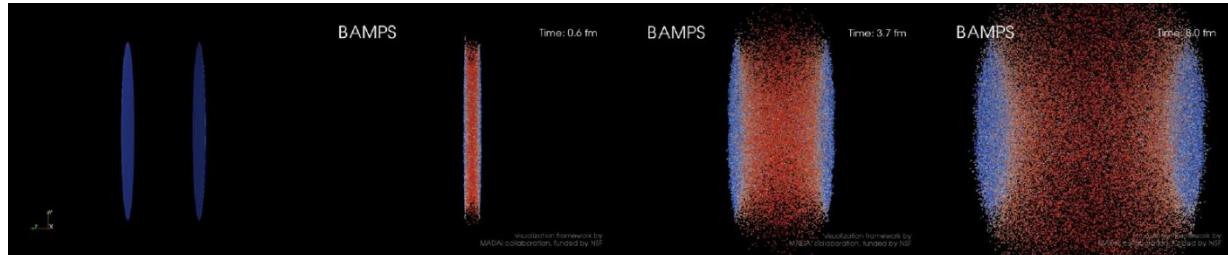


# Open heavy flavor and J/psi at RHIC and LHC

Jan Uphoff

with O. Fochler, Z. Xu and C. Greiner

Based on Phys. Rev. C 84, 024908 (2011) and arXiv:1205.4945



Hard Probes 2012, Cagliari, Sardinia  
31 May 2012

# Motivation

**Large heavy quark mass**

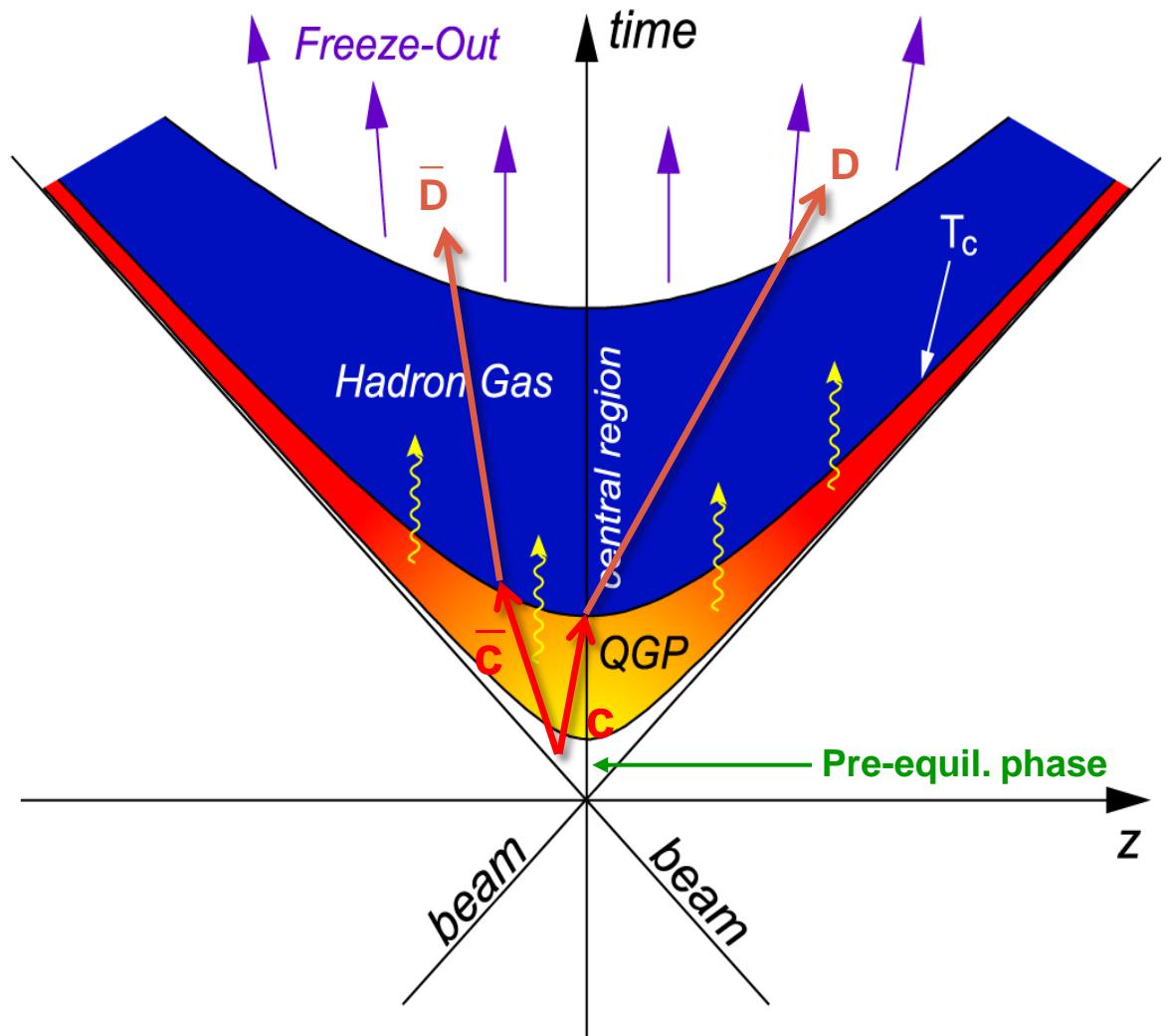
$$>> \Lambda_{\text{QCD}}$$

**Charm:  $M_c \approx 1.3 \text{ GeV}$**

**Bottom:  $M_b \approx 4.6 \text{ GeV}$**

→ **Heavy quark  
production at early  
stage of collision**

→ **ideal probe for this  
stage**



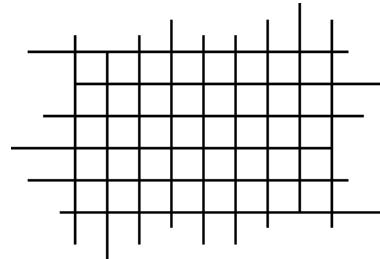
## BAMPS: Boltzmann Approach of MultiParton Scatterings

- 3+1 dimensional, fully dynamic parton transport model
- solves the Boltzmann equations for on-shell partons with pQCD interactions

$$\left( \frac{\partial}{\partial t} + \frac{\mathbf{p}_i}{E_i} \frac{\partial}{\partial \mathbf{r}} \right) f_i(\mathbf{r}, \mathbf{p}_i, t) = \mathcal{C}_i^{2 \rightarrow 2} + \mathcal{C}_i^{2 \leftrightarrow 3} + \dots$$

Z. Xu & C. Greiner,  
 Phys. Rev. C71 (2005)  
 Phys. Rev. C76 (2007)

- Divide collision zone into cells



- Using stochastic method

$$P_{2 \rightarrow 2} = v_{\text{rel}} \frac{\sigma_{2 \rightarrow 2}}{N_{\text{test}}} \frac{\Delta t}{\Delta^3 x}$$

- Testparticles to increase statistics

# BAMPS with $N_{\text{flavor}} = 3+2$

## Implemented processes

### Heavy Flavor

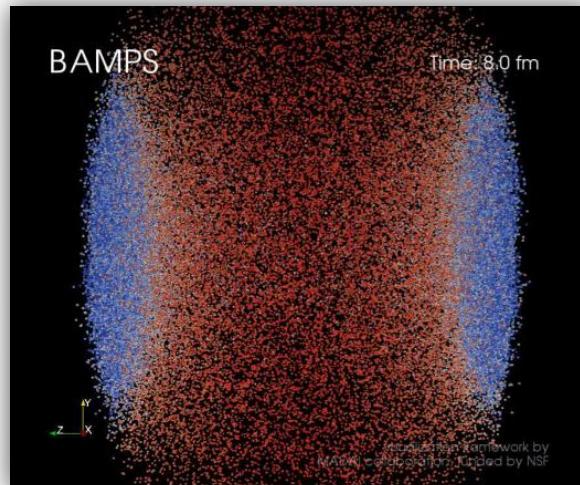
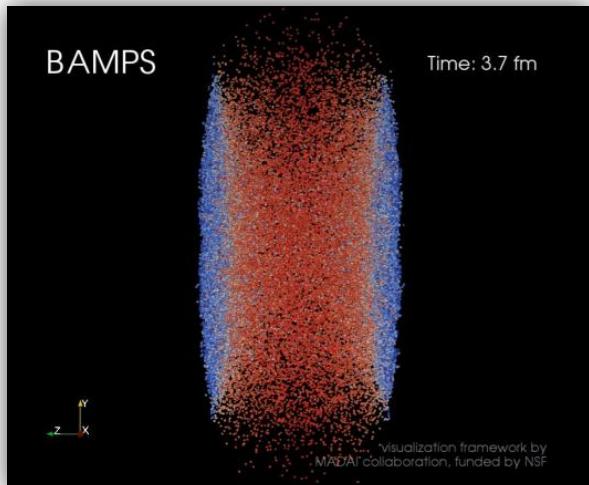
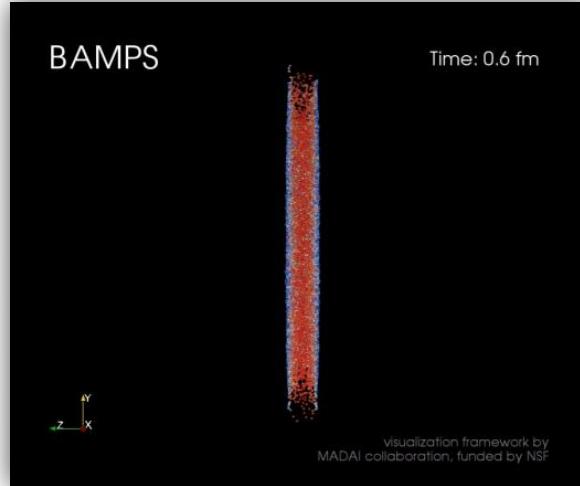
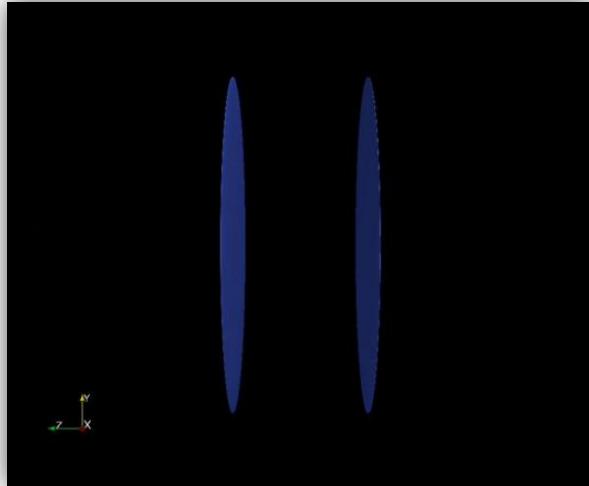
$$\begin{aligned}
 g + g &\rightarrow Q + \bar{Q} \\
 Q + \bar{Q} &\rightarrow g + g \\
 q + \bar{q} &\rightarrow Q + \bar{Q} \\
 Q + \bar{Q} &\rightarrow q + \bar{q} \\
 g + Q &\rightarrow g + Q \\
 g + \bar{Q} &\rightarrow g + \bar{Q} \\
 q + Q &\rightarrow q + Q \\
 q + \bar{Q} &\rightarrow q + \bar{Q} \\
 g + J/\psi &\rightarrow c + \bar{c} \\
 c + \bar{c} &\rightarrow g + J/\psi
 \end{aligned}$$

$$\begin{array}{lll}
 g g \rightarrow g g & & \mathbf{2} \rightarrow \mathbf{2} \\
 g g \rightarrow q \bar{q} & & \\
 q \bar{q} \rightarrow g g & \text{and} & q \bar{q} \rightarrow q' \bar{q}' \\
 q g \rightarrow q g & \text{and} & \bar{q} g \rightarrow \bar{q} g \\
 q \bar{q} \rightarrow q \bar{q} & & \\
 q q \rightarrow q q & \text{and} & \bar{q} \bar{q} \rightarrow \bar{q} \bar{q} \\
 q q' \rightarrow q q' & \text{and} & q \bar{q}' \rightarrow q \bar{q}' \\
 \end{array}$$

$$\begin{array}{lll}
 g g \leftrightarrow g g g & & \mathbf{2} \leftrightarrow \mathbf{3} \\
 q g \leftrightarrow q g g & \text{and} & \bar{q} g \leftrightarrow \bar{q} g g \\
 q \bar{q} \leftrightarrow q \bar{q} g & & \\
 q q \leftrightarrow q q g & \text{and} & \bar{q} \bar{q} \leftrightarrow \bar{q} \bar{q} g \\
 q q' \leftrightarrow q q' g & \text{and} & q \bar{q}' \leftrightarrow q \bar{q}' g
 \end{array}$$

# Heavy-ion collision at LHC

BAMPS simulation of QGP phase at LHC at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$



Visualization framework courtesy MADAI collaboration, funded by the NSF under grant# NSF-PHY-09-41373

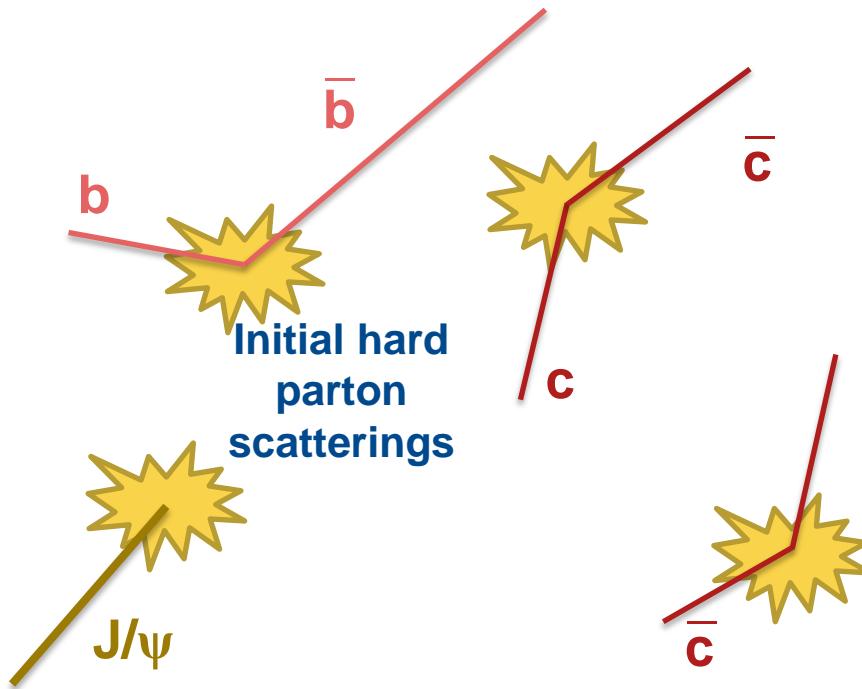
# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS



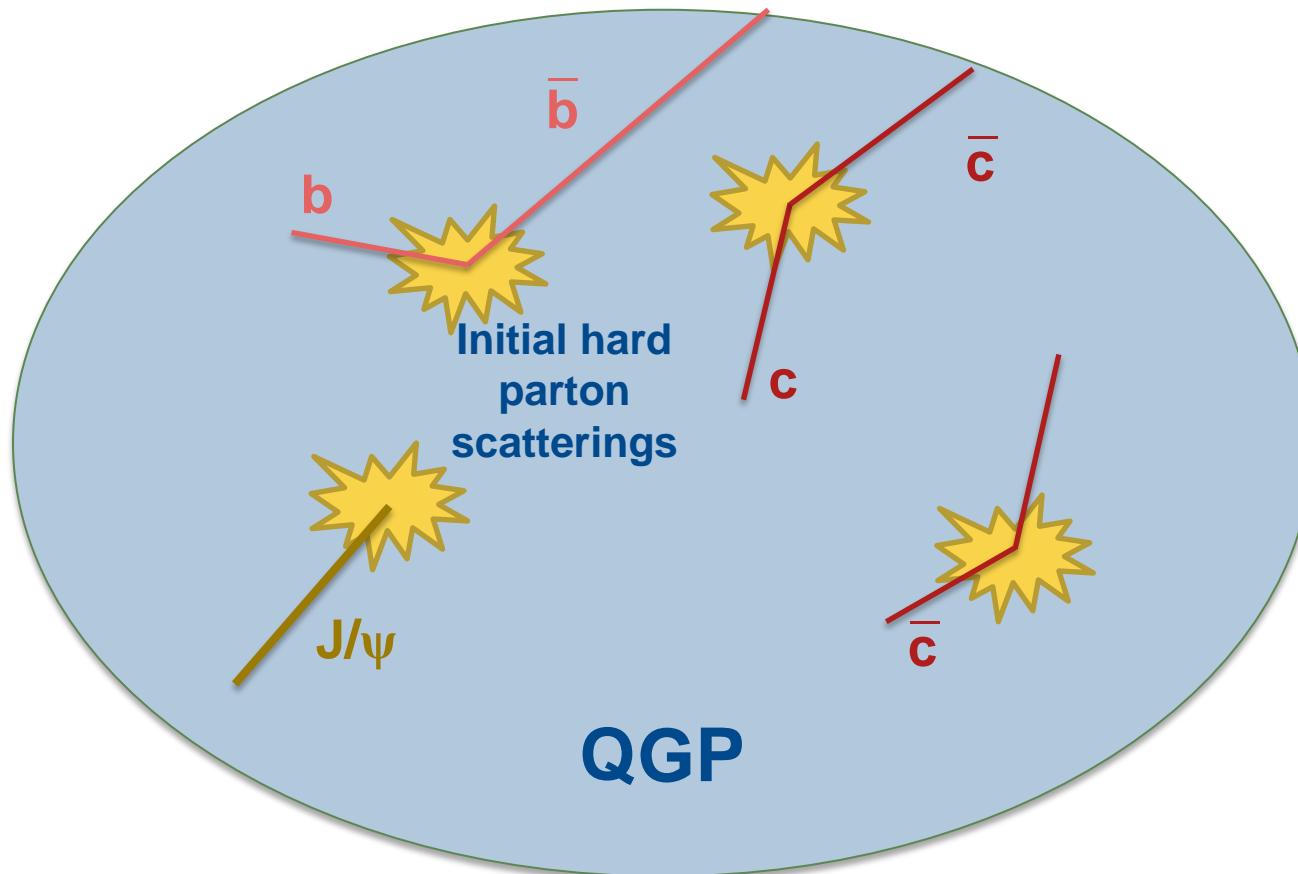
# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS



