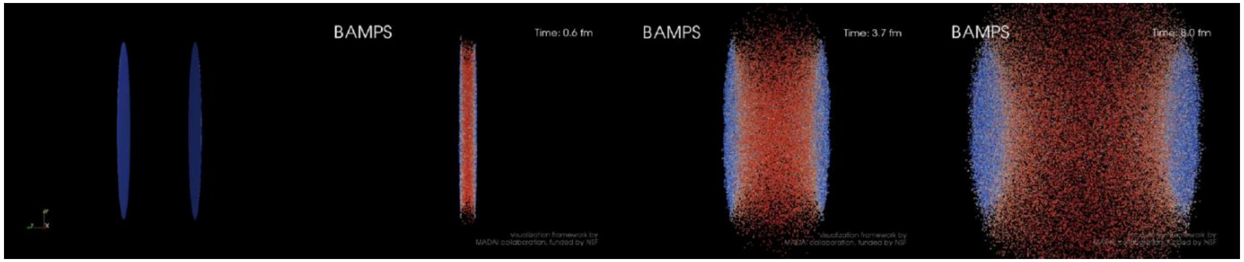
Heavy flavor at RHIC and LHC in a partonic transport model

Jan Uphoff

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

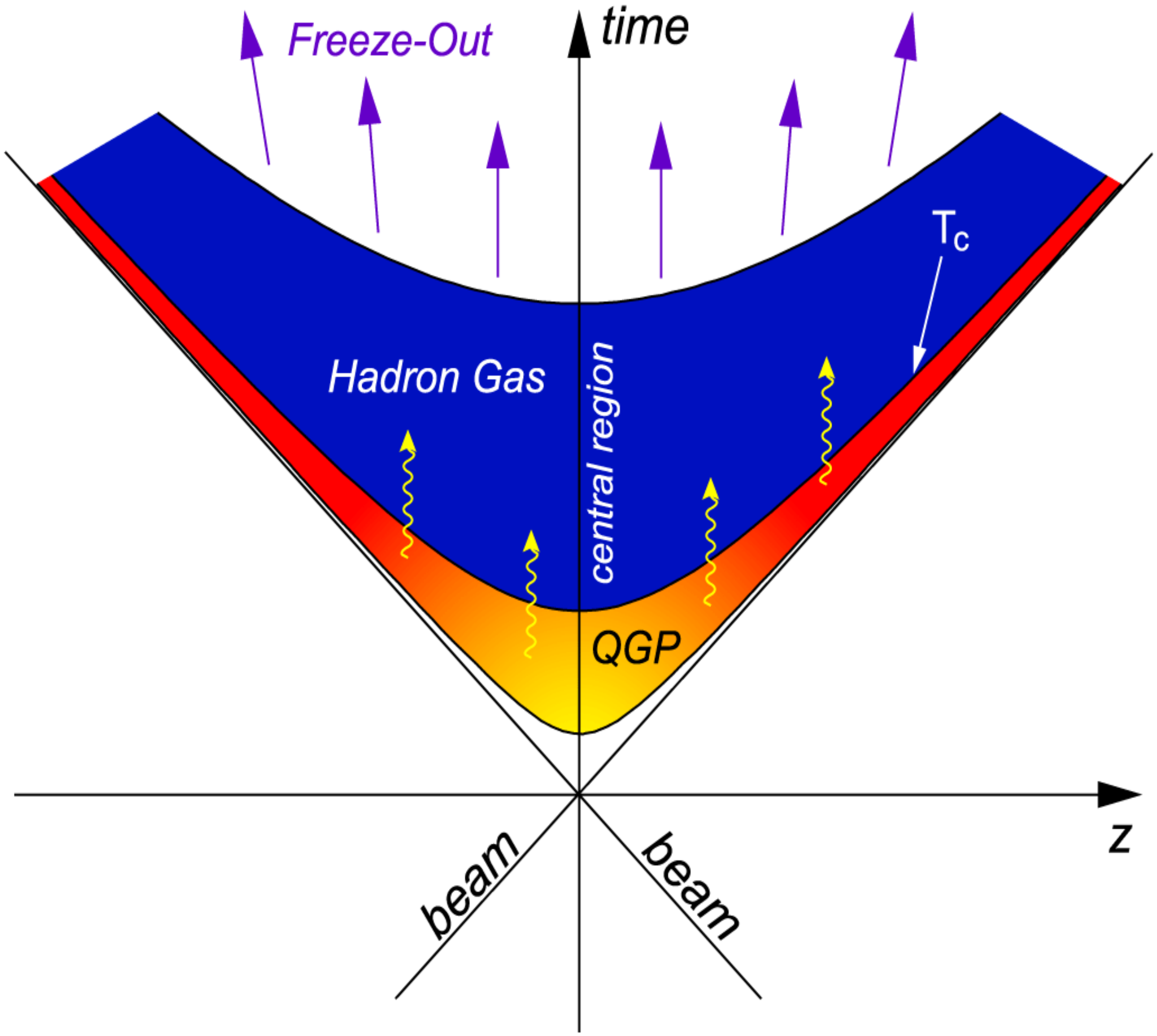
Based on arXiv:1104.2295 and 1104.2437



Hirschegg 2012: Facets of Strong-Interaction Physics

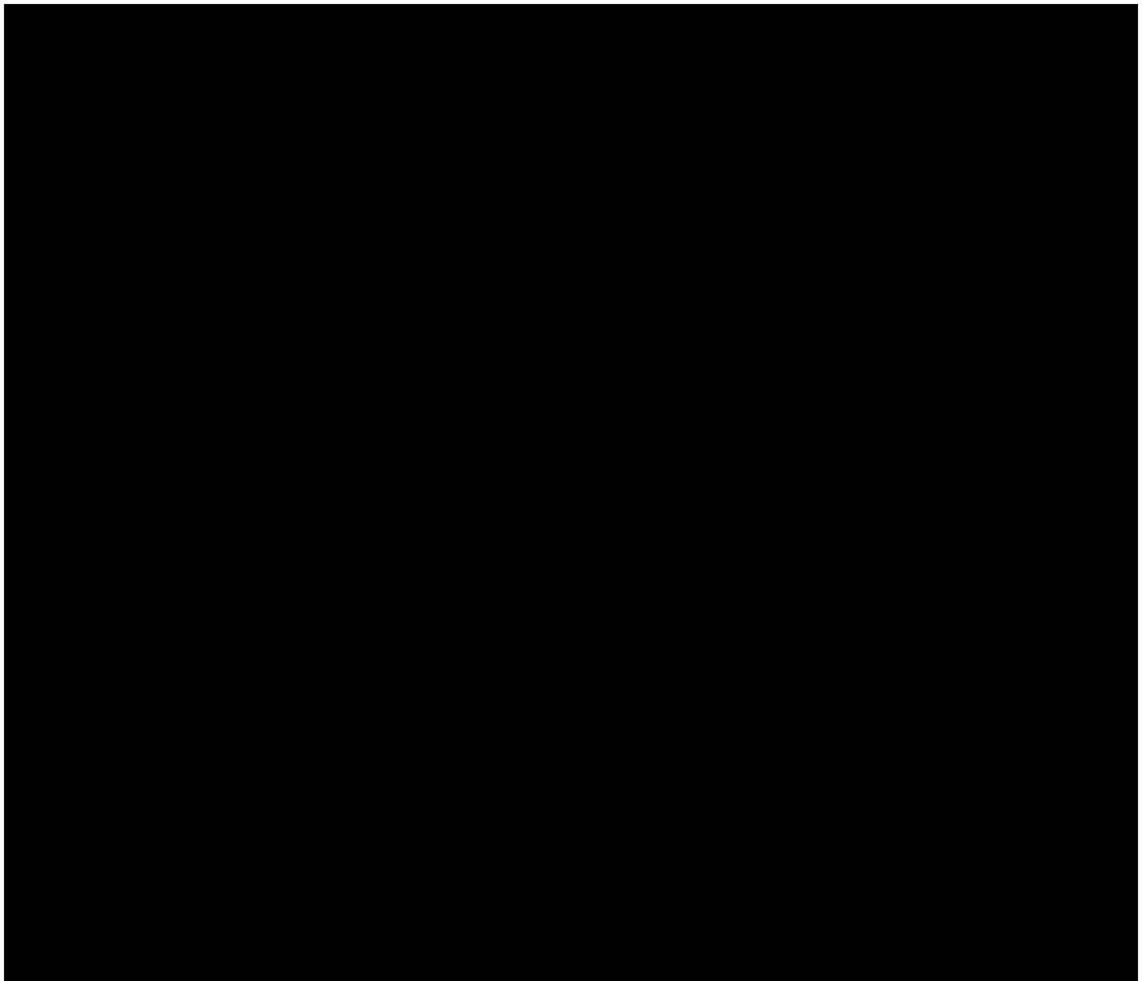
17 January 2012

Ultrarelativistic heavy ion collision



Heavy-ion collision at LHC

BAMPS simulation of QGP phase at LHC at s_{NN} = 2.76 TeV



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

Heavy quarks in heavy-ion collisions

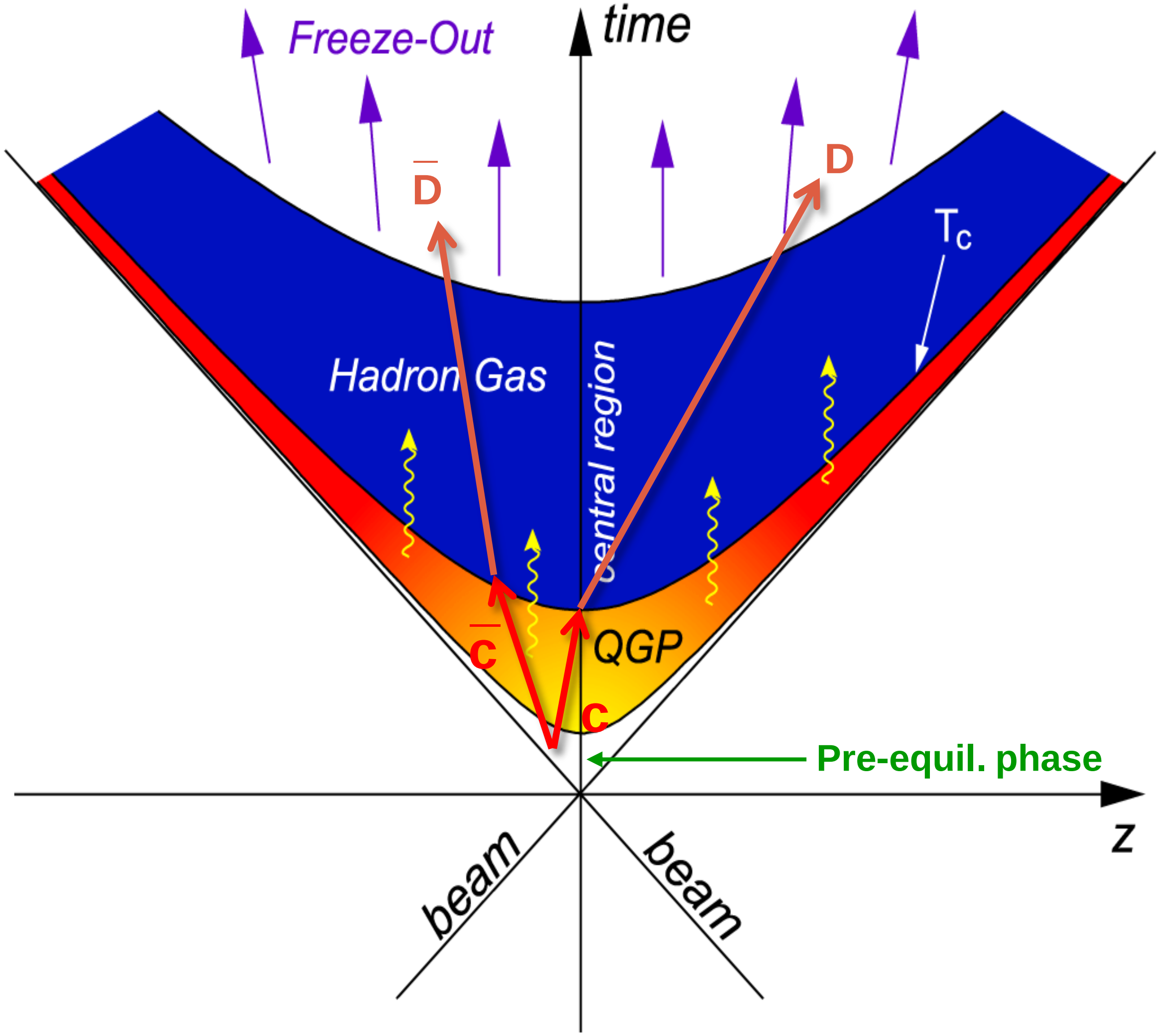
Large heavy quark mass $\gg \Lambda_{QCD}$

Charm: $M_c \approx 1.5$ GeV

Bottom: $M_b \approx 4.75$ GeV

➡ Heavy quark production at early stage of collision

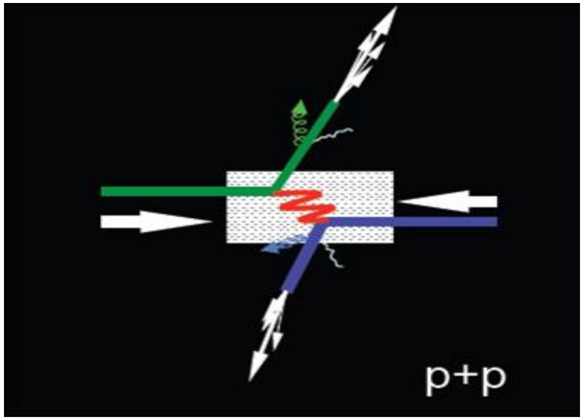
➡ ideal probe for this stage

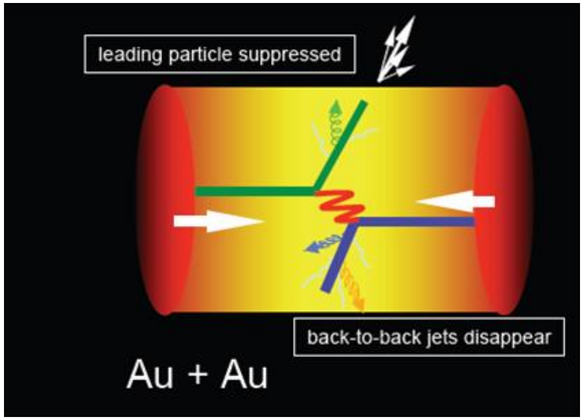


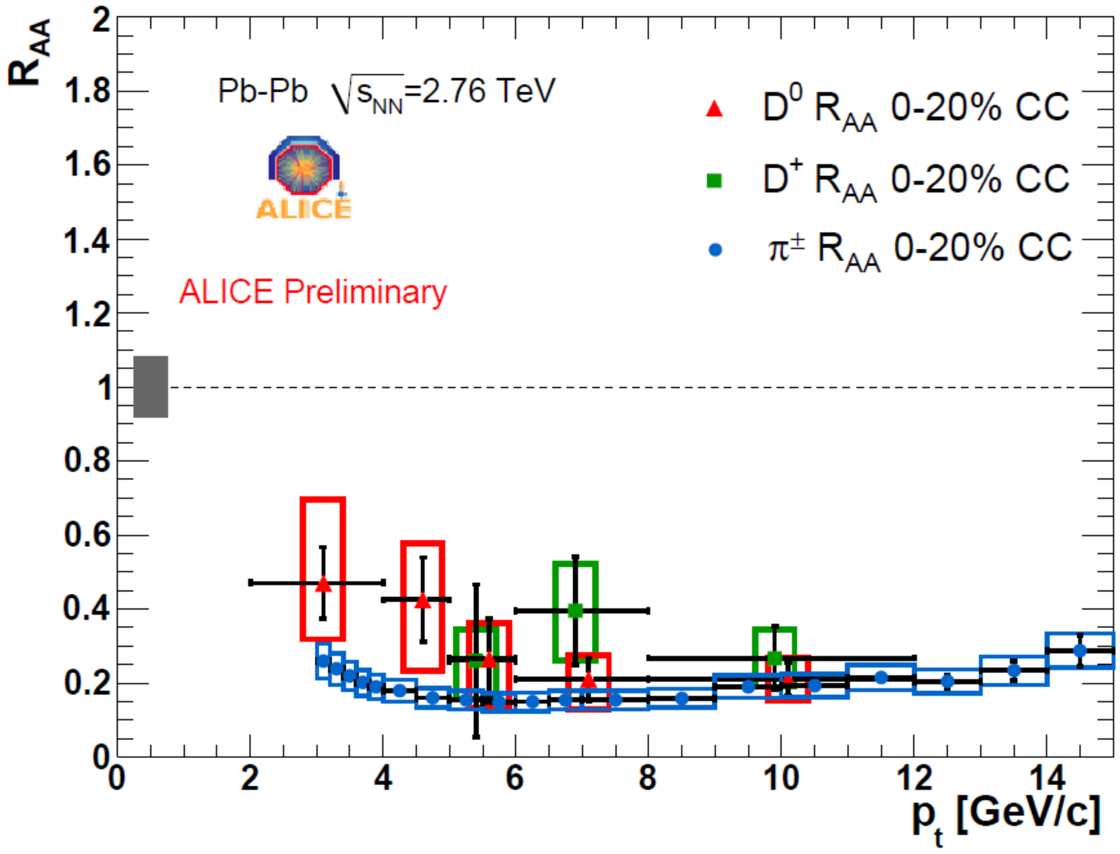
Motivation

Nuclear modification factor

$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T\mathrm{d}y|_{A+A}}{N_{\mathrm{bin}}\,\mathrm{d}N/\mathrm{d}p_T\mathrm{d}y|_{p+p}}$$





