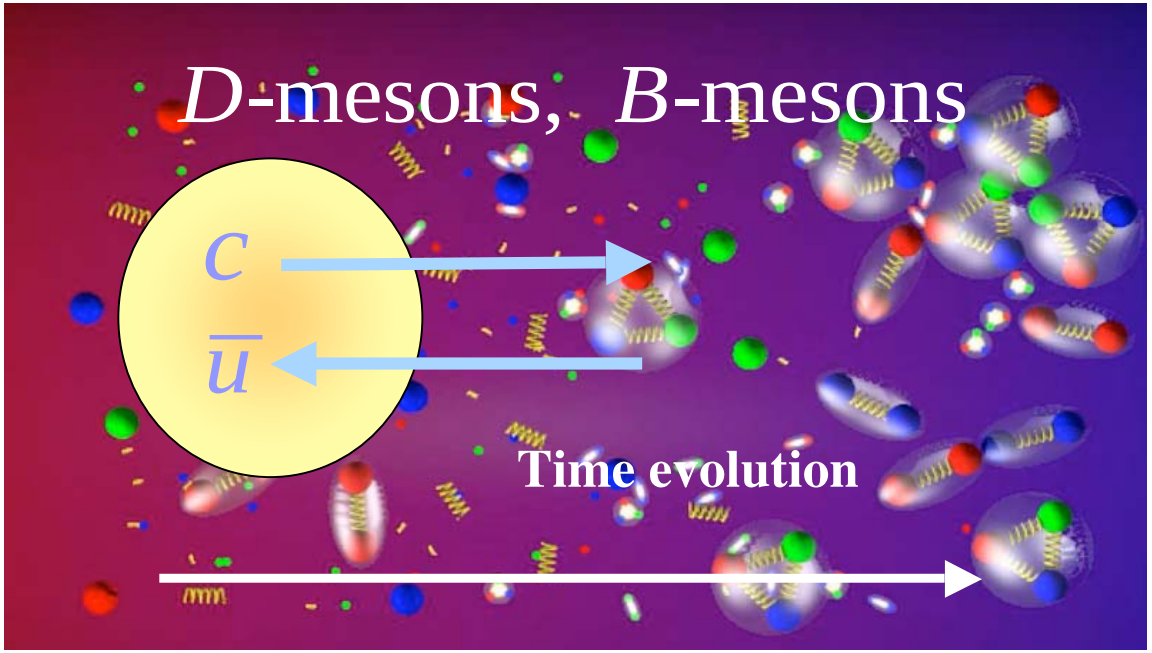
Collisional Dissociation of Heavy Mesons in the QGP



Ivan Vitev, Nuclear Theory, T-16 , LANL

"2007 AGS & RHIC Users' Meeting", June 18-22, 2007

BNL, Upton, NY

Los Alamos NATIONAL LABORATORY EST.1943

& Physics

Outline of the Talk

Based on: A. Adil, I. Vitev, Phys. Lett. B649, 139 (2007), hep-ph/0611109

Baseline D- and B- meson cross sections

- PQCD production mechanisms

Novel approach to heavy meson suppression

- Light hadron suppression and potential problems with heavy flavor
- Dissociation of heavy mesons in the QGP
- Unique signatures of such suppression mechanisms
- Suppression of non-photonic electrons at RHIC
- LHC results

Transport + quenching approach

- Drag and diffusion coefficients from pQCD
- Applications to heavy quark quenching and elliptic flow v_2

Future directions for heavy flavor

- Complete many-body PQCD simulations
- Direct determination of the heavy flavor

In preparation: H. van Hees, I. Vitev, [R. Rapp]

Perturbative Expansion for Heavy Mesons

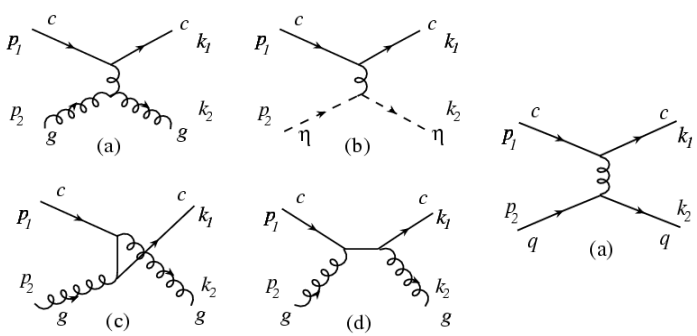
Single inclusive D - mesons

$$d\sigma^{(1)} \sim \phi_1(x_1,Q^2) \otimes \phi_2(x_2,Q^2) \otimes \frac{1}{2\hat{s}}\left|M\right|^2 \otimes D_1(z_1,Q^2)$$

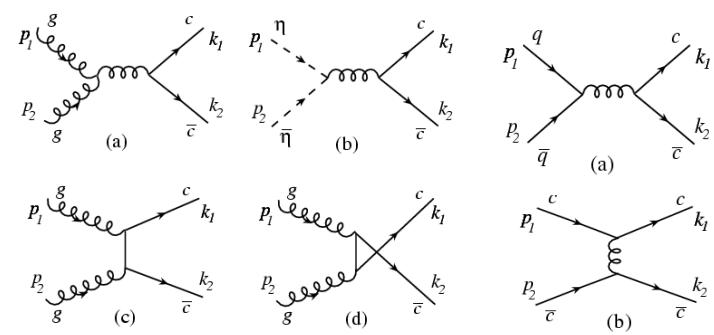
D - meson triggered back-to-back correlations

$$d\sigma^{(2)} \sim \phi_1(x_1,Q^2) \otimes \phi_2(x_2,Q^2) \otimes \frac{1}{2\hat{s}}\left|M\right|^2 \otimes D_1(z_1,Q^2) \otimes D_2(z_2,Q^2)$$

Flavor excitation



Flavor creation



Faster convergence of the perturbative series

Two different expansions

Slower convergence of the perturbative series

F. Olness et al., Phys.Rev.D59 (1999)

- Advantages: much faster convergence in α_s^n of the hard scatter $|M|^2$

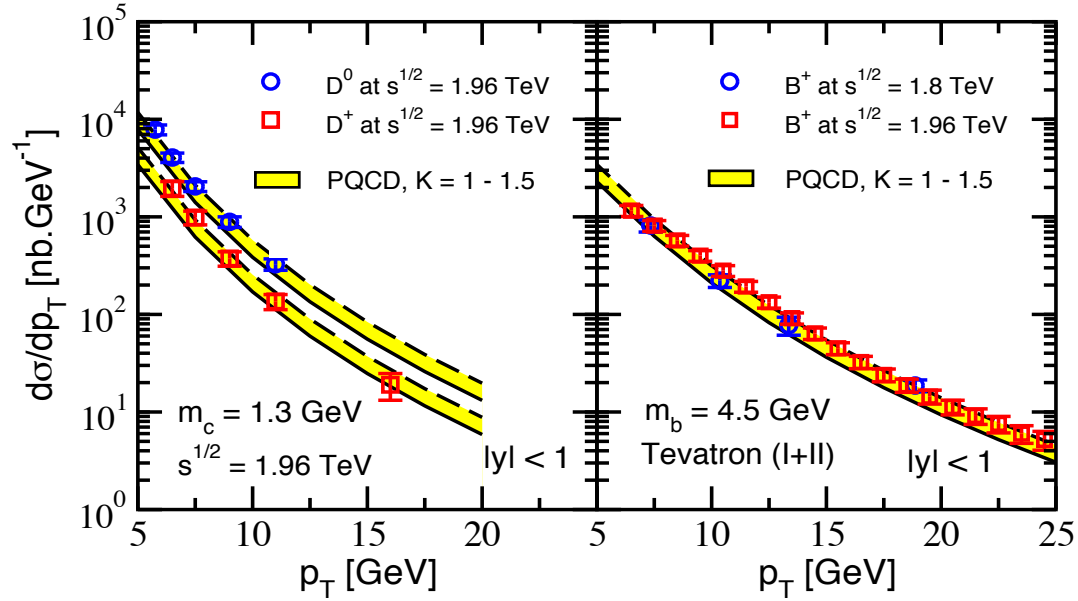
Heavy Quark Production in p+p Collisions

- Gluon fusion is not the dominant hard process in single inclusive open charm (bottom) production

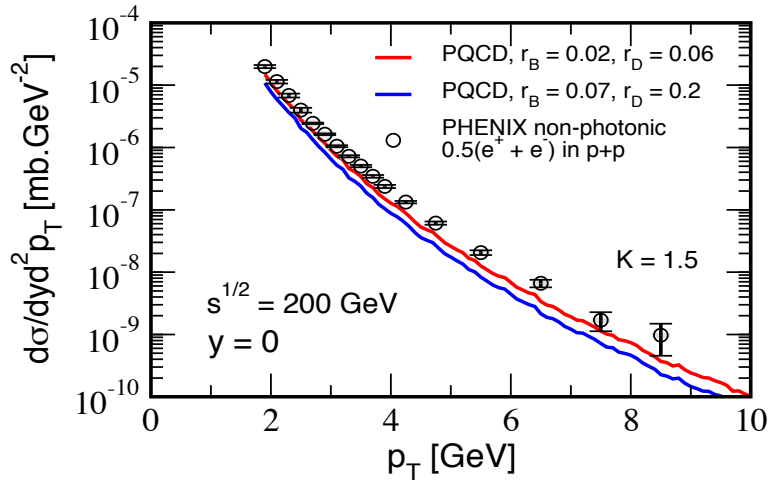
$$p + \bar{p} \rightarrow D + X$$

$$c + g \rightarrow c + g \qquad c + q(\bar{q}) \rightarrow c + q(\bar{q})$$

I.V.,T.Goldman,M.Johnson,J.W.Qiu, Phys.Rev.D74 (2006)



