Probing heavy quark energy loss through photon + Q production

RPP 2013

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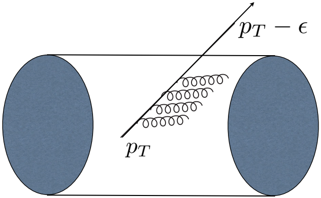
January 16, 2013

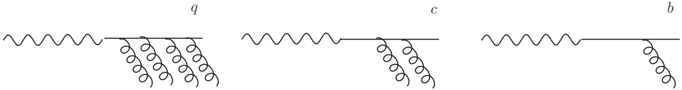
$\gamma + Q$ in $A - A$ Collisions

- arXiv:1211.6744 [I. Schienbein, F. Arleo, TS]
- Hard Probes - excellent tools for testing properties of QGP
- Compare to *pp* observables for estimate of parton energy loss
- Can have
  - Medium sensitive processes - Jets, hadrons, ...
  - Medium insensitive processes - photons, Z bosons, ...
- Combine both types of observables in one process
- γ - medium insensitive $\rightarrow E^{\gamma}$ not modified - a gauge for initial energy of jet
- (heavy) jet probes (massive) parton energy loss



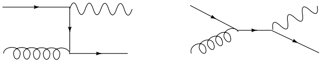
$\gamma + Q$ in $A - A$ Collisions [arXiv:1211.6744]

- Concentrate on heavy quarks Q (charm/bottom)
- Help clarify energy loss in the heavy quark sector and the expected hierarchy $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ [Dokshitzer Kharzeev 2001]



how are they produced?

- LO - $\mathcal{O}(\alpha\alpha_s)$ Compton Subprocess $g + Q \rightarrow Q + \gamma$



- NLO - $\mathcal{O}(\alpha\alpha_s^2)$

$$g + g \rightarrow Q + \bar{Q} + \gamma$$
$$g + Q \rightarrow g + Q + \gamma$$
$$Q + q \rightarrow q + Q + \gamma$$
$$Q + \bar{q} \rightarrow Q + \bar{q} + \gamma$$

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$$Q + \bar{Q} \rightarrow Q + \bar{Q} + \gamma$$
$$q + \bar{q} \rightarrow Q + \bar{Q} + \gamma$$

Energy Loss Implementation

1. obtain a $\gamma + Q$ event in vacuum with a given p_Q^{vac}, p_γ^{vac}
2. sample the energy loss ϵ according to a probability distribution - *quenching weight* $\mathcal{P}_i(\epsilon)$
3. construct medium modified four-momenta according to:

$$
\begin{aligned}
p_Q &= p_{TQ}(\cosh y_Q, \vec{e}_{TQ}, \sinh y_Q) \\
&= [p_{TQ}^{vac} - \epsilon / \cosh y_Q^{vac}](\cosh y_Q^{vac}, \vec{e}_{TQ}, \sinh y_Q^{vac})
\end{aligned}
$$

4. Use the modified four-vectors to evaluate observables $(p_{TQ}, p_{T\gamma}, q_T, ...)$

Quenching Weights

- Modify E_Q^{vac} so that $E_Q^{med} = E_Q^{vac} - \epsilon_Q$
- ϵ_Q obtained through rejection-acceptance method from quenching weight distribution
  - Armesto et al. Phys.Rev.D71:054027 2005
  - through multiple soft scattering - BDMPS-Z
  - $P(\epsilon) = p_0\delta(\epsilon) + p(\epsilon)$
  - Mass dependence enters as - m_Q/E_Q
  - when m_Q/E_Q large - energy loss substantially reduced
  - hierarchy $\epsilon_q > \epsilon_c > \epsilon_b$

2 particle final state observables

- p_{TQ}, $p_{T\gamma}$
- The two-particle final state - a range of observables
- Photon-jet pair momentum:

$$q_\perp = p_{T\gamma} - p_{TQ}$$

- Photon-jet energy asymmetry:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

- Momentum imbalance:

