Thermal Photons and Dileptons

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- Introduction
- Analysis
- Experimental Results
  - The p+p reference
  - Low mass dilepton enhancement in Au+Au
  - Direct virtual photons in Au+Au
- Comparison to Models
- HBD in 2010
- Summary

PHENIX publications:
Lepton-Pair Continuum Physics

Modifications due to QCD phase transition

Chiral symmetry restoration
continuum enhancement
modification of vector mesons

Sources “long” after collision:
- $\pi^0$, $\eta$, $\omega$ Dalitz decays
- $(\rho)$, $\omega$, $\phi$, $J/\psi$, $\psi^\prime$ decays

Early in collision (hard probes):
- Heavy flavor production
- Drell Yan, direct radiation

Baseline from p-p

Thermal (blackbody) radiation
- in dileptons and photons
- temperature evolution

Medium modifications of meson
- $\pi\pi \rightarrow \rho \rightarrow l^+l^-$
- chiral symmetry restoration

Medium effects on hard probes
- Heavy flavor energy loss

Large discovery potential at RHIC
Key Challenge for PHENIX: Pair Background

- No background rejection $\rightarrow$ Signal/Background $\geq 1/100$ in Au-Au
- Unphysical correlated background
  - Track overlaps in detectors
  - Not reproducible by mixed events: removed from event sample (pair cut)

- Combinatorial background: $e^+$ and $e^-$ from different uncorrelated source
  $$\pi^0 \rightarrow e^+(e^-)\gamma \quad \gamma \rightarrow e^+e^-$$
  - Need event mixing because of acceptance differences for $e^+$ and $e^-$
  - Use like sign pairs to check event mixing

- Correlated background: $e^+$ and $e^-$ from same source but not “signal”
  - “Cross” pairs
  - “jet” pairs

Use Monte Carlo simulation and like sign data to estimate and subtract background

Subtractions dominate systematic uncertainties
But are well under control experimentally!

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Estimate of Expected Sources

- **Hadron decays:**
  - Fit $\pi^0$ and $\pi^\pm$ data $p+p$ or $Au+Au$
  
  $E \frac{d^3 \sigma}{d^3 p} = \frac{A}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n}$

  - For other mesons $\eta$, $\omega$, $\rho$, $\phi$, $J/\psi$ etc. replace $p_T \rightarrow m_T$ and fit normalization to existing data where available

  **Hadron data follows “$m_T$ scaling”**

- **Heavy flavor production:**
  - $\sigma_c = N_{coll} \times 567\pm57\pm193\mu b$ from single electron measurement

  **Predict cocktail of known pair sources**
Dilepton Continuum in p+p Collisions

- Data and Cocktail of known sources represent pairs with \( e^+ \) and \( e^- \) PHENIX acceptance
- Data are efficiency corrected

Excellent agreement of data and hadron decay contributions with 30\% systematic uncertainties
Charm and Bottom Contribution

Subtract hadron decay contribution and fit difference:

\[ \sigma_c = 544 \pm 39 \text{ (stat)} \pm 142 \text{ (sys)} \pm 200 \text{ (model)} \ \mu b \]

Simultaneous fit of charm and bottom:

\[ \sigma_c = 518 \pm 47 \text{ (stat)} \pm 135 \text{ (sys)} \pm 190 \text{ (model)} \ \mu b \]

\[ \sigma_b = 3.9 \pm 2.4 \text{ (stat)} +3/-2 \text{ (sys)} \ \mu b \]

Consistent with PHENIX single electron measurement

\[ \sigma_c = 567 \pm 57 \pm 193 \ \mu b \]
Measuring direct photons via virtual photons:

- any process that radiates $\gamma$ will also radiate $\gamma^*$
- for $m << p_T$, $\gamma^*$ is “almost real”
- extrapolate $\gamma^* \rightarrow e^+e^-$ yield to $m = 0 \rightarrow$ direct $\gamma$ yield
- $m > m_\pi$ removes 90% of hadron decay background
- S/B improves by factor 10: 10% direct $\gamma \rightarrow$ 100% direct $\gamma^*$

Small excess at for $m << p_T$ consistent with pQCD direct photons
Au+Au Dilepton Continuum

Excess $150 < m_{ee} < 750$ MeV:
$4.7 \pm 0.4$(stat.) $\pm 1.5$(syst.) $\pm 0.9$(model)

hadron decay cocktail tuned to AuAu

Charm from PYTHIA filtered by acceptance
$\sigma_c = N_{\text{coll}} x 567 \pm 57 \pm 193 \mu b$

Charm “thermalized” filtered by acceptance
$\sigma_c = N_{\text{coll}} x 567 \pm 57 \pm 193 \mu b$

Intermediate-mass continuum: consistent with PYTHIA if charm is modified room for thermal radiation
More on Charm Region (1.2 < m < 2.8 GeV)

Differentially in mass shape is NOT what is expected from charm.

