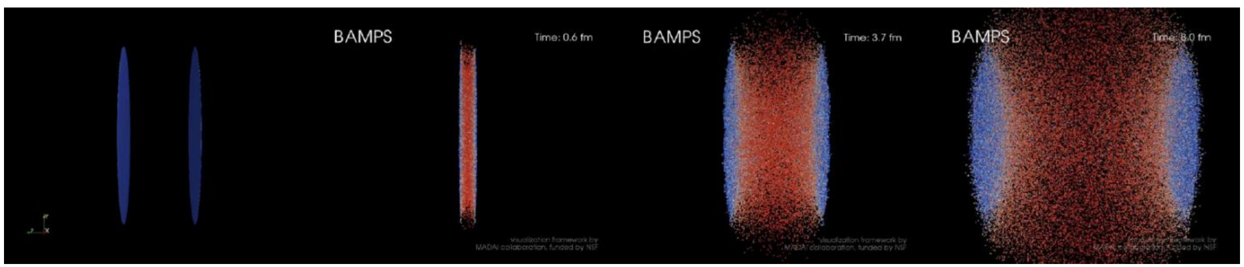
Open heavy flavor at RHIC and LHC

Jan Uphoff

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

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



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H-QM Helmholtz Research School Quark Matter Studies

NeD &TURIC, Hersonissos, Crete, Greece

28 June 2012

Motivation

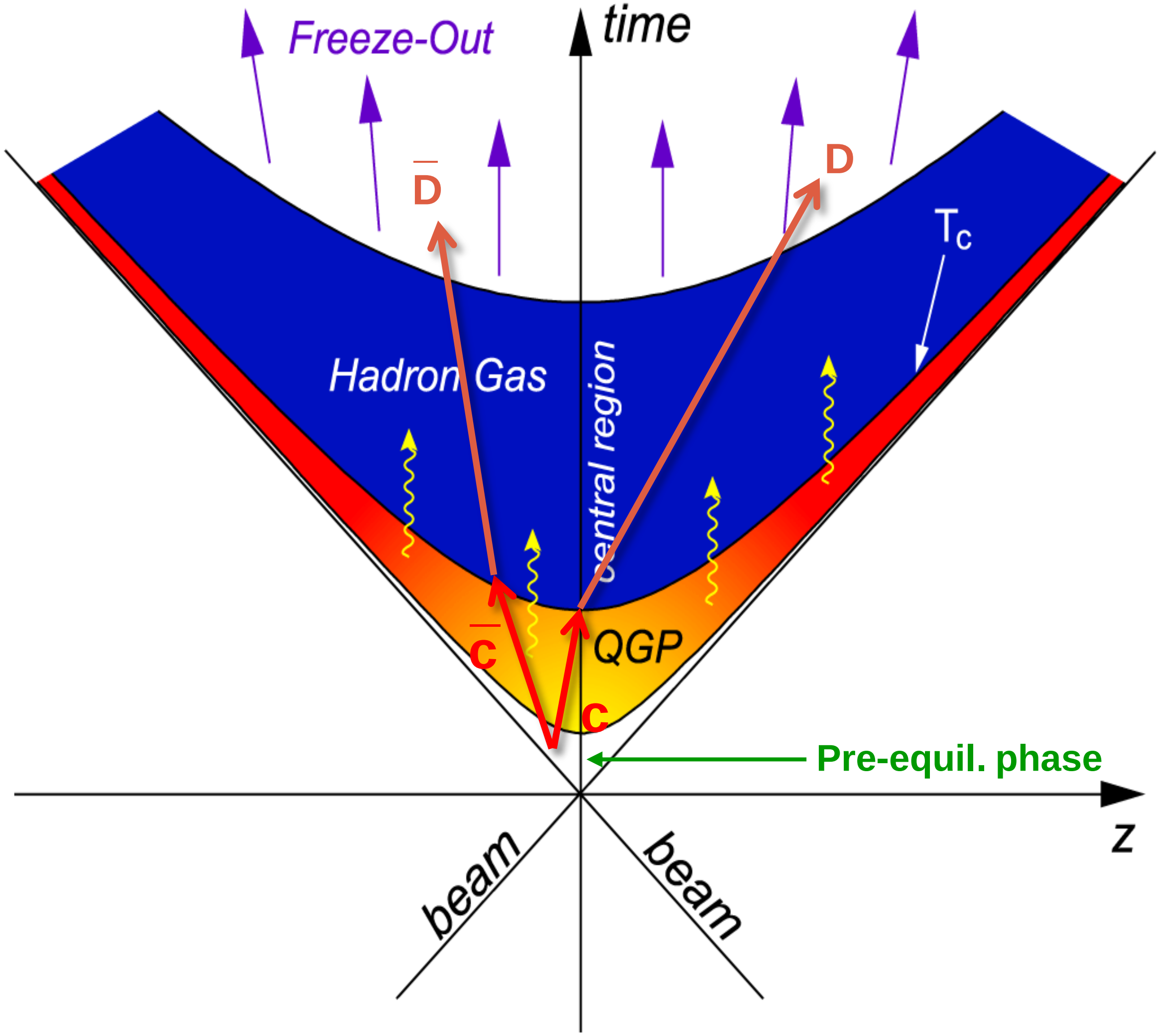
Large heavy quark mass

$\gg \Lambda_{QCD}$

Charm: $M_c \approx 1.3$ GeV

Bottom: $M_b \approx 4.6$ GeV

- Heavy quark production at early stage of collision
- ideal probe for this stage

