Jet Quenching and Energy Loss : Radiative, Collisional and Dissociative

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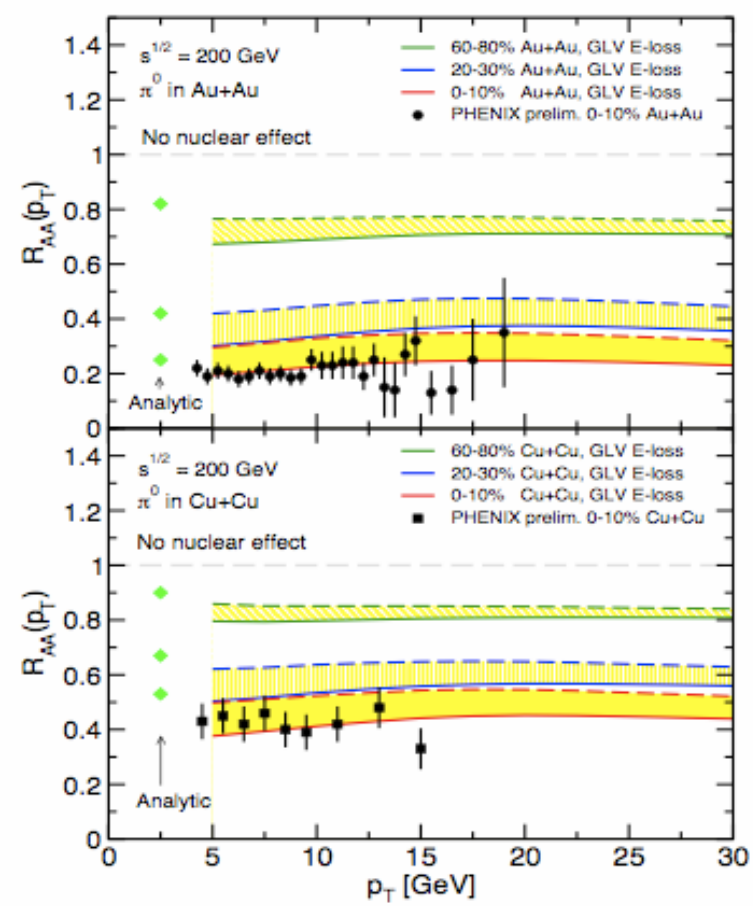
RHIC AGS User's Meeting, 2007

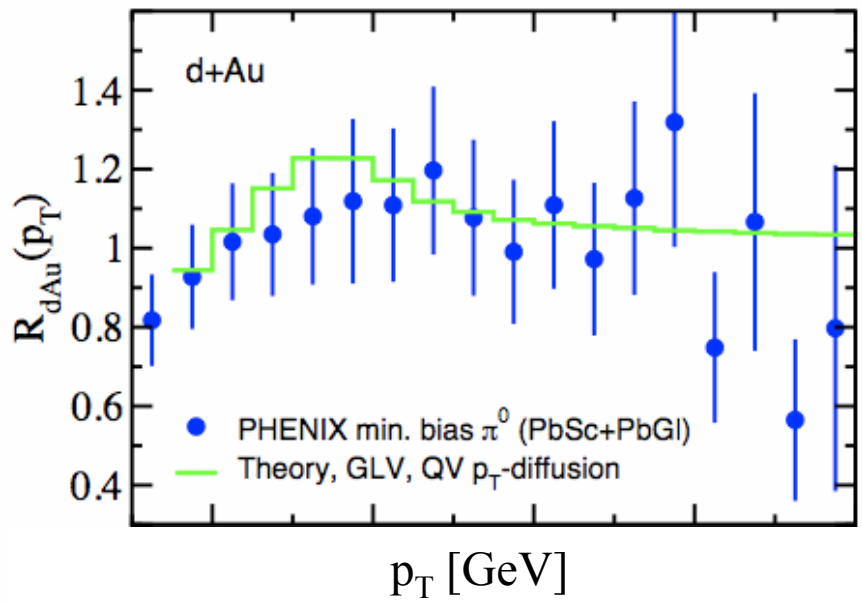
Adil, Gyulassy, Horowitz & Wicks : PRC **75**, 044906 (2007)
Adil & Vitev : PLB **649**, 139-146 (2007)
WHDG : Nuc. Phys. A **784**, 426-442 (2007)
Wicks & Gyulassy : In Preparation

Jet Quenching at RHIC - I
Light Quarks

Jet Quenching in A-A studied primarily using the nuclear modification factor.

$$R_{AA} = \frac{dN^h_{AA}}{T_{AA}\, d\sigma^h_{pp}}$$

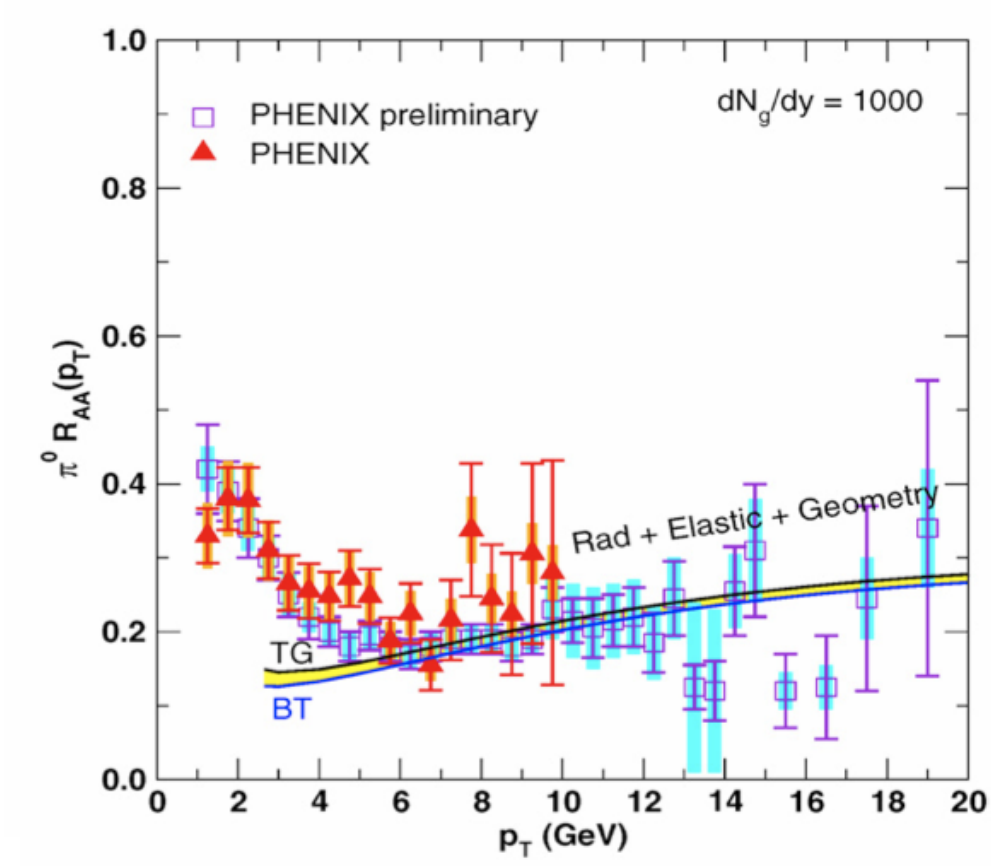




Vitev, arXiv:nucl-th/0603010

Note that only radiative energy loss used with fixed path length.

Jet Quenching at RHIC - II
Heavy Quarks



Wicks et al. arXiv:nucl-th/0512076

- Electrons from B/D decays
- Radiative Energy Loss using DGLV (both c + b)
- Radiative + Collisional + Geometry (both c + b)
- Radiative + Collisional + Geometry (only c)
- Other approaches use "fragility" and large $\hat{q}$ (AWS)

Adding Collisional à la WHDG

Pros

- Elastic non negligible for RHIC Physics (Mustafa etc.)
- Elastic "causes" radiative energy loss, include for self consistency
- Different energy loss mechanisms have different dependence on density, energy, path length

Cons

- Neglect finite time corrections (Djordjevic, Peigne et al., Adil et al.)
- Use simplified diffusion to model collisional energy loss fluctuations, not valid for small number of collisions

Finite Time Effects

Calculations for Collisional Energy Loss

QFT 2 -> 2

- Energy Loss as an integral over elastic collision cross-section

$$\frac{dE}{dx} \propto \int_{t_{min}}^{t_{max}} dt \frac{d\sigma}{dt}(E_f - E_i)$$

- Main Calculations
  - Bjorken, 1982 (First estimate)
  - Braaten & Thoma, 1991 (screening and 2 -> 2 processes at high energy)

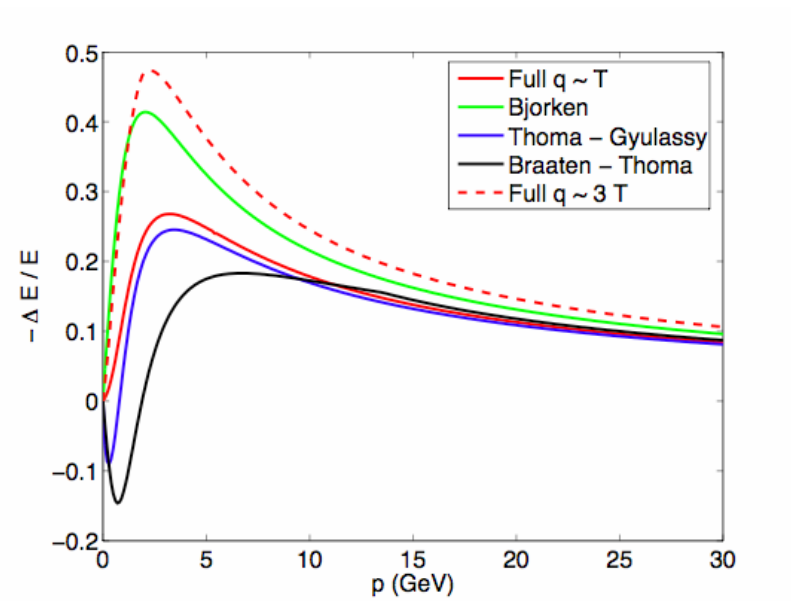
Linear Response

- Energy Loss as Joule Work done by 'induced' electric field on particle

$$\frac{dE}{dx} \propto \vec{E}_{ind} \cdot \vec{j}$$

- Main Calculations
  - Thoma & Gyulassy, 1991 (First consistent inclusion of screening)

Energy Loss Calculation



- Use current of one particle traveling at (E,p)

$$j^{\mu a}_{\infty,(1)}(\mathbf{x},t) = q^a v^\mu \delta(\mathbf{x} - \mathbf{v}t)$$

$$j^{\mu a}_{\infty,(1)}(\omega,\mathbf{k}) = 2\pi q^a v^\mu \delta(\omega - \mathbf{k}\cdot\mathbf{v}).$$

- Energy Loss is

$$\frac{dE}{dx} = -i\frac{C_F\alpha_s}{v2\pi^2}\int d\mathbf{k}\frac{\mathbf{k}\cdot\mathbf{v}}{k^2}\left(\frac{1}{\epsilon_\parallel} - \frac{k^2v^2 - (\mathbf{k}\cdot\mathbf{v})^2}{k^2 - (\mathbf{k}\cdot\mathbf{v})^2\epsilon_\perp}\right)$$

Integral can be done analytically in Leading Logarithm approx.