- Comparable to "NLO" results: (under-predicts the cross section by 30% - x 2)



Light Hadron Quenching in A+A (E-Loss)

- Small systems: **Quantum coherence**

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– **Static medium**

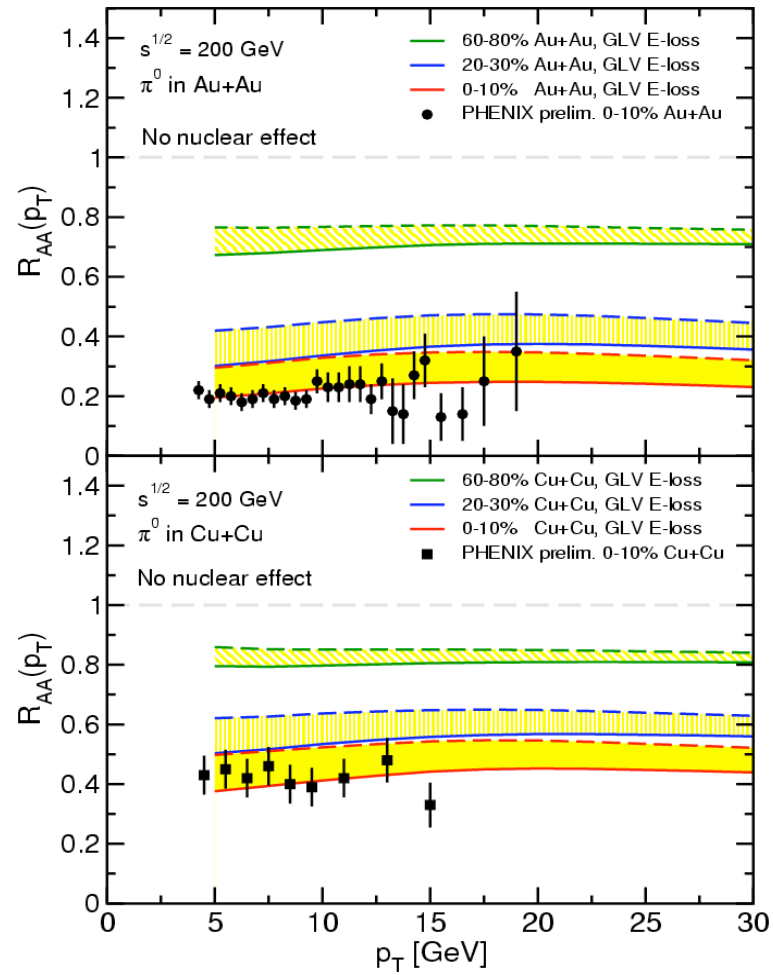
$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– **1+1D Bjorken**

- Jet Quenching: successful for light

$$R_{AA}(p_T, \eta) = \frac{1}{< N_{coll} >} \cdot \frac{d^2\sigma^{AA} / d\eta dp_T}{d^2\sigma^{NN} / d\eta dp_T}$$

Example: ~ 1000 N+N collisions in central Au+Au



I.V., Phys.Lett.B 639 (2006)

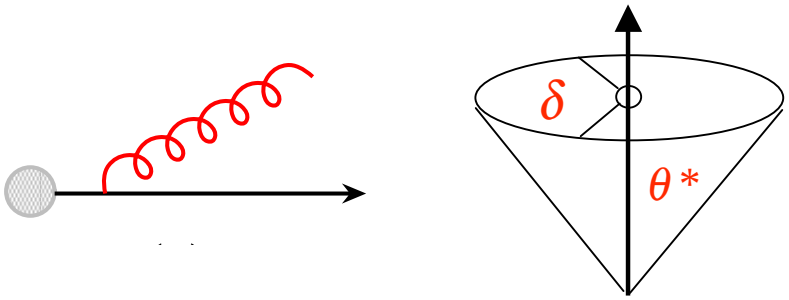
Heavy Quark Mass and Radiative Energy Loss

For massive quarks - "dead cone effect"

$$\frac{dN^{g}{}_{vac}}{d\omega d\sin\theta^{*} d\delta} \approx \frac{C_R \alpha_s}{\pi^2} \frac{1}{\omega \sin\theta^{*}}$$

$$\frac{dN^{g}{}_{vac}}{d\omega d\sin\theta^{*} d\delta} \approx \frac{C_R \alpha_s}{\pi^2} \frac{\sin\theta^{*}}{\omega\,(\sin^2\theta^{*} + M^2/E^2)}$$

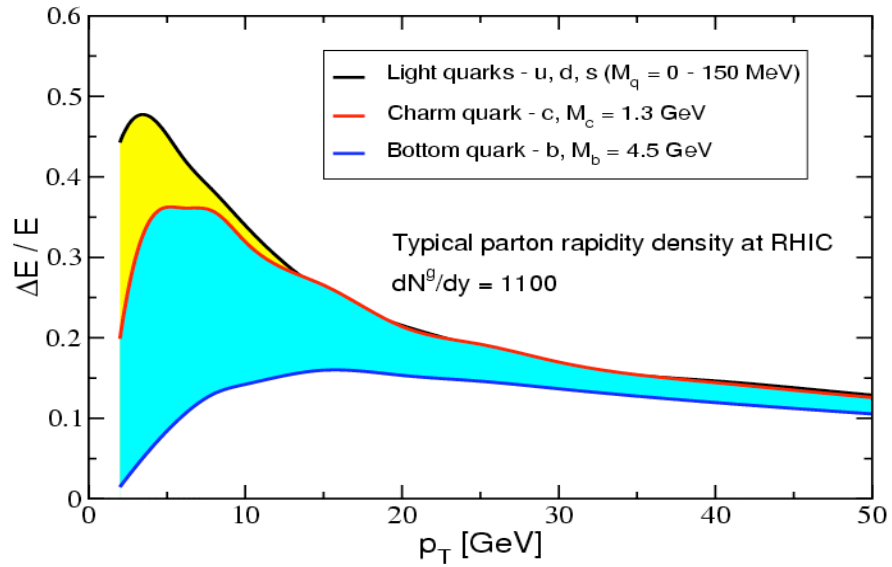
Cuts part of phase space



$$\left[\omega_{(1\ldots n)}\right]^{-1} \rightarrow \left[\omega_{(1\ldots n)} + \frac{m_g^2 + x^2 M^2}{2xE}\right]^{-1}$$

$$\frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2}} \rightarrow \frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2} + m_g^2 + x^2 M^2}, \quad x = \frac{k^+}{p^+} \approx \frac{\omega}{E}$$

M.Djordjevic, M.Gyulassy, Nucl.Phys.A (2004)

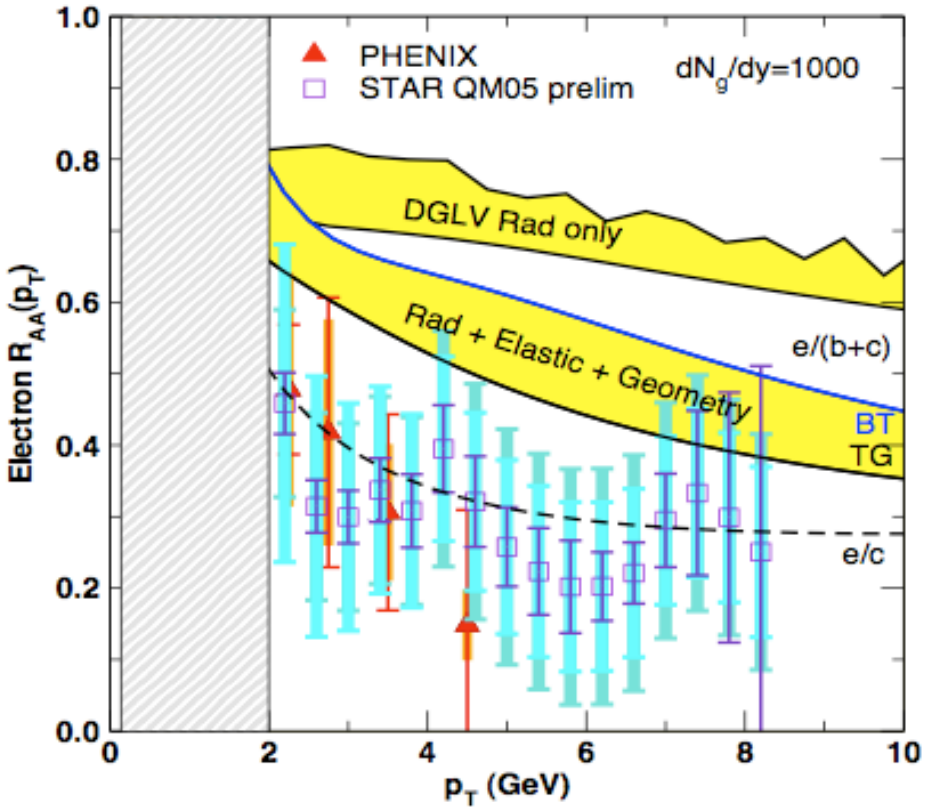


- Only for deep LPM in the final state. For comprehensive comparison of E-loss regimes, see

I.V., Phys. Rev. C (2007), hep-ph/0703002

Non-Photonic Electron / Heavy Flavor Quenching

Proceed to A+A collisions



S. Wicks et al., nucl-th/0512076

- Single electron measurements (presumably from heavy quarks) may be problematic for mainstream theory

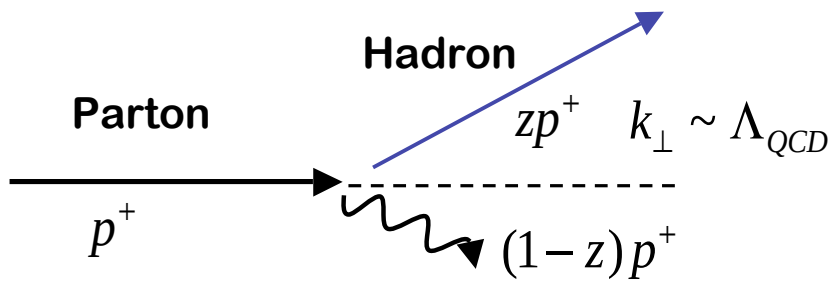
- Collisional energy loss is strongly overestimated in current applications

- Radiative Energy Loss using (D)GLV (both c + b)
- Radiative + Collisional + Geometry (both c + b) (overestimated)
- Deviation by a factor of two
- Is it accidental or is it symptomatic?

