

Predictions for the LHC: From Photons to Heavy Quarks



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Outline of the Talk

Four classes of predictions submitted to this workshop

Characteristics of the non-Abelian energy loss in the GLV approach

- Distribution in gluon energy and angular distribution of radiative gluons
- Mean energy loss, gluon number and probability distributions in Pb+Pb at the LHC

Light hadron production and suppression at the LHC

- Light hadron cross sections at the LHC. High transverse momentum suppression
- Redistribution of the lost energy and impact on inclusive particle production.
- Importance of cold nuclear matter effects in p+A and A+A collisions

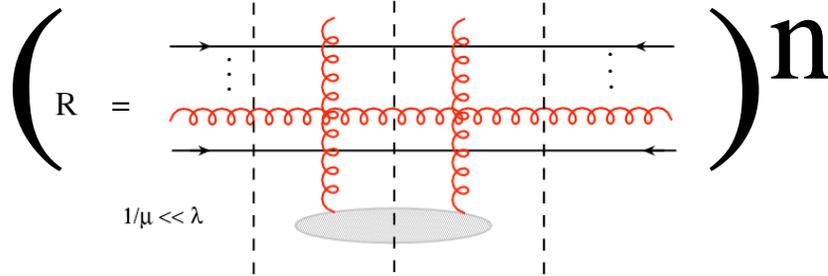
Direct photon production and suppression at the LHC

- Production cross sections at RHIC and the LHC
- Cold nuclear matter effects on pions versus direct photons in p+A reactions
- Direct photon quenching in Pb+Pb collisions at the LHC

Heavy meson production and suppression at the LHC

- Heavy flavor production and back-to-back correlations at the LHC
- Dissociation: new approach to D- and B-mesons suppression in the QGP
- Results for the LHC: inclusive charm and beauty and single electron quenching

Medium-Induced Energy Loss in GLV



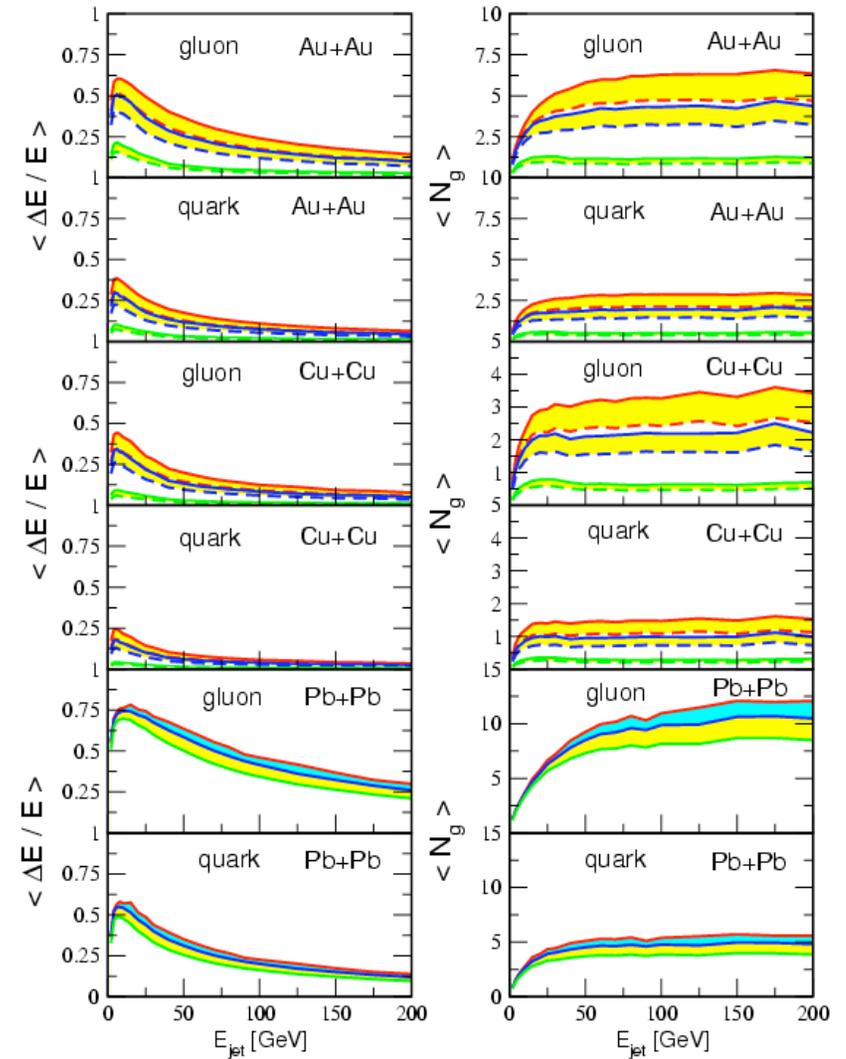
Applicability: Cronin effect, initial-state e-loss, final-state e-loss, meson dissociation, ...

$$k^+ \frac{dN_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN_g^n}{dk^+ d^2k_\perp} =$$

$$\sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[\prod_{i=1}^n \int_0^{L - \sum_{j=i+1}^n \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \int d^2q_i \left(\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q_i} - \delta^2(q_i) \right) \right]$$

$$\times \left[-2C_{(1\dots n)} \cdot \sum_{m=1}^n B_{(m+1\dots n)(m\dots n)} \left(\cos \left(\sum_{k=2}^m \omega_{(k\dots n)} \Delta z_k \right) \right. \right.$$

$$\left. \left. - \cos \left(\sum_{k=1}^m \omega_{(k\dots n)} \Delta z_k \right) \right) \right]$$

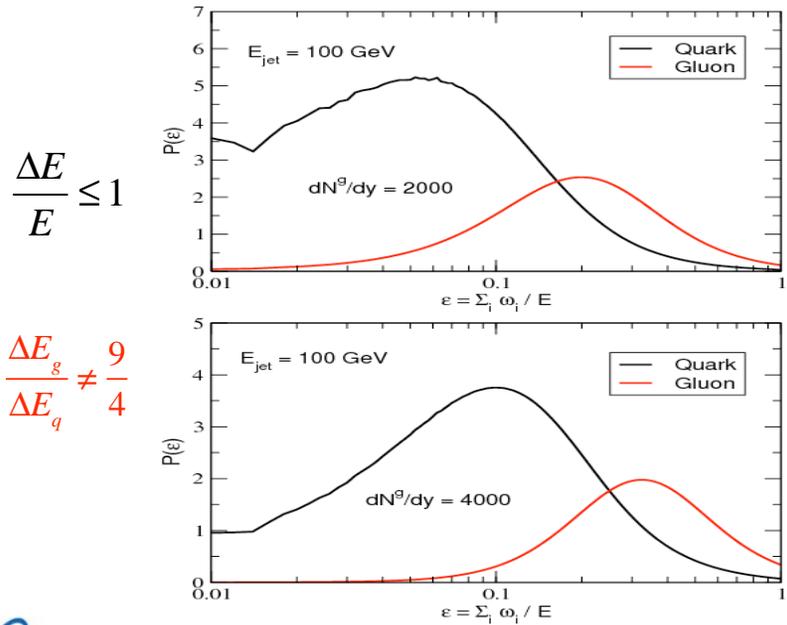


Probability Distributions and Medium Properties

$$\varepsilon = \sum_{i=1}^n \frac{\omega_i}{E} \quad \int_0^1 d\varepsilon' \frac{dN_g}{d\varepsilon}(\varepsilon') = \langle N_g \rangle \quad P_0(\varepsilon) = e^{-\langle N_g \rangle} \delta(\varepsilon)$$

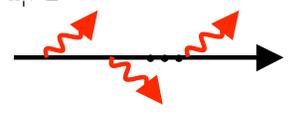
$$\int_0^1 d\varepsilon' P(\varepsilon') = 1, \quad \int_0^1 d\varepsilon' \varepsilon' P(\varepsilon') = \left\langle \frac{\Delta E}{E} \right\rangle$$

- **Small probability** not to radiate $P_0 = e^{-\langle N_g \rangle} \ll 1$



$$\frac{\Delta E}{E} \leq 1$$

$$\frac{\Delta E_g}{\Delta E_q} \neq \frac{9}{4}$$



Medium properties

RHIC

LHC

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

– **Static medium**

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

– **1+1D Bjorken**

$$dN^g / dy \sim 1200$$

$$dN^g / dy \sim 3500$$

Fundamental

$$T_0 = 400 \text{ MeV}$$

$$T_0 = 570 \text{ MeV}$$

$$\varepsilon(\tau_0) = 18 \text{ GeV} \cdot \text{fm}^{-3}$$

$$\varepsilon(\tau_0) = 75 \text{ GeV} \cdot \text{fm}^{-3}$$

Derivative

$$\langle\langle \hat{q} \rangle\rangle = 0.35 - 0.85 \text{ GeV}^2 \cdot \text{fm}^{-1}$$

$$\langle\langle \hat{q} \rangle\rangle = 1.0 - 2.5 \text{ GeV}^2 \cdot \text{fm}^{-1}$$



Gluon Energy and Angular Distributions

$$\frac{dN^g_{med}}{d\omega d^2k_{\perp}} \propto \int_0^{\infty} d^2q_{\perp} \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q_{\perp}} \frac{2(k_{\perp} - q_0) \cdot q_{\perp}}{((k_{\perp} - q_0) - q_{\perp})^2} \times \left[1 - \cos \frac{((k_{\perp} - q_0) - q_{\perp})^2 \Delta z}{2\omega} \right]$$