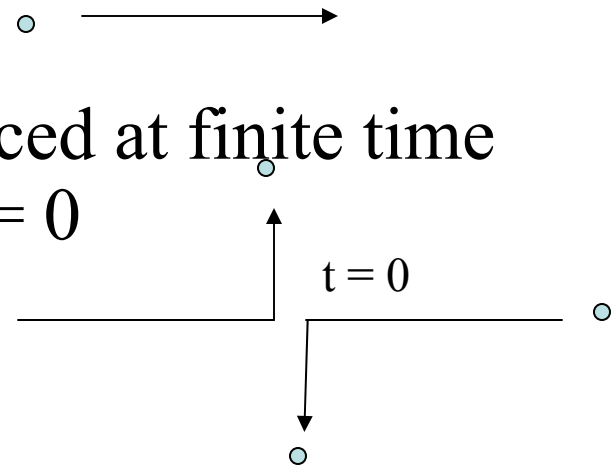
$$\frac{dE}{dx} = -\frac{C_F\alpha_s}{2}m_D^2\log\left(\frac{k_{max}}{m_D}\right)f(v)$$

$$f(v) = \frac{1}{v^2}\left(v - \frac{1}{2}(1-v^2)\log\left(\frac{1+v}{1-v}\right)\right)$$

Note that all previous results are presented in leading logarithm approximation.

But Wait…

- The current used in the previous calculation is "infinite time", i.e. forever live in a plasma of infinite spacetime extent



- Experimental jets are produced at finite time inside the medium, say at t = 0
- There must be "retardation" effects, a time delay to set up the induced field

Accounting for the Retardation

QFT 2 -> 2

- Work done by Magdalena Djordjevic, 2006.

$$H_{int} = -ig\Theta(t-t_0)\Theta(L/v-(t-t_0)) \times \int d^3x\bar{\psi}\gamma^\mu A_\mu\psi$$

- Interaction Hamiltonian adjusted to give interaction only for a finite time

Linear Response

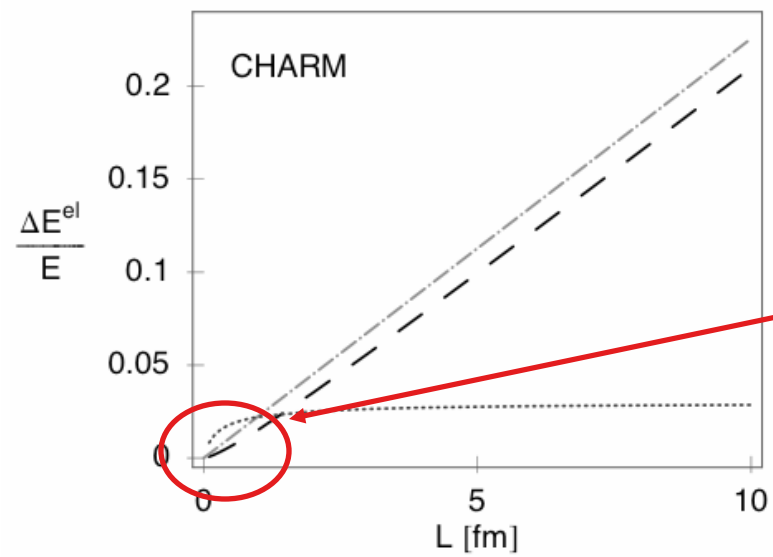
- Work done by S. Peigne et al., 2005.

$$j^{\mu a}_{(2)}(\mathbf{x},t) = q^a(v_1^\mu\delta(\mathbf{x}-\mathbf{v_1}t) - v_2^\mu\delta(\mathbf{x}-\mathbf{v_2}t))\Theta(t).$$

$$j^{\mu a}_{(2)}(\omega,\mathbf{k}) = iq^a\left(\frac{v_1^\mu}{\omega-\mathbf{k}\cdot\mathbf{v_1}+i\eta} - \frac{v_2^\mu}{\omega-\mathbf{k}\cdot\mathbf{v_2}+i\eta}\right)$$

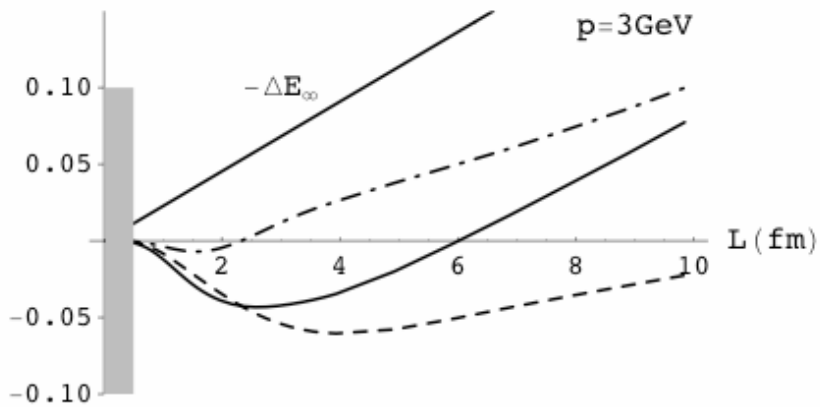
- The current used is adjusted in order to take the into account that the particle is not created at $t = -\infty$
- $V_2 = 0$ for ease of calculation

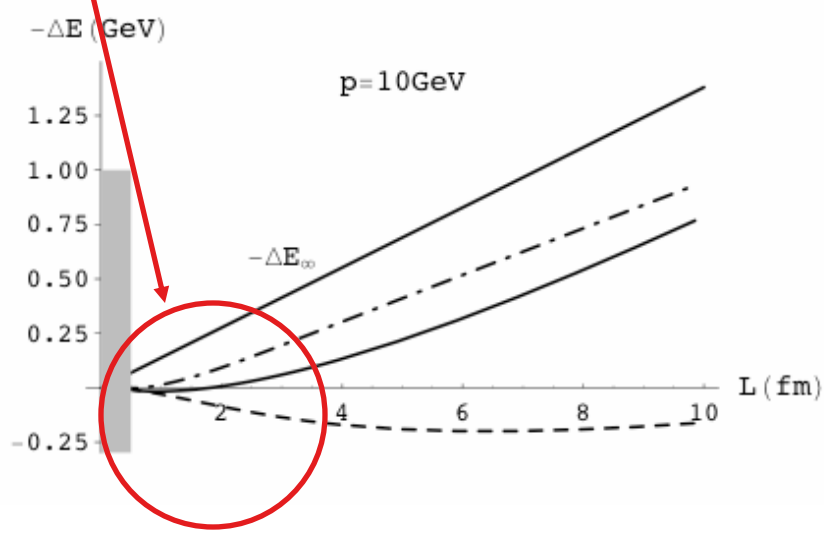
PROBLEM!!!!



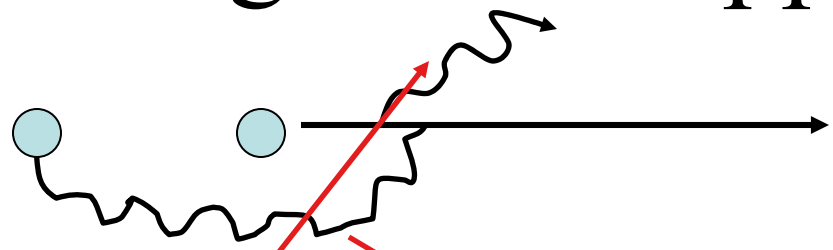
Significant Difference in the calculations for the retardation length

- Peigne et al. '05 include
  - creation radiation
  - 2 particle binding





Removing oranges from apples



Radiative

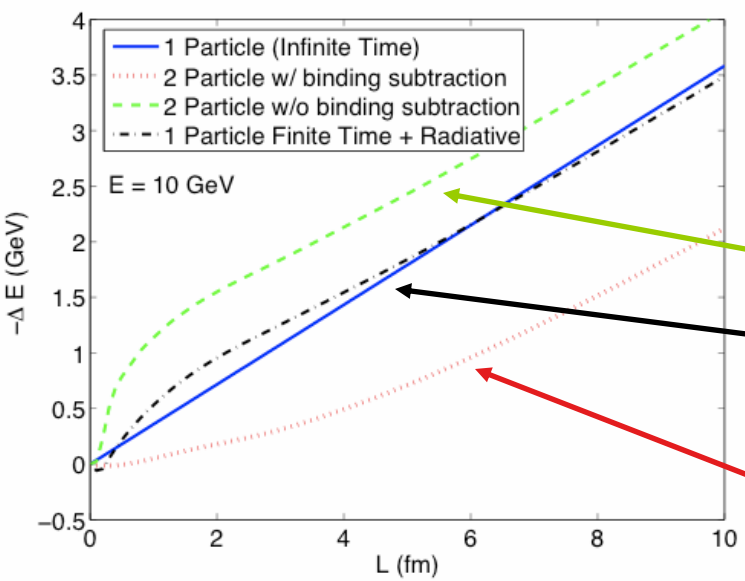
Binding

$$\Delta E \sim j_1^*(\omega,k) D_R(\omega,k)(j_1(\omega,k) + j_2(\omega,k))$$

D_R propagates modes with a radiative dispersion relation, need to be removed

Terms that go like $j_1 * D_R j_2$ are obviously due to interactions between particles as opposed to energy loss due to a plasma

The Binding Effect



Note that black line still includes radiative effects

- Look at finite time current

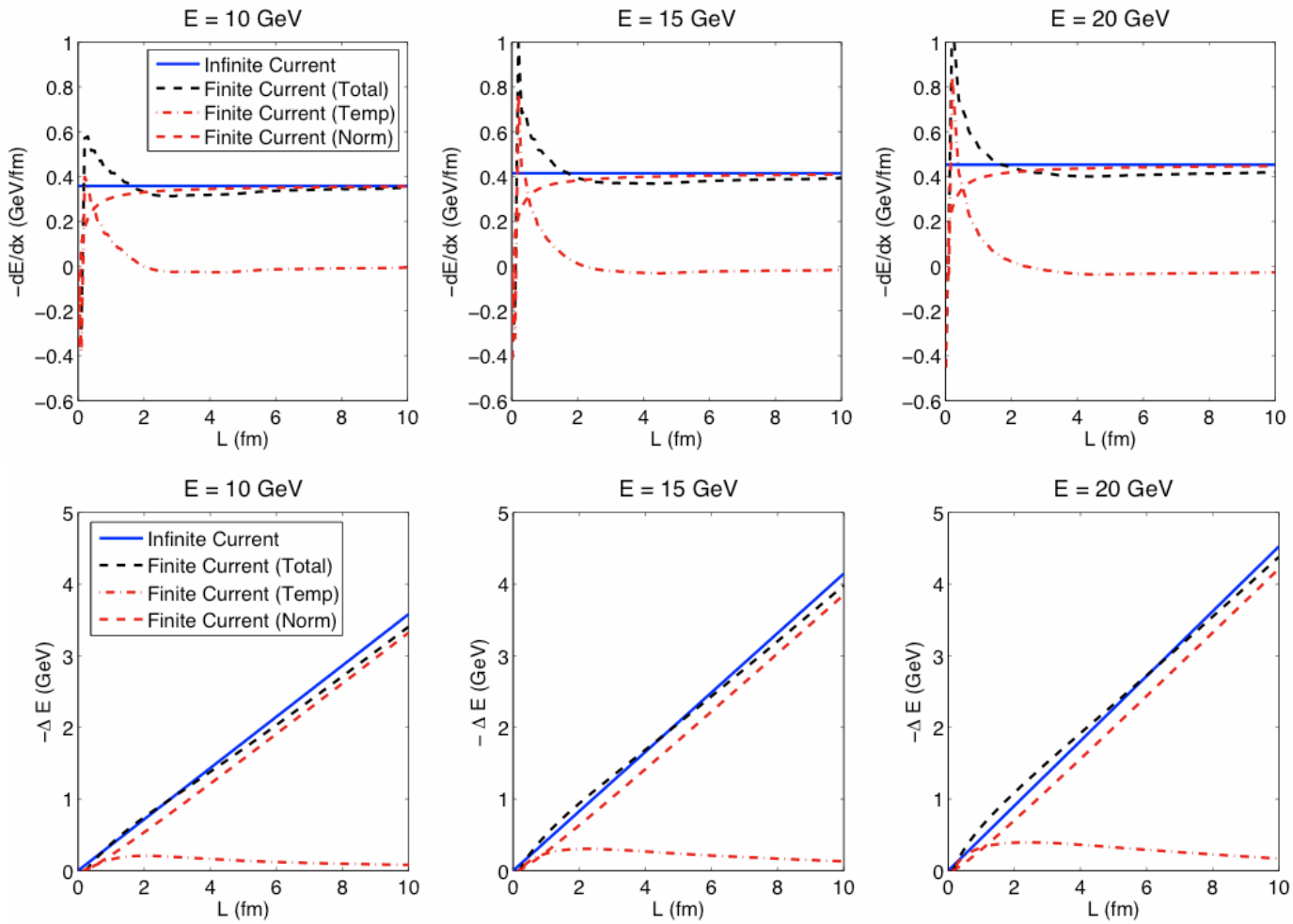
$$j^{\mu a}_{(2)}(\omega, \mathbf{k}) = iq^a \left(\frac{v_1^\mu}{\omega - \mathbf{k}\cdot\mathbf{v_1} + i\eta} - \frac{v_2^\mu}{\omega - \mathbf{k}\cdot\mathbf{v_2} + i\eta} \right)$$