Conceptually Different Approach to D / B

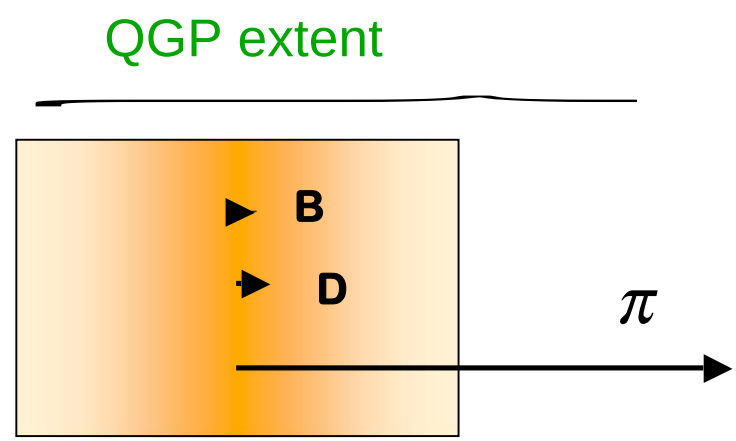
- Problem: treated in the same way as light quarks

$$p_q = \left[p^+, \frac{M_q^{\,2}}{2p^+}, 0 \right] \Rightarrow p_h = \left[zp^+, \frac{k_\perp^{\,2} + m_h^{\,2}}{2zp^+}, k_\perp \right] + p_g = \left[(1-z)p^+, \frac{k_\perp^{\,2}}{2(1-z)p^+}, -k_\perp \right]$$



$$\Delta y^+ = \frac{1}{\Delta p^-} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^+}{k_\perp^{\,2} + (1-z)m_h^{\,2} - z(1-z)M_q^{\,2}}$$

$$\tau_{\text{form}} = \Delta y^+ / (1+\beta_Q)$$



$\tau_{\text{form}}(p_T = 10\ GeV)$	π	D	B
	25 fm	1.6 fm	0.4 fm

- Fragmentation and dissociation of hadrons from heavy quarks inside the QGP

C.Y.Wong, Phys.Rev.C 72, (2005)

Fragmentation Probability for Heavy Quarks

Recall: $\Delta y^+(z, m_h, M_Q, p^+) = \frac{1}{\Delta p^-} = \frac{(0.2\ GeV.fm)\ 2z(1-z)p^+}{k_\perp^{\ 2} + (1-z)m_h^{\ 2} - z(1-z)M_q^{\ 2}}$

$\tau_{\text{form}}(z, m_h, M_Q, p^+) = \Delta y^+ / (1+\beta_Q)$

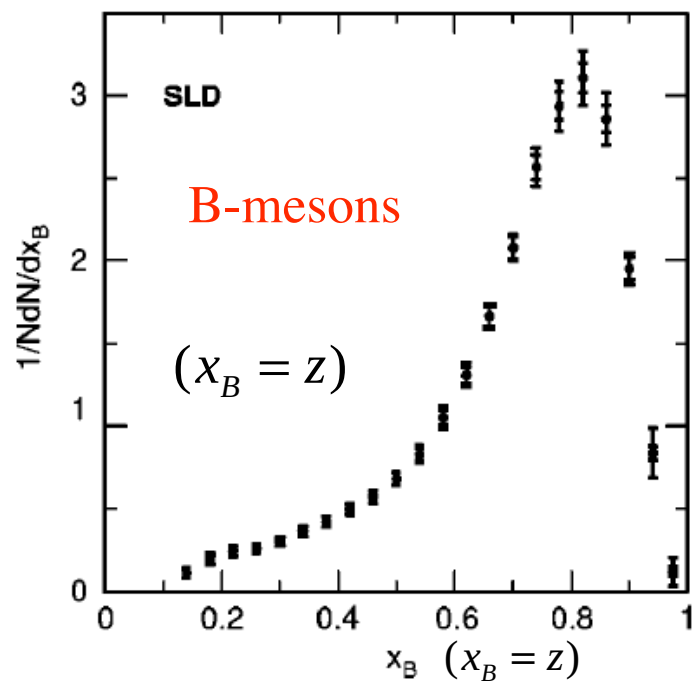
- Fragmentation probability

$$\int_0^1 D_{D_i, B_i/c,b}(z, Q^2)dz = f_i(D_i, B_i/c,b)$$

$$\sum_{i=1}^{n} f_i(B/b; D/c) = 1$$

Universal in the QCD factorization approach

$$\langle \tau_{\text{form}} \rangle = \sum_i \int_0^1 \tau_{\text{form}}(z, m_{hi}, M_Q, p^+) D_{h_i/Q}(z, Q^2)dz$$



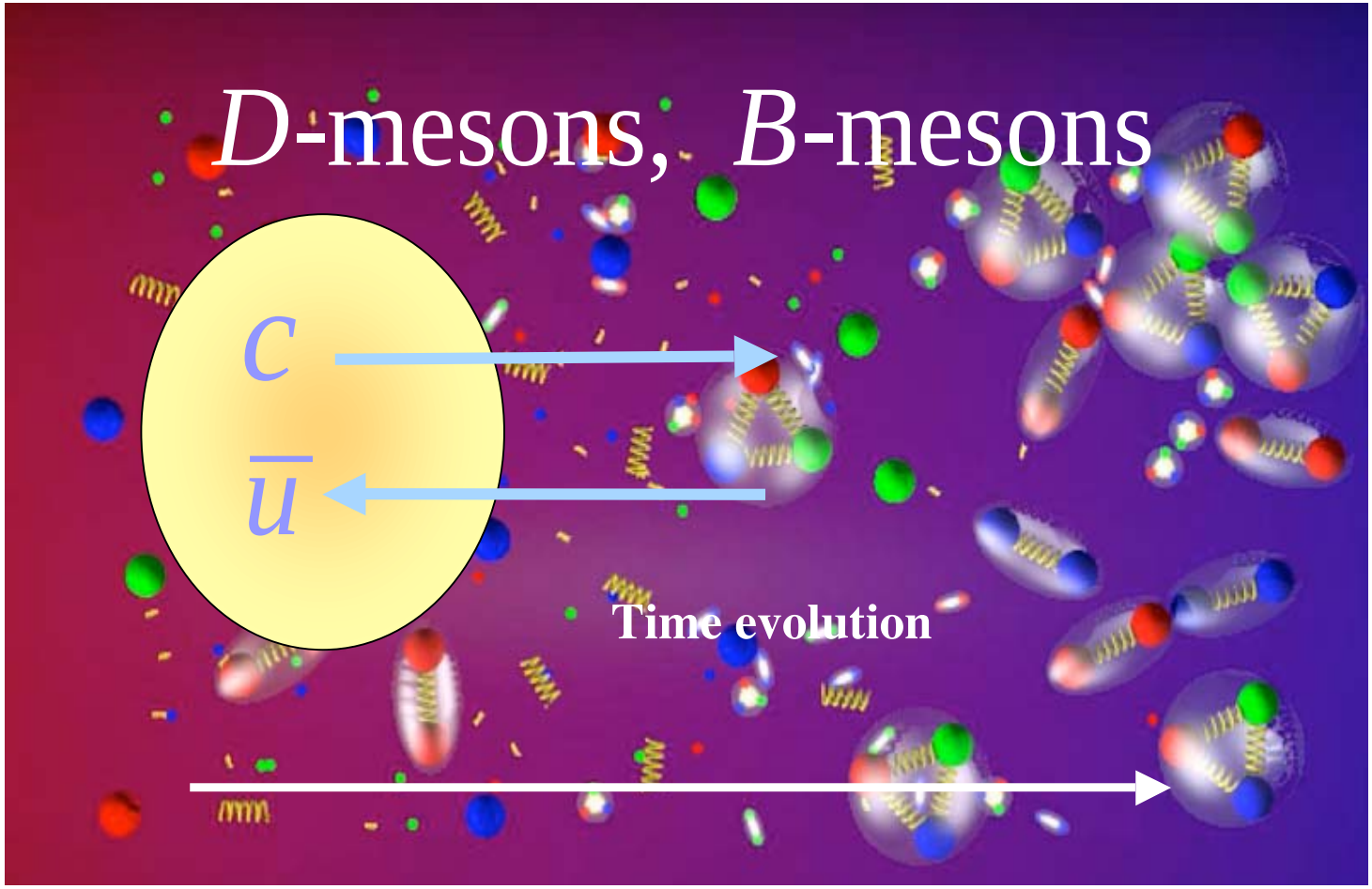
FFs from heavy quark EFT

K.Cheung,T.Z.Yuan, Phys.Rev.D53 (1996)

- Time-dependent implementation

$$N_Q(t) = N_Q(0)\exp\left[-\frac{t}{\langle \tau_{\text{form}} \rangle}\right]$$