$$z_{34} = -\frac{\vec{p}_{T\gamma} . \vec{p}_{TQ}}{p^2_{T\gamma}}$$

- 2 particle observables require NLO kinematics

Experimental Cuts & Event Rates

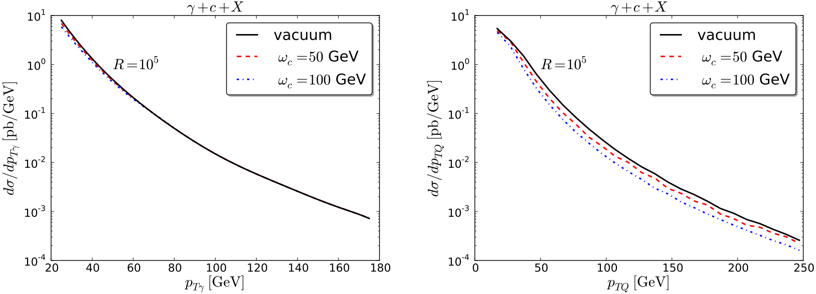
Cuts used for predictions

	p_T	Rapidity	Isolation/Jet radius	$\Delta\phi_{\gamma Q}$
Photon	$p_{T,\gamma}^{min} = 20$ GeV	$\lvert y_\gamma \rvert < 0.2$	$R = 0.4$, $\epsilon < 0.1 E_\gamma$	$> 3\pi/4$
Heavy quark jet	$p_{T,Q}^{min} = 12$ GeV	$\lvert y_Q \rvert < 0.2$	$R = 0.4$	—

Total cross-section and event numbers

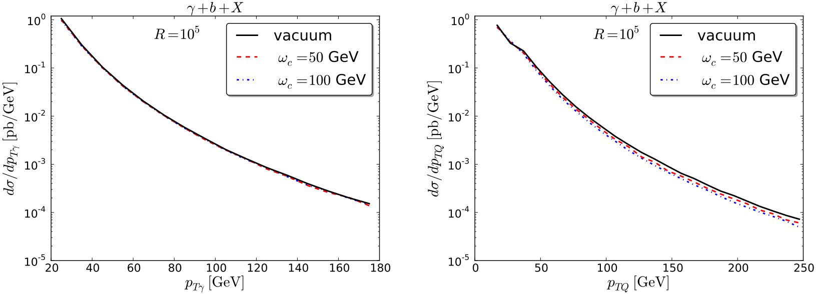
	$\sigma_{\gamma+Q}^{pp}$ [pb]	$\sigma_{\gamma+Q}^{PbPb}$ [nb]	$N_{\gamma+Q}^{Pb\ Pb}$
$\gamma + c$ ($\omega_c = 50$ GeV)	98	4200	2100
$\gamma + c$ ($\omega_c = 100$ GeV)	83	3556	1778
$\gamma + b$ ($\omega_c = 50$ GeV)	14.7	630	315
$\gamma + b$ ($\omega_c = 100$ GeV)	14.4	617	308

$\gamma + c$: $d\sigma/dp_T$



- γ - unaffected by medium, but $p_{T\gamma}$ spectra in medium reduced at low $p_{T\gamma}$ $\rightarrow$ experimental cuts
- Q - loses energy : p_{TQ} spectra reduced in medium
  - At small p_{TQ} : m_Q mildens energy loss
  - At larger p_{TQ} : suppression increases - mass effects not as relevant

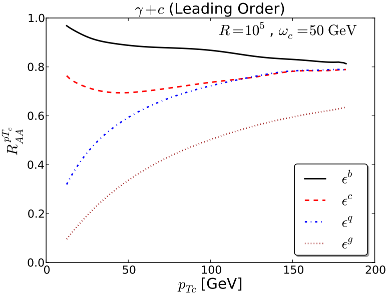
$\gamma + b$: $d\sigma/dp_T$

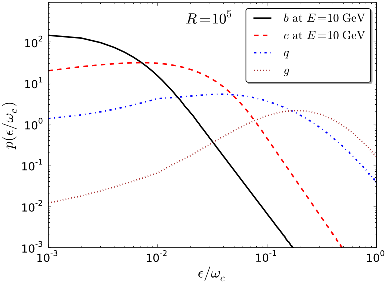


- Same effects as $\gamma + c$, but clearly reduced : $m_b > m_c$

Quenching factors & weights

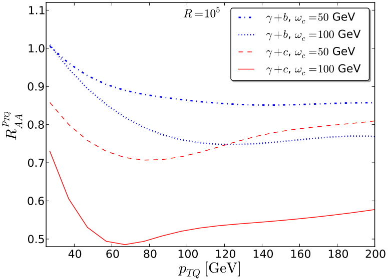
$$R_{AA}^{p_{TQ}} = \frac{d\sigma^{AA}/dp_{TQ}}{d\sigma^{pp}/dp_{TQ}}$$

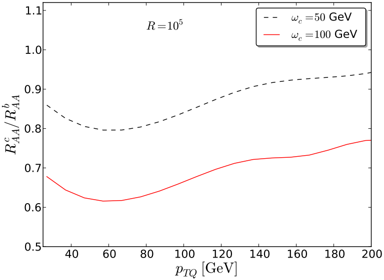




- $\gamma + c$ R_{AA} at LO using energy loss for b, c, q, g
- Quenching factors follow closely hierarchy of energy loss in BDMPS-Z quenching weights
  - $R_{AA}^b > R_{AA}^c > R_{AA}^q > R_{AA}^g$
  - Differences for quarks disappear at large p_T