Spectrum is steeper

True for most centralities (except maybe most central)
True for all Cu+Cu centralities!
Enhancement in IMR for peripheral collisions?!

Must measure heavy flavor contribution directly!!
Au+Au Dilepton Continuum

Excess $150 < m_{ee} < 750$ MeV:
$4.7 \pm 0.4\text{(stat.)} \pm 1.5\text{(syst.)} \pm 0.9\text{(model)}$
Centrality Dependence of Low Mass Continuum

**Excess region: 150 < m < 750 MeV**

- Yield / \( \frac{N_{\text{part}}}{2} \) in two mass windows
- \( \pi^0 \) region: production scales approximately with \( N_{\text{part}} \)
- Excess region: expect contribution from hot matter
  - in-medium production from \( \pi\pi \) or qq annihilation
  - yield should scale faster than \( N_{\text{part}} \) (and it does)

**\( \pi^0 \) region: m < 100 MeV**

**Excess mostly in central AuAu yield increase faster than \( N_{\text{part}} \)**
$p_T$ Dependence of Low Mass Enhancement

$p+p$ 

$\sqrt{s} = 200$ GeV 

- $0.0<p_T<0.5$ GeV/c $\times 10^4$
- $0.5<p_T<1.0$ GeV/c $\times 10^3$
- $1.0<p_T<1.5$ GeV/c $\times 10^2$
- $1.5<p_T<2.0$ GeV/c $\times 10^1$
- $2.0<p_T<2.5$ GeV/c

Low mass in Au+Au present at all $p_T$
Range ~ 500 MeV most prominent at lowest $p_T$

Au+Au 

min. bias Au+Au $\sqrt{s_{NN}} = 200$ GeV 

- $0.0<p_T<0.5$ GeV/c $\times 10^6$
- $0.5<p_T<1.0$ GeV/c $\times 10^5$
- $1.0<p_T<1.5$ GeV/c $\times 10^4$
- $1.5<p_T<2.0$ GeV/c $\times 10^3$
- $2.0<p_T<2.5$ GeV/c
- $2.5<p_T<3.0$ GeV/c $\times 10^2$
- $3.0<p_T<4.0$ GeV/c $\times 10^1$
- $4.0<p_T<5.0$ GeV/c $\times 10^0$

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Fit Mass Distribution to Extract the Direct Yield:

- Example: one $p_T$ bin for Au+Au collisions

$$\frac{d\sigma_{ee}}{dMdp_T^2dy} \approx \frac{2\alpha}{3\pi} \frac{1}{M} L(M) \frac{d\sigma_\gamma}{dp_T^2dy}$$

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30 \text{ MeV}$

Direct $\gamma^*$ yield fitted in range 120 to 300 MeV
Insensitive to $\pi^0$ yield
Interpretation as Direct Photon

Relation between real and virtual photons:

\[ L(M) = \sqrt{1 - \frac{4m_e^2}{M^2}(1 + \frac{2m_e^2}{M^2})} \]

\[ \frac{d\sigma_{ee}}{dMd\vec{p}_T^2dy} \approx \frac{2\alpha}{3\pi} \frac{1}{M} \frac{d\sigma_\gamma}{dp_T^2dy} L(M) \]

Extrapolate real \(\gamma\) yield from dileptons:

\[ M \times \frac{dN_{ee}}{dM} \rightarrow \frac{dN_\gamma}{dM} \quad \text{for} \quad M \rightarrow 0 \]

Virtual Photon excess
At small mass and high \(p_T\)
Can be interpreted as real photon excess

no change in shape
can be extrapolated to \(m=0\)
Dilepton Excess at High $p_T$ – Small Mass

Significant direct photon excess beyond pQCD in Au+Au

The internal conversion method should also work at LHC!
Search for Thermal Photons via Real Photons

PHENIX has developed different methods:
- Subtraction or tagging of photons detected by calorimeter
- Tagging photons detected by conversions, i.e. $e^+e^-$ pairs
- Results consistent with internal conversion method
First Measurement of Thermal Radiation at RHIC

Direct photons from real photons:
- Measure inclusive photons
- Subtract $\pi^0$ and $\eta$ decay photons at $S/B < 1:10$ for $p_T < 3$ GeV

Direct photons from virtual photons:
- Measure $e^+e^-$ pairs at $m_\pi < m << p_T$
- Subtract $\eta$ decays at $S/B \sim 1:1$
- Extrapolate to mass 0