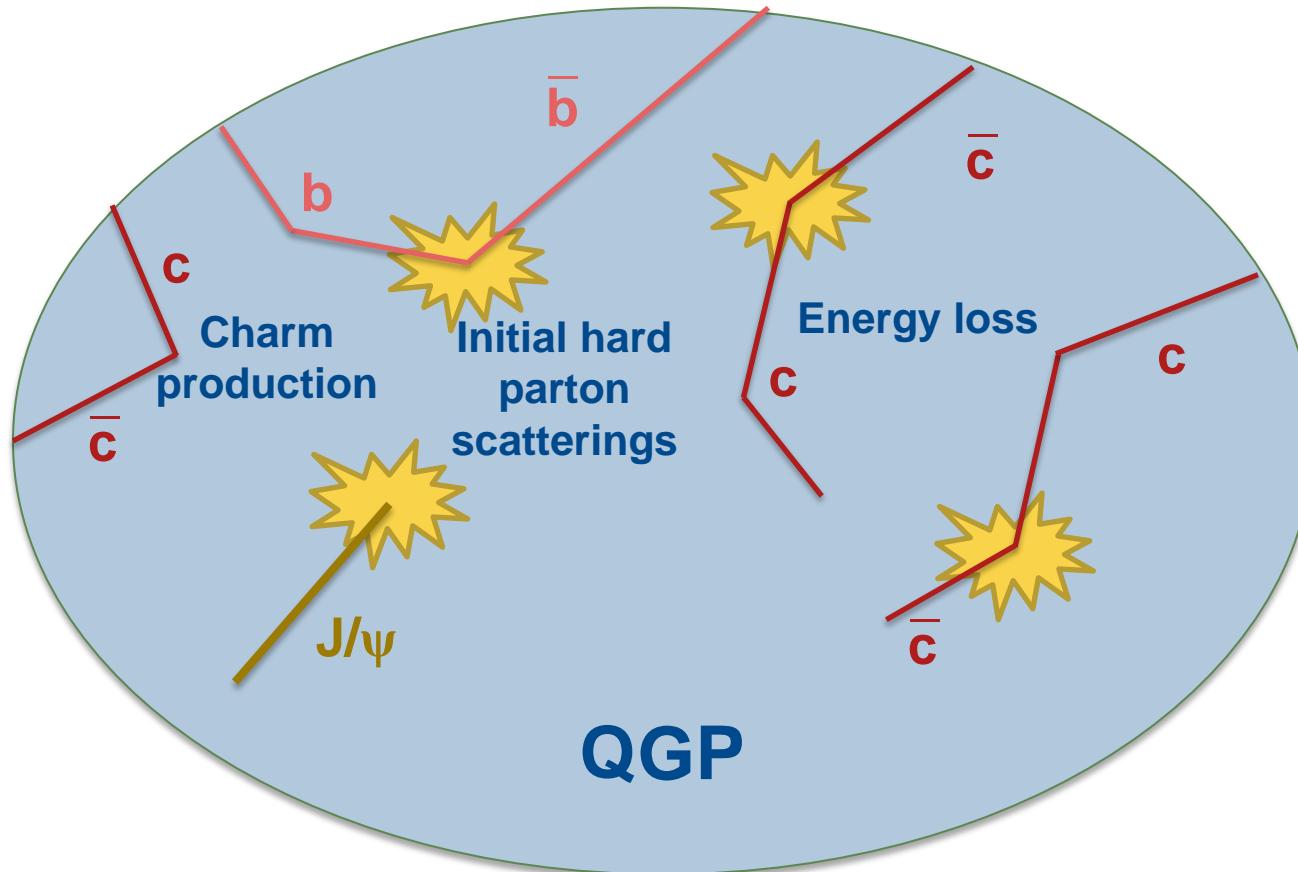
# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS



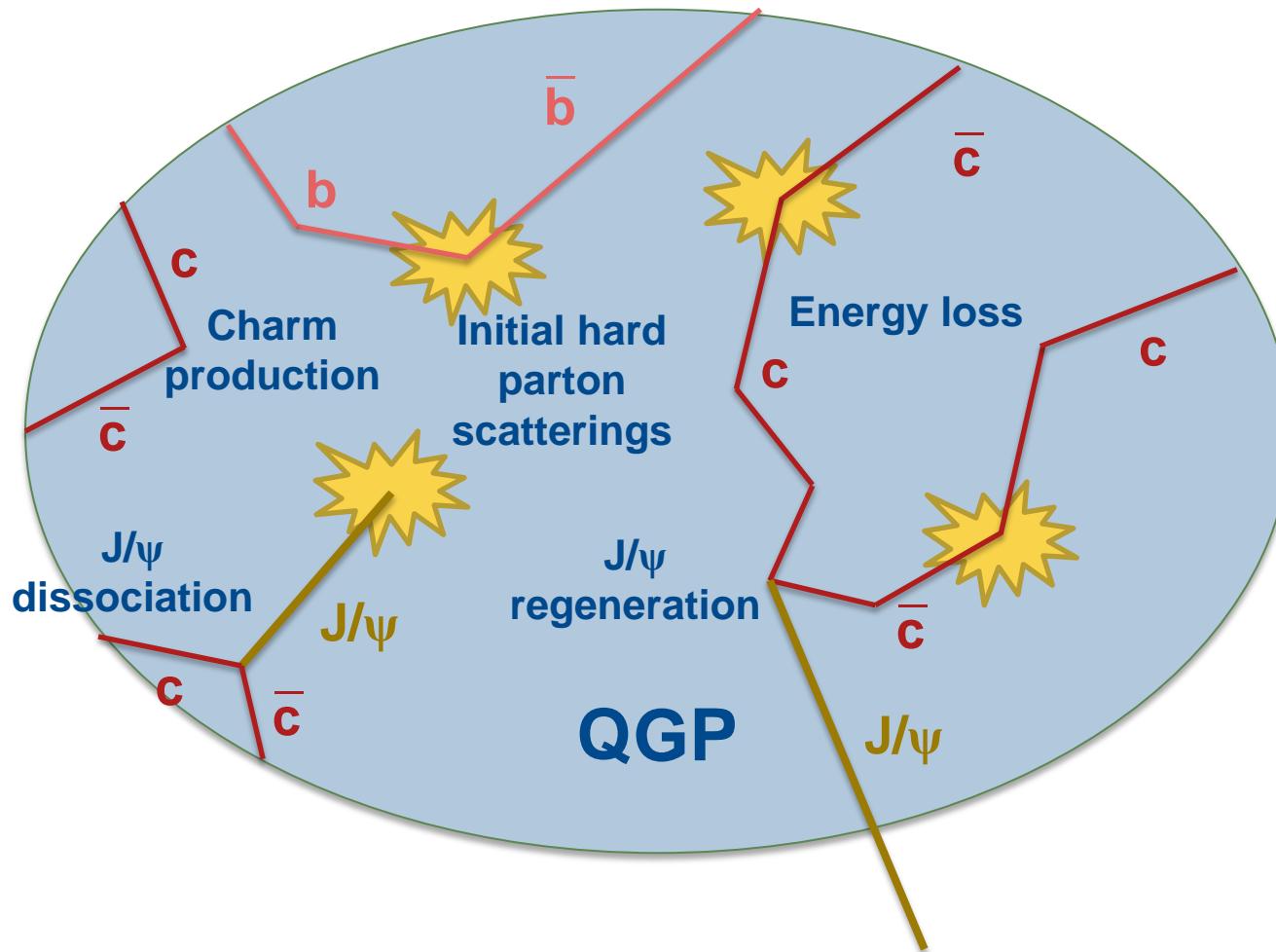
# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS



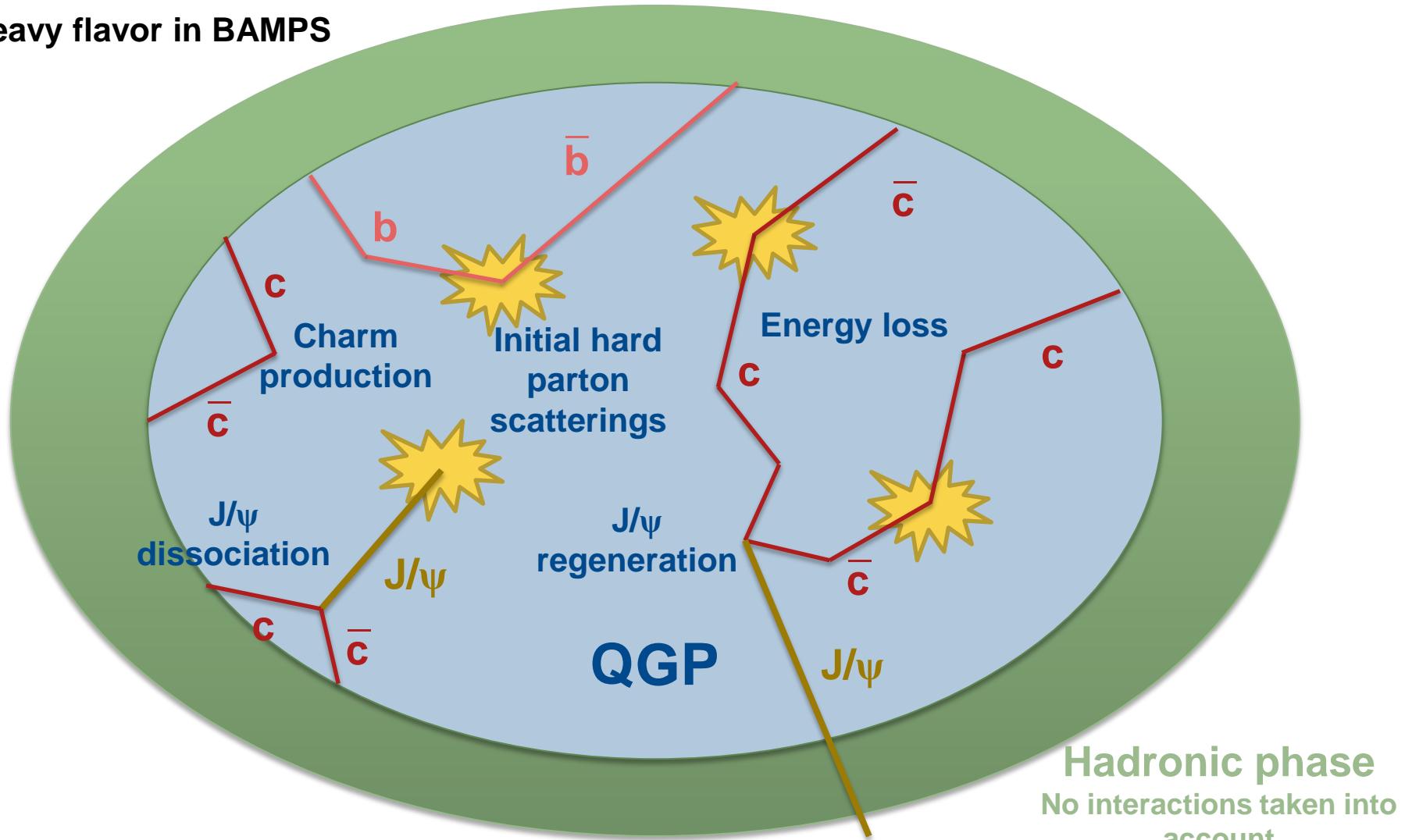
# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS

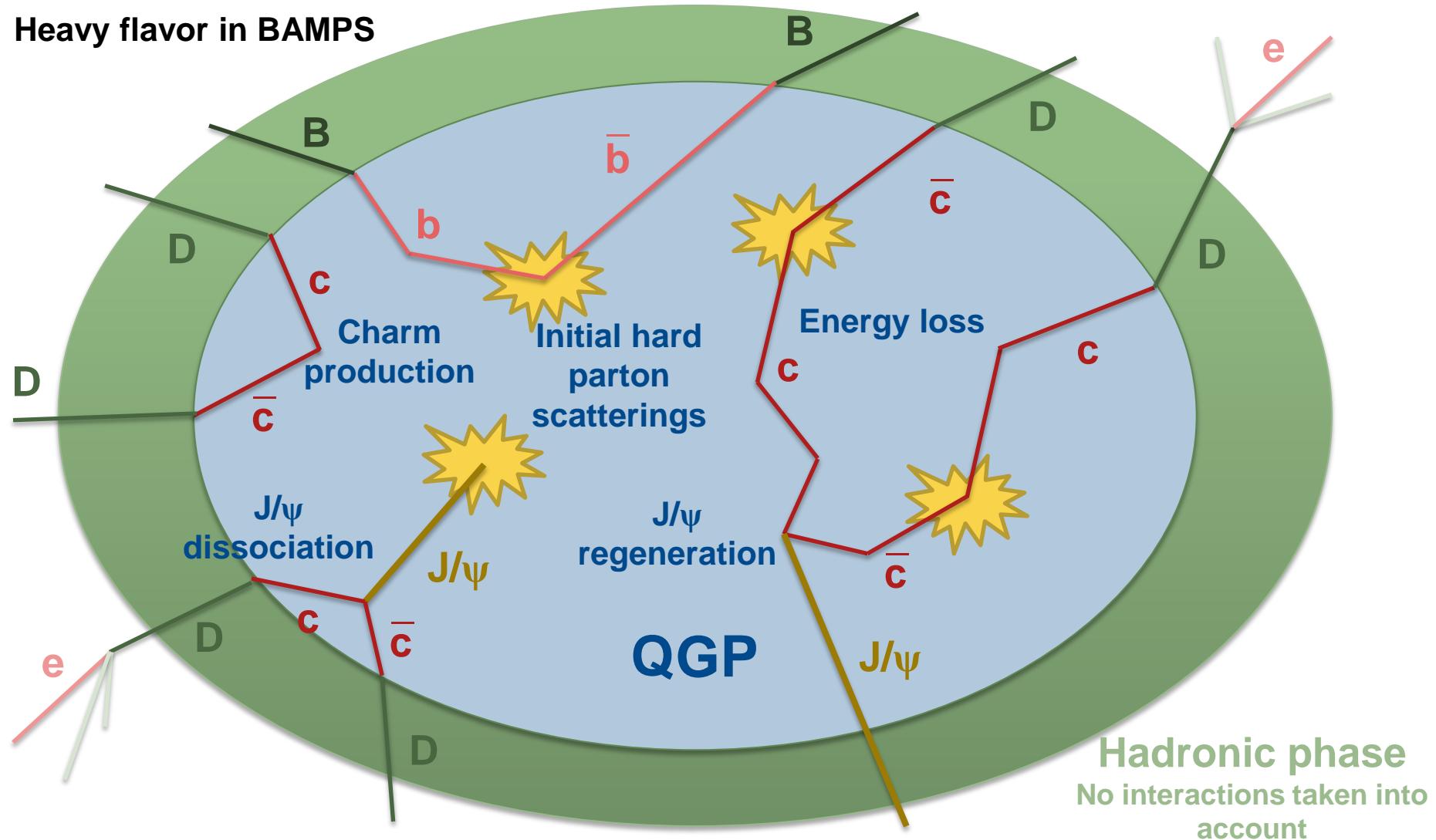


# Sketch of heavy-ion collision in BAMPS

## Heavy flavor in BAMPS



# Sketch of heavy-ion collision in BAMPS



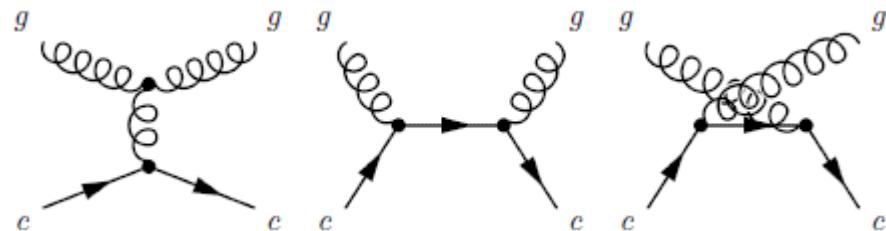
# Heavy quark scattering

Leading order perturbative QCD:

$$g + Q \rightarrow g + Q$$

$$q + Q \rightarrow q + Q$$

t channel is divergent for small t



$$\frac{1}{t} \rightarrow \frac{1}{t - \kappa m_D^2}$$

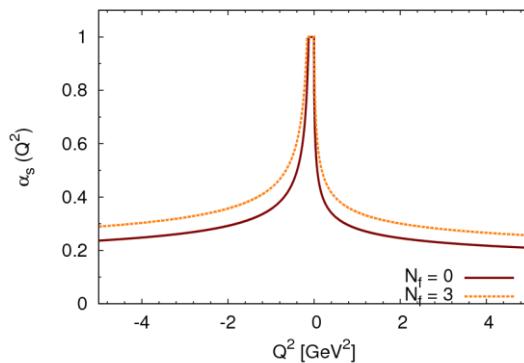
$\kappa$  can be fixed to

$$\kappa = \frac{1}{2e} \approx 0.184 \approx 0.2$$

by comparing dE/dx to  
HTL result beyond  
logarithmic accuracy

A. Peshier,  
arXiv:0801.0595  
[hep-ph]

P.B. Gossiaux,  
J. Aichelin,  
Phys.Rev.C78 (2008)

