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

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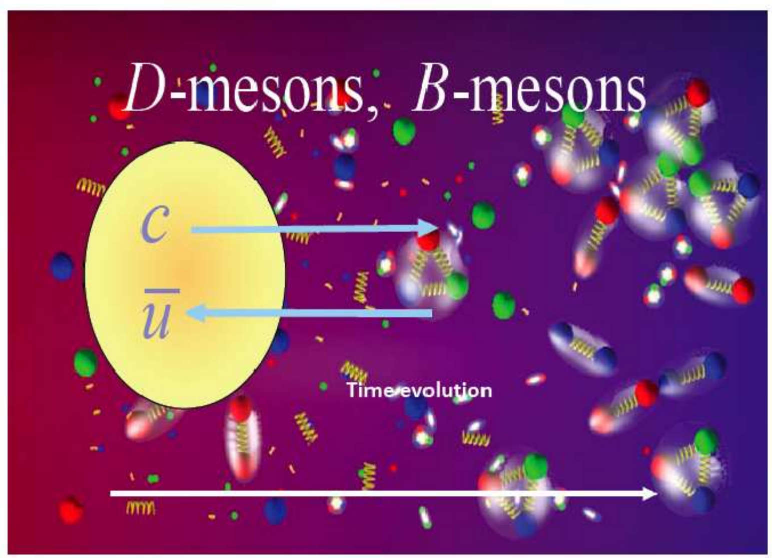
*(Rishi Sharma, Ivan Vitev, Ben-Wei Zhang Phys.Rev.C80:054902)*



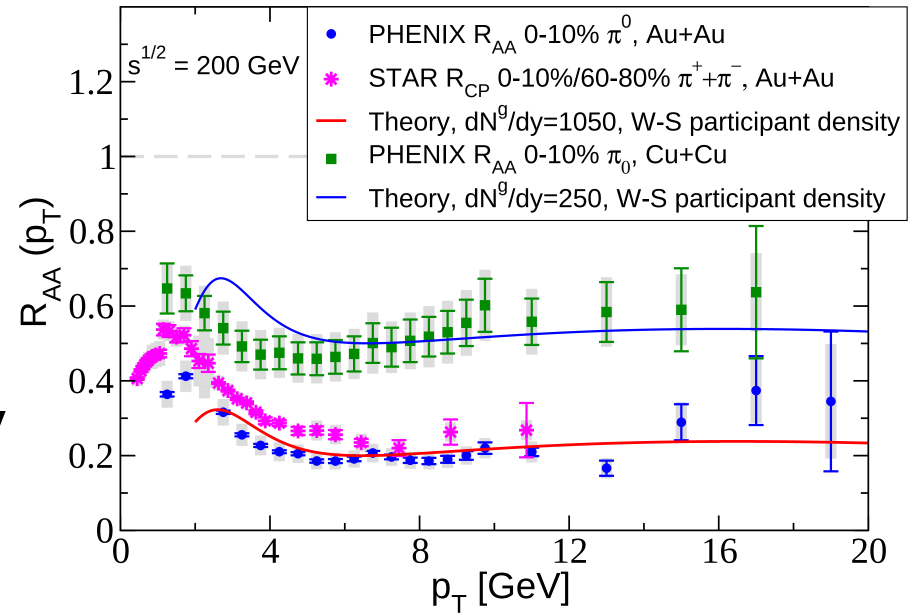
# Outline

- 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.

# Energy loss for light partons

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

- 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.