A New Paradigm



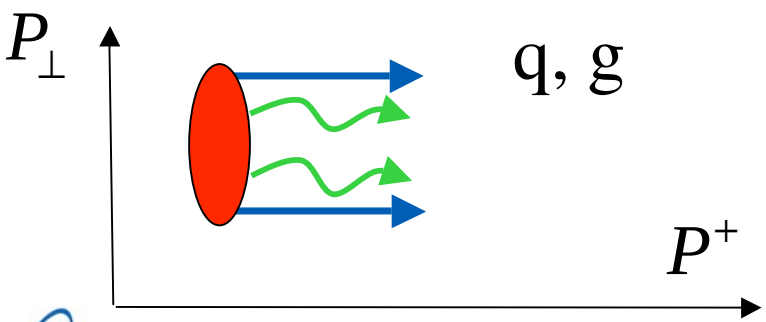
Light Cone Wave Functions

- Expansion in Fock components

$$\left|\psi_M;P_\perp,P^+\right\rangle=\sum_{i=2}^{n}\int\frac{dx_i}{\sqrt{2x_i}}\frac{d^2k_{\perp i}}{\sqrt{(2\pi)^3}}\psi_i(k_{\perp i},x_i)$$
$$\times\delta\left(\sum_{i=2}^{n}x_i-1\right)\delta\left(\sum_{i=2}^{n}k_{\perp i}\right)\left|i;k_{\perp i}+x_iP_\perp,x_iP^+\right\rangle$$

S.Brodsky, D.S.Hwang, B.Q.Ma, I.Schmidt, Nucl.Phys.B 592 (2001)

Fix two momentum scales



- Fixing the transverse momentum scale

Cornell potential $V(r)=-\frac{\xi}{r}+br$

$$\left[\boldsymbol{\alpha}\cdot\mathbf{p}+V+(m+S)\beta+\frac{\mathbf{p}^2}{2M_Q}+\left\{\frac{\boldsymbol{\alpha}\cdot\mathbf{p}}{2M_Q},V\right\}+\frac{1}{4M_Q}[\boldsymbol{\alpha}\cdot\mathbf{p},[\mathbf{p}^2,W]]\right]\psi=E\psi$$

$a0\rightarrow\max(r^2\rho(r))$, $a_0=2-3\ GeV^{-1}$

M. Avila, Phys.Rev.D49 (1994)

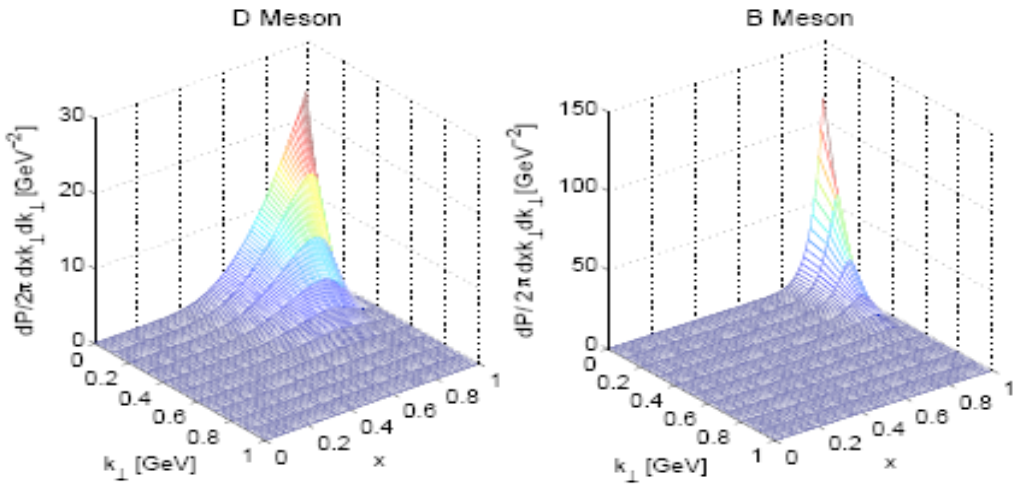
Fourier transform to momentum space

$$\psi(r)\sim e^{r^2/(2a_0^2)}\rightarrow\psi(k)\sim e^{k^2a_0^2/2}$$

Typical transverse momentum squared $\langle k_\perp^2\rangle=\frac{1}{2a_0^2}$

Light Cone Wave Functions

- Results for heavy flavor



$$\left| \psi\ (\Delta k_\perp, x) \right|^2 \sim Exp\left[-\frac{\Delta k_\perp^2 + 4m_Q^2(1-x) + 4m_q^2(x)}{4\Lambda^2 x(1-x)} \right]$$

From general theory of LCWF for the lowest-lying Fock state

- Fixing the longitudinal momentum fractions

$$\left(\frac{m_{\perp i}^{\ 2}}{x_i} = \frac{m_i^{\ 2} + k_{\perp i}^{\ 2}}{x_i} \right) = \left(\frac{m_{\perp j}^{\ 2}}{x_j} = \frac{m_i^{\ 2} + k_{\perp j}^{\ 2}}{x_j} \right)$$

Meson boost – equal quark longitudinal rapidity

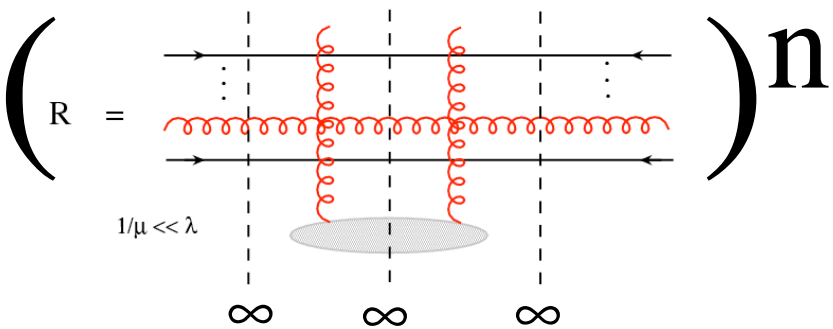
- Begin to understand hadron structure and parton distributions from first principles

$$\phi_{Q/M}(x) = \int dK d^2\Delta k_\perp \left| \psi\ (K, \Delta k_\perp, x, m_1, m_2) \right|^2$$

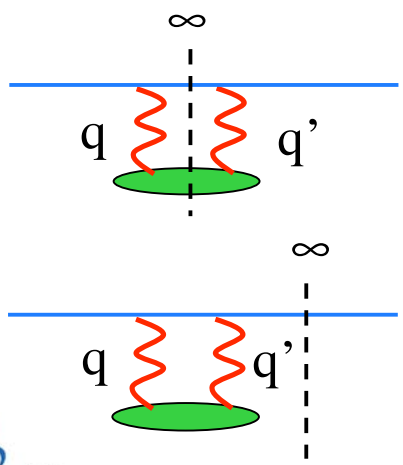
- Duality between FFs ad PDFs

- Models such as coalescence should use plausible wave functions, especially for heavy flavor

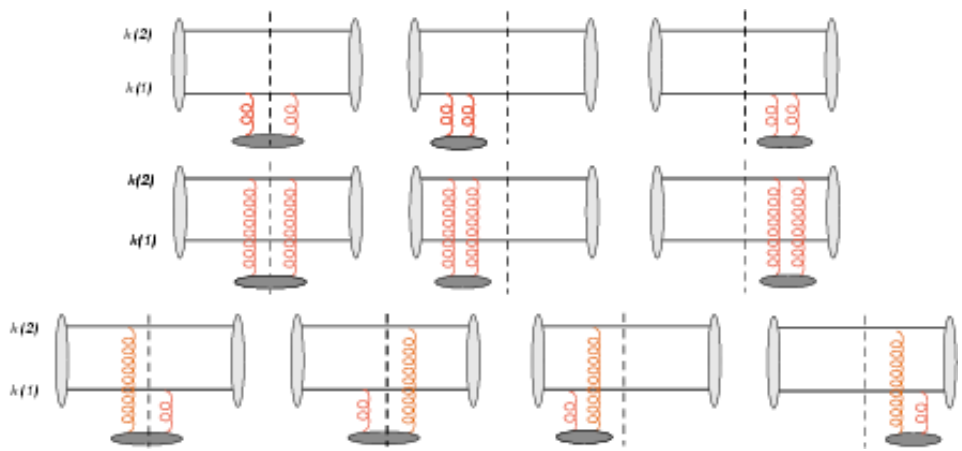
Heavy Meson Propagation in Dense Matter



- Solve for the color and kinematic structure of this operator which automatically ensures unitarity



- Single scattering in the medium



$$\sim \int d^2q_\perp d^2q'_\perp \; M_1{}^*(p-q_\perp)M_2(p-q'_\perp)\,\frac{d\sigma el}{d^2q_\perp}\;\delta^2(q_\perp - q'_\perp)$$

$$\sim \left(-\frac{1}{2}\right)\int d^2q_\perp d^2q'_\perp \; M_1{}^*(p-q_\perp-q'_\perp)M_2(p)\,\frac{d\sigma el}{d^2q_\perp}\;\delta^2(q_\perp + q'_\perp)$$

Medium-Modified Heavy Meson

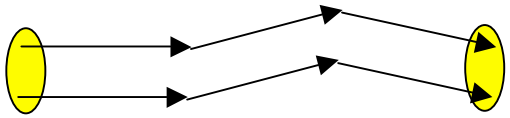
Initial distribution:

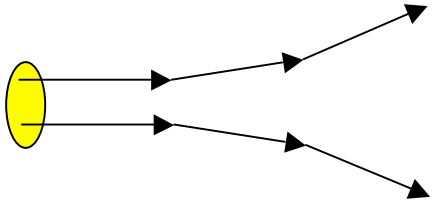
$$\left|\psi_i(\Delta k_\perp, x)\right|^2 = \left[\delta^2(K_\perp)\right] \times \left[\mathrm{Norm}^2 e^{-\frac{\Delta k_\perp^2}{4x(1-x)\Lambda^2}} e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}}\right]$$

Resum multiple scattering in impact parameter (B,b) space

- Heavy meson acoplanarity: $\langle K_\perp^2 \rangle = 2\left(2\mu^2 \frac{L}{\lambda_q}\xi\right) \qquad 2\left(2\mu^2 \frac{L}{\lambda_q}\xi\right) \equiv \int_0^L 2\left(2\mu^2(l)\frac{1}{\lambda_q(l)}\xi\right)dl$

$$\left|\psi_f(\Delta k_\perp, x)\right|^2 = \left[\frac{e^{-\frac{K_\perp^2}{4\chi\mu^2\xi}}}{4\chi\mu^2\xi}\right] \times \left[\mathrm{Norm}^2 \frac{x(1-x)\Lambda^2}{\chi\mu^2\xi + x(1-x)\Lambda^2} e^{-\frac{\Delta k_\perp^2}{4(\chi\mu^2\xi + x(1-x)\Lambda^2)}} e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}}\right]$$





?