- Schematically write energy loss as

$$j_1^*(D_R^{med} - D_R^{vac})(j_1(\omega, k) + j_2(\omega, k))$$

- The remaining answer is much closer to infinite time
- Peigne previous large suppression is due to this binding with $v_2 = 0$

The Result

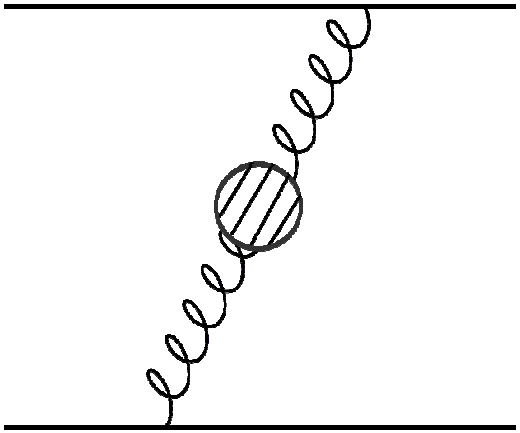


Collisional Energy Loss after Retardation ~ Infinite Case

Collisional Fluctuations

The Formalism

Similar treatment to:
Moore & Teaney Phys.Rev.C71:064904,2005
Djordjevic Phys.Rev.C74:064907,2006
Arnold, Moore, Yaffe JHEP 0305:051,2003



Massive jet, massless medium

$$\frac{dN}{d\omega} = \frac{1}{E^2}\frac{1}{v}\frac{1}{(2\pi)^4}\int_{|p-\sqrt{(\omega+E)^2-M^2}|}^{p+\sqrt{(\omega+E)^2-M^2}} dq \int_{\frac{1}{2}(q+\omega)}^{\infty} dk \int_0^{2\pi} d\phi \times \langle|\mathcal{M}|^2\rangle n(k)(1 \pm n(k'))$$

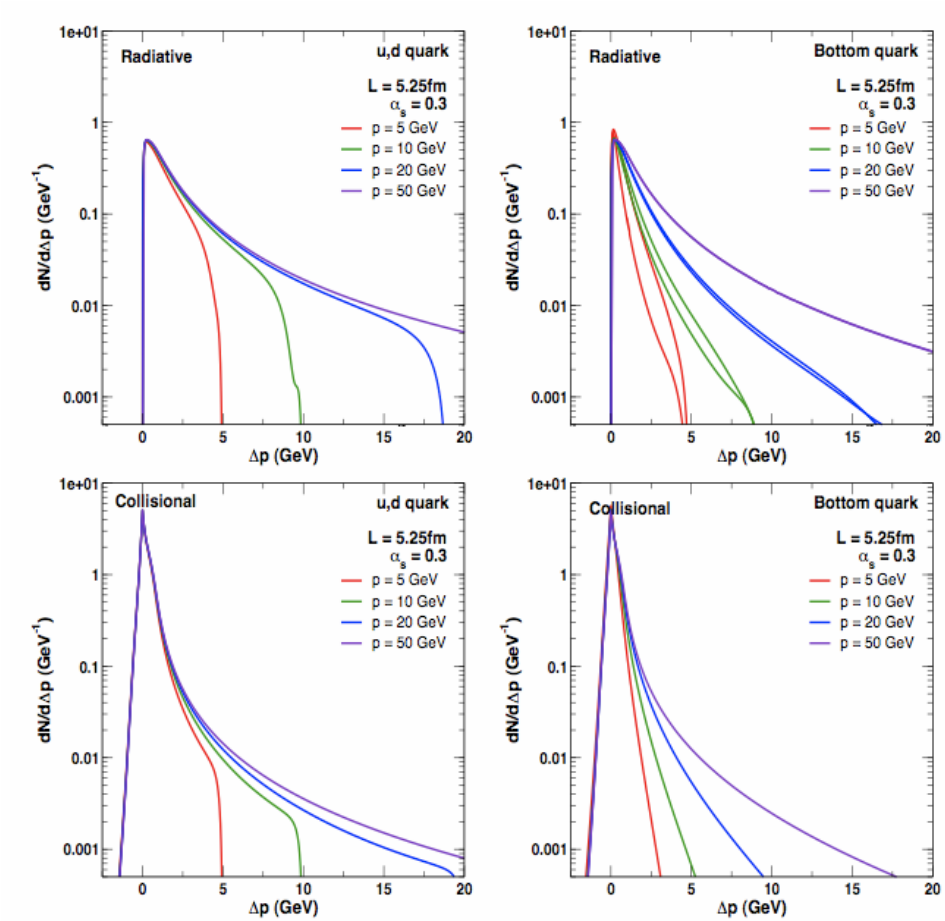
$$\langle|M|^2\rangle = 4g^4 k_{CF}\left(p^\mu p^{\mu'} + p^{\mu'}p'^\mu + (M^2 - p.p')g^{\mu\mu'}\right) D_{\mu\nu}(q) D^*_{\mu'\nu'}(q)\left(k^\nu k'^{\nu'} + k^{\nu'}k'^\nu + (m^2 - k.k')g^{\nu\nu'}\right)$$

