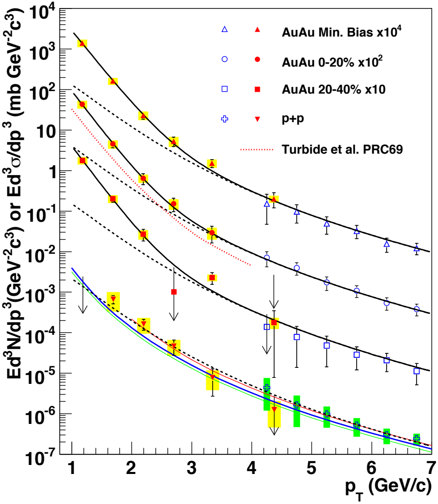
- mass spectrum for $m_{ee} < 0.5\ ^{\text{GeV}}/_{c^2}$ and $p_T > 1\ ^{\text{GeV}}/_{c}$ well discribed by cocktail + internal conversion photons
- χ^2/NDF near 1.0 for higher p_T bins
- dominant systematic uncertainty: particle composition in hadronic cocktail
  - $\frac{\eta}{\pi^0} = 0.48 \pm 0.03\ (0.08)$ ratio in p+p (Au + Au)
  - leads to $\approx 7\,\%$ (17 %) uncertainty

Results



- invariant yield (Au+Au) and invariant cross section (p+p) of direct photons
- yield of excess e^+e^- pairs is converted to direct photon yield assuming $S = 1$
  $\rightarrow \frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi m_{ee}} dn_\gamma$
- pQCD calculations consistent with p+p data for $p_T > 2$ GeV/c
- p+p can be described by modified power-law: $A_{pp}\left(1 + \frac{p_T^2}{b}\right)^{-n}$
- Au+Au data are above T_{AA} scaled p+p fit curve for $p_T < 2.5$ GeV/c

Results



- exponential + T_{AA} scaled p+p fit is fit to Au+Au data: $Ae^{-p_T/T} + T_{AA} \times A_{pp} \left(1 + \frac{p_T^2}{b}\right)^{-n}$
- only free parameters are A and T
- if direct photons are of thermal origin: inverse slope T refers to T_{init} of the dense matter
- red dotted curve: hydrodynamical model thermal photon spectrum in central Au+Au with $T_{\text{init}} = 370$ MeV

Fit results

centrality	A ($p_T > 1$ GeV/c)	T (MeV)	$\frac{\chi^2}{NDF}$
$0-20\%$	$1.50 \pm 0.23 \pm 0.35$	$221 \pm 19 \pm 19$	4.7 / 4
$20-40\%$	$0.65 \pm 0.08 \pm 0.15$	$217 \pm 18 \pm 16$	5 / 3
Min. Bias	$0.49 \pm 0.05 \pm 0.11$	$233 \pm 14 \pm 19$	3.2 / 4

- central Au+Au data for T_{init} can be reproduced with hydrodynamical models within factor 2
- models: $T_{\text{init}} \approx 300 - 600$ MeV at $\tau^0 \approx 0.6 - 0.15$ fm/c
- models are in qualitative agreement with data
- lattice QCD predicts phase transition to QGP at ≈ 170 MeV

Take home messages

- direct photons can be observed in heavy ion collisions
- yield for direct photons with $p_T > 4$ GeV unaffected by QGP
- thermal photons observed in Au+Au in contrast to p+p
  - indicates presence of QGP
- T_{init} can be measured
  - is in qualitative agreement with predictions of several models