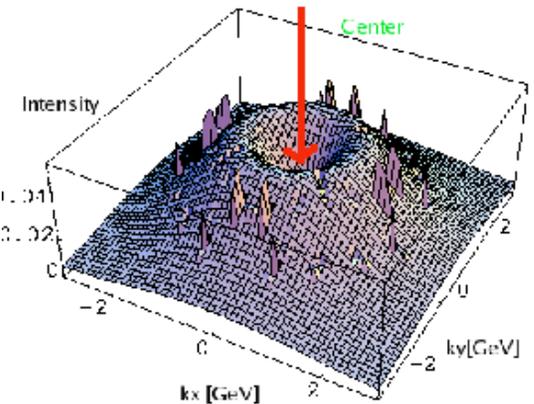
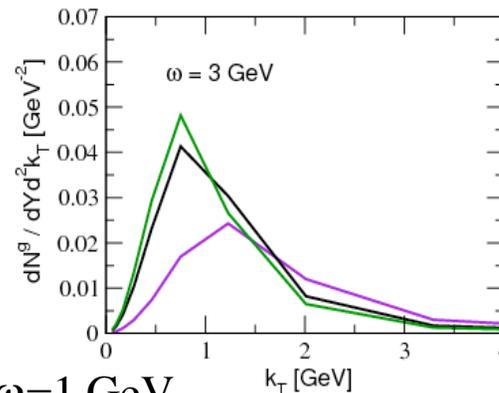
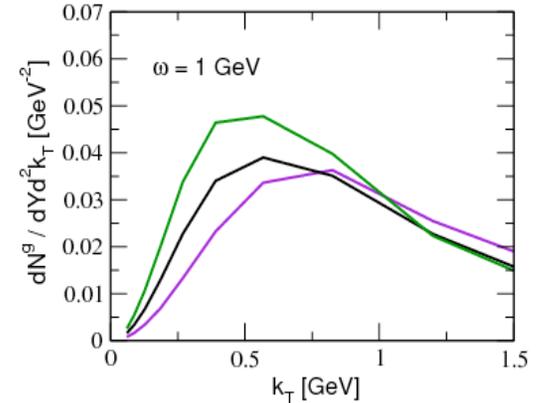
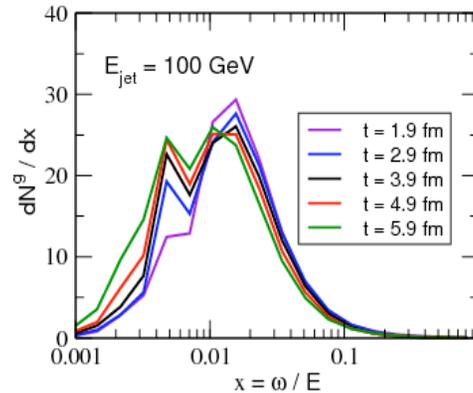
Gluon energy: ω

- **Gluon energies** range from $\omega=0.5$ GeV to $\omega=5$ GeV

Angle: $\theta = k_{\perp} / \omega$

- **Angles** range from $\theta \approx 1$ at $\omega=1$ GeV to $\theta \approx 0.3$ at $\omega=7$ GeV

Jet cone $R = \sqrt{\phi^2 + \eta^2}$ ($R = 0.4$)



Conditions: central Pb+Pb at the LHC

$dN^g / dy \approx 3500$ First order in opacity

Hard Probes from Factorized PQCD

$$\frac{d\sigma_{NN}^{h_1}}{dy_1 d^2 p_{T1}} = \sum_{abcd} \int_{x_a \min}^1 dx_a \int_{x_b \min}^1 dx_b \phi(x_a) \phi(x_b) \frac{\alpha_s^2}{(x_a x_b S)^2} \left| \bar{M}_{ab \rightarrow cd}^2 \right| \frac{D_{h_1/c}(z_1)}{z_1}$$

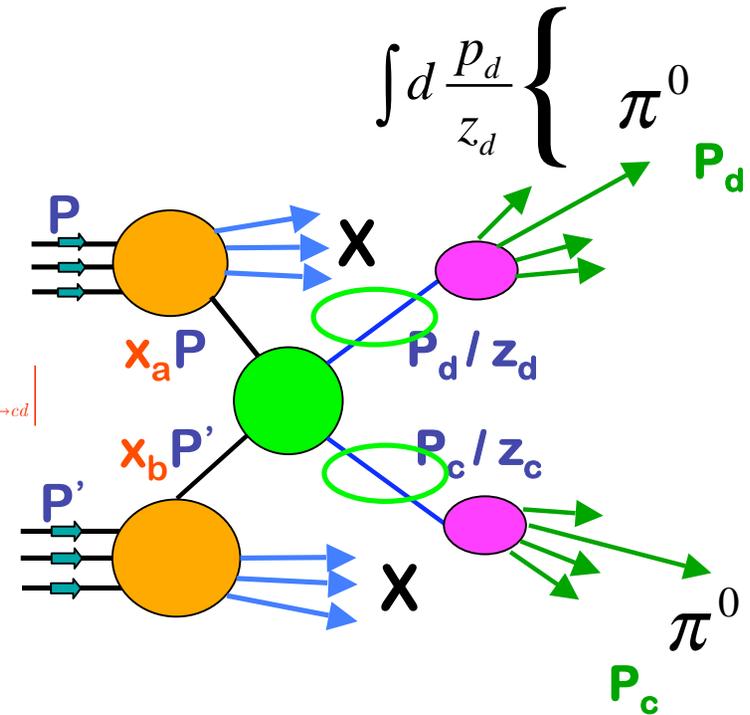
- Single and double inclusive **hard production** in PQCD - applicable **from photons to heavy quarks**

$$\frac{d\sigma_{NN}^{h_1 h_2}}{dy_1 dy_2 d^2 p_{T1} d^2 p_{T2}} = \frac{\delta(\Delta\varphi - \pi)}{p_{T1} p_{T2}} \sum_{abcd} \int_{z_1 \min}^1 dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\bar{x}_a) \phi(\bar{x}_b)}{\bar{x}_a \bar{x}_b} \frac{\alpha_s^2}{S^2} \left| \bar{M}_{ab \rightarrow cd}^2 \right|$$

- Single and double inclusive **hard production** in PQCD - applicable **from photons to heavy quarks**

Power laws: $\frac{d\sigma}{d^2 p_T} = \frac{A}{(p_T + p_0)^n} \approx \frac{A}{(p_T)^n}$

$$n = n(\sqrt{s}, p_T, \text{system})$$

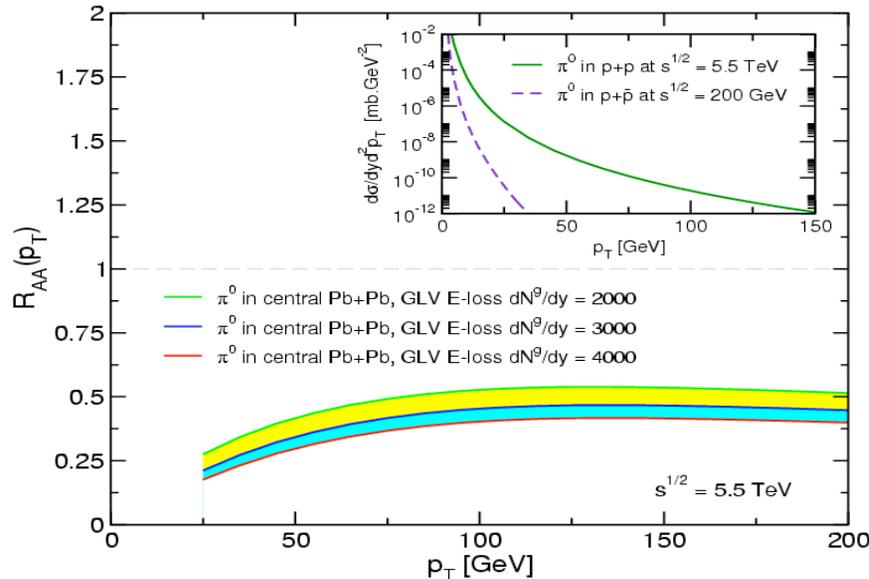


Quenching factor

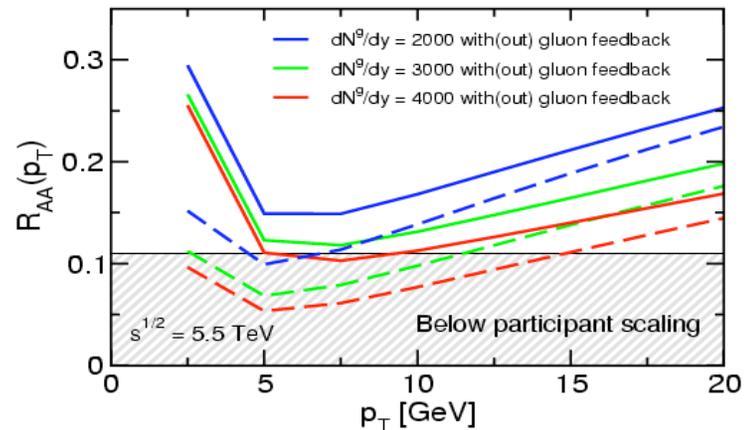
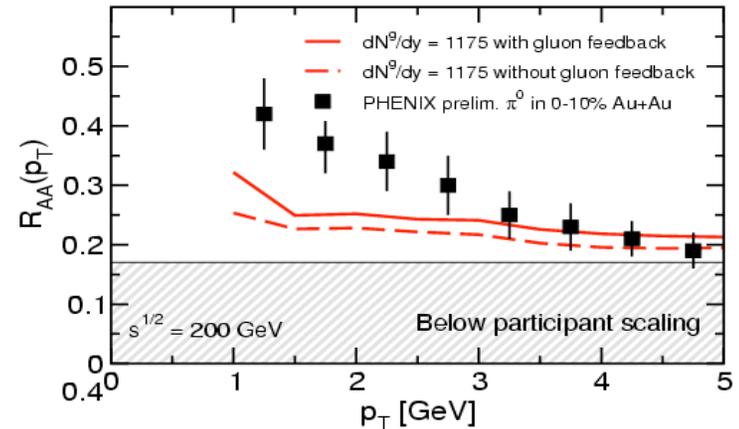
$$\ln R_{AA} = -(n-2)\varepsilon \quad \varepsilon = \left\langle \frac{\Delta E}{E} \right\rangle$$

Gluon Feedback to Single Inclusives

$$D_{h_1/c}(z_1) \rightarrow \int d\varepsilon P(\varepsilon) \frac{1}{1-\varepsilon} D_{h_1/c}\left(\frac{z_1}{1-\varepsilon}\right) + \int \frac{d\varepsilon}{\varepsilon} D_{h_1/g}\left(\frac{z_1}{\varepsilon}\right) \frac{dN^g(\varepsilon)}{d\varepsilon}$$



- High p_T suppression at the LHC can be **comparable and smaller** than at RHIC
- LHC quenching **follows the steepness of the partonic spectra.**