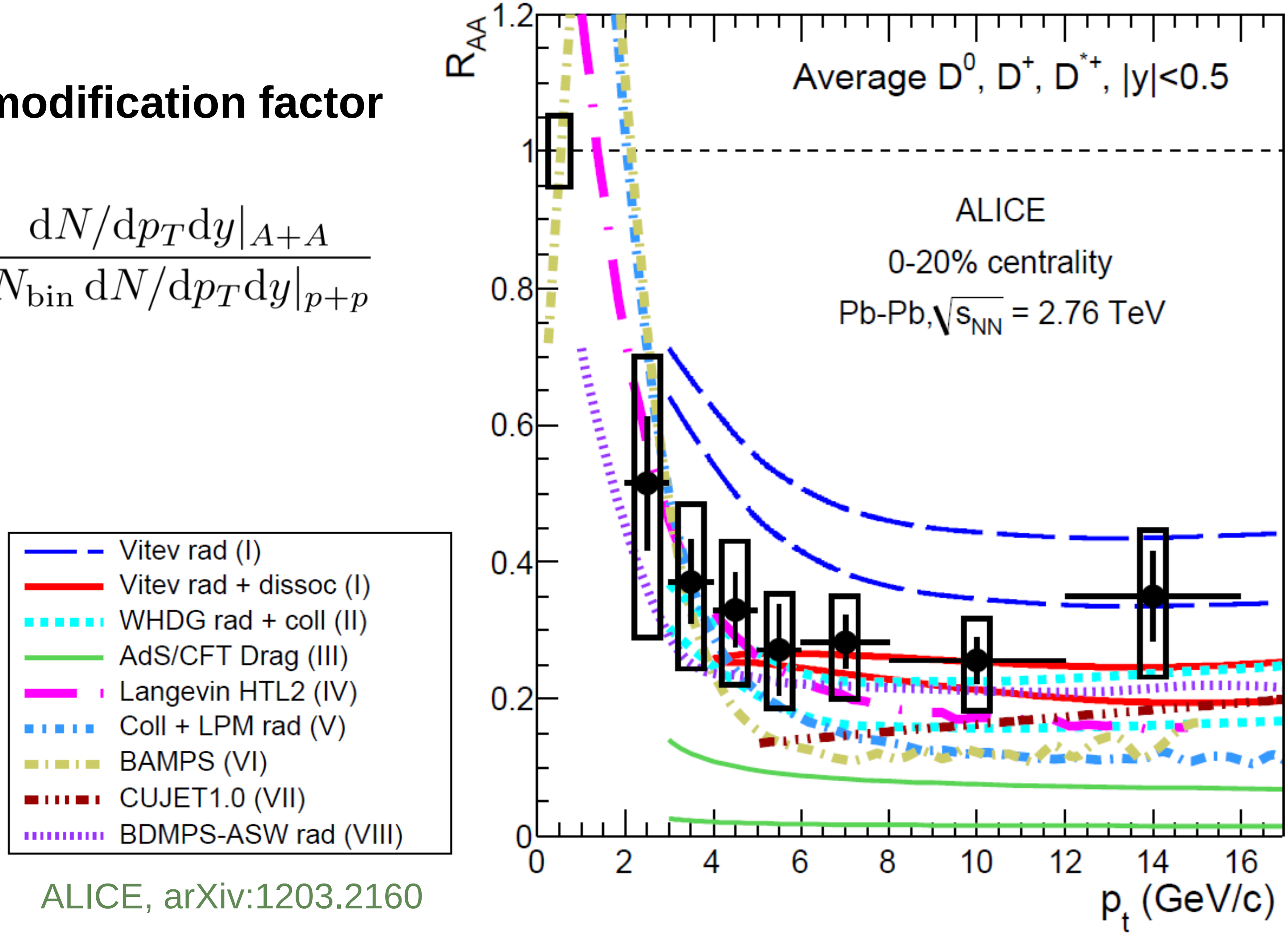


Motivation

Motivation

Nuclear modification factor

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



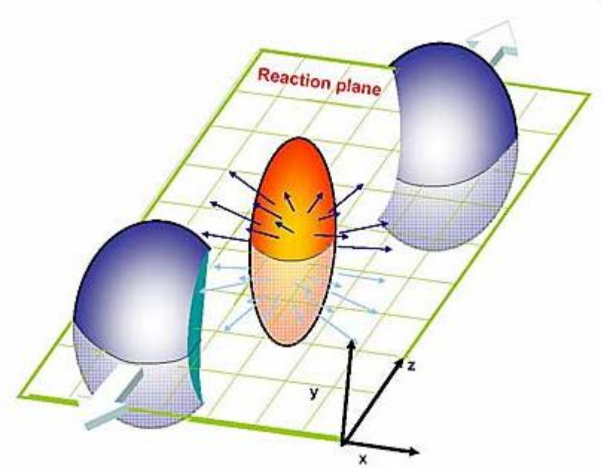
