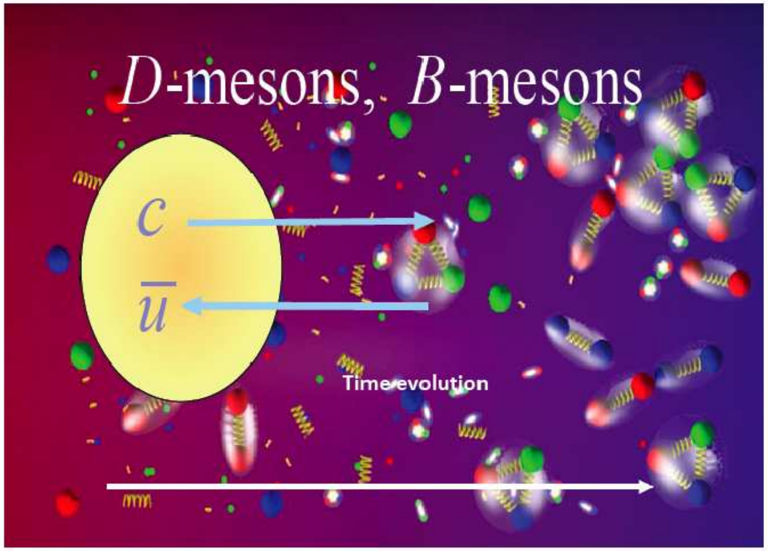
A light-front approach to heavy quark dynamics in the QGP.

Rishi Sharma

(Rishi Sharma, Ivan Vitev, Ben-Wei Zhang (0904.0032))



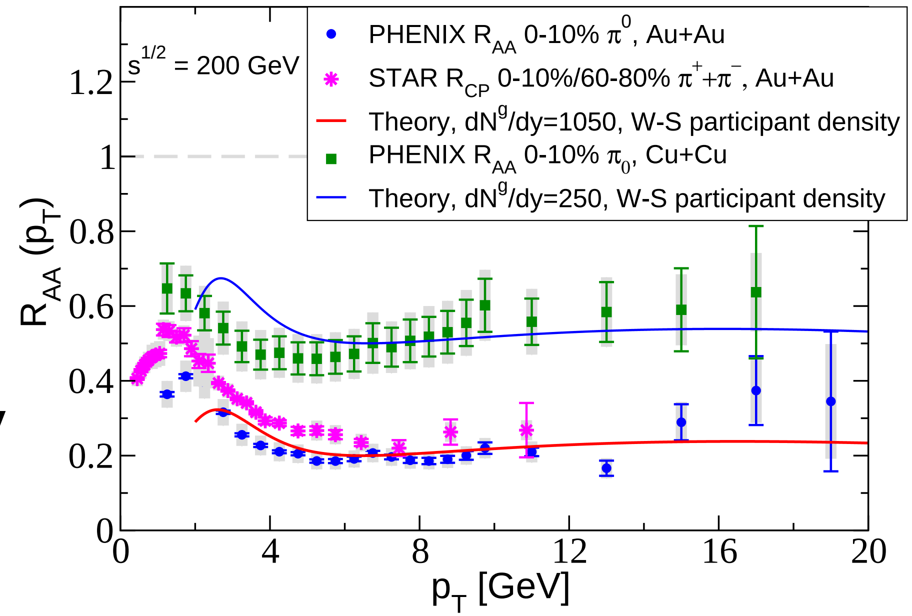
Outline

- Standard picture of energy loss.
  - Jet quenching for light hadrons.
  - Heavy quark puzzle at RHIC.
- Possibility of D and B mesons in a QGP.
- Heavy quark parton distribution (PDFs) and fragmentation functions (FFs).
- Combining collisional dissociation of heavy mesons with partonic level energy loss.
- Results for D and B mesons and their decay electrons in Cu and Au collisions at RHIC.
- Results for Pb collisions at the LHC.

The standard picture of energy loss

$$R_{AA}(p_T, \eta) = \frac{1}{\langle N_{coll} \rangle} \frac{\frac{d^2\sigma^{AA}}{d\eta dp_T}}{\frac{d^2\sigma^{NN}}{d\eta dp_T}}.$$

- The standard picture has been very successful in describing R_{AA} of light partons.
- The medium properties have been constrained by the measured particle multiplicities.
- $\frac{dN^g}{dy} = 1050$ for Au and $\frac{dN^g}{dy} = 250$ for Cu.



- The medium evolution has been modelled as a Bjorken expansion.

The heavy quark puzzle at RHIC

- Non photonic electrons show a very large suppression.
- Partonic energy loss is insufficient for heavy quarks.
- Include consistently the cold nuclear effects
  - Cronin effect from parton k_T broadening.
  - Initial radiative energy loss.
  - Shadowing due to coherent final state scattering.
- The suppression of B mesons is too small.