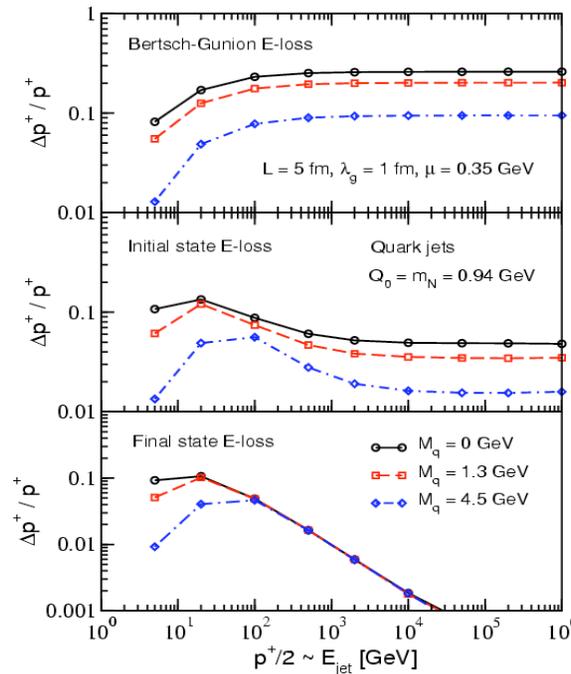
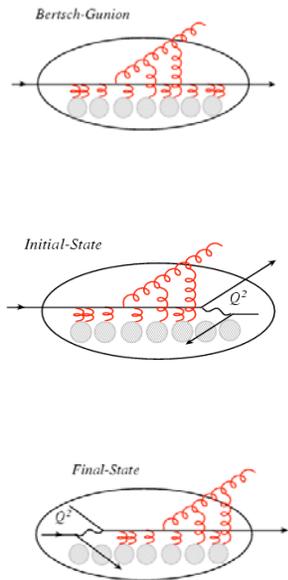


- The **redistribution of the lost energy is very important at the LHC**. 100% correction and $p_T < 15$ GeV affected

Cold Nuclear Matter Effects

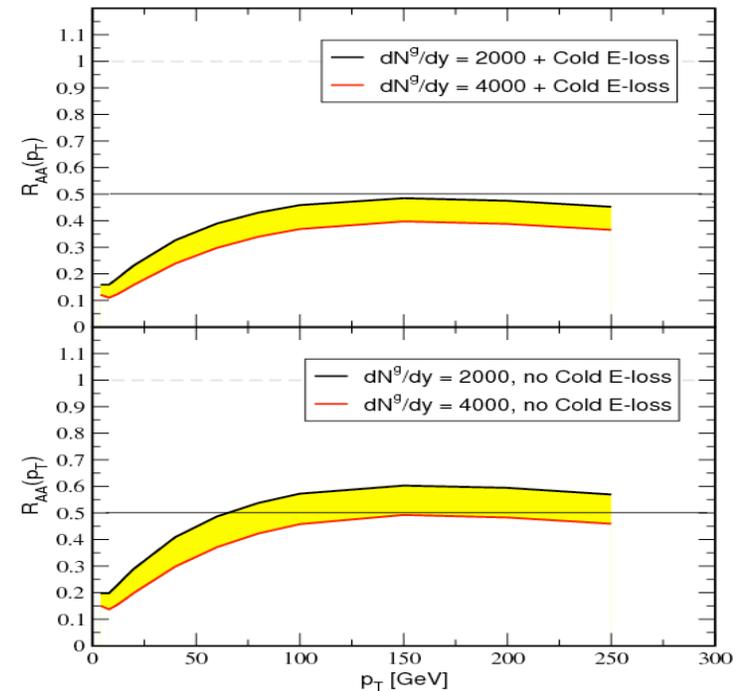
Initial-state E-loss

$$\frac{\omega dN^g}{d\omega d^2k_\perp} = \frac{C_R \alpha_s}{\pi^2} \int_0^{s/4} d^2q_\perp \frac{\mu_{\text{eff}}^2}{(q_\perp^2 + \mu^2)^2} \left[\frac{L}{\lambda_g} \frac{q_\perp^2}{k_\perp^2 (k_\perp - q_\perp)^2} - 2 \frac{q_\perp^2 - 2k_\perp \cdot q_\perp}{k_\perp^2 (k_\perp - q_\perp)^2} \frac{k^+}{k_\perp^2 \lambda_g} \sin \frac{k_\perp^2 L}{k^+} \right]$$



Energy scale

$$E = p_T \cosh(y_{\text{jet}} - y_{\text{target}})$$



- Effect of cold nuclear matter energy loss is equal to the doubling of the parton rapidity density

Direct Photon Production at RHIC and the LHC

- Direct photon production calculated in the QCD factorization approach

Prompt photons $D_{\gamma/\gamma}(z) = \delta(z - 1)$

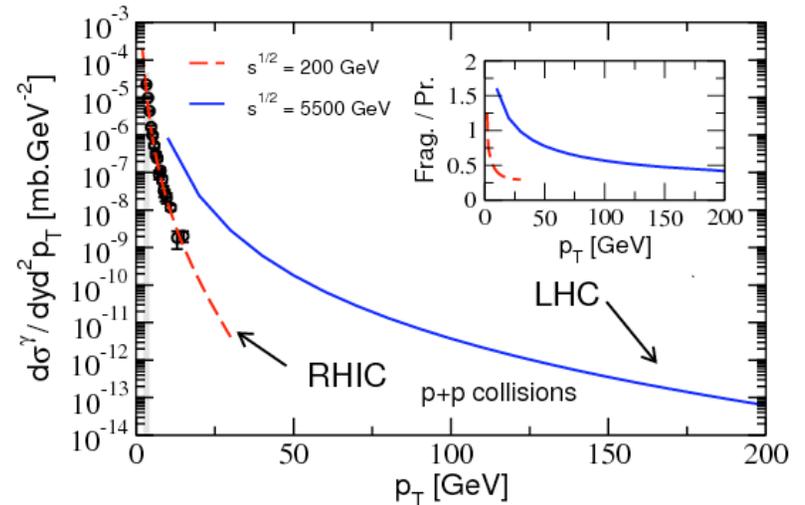
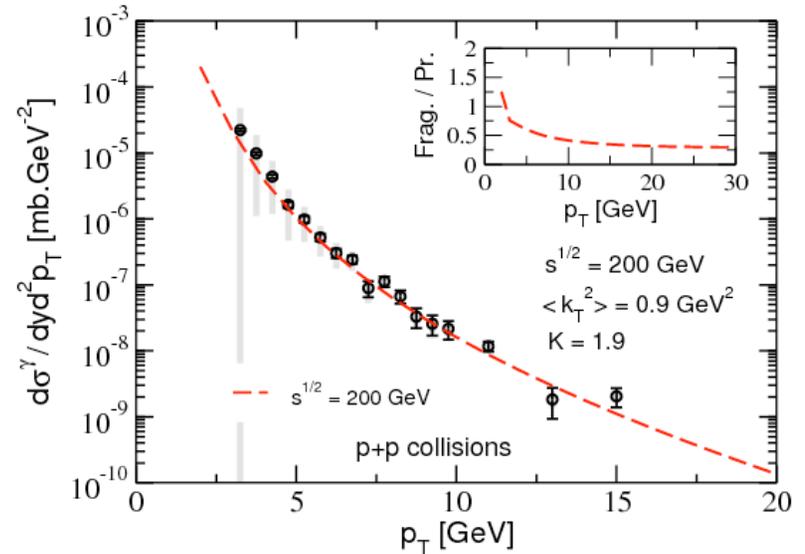
Fragmentation photons $\begin{cases} D_{\gamma/q}(z) \\ D_{\gamma/g}(z) \end{cases}$
Suppressed

- Fragmentation functions: Owens

$$R = \frac{d\sigma / dy d^2 p_T(\text{fragmentation})}{d\sigma / dy d^2 p_T(\text{prompt})}$$

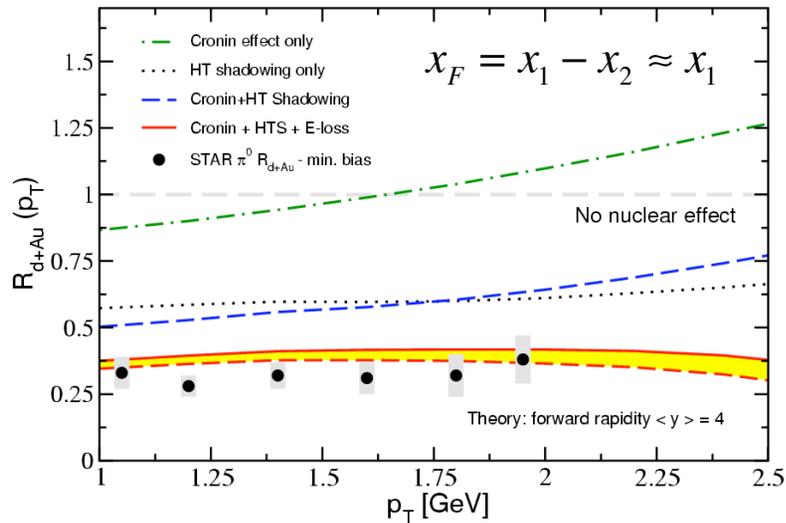
Determines the final-state interactions

- Same ratio in NLO, Wogelsang

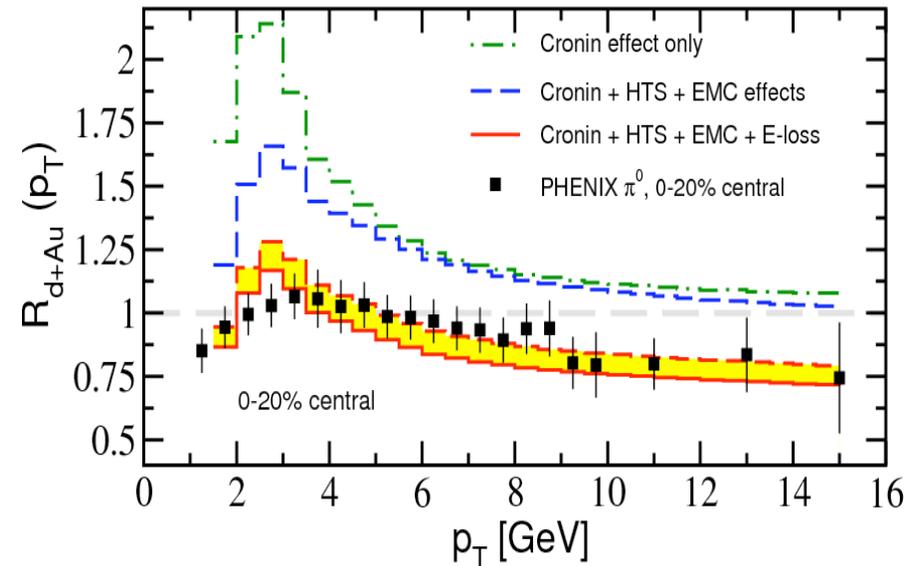
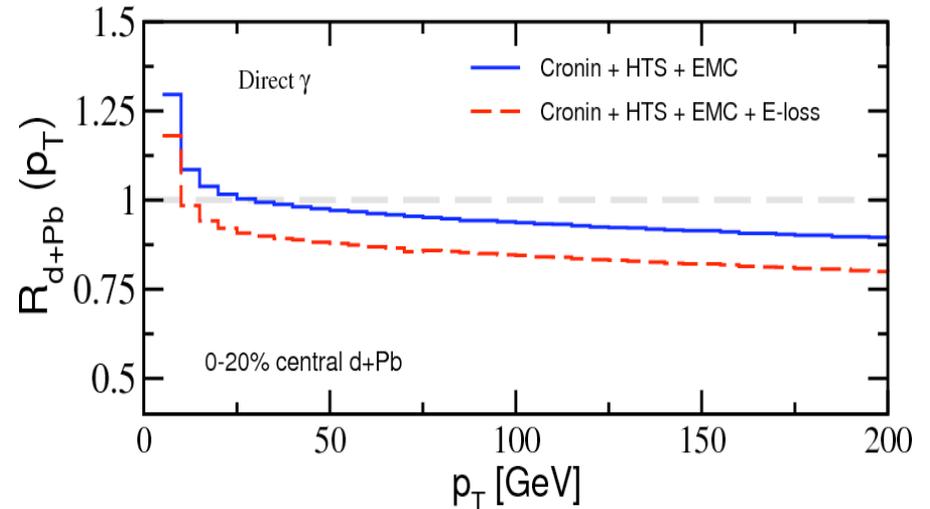