Adapted from Wicks, LHC Last Call

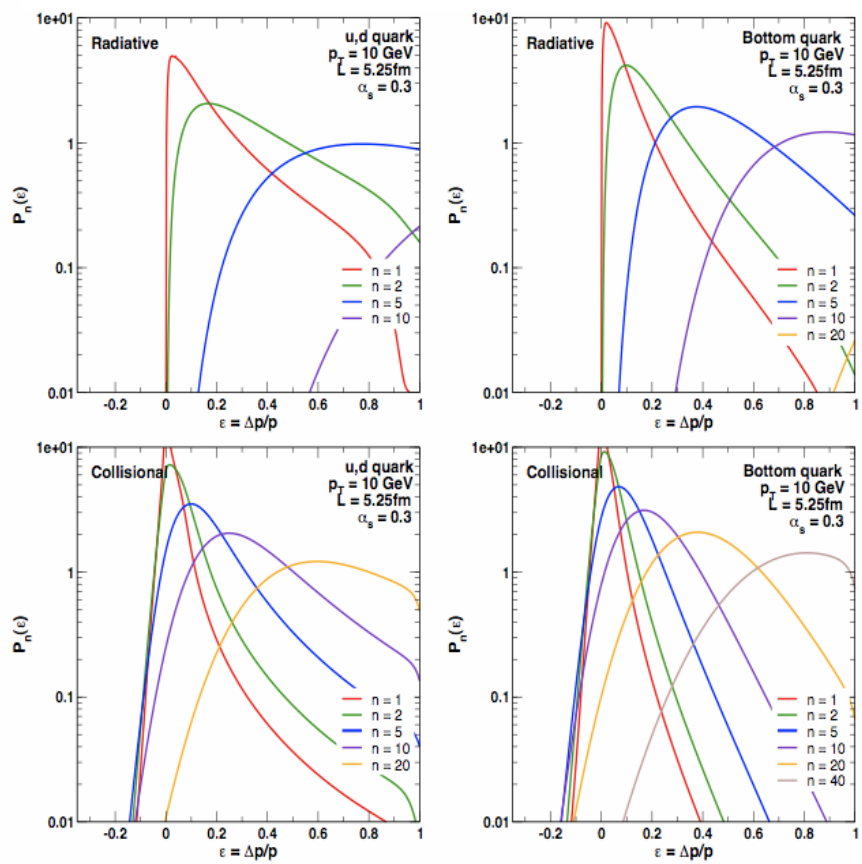
$$\mu_{mag} = \mu_D$$

The Distributions

Single Collision / Radiation

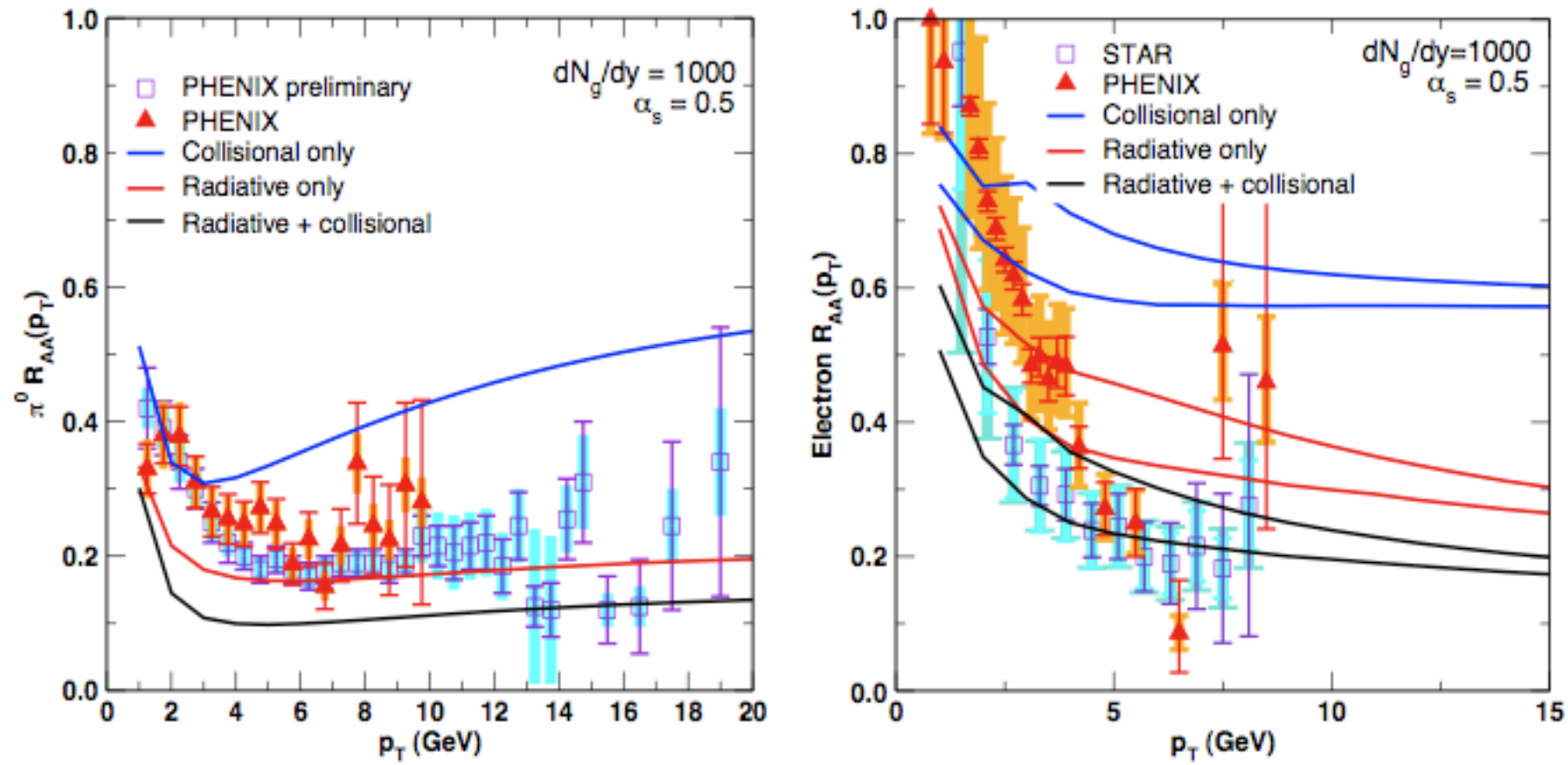


Poisson Convoluted



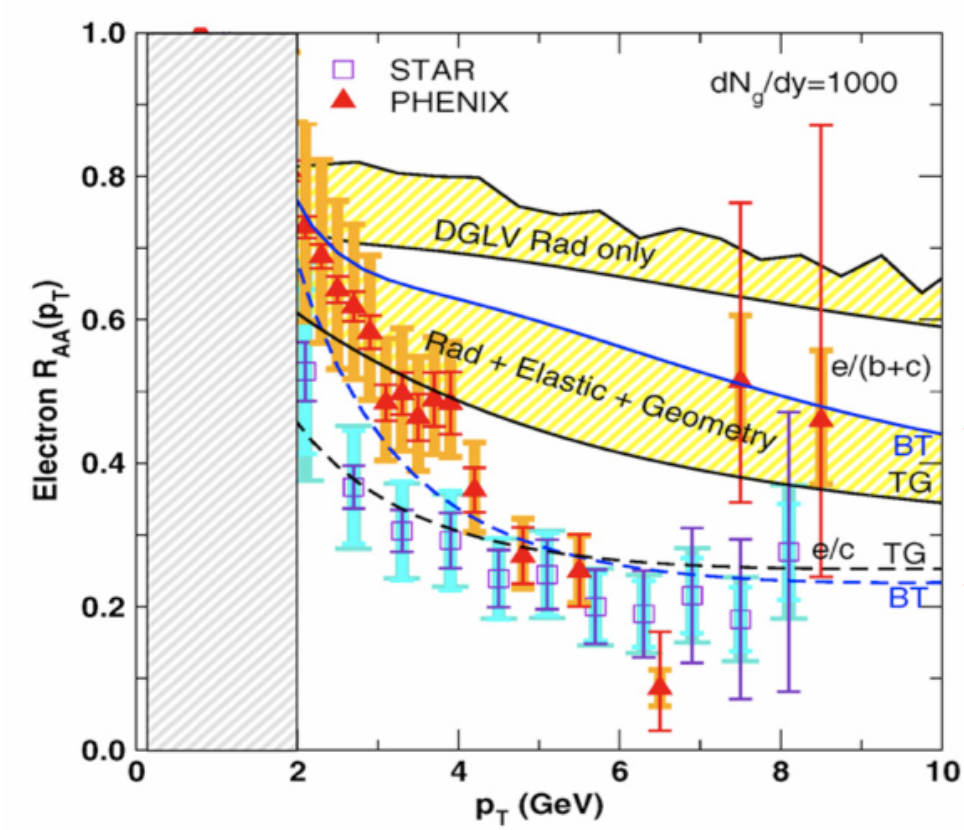
Adapted from Wicks, LHC Last Call

The R_{AA}



Adapted from Wicks, LHC Last Call

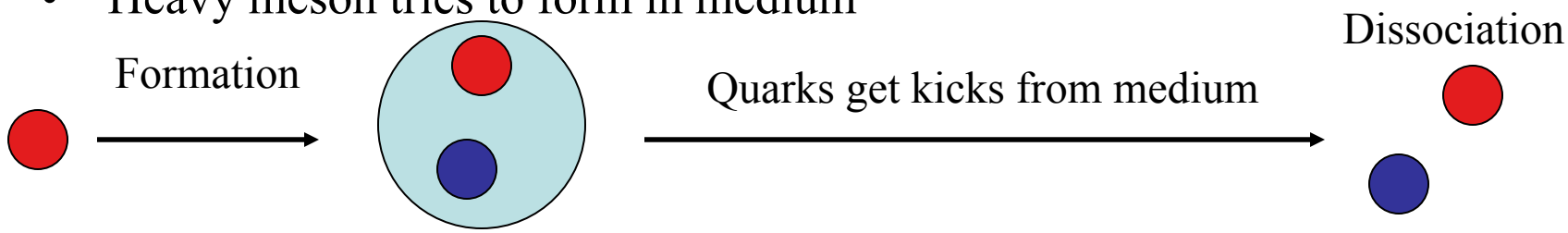
In-Medium Dissociation



Even with the inclusion of collisional energy loss and geometric fluctuations, we still don't seem to be doing enough

The Idea of Meson Dissociation

- Assumption has always been free quark energy loss followed by hadronization
  - Good for light quarks but not for heavies
  - Formation time of D meson ~ 1 fm but Pion ~ 10 fm
- Heavy meson tries to form in medium



- Model using coupled rate equations

$$\partial_t f^i(p,t) = -\frac{1}{\langle \tau_{form} \rangle} f^i(p,t) + \int dz \frac{1}{\tau_{diss}(z)} f^j(p,t) \frac{D_{j\to i}(z)}{z^2}$$

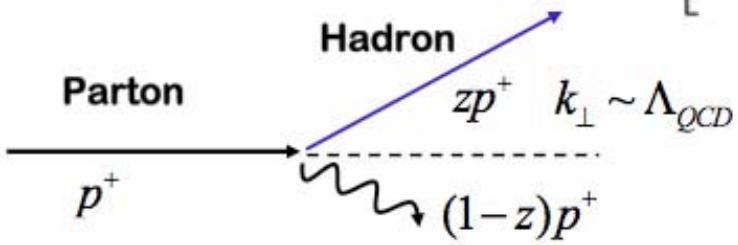
- Dissociation calculated using multiple collision formalism with meson wave functions

Slide from Ivan Vitev, QM 2006

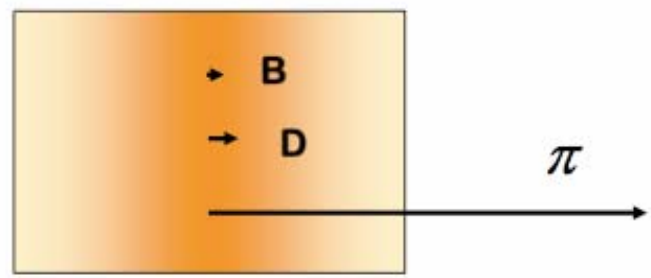
Conceptually Different Approach

- **Problem**: treated in the same way as light quarks!

$$\left[p^+, \frac{M_Q^2}{2p^+}, 0\right] \rightarrow \left[zp^+, \frac{\mathrm{k}^2 + m_h^2}{2zp^+}, \mathrm{k}\right] + \left[(1-z)p^+, \frac{\mathrm{k}^2}{2(1-z)p^+}, -\mathrm{k}\right]$$



$$\Delta y^+ \simeq \frac{1}{\Delta p^-} = \frac{2z(1-z)p^+}{\mathrm{k}^2 + (1-z)m_h^2 - z(1-z)M_Q^2}$$



$$\tau_{\rm form} = \frac{\Delta y^+}{1+\beta_Q}, \quad \beta_Q = \frac{p_Q}{E_Q}$$

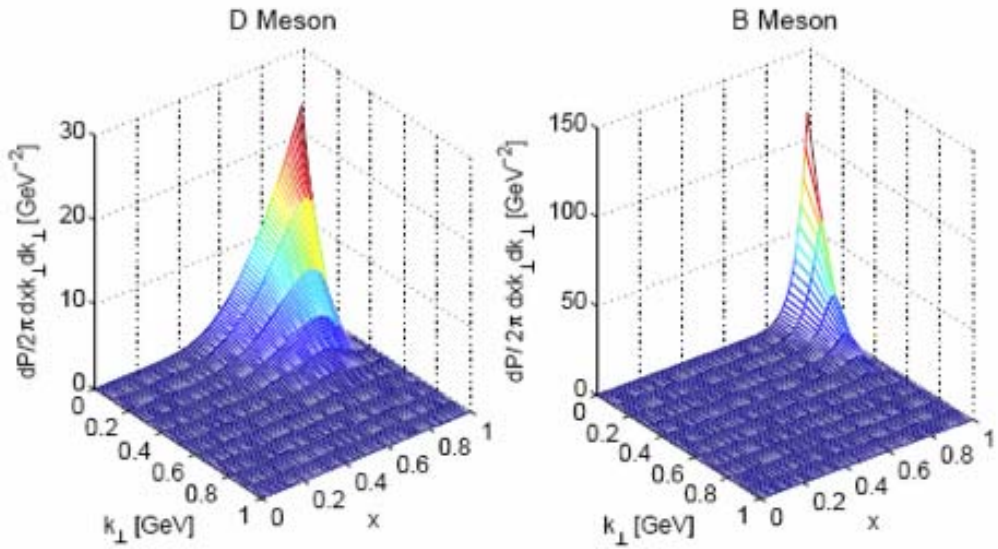
$\tau_f(p_T = 10\ GeV)$

π	D	B
10 fm	1.0 fm	0.35 fm

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

Slide from Ivan Vitev, QM 2006

Lightcone Wave Function



- **The momentum distribution**

$$|\psi(\mathbf{K}, \Delta\mathbf{k}; x, m_1, m_2)|^2$$

$$= \mathrm{Norm}^2 e^{-\frac{\Delta\mathbf{k}^2 + 4m_1^2(1-x) + 4m_2^2 x}{4x(1-x)\Lambda^2}} \times \delta^2(\mathbf{K})$$

$$|\Psi_M, P^+, \mathbf{P}_\perp\rangle = \sum_{n\geq 2} \int \prod_{i=1}^{n} (P^+)^{\frac{n}{2}} \frac{dx_i d^2\mathbf{k}_{\perp,i}}{\sqrt{2x_i}}$$

$$\times \delta\left(\sum_{i=1}^{n} x_i P^+ - P^+\right) \delta^2\left(\sum_{i=1}^{n} \mathbf{k}_{\perp,i} + x_i \mathbf{P}_\perp - \mathbf{P}_\perp\right)$$

$$\times \psi(\mathbf{k}_{\perp,i}, x_i) |\mathbf{k}_{\perp,i} + x_i \mathbf{P}_\perp, x_i P^+\rangle$$

- **PDFs**

$$\phi_{Q/M}(x) = \int d^2\Delta\mathbf{k} d^2\mathbf{K} \, |\psi(\mathbf{K}, \Delta\mathbf{k}; x, m_1, m_2)|^2$$

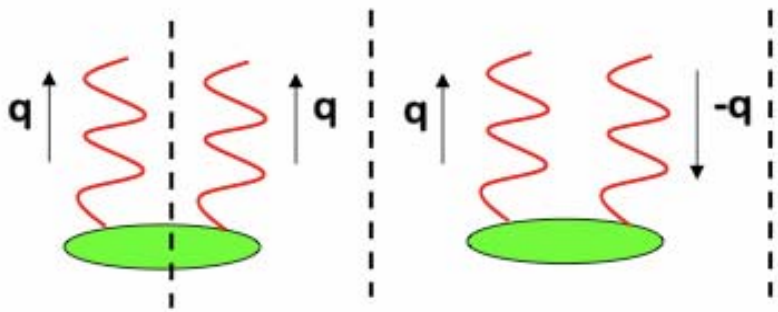
$$= \mathrm{Norm}^2 4\pi x(1-x)\Lambda^2 e^{-\frac{m_1^2(1-x) + m_2^2 x}{x(1-x)\Lambda^2}}$$

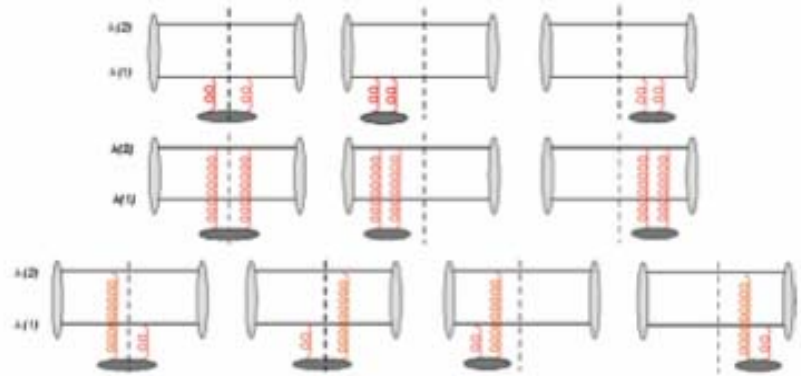
S. Brodsky, Acta Phys. Polonica B (2003)