- Broadening (separation) the q q-bar pair:

$$\psi_f(\Delta k_\perp, x) = a\psi_M(\Delta k_\perp, x) + (1-a)\psi_{q\bar{q}\ \text{dissociated}}(\Delta k_\perp, x)$$

Dissociation Rate and Rate Equations

- Distortion of the light cone wave function leads to meson decay

Meson survival probability:

$$P_{\text{surv.}}\left(\frac{\mu^2}{\lambda}L\xi\right)=\left|\int dx d^2\Delta k_\perp\ \psi^*_f(x,\Delta k_\perp)\psi_i(x,\Delta k_\perp)\right|^2$$

Dissociation time:

$$\langle\tau_{\text{diss}}\rangle=\frac{d}{dt}\ln\left(1-P_{\text{surv.}}\left(\frac{\mu^2}{\lambda_q}L(t)\xi\right)\right)$$

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

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

Solve with the initial conditions

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

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

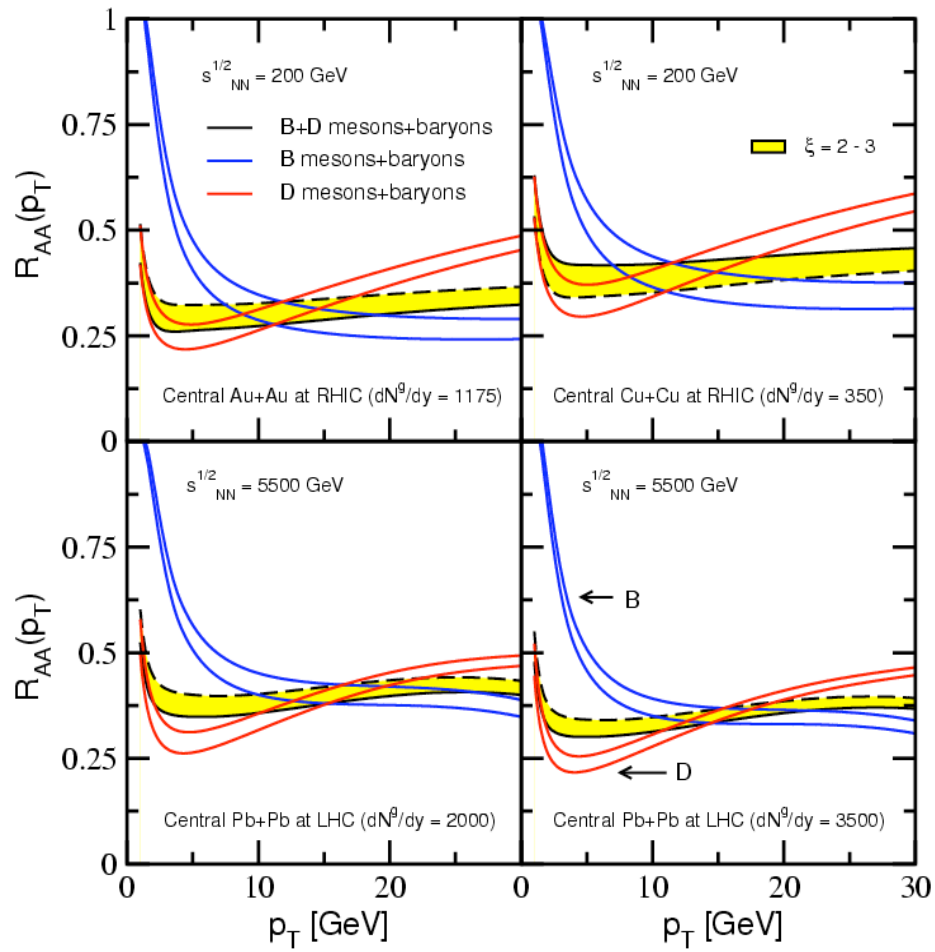
Find the asymptotic solutions

$$t\gg\max(L_{QGP},\ \tau_{form})$$

D- and B-meson Suppression at RHIC and LHC

- Suppression $R_{AA}(p_T) \sim 0.25$ is large
- Similar to light π^0, however, different physics mechanism
- B-mesons as suppressed as D-mesons at $p_T \sim 10$ GeV (unique feature)
- A chance to really determine the physics of heavy flavor suppression

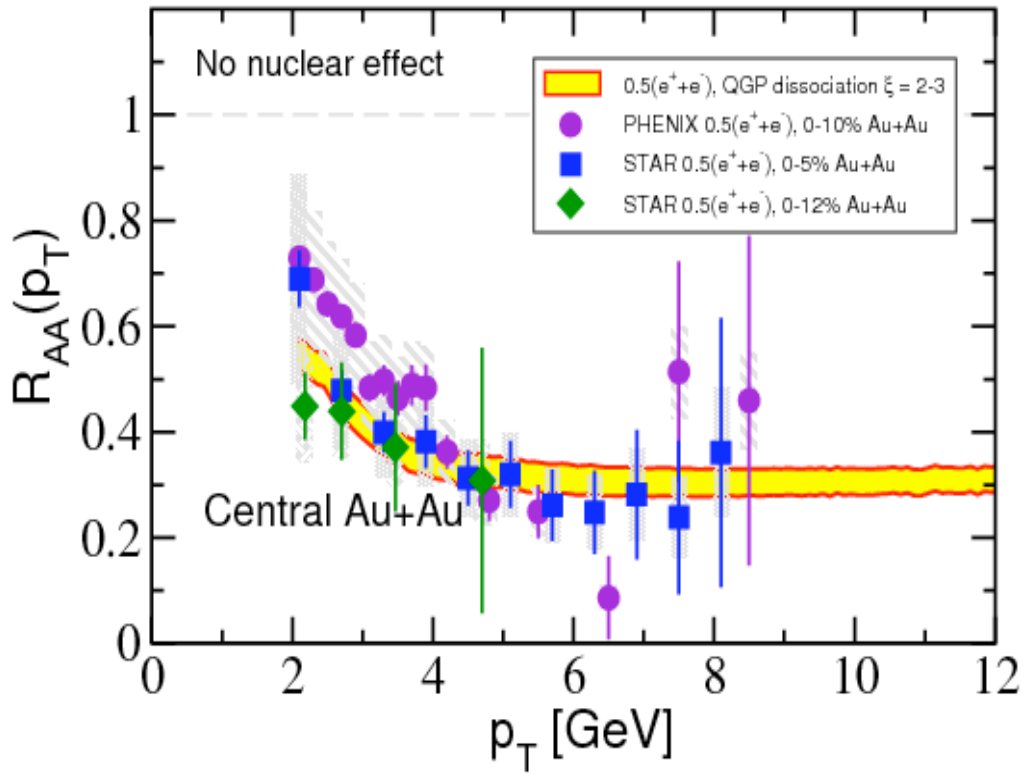
Velocity factor $\beta = p / E$
important at small/intermediate p_T



Quenching of Non-Photonic Electrons

- Full semi-leptonic decays of C- and B- mesons and baryons included. PDG branching fractions and kinematics. PYTHIA event generator

$$R_{AA}^{e^{\pm}}(p_T) = \frac{d\sigma_{AA}^{e^{\pm}} / dyd^2 p_T}{\langle N_{\text{coll}} \rangle d\sigma_{pp}^{e^{\pm}} / dyd^2 p_T}$$



- B-mesons are included. They give a major contribution to (e^++e^-)

Note on applicability

D-, B-mesons to $R_{AA}(D) = R_{AA}(B)$

(e^++e^-) to 25 GeV

Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i}\left(p_i A_i(p,t) + \frac{\partial}{\partial p_i} B_{ij}(p,t) \right) \partial f(p,t)$$

- Drag coefficient:

$$A_i(p,t) = \frac{1}{p_i}\frac{\langle \delta p_i \rangle}{\delta t}$$

[Fractional momentum loss per unit time]

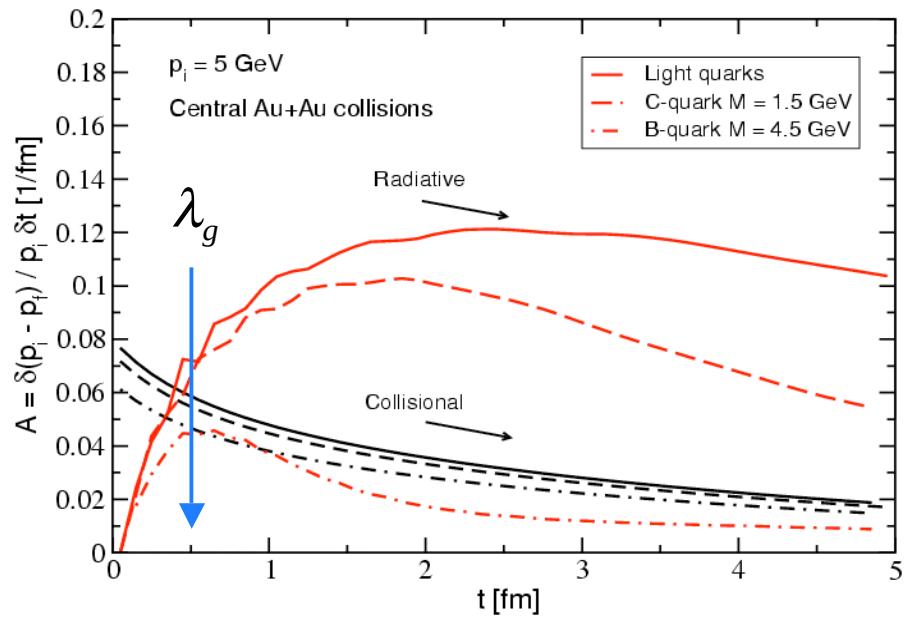
- Diffusion coefficient:

$$B_{ji}(p,t) = \frac{1}{2}\frac{\langle \delta p_j \delta p_i \rangle}{\delta t}$$