Cold Nuclear Matter Effects for π^0 and Direct γ

• Where it starts from



- Dynamical shadowing (coherent final state scattering)
- Cronin effect (initial state transverse momentum diffusion)
- Initial state energy loss (final state at these energies - negligible)



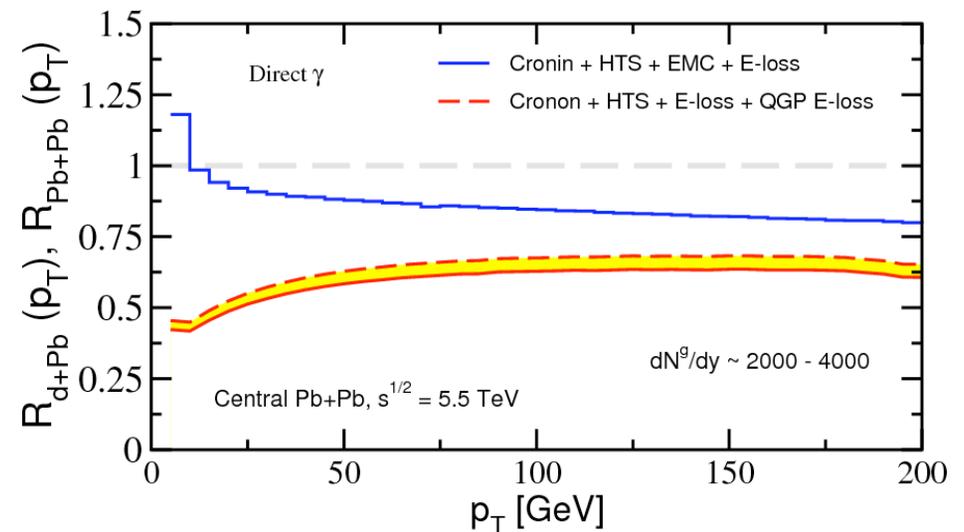
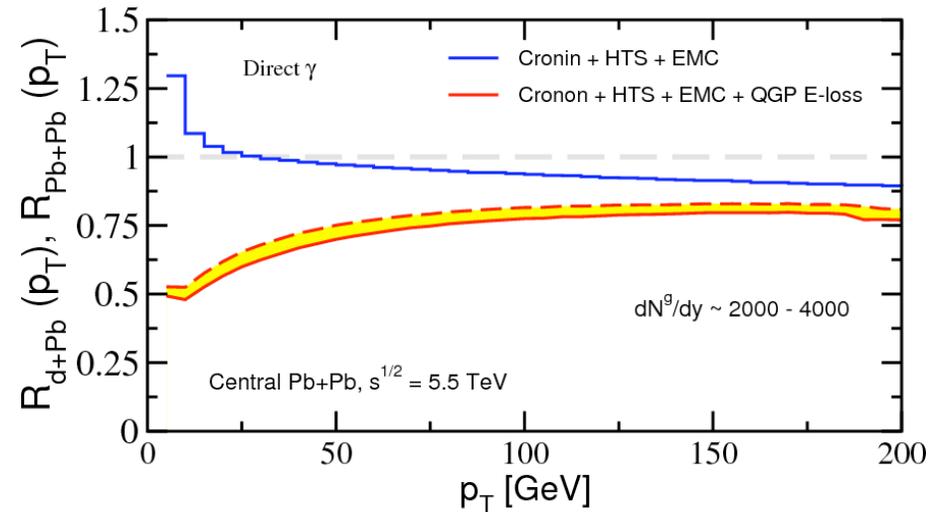
Direct Photon Quenching at the LHC

Reminder: **isospin** and **Initial-state energy loss** effects

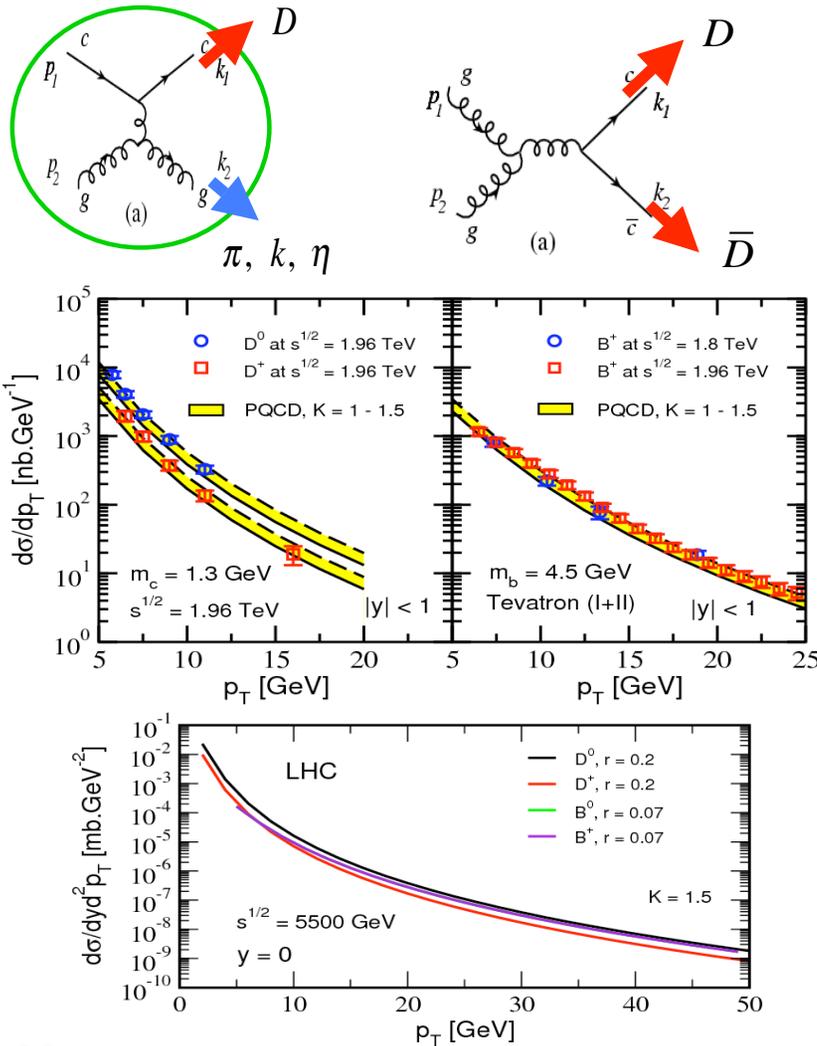
Nuclear modification $R_{AA}(\gamma)$ follows the ratio:

$$R = \frac{d\sigma / dy d^2 p_T (\text{fragmentation})}{d\sigma / dy d^2 p_T (\text{prompt})}$$

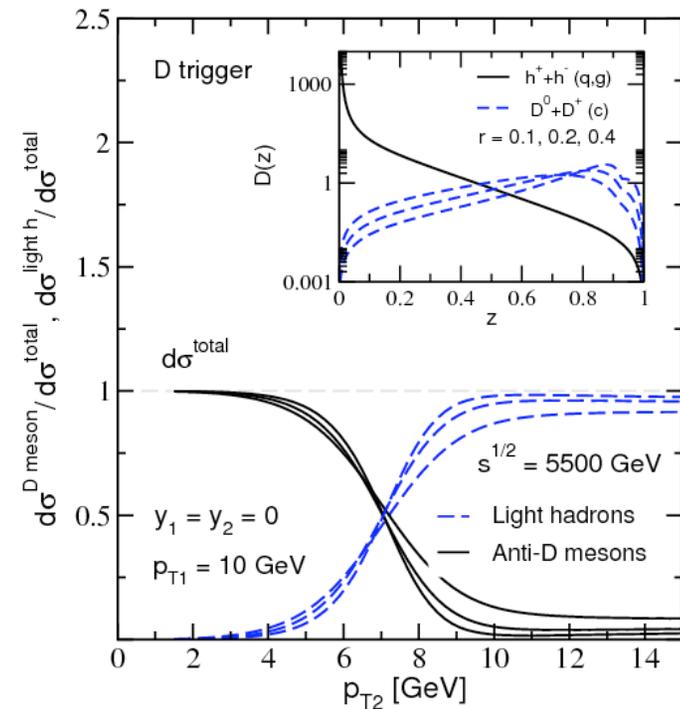
Correction to the energy in **photon-tagged jets**



Heavy Quark Production and Correlations

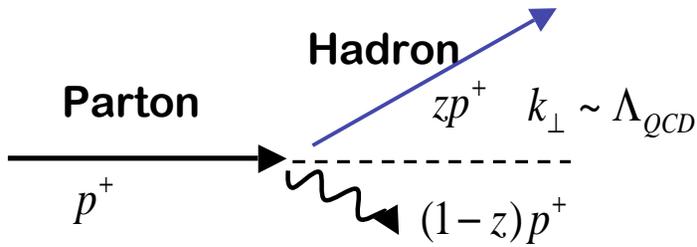


- Fast convergence of the perturbative series
- Possibility for novel studies of heavy quark-triggered (D and B) jets: hadron composition of associated yields