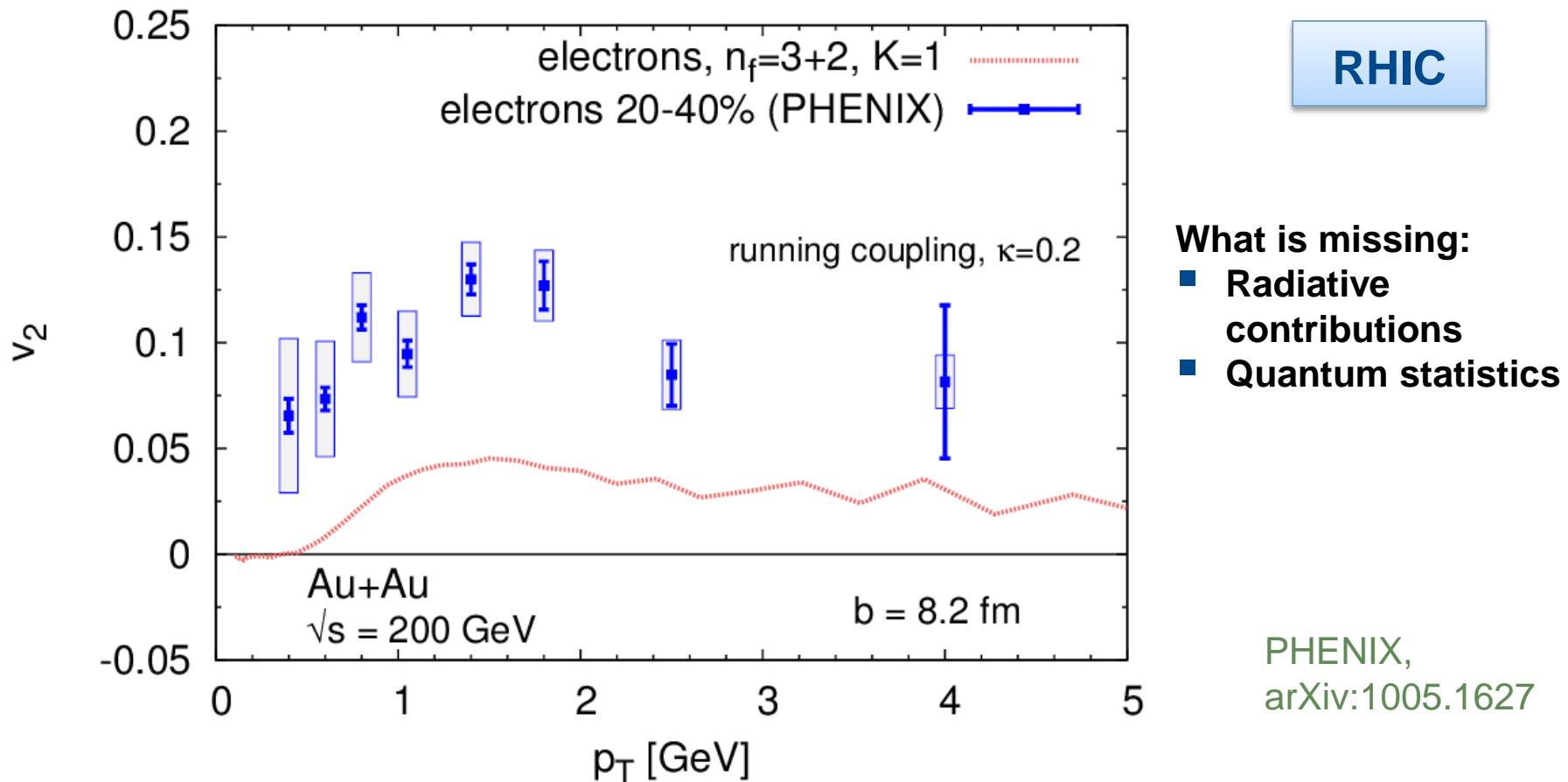


Introduce a running coupling constant for all channels

Details: JU, Fochler, Xu, Greiner  
Phys. Rev. C 84 (2011)

# Heavy quark elliptic flow $v_2$ at RHIC

$$\sigma_{gQ \rightarrow gQ} \rightarrow K \sigma_{gQ \rightarrow gQ}$$



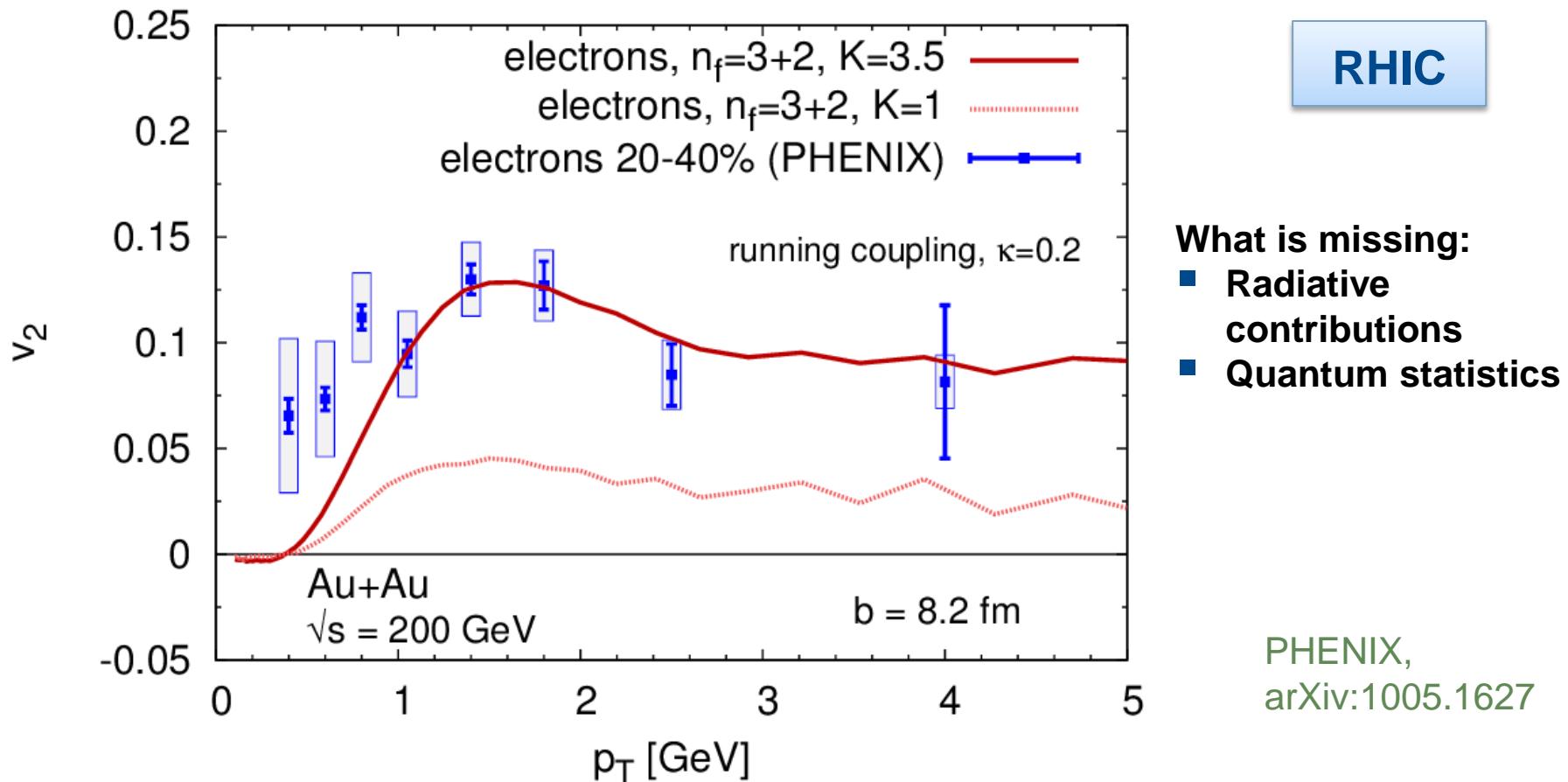
only elastic heavy quark processes

JU, Fochler, Xu, Greiner  
arXiv:1205.4945

PHENIX,  
arXiv:1005.1627

# Heavy quark elliptic flow $v_2$ at RHIC

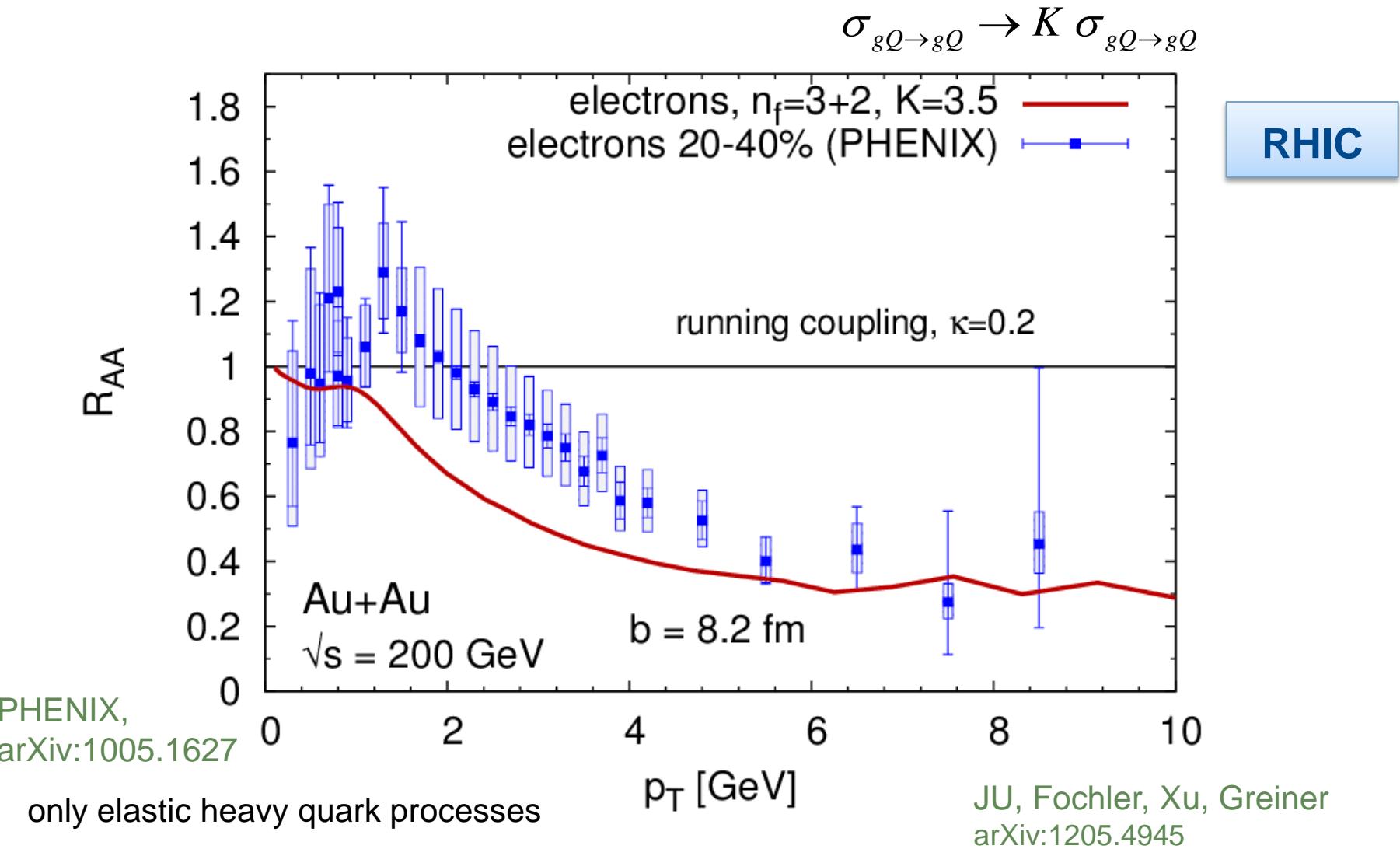
$$\sigma_{gQ \rightarrow gQ} \rightarrow K \sigma_{gQ \rightarrow gQ}$$