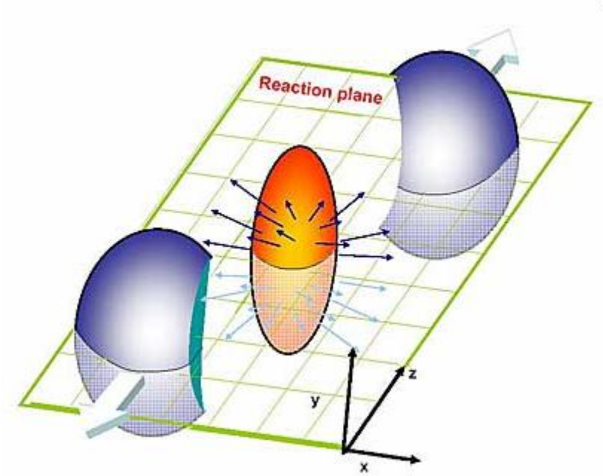


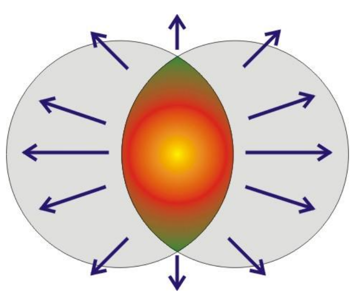
Motivation

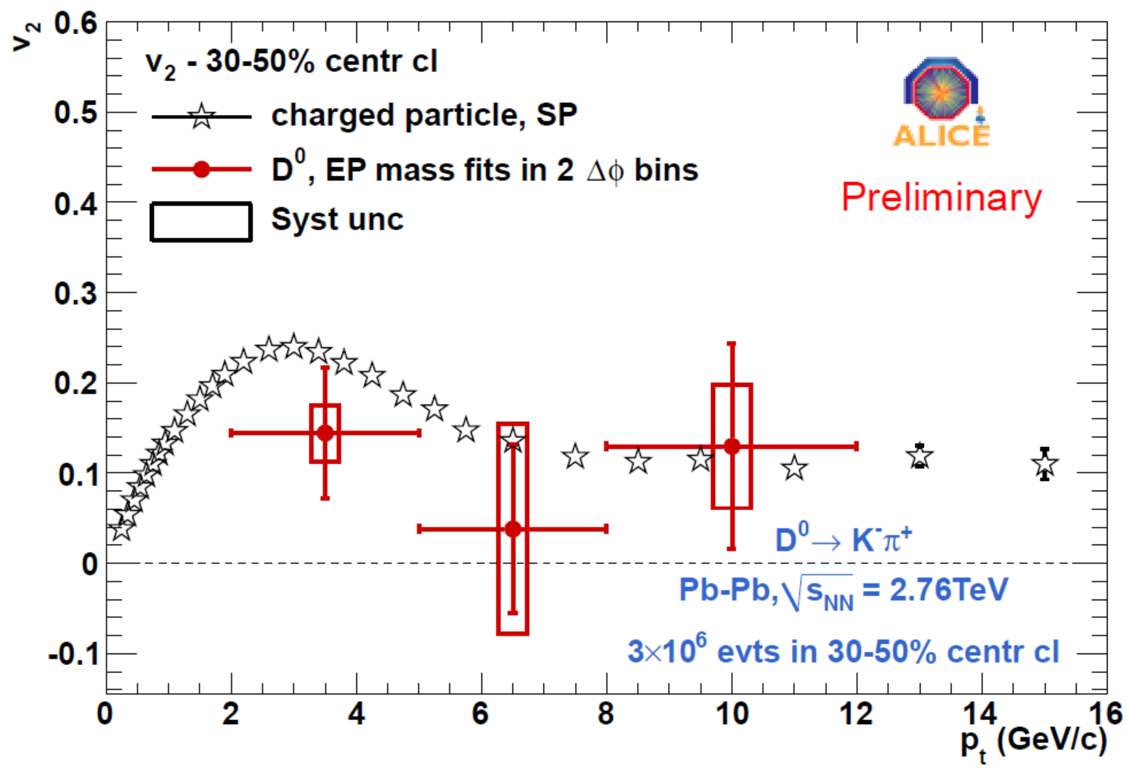
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

Elliptic flow

$$\frac{d^3N}{p_T dp_T dy d\phi}(p_T, y, \phi) = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2v_2(p_T, y)\cos(2\phi) + \ldots\right]$$







BAMPS

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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**

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

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

Implemented processes:

$$g + g \to g + g$$
$$g + g \to g + g + g$$
$$g + g + g \to g + g$$

Light quarks have been implemented but are not included in the present calculation

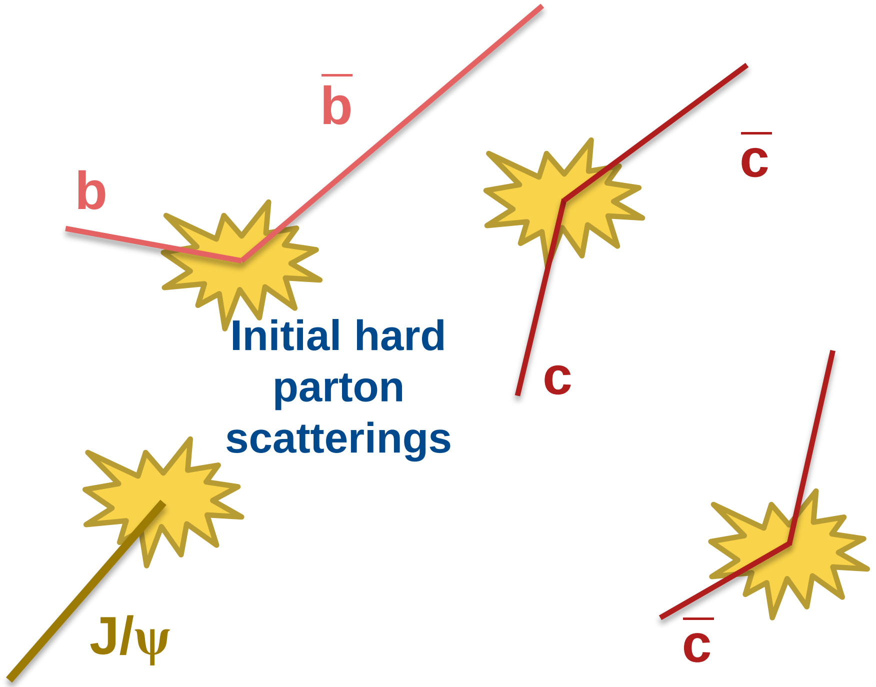
$$g + g \to Q + \bar{Q}$$
$$Q + \bar{Q} \to g + g$$
$$g + Q \to g + Q$$
$$g + \bar{Q} \to g + \bar{Q}$$
$$g + J/\psi \to c + \bar{c}$$
$$c + \bar{c} \to g + J/\psi$$

Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS

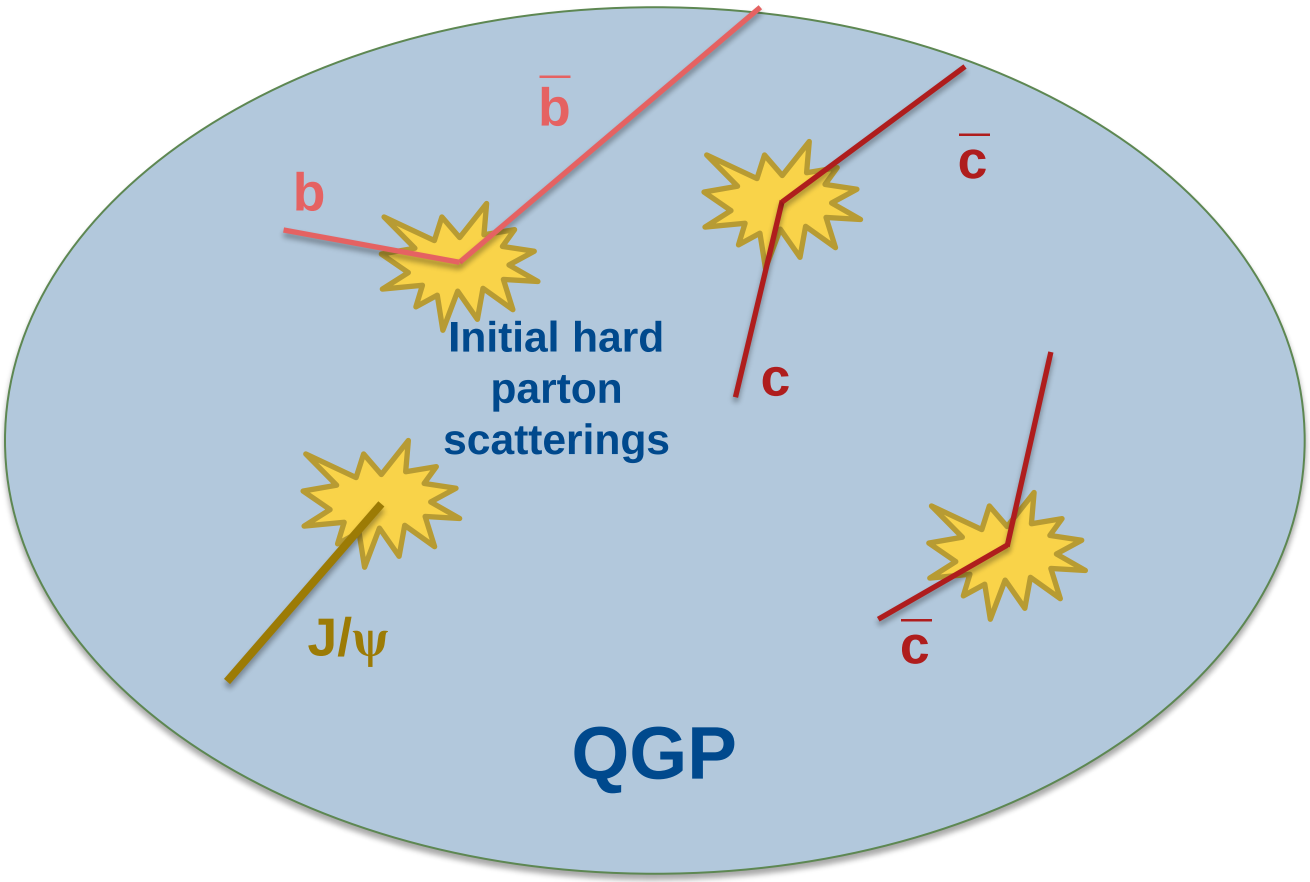
Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS



Sketch of heavy-ion collision in BAMPS

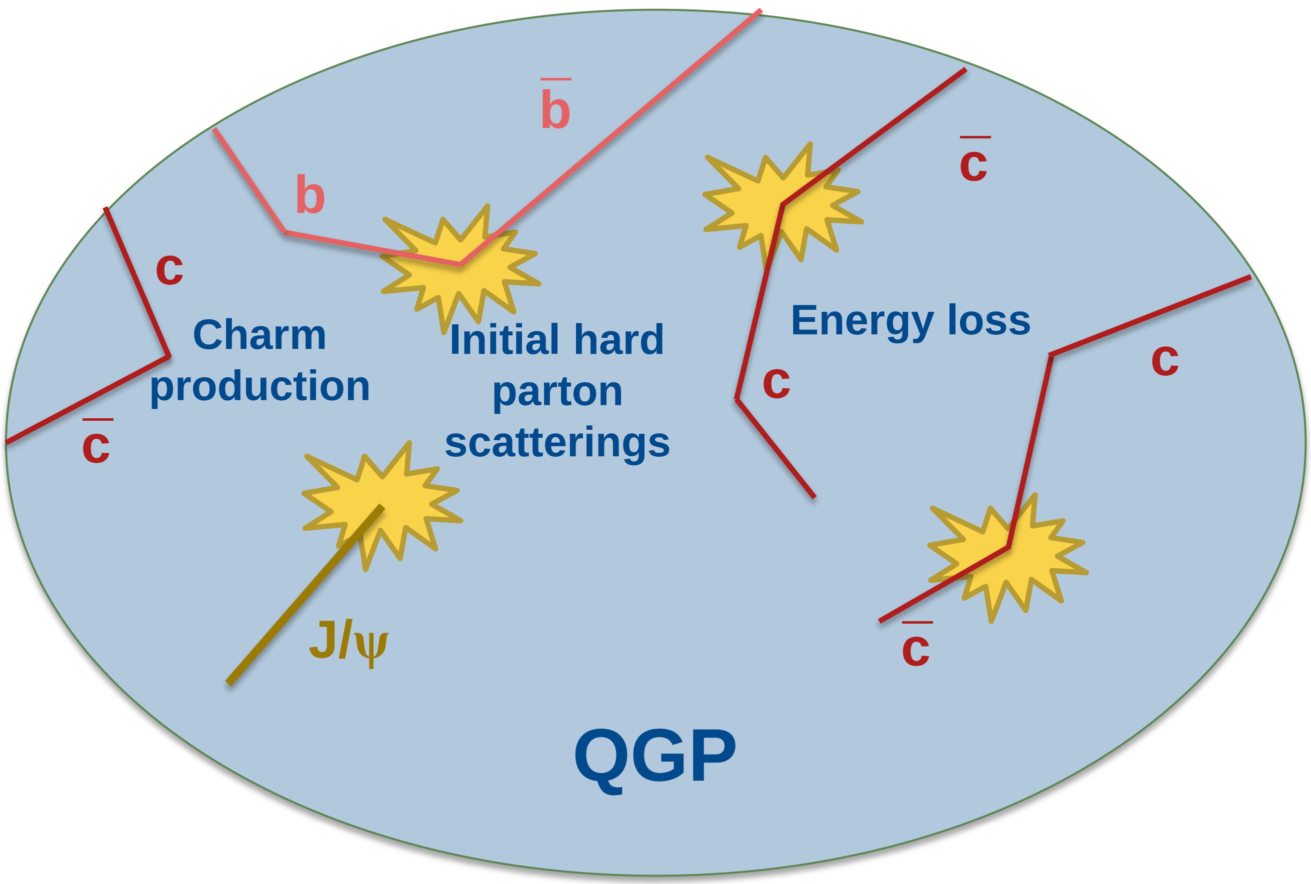
Heavy flavor in BAMPS



Sketch of heavy-ion collision in BAMPS

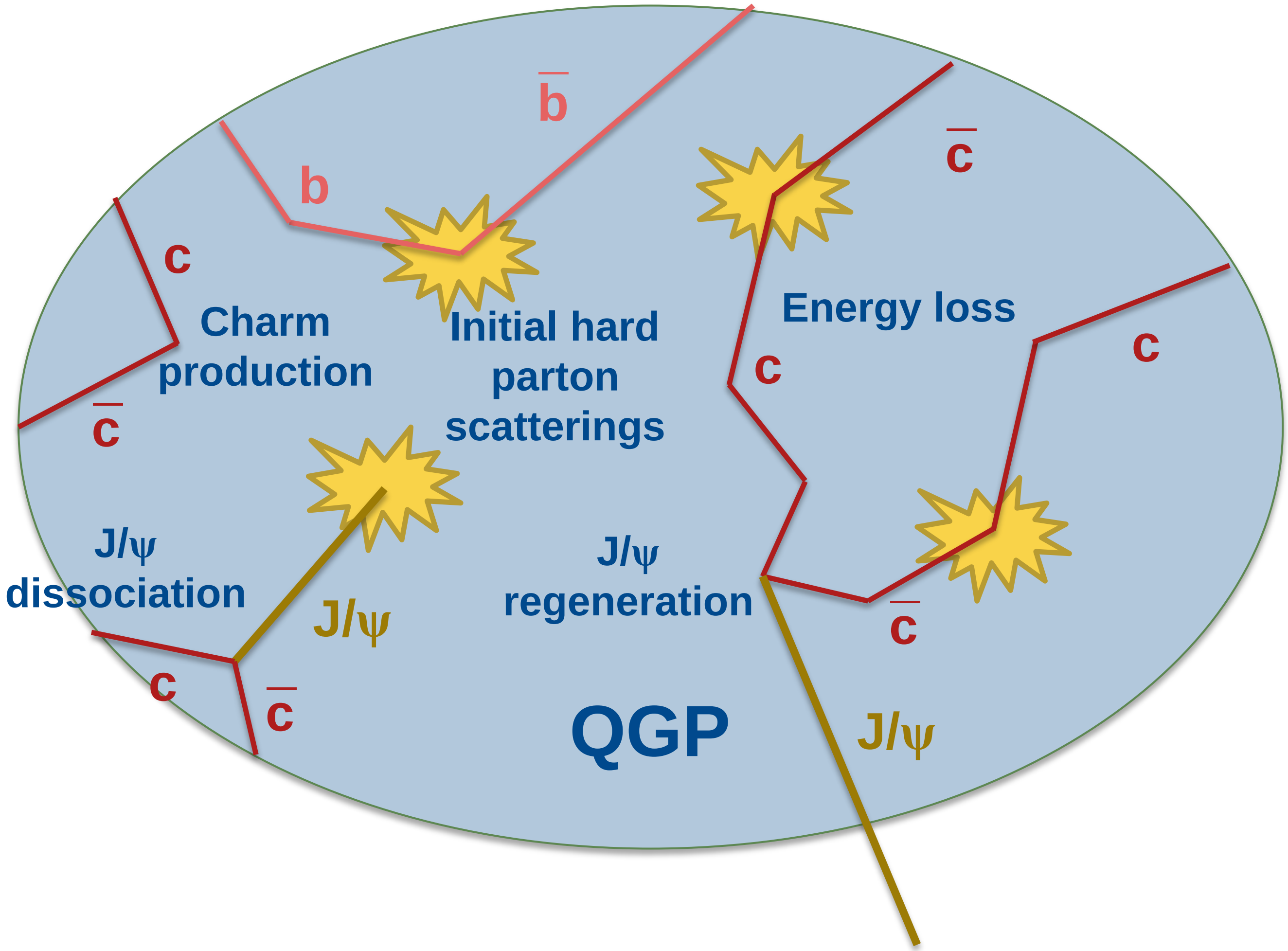
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Heavy flavor in BAMPS



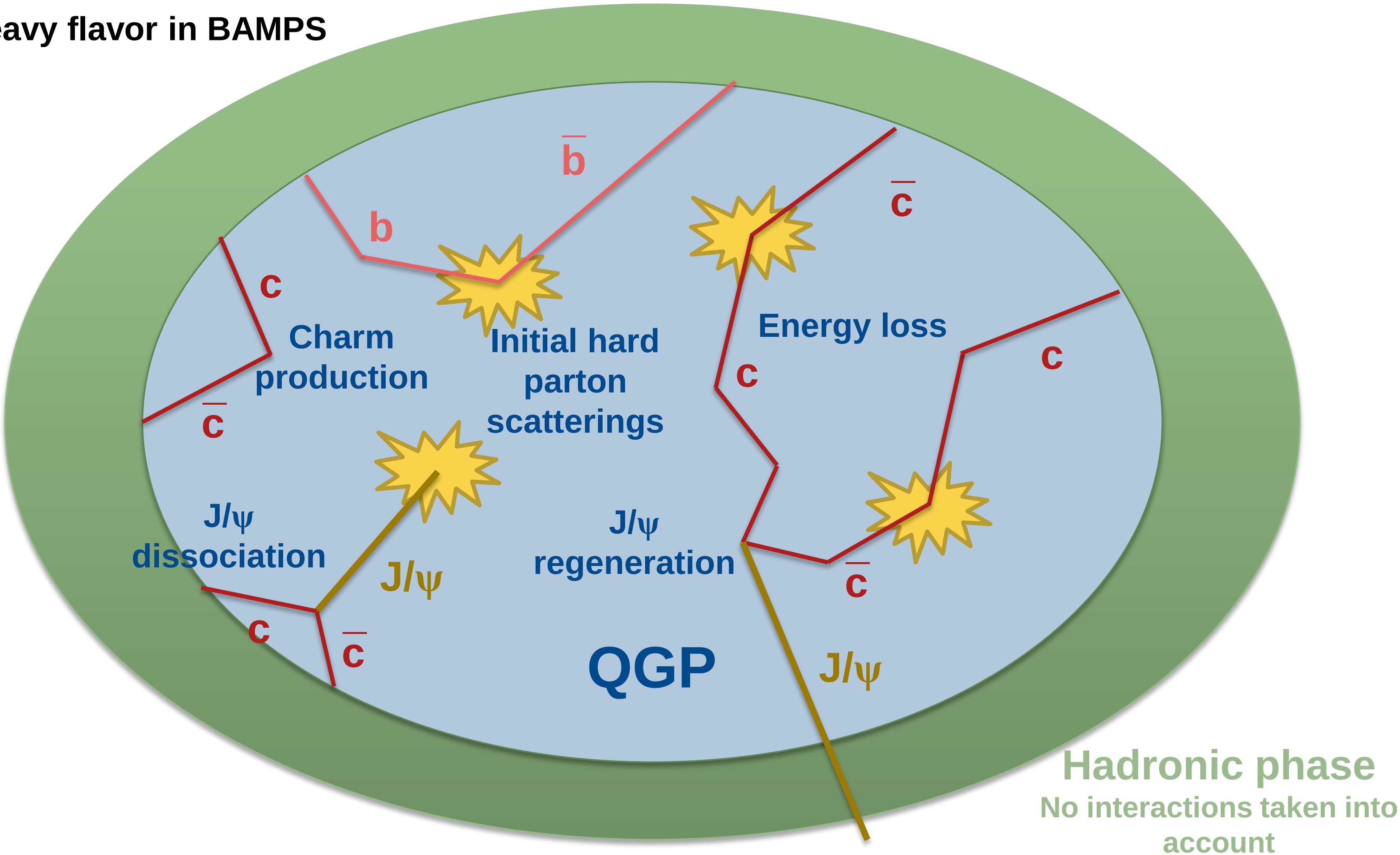
Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS