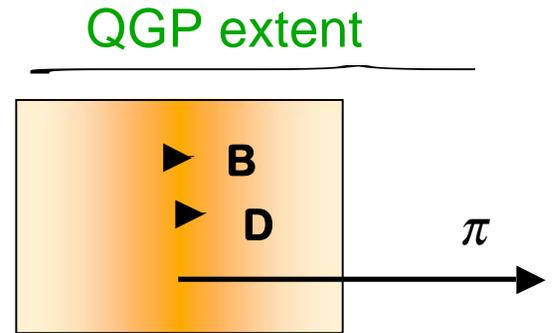


Conceptually Different Approach to D / B

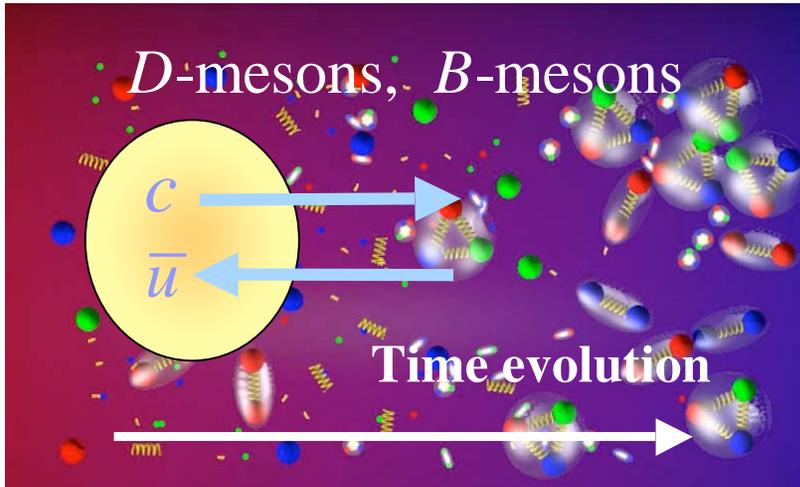
- **Problem:** treated in the same way as light quarks



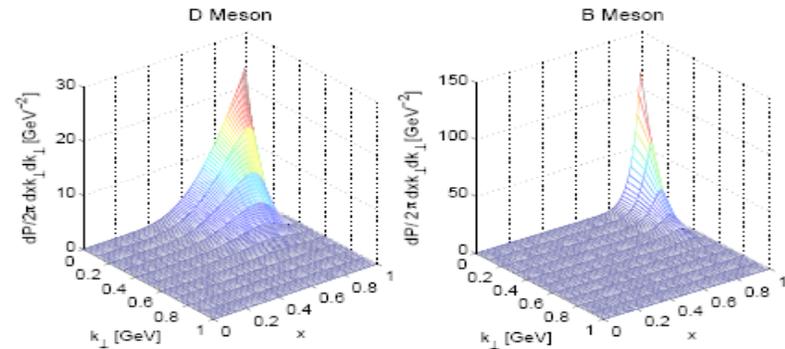
$\tau_{\text{form}}(p_T = 10 \text{ GeV})$		
π	D	B
25 fm	1.6 fm	0.4 fm



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



Lowest order lightcone Fock component



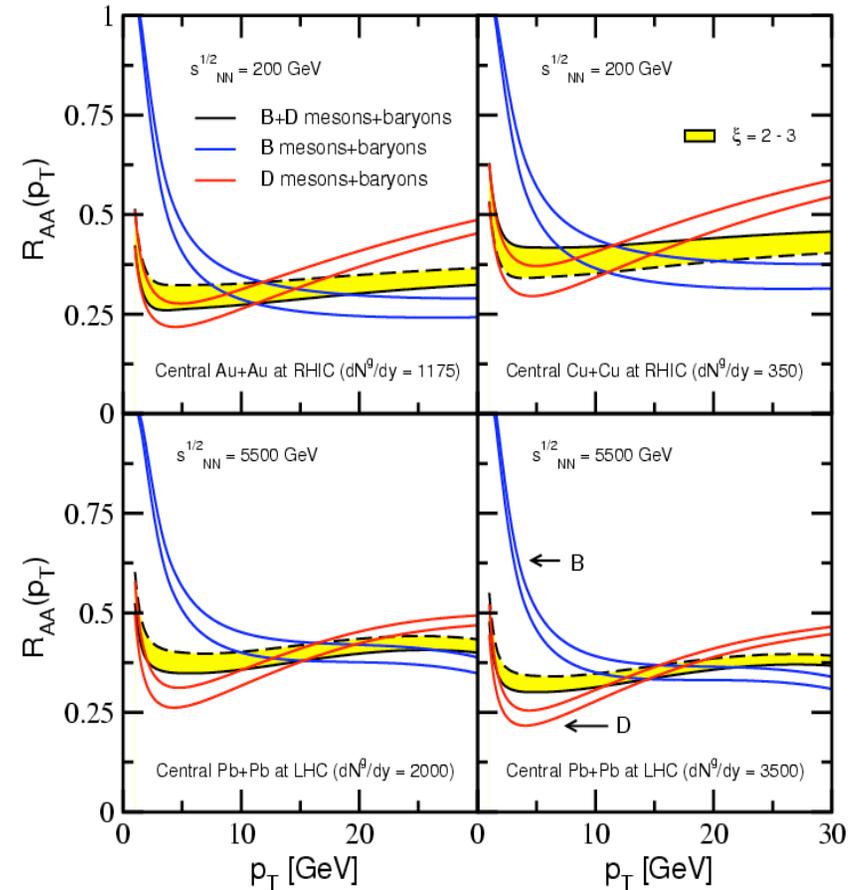
$$P_{\text{dissoc.}} \left(\frac{\mu^2}{\lambda} L\xi \right) = 1 - \left| \int dx d^2 \Delta k_{\perp} \psi_f^*(x, \Delta k_{\perp}) \psi_i(x, \Delta k_{\perp}) \right|^2$$

Heavy Meson Dissociation at RHIC and LHC

Coupled rate equations

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

- The asymptotic solution in the QGP - sensitive to $t_0 \sim 0.6$ fm and expansion dynamics
- Features of energy loss ($\bar{x} < 1$, $\bar{z} < 1$)
- B-mesons as suppressed as D-mesons at $p_T \sim 15-20$ GeV at the LHC



Unique feature

Quenching of Non-Photonic Electrons

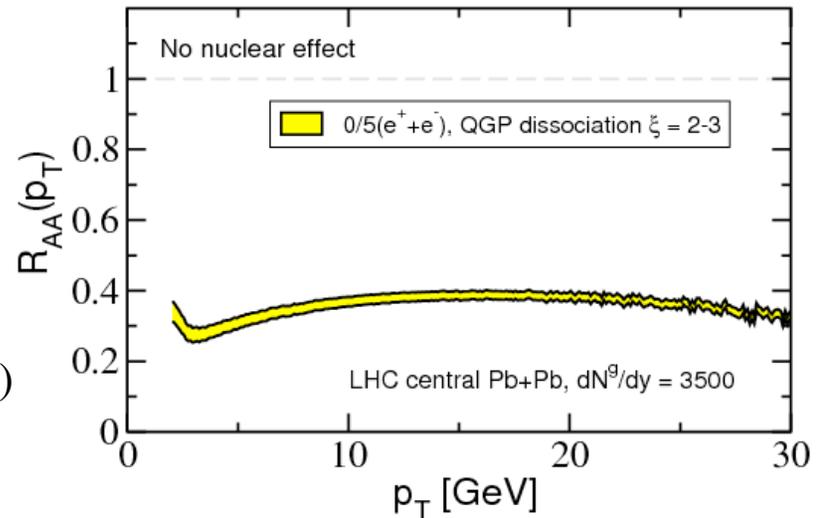
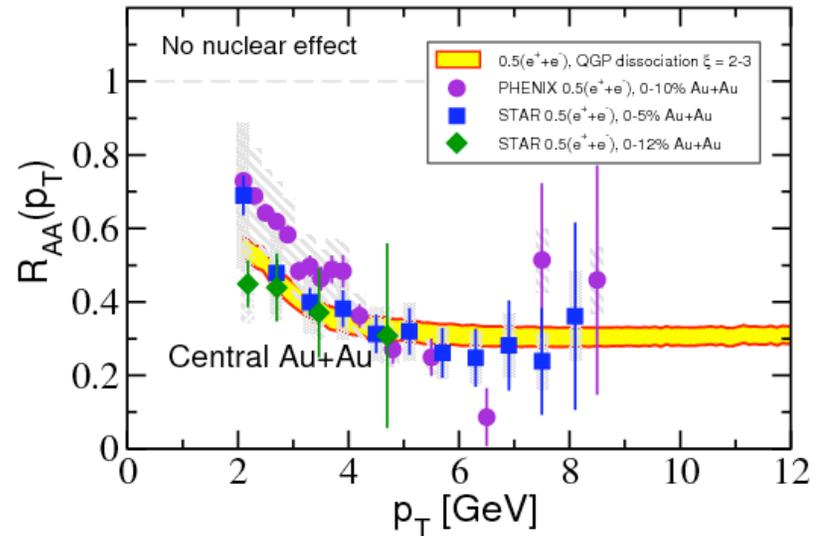
- Full semi-leptonic decays of C- and B-mesons and baryons included. PDG branching fractions and kinematics. PYTHIA event generator

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

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



References to the Four Contributions, Collabs.

Energy loss

- [1] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. Lett. **85**, 5535 (2000).
- [2] M. Gyulassy, P. Levai and I. Vitev, Phys. Lett. B **538**, 282 (2002).
- [3] I. Vitev, Phys. Lett. B **630**, 78 (2005).
- [4] I. Vitev, Phys. Lett. B **639**, 38 (2006).
- [5] I. Vitev, Phys. Rev. C in press (2007), hep-ph/0703002.