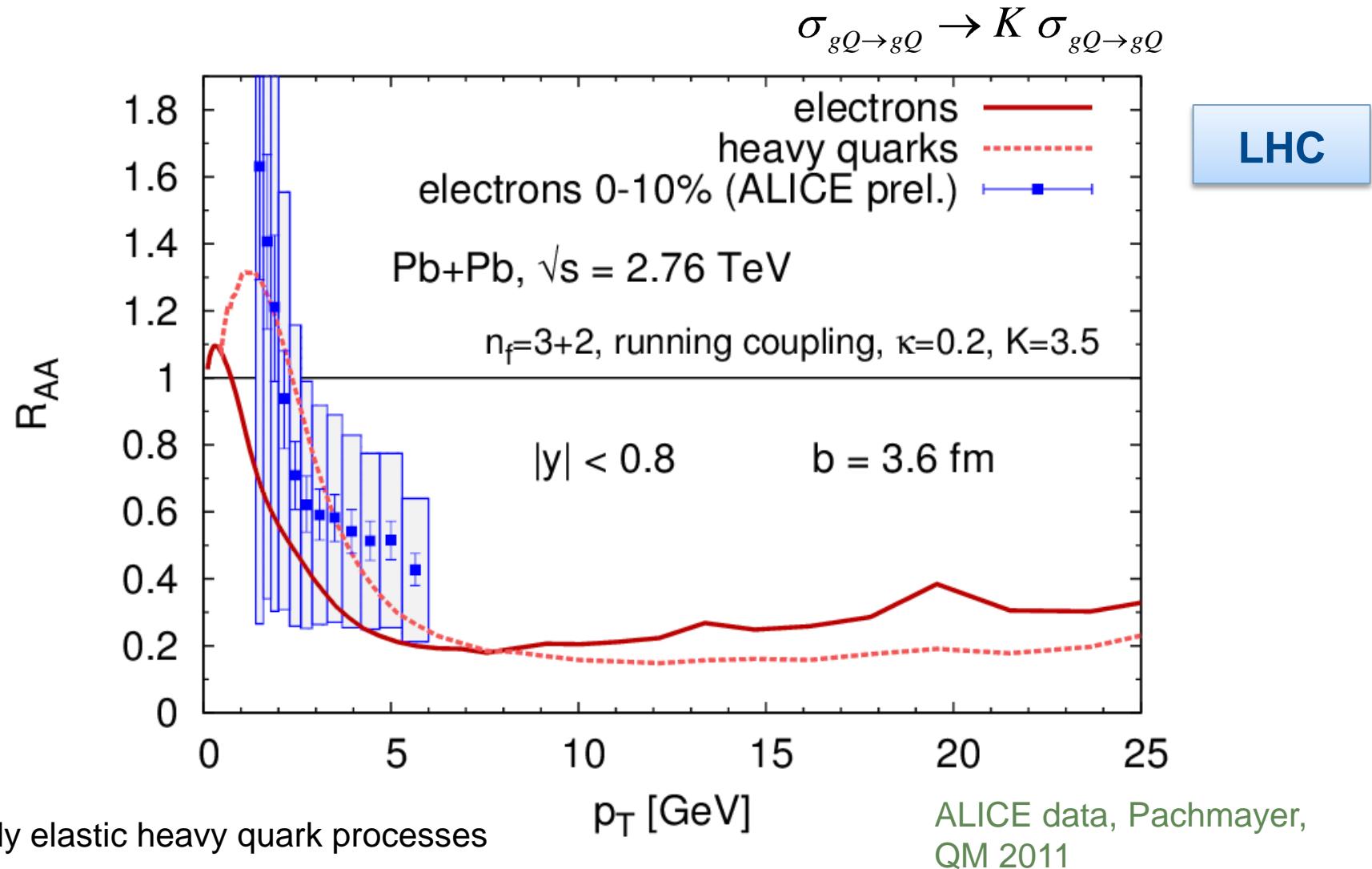
only elastic heavy quark processes

JU, Fochler, Xu, Greiner  
arXiv:1205.4945

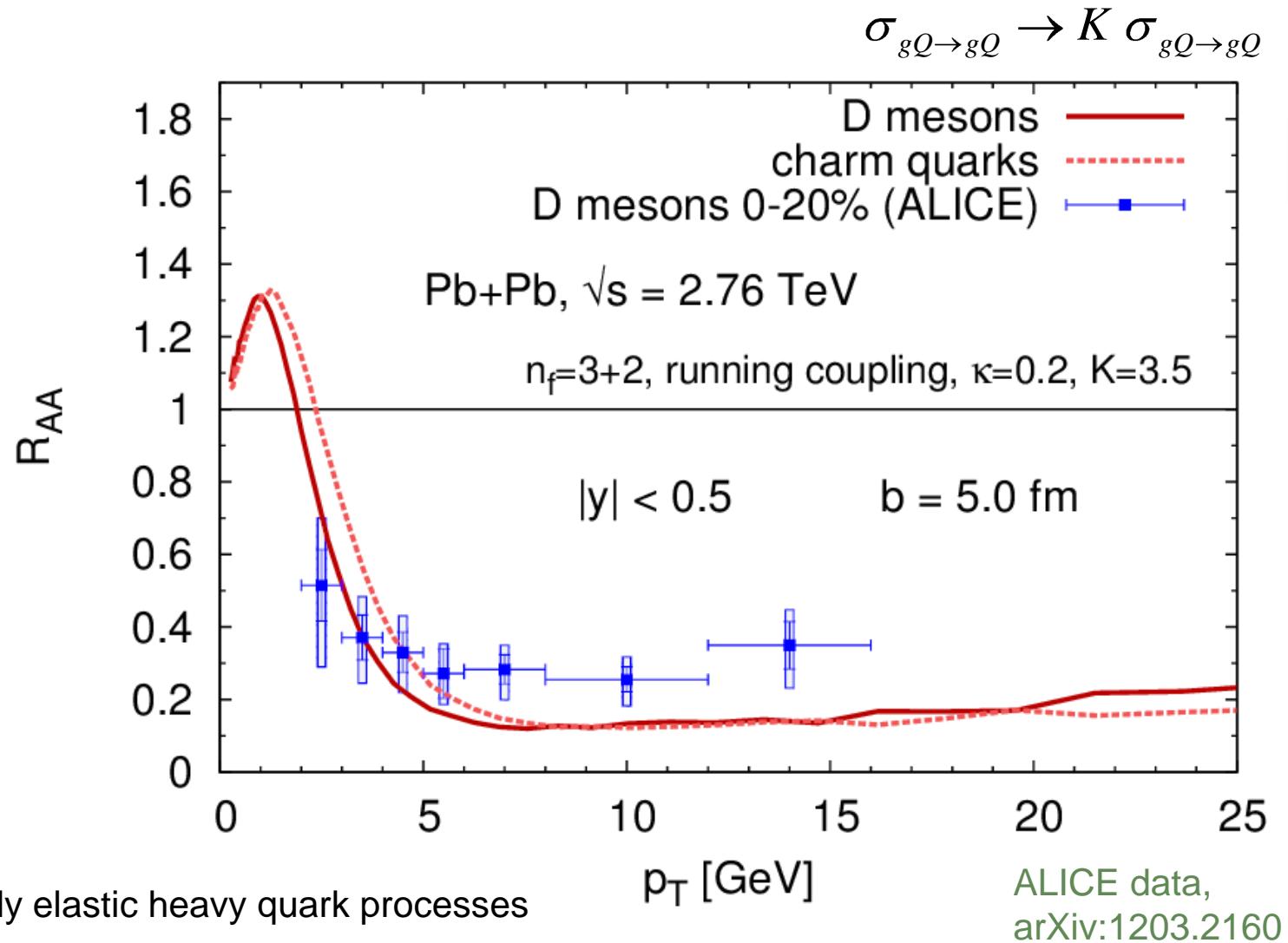
# Heavy quark $R_{AA}$ at RHIC



# Heavy flavor electron $R_{AA}$ at LHC

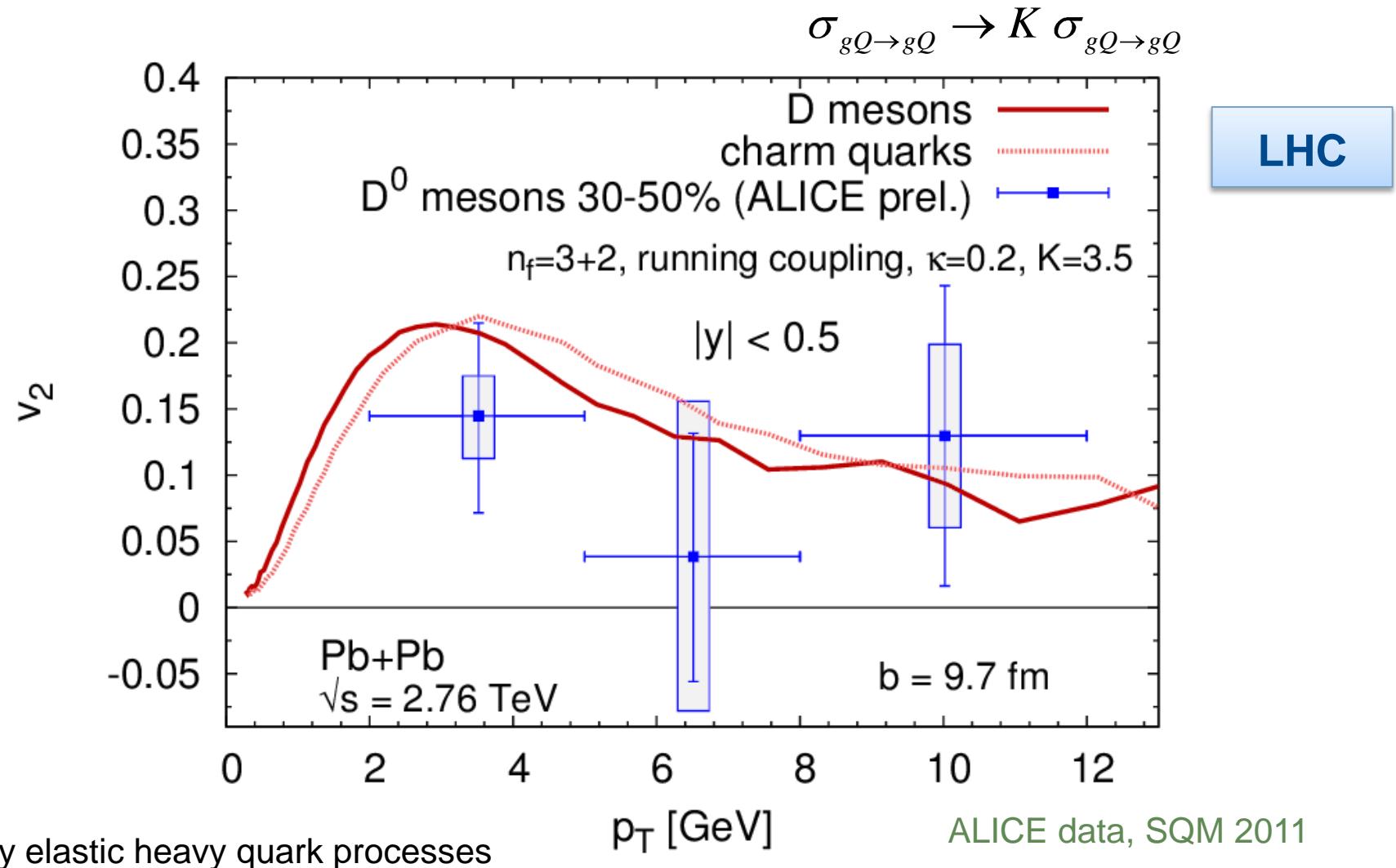


# D meson $R_{AA}$ at LHC

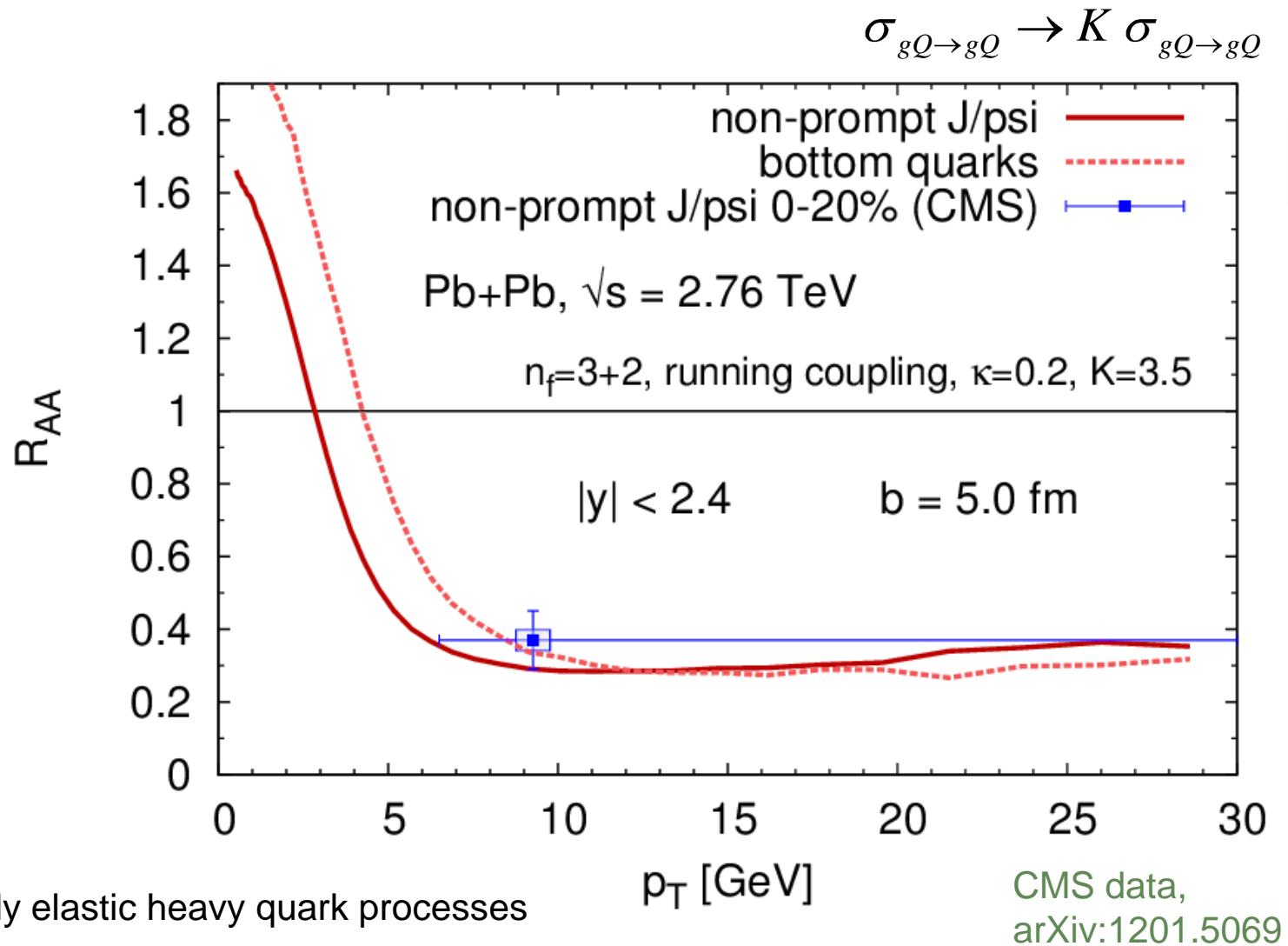


LHC

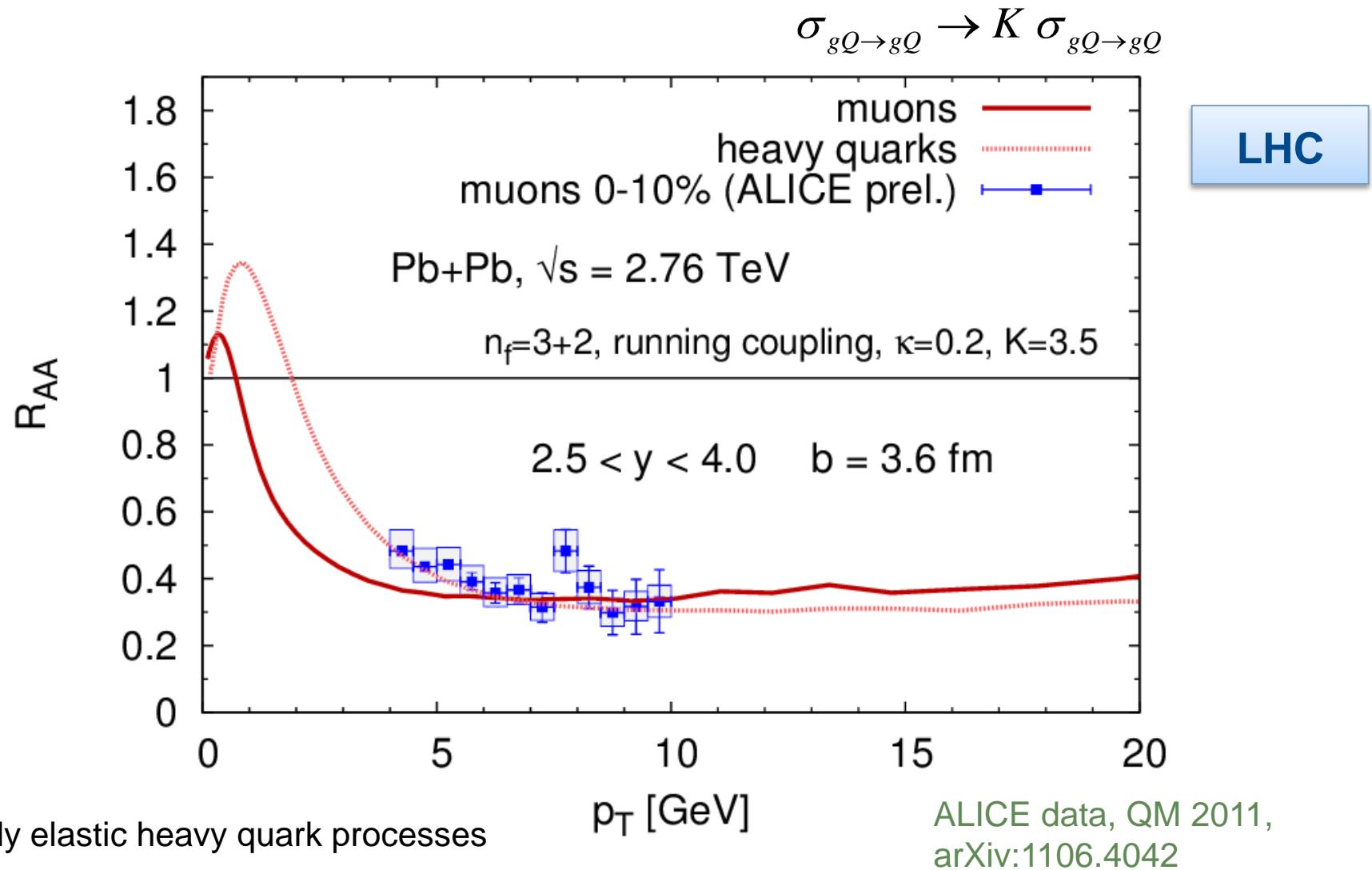
# D meson $v_2$ at LHC



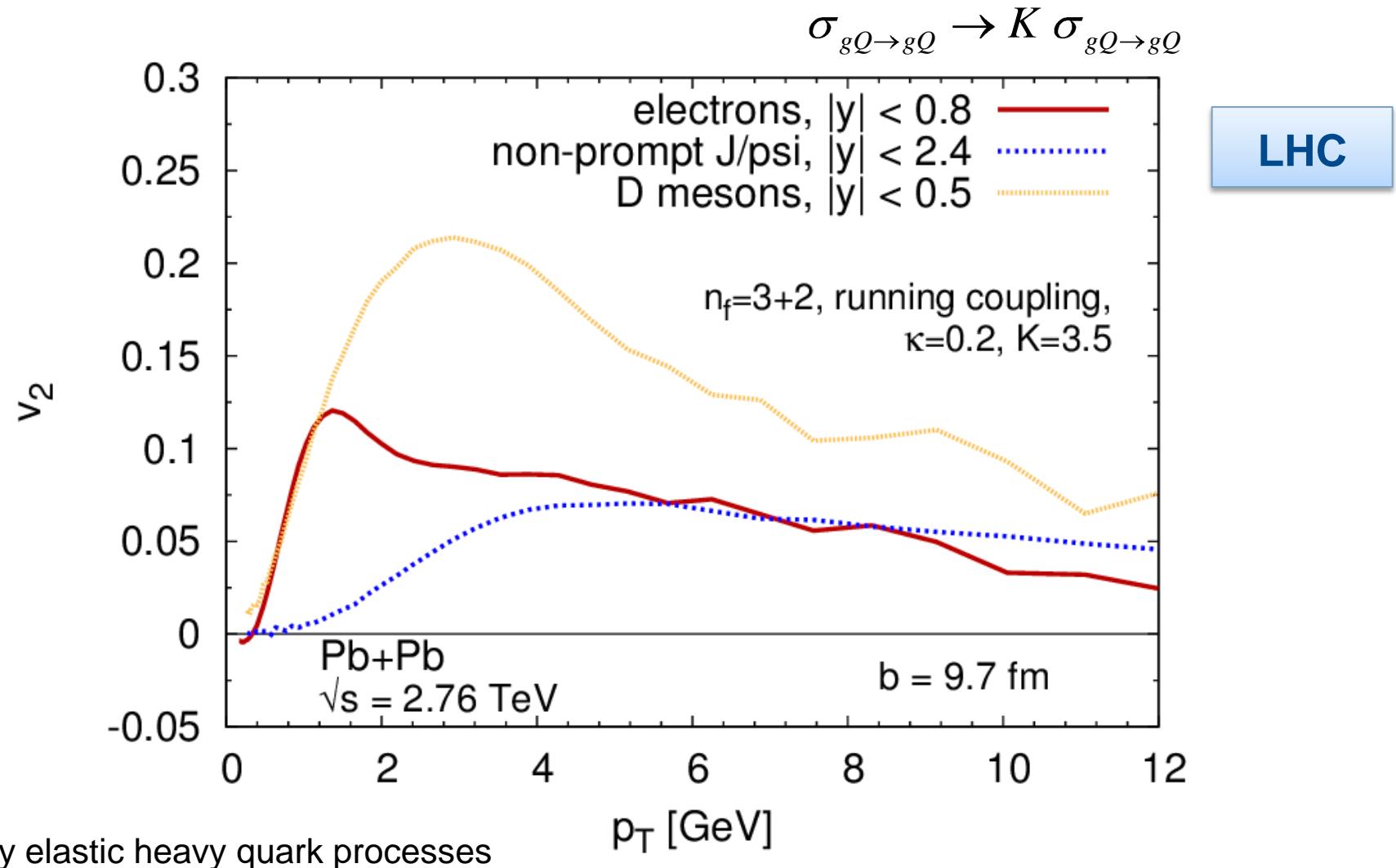
# Non-prompt J/psi R<sub>AA</sub> at LHC