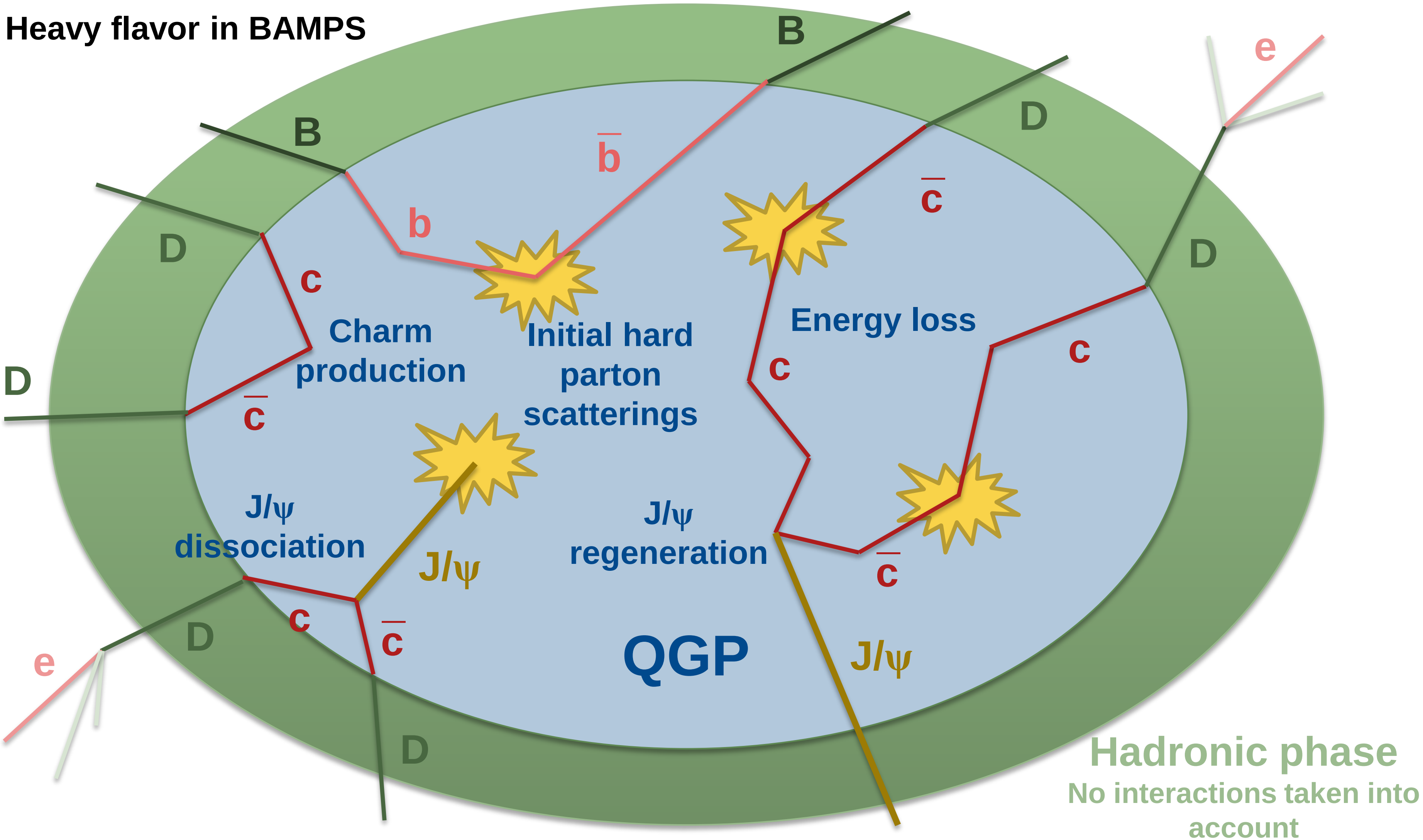
Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS



Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS

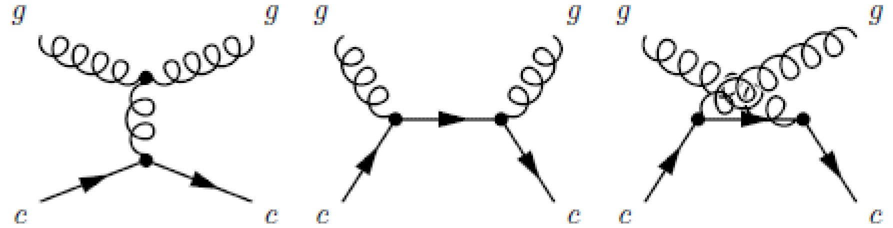


Heavy quark scattering

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Leading order perturbative QCD:

$$g + Q \to g + Q$$
$$g + \bar{Q} \to g + \bar{Q}$$



t channel is divergent for small t

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

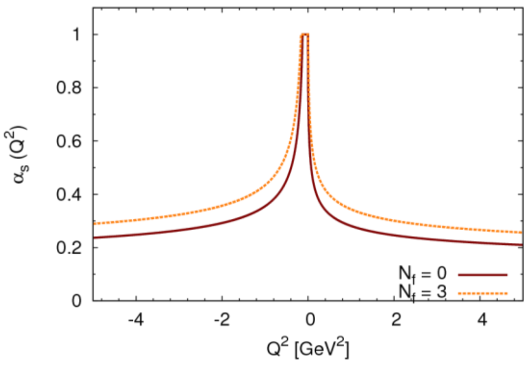
κ **can be fixed to**

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

by comparing dE/dx to HTL result beyond logarithmic accuracy

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

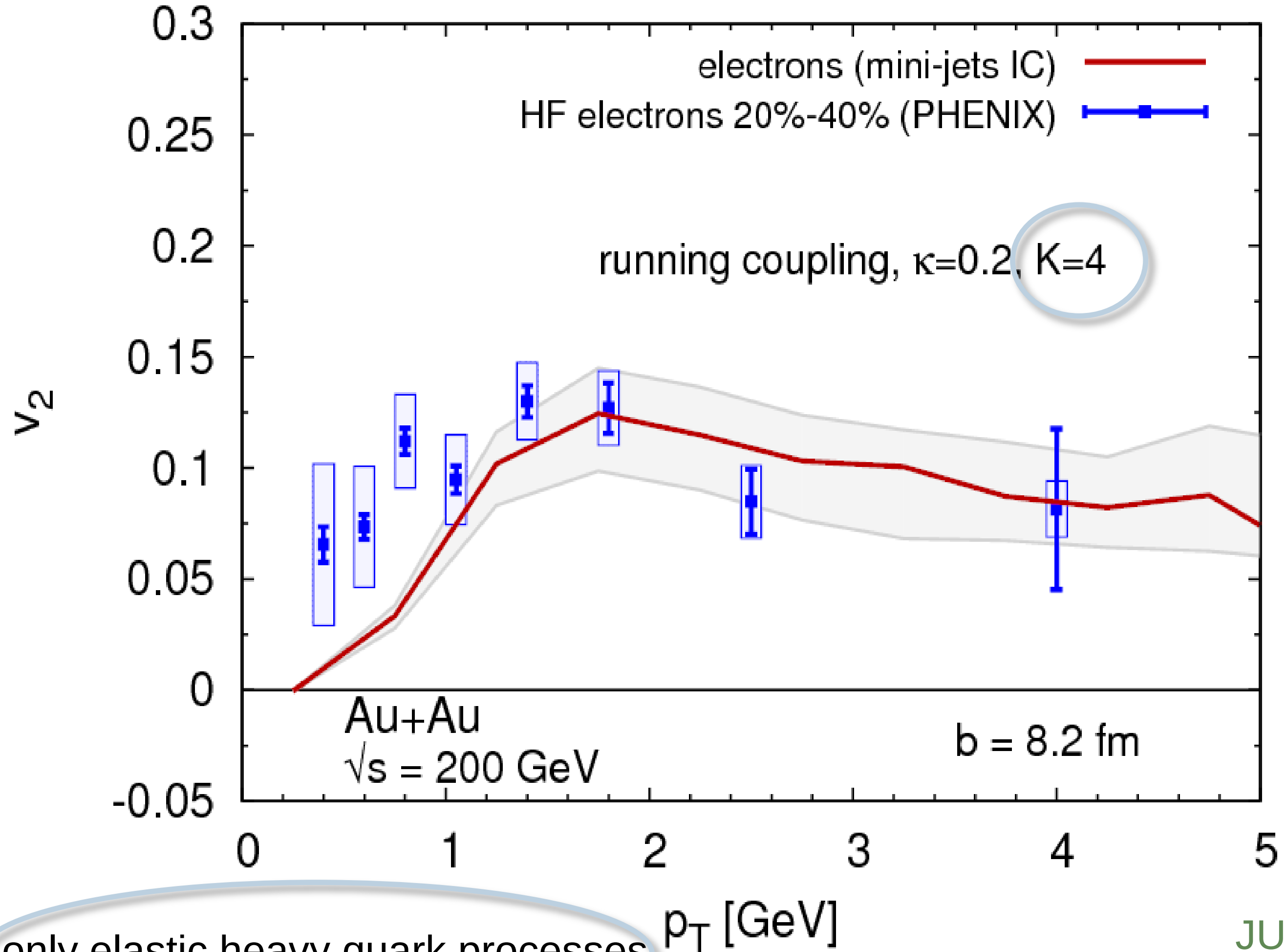
P.B. Gossiaux, J. Aichelin, Phys.Rev.C78 (2008)



Introduce a running coupling constant for all channels

Heavy quark elliptic flow v_2 at RHIC

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



only elastic heavy quark processes

RHIC

What is missing:

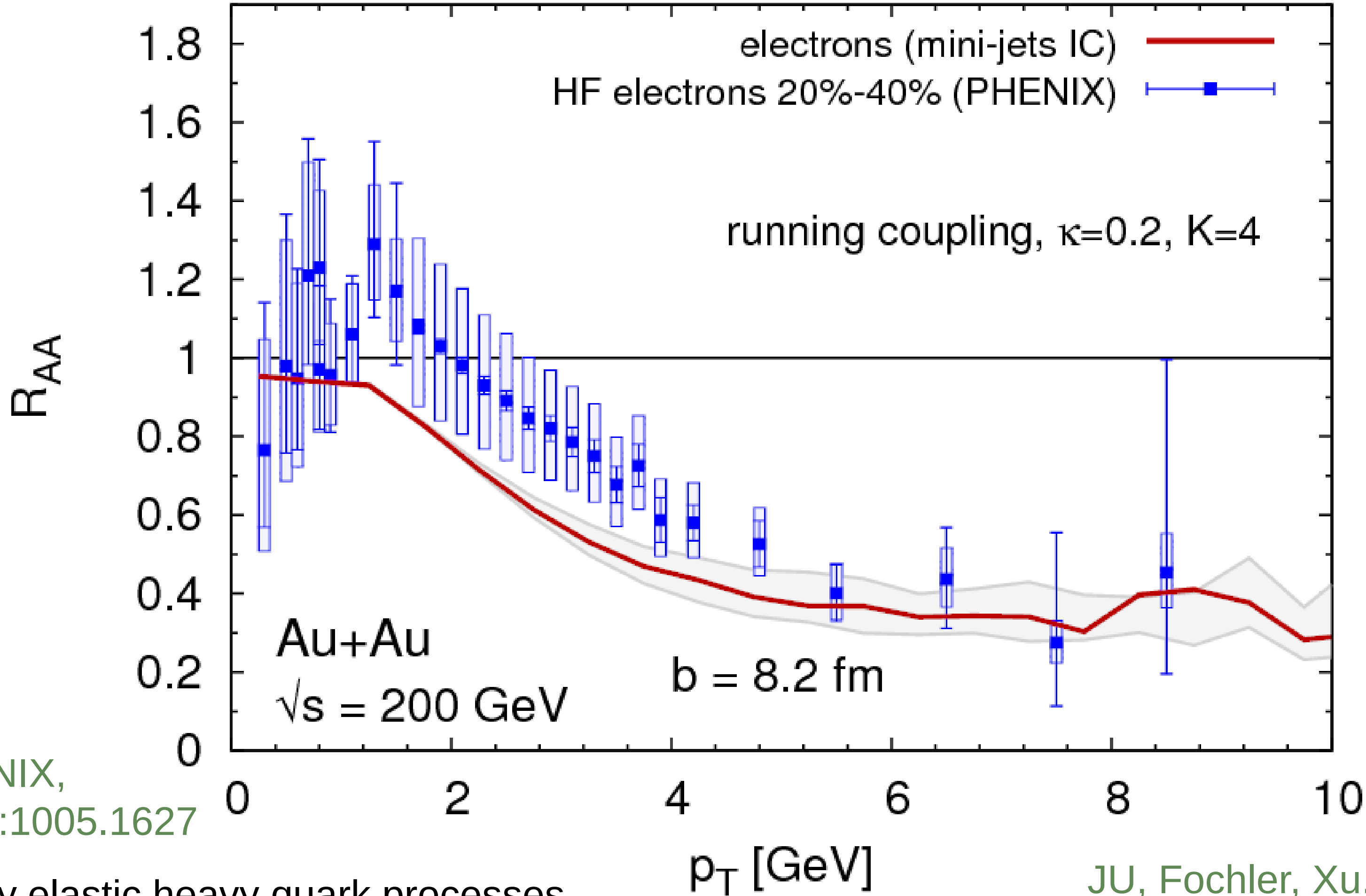
- **Radiative contributions**
- **Quantum statistics**