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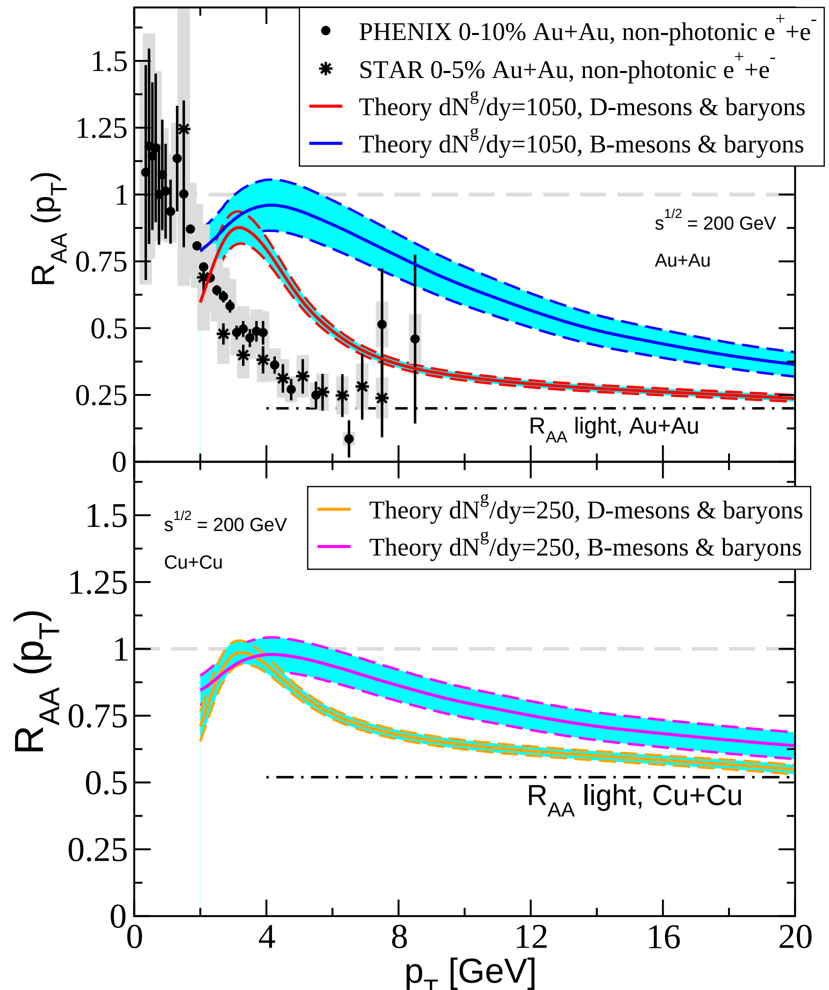
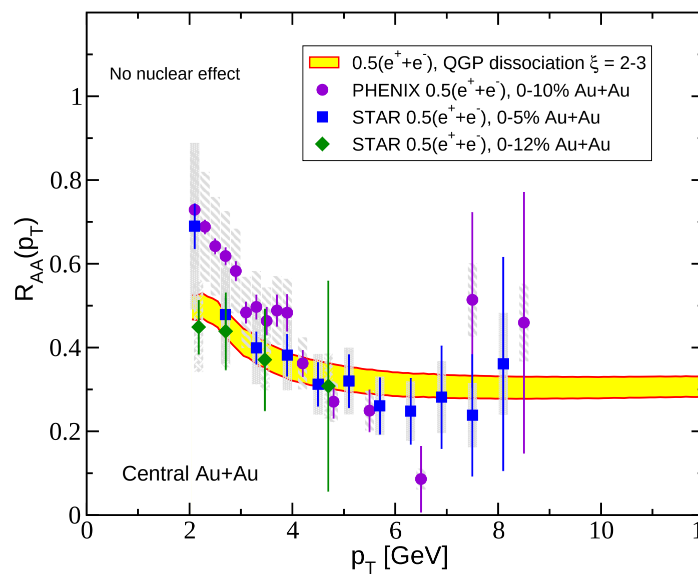


- A natural mechanism for $R^B_{AA} = R^D_{AA}$?

Formation time for heavy mesons

- The virtuality associated with meson production gives an estimate of the time of formation.
- $\tau_{\rm form} = \frac{1}{1+\beta_h} \frac{2z(1-z)p^+}{(k^\perp)^2+(1-z)M_h^2 - z(1-z)M_Q^2} (0.2{\rm GeV fm})$.
- For a $p_T = 10$ GeV meson, we get the following $\tau_{\rm form}$ values, to be compared to $\tau_L \sim 5-6$fm, the length of the medium.

	π	D	B
$\tau_{\rm form}$	20 fm	1.5 fm	0.4 fm



- We extend previous work *(Vitev, Adil (2006))* (i)Include partonic energy loss. (ii)Clarify role of mesons in QGP.

Can heavy-light mesons exist in QGP?