ALICE, arXiv:1203.2160

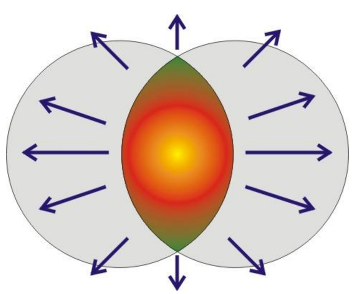
Motivation

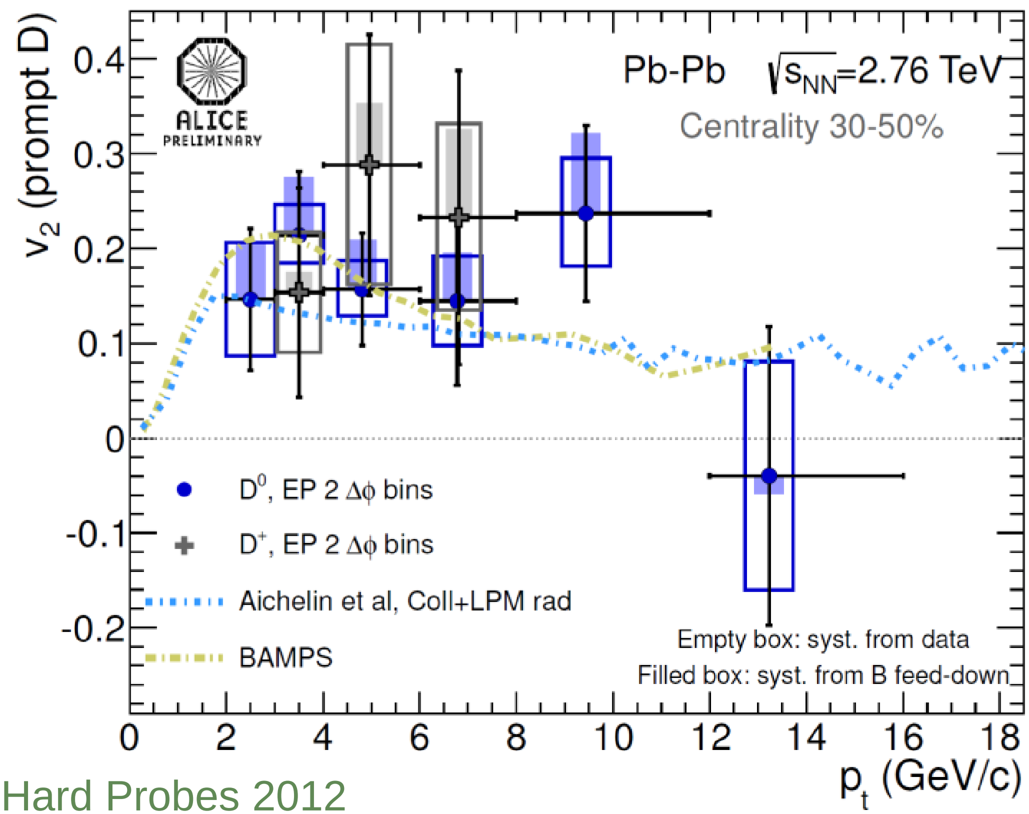
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

