Thermal Photon Flow:
Some details and a new perspective

Sarah Campbell
ECT* Workshop
“Electromagnetic probes of Strongly Interacting Matter”
May 23, 2012 -- Trento, Italy
Outline

• Some details about the PHENIX thermal photon measurements
• No theory comparisons
  – Gabor discussed this in this morning’s talk
• New idea...
Fit $m_{ee}$ at $p_T > 1$ to find $r_\gamma$

$$f(m_{ee}) = (1 - r_\gamma)f_c(m_{ee}) + r_\gamma f_{dir}(m_{ee})$$

$$r_\gamma = R_\gamma = \frac{\text{direct } \gamma}{\text{inclusive } \gamma}$$

- Fit for $m_{ee}$ in 0.15-0.3 GeV/c$^2$ in $p_T$ slices

No excess in d+Au

Excess in Cu+Cu

Excess in Au+Au

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$r = 0.189 \pm 0.0213$

$\chi^2$/NDF = 12.2/6

PRL 104 132301 (2010)
Direct photon $p_T$ spectra

$$dN_{\text{real dir. } \gamma} \propto r_{\gamma} dN_{\text{incl. virtual } \gamma}$$

- Additional thermal yield
  - $T_{\text{ave}} = \text{inverse slope of expo.}$

$T_{\text{ave}} = 233 \pm 14 \pm 19$ MeV

$T_{\text{ave}} = 221 \pm 19 \pm 19$ MeV

$T_{\text{ave}} = 217 \pm 18 \pm 16$ MeV

NLO pQCD

$T_{\text{init}} \sim 300 \text{ to } 600 \text{ MeV}$

$\tau_0 \sim 0.15 - 0.5 \text{ fm/c}$

Dashed lines $T_{AA}$-scaled p+p
Solid lines $T_{AA}$-scaled p+p + expo
PRL 104 132301 (2010)
Measuring $v_2^{\gamma,\text{dir}}$

Calculated with a cocktail assuming KE$_T$ and m$_T$ scaling and measured $v_2^{\pi^0}$

MB Au+Au

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PRL 109 122302 (2012)
Thermal photon flow

- Low $p_T$, $v_2$ large
  - $p_T$ spectra $\rightarrow$ produced early in collision
  - No time to build up the pressure gradients for large partonic flow

- High $p_T$, $v_2 \sim 0$
  - Consistent with hard scattering
“Thermal photon $v_2$ is as large at the pion $v_2$”
Hadronic flow

Bulk expansion

Recombination

$n_q$ scaling

Jets

$n_q$ scaling

$v_2 \times 1.6$ for 0-20%

$v_2 / n_q$

$v_2 / n_q$

$p_T (GeV/c)$

$KE_T / n_q (GeV)$

$0.05$

$0.10$

$0.15$

$0.20$

$0.25$

$0.30$

$0.00$

$0.02$

$0.04$

$0.06$

$0.08$

$0.10$

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Simple Coalescence

- Quarks: \( \frac{dN}{d\varphi} \sim 1 + 2\nu_{2,q}(p_T) \cos(2\varphi) \)
- Mesons: \( \nu_2(p_T) = 2\nu_{2,q}(p_T/2) \)
- Baryons: \( \nu_2(p_T) = 3\nu_{2,q}(p_T/3) \)
- Assumes co-moving quarks of same momentum
  - \( p_{T,M} \rightarrow 2p_{T,q} \) \( p_{T,B} \rightarrow 3p_{T,q} \)
  - Momentum conservation maintained by mean field interaction
- Quarks close in phase space
- Why not increase q-qbar annihilation cross-section?
  - Produce more thermal photons during crossover
If we assume $n_{q, \gamma} = 2$

$v_2 * 1.6$ for 0-20%

$20-40\%$

PRC 85 064914 (2012)
PRL 109 122302 (2012)
Compare $n_q$-scaled $v_2$ for $\gamma$ and hadrons

- $\chi^2 = \sum_{c,h,p_T/nq} \left( v_{2,\gamma}/n_{q,\gamma} - v_{2,h}/n_{q,h} \right)^2 / (\sigma_{\gamma}^2 + \sigma_h^2)$
  - Sum over centrality, hadron for each $\gamma$ data point in $p_T/n_q$
  - $\sigma^2 = \sigma_{\text{sys}}^2 + \sigma_{\text{stat}}^2$

- Match $v_{2,\gamma}$ and $v_{2,h}$ points so $p_{T,\gamma}/n_{q,\gamma} \sim p_{T,h}/n_{q,h}$
  - Need to be within 0.1 to be a match

- NDF = # points – 1 parameter $\rightarrow n_{q,\gamma}$
  - As changes $n_{q,\gamma}$, NDF changes

- Find $n_{q,\gamma}$ at minimum $\chi^2$/NDF
  - $n_{q,\gamma}$ error range from $\chi^2$/NDF + 1

- Alternate comparison: use $K E_T/n_q$ to match
Example $n_{q,\gamma}=2$ with $p_T/n_q$ match

- $\chi^2 = 16.739$
- NDF = 39
- $\chi^2 / \text{NDF} = 0.429$
Example $n_{q,\gamma}=3$ with $p_T/n_q$ match

- $\chi^2 = 226.384$
- NDF = 51
- $\chi^2 / \text{NDF} = 4.439$

- 0-20%
- 20-40%

- $\gamma$
- $\pi$
- $\gamma$
- $K$
- $\gamma$
- $p$
$\chi^2/\text{NDF}$ space in $n_{q,\gamma}$

$n_{q,\gamma}$ ranges:

1.19 - 2.38

1.17 - 2.34

$p_T/n_q$ and $KE_T/n_q$ are consistent

$n_{q,\gamma}$ minima: 1.79, 1.82
Limit to regions where hadrons $n_q$-scale

• Upper limit:
  – $KE_T/n_q < 1$
    for 20-40%
  – $p_T/n_q < 1.3$
    for 20-40%

• Lower Limit:
  – $KE_T/n_q > 0.6$
  – $p_T/n_q > 0.6$

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χ²/NDF space with limits

<table>
<thead>
<tr>
<th>p_T/n_q range</th>
<th>Min. n_{q,γ}</th>
<th>Range of n_{q,γ}</th>
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<tbody>
<tr>
<td>Whole range</td>
<td>1.82</td>
<td>1.17-2.34</td>
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<tr>
<td>Upper limit</td>
<td>2.06</td>
<td>1.07-2.70</td>
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<tr>
<td>Upper &amp; lower limit</td>
<td>1.82</td>
<td>1.06-2.66</td>
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<td>1.12-2.68</td>
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<tr>
<td>Upper &amp; lower limit</td>
<td>1.79</td>
<td>1.12-2.69</td>
</tr>
</tbody>
</table>
What does $n_{q,\gamma} = 2$ mean?

- Suggests photon production from $q$-$\bar{q}$ at the cross-over?
  - Increase in $q$-$\bar{q}$ cross-section due to a coalescence-like effect?

- Originally, I thought:
  - $n_{q,\gamma} = 2 \rightarrow q$-$\bar{q}$ annihilation
  - $n_{q,\gamma} = 4 \rightarrow$ meson-meson interactions
    - Only true if mesons are co-moving and at same momentum

- Looks like $\gamma$ & $p$ drop together
  - Due to increase in hard processes/jet contribution?

How is this included in theoretical models?
Next step: Simple Monte Carlo

1st quark:

1.) Randomly pick $\eta$ from a flat distribution

2.) Randomly pick $p_T$

3.) Calculate $v_2$ from $p_T$

4.) Randomly pick $\varphi$

$Ae^{-1/T}$

\[ N(1 + 2v_2\cos(2\varphi)) \]

2nd, 3rd quarks:

5.) Assume at the same $\varphi, \eta$ as 1st quark

6.) Randomly pick $p_T$ from conditional prob. distrib.

$\rightarrow$ restrict to +/- $\delta p_T$ around 1st quark’s $p_T$

Make pairs:

7.) For pion and proton: conserve $p, E$ or KE

- Parameters: $T, \gamma, \mu, \beta, A, \delta p_T$
Backup
Photon sources

- High $p_T$
  - hard processes $\rightarrow v_2 = 0$
  - Frag $\rightarrow v_2 > 0$
  - Jet conv, Brems $\rightarrow v_2 < 0$

- Low $p_T$
  - Thermal $\rightarrow v_2 > 0$
  - $q$-$q\bar{q}$ annihilation in QGP
  - Hadron annihilation

$n_q = 2$
Photons from dielectrons

- Virtual photons produce e⁺e⁻ pairs
  - \( m_{ee} << p_T \rightarrow p_T > 1, m_{ee} < 0.3 \)
  - \( m_{ee} > 0.15 \rightarrow \) avoid large \( \pi^0 \) backgrounds
- Thermal photon production
  \[
  \frac{d^2N_{ee}}{dM^2} = \frac{\alpha L(M)}{3\pi M^2} S(M, q) dN_{\gamma}
  \]
  - As \( m_{ee}/p_T \rightarrow 0, \) then \( L(m_{ee}) \rightarrow 1, S(m_{ee}) \rightarrow 1 \)

\[
\frac{d^2N_{ee}}{dm_{ee}dp_T} \approx \frac{2\alpha}{3\pi} \frac{1}{m_{ee}} \frac{dN_{\gamma}}{dp_T}
\]

- Thermal photon component, \( f_{\text{dir}} \propto 1/m_{ee} \)
  - Filter by acceptance, smear by resolution
Au+Au low $p_T$ photons

- External conversion method
- Photons convert in back of HBD
  - Off-vertex decay ($r_{\text{conv}} \sim 60$ cm) $\pi^0$
- Apparent mass from mis-reconstructed momentum
  - In PHENIX 2007 data, collision vertex assumed
  - $m_{ee} \propto r_{\text{conv}}$
- $R_\gamma$ method
  - Measure $\pi^0$ by tagging inclusive $\pi^0$ photons

$R_\gamma = \frac{N_{\gamma^\text{incl}}}{N_{\gamma^\text{inv}}}^{2007}$

2007 Run 7 Data, $|\eta|<0.35$

Min. Bias Centrality

$\bullet$ external conversions (PHENIX preliminary)

Example $n_{q,\gamma}=4$ with $p_T/n_q$ match

- $\chi^2 = 768.049$
- $NDF = 61$
- $\chi^2 / NDF = 12.591$

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$\chi^2$/NDF space in $n_{q,\gamma}$

- $p_T/n_q$ match
- $KE_T/n_q$ match

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Extract $v_{2,q}(p_{T,q})$ from $n_q$-scaled $\pi$, $K$, $p$

- Fit $v_2/n_q$ vs $K_{E_T}/n_q$ with scaled GammaDist
  - Probability density of Gamma distribution
    - 3 parameters ($\gamma$, $\mu$, $\beta$) + scale parameter $A$
  - Exclude protons when they separate in 20-40%, $K_{E_T} > 1$
Also seen at LHC in ALICE

Using conversions

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n_q scaling at the LHC

• n_q scaling for pi, K → not for pbar
  – Pbar blueshifted by 0.2 GeV/c

arXiv:1107.0080
arXiv:1207.1886