- We solve the Dirac equation with a thermal potential.
- The potential $V(r)$ at temperature T is given by lattice studies *(Kaczmarek, Petreczsky, Zantow, Karsch (2004))*.
- Explored for J/ψ, Υ by *(Petreczsky, Mocsy (2007)*.

$$V(r) = \begin{cases} -\frac{\alpha}{r} + \sigma r & r < r_{med}(T) \\ -\frac{\alpha_1(T)\exp(-\mu(T) r)}{r} + \sigma r_{med}(T) & r > r_{med}(T) \end{cases} .$$

- $\sigma = 0.22$ GeV^2, $\alpha = 0.45$, $r_{med} = 0.4 T_c/T$ fm.
- We separate the vector and scalar part of the potential to write the Dirac equation.

Can heavy-light mesons exist in QGP?

- The wavefunctions have a form

$$r\psi(\mathbf{r}) = \begin{pmatrix} G(r) \\ i\sigma\cdot\hat{\mathbf{r}}F(r) \end{pmatrix} \mathcal{Y}_{jls}^{j_3} \text{ where,}$$

$$F'(r) - \frac{\kappa}{r}F(r) = (-E + V_v(r) + m + V_s(r))G(r)$$

$$G'(r) + \frac{\kappa}{r}G(r) = (E - V_v(r) + m + V_s(r))F(r)$$

- The existence of bound states above T_c sensitive to parameters like σ, m.
- We do find bound states but with binding energy smaller than T, above T_c.
- For example, taking $m \sim 0.7m(T)$.

T GeV	0	0.08	0.15	0.19	0.23	0.30
E_b GeV	0.73	0.61	0.10	0.04	0.03	0.01

Two scenarios

- - The weakly bound states at equilibrium will be dissociated rapidly through scattering.
  - For a jet moving rapidly through the medium, a subtle question of time scales.
  - $\tau_{\rm eq}$, time taken for a meson to “realize” it is in a thermal medium versus $\tau_{\rm diss}$, the dissociation time scale. $\tau_{\rm eq} \sim r/\gamma$.
- Two scenarios arise:
  - If $\boxed{\tau_{\rm eq} > \tau_{\rm diss}}$ the wavefunction in the medium is better approximated by a vacuum wavefunction.
  - If $\tau_{\rm eq} < \tau_{\rm diss}$ the wavefunction in the medium is better approximated by a thermal wavefunction. Such a meson will dissociate very rapidly.

Light cone wavefunctions of mesons

- To calculate $\tau_{\rm diss}$, the PDFs $\phi_{Q/H}(x)$ and FFs $D_{H/Q}(z)$, need light cone wavefunctions of the mesons. *(Brodsky, Pauli, Pinsky (1997)); Braaten, Cheung, Yuan (1993); Ma (1984)*
- The lowest Fock component light cone wavefunction has the form
$$|\vec{P}^+; J\rangle = a_h^\dagger(\vec{P}^\perp; J)|0\rangle = \int \frac{d^2k^\perp}{(2\pi)^3} \frac{dx}{2\sqrt{x(1-x)}} \frac{\epsilon_{s_1 s_2}}{\sqrt{2}} \frac{\delta_{c_1 c_2}}{\sqrt{3}} \psi(x, k^\perp)$$
$$\times a_Q^{\dagger\, s_1 c_1}(x\vec{P}^+ + k^\perp) b_q^{\dagger\, s_2 c_2}((1-x)\vec{P}^+ - k^\perp)|0\rangle.$$
- $\psi(k^\perp, x)$ is proportional to $\exp\left(-\frac{k_\perp^2 + 4m_Q^2(1-x) + 4m_q^2 x}{4\Lambda^2 x(1-x)}\right)$, where Λ is related to the width in momentum space.

PDFs

- We find the PDFs and FFs from their operator definitions *(Collins, Soper (1981))*.

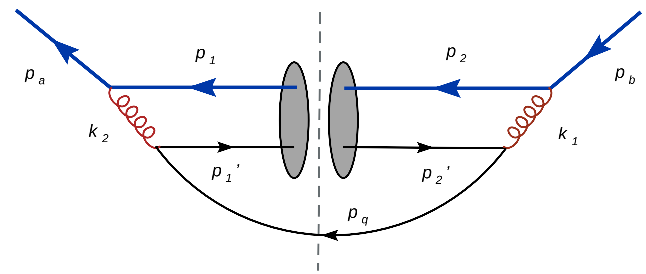
$$\phi_{Q/h}(x) = \int \frac{dy^-}{2\pi} e^{-ixP^+y^-} \langle P^+ | \bar{\psi}_Q(y^-, \mathbf{0}) \frac{\gamma^+}{2} \psi_Q(0, \mathbf{0}) | P^+ \rangle$$

- In the two Fock component approximation, $\phi_{Q/h}(x) = \frac{1}{2(2\pi)^3} \int d\bar{x} d^2k^\perp |\psi(\bar{x}, k^\perp)|^2 \delta(x - \bar{x})$.