Elliptic flow

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







ALICE, Hard Probes 2012

BAMPS

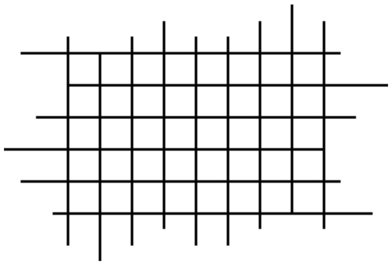
BAMPS: Boltzmann Approach of MultiParton Scatterings

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

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

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

- **Divide collision zone into cells**



- **Using stochastic method**

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

- **Testparticles to increase statistics**

BAMPS with N_{flavor} = 3+2

Implemented processes

Heavy Flavor

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

2 → 2

$g\,g \rightarrow g\,g$

$g\,g \rightarrow q\,\bar{q}$

$q\,\bar{q} \rightarrow g\,g$ and $q\,\bar{q} \rightarrow q'\,\bar{q}'$

$q\,g \rightarrow q\,g$ and $\bar{q}\,g \rightarrow \bar{q}\,g$

$q\,\bar{q} \rightarrow q\,\bar{q}$

$q\,q \rightarrow q\,q$ and $\bar{q}\,\bar{q} \rightarrow \bar{q}\,\bar{q}$

$q\,q' \rightarrow q\,q'$ and $q\,\bar{q}' \rightarrow q\,\bar{q}'$

2 ↔ 3

$g\,g \leftrightarrow g\,g\,g$

$q\,g \leftrightarrow q\,g\,g$ and $\bar{q}\,g \leftrightarrow \bar{q}\,g\,g$

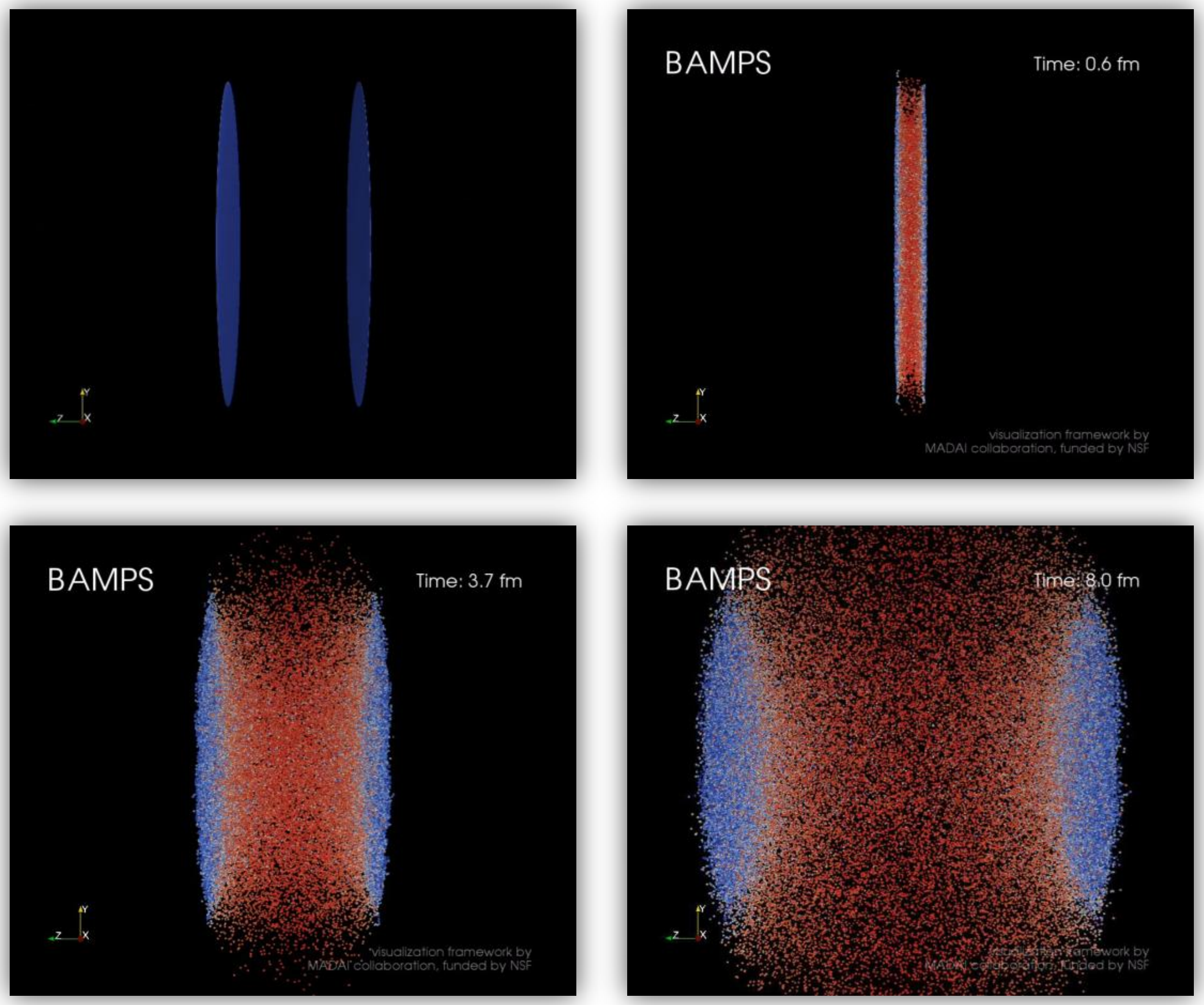
$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$