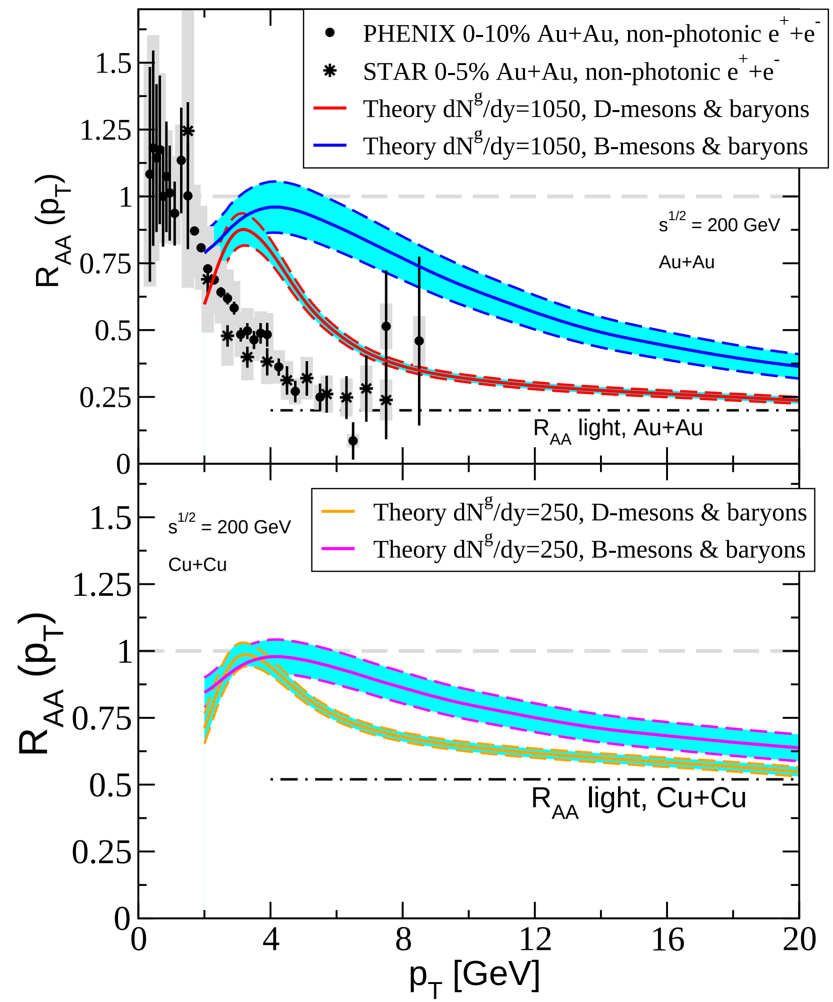

- The medium evolution has been modelled as a Bjorken expansion.

# Cold nuclear matter effects

- Cronin effect from parton $k_T$ broadening. Leads to enhancement of the spectrum at $p_T \sim 4GeV$.
- Shadowing due to coherent final state scattering. Enhanced by a factor of $A^{1/3}$ because of coherence for small $x$.
- Cold nuclear matter energy loss.
- Including these give the "modified" parton distributions for nuclei, which can be used to calculate $\frac{d\sigma^{q\ \mathrm{Cold}}(p_T)}{dy d^2\mathbf{p}_T}$ .
- *(Vitev, Goldman, Johnson and Qiu (2006).)*

# 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
- The suppression of $B$ mesons is too small.
- A natural mechanism for $R^B_{AA} = R^D_{AA}$?

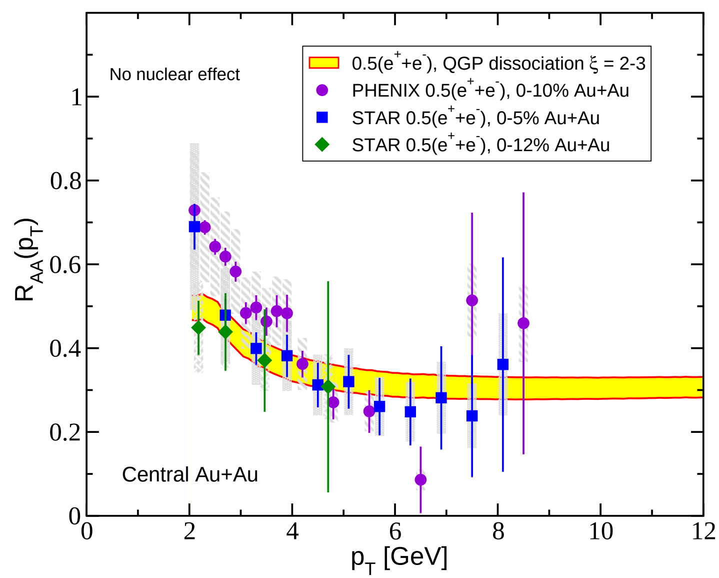


# Formation time for heavy mesons

- The virtuality associated with meson production gives an estimate of the time of formation.
- $\tau_{\rm form} = \frac{1}{1+\beta_h} \frac{2z(1-z)p^+}{(k^\perp)^2+(1-z)M_h^2-z(1-z)M_Q^2}(0.2\mathrm{GeV fm})$.
- 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.

| | $\pi$ | $D$ | $B$ |
|---|---|---|---|
| $\tau_{\rm form}$ | 20 fm | 1.5 fm | 0.4 fm |

- We extend previous work *(Vitev, Adil (2006))* (i)Include partonic e-loss. (ii)CNM effects. (iii) 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 $J/\psi$, $\Upsilon$ 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$^2$, $\alpha = 0.45$, $r_{med} = 0.4T_c/T$ fm.