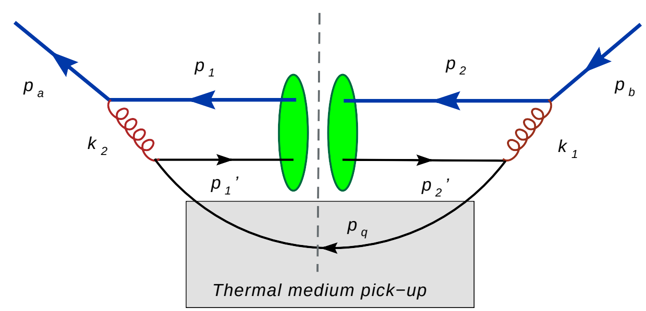
Fragmentation Functions

$$D_{h/Q}(z) = z \int \frac{dy^-}{2\pi} e^{i\frac{p^+}{z}x^-} \frac{1}{3}\mathrm{Tr}_{color} \frac{1}{2}\mathrm{Tr}_{Dirac}\Big[\frac{\gamma^+}{2} \times \langle 0|\psi(y^-,\mathbf{0})a_h^\dagger(P^+)a_h(P^+)\bar{\psi}(0,\mathbf{0})|0\rangle\Big]$$

- Need to go to α_s^2 to calculate $D(z)$.



- Thermal "pick-up" of the light quark suppressed by $\frac{1}{\exp(E_q/T)+1}$.



Calculated PDFs and FFs

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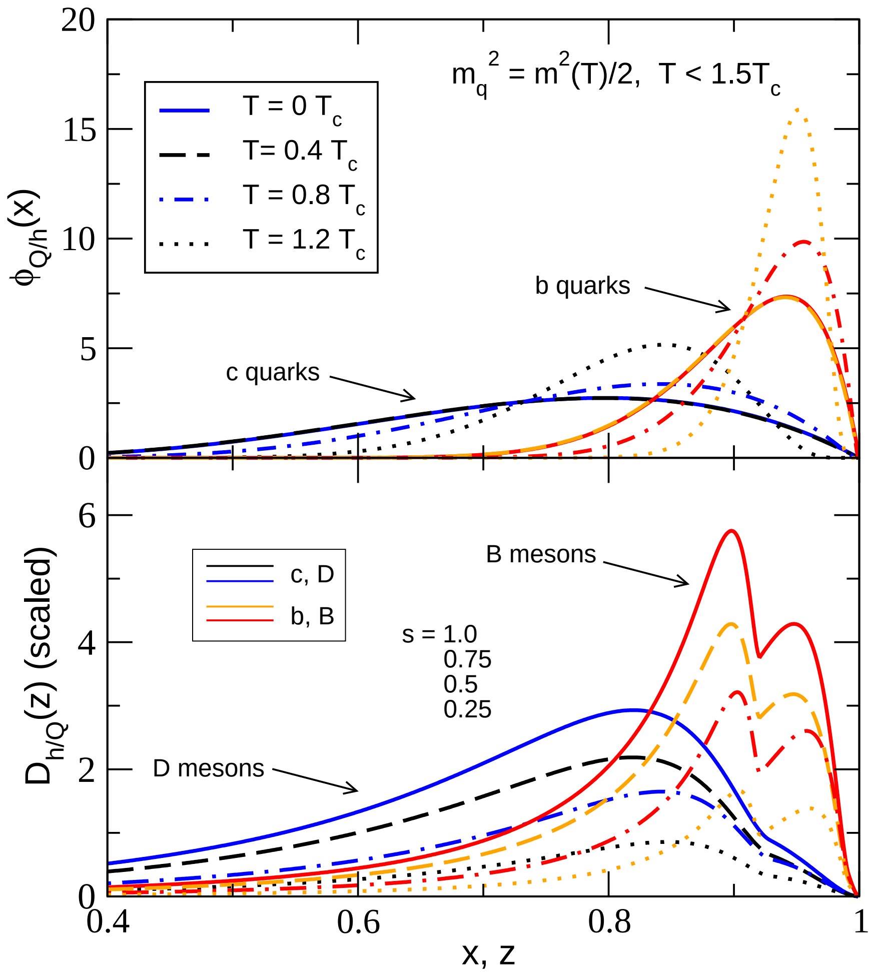
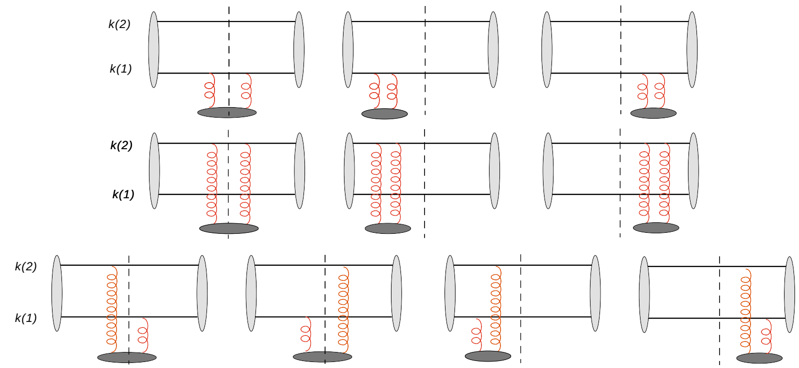


- The PDFs become narrower as temperature is increased, reflecting the behavior of $\psi(x, k^{\perp})$.
- The shape of the FFs is governed by $r = \frac{\sqrt{m_q^2 + \langle k_T^2 \rangle}}{\sqrt{m_Q^2 + \langle k_T^2 \rangle} + \sqrt{m_q^2 + \langle k_T^2 \rangle}}$ and doesn't change much.