S. Brodsky, Phys.Rev.D (2002)

Collisional Dissociation of Mesons

- Direct and virtual interactions





$$M^*_{n-1}(\mathrm{K},\mathrm{k})\Big[e^{-\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{K}}e^{-\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{K}}\otimes\Big(e^{-\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{-\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{k}}+e^{+\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{+\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{k}}+e^{-\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{+\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{k}}+e^{+\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{-\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{k}}\Big)$$
$$-\hat{1}\otimes\Big(\hat{1}-\hat{1}-e^{-2\mathbf{q}_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{+0_n\cdot\overrightarrow{\nabla}_\mathrm{k}}-e^{+0_n\cdot\overleftarrow{\nabla}_\mathrm{k}}e^{-2\mathbf{q}_n\cdot\overrightarrow{\nabla}_\mathrm{k}}\Big)\Big]M_{n-1}(\mathrm{K},\mathrm{k})$$

- Final state wave function

$$|\psi_f(\mathrm{k},\mathrm{K})|^2 = \int\frac{d^2\mathrm{k}}{(2\pi)^2}\frac{d^2\mathrm{K}}{(2\pi)^2}e^{-i\mathbf{b}\cdot\mathbf{k}}e^{-\chi\mu^2\xi B^2}$$
$$\times e^{-i\mathbf{B}\cdot\mathbf{K}}e^{-b^2(\chi\mu^2\xi+x(1-x)\Lambda^2)}$$
$$=\frac{e^{-\frac{\mathrm{K}^2}{4\chi\mu^2\xi}}}{4\pi\chi\mu^2\xi}\frac{e^{-\frac{\mathrm{k}^2}{4(\chi\mu^2\xi+x(1-x)\Lambda^2)}}}{4\pi(\chi\mu^2\xi+x(1-x)\Lambda^2)}$$

- Resummed all interactions above (L/λ enhanced)

Slide from Ivan Vitev, QM 2006

Survival and Dissociations Probabilities

Simple two component system :

$$\psi_0 \equiv \psi_M$$ Meson

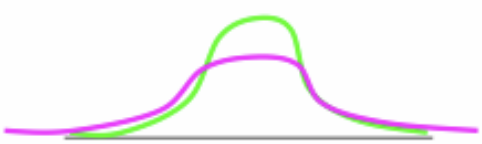
$$\psi_f \equiv a\psi_M + (b)\psi_{Q\bar{q}}$$ Meson + Free Q-qbar pair

Survival probability:

$$P_s = | a |^2$$

$$P_s(\chi,\xi,\mu) = \left| \int d^2\mathbf{k}dx\, \psi_f^*(\mathbf{k})\psi_0(\mathbf{k}) \right|^2$$

$$= \left| \int dx\, \mathrm{Norm}^2\, 4\pi x(1-x)\Lambda^2\, e^{-\frac{m_1^2(1-x)+m_2^2 x}{x(1-x)\Lambda^2}} \times \left[\frac{2\sqrt{x(1-x)\Lambda^2}\sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}}{\sqrt{x(1-x)\Lambda^2}^2 + \sqrt{\chi\mu^2\xi + x(1-x)\Lambda^2}^2} \right] \right|^2$$



Dissociation probability:

$$P_d(p_T, m_Q, t) = 1 - P_s(p_T, m_Q, t)$$

Slide from Ivan Vitev, QM 2006

Slide from Ivan Vitev, QM 2006

Rate Equations

- **Notation and in intial conditions**

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

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

$$\frac{1}{\langle\tau_{\rm diss}(p_T,t)\rangle} = \frac{\partial}{\partial t}\ln P_d(p_T,m_Q,t)$$

$$\langle\tau_{\rm form}(p_T,t)\rangle = \sum_i \int_0^1 dz\, D_{H_i/Q}(z)\tau_{\rm form}(z,p_T,m_Q,t)$$

- **Coupled ordinary differential equations**

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

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

Loss term

Gain term

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Quenching of Non-Photonic Electrons

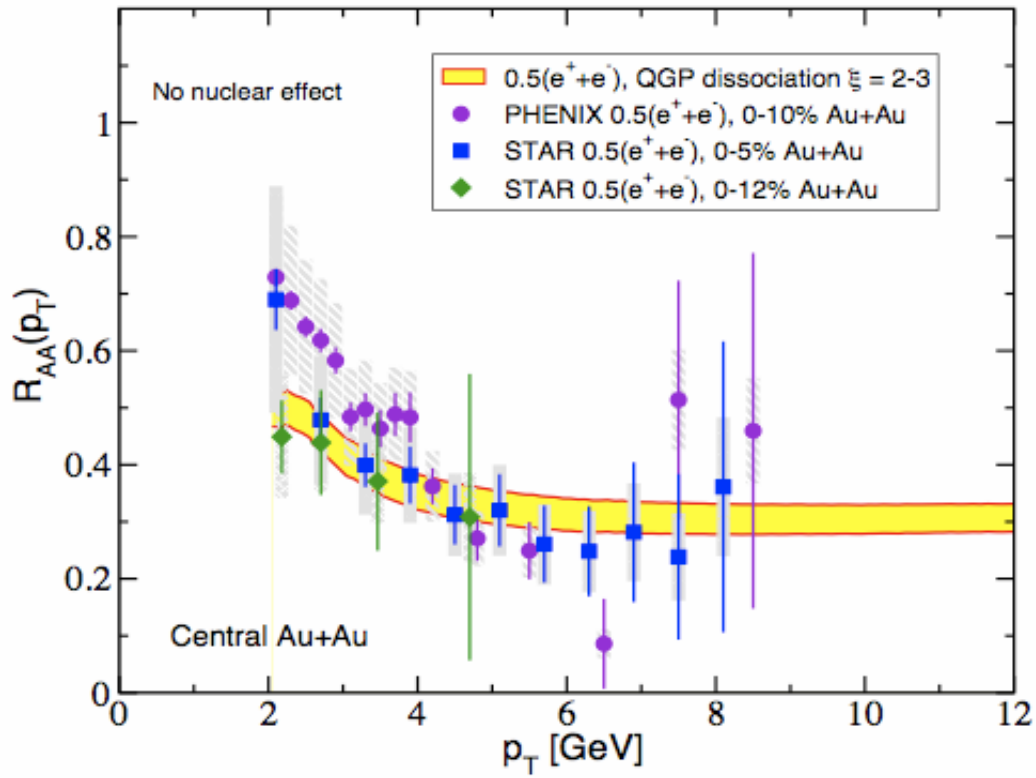
- PYTHIA used to decay all B- and D-mesons / baryons into (e^++e^-)

- Suppression $R_{AA}(p_T) \sim 0.25$ is large

- Similar to light π^0, however, different physics mechanism

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

A.Adil, I.V., PLB 649, 139-146



Predictions also made for Cu+Cu (RHIC) and Pb+Pb (LHC)

Conclusions - Finite Time Coll

- Must always be careful and compare apples to apples
  - We did a complete and careful calculation of collisional energy loss
  - After removal of radiative and *unrealistic* binding effects two different calculations give very similar results making collisional energy loss a viable component
- The binding effect is real (but not simple singlet)
  - Jets are created back to back and their interactions is part of the p-p process and leads to induced energy loss
  - Need to calculate and include binding effect for $v_2 \neq 0$ and a more realistic charge correlation
  - Maybe helpful for v_2 at moderate p_T?
- Finite time calculation in expanding medium

Conclusion - Collisional Fluctuations

- Fluctuations of all Sorts are Important
  - Geometric fluctuations matter, no fixed lengths
  - Collisional fluctuations are important and non Gaussian.
  - Not a simple drag-diffusion process.
- Significant Remaining Uncertainties
  - Value of α_S / Running (Vitev, Peshier …)
  - Interference b/w Radiative/Collisional, Poisson

Conclusions - Dissociation

- The vacuum fragmentation approximation is not as good for heavy quarks as it is for light quarks
- One can get large energy loss due to repeated dissociation and fragmentation of hadrons
  - Energy loss comes from the peaking of wavefunctions in ‘x’
- Bottom quark quenched at the same level as charm quark
  - This is a unique signature of the process
  - p_T Dependence of Energy Loss also a good discriminator
- Need to implement further details
  - Accompanied partonic energy loss
  - Geometric fluctuations

Acknowledgments

I would like to thank the organizers for inviting me.

I gratefully acknowledge many consultations and collaborations with:

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Bonus Slides

Linear Response Formulation

$$\frac{dE}{dx} = \int \frac{d\omega d\mathbf{k}}{(2\pi)^4} e^{-i(\omega - \mathbf{k}\cdot\mathbf{v})\frac{L}{v}} \frac{q^a}{v} \mathbf{v} \cdot \mathbf{E}^a_{ind}(\omega, \mathbf{k})$$

Joule Heating (Fourier Space)

$$\mathbf{E}^a = D^{\perp}_R(\omega, \mathbf{k})(1 - \hat{\mathbf{k}}\hat{\mathbf{k}})\mathbf{j}^a + \hat{\mathbf{k}} D^{\parallel}_R(\omega, \mathbf{k}) j^{0a}$$

$$\mathbf{E}^a_{vac} = D_R(\omega, \mathbf{k})(\omega \mathbf{j}^a - \mathbf{k} j^{0a})$$

Solutions of Macro/Vacuum Maxwell (Abelianized QCD)

$$D_R(\omega, k) = \frac{-4\pi i}{(\omega + i\eta)^2 - k^2}$$

Vacuum Propagator

$$D^{\perp}_R(\omega, \mathbf{k}) = \frac{4\pi i \omega}{k^2 - (\omega + i\eta)^2 \epsilon_{\perp}(\omega + i\eta, \mathbf{k})}$$

Transverse Medium Propagator

$$D^L_R(\omega, \mathbf{k}) = \frac{-4\pi i}{k \epsilon_{\parallel}(\omega + i\eta, \mathbf{k})}$$

Longitudinal Medium Propagator

$$\epsilon_{\perp}(\omega, k) = 1 - \frac{\Pi_{\perp}(\omega, k)}{\omega^2} \quad \epsilon_{\parallel}(\omega, k) = 1 + \frac{\Pi_{\parallel}(\omega, k)}{k^2}$$

Electric Permittivities

$$\Pi_{\perp}(\omega, \mathbf{k}) = \frac{1}{2} m_D^2 \left(\frac{\omega}{k}\right)^2 \left(1 - \frac{\omega^2 - k^2}{2\omega k} \log\left(\frac{\omega + k}{\omega - k}\right)\right)$$

$$\Pi_{\parallel}(\omega, \mathbf{k}) = m_D^2 \left(1 - \frac{\omega}{2k} \log\left(\frac{\omega + k}{\omega - k}\right)\right)$$

HTL Self Energies

$$m_D^2 = 4\pi\alpha_s T^2 (1 + \frac{N_F}{6})$$

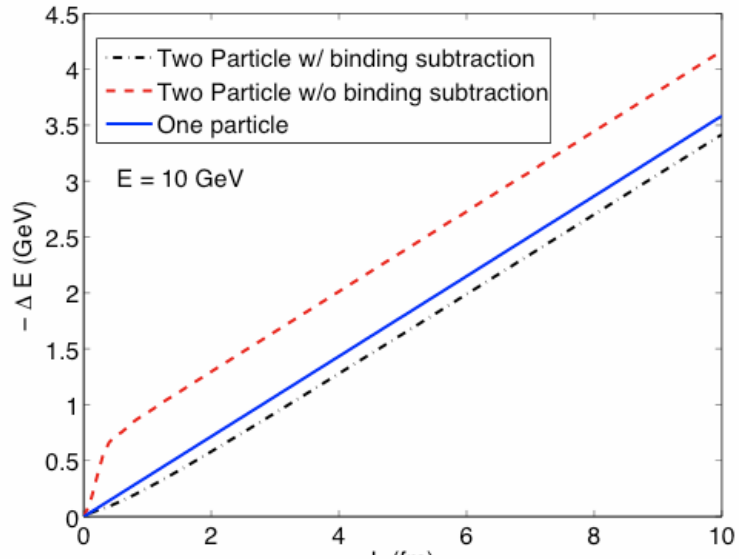
Is the Current Correct?