# Can heavy-light mesons exist in QGP?

- The existence of bound states above $T_c$ sensitive to parameters like $\sigma$, $m$.
- 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 $\Lambda$ is related to the width in momentum space.

# PDFs

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

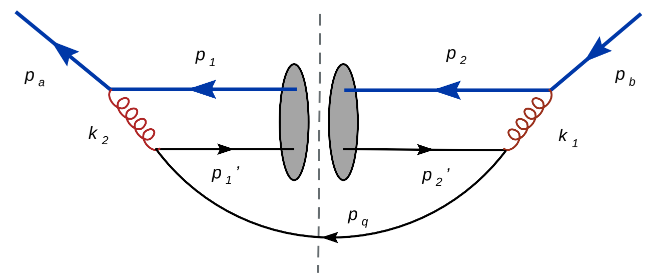
$$\phi_{Q/h}(x) = \int \frac{dy^-}{2\pi} e^{-ixP^+y^-} \langle P^+ | \bar{\psi}_Q(y^-, \mathbf{0}) \frac{\gamma^+}{2} \psi_Q(0, \mathbf{0}) | P^+ \rangle$$

- 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

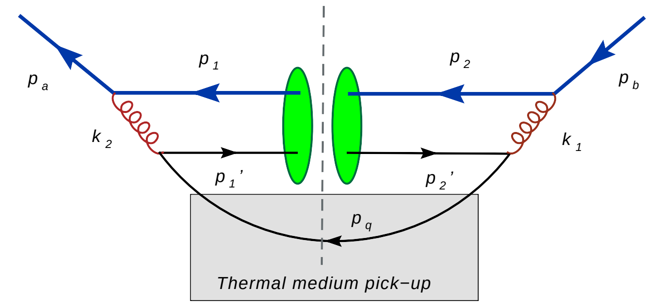
$$D_{h/Q}(z) = z \int \frac{dy^-}{2\pi} e^{i\frac{p^+}{z}x^-} \frac{1}{3}\mathrm{Tr}_{color}\frac{1}{2}\mathrm{Tr}_{Dirac}\Big[\frac{\gamma^+}{2} \times \langle 0|\psi(y^-,\mathbf{0})a_h^\dagger(P^+)a_h(P^+)\bar{\psi}(0,\mathbf{0})|0\rangle\Big]$$