Equilibration is imposed by Einstein's fluctuation-dissipation relation:

$$B_{||}(p,t) = T(t)E(p)A_i(p,t)$$

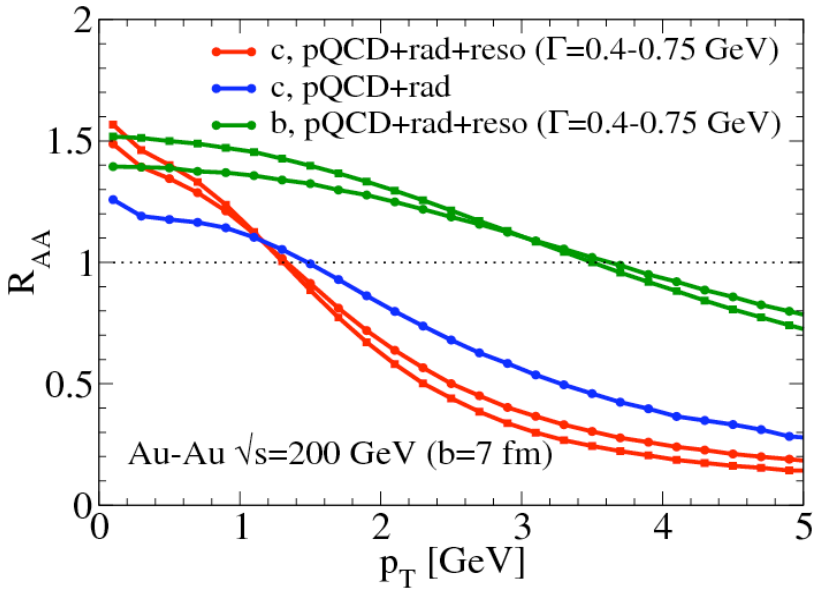
H. van Hees, I.Vitev, [R. Rapp], in preparation



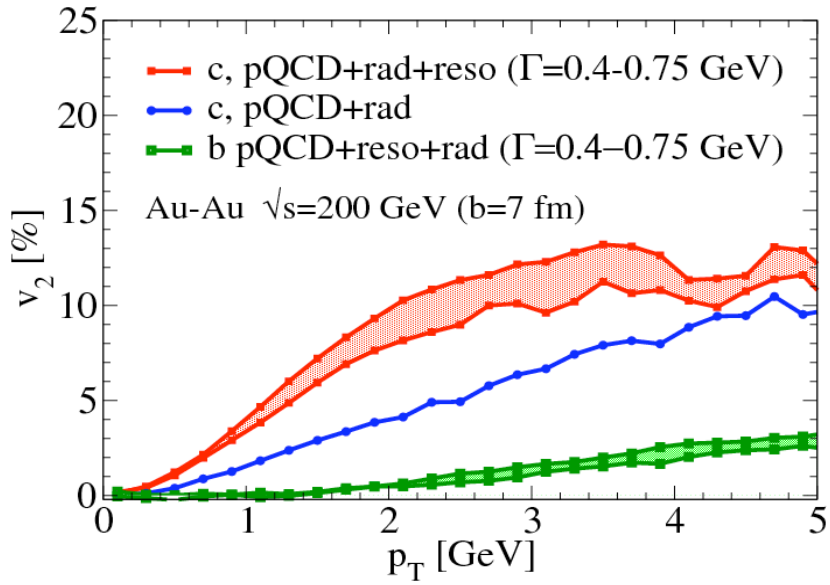
- Radiative energy loss is dominant except for b-quarks and very small systems

Transport + Quenching Approach

Numerical results for c, b diffusion



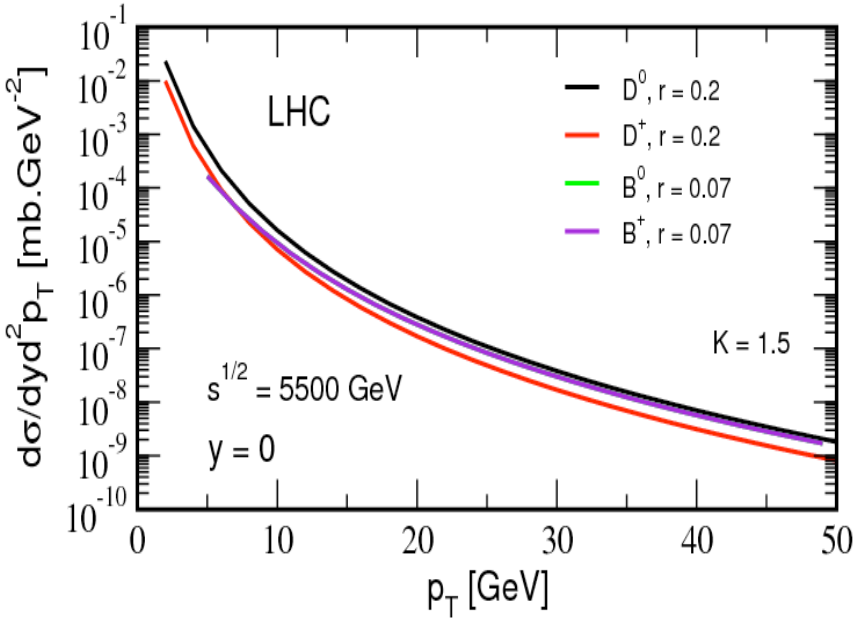
Elliptic flow (azimuthal asymmetry)



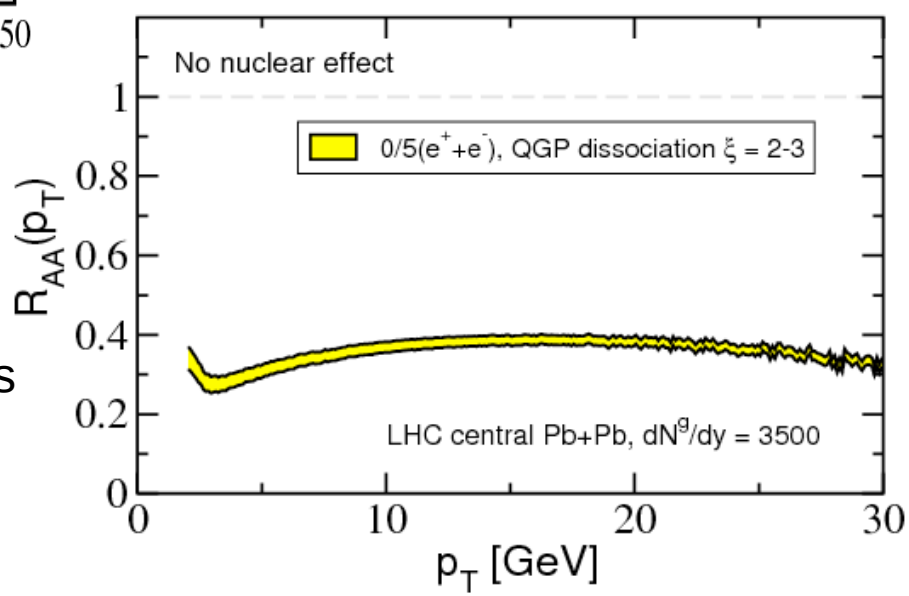
- The suppression and v_2 are large with E-loss and q-resonance interactions combined
- Normal hierarchy: c quarks are significantly more suppressed than b-quarks
- Measurements can constrain the QGP parameters in a correlated way

$$\left[\varepsilon_0 \approx 15\ \mathrm{GeV/fm}^3,\ \tau_0 \approx 0.6\ \mathrm{fm},\ T_0 \approx 370\ \mathrm{MeV},\ dN^g/dy \approx 1000\right]$$

Situation at the LHC



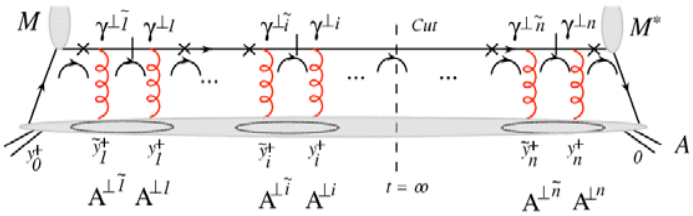
- The asymptotic solution in the QGP - sensitive to t_0~0.6 fm and expansion dynamics
- Features of energy loss
- Suppression at the LHC not different when compared to RHIC



- Harder spectra at the LHC
- Electrons spectra from B-mesons and D-mesons decays contribute cross at higher p_T

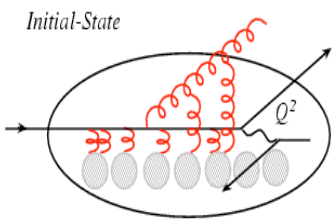
Future Calculations for Heavy Flavor at RHIC

- Dynamical nuclear shadowing



J.W. Qiu, I.V., Phys. Lett. B 632 (2006)