- The actual current should be one modeling a 2 -> 2 process. (Very complicated!!)

$$
\begin{aligned}
j^{\mu a} &= \Theta(t)\left(q_1^a v_1^\mu \delta(\mathbf{x}-\mathbf{v}_1 t) + q_2^a v_2^\mu \delta(\mathbf{x}-\mathbf{v}_2 t - \mathbf{b})\right) \\
&\quad + \Theta(-t)\left(q_1^a v_1^{'\mu} \delta(\mathbf{x}-\mathbf{v}_1' t) + q_2^a v_2^{'\mu} \delta(\mathbf{x}-\mathbf{v}_2' t - \mathbf{b})\right)
\end{aligned}
$$

- Averaging over the initial colors of the incoming partons drops interactions to zero
- Enhanced in Peigne current due to
  - $v_2 = 0$
  - Exactly anti correlated charge

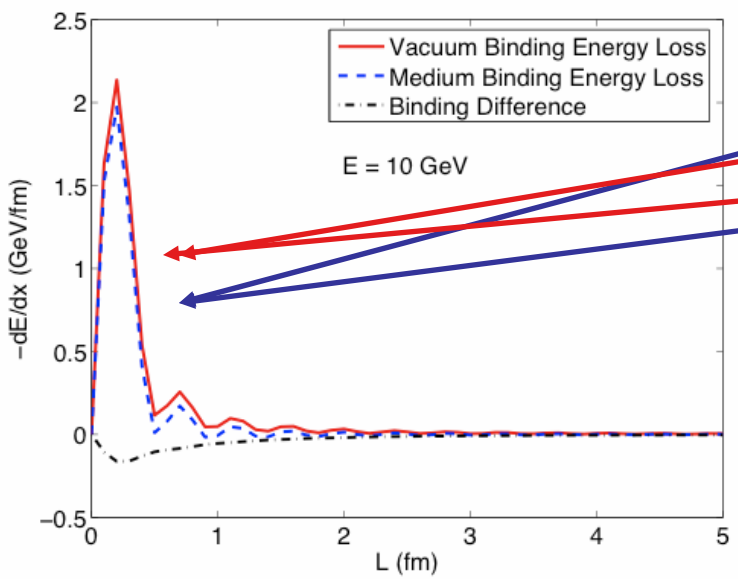
The Binding Effect - I



- First look at infinite time with two particles

$$j^{0a}_{\infty,(2)}(\omega,\mathbf{k}) = 2\pi q^a\left(\delta(\omega-\mathbf{k}\cdot\mathbf{v})-\delta(\omega)\right)$$

- $$\mathbf{j}^{a}_{\infty,(2)}(\omega,\mathbf{k}) = 2\pi q^a \mathbf{v}\delta(\omega-\mathbf{k}\cdot\mathbf{v})$$



- Note the suppression in the energy loss

$$j_1^*(D_R^{med}-D_R^{vac})(j_1(\omega,k)+j_2(\omega,k))$$

- Enhanced due to $v_2 = 0$.

Radiative Effects : Vacuum Singularity Structure

$$W = \int dt d\mathbf{x} \mathbf{j}^a(\mathbf{x},t) \cdot \mathbf{E}^a(\mathbf{x},t)$$
$$= \int \frac{d\omega d\mathbf{k}}{(2\pi)^4} \mathbf{j}^{a*}(\omega,\mathbf{k}) \cdot \mathbf{E}^a(\omega,\mathbf{k})$$

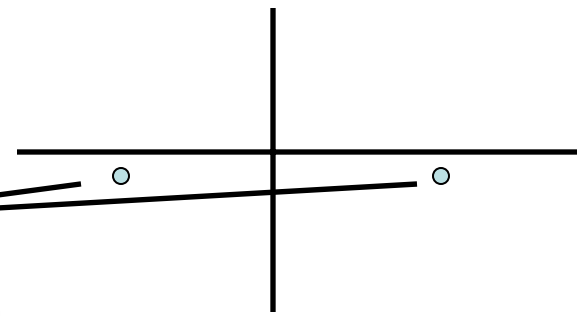
Total Work Done on Current

$$W = \int \frac{d\omega d\mathbf{k}}{(2\pi)^4} D_R(\omega,\mathbf{k})(\omega(|\mathbf{j}_\perp|^2 + |j_\parallel|^2) - k j_\parallel^* j^0)$$

Work Done by self Electric Field

$$D_R(\omega,\mathbf{k}) = PV\left(\frac{-4\pi i}{\omega^2 - k^2}\right) + D_{rad}(\omega,\mathbf{k})$$

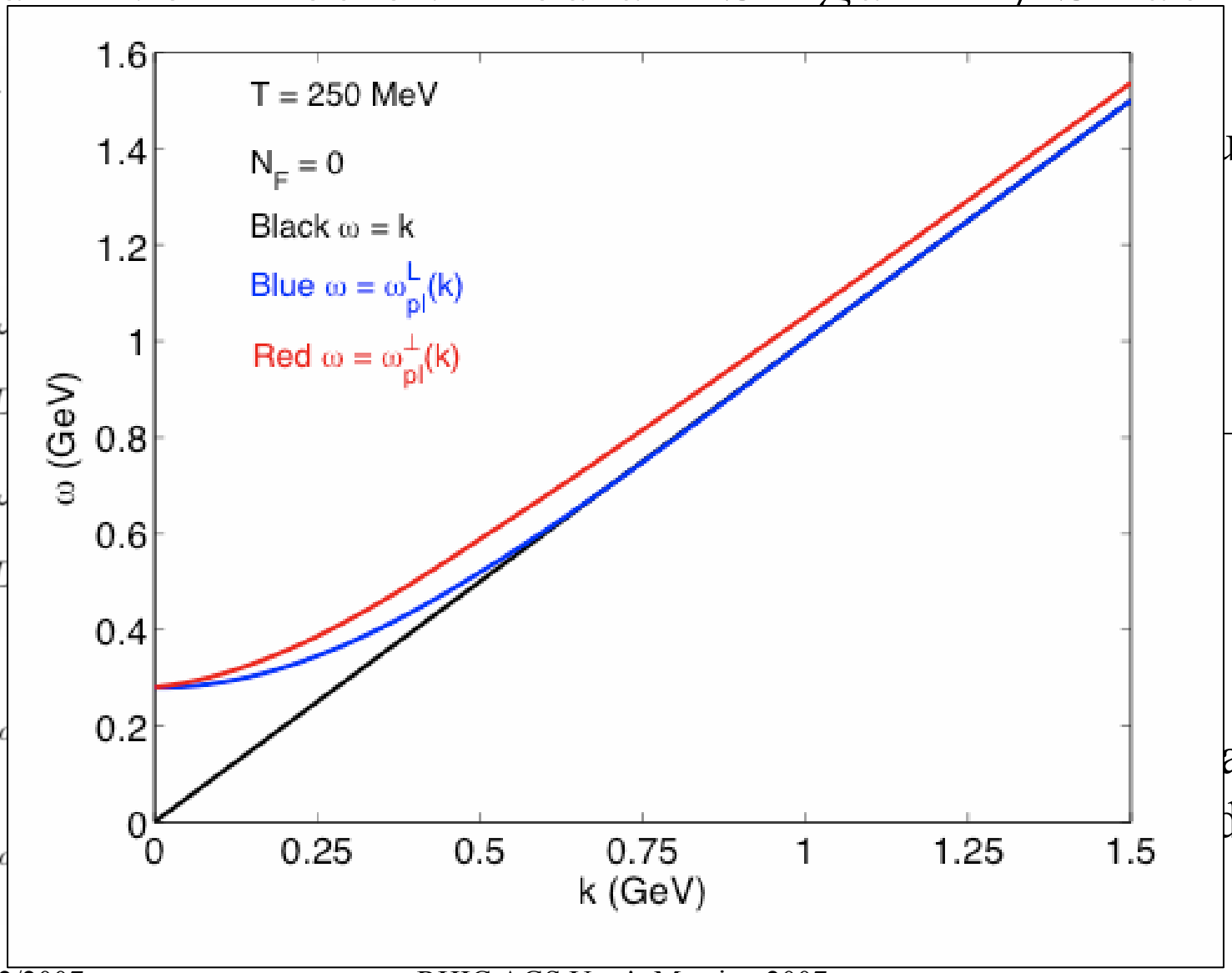
$$D_{rad}(\omega,\mathbf{k}) = -\frac{4\pi^2}{2k}(\delta(\omega - k) - \delta(\omega + k))$$



$$W_{\rm rad} = -\int \frac{d\mathbf{k}}{4\pi^2}\{|\mathbf{j}_\perp|^2 + |j_\parallel|^2 - \frac{1}{2}(j^{0*} j_\parallel + j_\parallel^* j^0)\}$$
$$= -\int \frac{d\mathbf{k}}{4\pi^2}|\mathbf{j}_\perp|^2$$

Energy Lost to Creation Radiation Included in our Calculation

Radiative Effects : Medium Singularity Structure



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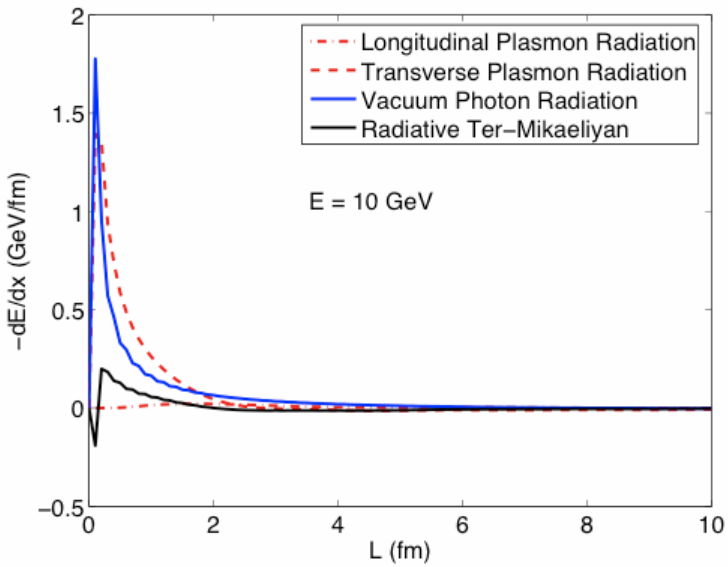
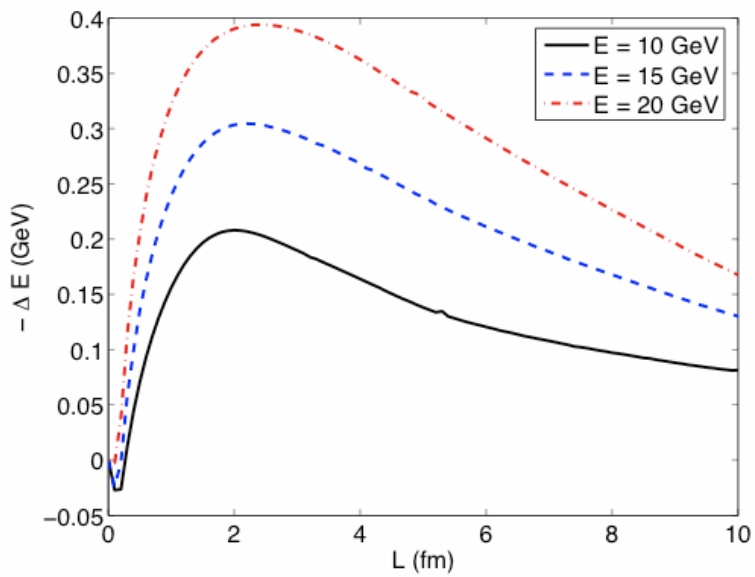
dium.