PHENIX, arXiv:1005.1627

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

Heavy quark R_{AA} at RHIC

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



RHIC

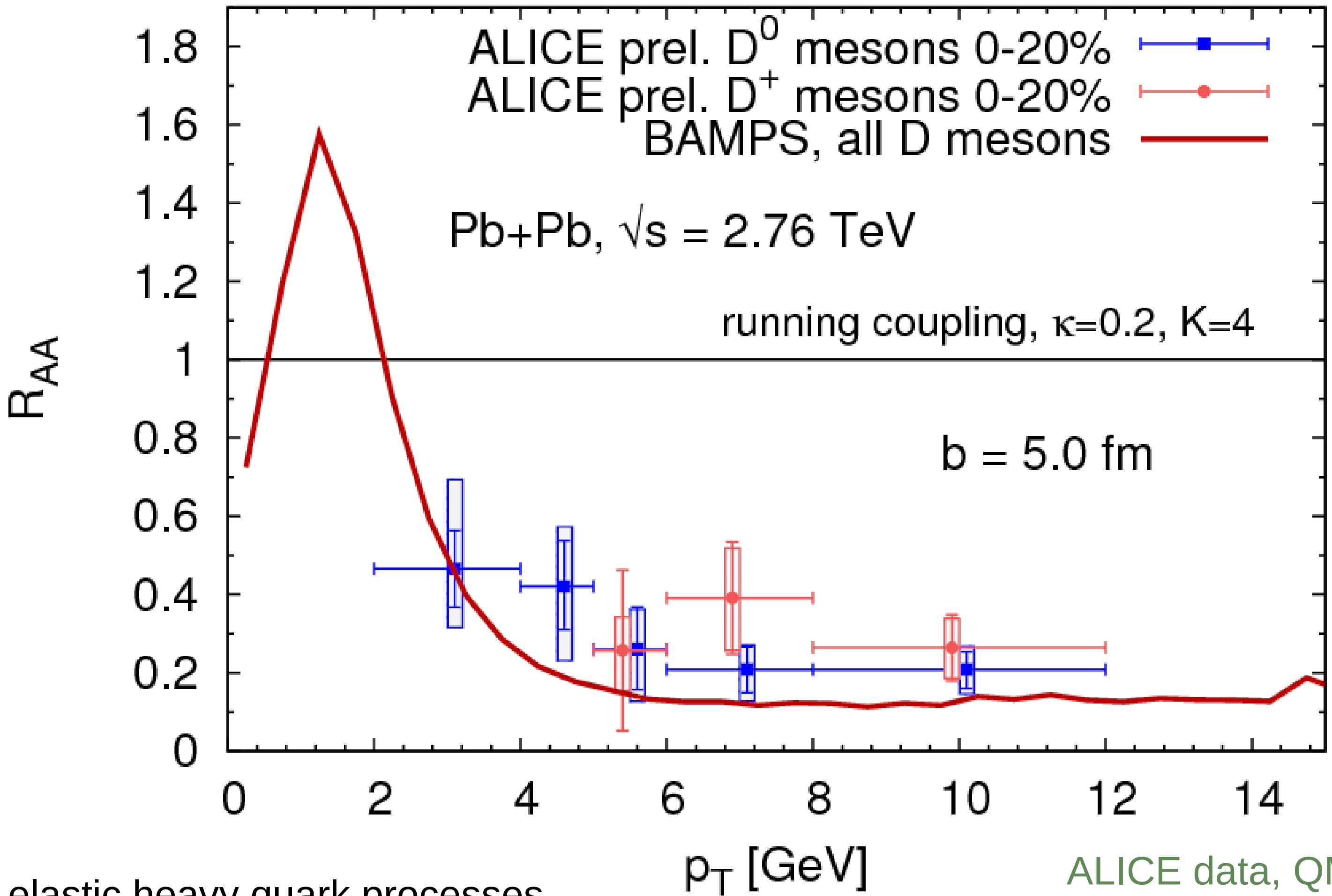
PHENIX, arXiv:1005.1627

only elastic heavy quark processes

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

D meson R_{AA} at LHC

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



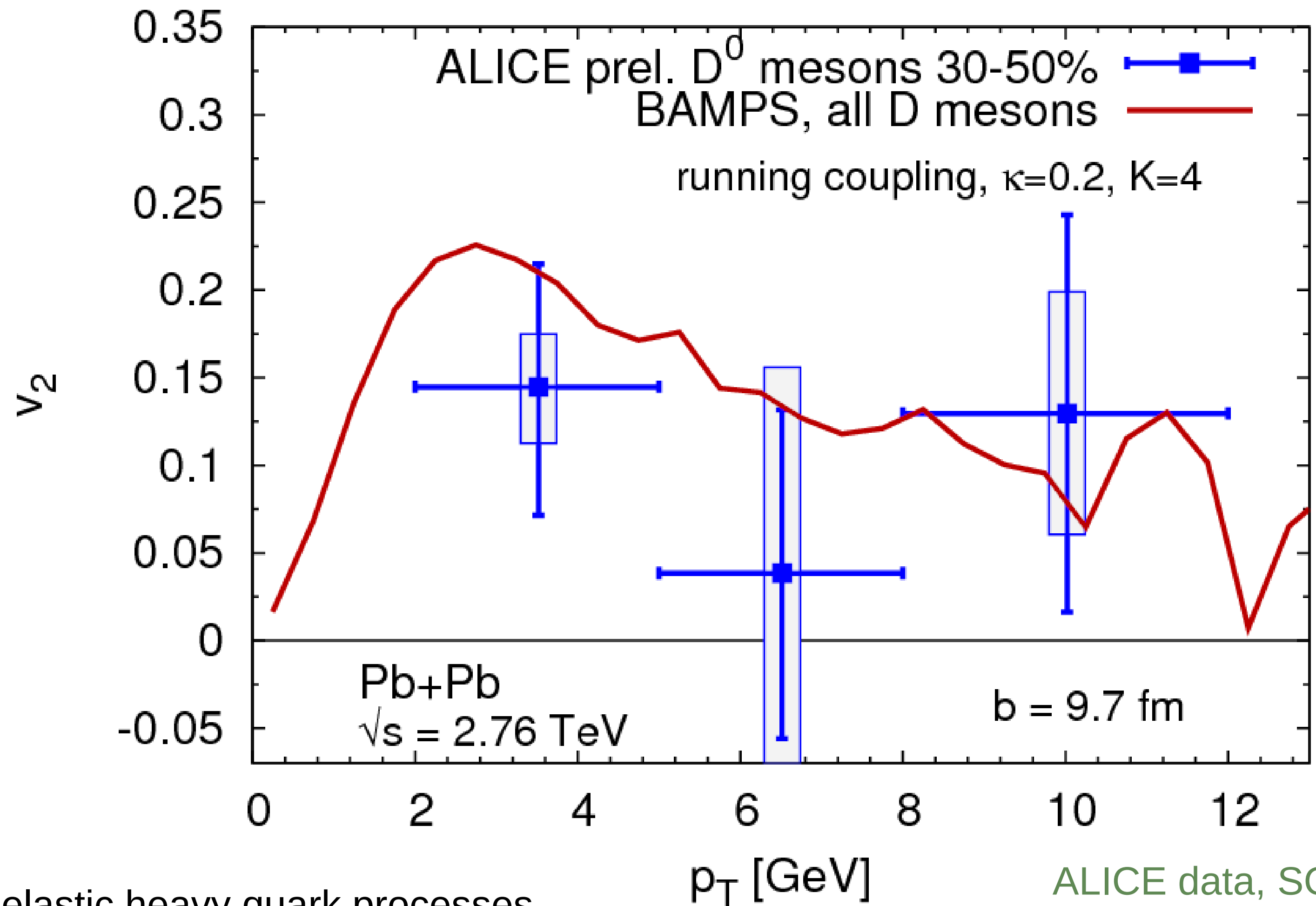
LHC

only elastic heavy quark processes

ALICE data, QM 2011, arXiv:1106.5931

D meson v_2 at LHC

$$\sigma_{gQ \to gQ} \to K\,\sigma_{gQ \to gQ}$$



LHC

only elastic heavy quark processes

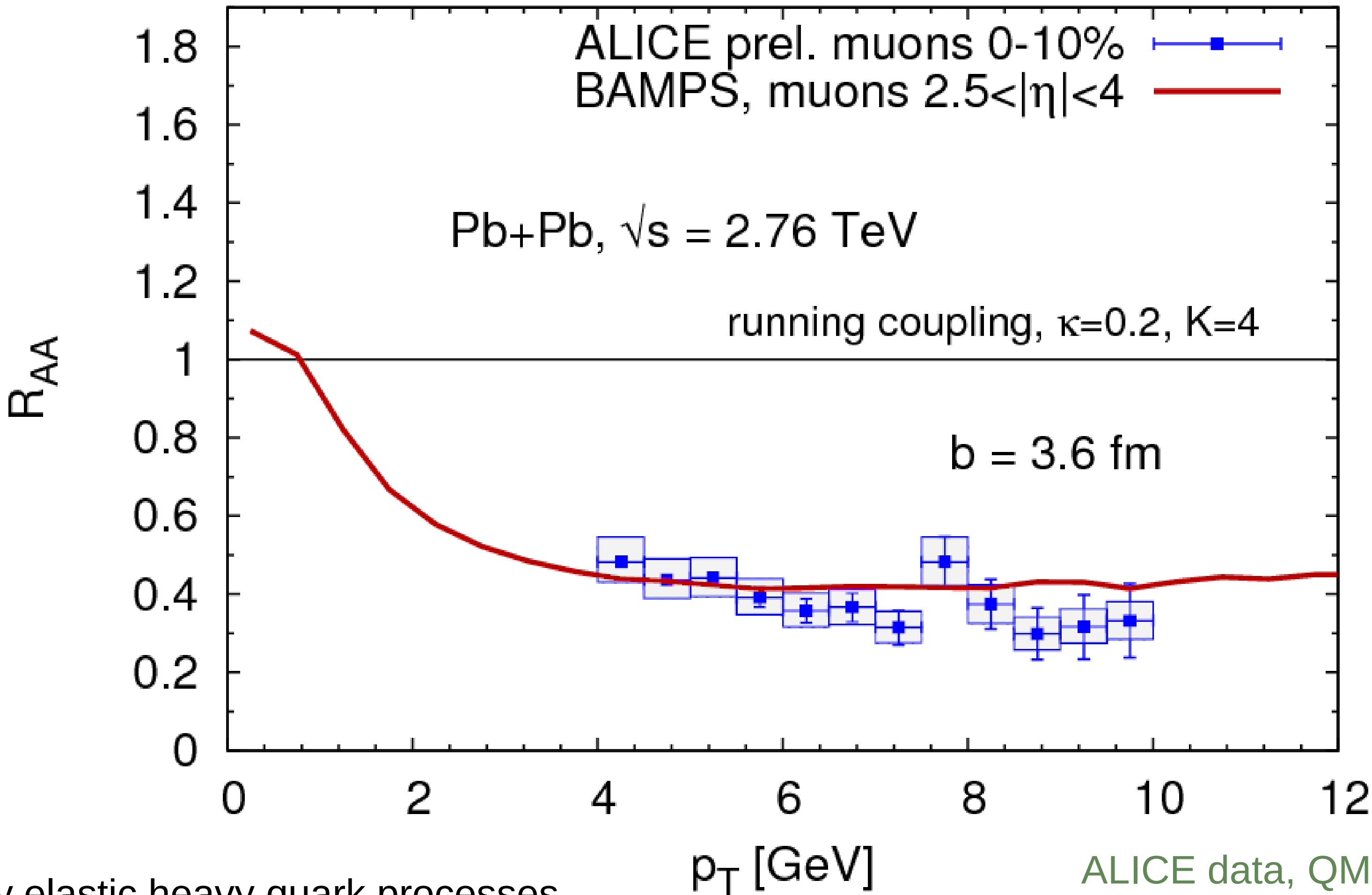
ALICE data, SQM 2011

Muon R_{AA} at forward rapidity at LHC

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

preliminary

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



LHC

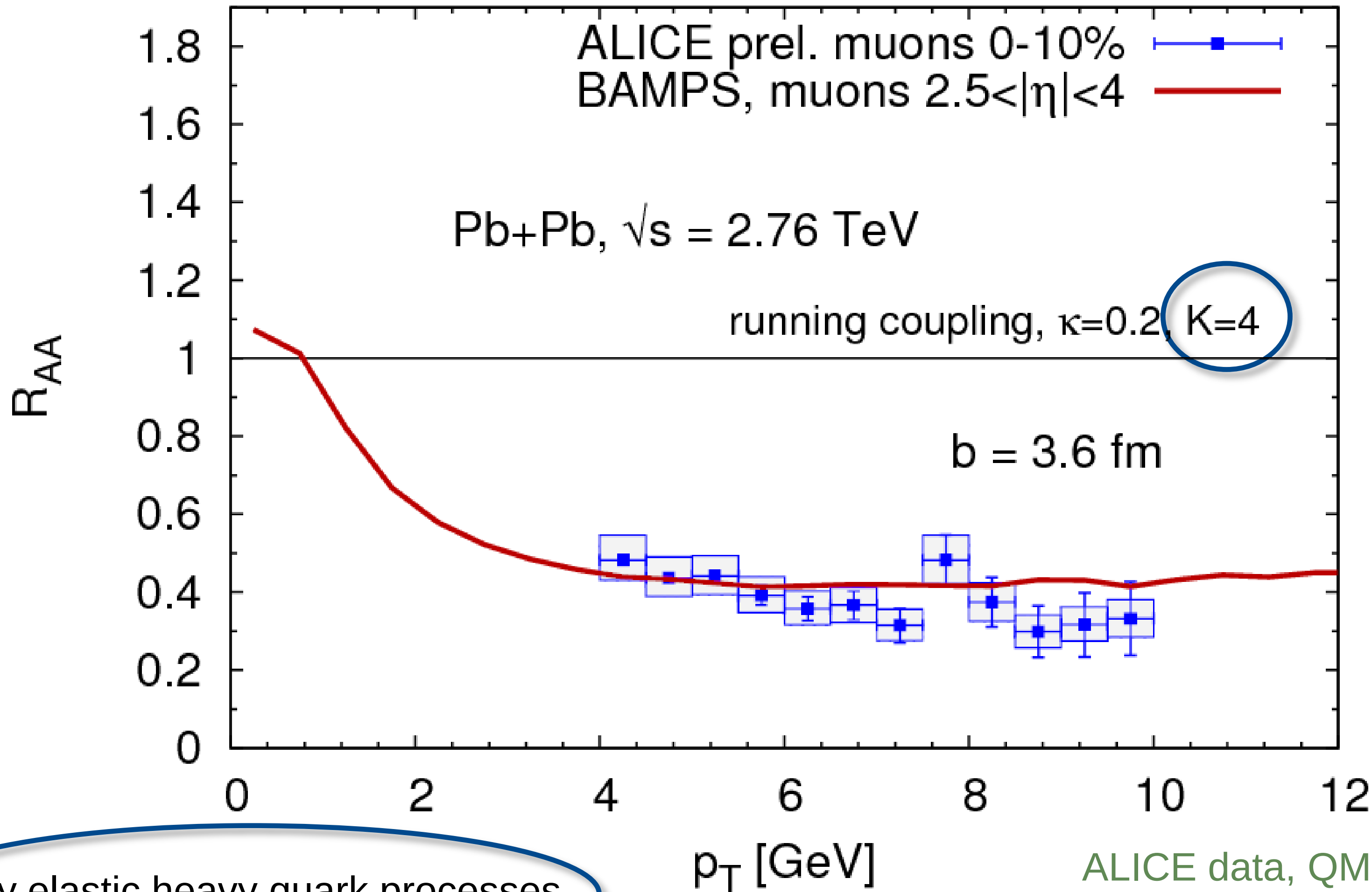
only elastic heavy quark processes

ALICE data, QM 2011, arXiv:1106.4042

Muon R_{AA} at forward rapidity at LHC

preliminary

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



LHC

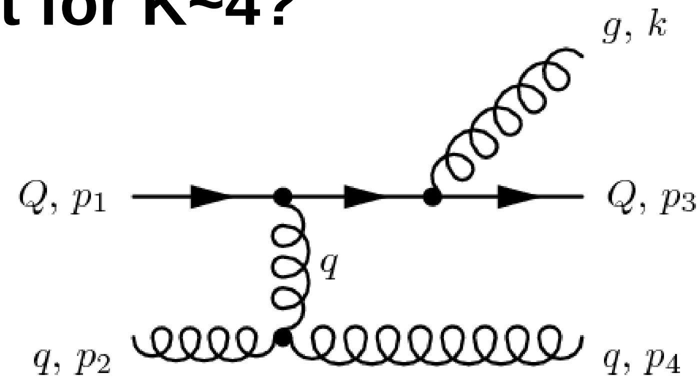
only elastic heavy quark processes

ALICE data, QM 2011, arXiv:1106.4042

Radiative processes

Can radiative processes account for K~4?

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

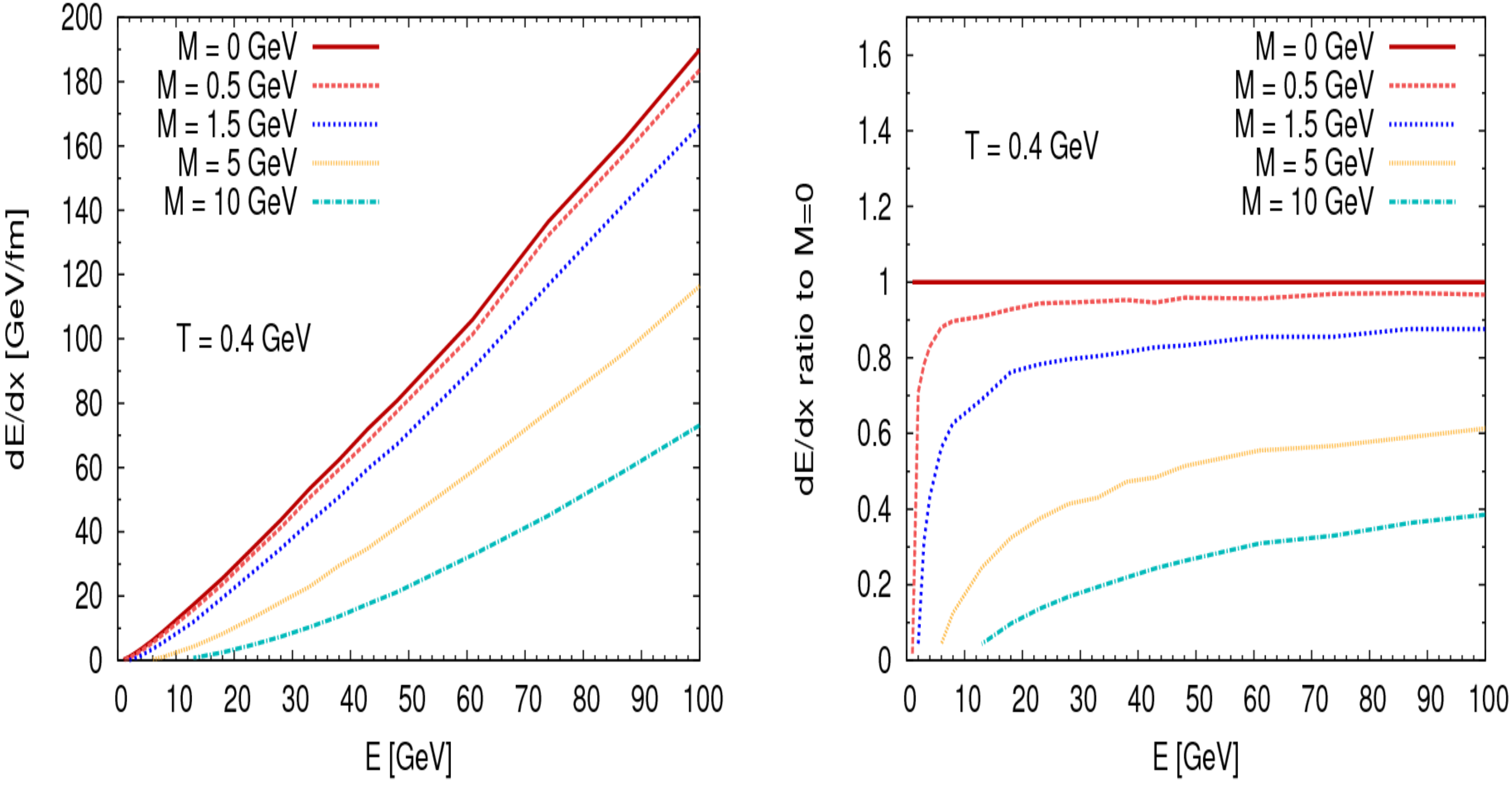


Gunion-Bertsch matrix element generalized to heavy quarks:

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

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

Energy loss in static medium

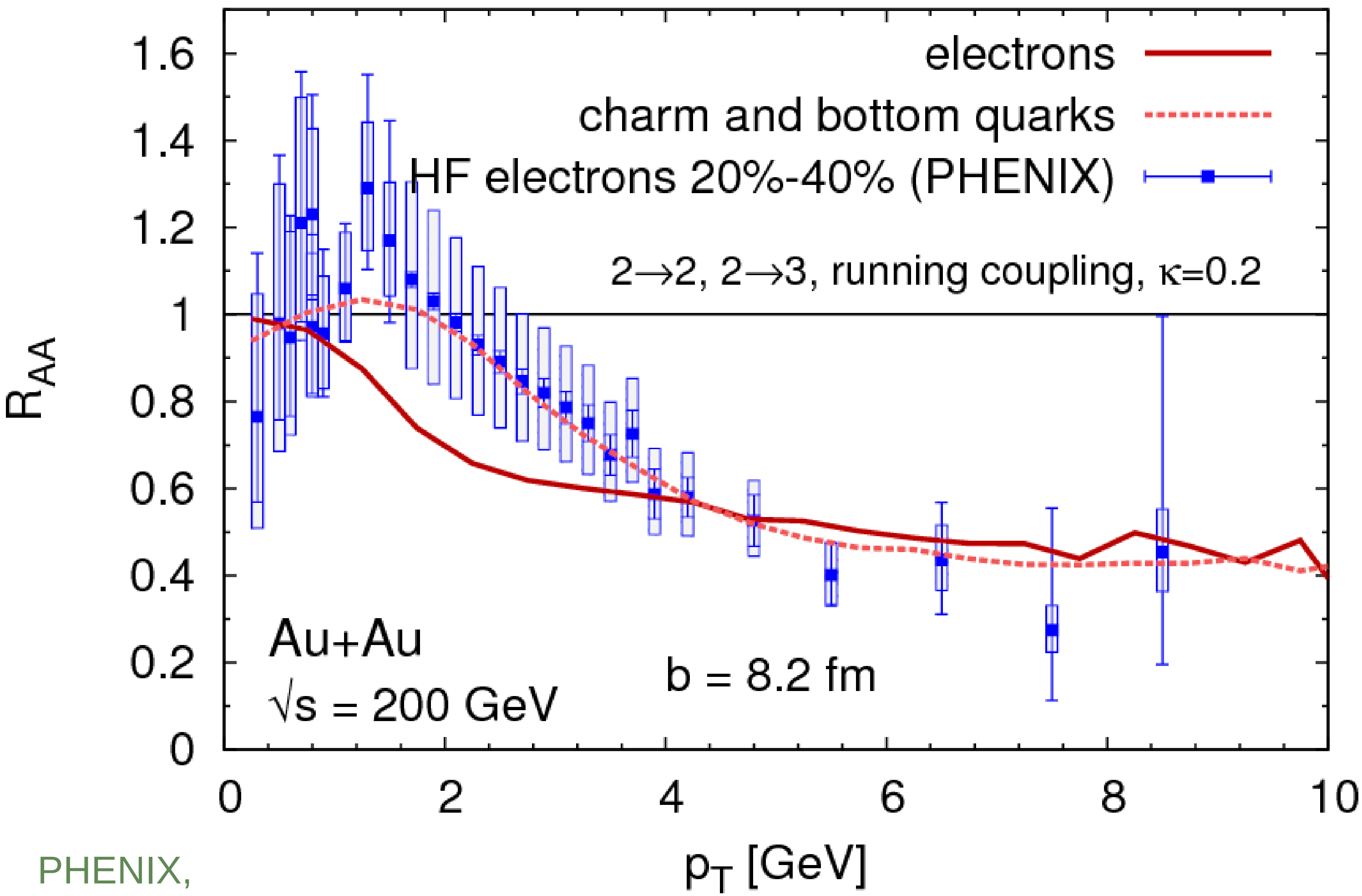


Fixed coupling, without LPM effect

Heavy quark R_{AA} at RHIC with 2->3

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

preliminary



RHIC

PHENIX,
arXiv:1005.1627

Conclusions & outlook

Full space-time evolution of QGP with charm and bottom quarks

- **Running coupling and improved Debye screening yield results that can explain experimental v_2 and R_{AA} at RHIC and LHC if K=4 is introduced**
- **Importance of $2 \rightarrow 3$ processes estimated in energy loss calculations in static medium**
- **Preliminary results with $2 \rightarrow 3$ in full cascade are promising**