First thermal photon measurement:
$T_{\text{ini}} > 220$ MeV $> T_C$

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p_T Dependence of Low Mass Enhancement

Low mass in Au+Au present at all p_T
Range ~ 500 MeV most prominent at lowest p_T
A Look at $p_T < 1$ GeV

1/m $dN/dm$ is not constant
How to extrapolate to $m=0$??
m=0 still real photon yield

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A bit of my own speculation

Use a linear extrapolation to $m=0$ also for $p_T < 1$ GeV

Important to check with Real photons!!!
Apply acceptance correction

Case A: $\gamma^*$ and $e^+e^-$ in acceptance

Case B: $\gamma^*$ in acceptance
$e^+$ and/or $e^-$ NOT in acceptance

correction depends on source
virtual photon polarization
$\gamma^*$ different from charm
additional uncertainties!!
Mass Dependent Dilepton $p_T$ Spectra

Above $m_\pi$ Au+Au data enhanced for all $p_T$ most prominent for $p_T < 1$ GeV/c
Local Slopes from Subtracted $m_T$ Spectra

- Subtract cocktail and fit two exponentials in $m_T - m_0$

- Calculate local inverse slope from average $m_T$ for two ranges:
  
  \[
  0 < m_T - m_0 < 600 \text{ MeV} \\
  0.6 < m_T - m_0 < 2.5 \text{ GeV}
  \]

**Graph:**
- $300 < m < 750 \text{ MeV}$: 
  
  \[
  258 \pm 37 \pm 10 \text{ MeV}
  \]

- $92 \pm 11 \pm 9 \text{ MeV}$

**Soft component below $m_T \sim 500 \text{ MeV}$:**

\[
T_{\text{eff}} \sim 100 \text{ MeV} \quad \text{independent of mass}
\]

more than 50% of yield
Comparison to Theoretical Models

A short reminder:

- Models for contributions from hot medium (mostly $\pi\pi$ from hadronic phase)
  - Vacuum spectral functions
  - Dropping mass scenarios
  - Broadening of spectral function

- Broadening of spectral functions worked well at SPS energies (CERES and NA60)

$\pi\pi$ annihilation with medium modified $\rho$ works very well at SPS energies!
In Medium Mesons at RHIC???

- Models calculations with broadening of spectral function:

- \( \pi \pi \) annihilation with medium modified \( \rho \) insufficient to describe RHIC data!

- Rapp & vanHees

- Dusling & Zahed

- Bratkovskaya & Cassing
Model Comparison in $p_T$ after Cocktail Subtraction

Also corrected for pair acceptance

- **$\pi\pi$-annihilation with meson broadening**
  - Hadronic medium insufficient to account for data
  - Unlikely that hadronic contributions were overlooked

- Could there be more contribution from early phase?
  - Models include annihilation based on pQCD
  - Thermal virtual photon contribution?!
Thermal Virtual Photon Contribution

Theory calculation by Ralf Rapp

\[ M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy} \]

Real photon yield
Turbide, Rapp, Gale PRC69,014903(2004)

Expect virtual photon yield from QGP! But too small to account for enhancement at low mass

Maybe perturbative calculation not valid at \( dN_g/dy \sim 1000 \)

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Calculation of Thermal Photons

- Reasonable agreement with data
  - factors of two to be worked on...

- Initial temperatures and times from theoretical model fits to data:
  - 0.15 fm/c, 590 MeV (d’Enterria et al.)
  - 0.2 fm/c, 450-660 MeV (Srivastava et al.)
  - 0.5 fm/c, 300 MeV (Alam et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.)

- Correlation between T and \( \tau_0 \)

\[
T_{\text{ini}} = 300 \text{ to } 600 \text{ MeV} \\
\tau_0 = 0.15 \text{ to } 0.5 \text{ fm/c}
\]
Future of the Dilepton Continuum at RHIC

Key experimental issues
- Large combinatorial background prohibits precision measurements in low mass region!
- Disentangle charm and thermal contribution in intermediate mass region!

Need tools to reject photon conversions and Dalitz decays and to identify open charm

PHENIX → hadron blind detector (HBD) vertex tracking (VTX)

HBD is fully operational
- Proof of principle in 2007
- Successful data taking with p+p 2009
- Recorded large Au+Au data set in 2010
HBD Construction

“Standard” CERN Cu GEM foils in HBD

CSI photocathodes on gold GEM foils

2nd HBD installed in PHENIX
Data Analysis from 200 GeV p+p Run 2009

Use reconstructed Dalitz pairs ($m_{ee} < 150$ MeV/c) in PHENIX Central Arms
Match to single or double clusters in HBD

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<tr>
<th>Charge of the matched clusters</th>
<th>Pulse height</th>
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<td>Dalitz open pairs</td>
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- Single cluster in HBD
  - ~ 22 p.e.