Light hadrons

- [1] M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B **594**, 371 (2001).
- [2] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002).
- [3] I. Vitev, Phys. Lett. B **562**, 36 (2003).
- [4] I. Vitev, Phys. Lett. B **639**, 38 (2006).
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Direct photons

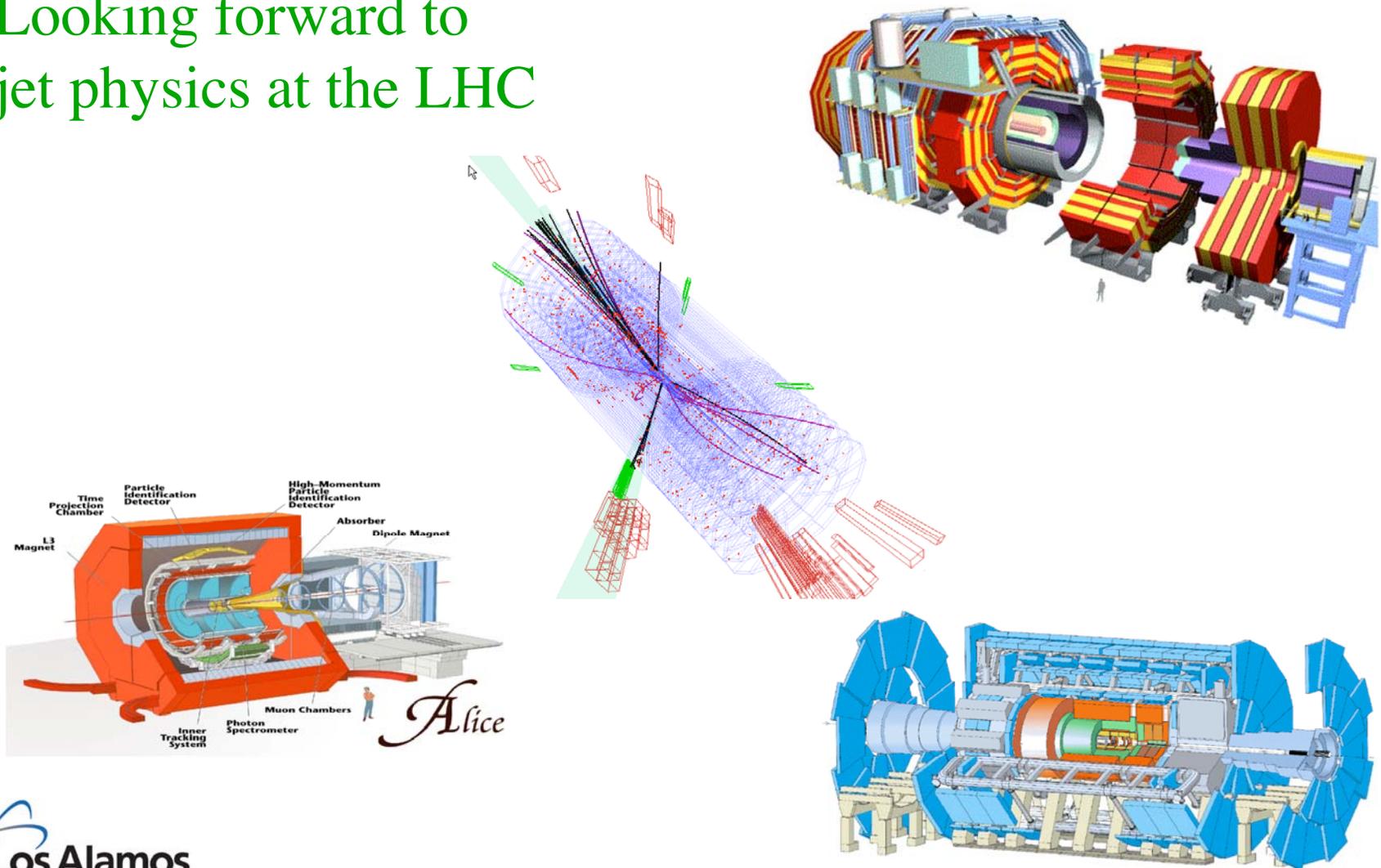
- [1] I. Vitev, “Are jets quenched in cold nuclei?”, in preparation.
- [2] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002).
- [3] J. w. Qiu and I. Vitev, Phys. Lett. B **632**, 507 (2006).
- [4] J. w. Qiu and I. Vitev, Phys. Rev. Lett. **93**, 262301 (2004).
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Heavy flavor

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- [2] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. D **66**, 014005 (2002).
- [3] A. Adil and I. Vitev, Phys. Lett. B **649**, 139 (2007).
- [4] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002);
- [5] I. Vitev, A. Adil and H. van Hees, hep-ph/0701188.

Conclusions

Looking forward to
jet physics at the LHC



Scales in Thermalized QGP (GP)

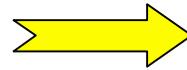
• Experimental: Bjorken expansion

$$\frac{dN^g}{dy} \approx \frac{3}{2} \left| \frac{d\eta}{dy} \right| \frac{dN^{ch}}{d\eta} \quad \frac{dN^g}{dy} = 1200$$

$$\rho_{\text{exp}}(\tau) = \frac{1}{A_{\perp} \tau} \frac{dN^g}{dy}, \quad A_{\perp} = 120 \text{ fm}^2$$

$$\tau_0 = 0.6 \text{ fm}$$

$$\Rightarrow \rho_{\text{exp}}(\tau_0) = 17 \text{ fm}^{-3}$$



$$T = 400 \text{ MeV}$$



• Theoretical: Gluon dominated plasma

$$\rho_{\text{theory}}(T) = \#DoF \int_0^{\infty} \frac{1}{e^{p/T} - 1} \frac{4\pi p^2 dp}{(2\pi)^3} = \frac{\#DoF}{\pi^2} \zeta[3] \times T^3$$

where $\#DoF = 2(\text{polarization}) \times 8(\text{color})$, $\zeta[3] = 1.2$

• Energy density

$$\varepsilon_{\text{theory}}(T) = \frac{\pi^4}{30\zeta[3]} \times \rho_{\text{theory}}(T) \times T$$

$$\varepsilon_{\text{exp}}(\tau_0) = 18 \text{ GeV} \cdot \text{fm}^{-3} \geq 100 \times 0.14 \text{ GeV} \cdot \text{fm}^{-3}$$

• Transport coefficients (not a good measure for expanding medium)

$$\mu_D \approx gT, \quad g = 2 - 2.5 \quad (\alpha_s = \frac{g^2}{4\pi} = 0.3 - 0.5)$$

$$\sigma^{gg} = \frac{9\pi\alpha_s^2}{2\mu_D^2}, \quad \lambda_g = \frac{1}{\sigma^{gg} \rho}$$

$$\left. \begin{array}{l} \mu_D = 0.8 - 1 \text{ GeV} \\ \lambda_g = 0.75 - 0.42 \text{ fm} \end{array} \right\}$$

$$\hat{q} = \frac{\mu_D^2}{\lambda_g} = \frac{9\pi\alpha_s^2}{2} \rho$$

$$\hat{q} = 1 - 2.5 \text{ GeV}^2 \cdot \text{fm}^{-1}$$

• Define the average for Bjorken

$$\langle\langle \hat{q} \rangle\rangle = \frac{2}{(L - z_0)^2} \int_{z_0}^L \hat{q}(z) z dz$$

$$\langle\langle \hat{q} \rangle\rangle = 0.35 - 0.85 \text{ GeV}^2 \cdot \text{fm}^{-1}$$

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

- Theoretical reason:** the only way to formulate energy loss **without unphysical sensitivity** to the formation time



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

– Static medium

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

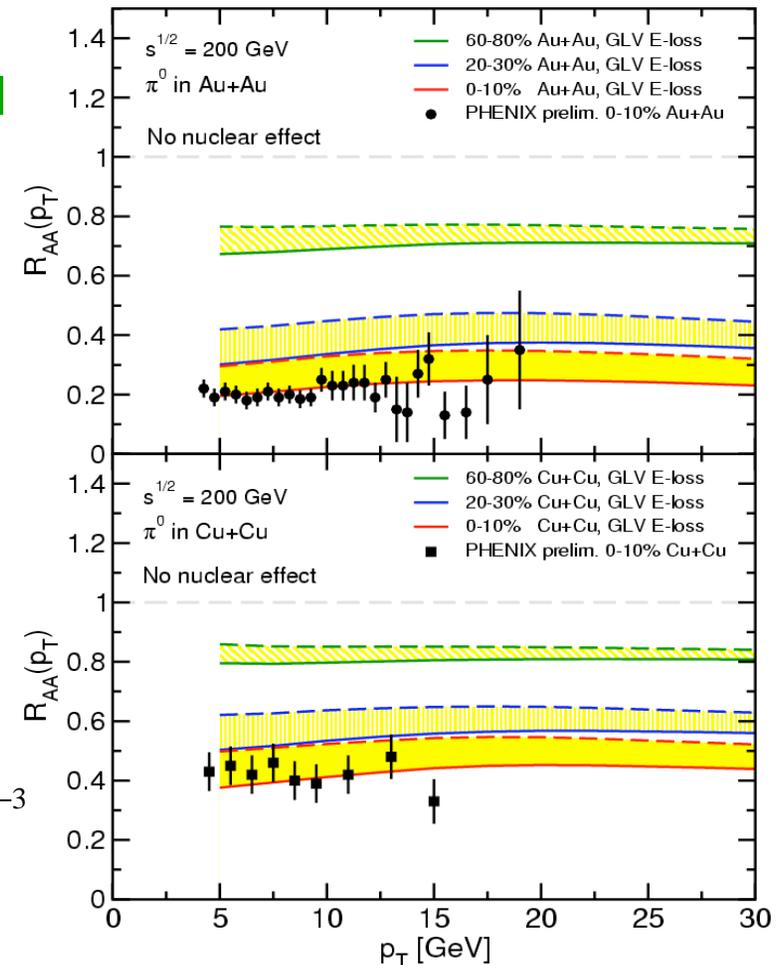
– 1+1D Bjorken

$$T = 400 \text{ MeV}$$

$$\varepsilon_{\text{exp}}(\tau_0) = 18 \text{ GeV} \cdot \text{fm}^{-3} \geq 100 \times 0.14 \text{ GeV} \cdot \text{fm}^{-3}$$

$$\langle\langle \hat{q} \rangle\rangle = 0.35 - 0.85 \text{ GeV}^2 \cdot \text{fm}^{-1}$$

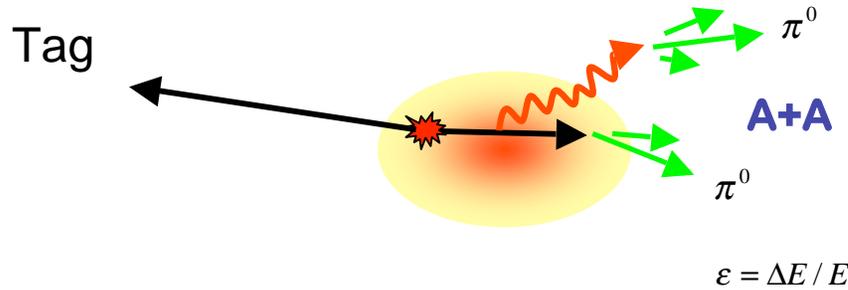
Significantly different values are indicative a theoretical inconsistency