By the way … Ter-Mikaeliyan Effect



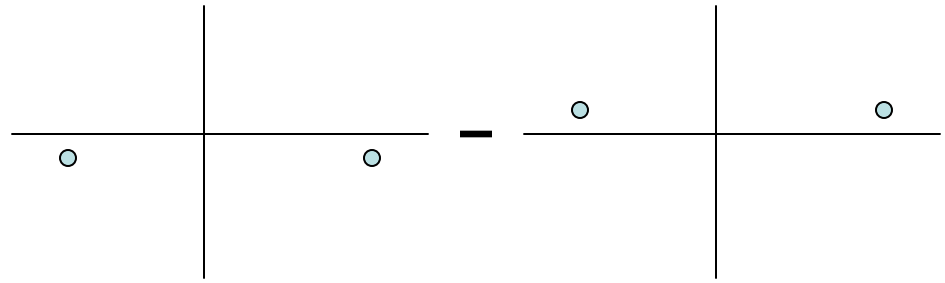


- The Radiative Energy Loss enters our calculation as medium - vacuum
- The difference between creation radiation in the medium with respect to the vacuum is the Ter-Mikaeliyan effect
- First studied in QCD by Djordjevic et al. We need to subtract this from our calculations

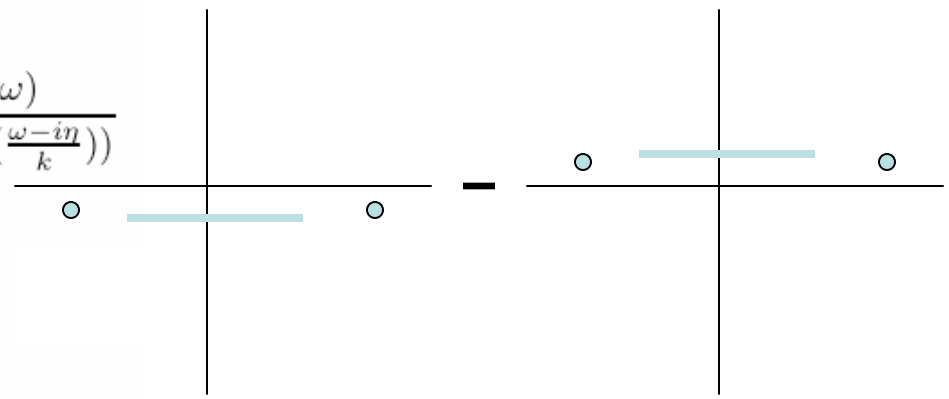
Subtracting the Radiative Effects

$$\begin{aligned} D_R(\omega,\mathbf{k}) &= D_R(\omega,\mathbf{k}) - D_A(\omega,\mathbf{k}) + D_A(\omega,\mathbf{k}) \\ &= D_-(\omega,\mathbf{k}) + D_A(\omega,\mathbf{k}) \end{aligned}$$

$$\begin{aligned} D_-(\omega,\mathbf{k}) &= D_R(\omega,\mathbf{k}) - D_A(\omega,\mathbf{k}) \\ &= -\frac{4\pi^2}{k}\left(\delta(\omega-k) - \delta(\omega+k)\right) \end{aligned}$$



$$\begin{aligned} D_-^{\perp}(\omega,\mathbf{k}) &= A^{\perp}(\omega,\mathbf{k}) + 2D_{rad}^{\perp}(\omega,\mathbf{k}) \\ A^{\perp}(\omega,\mathbf{k}) &= \frac{2\pi^2 m_D^2 \omega^2(\omega^2-k^2)\Theta(k+\omega)\Theta(k-\omega)}{k^3(k^2-\omega^2+\Pi_{\perp}(\frac{\omega+i\eta}{k}))(k^2-\omega^2+\Pi_{\perp}(\frac{\omega-i\eta}{k}))} \\ D_-^{\parallel}(\omega,\mathbf{k}) &= A^{\parallel}(\omega,\mathbf{k}) + 2D_{rad}^{\parallel}(\omega,\mathbf{k}) \\ A^{\parallel}(\omega,\mathbf{k}) &= \frac{-4\pi^2 m_D^2 \omega\Theta(k+\omega)\Theta(k-\omega)}{(k^2+\Pi_{\parallel}(\frac{\omega+i\eta}{k}))(k^2+\Pi_{\parallel}(\frac{\omega-i\eta}{k}))} \end{aligned}$$

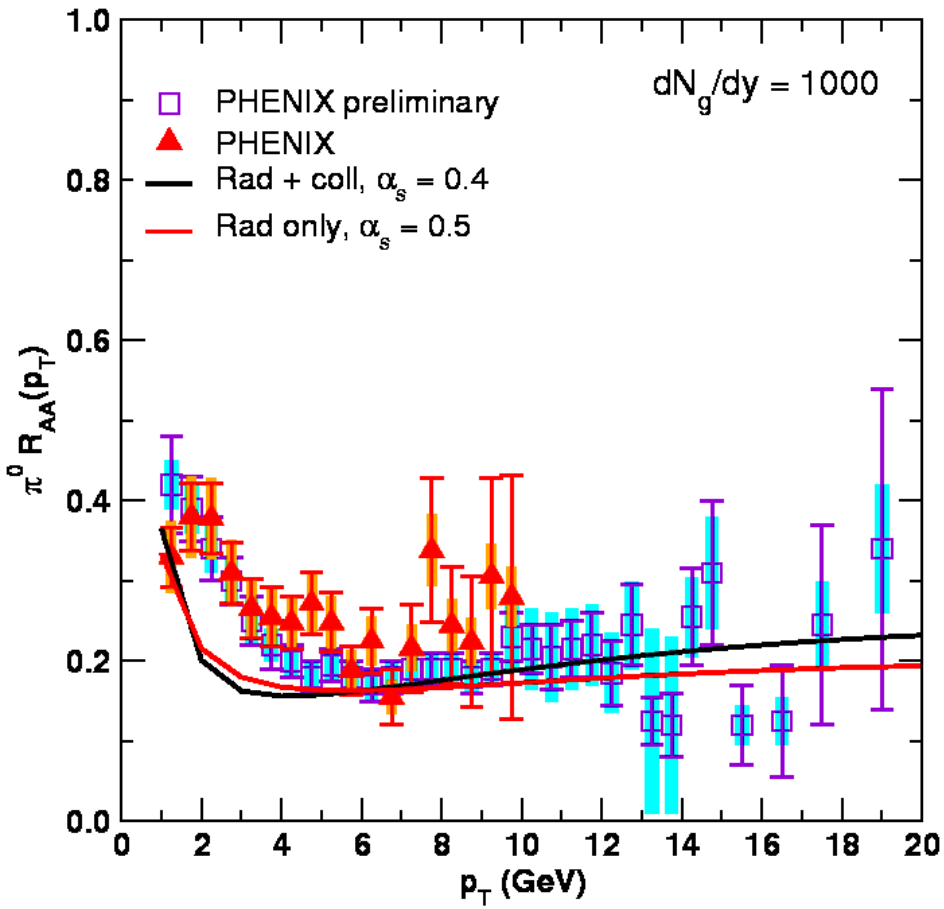


Isolates pole structure and one radiative pole can be removed

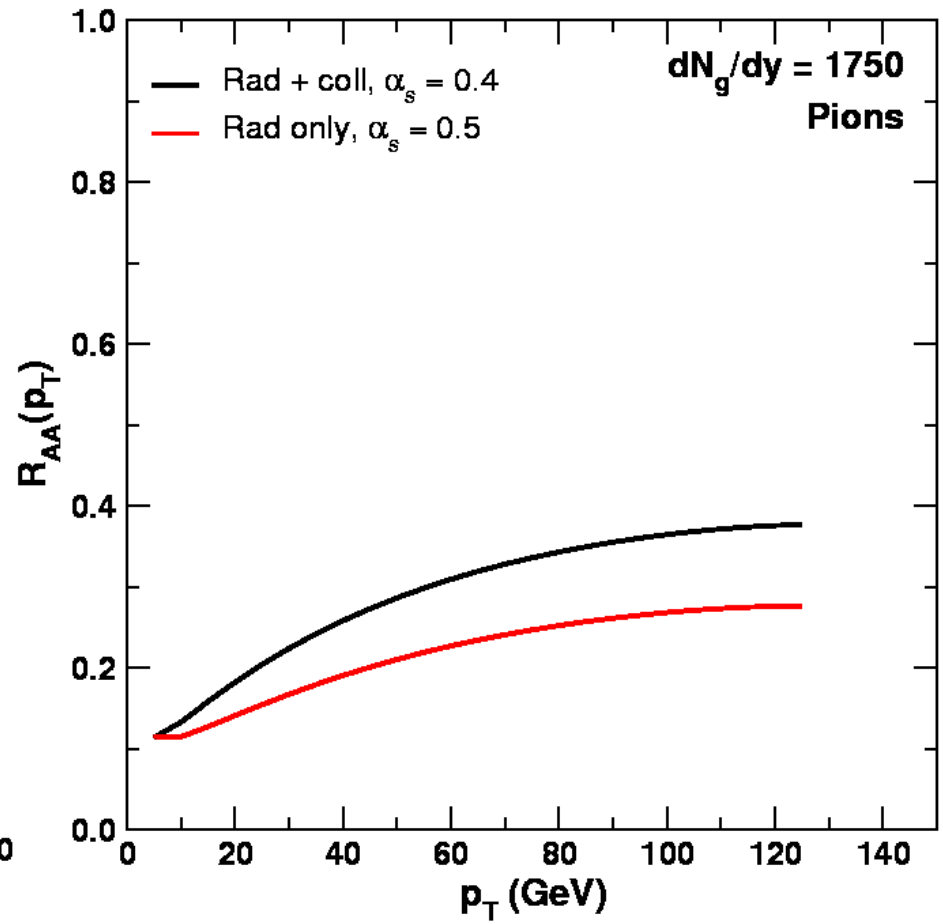
Advanced Green Function is easily contour integrated over