Further details on arXiv:1104.2295 and 1104.2437

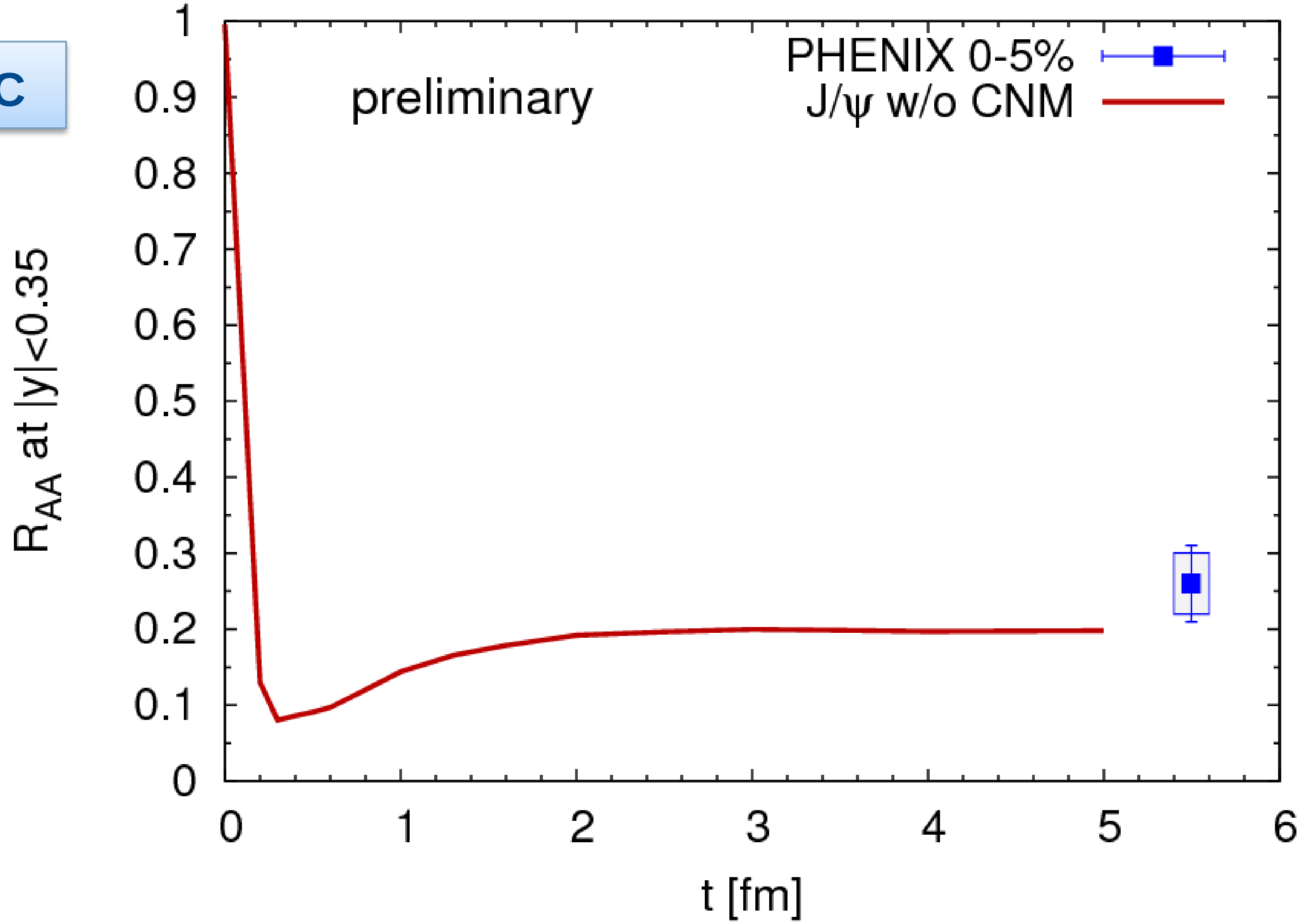
Future tasks:

- **Further study of radiative heavy quark scattering in full cascade**
- **Light quark interactions with heavy quarks**
- **Further study of J/ψ suppression, also at LHC**

Thank you for your attention.

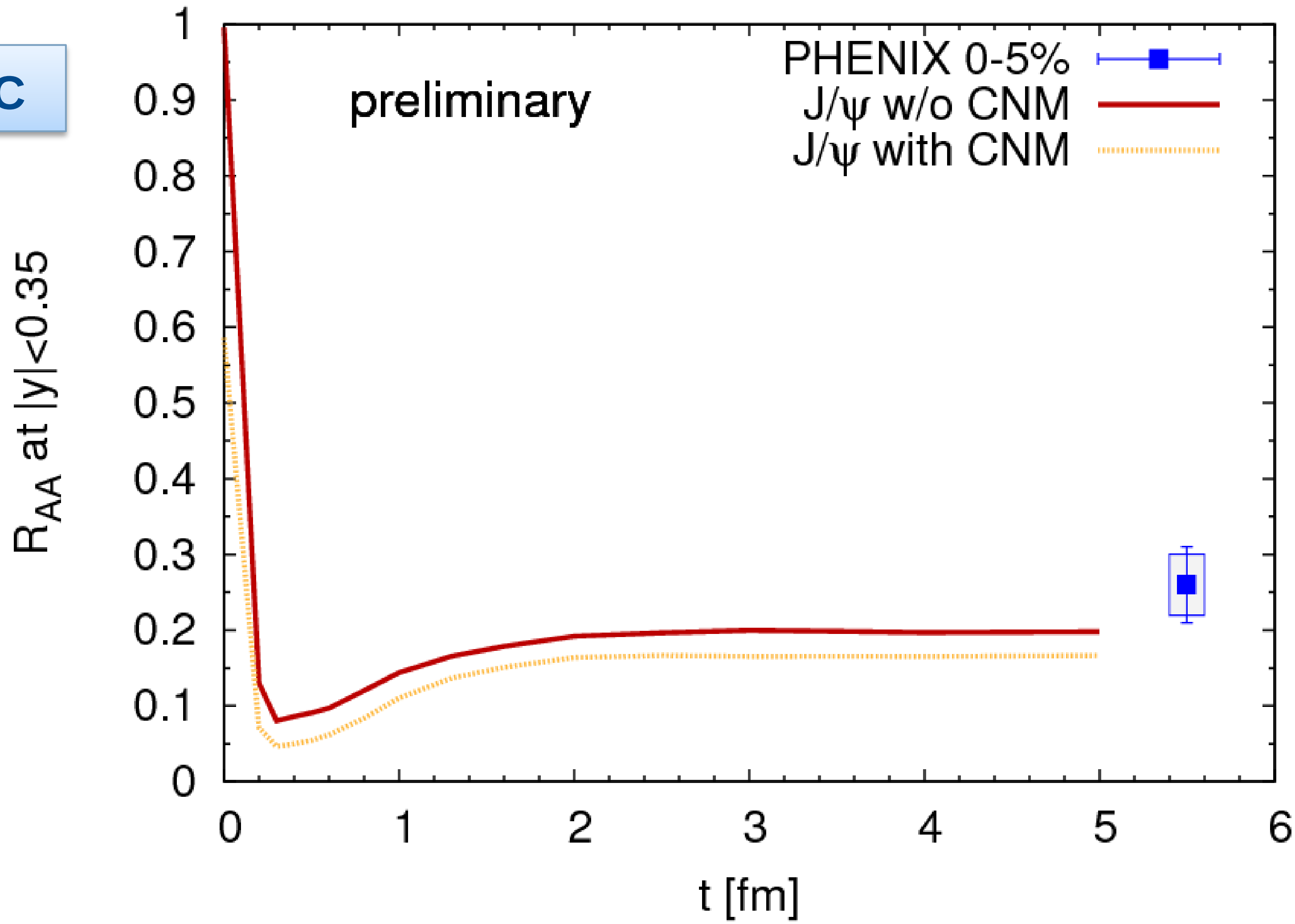
J/ψ production

RHIC



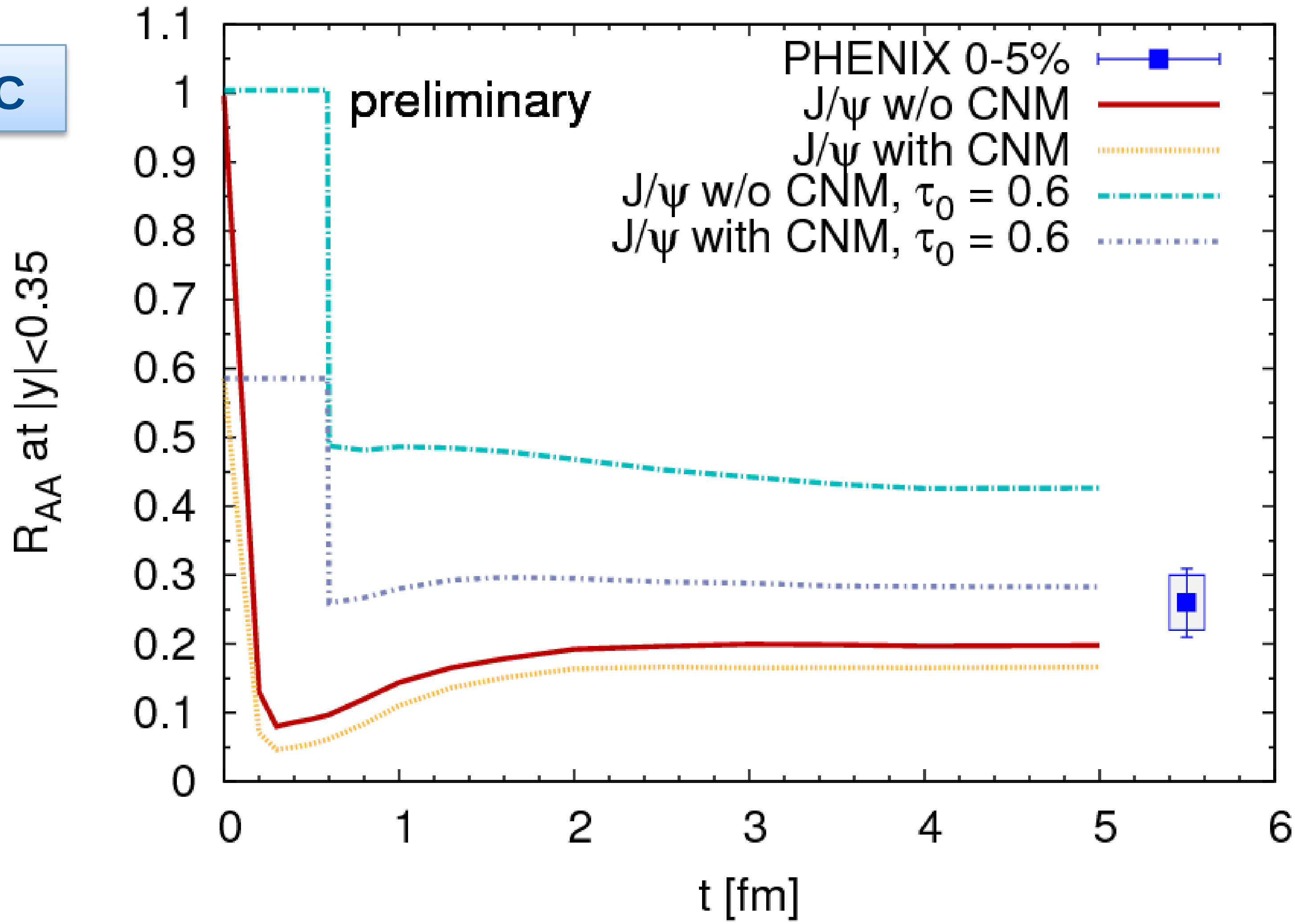
J/ψ production

RHIC



J/ψ production

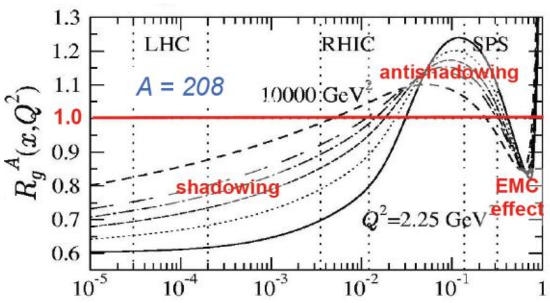
RHIC



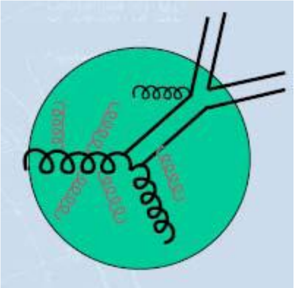
J/ψ suppression

Cold nuclear matter effects

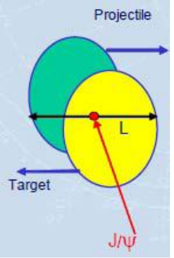
- **Shadowing**



- **Cronin effect**



- **Nuclear absorption**

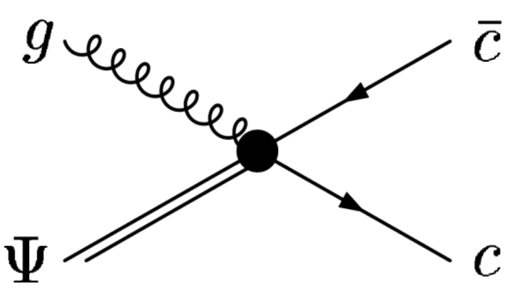


Hot nuclear matter effects

- **J/psi dissociation**
  - If $T > T_d = 2\ T_c = 330$ MeV
  - Via $J/\psi + g \rightarrow c + \bar{c}$

- **J/psi regeneration**

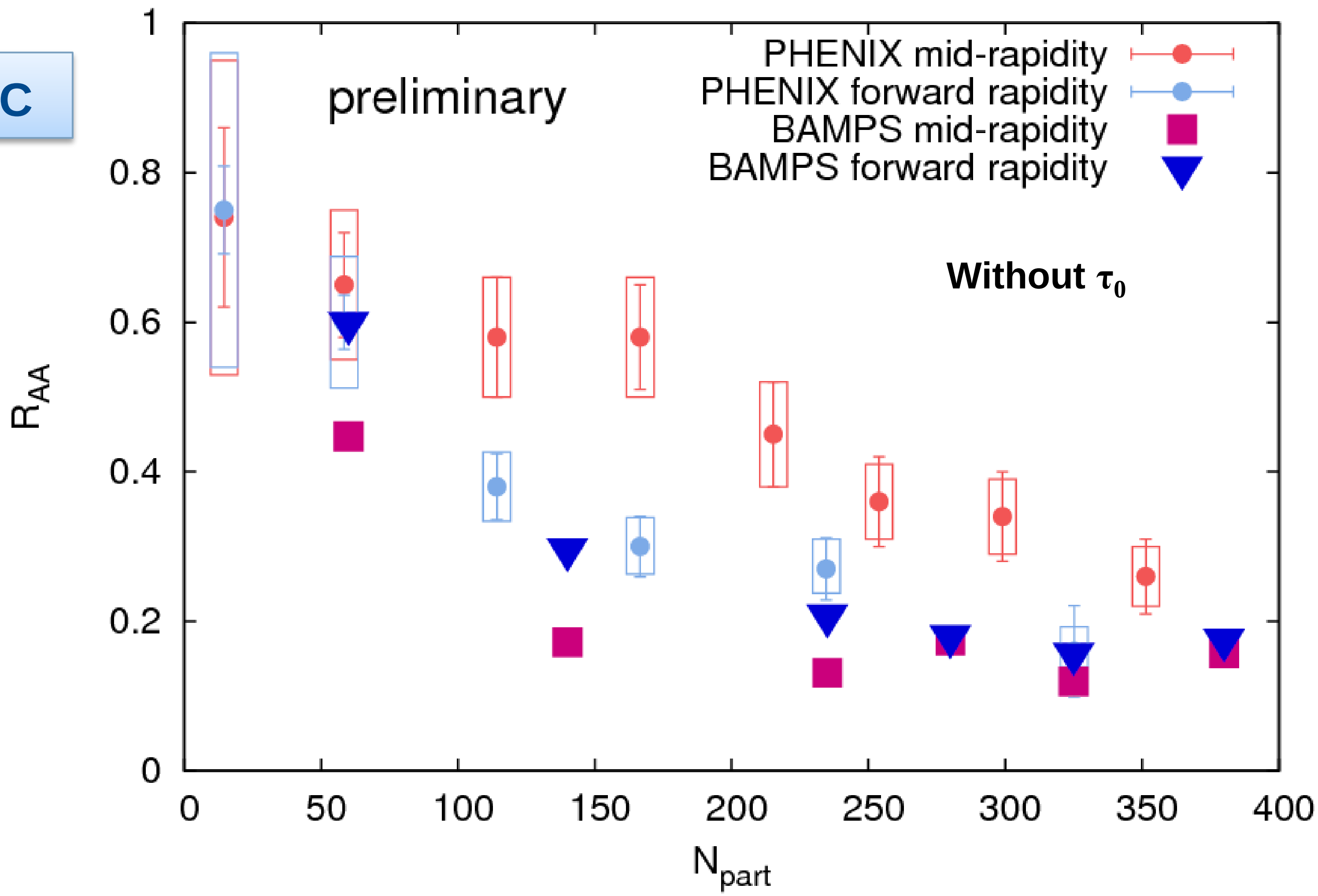
via $c + \bar{c} \rightarrow J/\psi + g$