Meson dissociation and rate equations



(Adil, Vitev)

- Dissociation probability $P_{\rm diss}(t) = 1 - |\langle \psi_t^*(\Delta k, x) | \psi_i(\Delta k, x) \rangle|^2$

- $\tau_{\rm diss} = \dfrac{1}{P_{\rm diss}(t)} \dfrac{dP_{\rm diss}(t)}{dt}$.

- Rate equations.

$$\partial_t f^Q(p_T,t) = \frac{-f^Q(p_T,t)}{\langle \tau_{\rm form}(p_T,t)\rangle} + \frac{1}{\langle \tau_{\rm diss}(\frac{p_T}{\bar{x}},t)\rangle} \int_0^1 \frac{dx}{x^2} \phi_{Q/H}(x) f^H(\frac{p_T}{x},t)$$

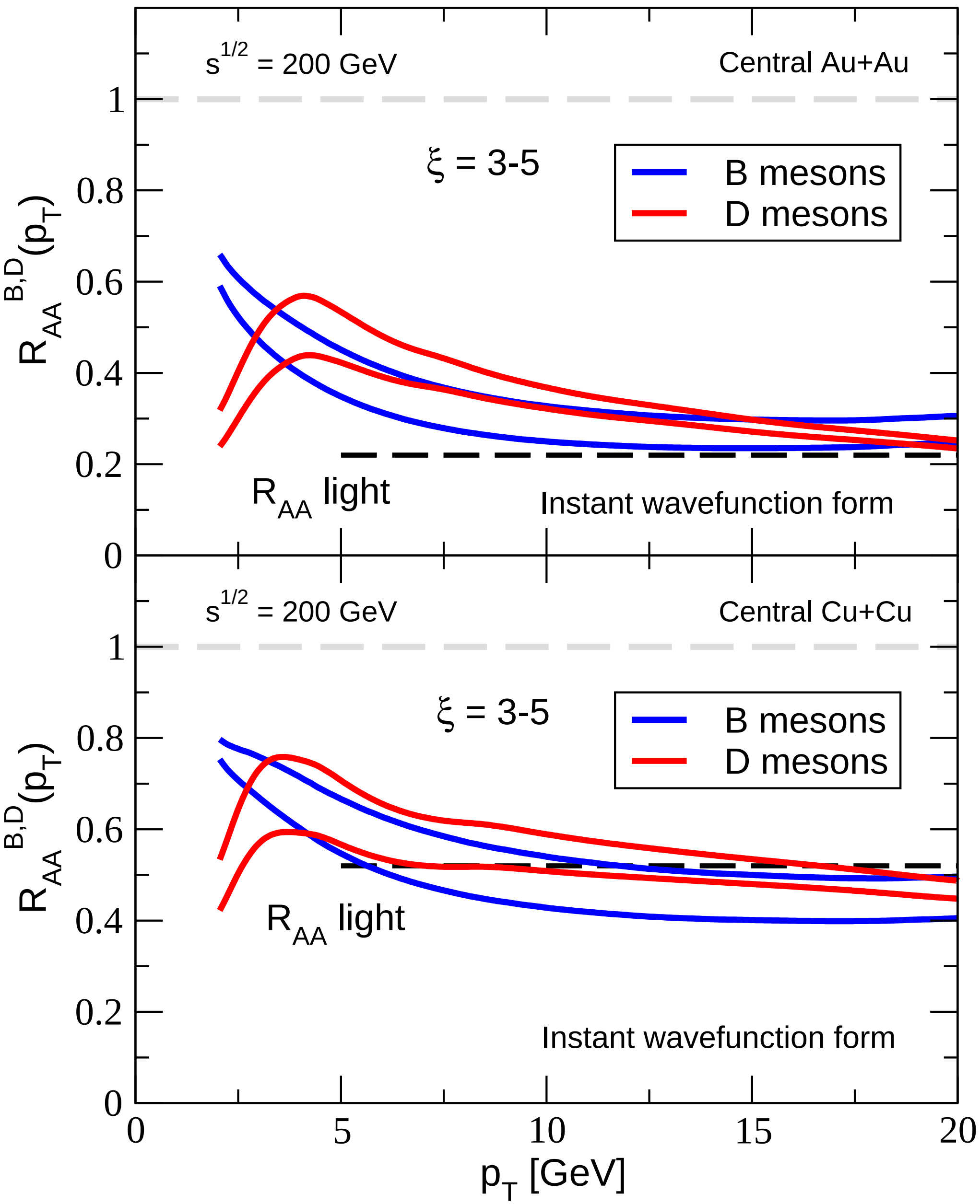
$$\partial_t f^H(p_T,t) = \frac{-f^H(p_T,t)}{\langle \tau_{\rm diss}(p_T,t)\rangle} + \frac{1}{\langle \tau_{\rm form}(\frac{p_T}{\bar{z}},t)\rangle} \int_0^1 \frac{dz}{z^2} D_{H/Q}(z) f^Q(\frac{p_T}{z},t)$$