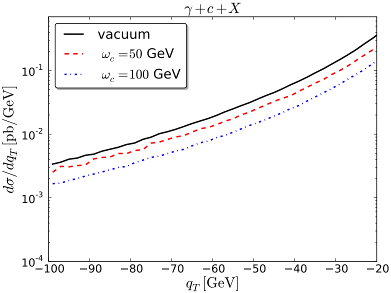
R_{AA} NLO

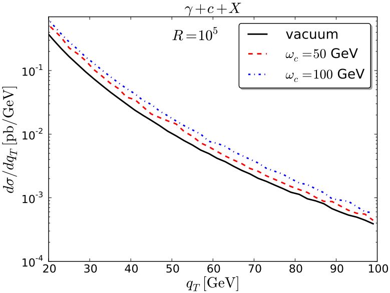




- Quenching factors at NLO similar to R_{AA} at LO
- Sensitivity to ω_c value - $50, 100$ GeV

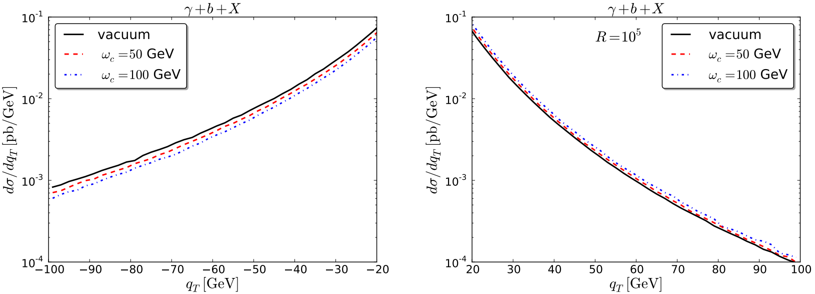
q_T : $\gamma + c$





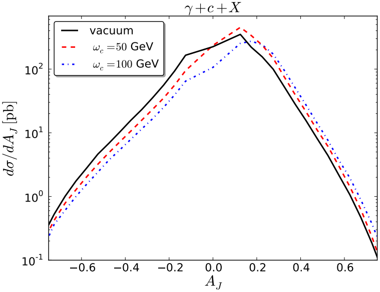
- medium spectra are right-shifted with respect to vacuum spectrum
- larger shift in energy for -ve q_T : $q_T \simeq p_{T\gamma}^{\min} - p_{TQ}$
- p_{TQ} grows for decreasing q_T - mass effects less pronounced - larger energy loss
- converse for $q_T > 0$

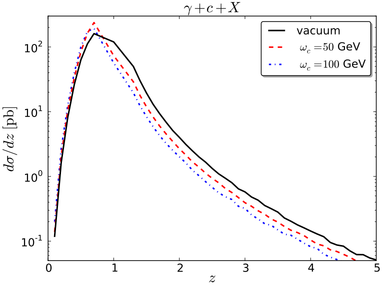
q_T : $\gamma + b$



- Same effects as $\gamma + c$, but clearly reduced : $m_b > m_c$

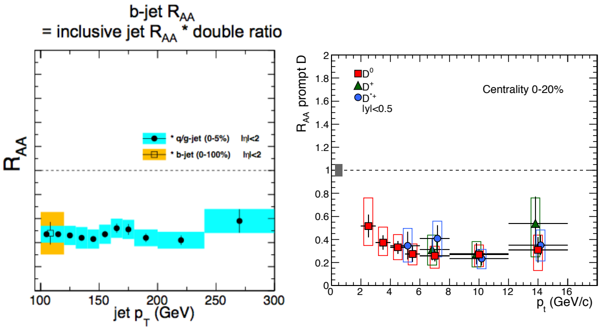
A_J & z





- A_J very similar to q_T : in-medium curves shifted to the right; shift larger for $A_J < 0$
- The $z < 1$ region corresponds to $p_{TQ} < p_{T\gamma}$ and $z > 1$ to $p_{TQ} > p_{T\gamma}$ - medium spectra left-shifted

Some Recent Measurements



- CMS preliminary b-jet R_{AA}
- arXiv:1203.2160v4 - ALICE D-meson suppression factor
- Indicate similar light and heavy particle suppression

Summary

- $\gamma + Q$ production in $A - A$ collisions excellent probe for heavy quark energy loss
- Access to hierarchy of energy loss
- Need constrained nPDFs to disentangle the energy loss