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

E-loss in Back-to-Back Di-jets and Correlations

- Angular gluon distribution

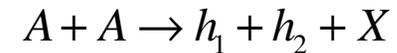


$$D_{h_1/d}(z_2)\delta(\Delta\phi - \pi) \rightarrow \frac{1}{1-\epsilon} D_{h_1/d}\left(\frac{z_2}{1-\epsilon}\right) f_{med}(\Delta\phi)$$

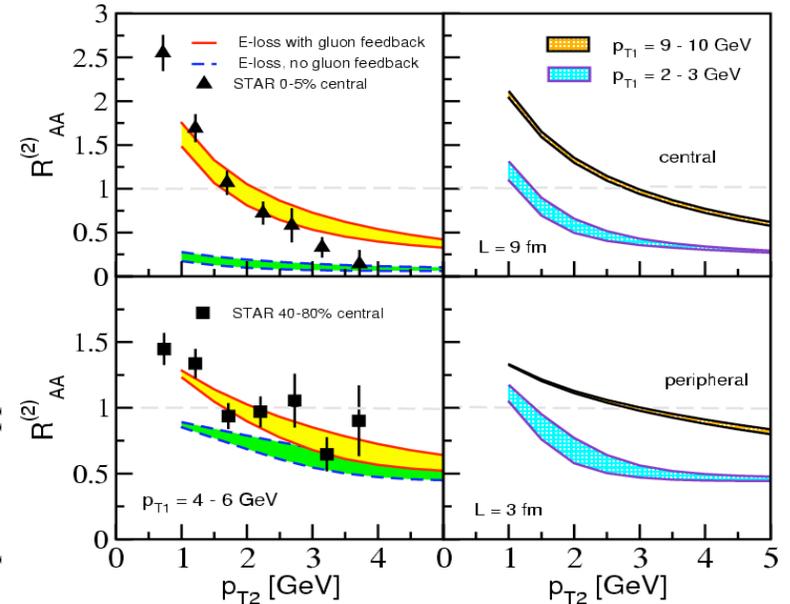
$$+ \frac{p_{T1}}{z_1} \int_0^1 \frac{dz_g}{z_g} D_{h_1/g}(z_g) \int_{-\pi/2}^{\pi/2} d\phi \frac{dN^g(\phi)}{d\omega d\phi} f_{vac}(\Delta\phi - \phi)$$

- Multi-particle modification

$$R_{AA}^{(2)} = \frac{d\sigma_{AA}^{h_1 h_2}}{dy_1 dy_2 dp_{T1} dp_{T2}} \frac{\langle N_{bin} \rangle}{d\sigma_{pp}^{h_1 h_2}} \frac{1}{dy_1 dy_2 dp_{T1} dp_{T2}}$$



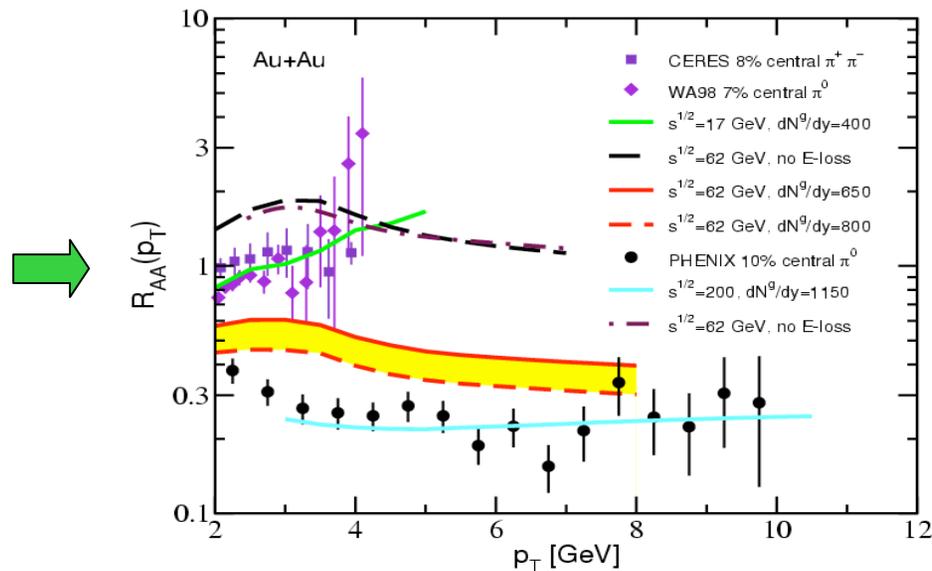
Two particle suppression / enhancement in A+A reactions



I.Vitev, Phys.Lett.B630 (2005)

When One \neq One

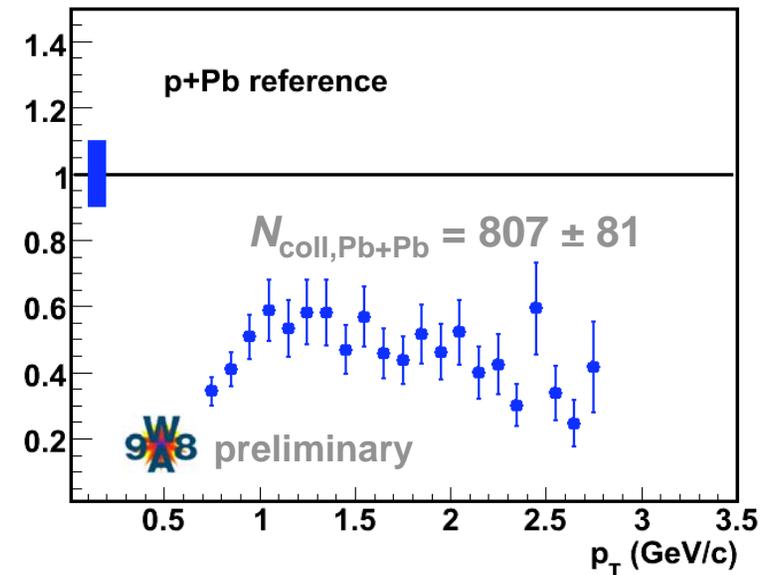
- Theoretical results: **cancellation** between factor of 4 Cronin enhancement and 2- to 3-fold quenching



I.V., Phys.Lett.B 632 (2005)

- Experimental findings:

$$R_{Pb+Pb} / R_{p+Pb}$$



S.Bathe., LANL seminar

- With **any multiple scattering effect** there is **no reason to expect** $R_{AB}(P_T) = 1$
- If one understands this in **A+A collisions** one should also accept this is **p+A collisions**

Langevin Simulation of Heavy Quark Diffusion

Input in a Langevin simulation of heavy quark diffusion

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

H. van Hees, I.V., R. Rapp, in preparation

- **Drag coefficient:**

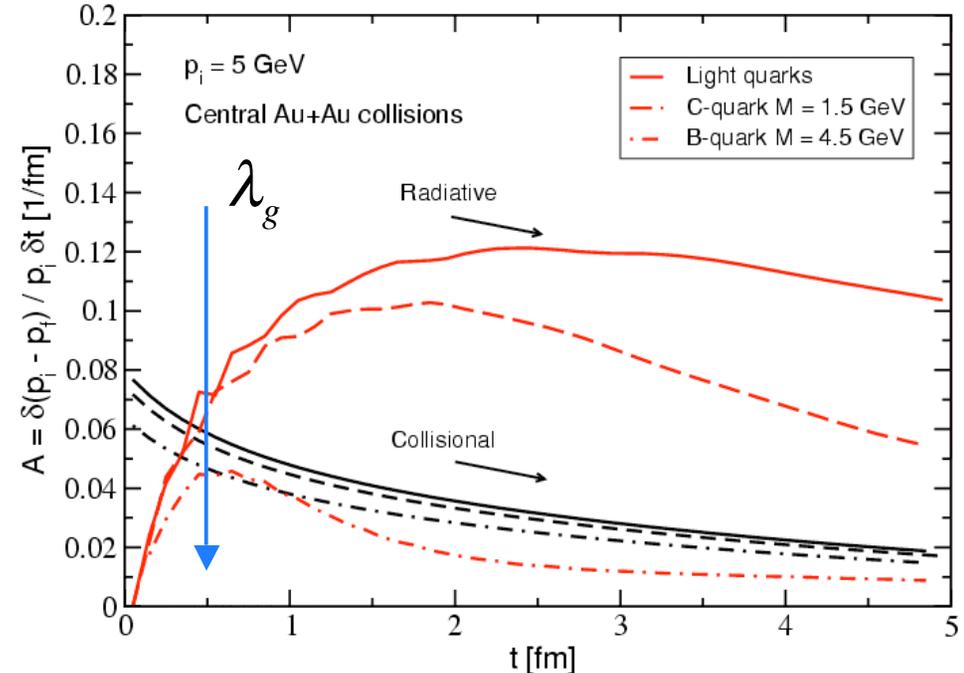
$$A_i(p,t) = \frac{1}{p_i} \frac{\langle \delta p_i \rangle}{\delta t}$$

- **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:

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



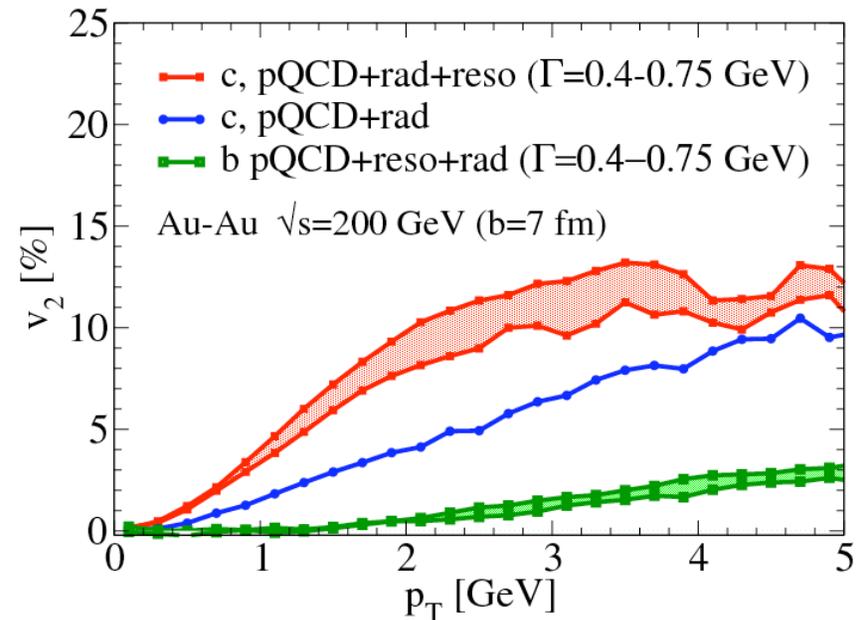
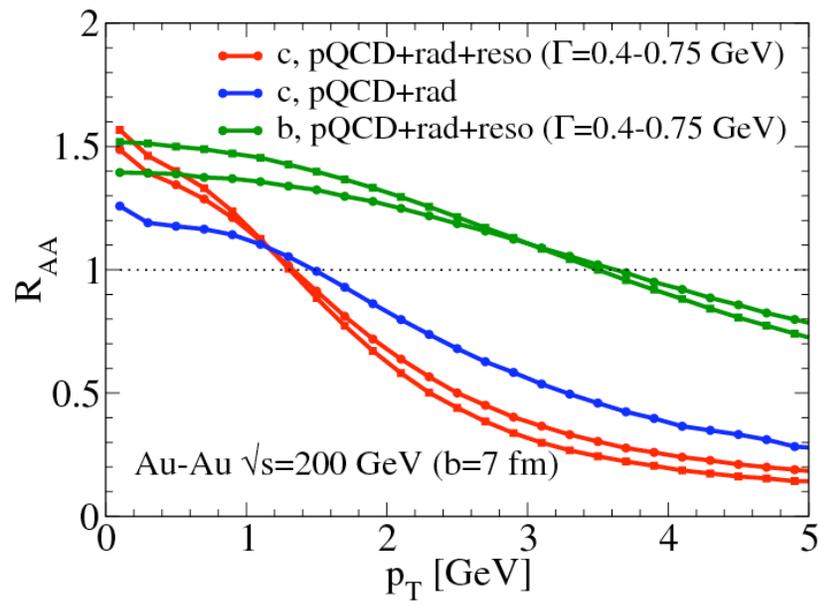
Radiative energy loss is **dominant** except for **b-quarks** and **very small systems**