$$f^Q(p_T,t) = \frac{d\sigma^Q(t)}{dyd^2p_T}\ , \quad f^Q(p_T,t=0) = \frac{d\sigma^Q_{PQCD}}{dyd^2p_T}$$

$$f^H(p_T,t) = \frac{d\sigma^H(t)}{dyd^2p_T}\ , \quad f^H(p_T,t=0) = 0$$

- One can estimate the time spent in the partonic form, $\tau_{\rm p}$ by $\dfrac{t_{\rm p}(p_T)}{t_{\rm total}} = \dfrac{\int_0^{L_{QGP}} dt\, t\, f^Q(p_T,t)}{\int_0^{L_{QGP}} dt\, t\, f^Q(p_T,t) + \int_0^{L_{QGP}} dt\, t\, f^H(p_T,t)}$.

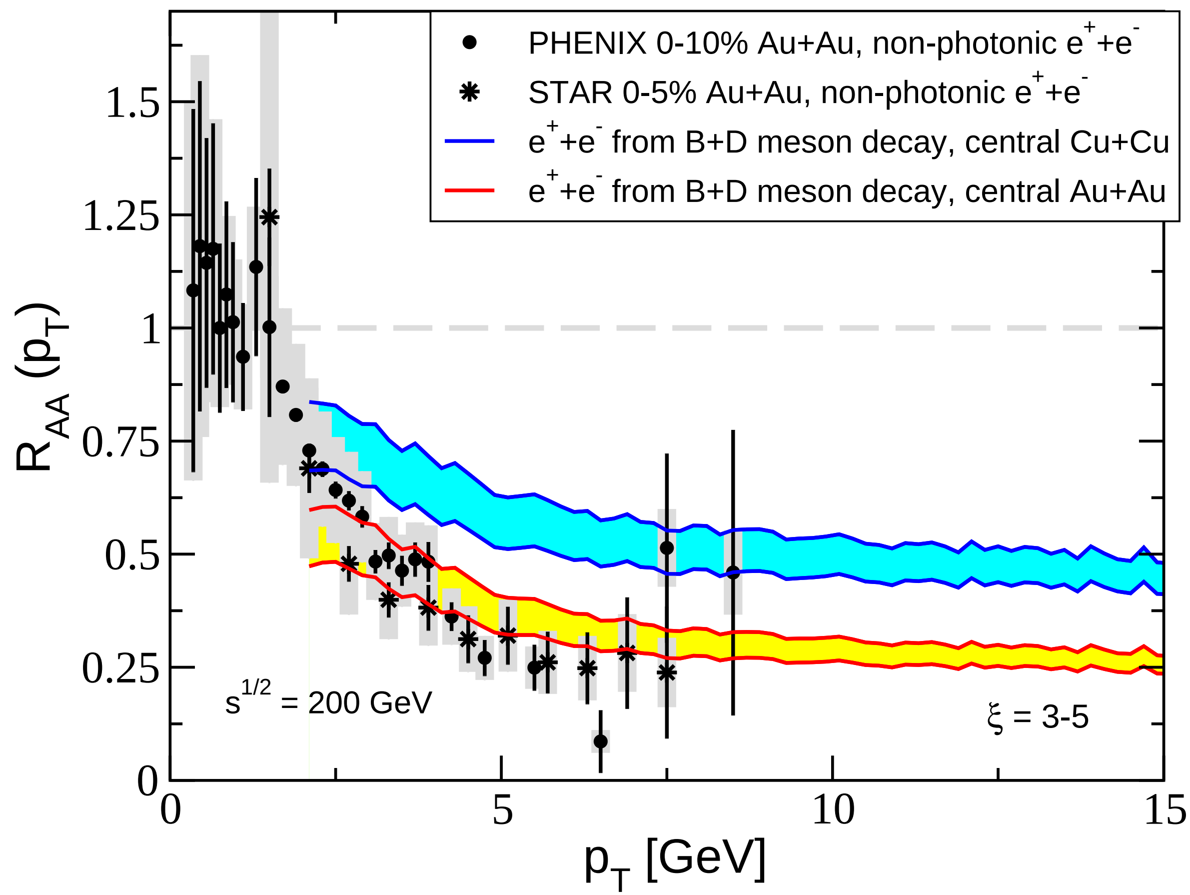
B and D meson results at RHIC



- The D and B meson suppression are comparable for $p_T \gtrsim 4$ GeV.
- This can be soon tested when results for R^D_{AA} and R^B_{AA} will be separately available.
- Cronin effect plays an important role near $p_T \sim 4$ GeV.