Bhanot+Peskin 79

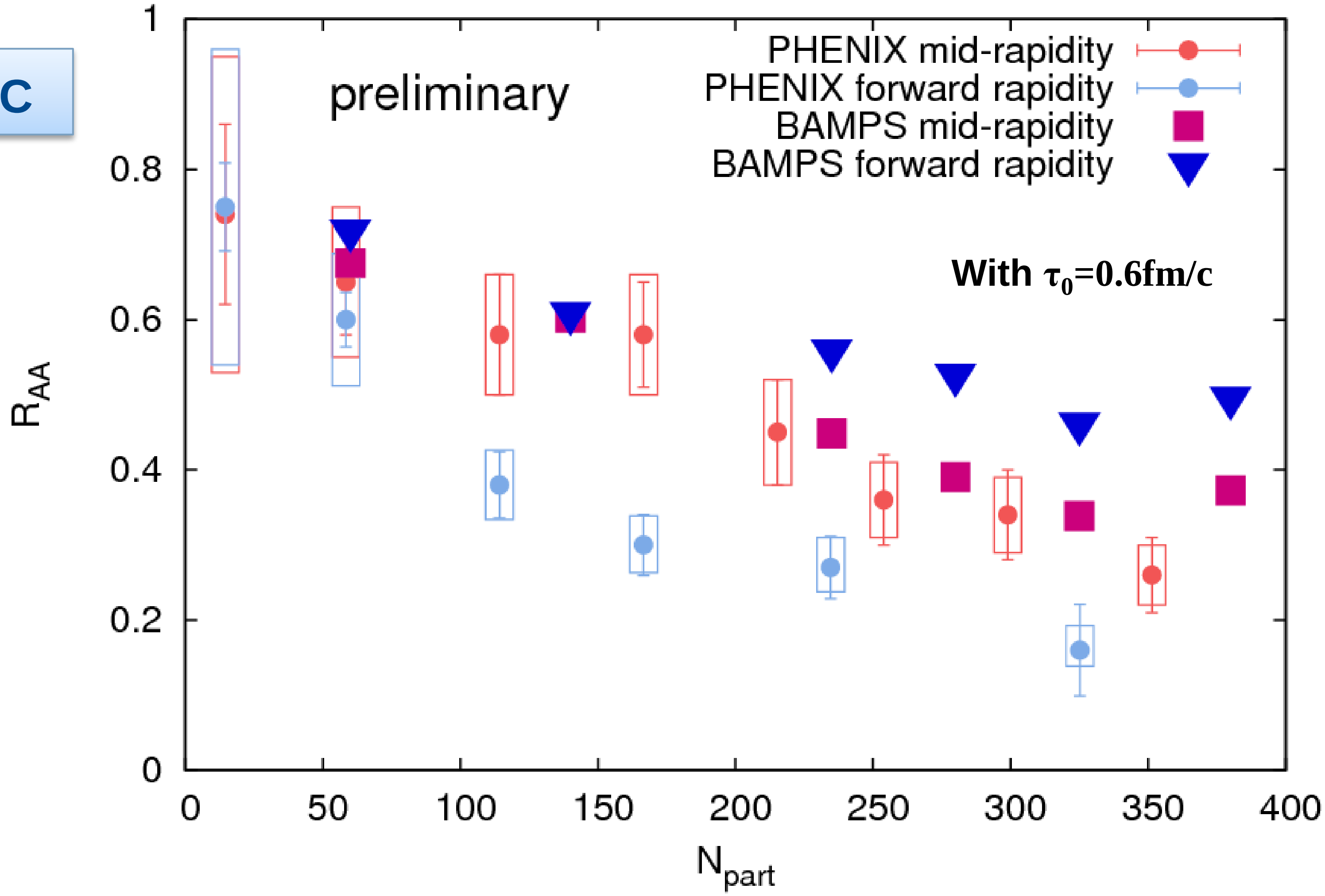
J/ψ production

RHIC



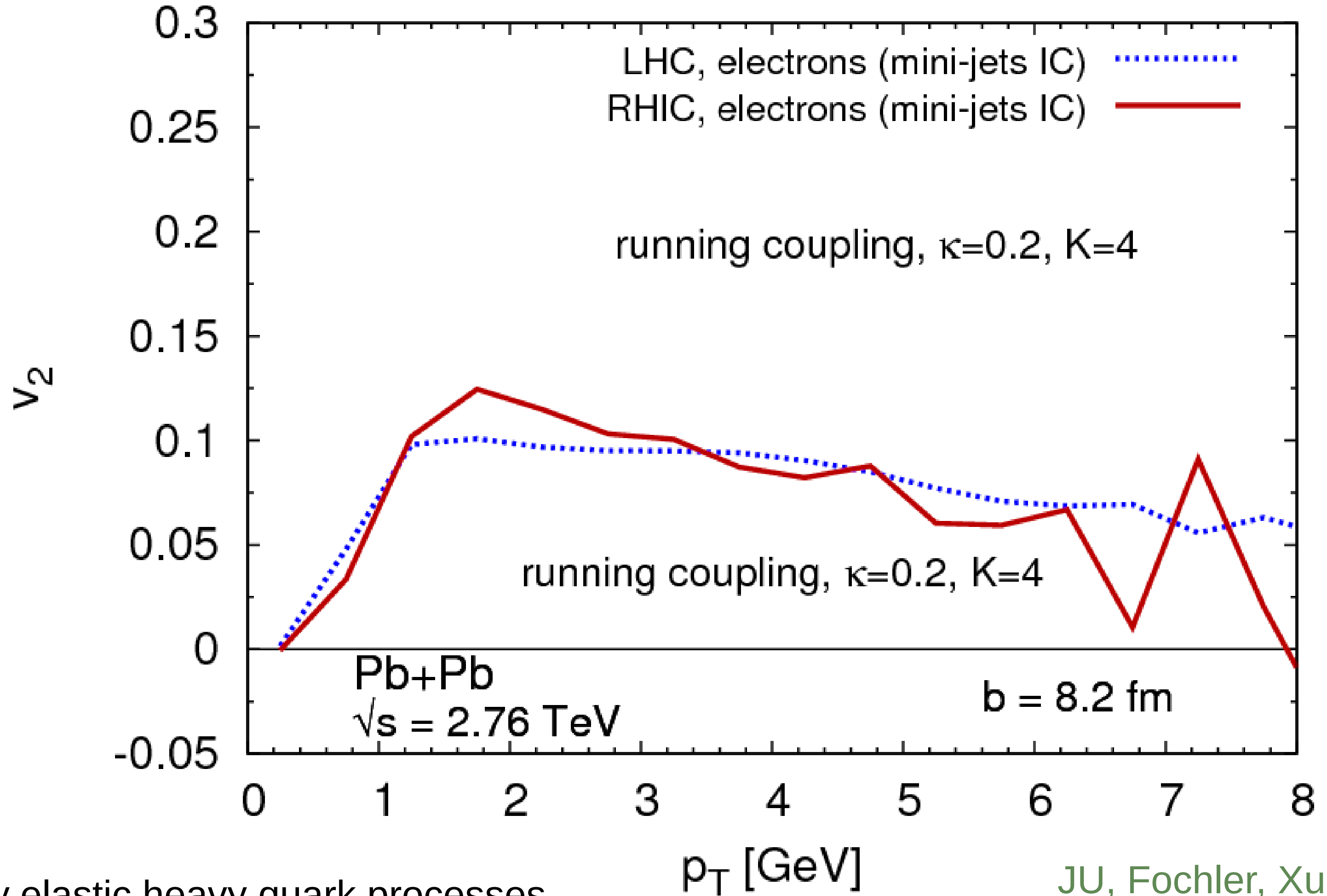
J/ψ production

RHIC



Heavy quark elliptic flow v_2 at LHC

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$



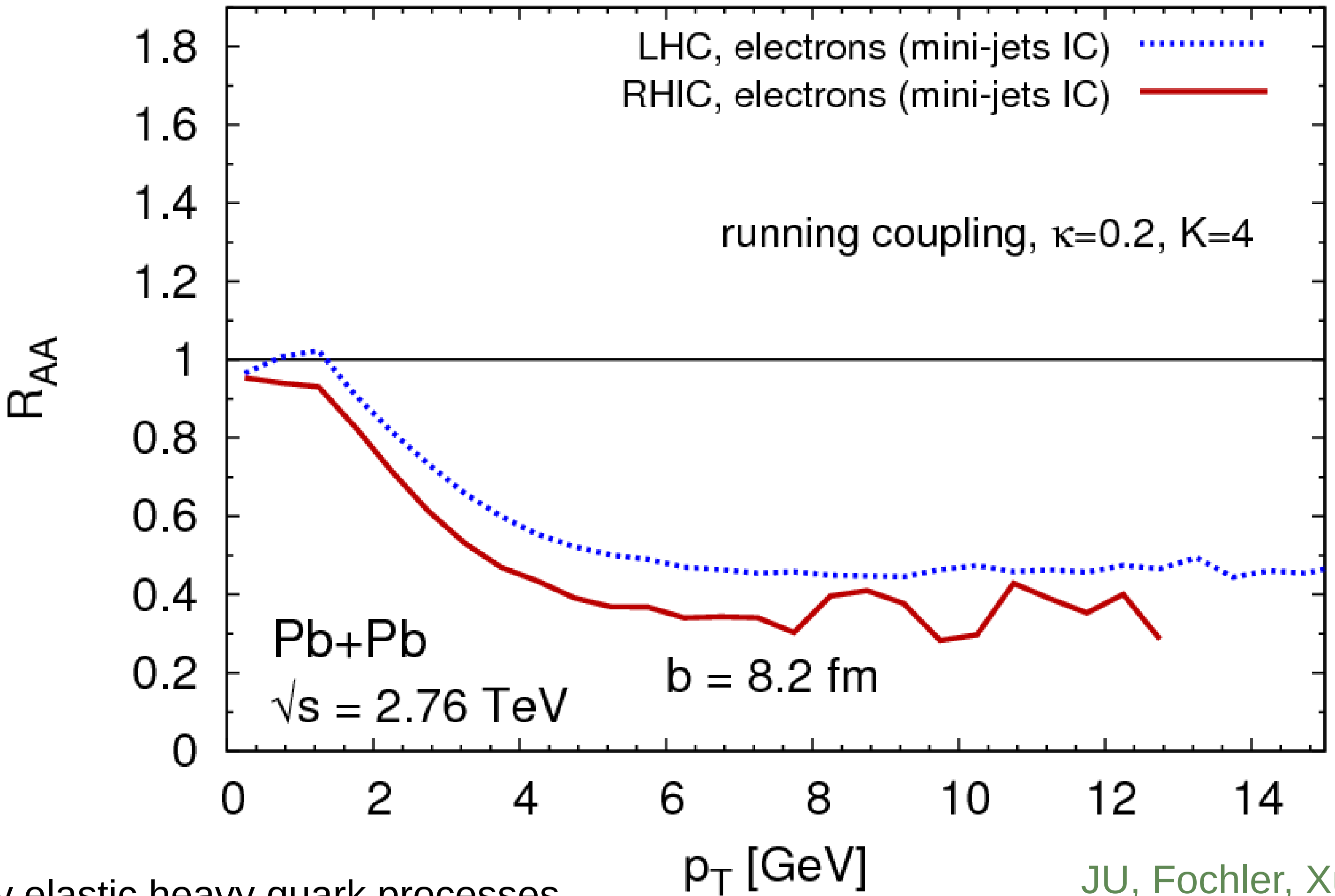
LHC

only elastic heavy quark processes

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

Heavy quark R_{AA} at LHC

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

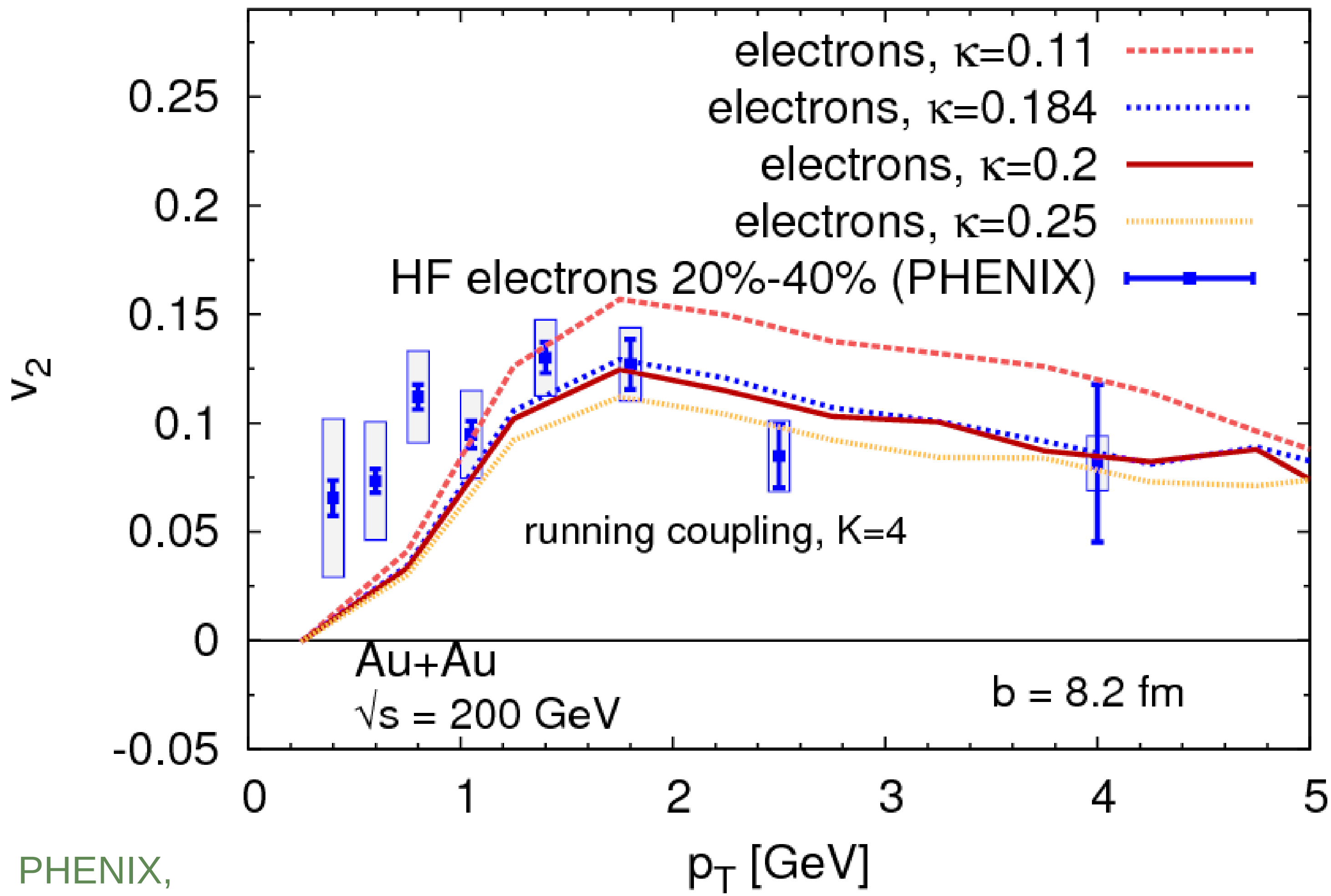


LHC

only elastic heavy quark processes

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

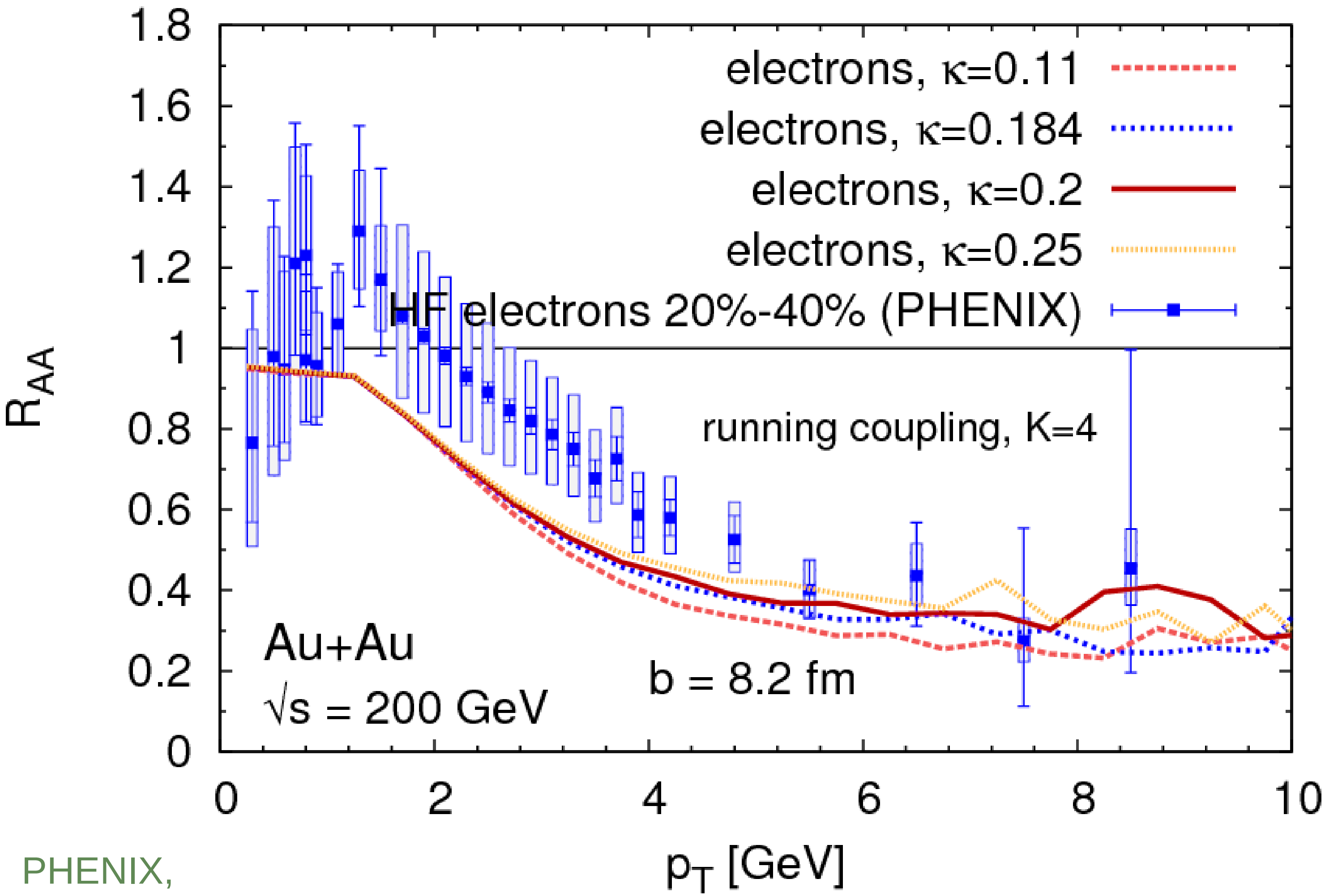
Heavy quark elliptic flow v_2 at RHIC



RHIC

PHENIX,
arXiv:1005.1627

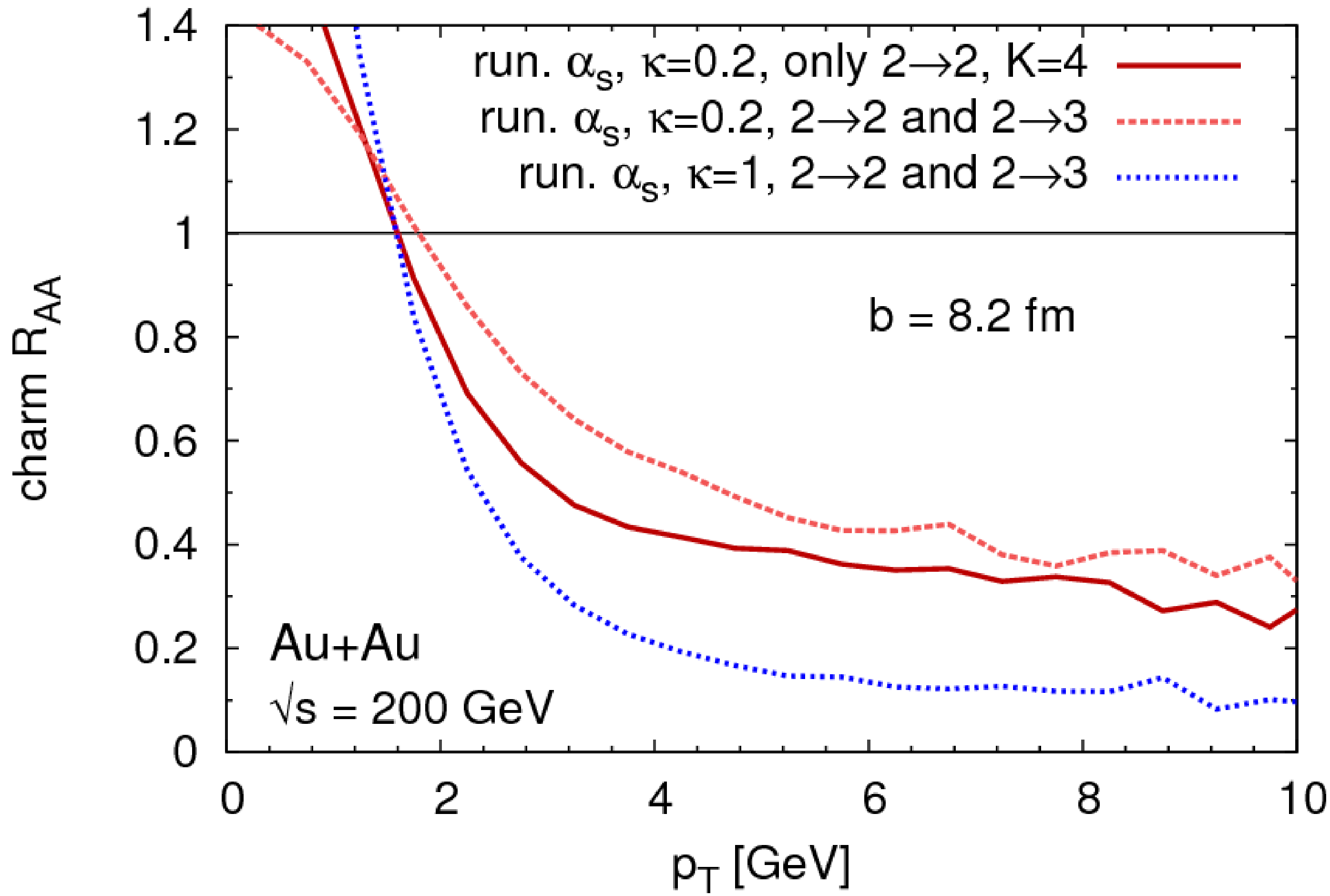
Heavy quark elliptic flow v_2 at RHIC



RHIC

PHENIX,
arXiv:1005.1627

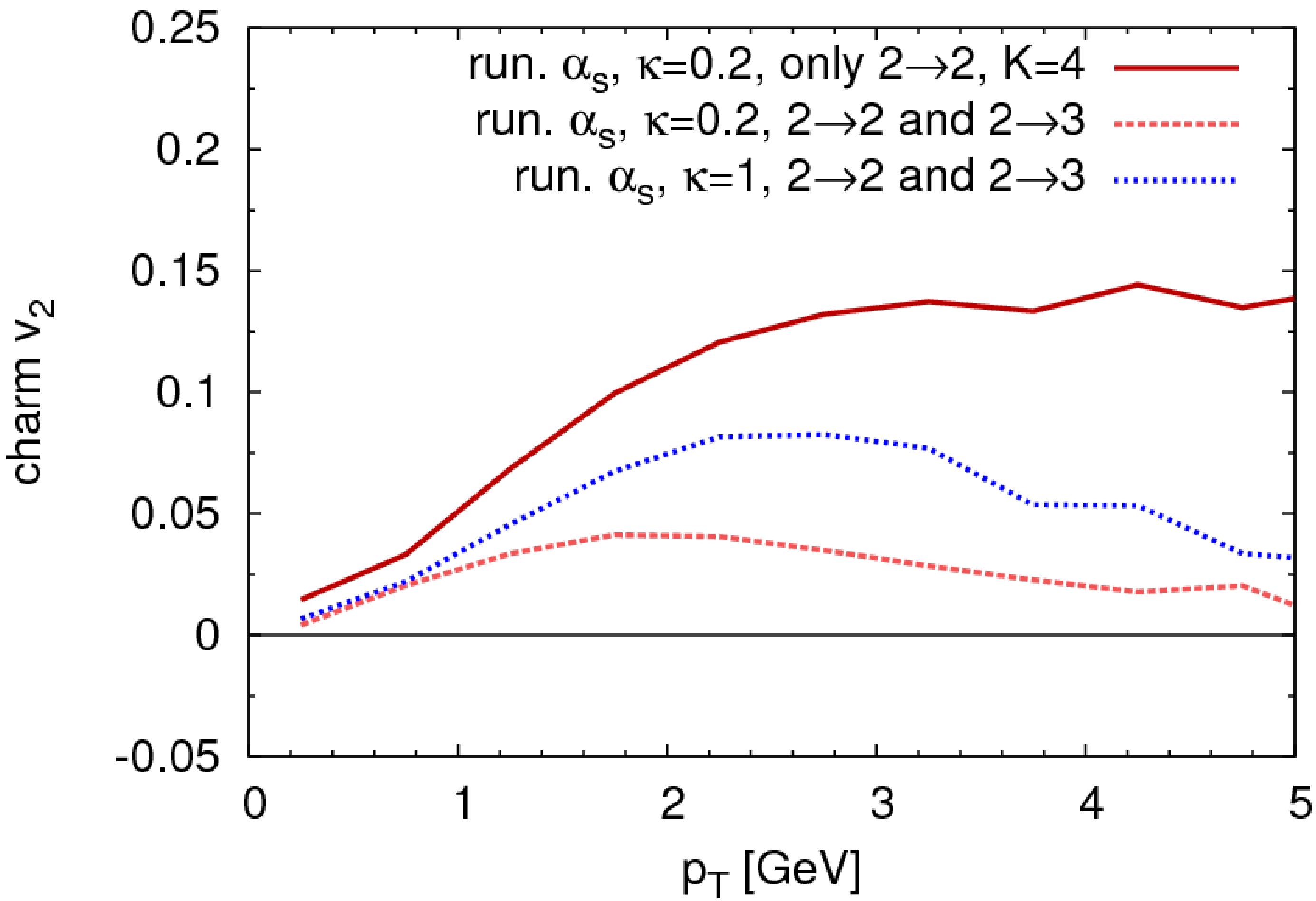
Charm R_{AA} at RHIC



For R_{AA} 2→3 processes can indeed account for K=4