Transport + Quenching Approach

Numerical results for heavy quark diffusion

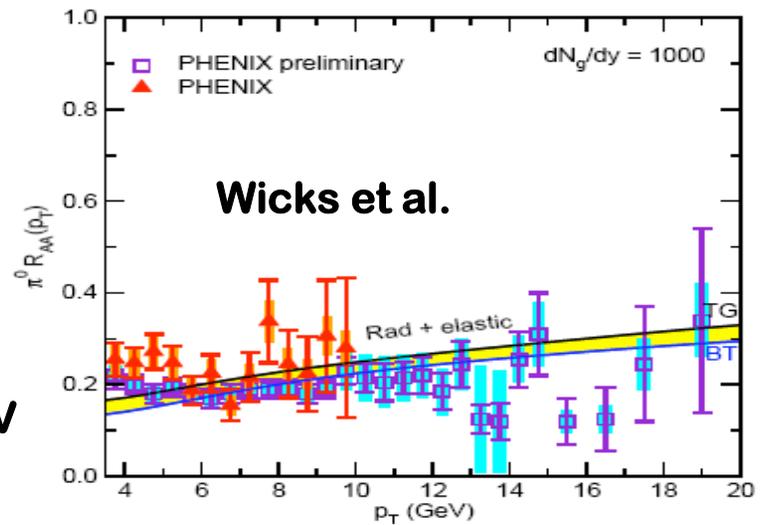
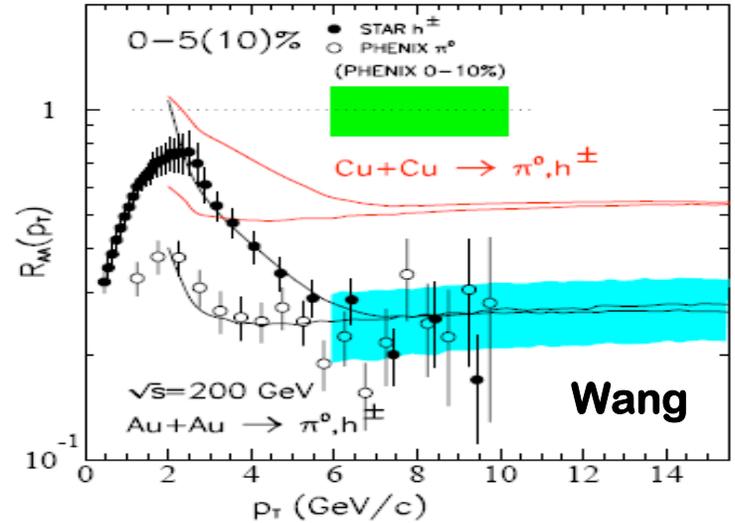
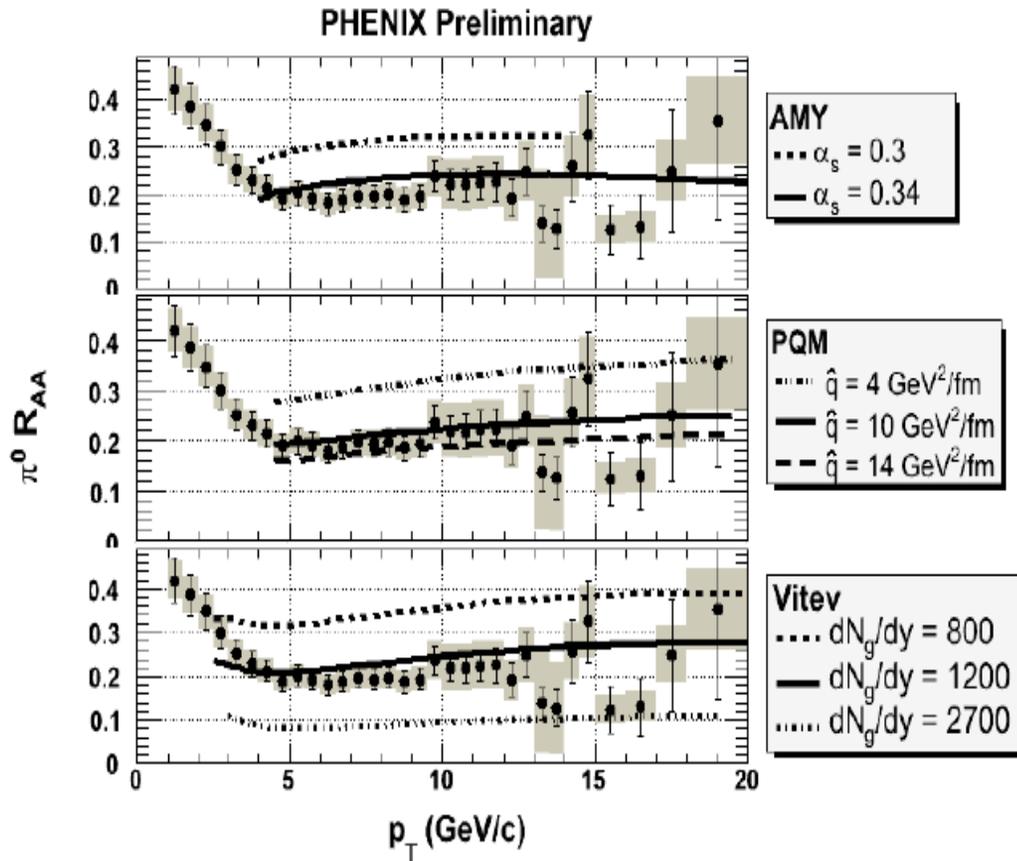
Results are **preliminary**

H. van Hees, I.V., R. Rapp, in preparation



- The suppression and v_2 are **large** when **e-loss** and **q-resonance interactions** are combined
- **Normal hierarchy**: c quarks are significantly more suppressed than b-quarks

Comparison to Other Models



How do you build
 from $T = 400 \text{ MeV}$

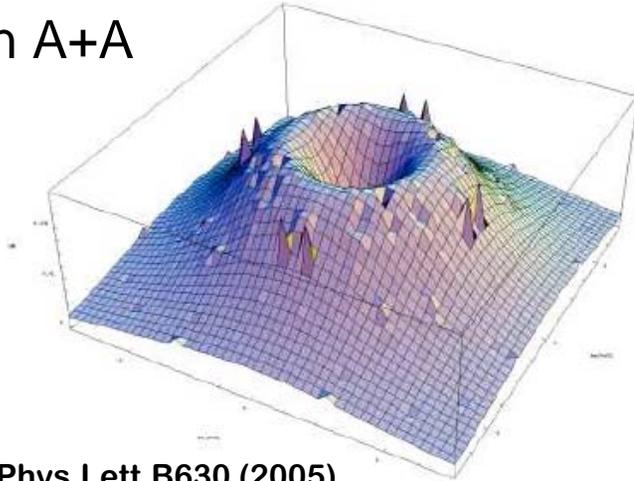
$$\hat{q} = \frac{\mu^2}{\lambda_g} = 100 \text{ GeV}^2 / \text{fm}$$

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

LHC: from $T = 1 \text{ GeV}$

What Happens to Medium-Induced Radiation?

In A+A



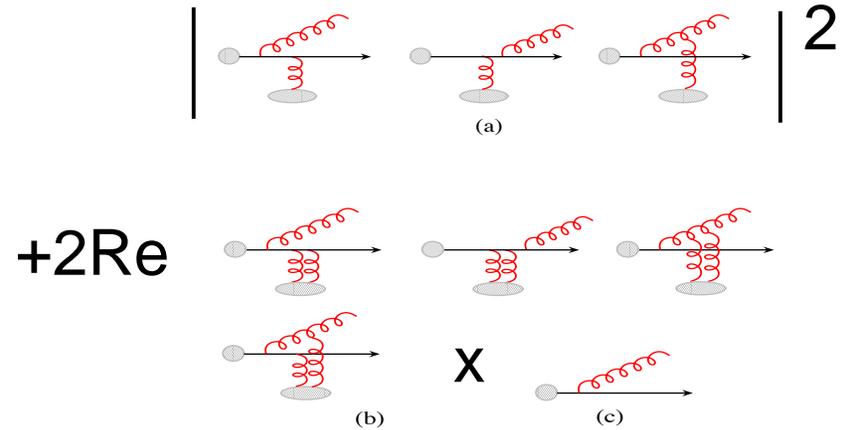
I.V., Phys.Lett.B630 (2005)

$$\frac{dN_{med}^g}{d\omega d\sin\theta * d\delta} \propto \left(|M_a|^2 + 2 \text{Re} M_b^* M_c \right) + \dots$$

First **quantitative** PQCD calculation

How about p+A?

$$y^g = \frac{1}{2} \ln \frac{k^+}{k^-} = \frac{1}{2} \ln \frac{(xp^+)^2}{k_{\perp}^2}$$



• Cancellation of collinear radiation

$$k_{\perp} \rightarrow 0, k_{\perp} / \omega \rightarrow 0$$