Results for decay electrons

- Obtained by decaying the C and B spectra to electrons using PYTHIA.
- For Au, the results can be compared to existing data.



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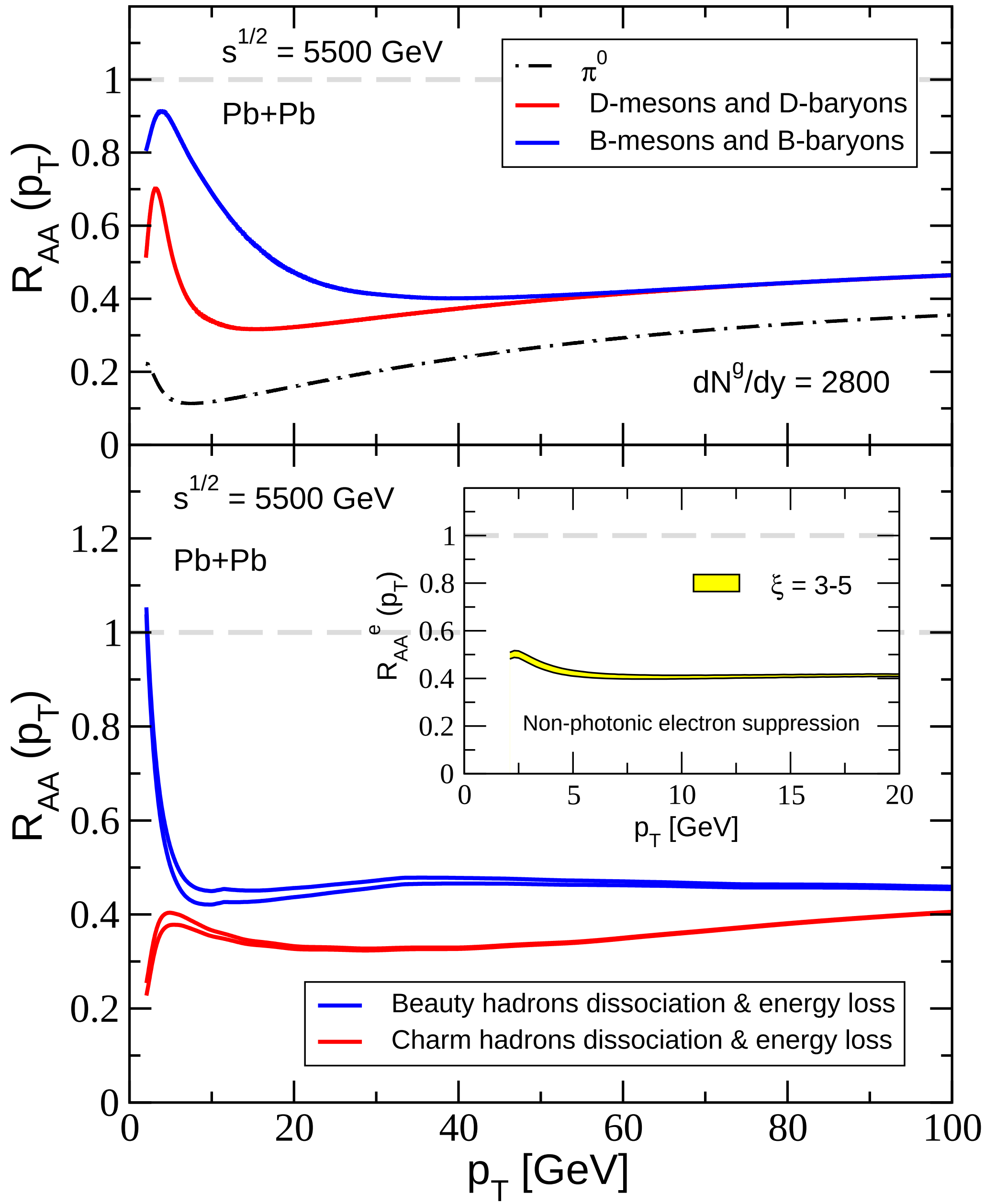
Results for the LHC



- The LHC will cover a larger range in p_T.
- We can test if $R^B_{AA} \sim R^D_{AA}$ for $p_T \gtrsim 40$ GeV (partonic only) or 10 GeV (dissociation+partonic).
- We also find a very sharp drop in R^B_{AA} near 10 GeV.

Conclusions

- Standard picture too simplified for heavy quarks and formation and subsequent dissociation of heavy mesons may be important.
- Meson like bound states can exist in the QGP for short times.
- We include both dissociation and partonic level energy loss and obtain comparable suppression for B and D quarks at RHIC.
- At the LHC for $p_T \gtrsim 10$ obtain $R_{AA}^D \simeq R_{AA}^B \simeq 0.4$.

Future directions

- One can try to extend the theory of jet shapes of light mesons *(Vitev, Wicks, Zhang (2008))* to heavy quarks (see presentation by *Ivan Vitev*).
- Dissociation may play a role for Quarkonia. Furthermore, quarkonia may thermalize faster because they are smaller.