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}

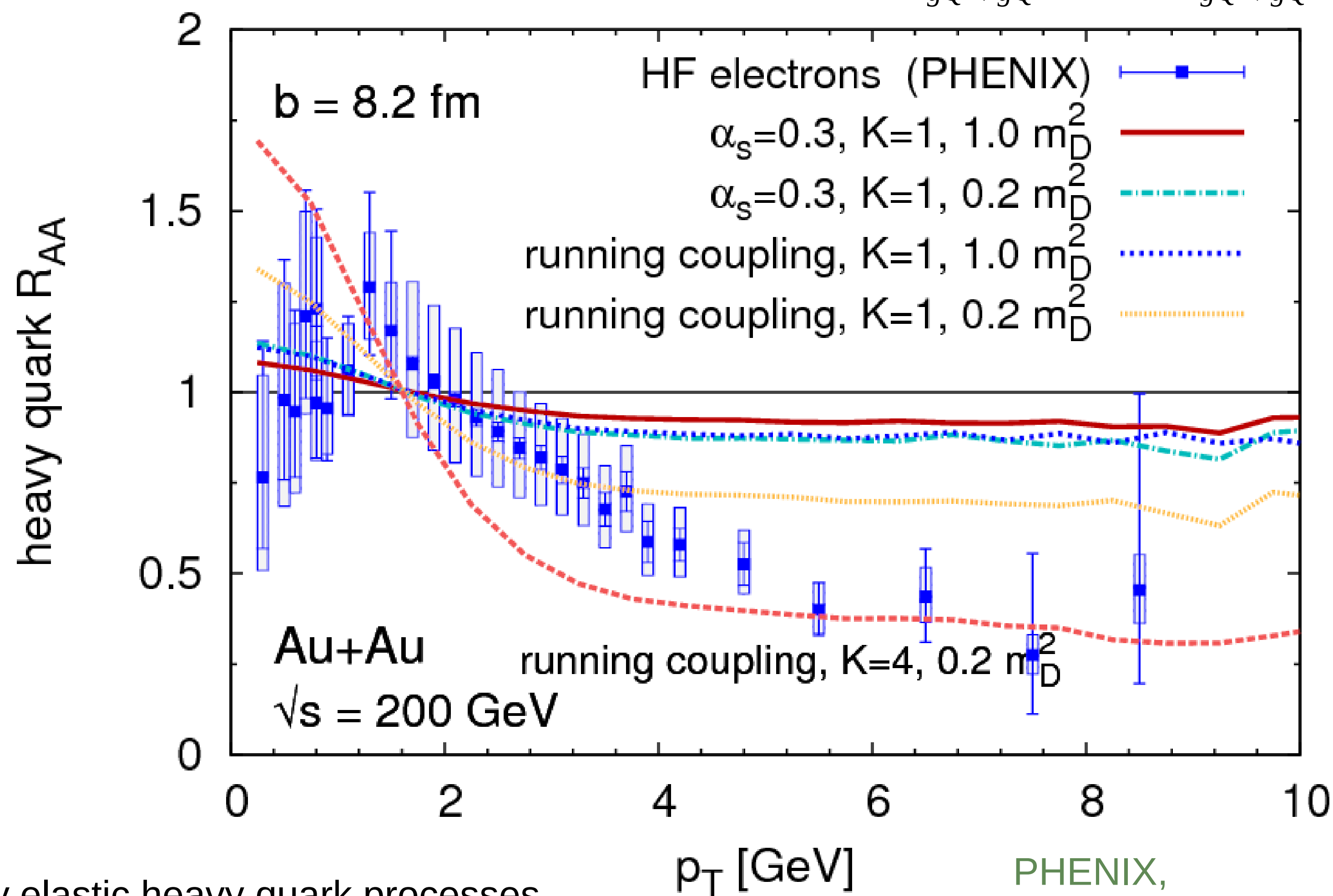
Reason: LPM effect

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

Heavy quark R_{AA} at RHIC

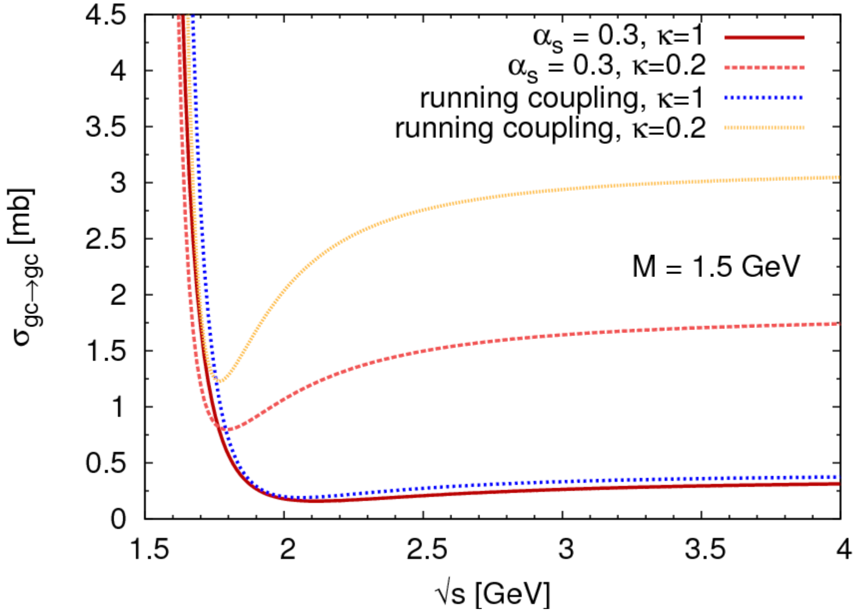
$$\sigma_{gQ \to gQ} \to K \, \sigma_{gQ \to gQ}$$

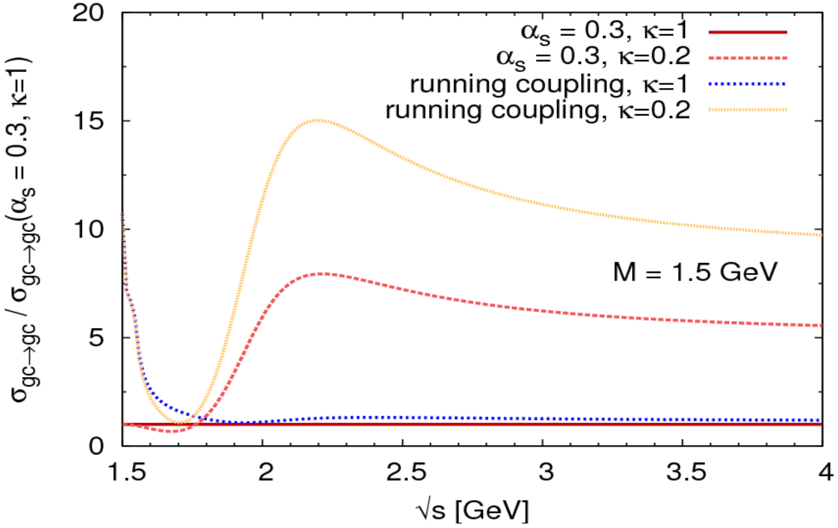


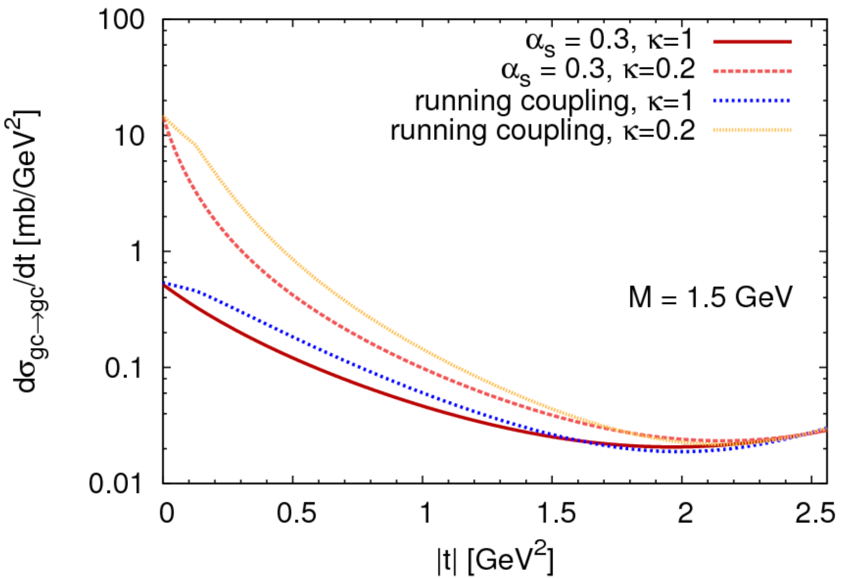
only elastic heavy quark processes

PHENIX, arXiv:1005.1627

Heavy quark scattering cross section



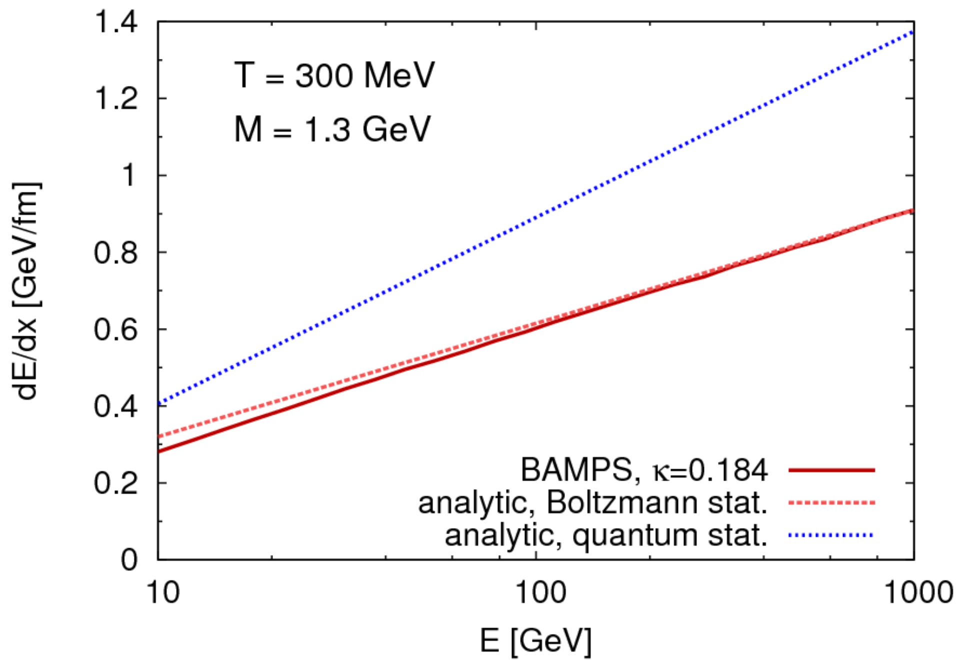




Heavy quark scattering

Compare to analytic formula

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



Fragmentation and Decay

- **Peterson fragmentation**

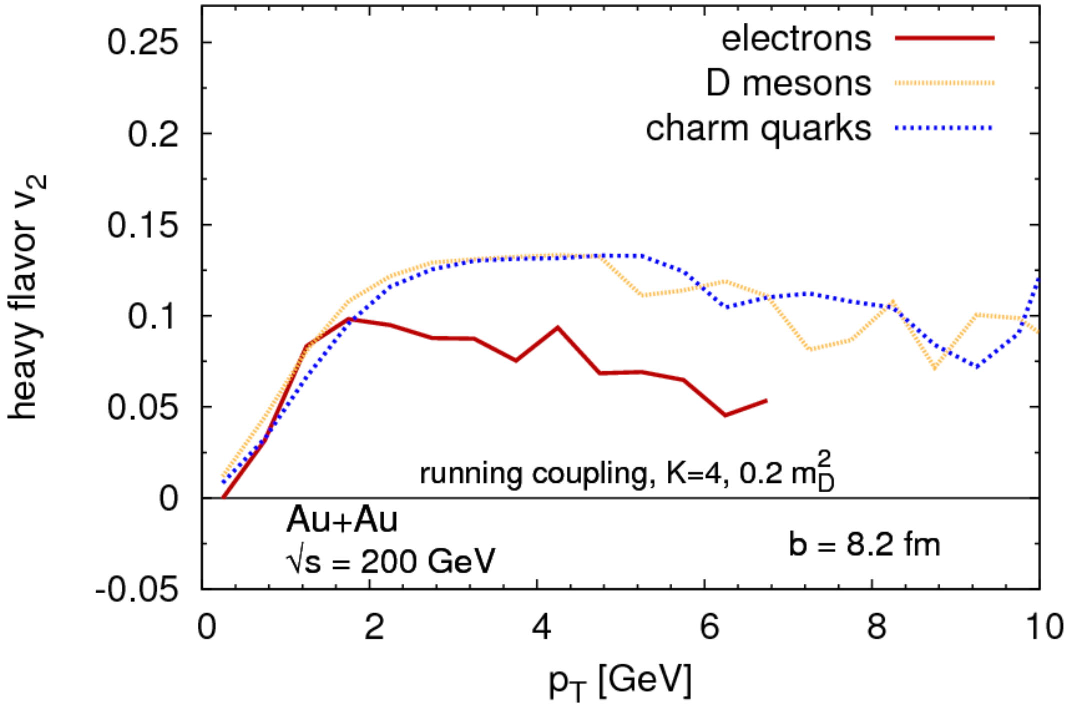
Peterson et al., Phys. Rev. D27 (1983)

$$D_{H/Q}(z) = \frac{N}{z\left(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right)^2}$$

$$z = \frac{|\vec{p}_H|}{|\vec{p}_Q|}$$

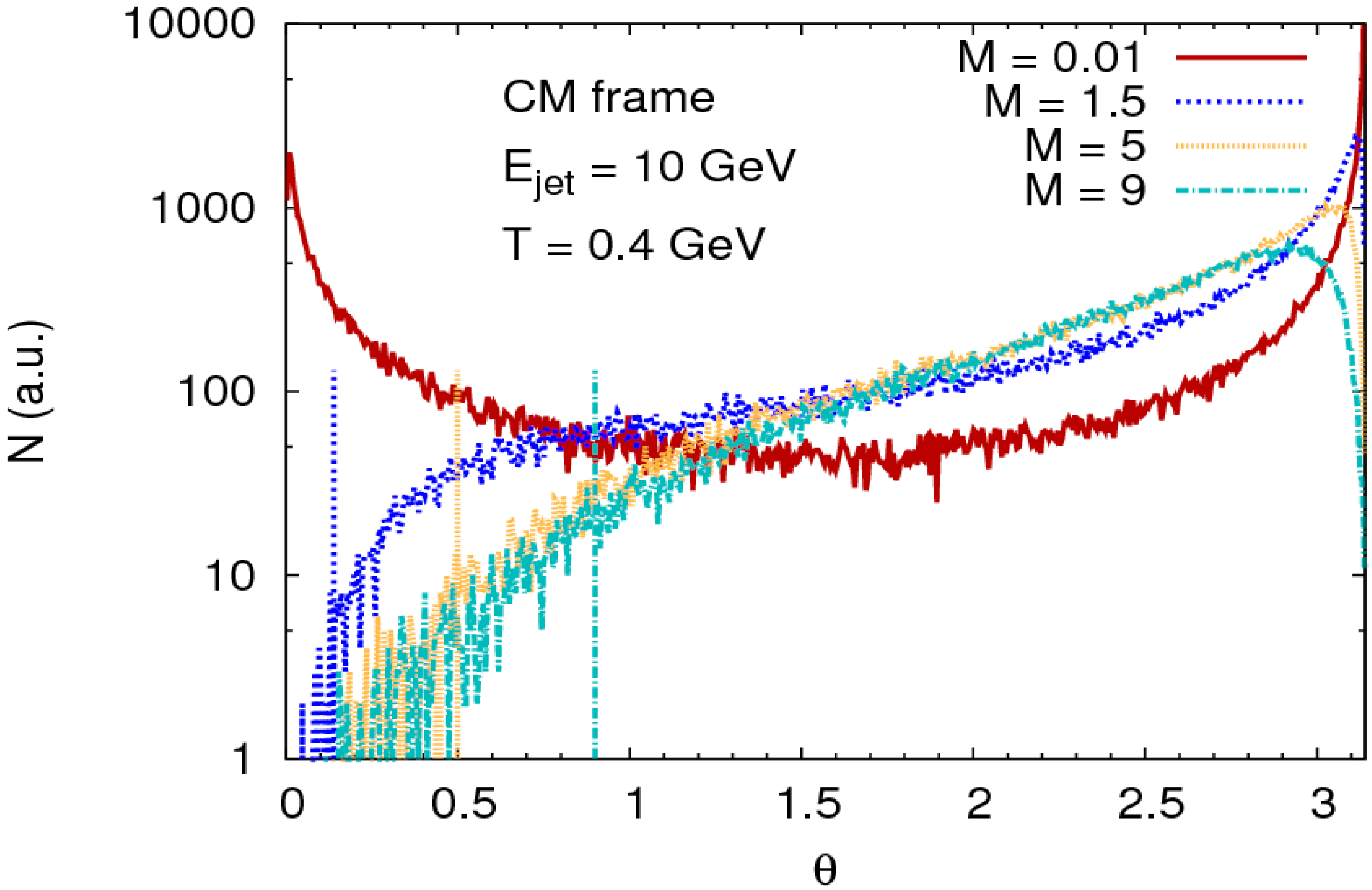
$$\epsilon_c = 0.05$$
$$\epsilon_b = 0.005$$