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



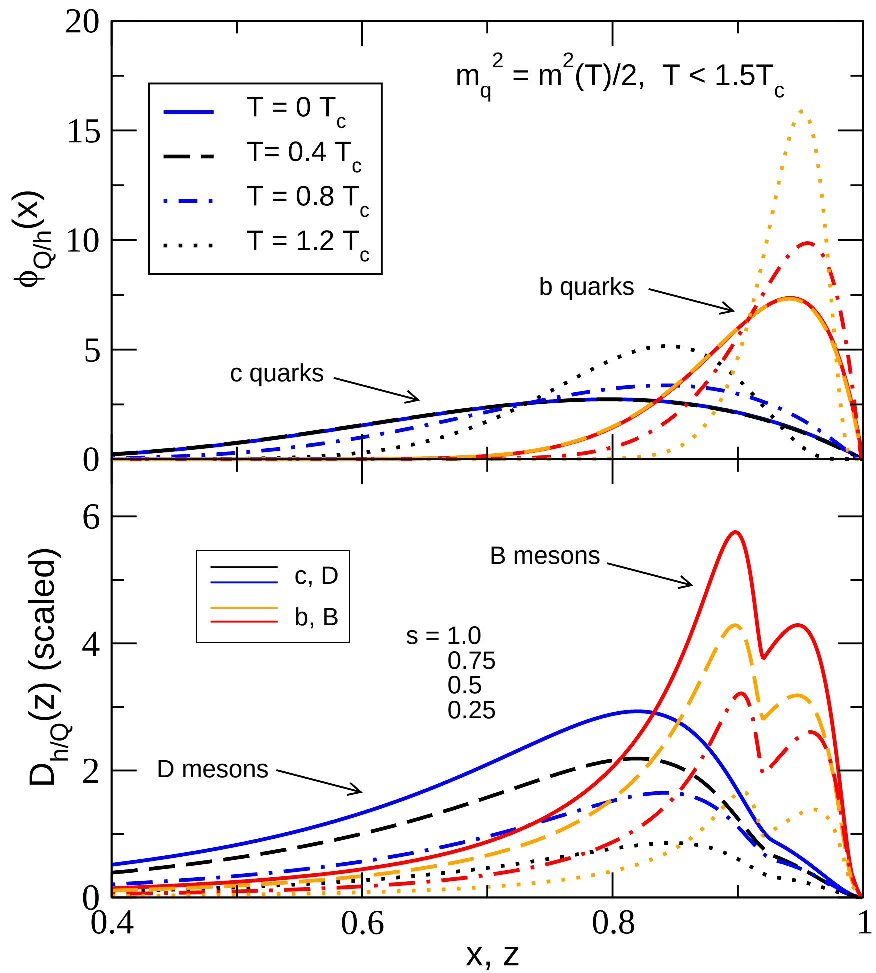
# Thermal effects

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



# Calculated PDFs and FFs

- 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

- Dissociation probability $P_{\rm diss}(t) = 1 - |\langle \psi_t^*(\Delta k)|\psi_i(\Delta k)\rangle|^2$
- $\tau_{\rm diss} = \frac{1}{P_{\rm diss}(t)} \frac{dP_{\rm diss}(t)}{dt}$.
- Rate equations

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

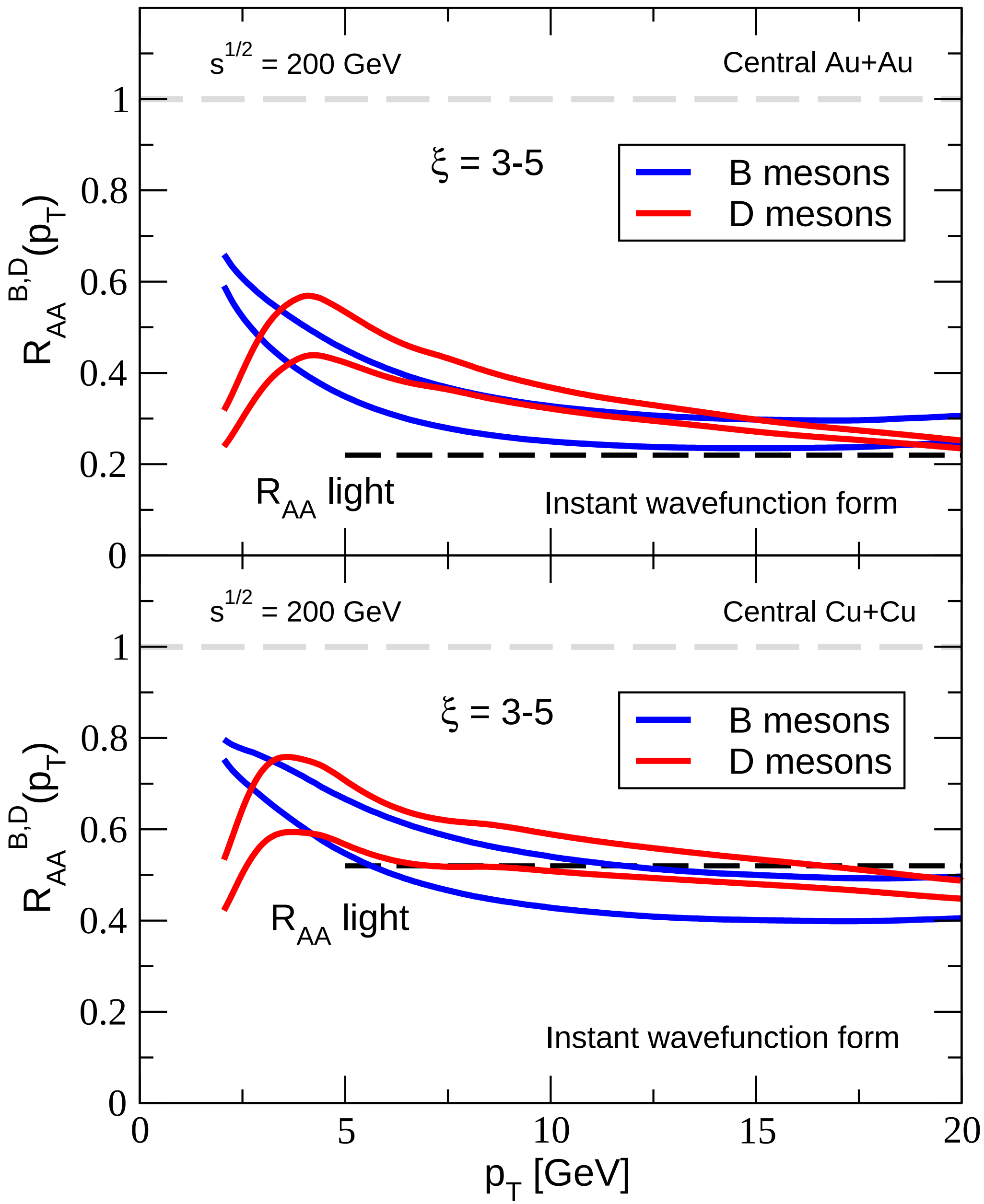
$$\partial_t f^H(p_T,t) = \frac{-f^H(p_T,t)}{\langle \tau_{\rm diss}(p_T,t)\rangle} + \frac{1}{\langle \tau_{\rm form}(\frac{p_T}{\bar{z}},t)\rangle} \int_0^1 \frac{dz}{z^2} D_{H/Q}(z) f^Q(\frac{p_T}{z},t)$$