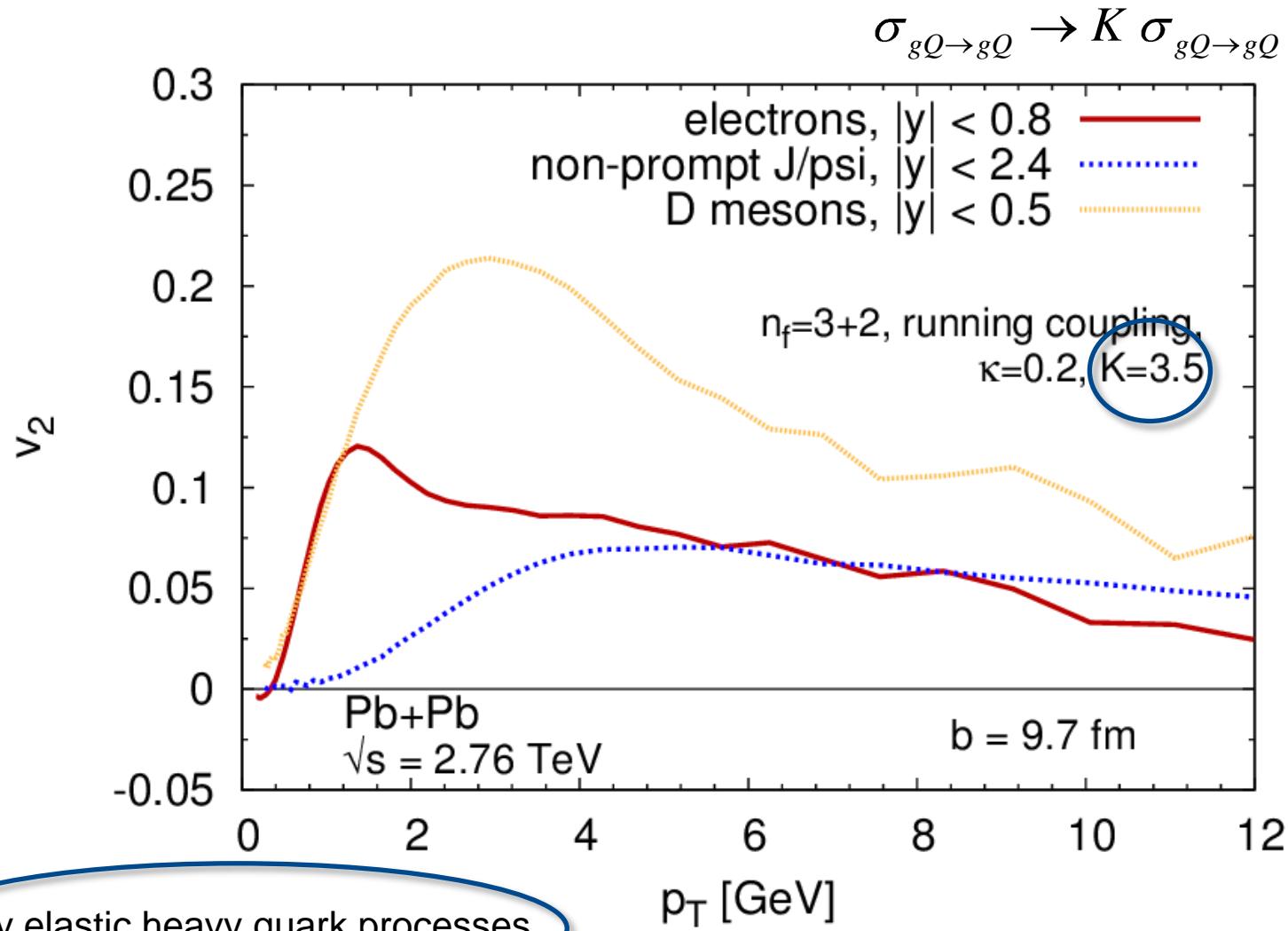
# Muon $R_{AA}$ at forward rapidity at LHC



# $v_2$ predictions for the LHC



# $v_2$ predictions for the LHC

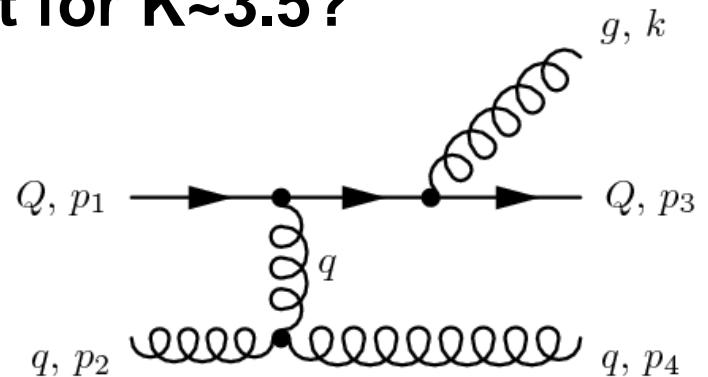


LHC

# Radiative processes

**Can radiative processes account for  $K \sim 3.5$ ?**

$$g + Q \rightarrow g + Q + g$$

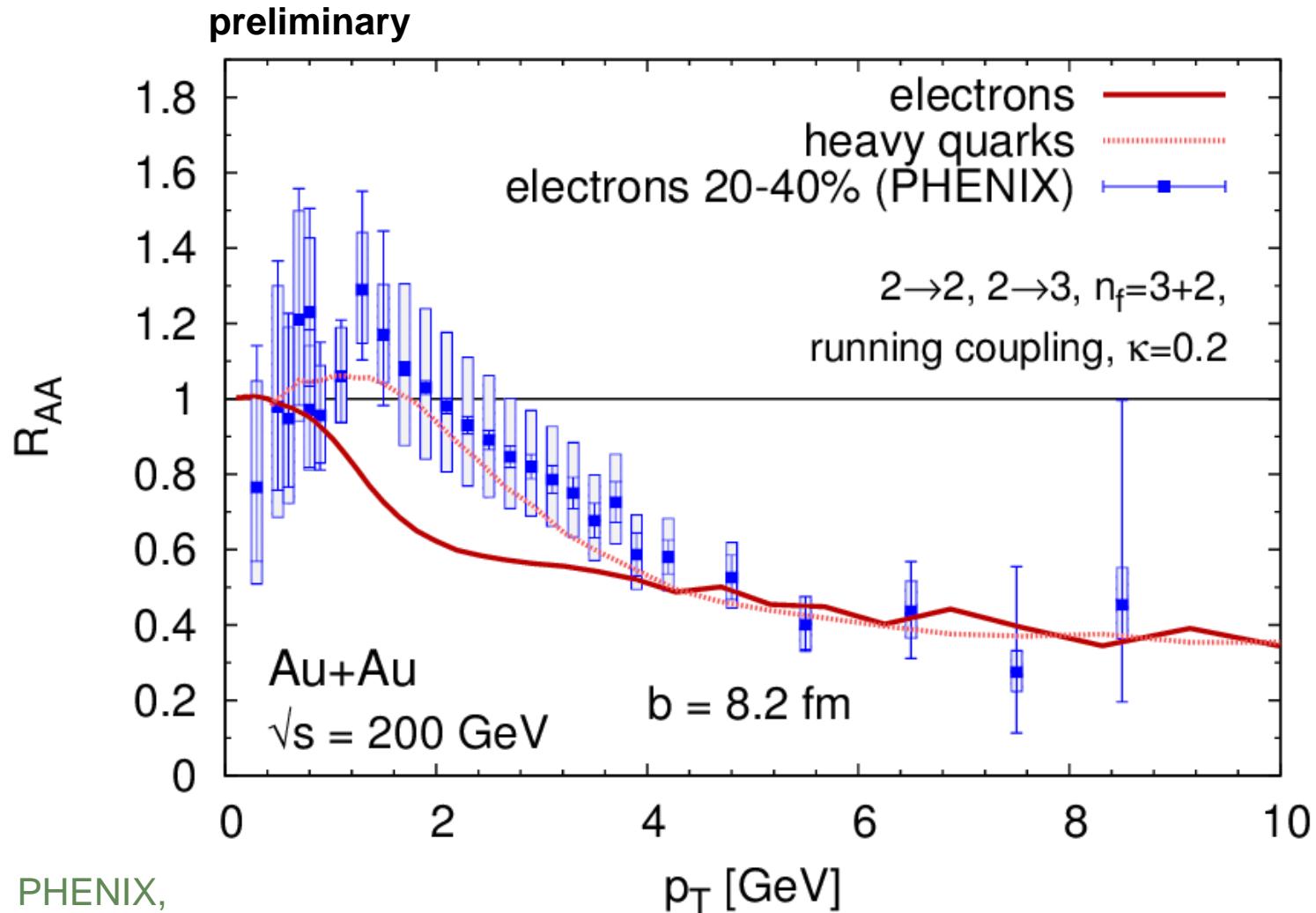


**Gunion-Bertsch matrix element generalized to heavy quarks:**

$$|\overline{\mathcal{M}}_{gQ \rightarrow gQg}|^2 = 12g^2 \left| \overline{\mathcal{M}}_0^{gQ} \right|^2 \left[ \frac{\mathbf{k}_\perp}{k_\perp^2 + x^2 M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + x^2 M^2} \right]^2$$

In accordance to scalar QCD result from  
 Gossiaux, Aichelin, Gousset, Guiho, J.Phys.G37 (2010)

# Heavy quark $R_{AA}$ at RHIC with $2 \rightarrow 3$



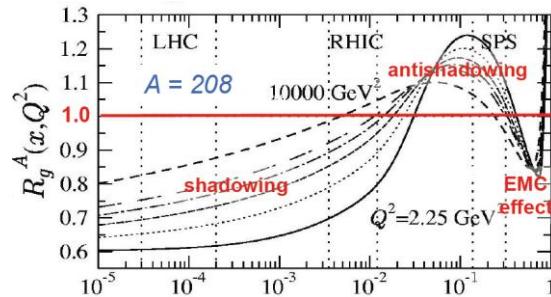
RHIC

PHENIX,  
arXiv:1005.1627

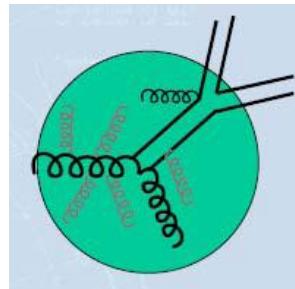
# J/ $\psi$ suppression

## Cold nuclear matter effects

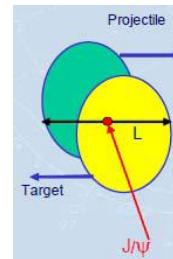
- **Shadowing**



- **Cronin effect**



- **(Nuclear absorption)**



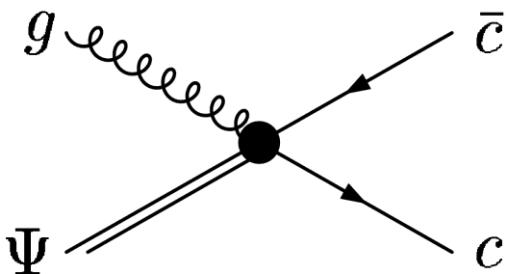
## Hot nuclear matter effects

- **J/ $\psi$  dissociation**

- If  $T > T_d$  (dissociation temperature)
- Via  $J/\psi + g \rightarrow c + \bar{c}$

- **J/ $\psi$  regeneration**

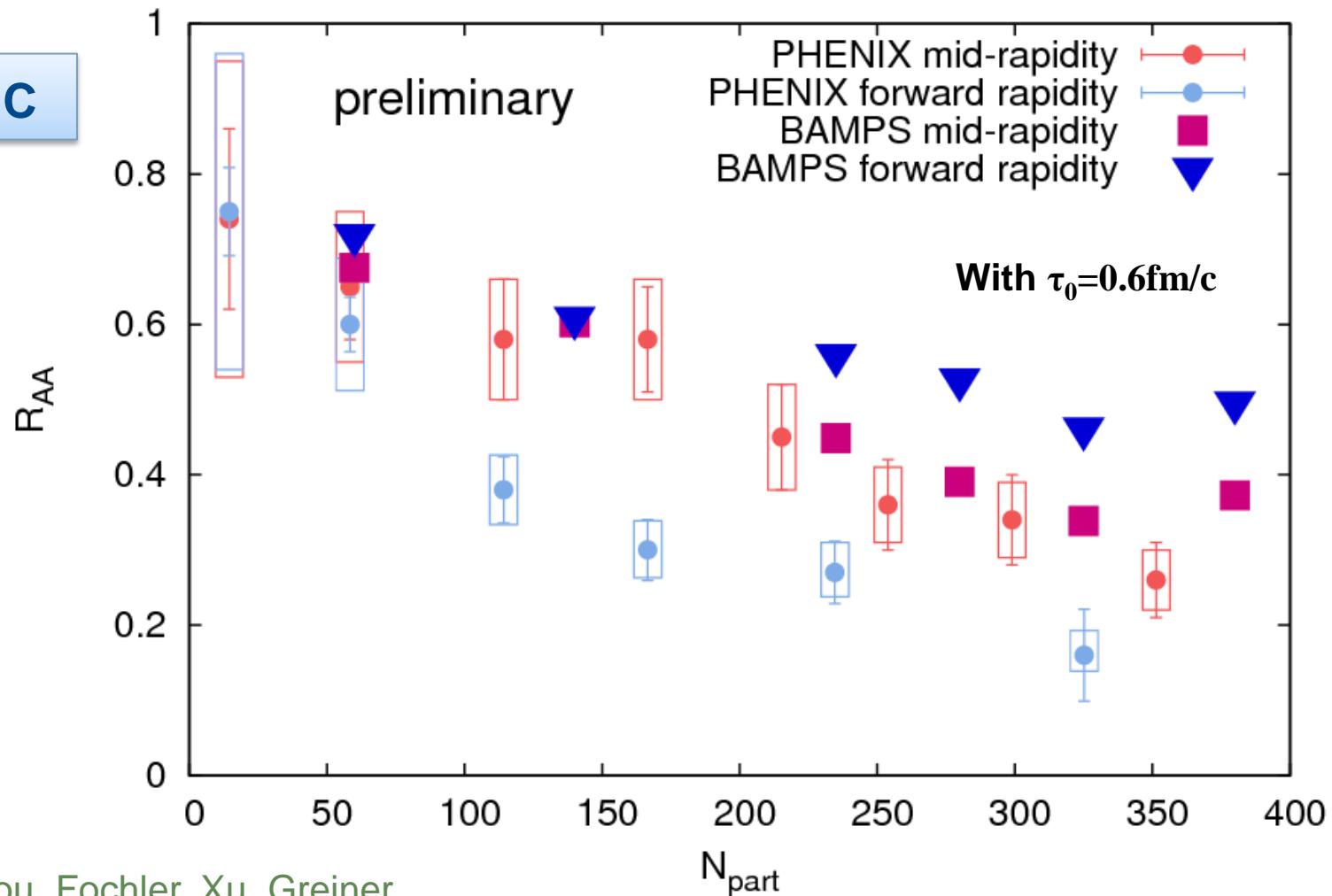
via  $c + \bar{c} \rightarrow J/\psi + g$



Bhanot+Peskin 79

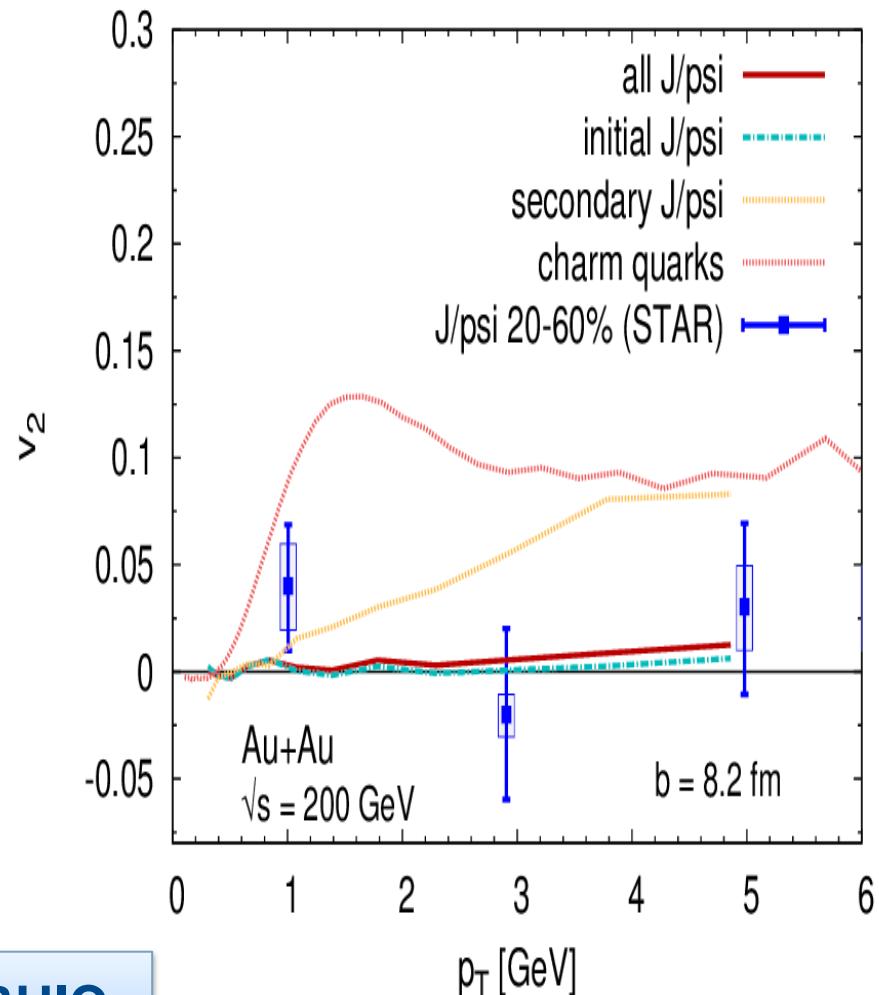
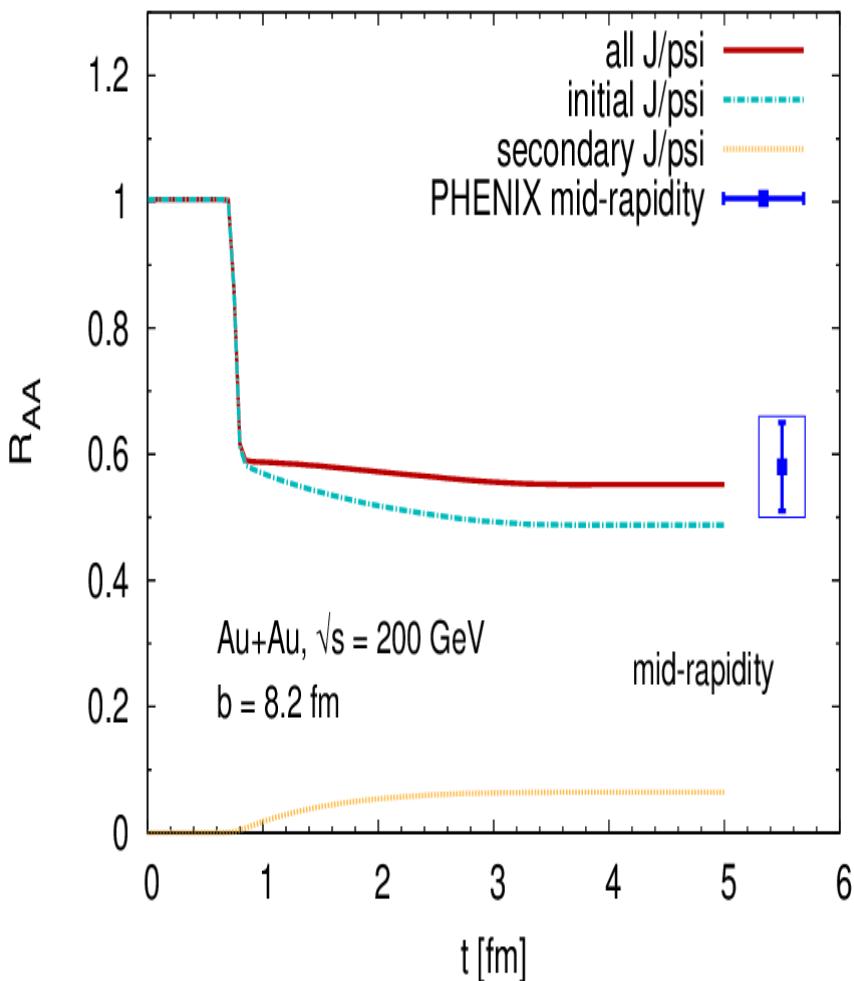
# J/ $\psi$ production