- **Decay to electrons with PYTHIA**



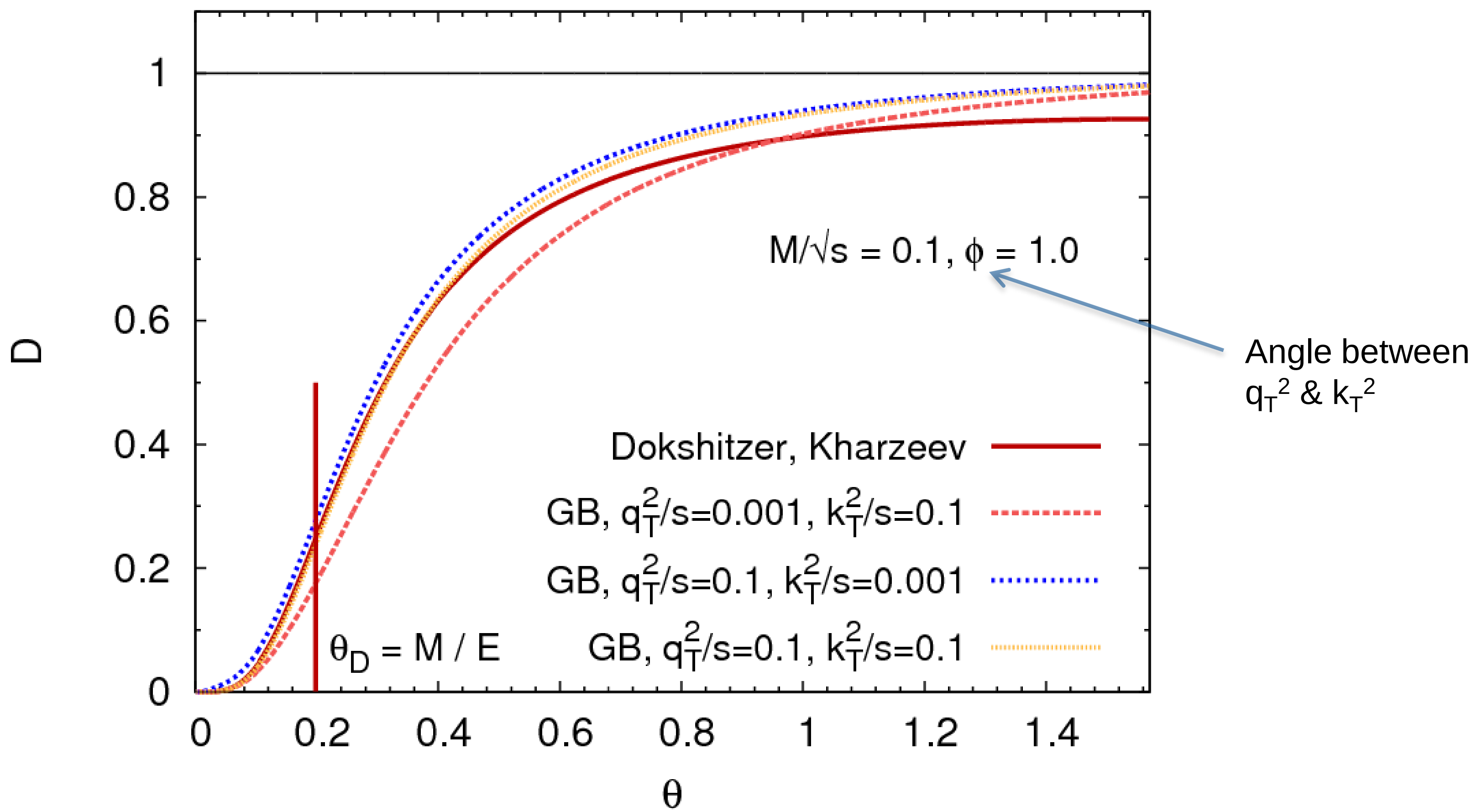
Impact of hadronization and decay small

Θ dependence in static medium



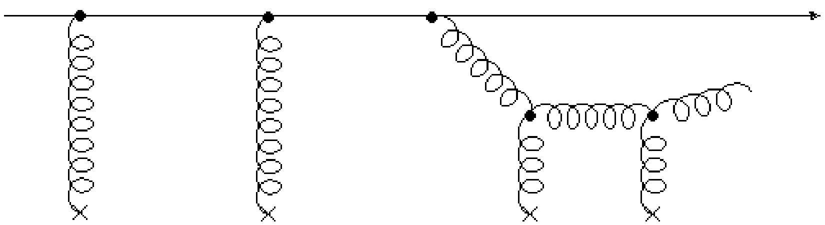
Dead cone effect

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



LPM effect

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

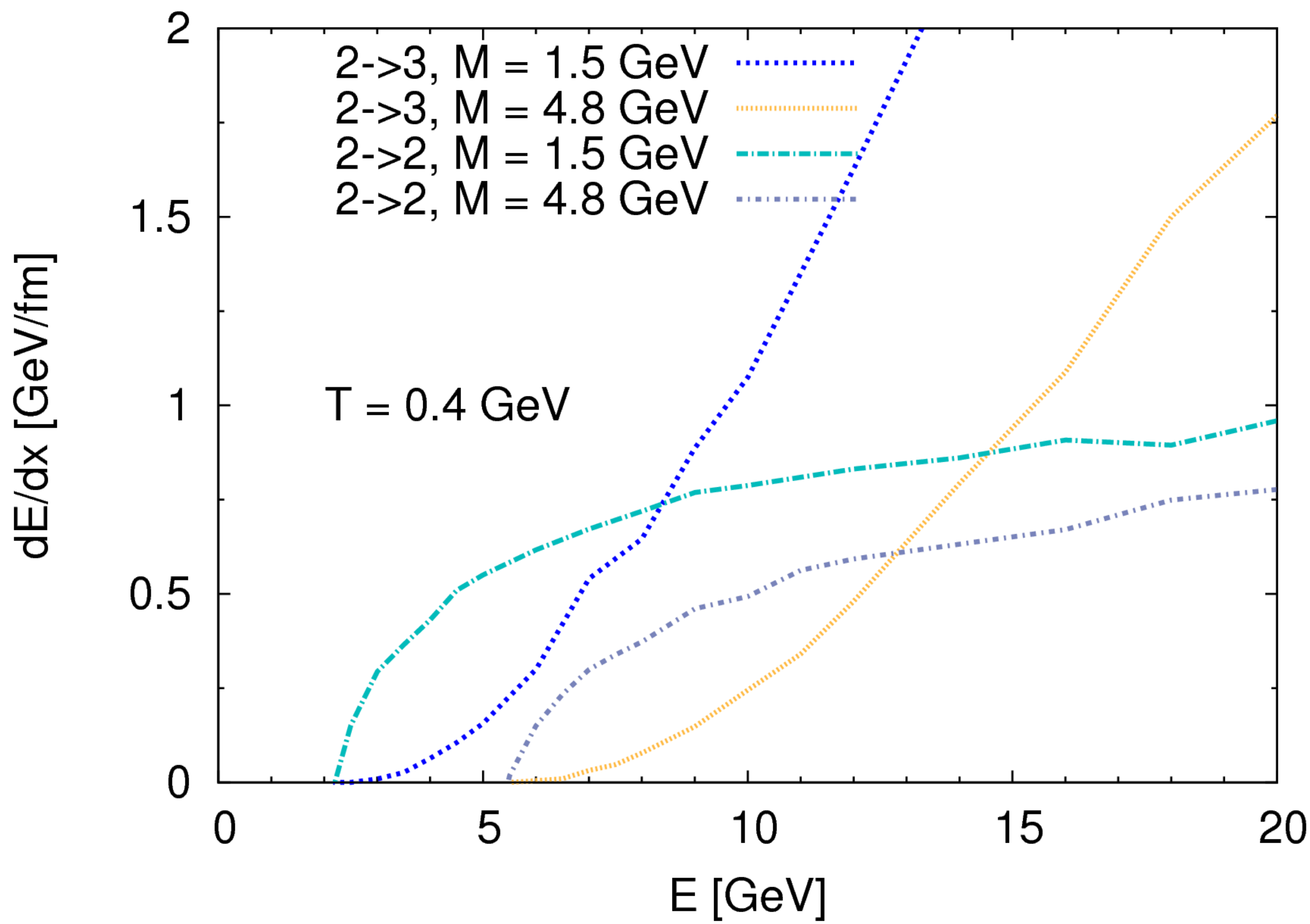


$$\lambda > \tau$$

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

➡ Bethe-Heitler regime, independent scatterings

Energy loss in static medium



Running coupling, with LPM effect

Initial conditions

Gluons:

- **PYTHIA**
  scaling to heavy-ion collisions with Glauber model (considering shadowing) and energy conservation

- **Minijets**
  (low p_T cut-off at 1.4 GeV)

- **Color glass condensate**
  H.J. Drescher & Y. Nara, Phys. Rev. C75 (2007)

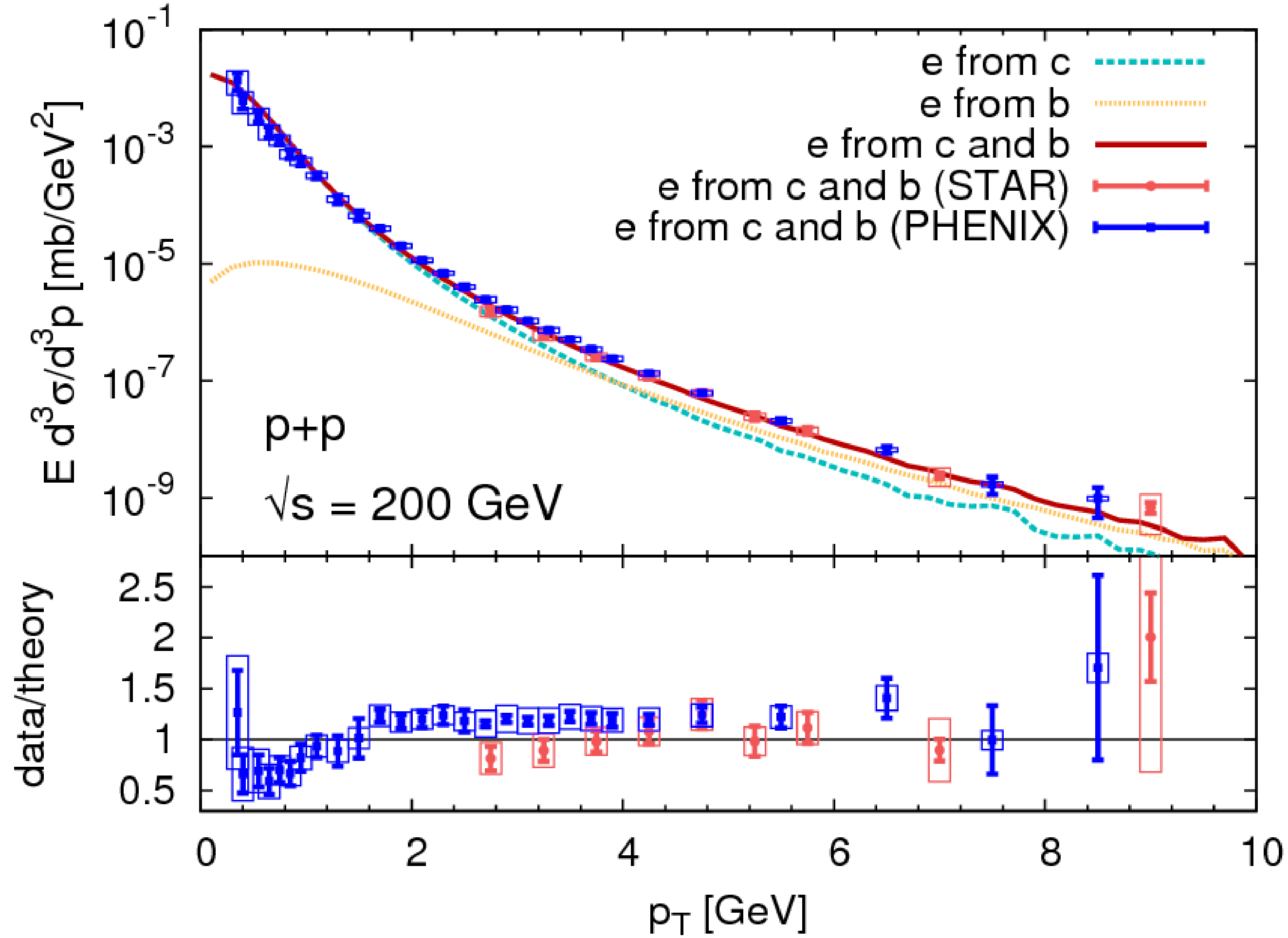
Heavy quarks:

- **PYTHIA**
  Monte Carlo Event Generator for nucleon-nucleon collisions

- **NLO pQCD**
  Distributions from R. Vogt

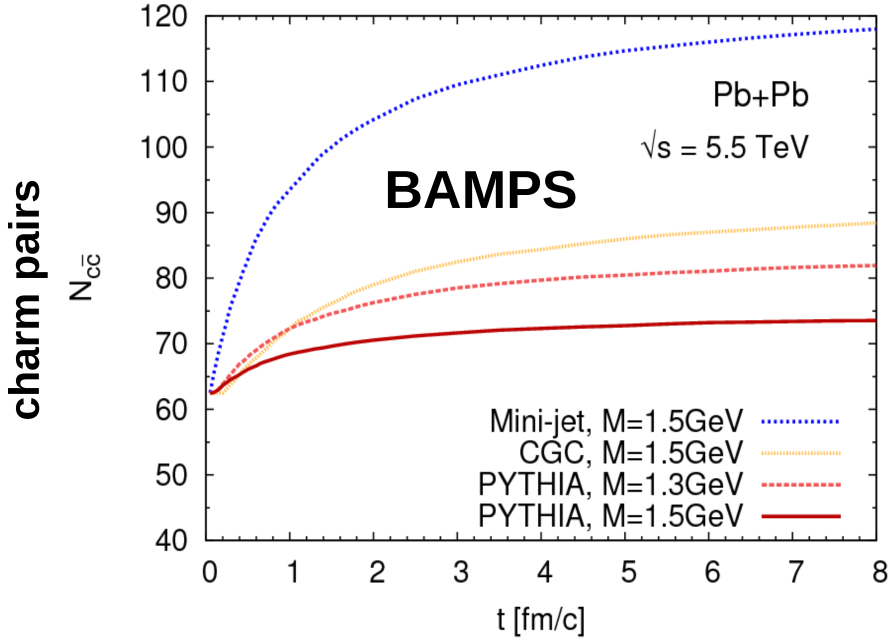
- **MC@NLO**
  Next-to-leading order matrix elements

Initial heavy quark distribution



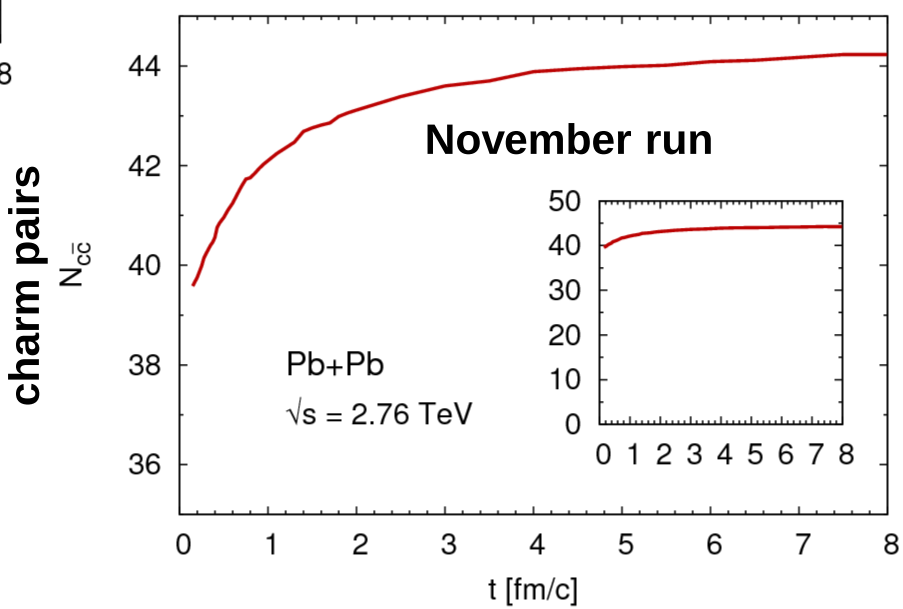
$$\mu_F = \mu_R = 0.65\,\sqrt{p_T^2 + M_c^2}\ \text{for charm}\ (M_c = 1.3\,\text{GeV})$$
$$\mu_F = \mu_R = 0.4\,\sqrt{p_T^2 + M_b^2}\ \text{for bottom quarks}\ (M_b = 4.6\,\text{GeV})$$

Charm production in the QGP at LHC



LHC

Large secondary production
→ Can even be comparable to initial production



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