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

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

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

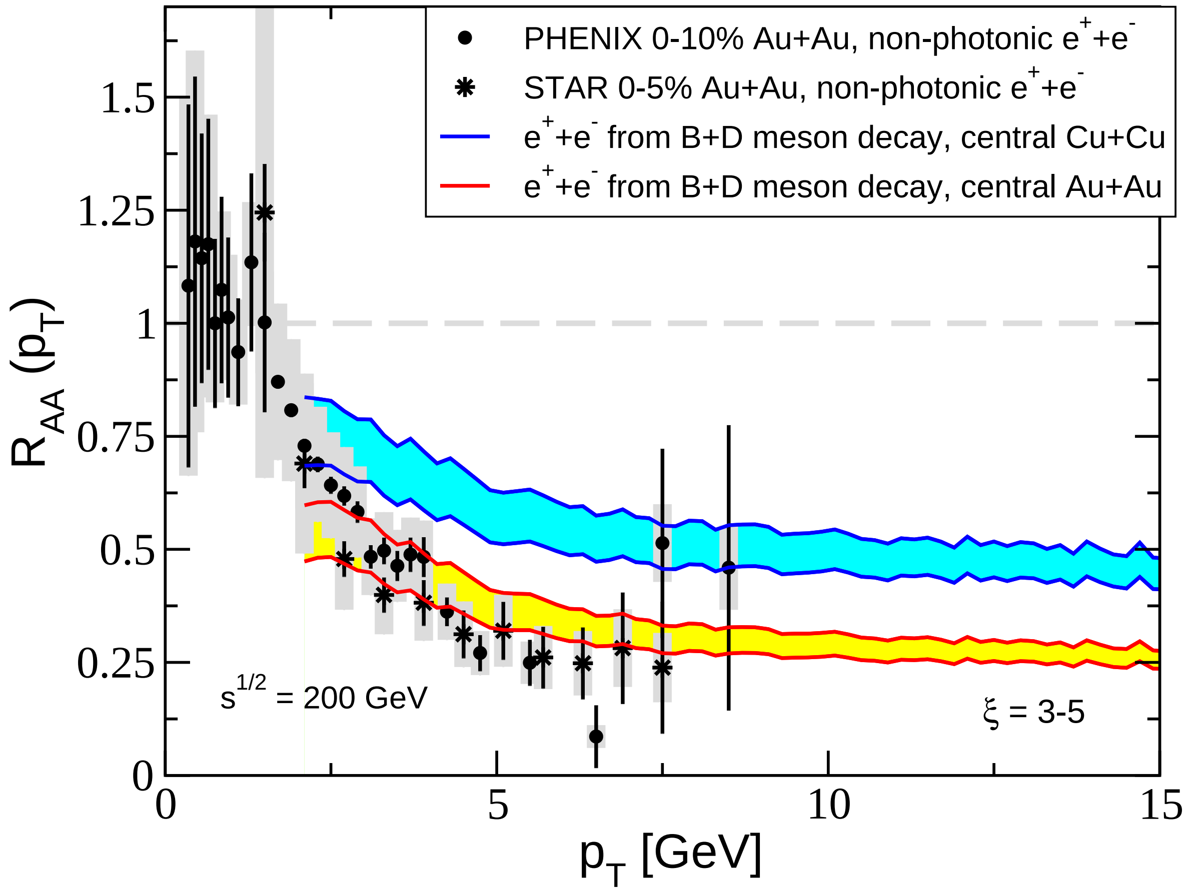
# $B$ and $D$ meson results at RHIC




- 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.