RHIC



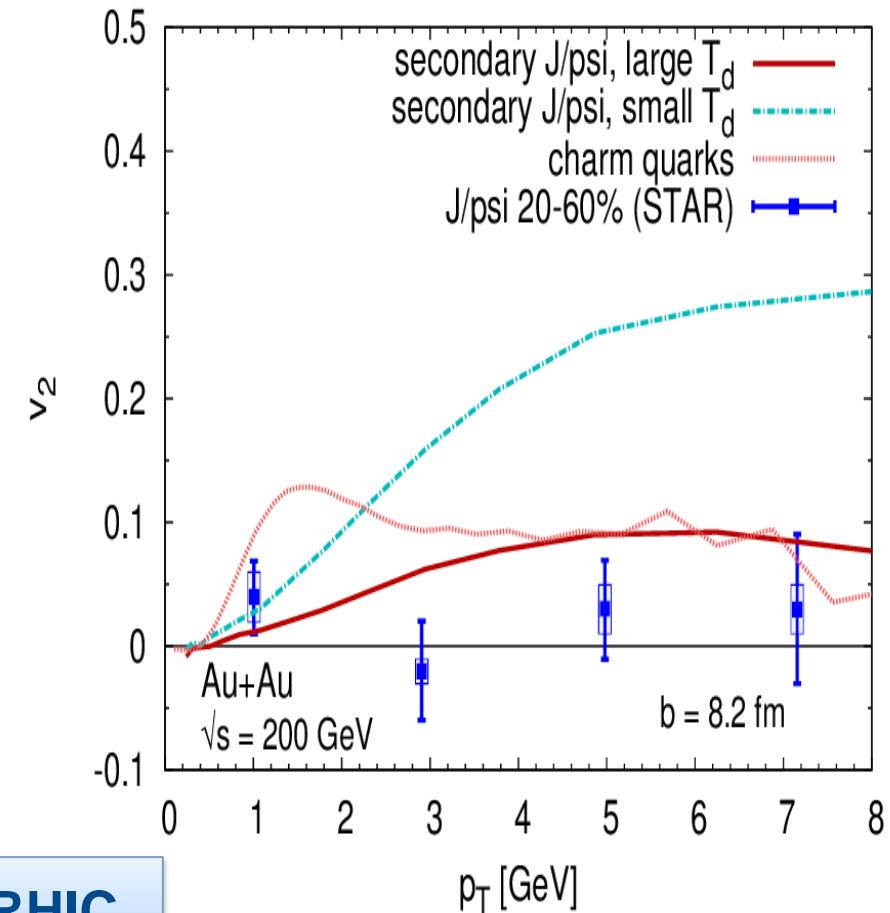
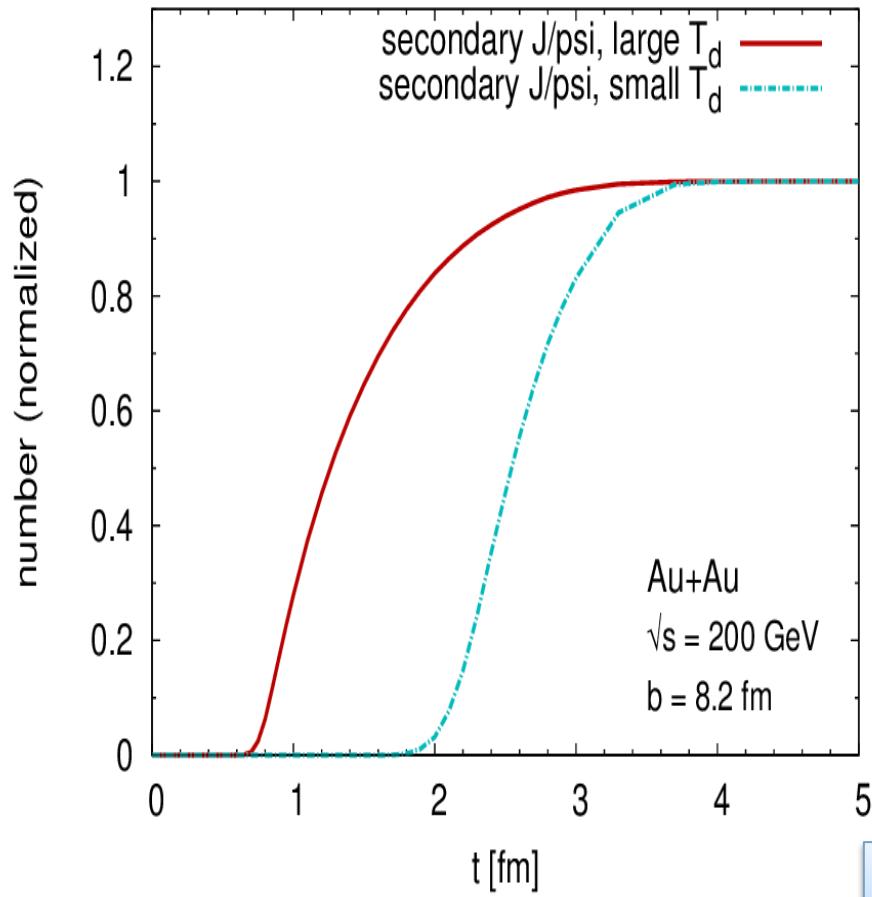
JU, Zhou, Fochler, Xu, Greiner  
arXiv:1104.2437

# J/ $\psi$ elliptic flow



RHIC

# Secondary J/ $\psi$ elliptic flow



**Secondary  $J/\psi$  flow is sensitive on production time**

# Conclusions & outlook

## Full space-time evolution of QGP with charm and bottom quarks and J/ $\psi$

- Running coupling and improved Debye screening yield results that can explain experimental  $v_2$  and  $R_{AA}$  at RHIC if  $K=3.5$  is introduced
- Good agreement with D meson  $v_2$  and  $R_{AA}$  at LHC
- Good agreement with non-prompt J/psi and muon  $R_{AA}$  at LHC
- Preliminary results with  $2 \rightarrow 3$  in full cascade are promising
- Qualitative studies of J/ $\psi$  suppression and elliptic flow

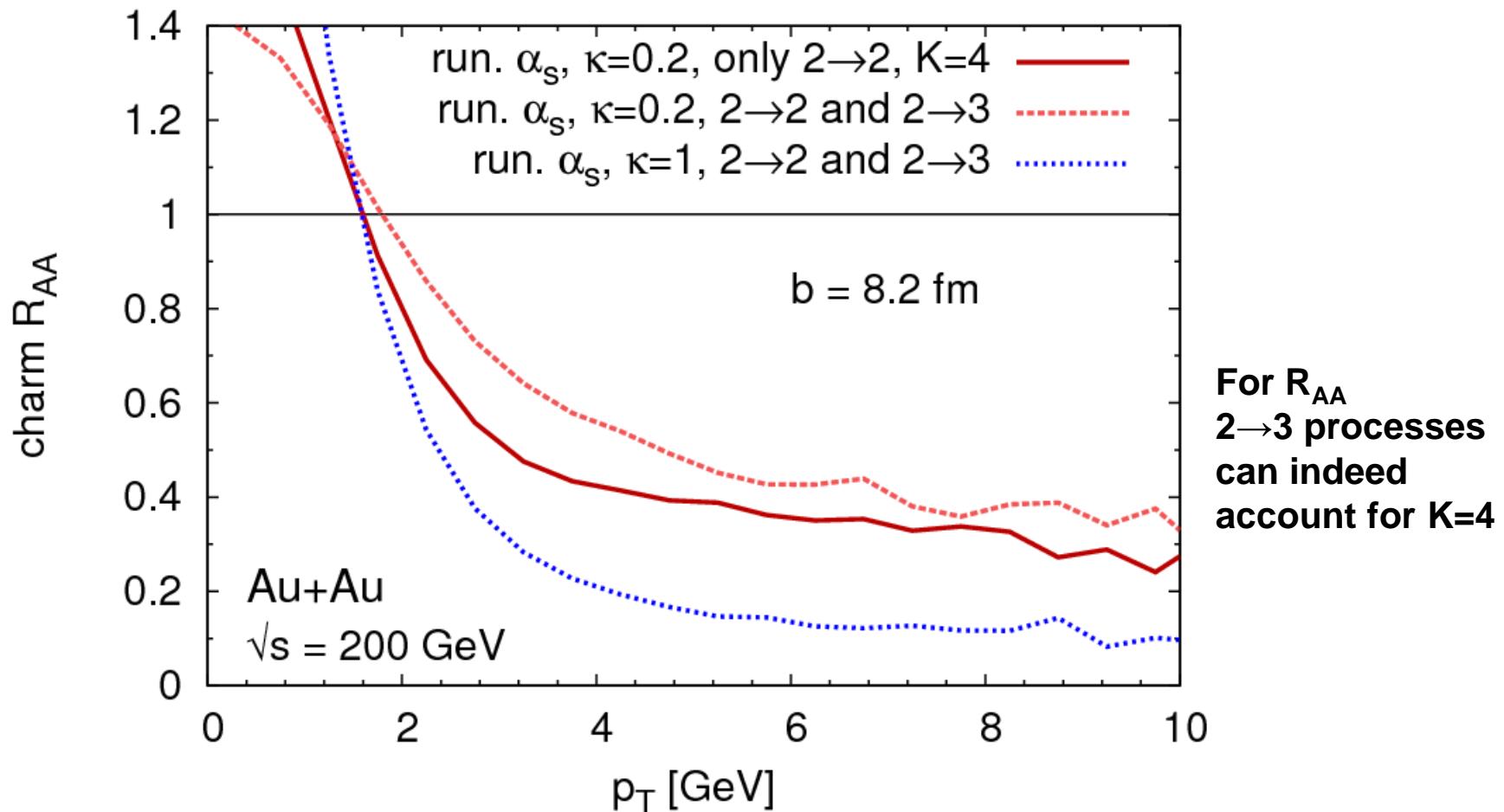
Further details in Phys. Rev. C 84, 024908 (2011) and arXiv:1205.4945

## Future tasks:

- Further study of radiative heavy quark scattering in full cascade
- J/ $\psi$  calculations at RHIC and LHC

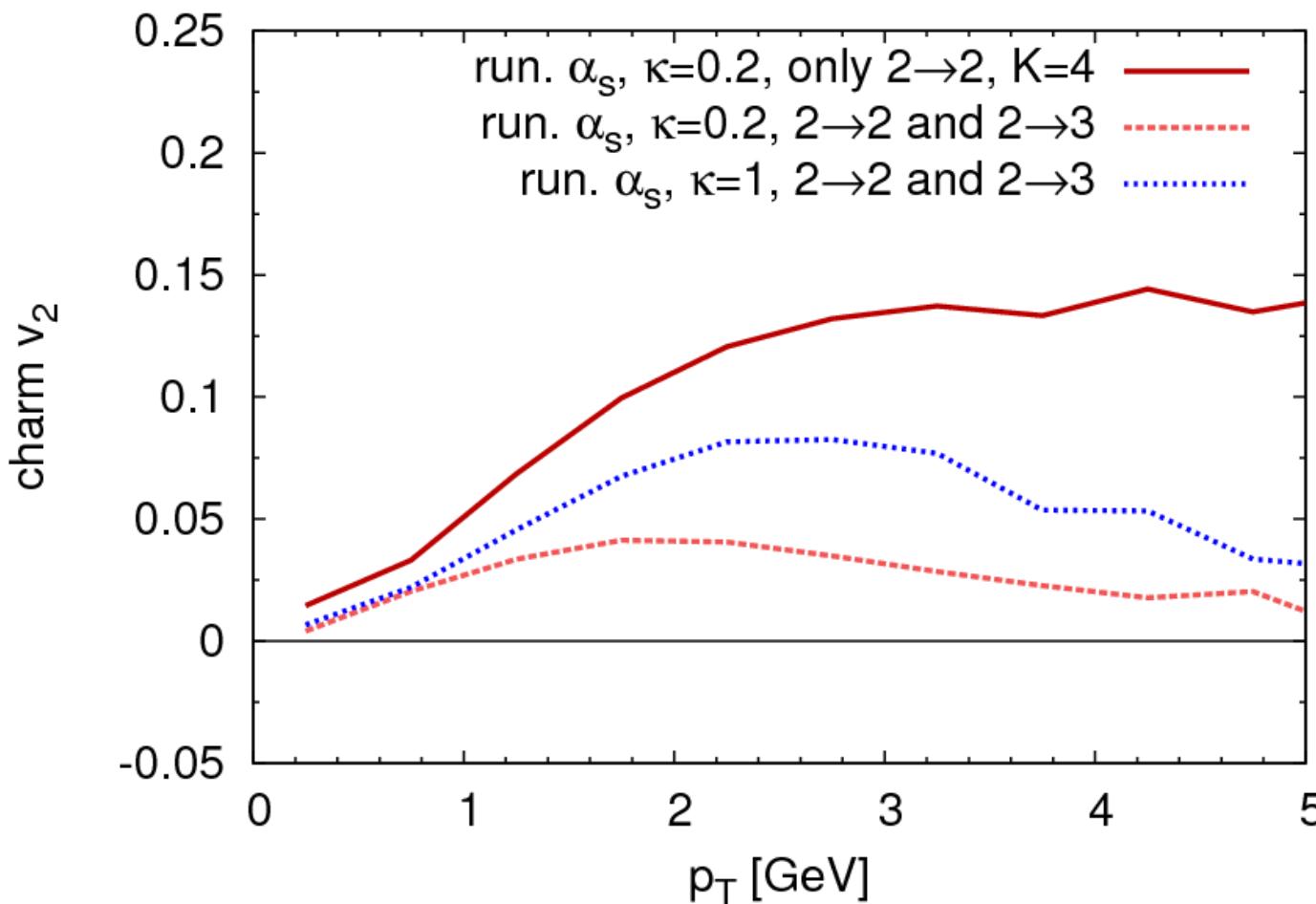
**Thank you for your attention.**

# Charm R<sub>AA</sub> at RHIC



Only charm quarks (no heavy flavor electrons!) for better comparison

# Charm elliptic flow $v_2$ at RHIC



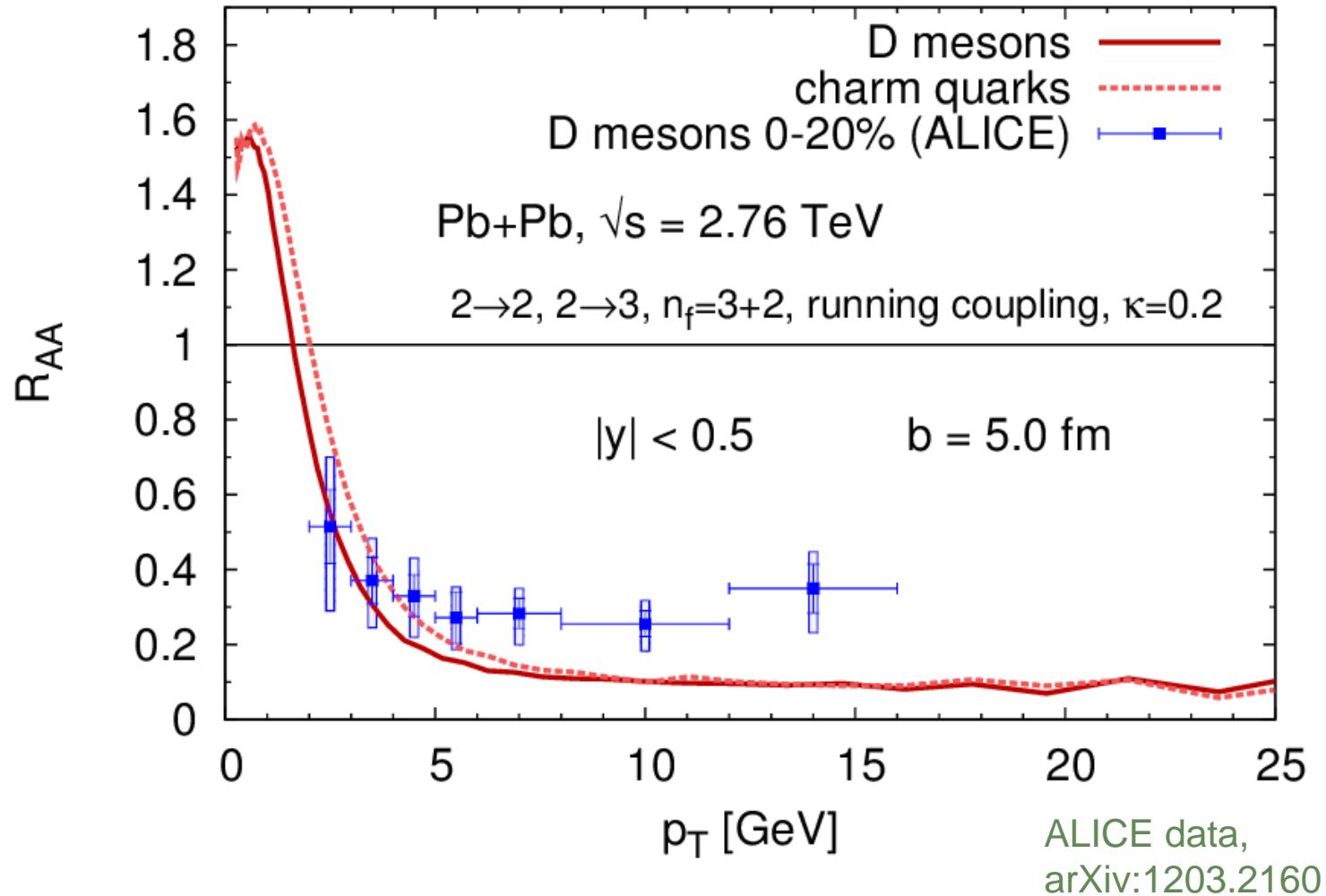
**For  $v_2$**   
**2→3 processes**  
**cannot explain**  
**missing factor**  
**K=4**