Backup slides

- BACKUP SLIDES

Some definitions

- $$\chi \mu^2 \xi = \beta_Q \frac{\mu_0^2}{\lambda_0} \xi \ln \frac{t}{t_0} \ .$$

- $$\begin{aligned} \langle \tau_{\rm form}(p_T, t) \rangle &= \Bigg[\sum_i \int_0^1 dz\, D_{H_i/Q}(z) \\ &\quad \times \tau_{\rm form}(z, p_T, m_Q, t) \Bigg] \ . \end{aligned}$$

Fragmentation functions

- $D_{h/Q}(z) = \int \frac{dx_1 d^2k_1^\perp \; \psi(x_1,k_1^\perp)}{(2\pi)^3 2\sqrt{x_1(1-x_1)}} \frac{dx_1 d^2k_1^\perp \; \psi^*(x_1,k_1^\perp)}{(2\pi)^3 2\sqrt{x_1(1-x_1)}} \frac{\epsilon_{s_1 s_1'}}{\sqrt{2}} \frac{\epsilon_{s_2 s_2'}}{\sqrt{2}} \frac{\alpha_s^2 C_F^2}{3}$

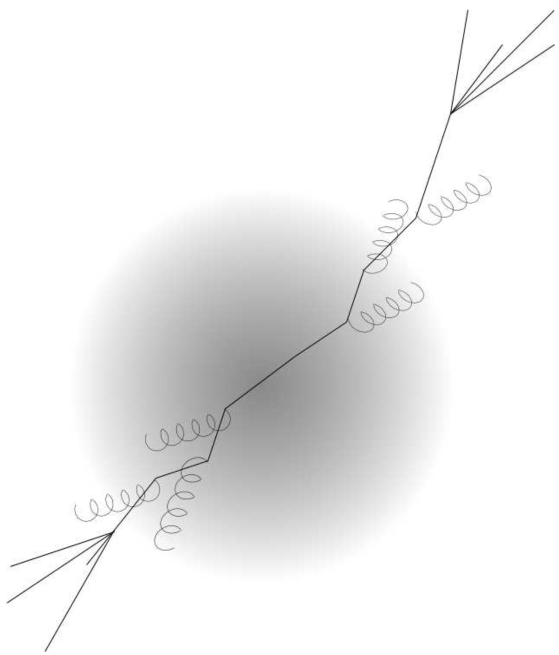
$$\int ds \; \theta\left(s - \frac{m_h^2}{z} - \frac{m_q^2}{1-z}\right) \mathrm{Tr}\left[\gamma^+ \frac{i}{\not{p}_a - m_Q} \gamma^\mu u_{s_1}(p_1) \bar{v}_{s_1'}(p_1') \gamma^\nu (\not{p}_q + m_q)\right.$$
$$\left.\gamma^\sigma v_{s_2'}(p_2') \bar{u}_{s_2}(p_2) \gamma^\lambda \frac{i}{\not{p}_b - m_q} \Pi_{\mu\nu}(p_a - p_q) \Pi_{\sigma\lambda}(p_b - p_q)\right] \frac{1}{\mathrm{Tr}[\gamma^+(\not{p})]}$$

- Their shape is determined by $r = \frac{\sqrt{m_q^2 + \langle k_T^2 \rangle}}{\sqrt{m_Q^2 + \langle k_T^2 \rangle}\sqrt{m_q^2 + \langle k_T^2 \rangle}}$

The standard picture

- Assume partons lose energy in the medium and fragment outside.

$$\left(N^{AB}_{\mathrm{bin.}}\right)^{-1} \frac{d\sigma^{q,g}_{AB}}{dy d^2\mathbf{p}_T} = K \sum_{abcd} \int dy_d \int d^2\mathbf{k}_a d^2\mathbf{k}_b \frac{f(k_b) f(k_b)}{|J(k_a,k_b)|} \frac{\alpha_s(\mu_r)}{2S} |\overline{M}_{ab\to cd}|^2 \times \frac{\phi_{a/N}\left(\frac{\tilde{x}_a}{1-\epsilon_a},\mu_f\right)\phi_{b/N}\left(\frac{\tilde{x}_b}{1-\epsilon_b},\mu_f\right)}{\tilde{x}_a \tilde{x}_b}$$



- Convolve with $P(\epsilon)$ to obtain the final spectrum.

$$\frac{d\sigma^{q,g\;Quench}_{AB}(p_T)}{dy d^2\mathbf{p}_T} = \int_0^1 \frac{d\epsilon}{(1-\epsilon)^2} P(\epsilon) \frac{d\sigma^{q,g}_{AB}\left(\frac{p_T}{1-\epsilon}\right)}{dy d^2\mathbf{p}_T}$$

- *Gyulassy, Vitev, Levai (2000); Armesto, Salgado, Wiedemann (2003); Arnold, Moore, Yaffe (2002); Wang, Guo (2000)*