<table>
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</table>

- Double cluster in HBD
  - ~ 40 p.e.

90% Dalitz and photon conversion rejection
At 80% pair efficiency
HBD Background Rejection

Rejection in p+p:
- Track matching to HBD
  - Remove late conversions
  - Remove miss identified pions
- Improve S/B by ~ factor 2

- HBD rejection
  - Cut on cluster size
  - Reject tracks with nearby cluster
- Improve S/B by factor > 10

Rejection in Au+Au
- Work in progress
  - works for peripheral collisions
  - Central collisions need refined algorithm
  - ~ 12 PE from scintillation light per channel
Expected Run 10 Performance

\[
\frac{1}{\sqrt{S_{\text{eff}}}} = \sqrt{\frac{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}{S}} = \sqrt{(\sqrt{S + BG})^2 + (BG \times \sqrt{\sigma_{\text{like}}^2 + (0.2\%)^2})^2}
\]

- **published** \( S \) 200 GeV Au+Au
  - 8 \( 10^8 \) min. bias events analyzed
- **Run 10** 200 GeV Au+Au
  - 7 \( 10^9 \) min. bias events recorded ± 20cm
  - HBD rejection improves factor ~15
  - Improve errors by factor ~10
- **Run 10** 62.4 GeV Au+Au
  - 6 \( 10^8 \) min. bias events recorded ± 20cm
  - Reduced multiplicity
  - Improve errors by factor 4
- **Run 10** 32.9 GeV Au+Au
  - 2 \( 10^8 \) min. bias events recorded ± 20cm
  - Further reduced multiplicity
  - Improved errors by factor 2

Expect greatly improved data compared to Run 4
Summary

- **Dilepton Data from PHENIX**
  - well established p+p reference
  - discovered a low mass enhancement in central Au+Au
    mostly in central collisions
    mostly at low m_T component with T~ 100 MeV independent of mass
  - first measurement of thermal photons
    indicate initial temperature > 220 MeV

- **Model comparison**
  - \(\pi\pi\) annihilation with collision broadening insufficient to explain data
    much of the radiation does not come from the hadronic phase!
  - more complete calculation of QGP contribution needed
    maybe in sQGP perturbative approach not ideal!
  - thermal radiation from QGP consistent with direct photon data
    initial temperature 300 to 600 MeV
    uncomfortably large differences between calculations!

- **Outlook:** expect more precise results to come soon
  - d+Au data from run-8 \(\rightarrow\) address IMR excess and give precision baseline
  - Au+Au with HBD from run-10 at 200, 62.4 and 32.9 GeV
Combinatorial Background: Like Sign Pairs

- Shape from mixed events
  - Excellent agreements for like sign pairs

- Normalization of mixed pairs
  - Small correlated background at low masses from double conversion or Dalitz+conversion
  - Normalize $B_{++}$ and $B_{--}$ to $N_{++}$ and $N_{--}$ for $m > 0.7$ GeV
  - Normalize mixed $+ -$ pairs to
    \[
    \langle N_{--} \rangle = 2\sqrt{\langle N_{++} \rangle \langle N_{--} \rangle}
    \]
  - Subtract correlated BG

- Systematic uncertainties
  - statistics of $N_{++}$ and $N_{--}$: $0.12\%$
  - different pair cuts in like and unlike sign: $0.2\%$

Normalization of mixed events:
systematic uncertainty = $0.25\%$
Differential Background Subtraction

Good agreement between mixed event background and like sign events within systematic errors

0.25% central Au+Au to 3% p+p
**p-p Raw Data: Correlated Background**

### Cross pairs
- Simulate cross pairs with decay generator
- Normalize to like sign data for small mass

### Jet pairs
- Simulate with PYTHIA
- Normalize to like sign data

### Unlike sign pairs
- Same simulations
- Normalization from like sign pairs

### Alternative method
- Correct like sign correlated background with mixed pairs

$$FG_+(m_T, p_T) = 2\sqrt{FG_+FG_{++}} \times \frac{BG_+}{2\sqrt{BG_-BG_{++}}}$$

**Signal:** $S/B \geq 1$
Uncertainty of Background Subtractions

Combinatorial background $\sigma_{\text{signal}} / \text{signal} = \sigma_{\text{BG}} / \text{BG} \times \text{BG/signal}$

$3\% \times 3 = 10\%$

$0.25\% \times 170 = 50\%$

Subtractions dominate systematic uncertainties but are well under control experimentally!
Cu+Cu Au+Au Comparison

PHENIX Preliminary

STONY BROOK