- Dynamical nuclear shadowing



$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \times \ln \frac{Q_0}{\mu}$$

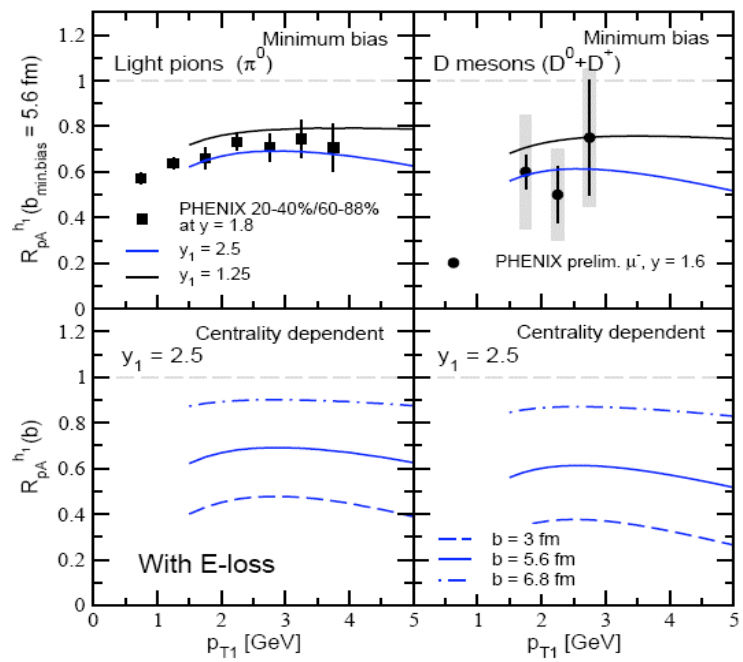
I.V., Phys. Rev. C (2007), hep-ph/0703002

Carry systematic calculations in A+A at forward rapidity

Experimental y = 1.4-2.2

Very similar behavior of charm quarks (D-mesons) to light hadrons

$$d + A \to \pi^0 + X \quad d + A \to D + X$$



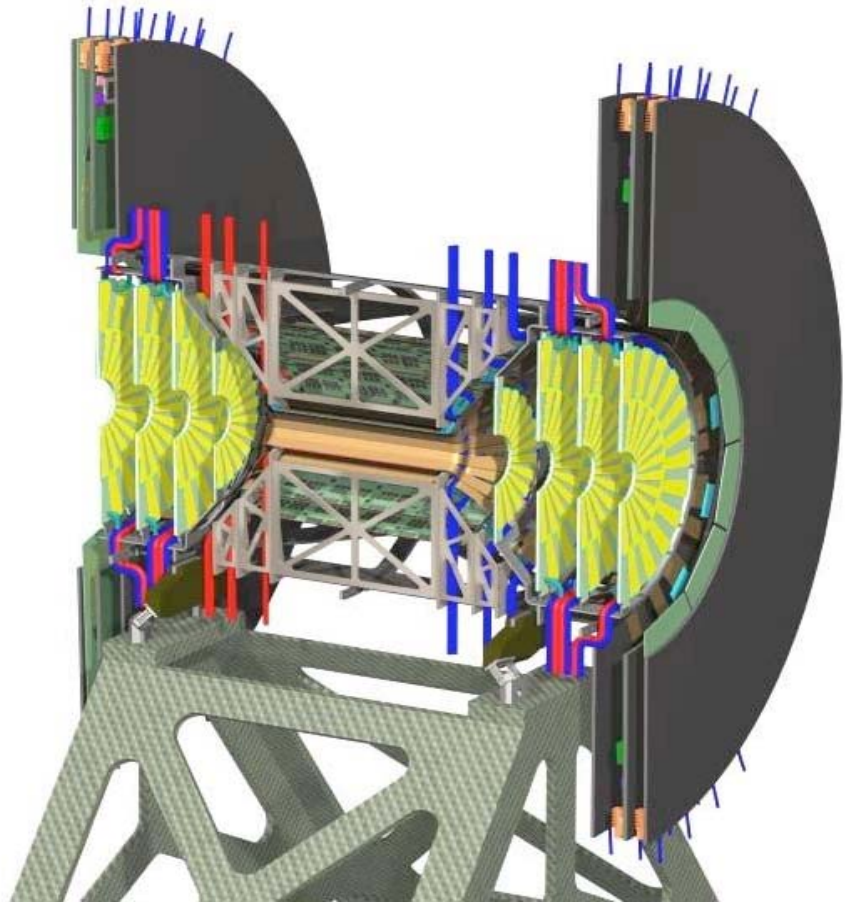
I.V., T.Goldman, M.Johnson, J.W.Qiu, Phys. Rev. D 74 (2006)

Experimental Tools for Heavy Mesons

- Vertex detectors at midrapidity
- Vertex detectors at forward rapidity

Experimentally validate / disprove theories

Collisional dissociation	Mainstream approach
$R_{AA}(p_T;B) \approx R_{AA}(p_T;D)$	$R_{AA}(p_T;B) \gg R_{AA}(p_T;D)$



- Best reason to measure D- and B-mesons separately

Summary of Open Heavy Flavor Modification

Cold nuclear matter effects on open heavy flavor

- Determined the baseline heavy flavor production in p+p collisions
- Suggest heavy / light correlations to determine the the hard processes
- Progress in understanding cold nuclear matter initial state energy loss

Collisional QGP-induced B- / D-meson dissociation

- Derived formation and dissociation times in the QGP. They are short
- Improved description of non-photonic electron quenching
- B-mesons are as suppressed as D-mesons at p_T ~ 10 GeV, unique

Langevin simulation of heavy quark diffusion

- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

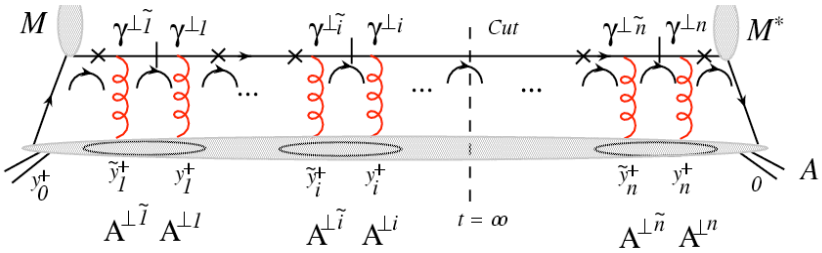
Future directions

- Combine cold nuclear matter effects with the QGP suppression models to predict the open heavy flavor modification at forward rapidity

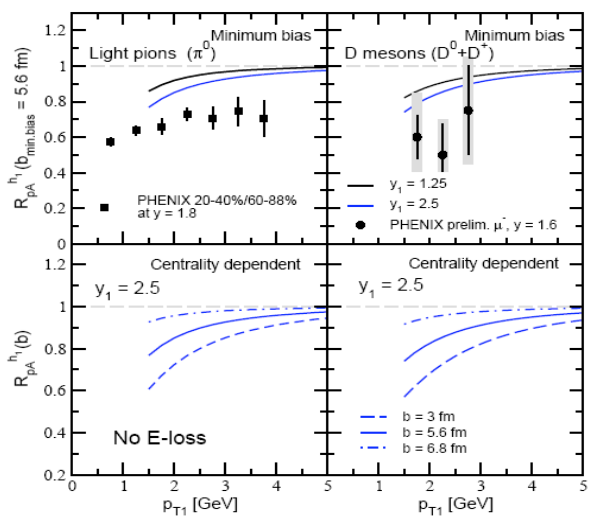
Backup

Cold Nuclear Matter Effects in PQCD

- Shadowing arises from coherent final-state multiple scattering

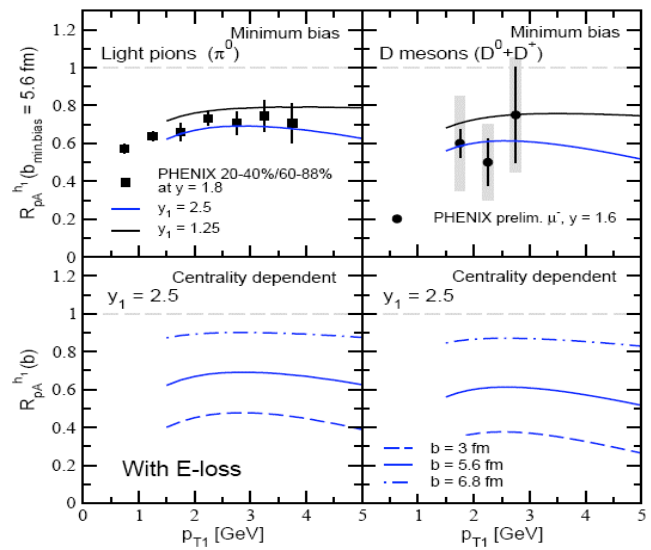


$$F(x_b) = \frac{\phi(x_b)}{x_b}\left|\bar{M}^{\,2}_{ab\blacklozenge\,cd}\right| , \quad F(x_b) \rightarrow F\left(x_b + x_b C_d \frac{\xi^2}{-t+m_d^2}\,(A^{1/3}-1)\right)$$



- Cold nuclear matter energy loss plays an important role (may be dominant) in p+A

- Experimental y = 1.4-2.2



I. Vitev, T.Goldman, M.Johnson, J.W.Qiu, Phys. Rev. D 74 (2006)

Very similar behavior of charm quarks (D-mesons) to light hadrons

Strategy for Calculating HF Suppression

- Calculate the baseline D- and B-meson cross sections in p+p collisions

- Calculate the fragmentation probability of heavy quarks

- Calculate the QGP-induced dissociation probability for heavy mesons

- Solve the system of coupled rate equations and predict the heavy quark (single electron) suppression