**Different impact**  
**of 2→3**  
**processes on  $v_2$**   
**and  $R_{AA}$**   
**Reason:**  
**LPM effect**

**kappa=1 is even**  
**better since 2→3**  
**processes more**  
**important due to**  
**LPM effect**

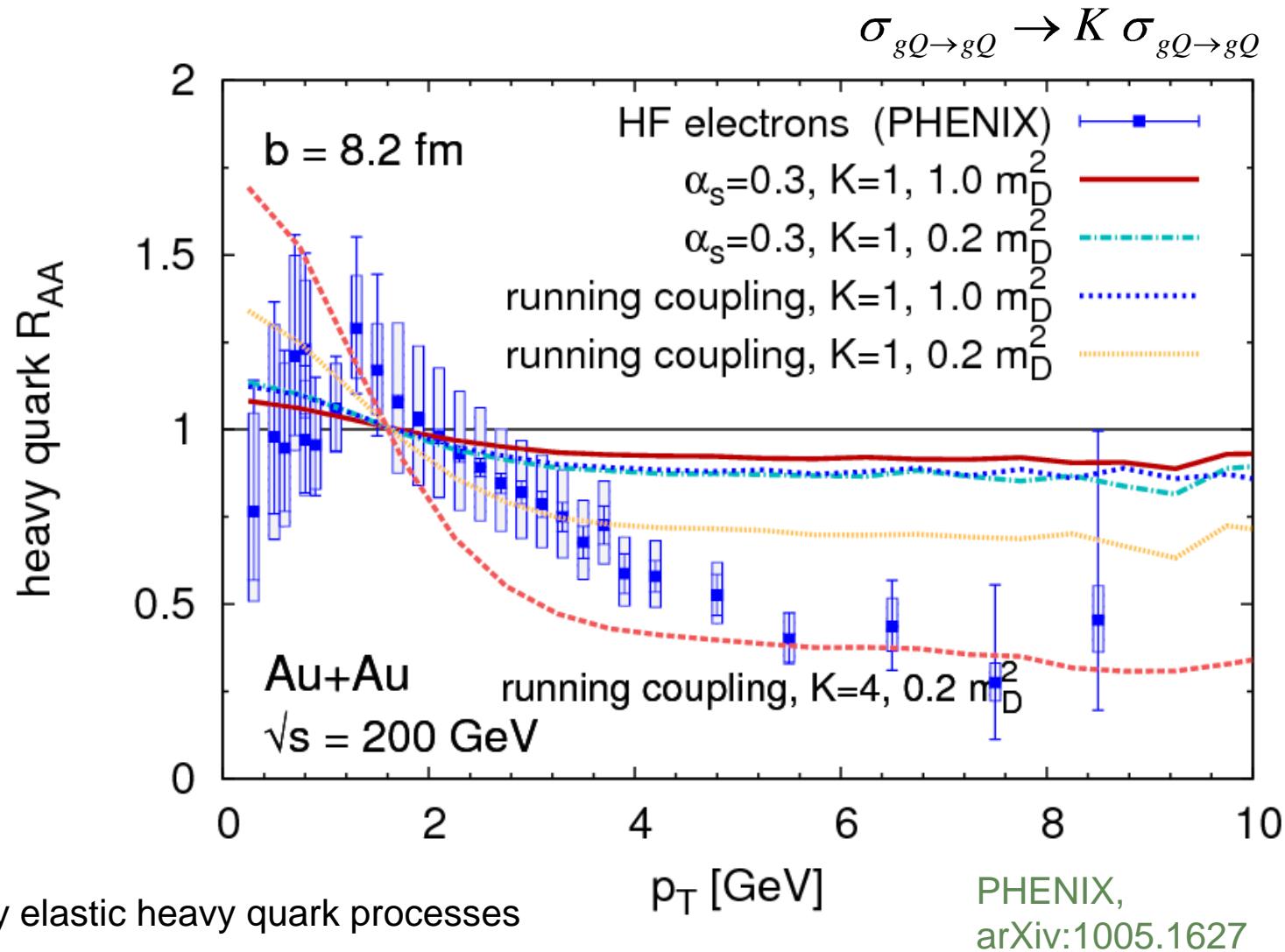
Only charm quarks (no heavy flavor electrons!) for better comparison

# D meson $R_{AA}$ at LHC with 2->3

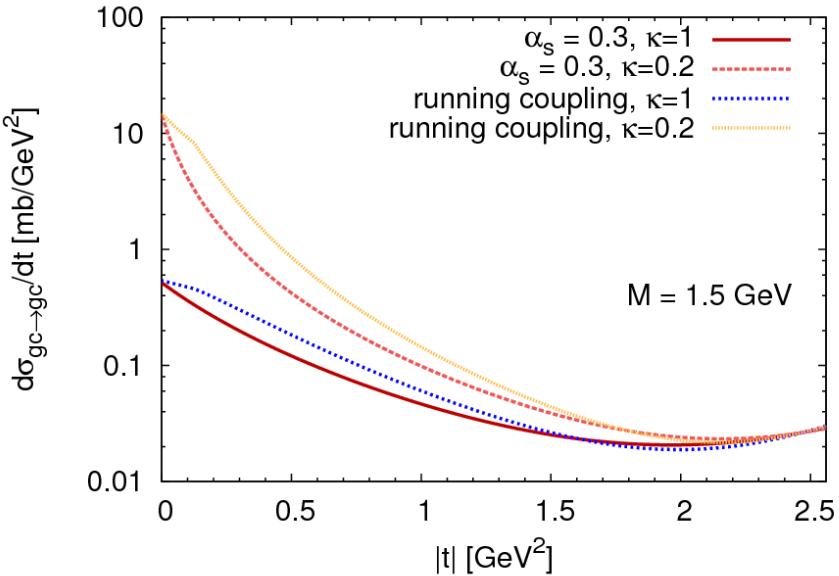
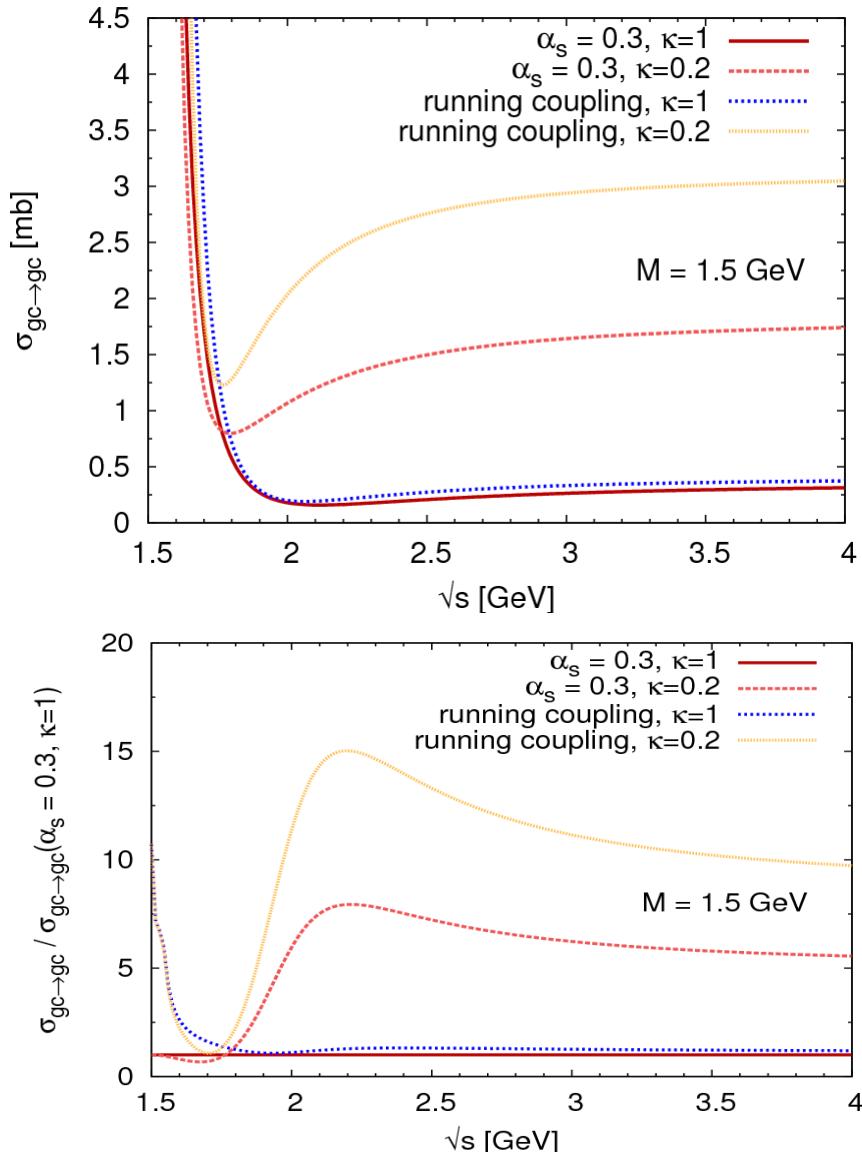


LHC

# Heavy quark $R_{AA}$ at RHIC



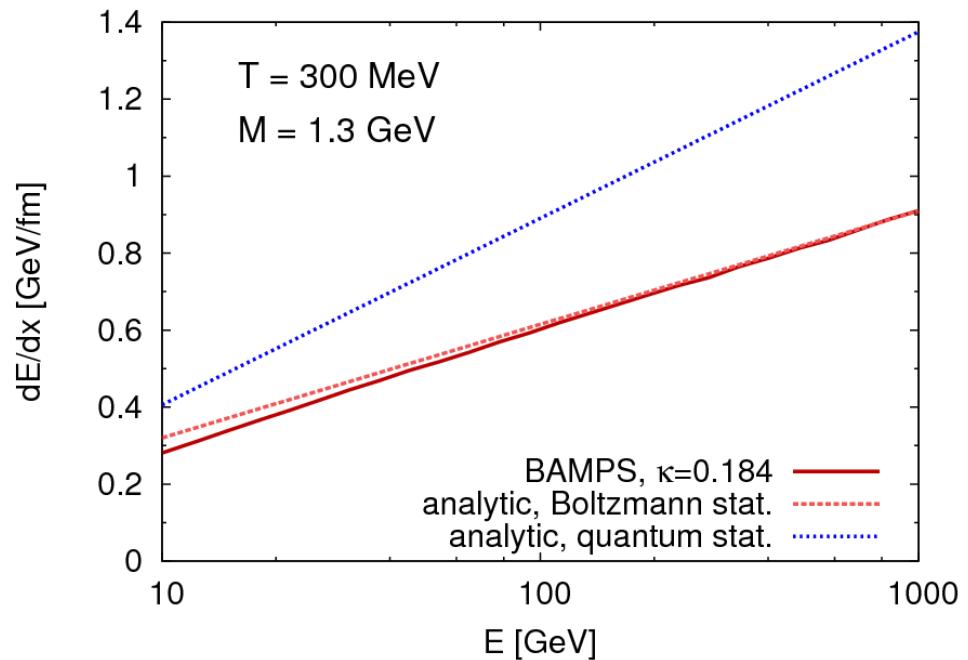
# Heavy quark scattering cross section



# Heavy quark scattering

## Compare to analytic formula

$$\frac{dE}{dx} = \frac{8\alpha_s^2 T^2}{\pi} \left[ \left(1 + \frac{n_f}{3}\right) \ln \frac{ET}{m_D^2} + \frac{2}{9} \ln \frac{ET}{M^2} \right. \\ \left. + \left(\ln 2 - \frac{1}{4} - \frac{\gamma}{3}\right) n_f \right. \\ \left. + \frac{31}{9} \ln 2 - \frac{101}{108} - \frac{11\gamma}{9} \right]$$



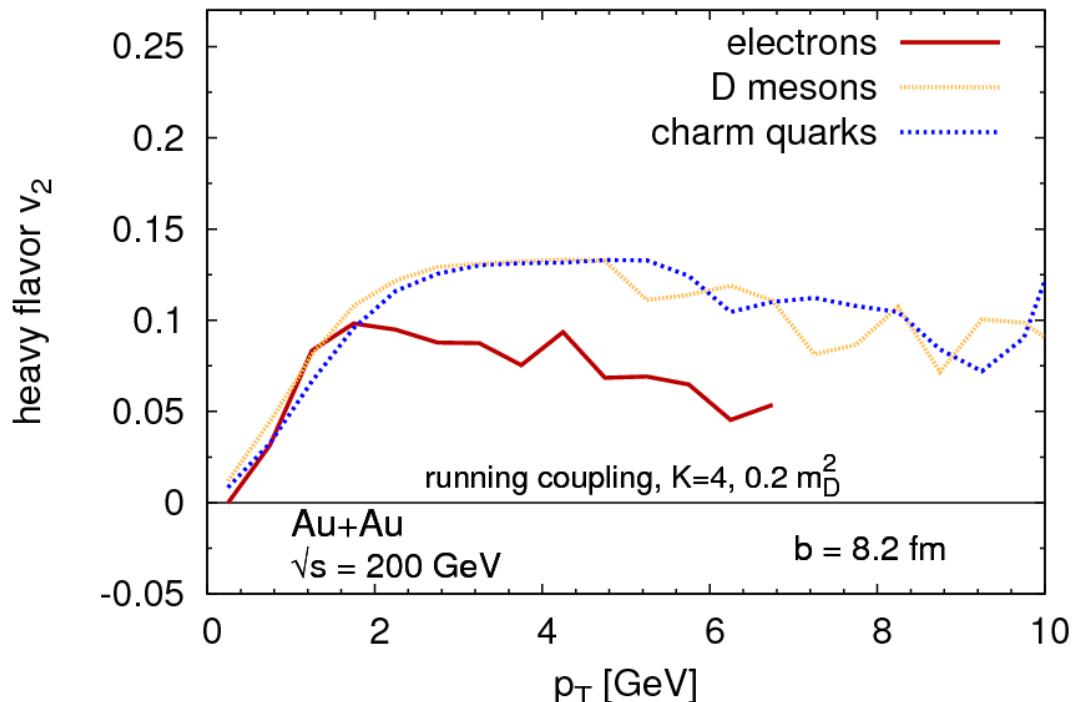
# Fragmentation and Decay

- Peterson fragmentation

Peterson et al., Phys. Rev. D27 (1983)

$$D_{H/Q}(z) = \frac{N}{z \left(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right)^2} \quad z = \frac{|\vec{p}_H|}{|\vec{p}_Q|} \quad \begin{aligned} \epsilon_c &= 0.05 \\ \epsilon_b &= 0.005 \end{aligned}$$

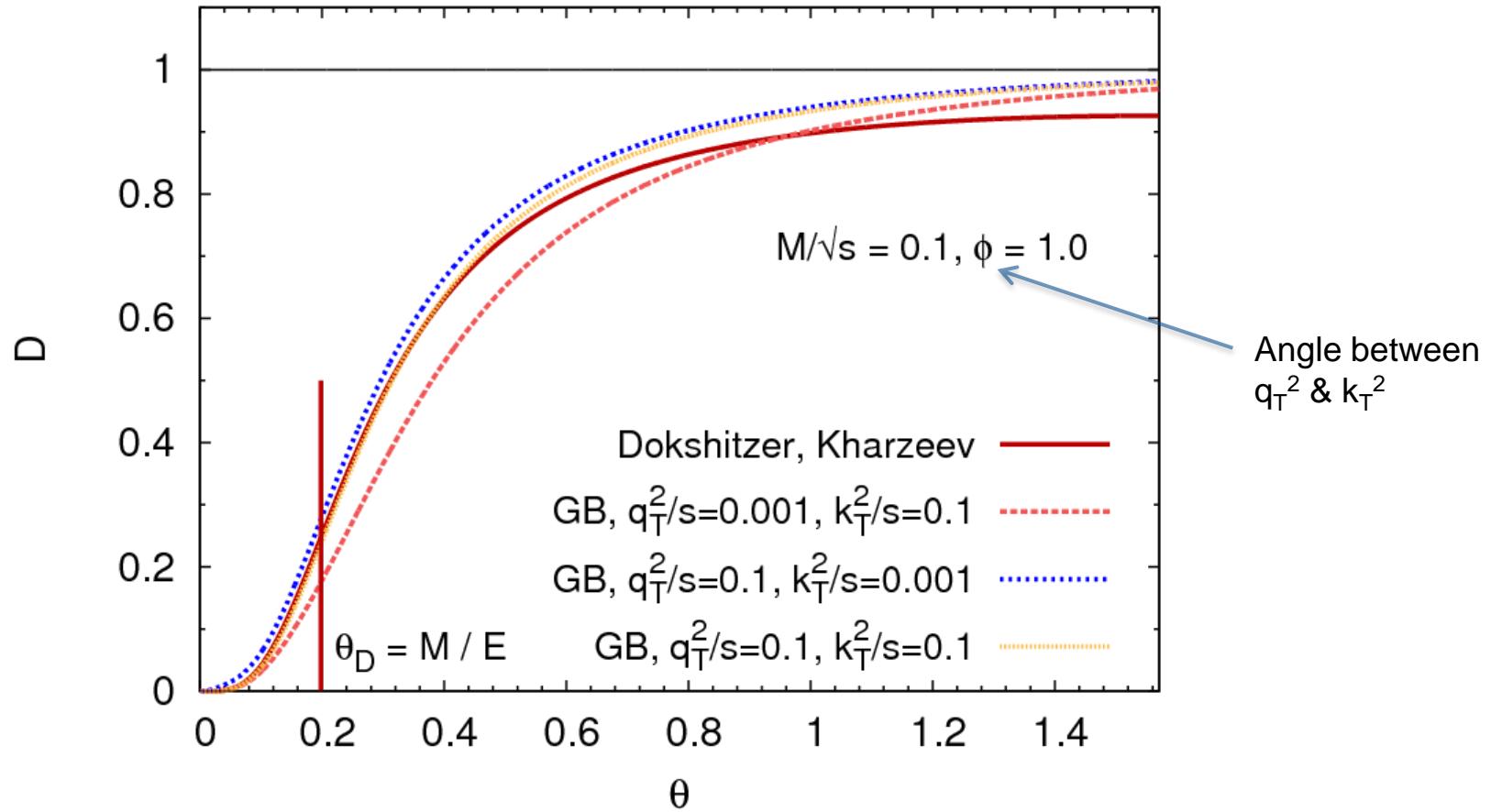
- Decay to electrons with PYTHIA



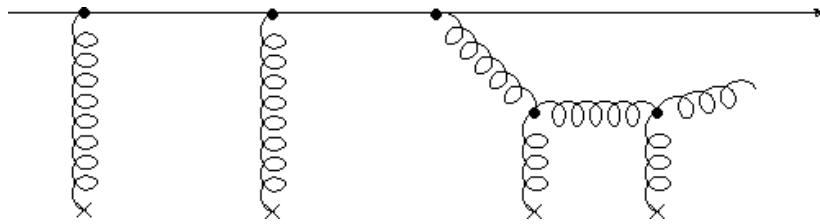
Impact of hadronization and decay small

# Dead cone effect

$$|\overline{\mathcal{M}}_{gQ \rightarrow gQg}|^2 = 12g^2 \left| \overline{\mathcal{M}}_0^{gQ} \right|^2 \left[ \frac{\mathbf{k}_\perp}{k_\perp^2 + x^2 M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + x^2 M^2} \right]^2$$



