Probing AdS/CFT with Heavy Quarks

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Introduction

• AdS/CFT looks promising, pQCD also has its successes

• Desire a robust probe that can cleanly falsify one or both formalisms:
  - Try Heavy Quarks!
Quantitative AdS/CFT with Jets

• Langevin model
  - Collisional energy loss for heavy quarks
  - Restricted to low $p_T$
  - pQCD vs. AdS/CFT computation of $D$, the diffusion coefficient

• ASW model
  - Radiative energy loss model for all parton species
  - pQCD vs. AdS/CFT computation of $\hat{q}$
  - Debate over its predicted magnitude

• ST drag calculation
  - Drag coefficient for a massive quark moving through a strongly coupled SYM plasma at uniform $T$
  - not yet used to calculate observables: let’s do it!
Looking for a Robust, Detectable Signal

- Use future detectors’ identification of $c$ and $b$ to distinguish between pQCD, AdS/CFT
  
  • $R_{AA} \sim (1-\varepsilon(p_T))^n(p_T)$, where $p_f = (1-\varepsilon)p_i$ (i.e. $\varepsilon = 1-p_f/p_i$)
  • Asymptotic pQCD momentum loss:
    
    $$\varepsilon_{\text{rad}} \sim \alpha_s \hat{\ell}^2 \log(p_T/M_q)/p_T$$
  • String theory drag momentum loss:
    
    $$\varepsilon_{\text{ST}} \sim 1 - \exp(-\mu L), \quad \mu = \pi \lambda^{1/2} T^2/2M_q$$


- Independent of $p_T$ and strongly dependent on $M_q$!
- $T^2$ dependence in exponent makes for a very sensitive probe

- Expect: $\varepsilon_{\text{pQCD}} \to 0$ vs. $\varepsilon_{\text{AdS}}$ indep of $p_T$!!
  
  • $dR_{AA}(p_T)/dp_T > 0 \Rightarrow$ pQCD; $dR_{AA}(p_T)/dp_T < 0 \Rightarrow$ ST
Model Inputs for LHC Predictions

- AdS/CFT Drag: nontrivial mapping of QCD to SYM
  - “Obvious”: $\alpha_s = \alpha_{\text{SYM}} = \text{const.}, T_{\text{SYM}} = T_{\text{QCD}}$
    - $D/2\pi T = 3$ inspired: $\alpha_s = .05$
    - pQCD/Hydro inspired: $\alpha_s = .3$ ($D/2\pi T \sim 1$)
  - “Alternative”: $\lambda = 5.5$, $T_{\text{SYM}} = T_{\text{QCD}}/3^{1/4}$
    - Start loss at thermalization time $\tau_0$; end loss at $T_c$

- WHDG convolved radiative and elastic energy loss
  - $\alpha_s = .3$

- WHDG radiative energy loss (similar to ASW)
  - $\hat{q} = 40, 100$

- Use realistic, diffuse medium with Bjorken expansion
  - PHOBOS ($dN_g/dy = 1750$); KLN model of CGC ($dN_g/dy = 2900$)
LHC $c, b$ $R_{AA} p_T$ Dependence

- Significant rise in $R$
- Use of this $R$ simply allows $p_Q$ to be part of QCD expression allowing $p_T$ saturation below .2

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An Enhanced Signal

• But what about the interplay between mass and momentum?
  
  - Take ratio of c to b \( R_{\text{AA}}(p_T) \)

  • pQCD: Mass effects die out with increasing \( p_T \)
    \[
    R_{\text{PQCD}}^{cb}(p_T) \sim 1 - \alpha_s n(p_T) L^2 \log(M_b/M_c) (\hat{q}/p_T) 
    \]
    - Ratio starts below 1, asymptotically approaches 1.
    Approach is slower for higher quenching

  • ST: drag independent of \( p_T \), inversely proportional to mass. Simple analytic approx. of uniform medium gives
    \[
    R_{\text{PQCD}}^{cb}(p_T) \sim n_bM_c/n_cM_b \sim M_c/M_b \sim .27 
    \]
    - Ratio starts below 1; independent of \( p_T \)
LHC $R^{c}_{AA}(p_T)/R^{b}_{AA}(p_T)$ Prediction

- **Recall the Zoo:**
  - Taking the ratio cancels most normalization differences seen previously.
  - pQCD ratio asymptotically approaches 1, and more slowly so for increased quenching (until quenching saturates).
  - AdS/CFT ratio is flat and many times smaller than pQCD at only moderate $p_T$. 

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But There’s a Catch

- Speed limit estimate for applicability of AdS/CFT drag computation
  - $\gamma < \gamma_{\text{crit}} = (1 + 2M_q/\lambda^{1/2} T)^2$
  - $\sim 4M_q^2/(\lambda T^2)$
  - Limited by $M_{\text{charm}} \sim 1.2$ GeV

- Ambiguous $T$ for QGP
  - Smallest $\gamma_{\text{crit}}$ for largest $T = T(\tau_0, x=y=0): (O)$
  - Largest $\gamma_{\text{crit}}$ for smallest $T = T_c: (||)$
LHC $R_{AA}^c(p_T)/R_{AA}^b(p_T)$ Prediction (with speed limits)

- $T(\tau_0)$: (O), corrections unlikely for smaller momenta
- $T_c$: (|), corrections likely for higher momenta

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Measurement at RHIC

- Future detector upgrades will allow for identified $c$ and $b$ quark measurements

- RHIC production spectrum significantly harder than LHC
  
  - $n_c \neq n_b \neq \text{const.}$
  
  - NOT slowly varying
    - No longer expect pQCD $dR_{AA}/dp_T > 0$
  
  - Large $n$ requires corrections to naïve $R^{cb} \sim M_c/M_b$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Comparison of RHIC and LHC production spectra.}
\end{figure}
RHIC $c, b$ $R_{AA}$ $p_T$ Dependence

- Large increase in $n(p_T)$ overcomes reduction in E-loss and makes pQCD $dR_{AA}/dp_T < 0$, as well

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RHIC $R^{cb}$ Ratio

- Wider distribution of AdS/CFT curves due to large $n$: increased sensitivity to input parameters
- Advantage of RHIC: lower $T$ => higher AdS speed limits

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Conclusions

- Year 1 of LHC could show qualitative differences between energy loss mechanisms:
  - $dR_{AA}(p_T)/dp_T > 0$ => pQCD; $dR_{AA}(p_T)/dp_T < 0$ => ST
- Ratio of charm to bottom $R_{AA}$, $R_{cb}^c$, will be an important observable
  - Ratio is: flat in ST; approaches 1 from below in pQCD partonic E-loss
  - A measurement of this ratio NOT going to 1 will be a clear sign of new physics: pQCD predicts ~ 2-3 times increase in $R_{cb}^c$ by 30 GeV — this can be observed in year 1 at LHC

- Measurement at RHIC will be possible
  - AdS/CFT calculations applicable to higher momenta than at LHC due to lower medium temperature

- Universality of pQCD and AdS/CFT Dependencies?