Detailed Analysis to LO

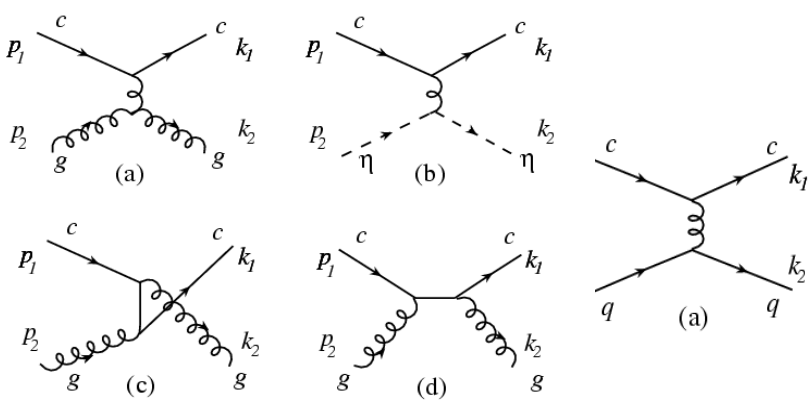
Single inclusive D - mesons

$$\frac{d\sigma_{NN}^{D_1}}{dy_1 d^2 p_{T_1}} = K_{NLO} \sum_{abcd} \int_{x_{1,2}\le 1} dy_2 \int_{x_{1,2}\le 1} dz_1 \times \frac{1}{z_1^2} D_{D_1/c}(z_1) \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2$$

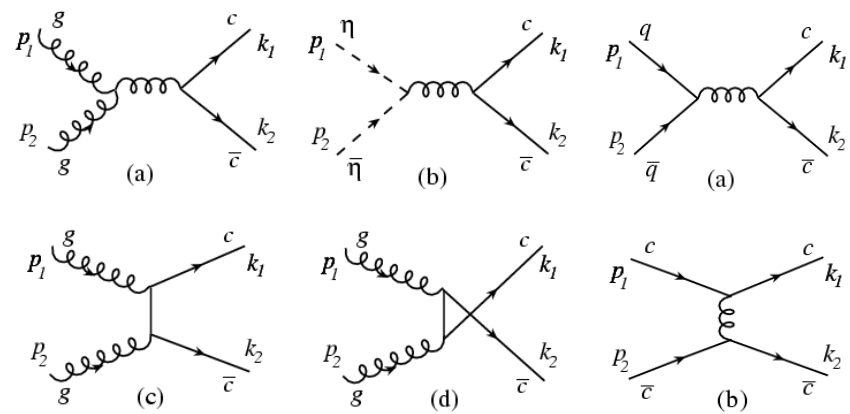
D - meson triggered back-to-back correlations

$$\frac{d\sigma_{NN}^{D_1 h_2}}{dy_1 dy_2 dp_{T_1} dp_{T_2}} = K_{NLO} \sum_{abcd} 2\pi \int_{\mathcal{D}} \frac{dz_1}{z_1} D_{D_1/c}(z_1) D_{h_2/d}(z_2) \times \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2$$

Flavor excitation



Flavor creation



Faster convergence of the perturbative series

Slower convergence of the perturbative series

F.Olness et al., Phys.Rev.D59 (1999)

Two different expansions

Summary of Open Heavy Flavor Modification

Collisional QGP-induced B- / D-meson dissociation

- Derived formation and dissociation times in the QGP. They are short
- Solved the set of coupled rate equations. More sensitive to QGP properties and formation / expansion dynamics than e-loss
- B-mesons are as suppressed as D-mesons at p_T ~ 10 GeV, unique

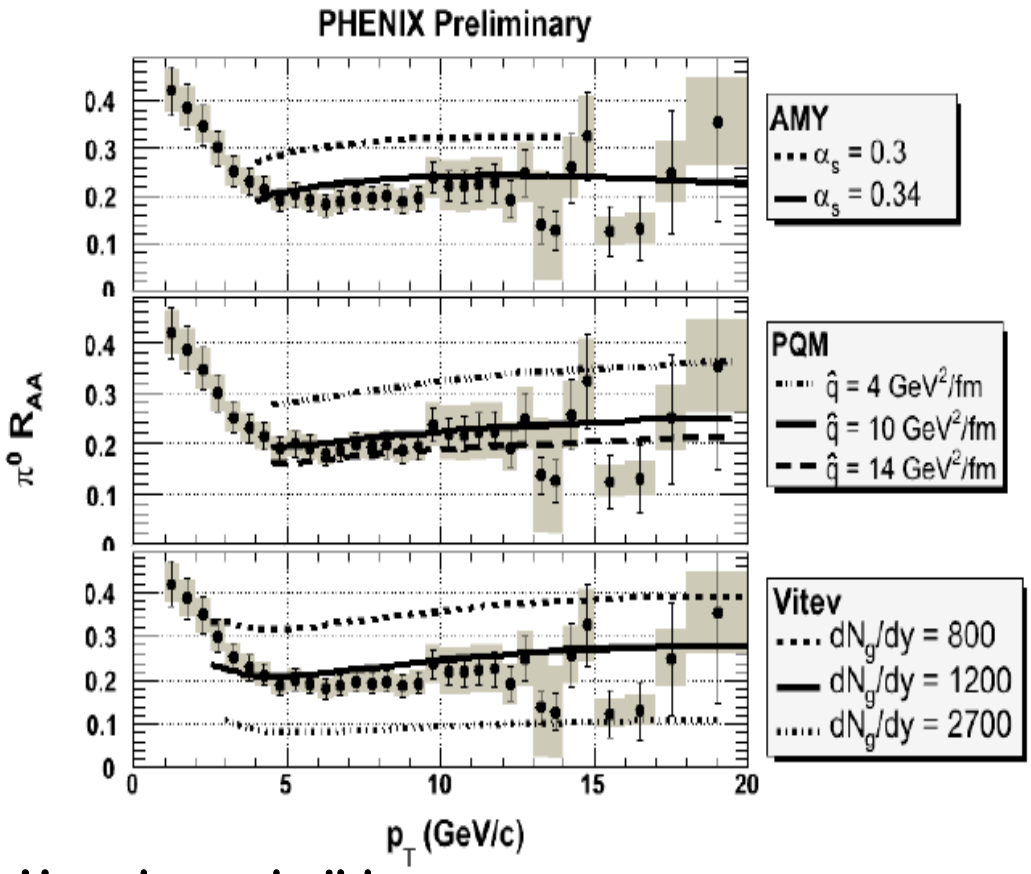
Langevin simulation of heavy quark diffusion

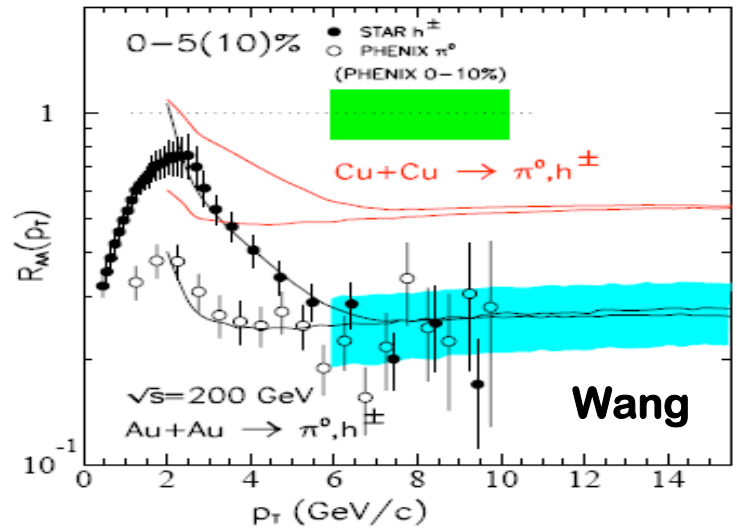
- Calculated drag and diffusion from the collisional and radiative e-loss
- Normal suppression hierarchy: B- much less suppressed than D- mesons

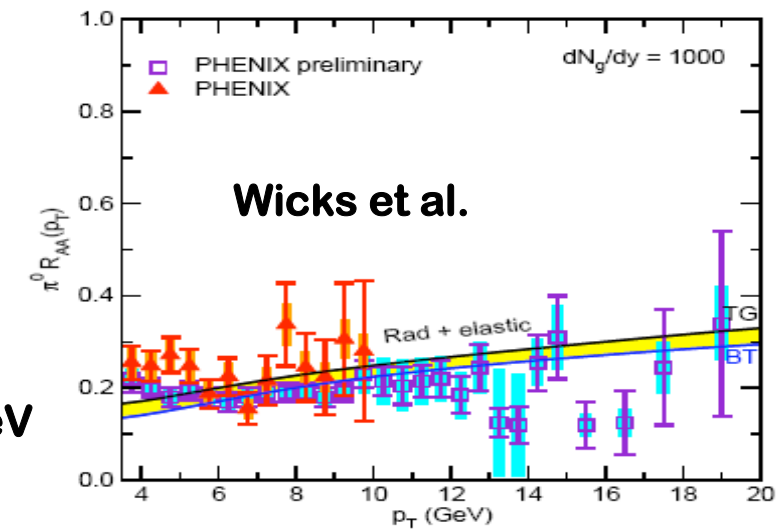
Cold nuclear matter effects on open heavy flavor

- Calculated dynamical shadowing from coherent final state interactions
- Calculated the cold nuclear matter initial state energy loss
- Combine with the QGP suppression to make predictions at forward rapidity

Comparison to Other Models







How do you build from T = 400 MeV

$$\hat{q} = \frac{\mu^2}{\lambda_g} = 10\ GeV^2 / fm$$

$$\hat{q} = \frac{\mu^2}{\lambda_g} = 100\ GeV^2 / fm$$

LHC: from T = 1 GeV

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Ivan Vitev, LANL