Predicting LHC

RHIC

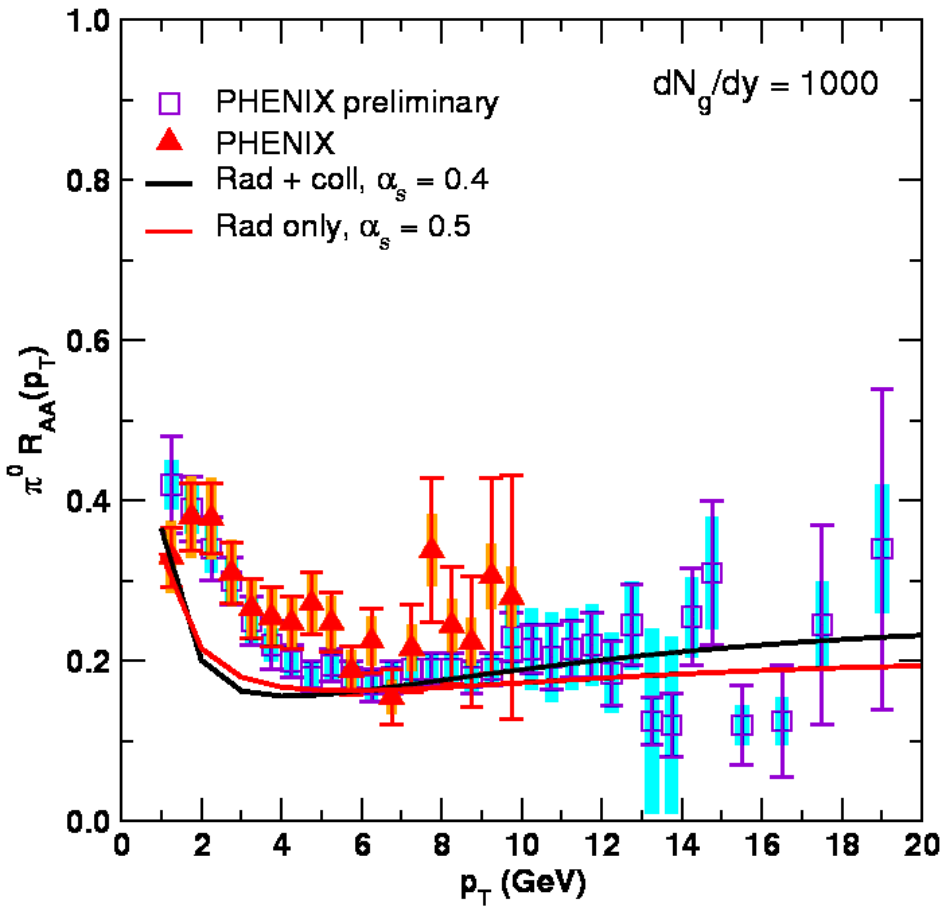


LHC

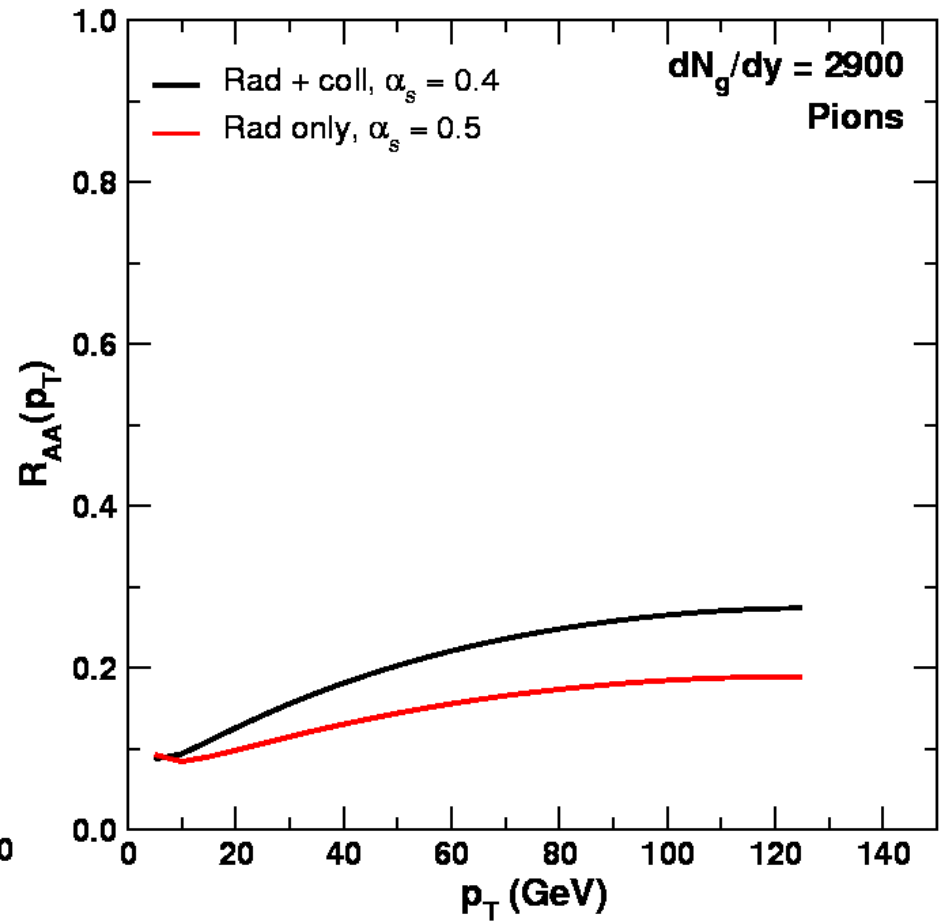


Predicting LHC

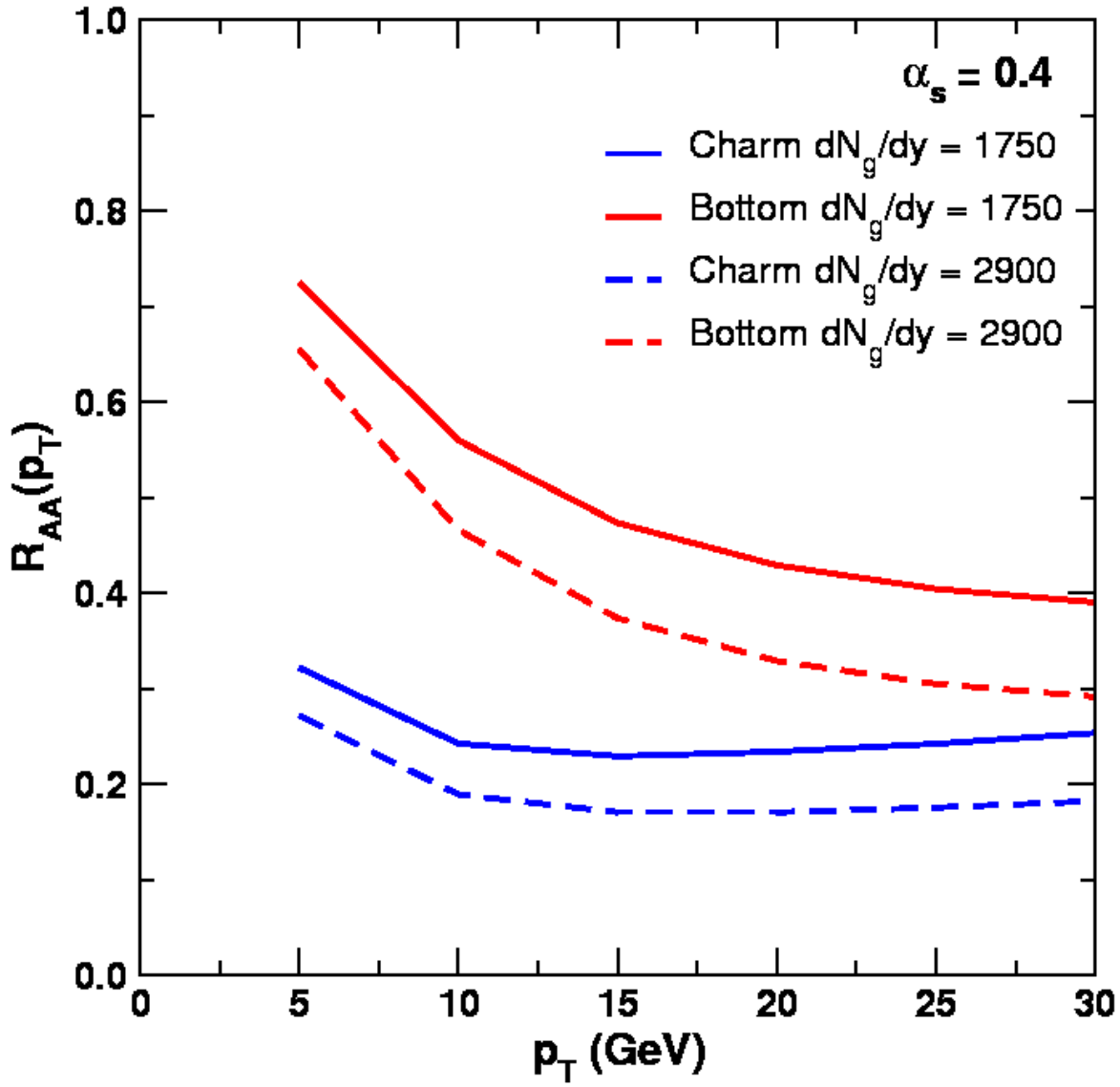
RHIC



LHC

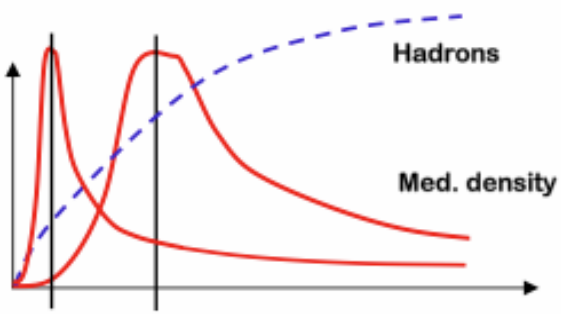


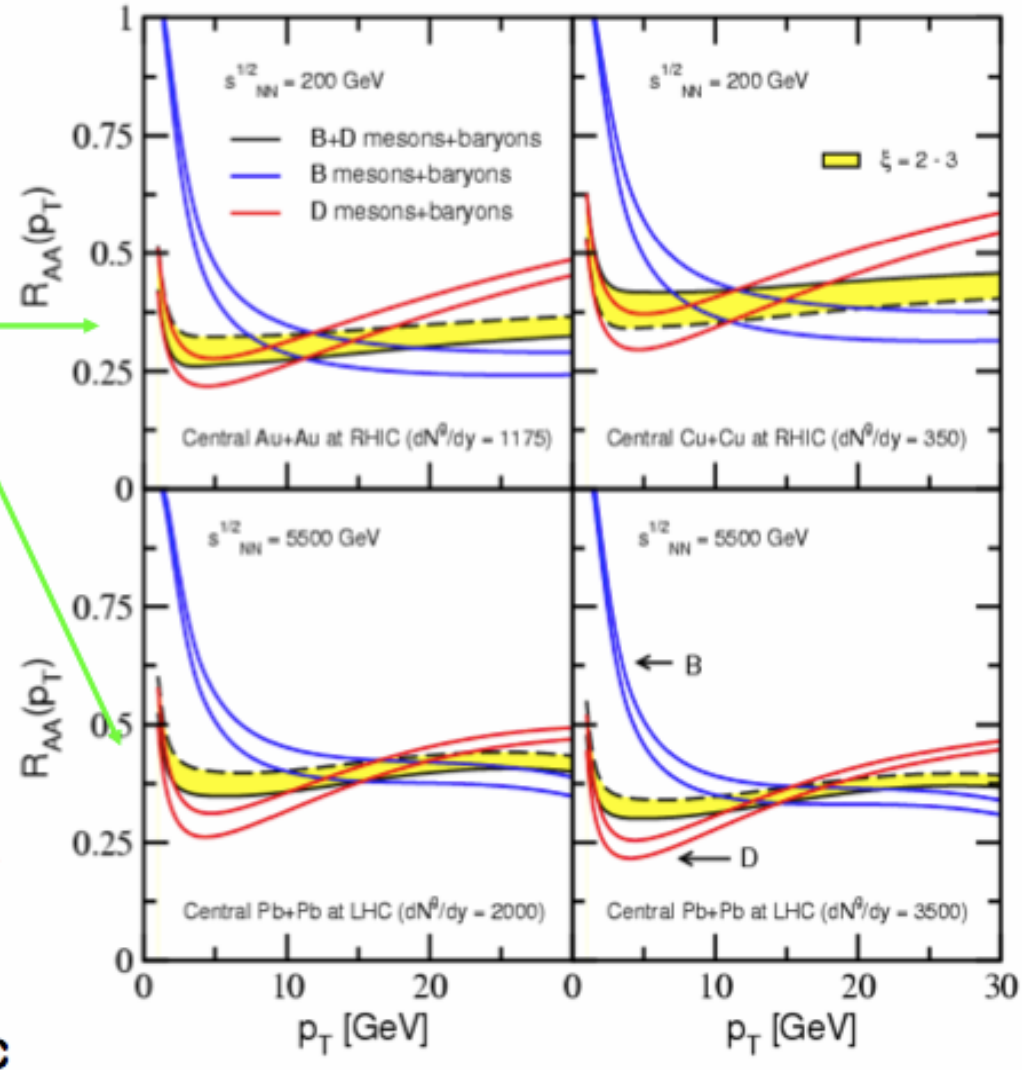
Predicting - LHC



D- and B-meson Suppression

- Note the different p_T dependence of B versus D quenching
  - Effective energy loss (depends on the slope of the spectra)
    - Critical: finite $\tau_0 = 0.6\ fm$ formation time to develop density and momentum transfers





- Predictions for Cu+Cu and the LHC

Slide from Ivan Vitev, QM 2006