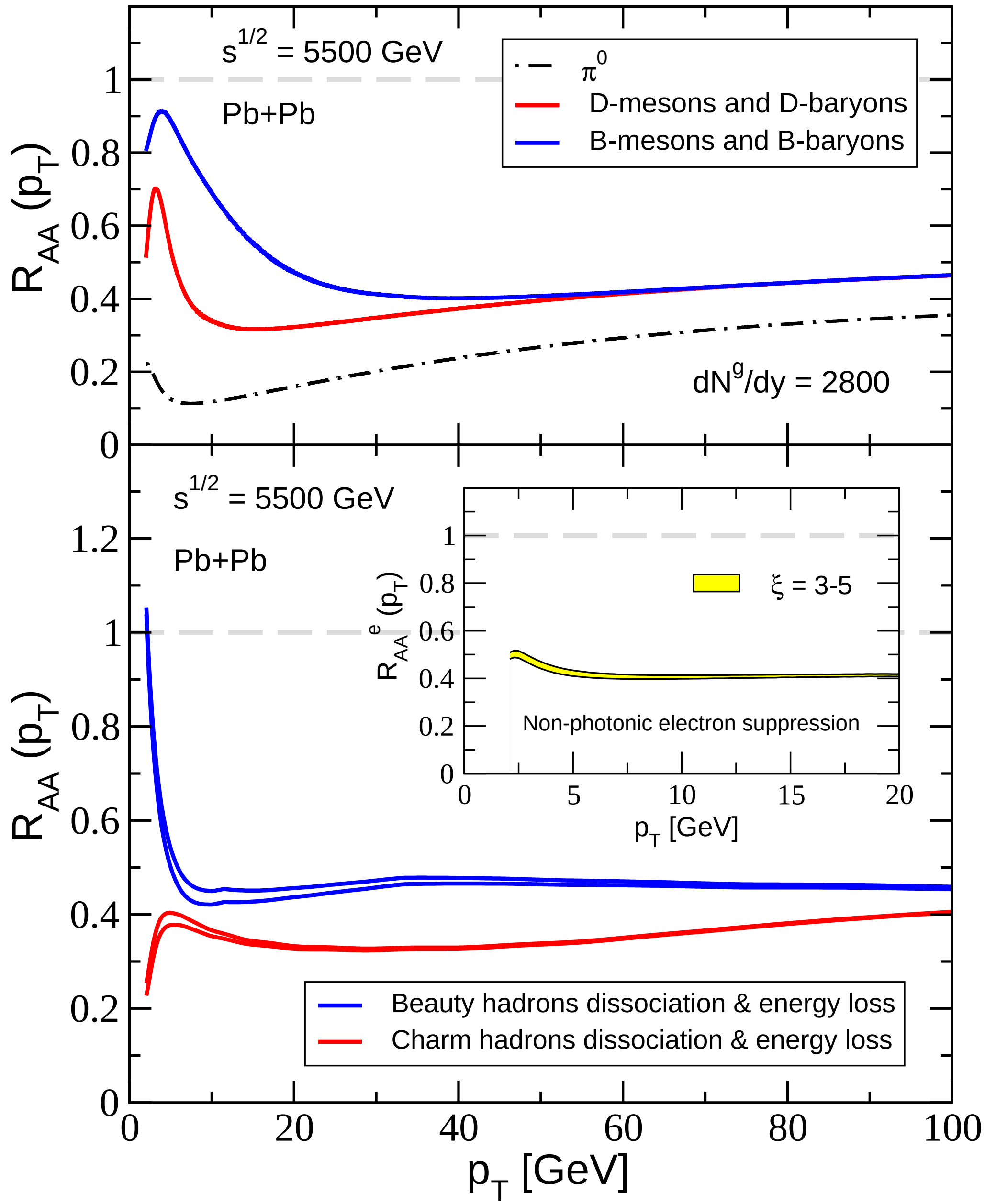
# Results for decay electrons

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




*(Sharma, Vitev, Zhang Phys.Rev.C80:054902)*

# 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

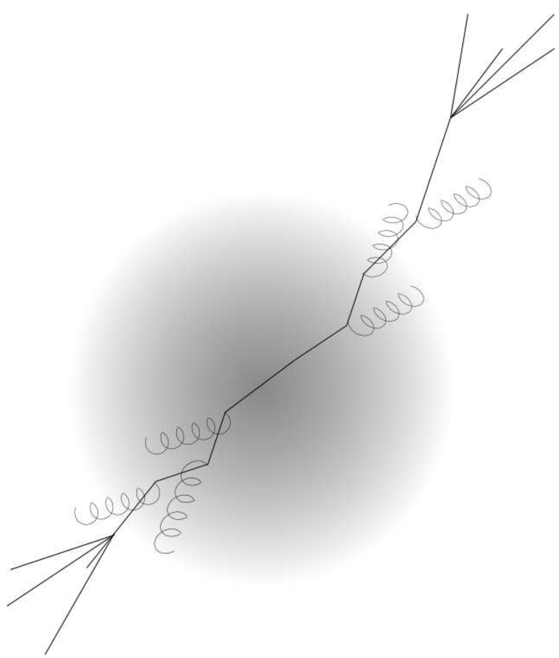
- Dissociation may play a role for Quarkonia suppression also.
- Furthermore, quarkonia may thermalize faster because they are smaller, which means the calculation of in medium distribution and fragmentation functions will be important.

# Backup slides

- Backup slides

# The standard picture

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

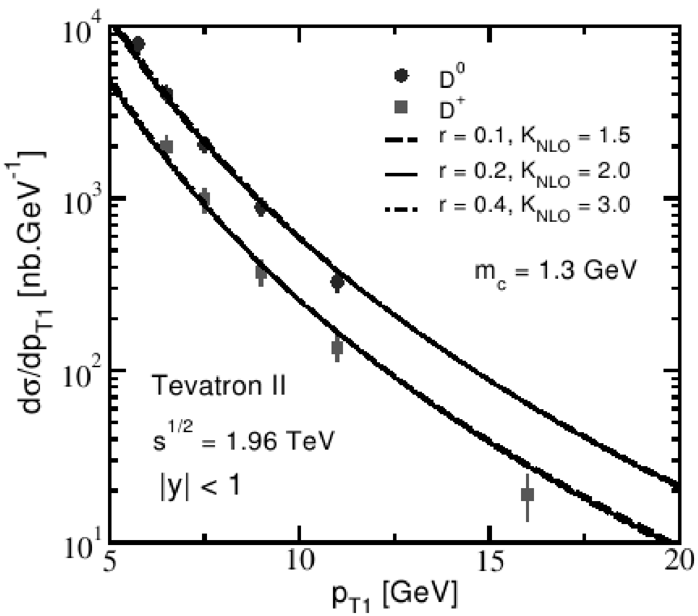


- Calculate $\frac{d\sigma^{q\ \mathrm{Cold}}(p_T)}{dyd^2\mathbf{p}_T}$ including cold nuclear matter effects.
- Convolve with the energy loss distribution $P(\epsilon)$ to obtain the final spectrum.

$$\frac{d\sigma^{q\ \mathrm{Quench}}(p_T)}{dyd^2\mathbf{p}_T} = \int_0^1 \frac{d\epsilon}{(1-\epsilon)^2} P(\epsilon) \frac{d\sigma^{q\ \mathrm{Cold}}\left(\frac{p_T}{1-\epsilon}\right)}{dyd^2\mathbf{p}_T}$$

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

# $p - p$ baseline




*Vitev, Goldman, Johnson, Qiu*

- $c$ quark parton distribution functions are most important for open charm production.
- A $K$ factor of about $2$ used. Cancels out in $R_{AA}$.

# Fragmentation functions

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

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

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

# Some definitions

- $$\langle \tau_{\rm form}(p_T,t)\rangle = \left[\sum_i \int_0^1 dz\, D_{H_i/Q}(z) \times \tau_{\rm form}(z,p_T,m_Q,t)\right].$$

- $$\xi = \log(\frac{2e^{-\gamma}}{b\mu}) + \frac{5}{16}$$

with $b\mu \ll 1$. $\Delta k^2 \sim (L/\lambda)\mu^2\xi$.