# LPM effect

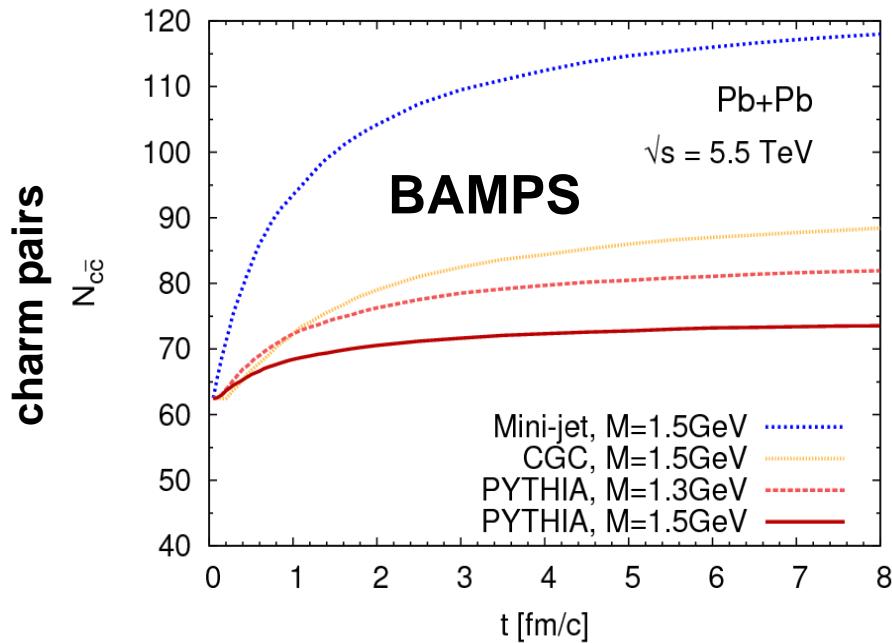


$$\lambda > \tau$$

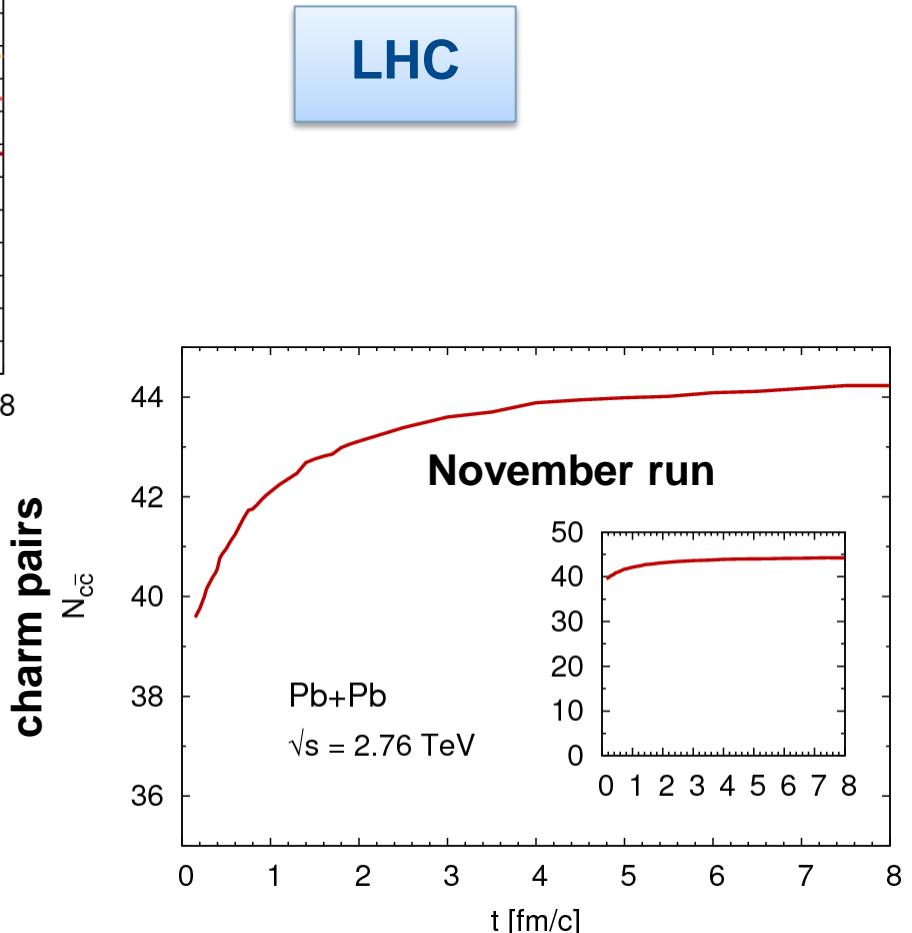
$2 \rightarrow 3$  only allowed if mean free path of jet larger than formation time of radiated gluon

→ Bethe-Heitler regime, independent scatterings

# Charm production in the QGP at LHC

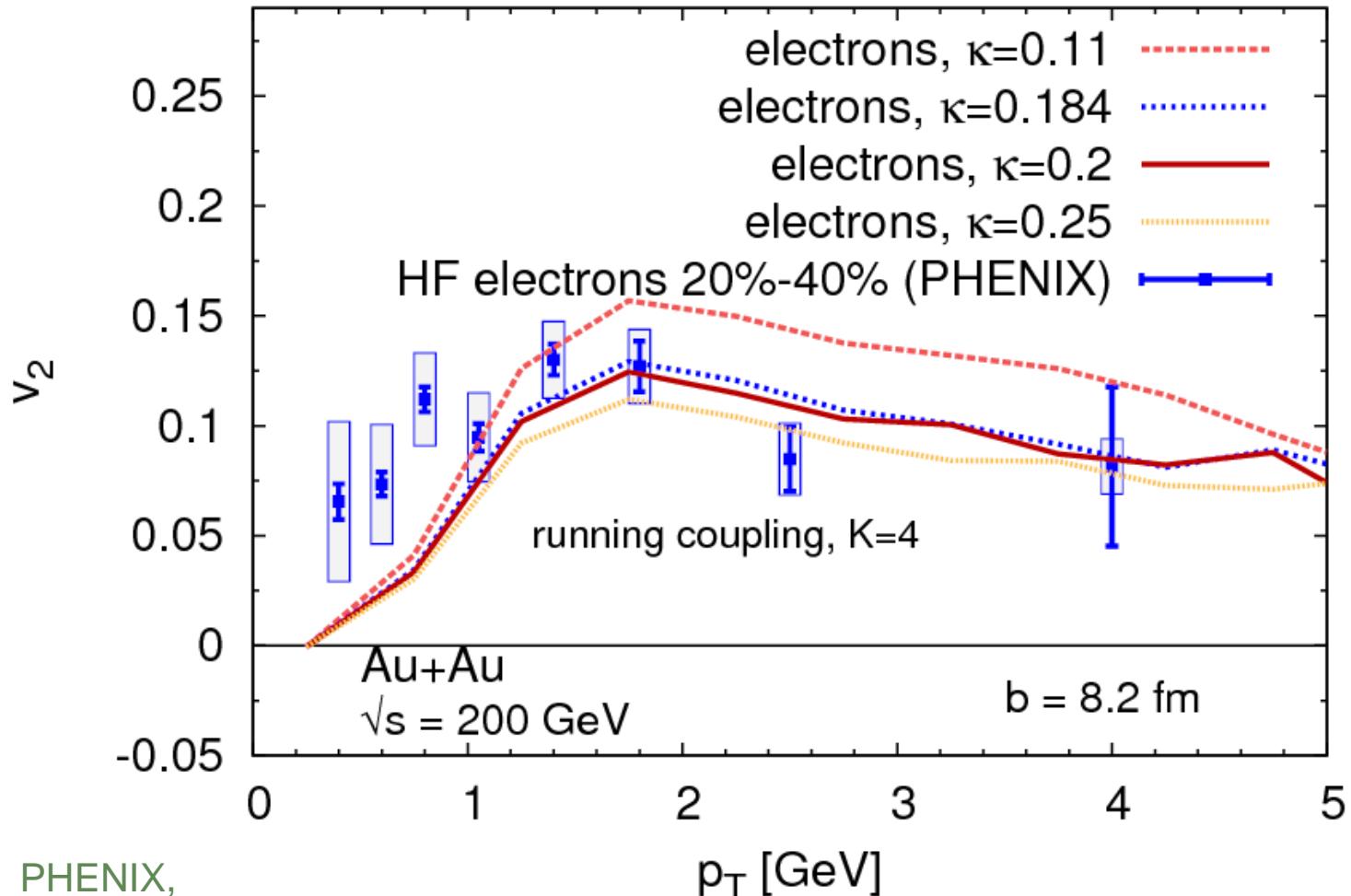


**Large secondary production**  
 → Can even be comparable to initial production



JU, Fochler, Xu, Greiner  
 Phys. Rev. C 82 (2010)

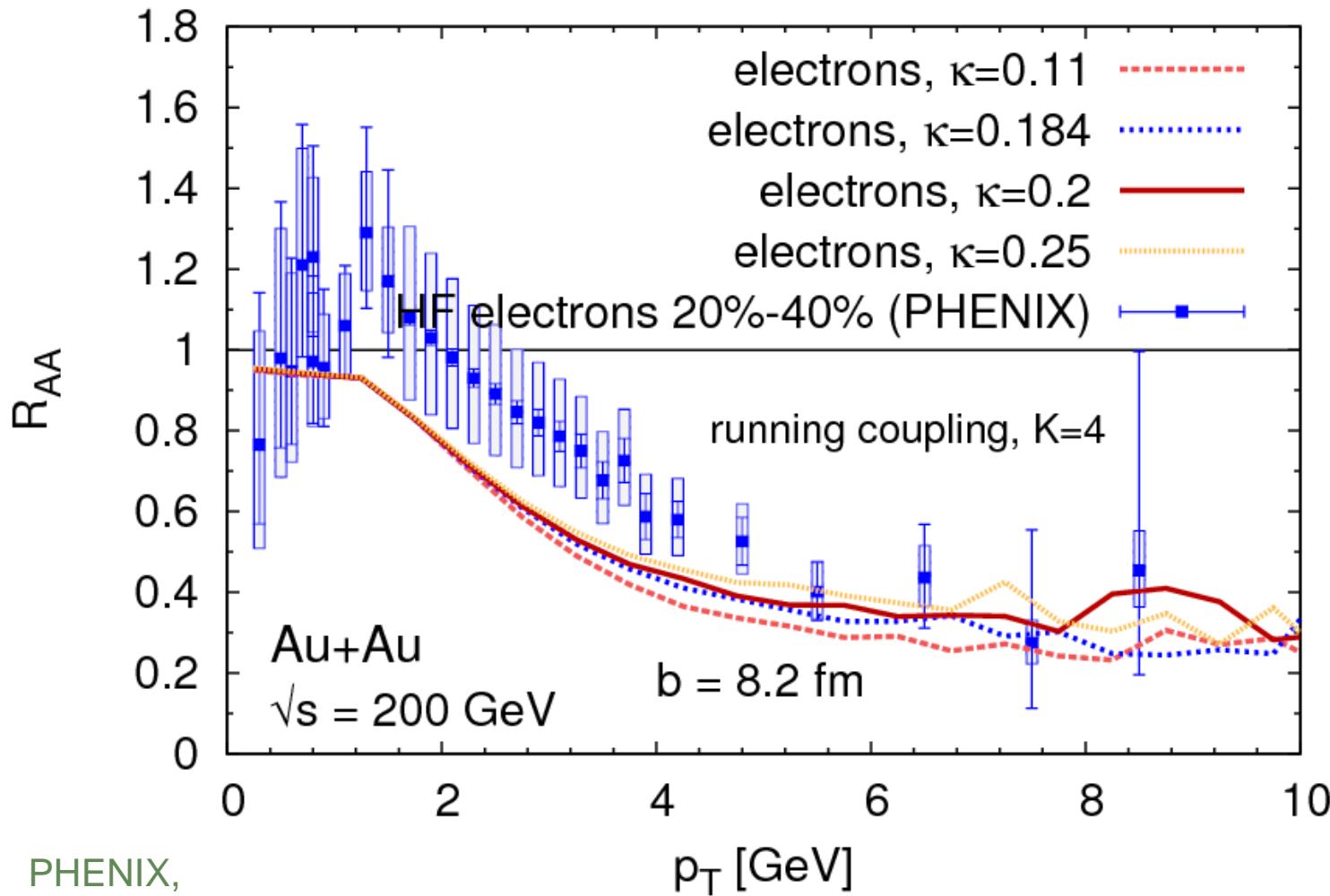
# Heavy quark elliptic flow $v_2$ at RHIC



RHIC

PHENIX,  
arXiv:1005.1627

# Heavy quark elliptic flow $v_2$ at RHIC

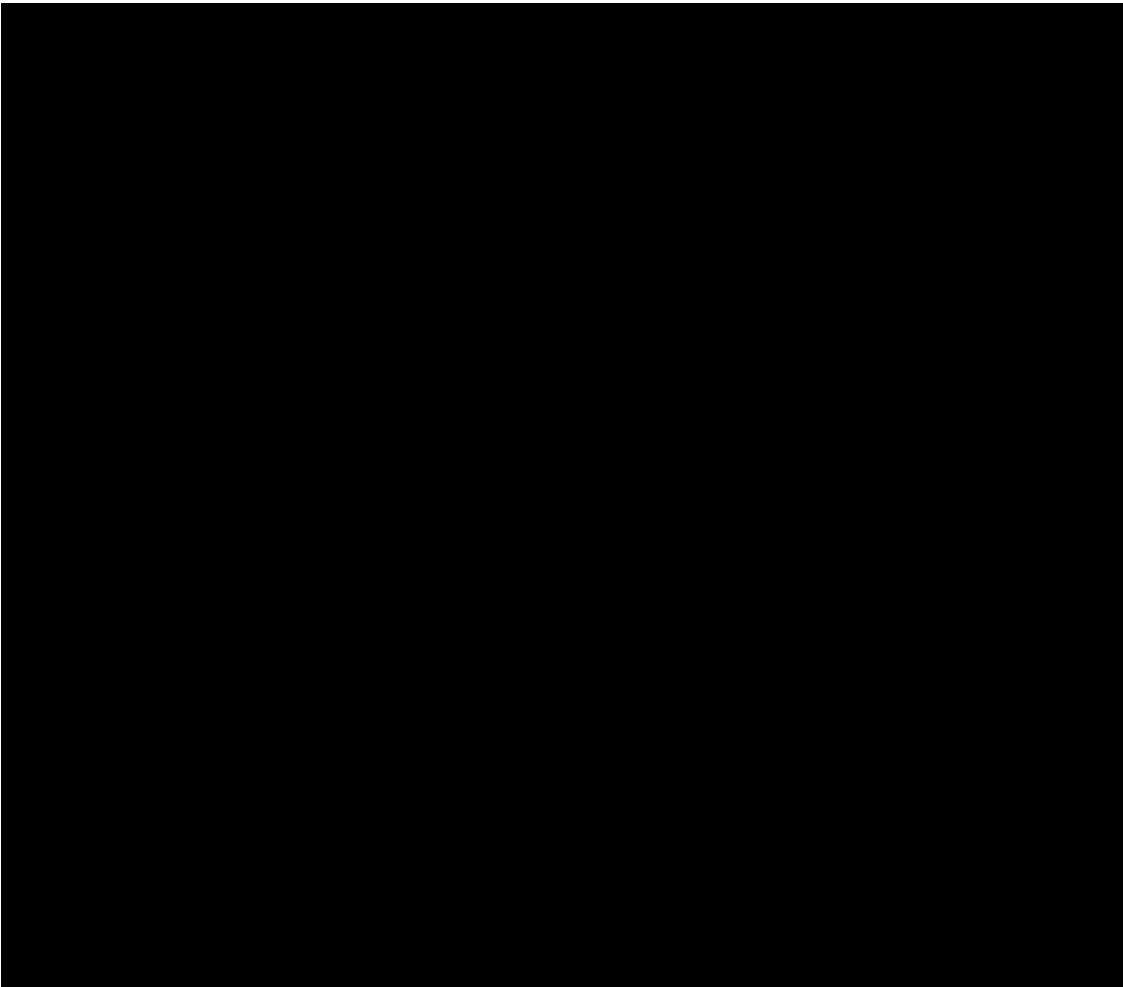


**RHIC**

PHENIX,  
arXiv:1005.1627

# Heavy-ion collision at LHC

BAMPS simulation of QGP phase at LHC at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$



Visualization framework  
courtesy MADAI  
collaboration, funded by  
the NSF under grant# NSF-  
PHY-09-41373