$q\,q \leftrightarrow q\,q\,g$ and $\bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$

$q\,q' \leftrightarrow q\,q'\,g$ and $q\,\bar{q}' \leftrightarrow q\,\bar{q}'\,g$

Heavy-ion collision at LHC

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



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

Sketch of heavy-ion collision in BAMPS

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Heavy flavor in BAMPS

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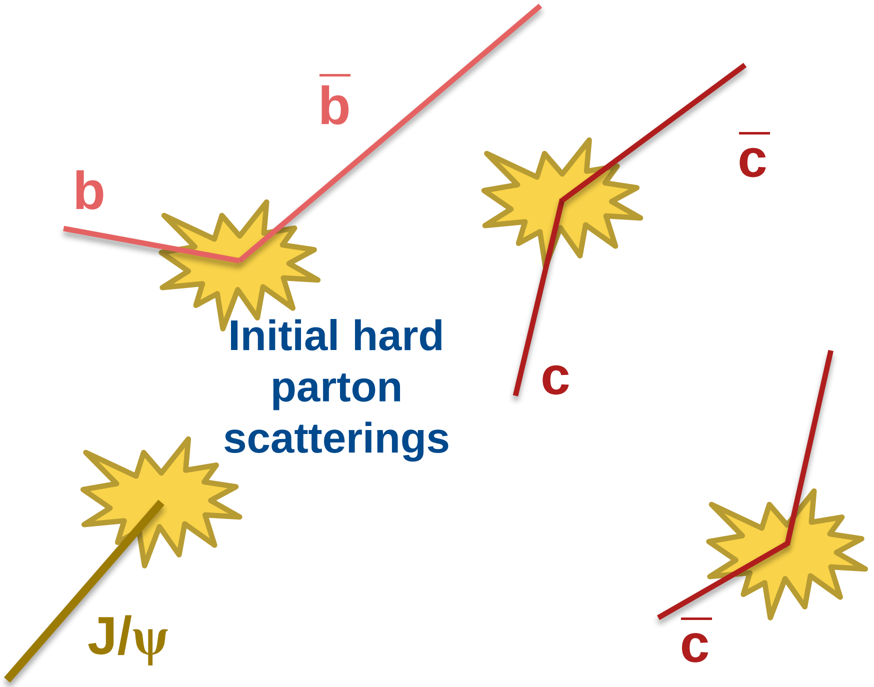
Heavy flavor in BAMPS



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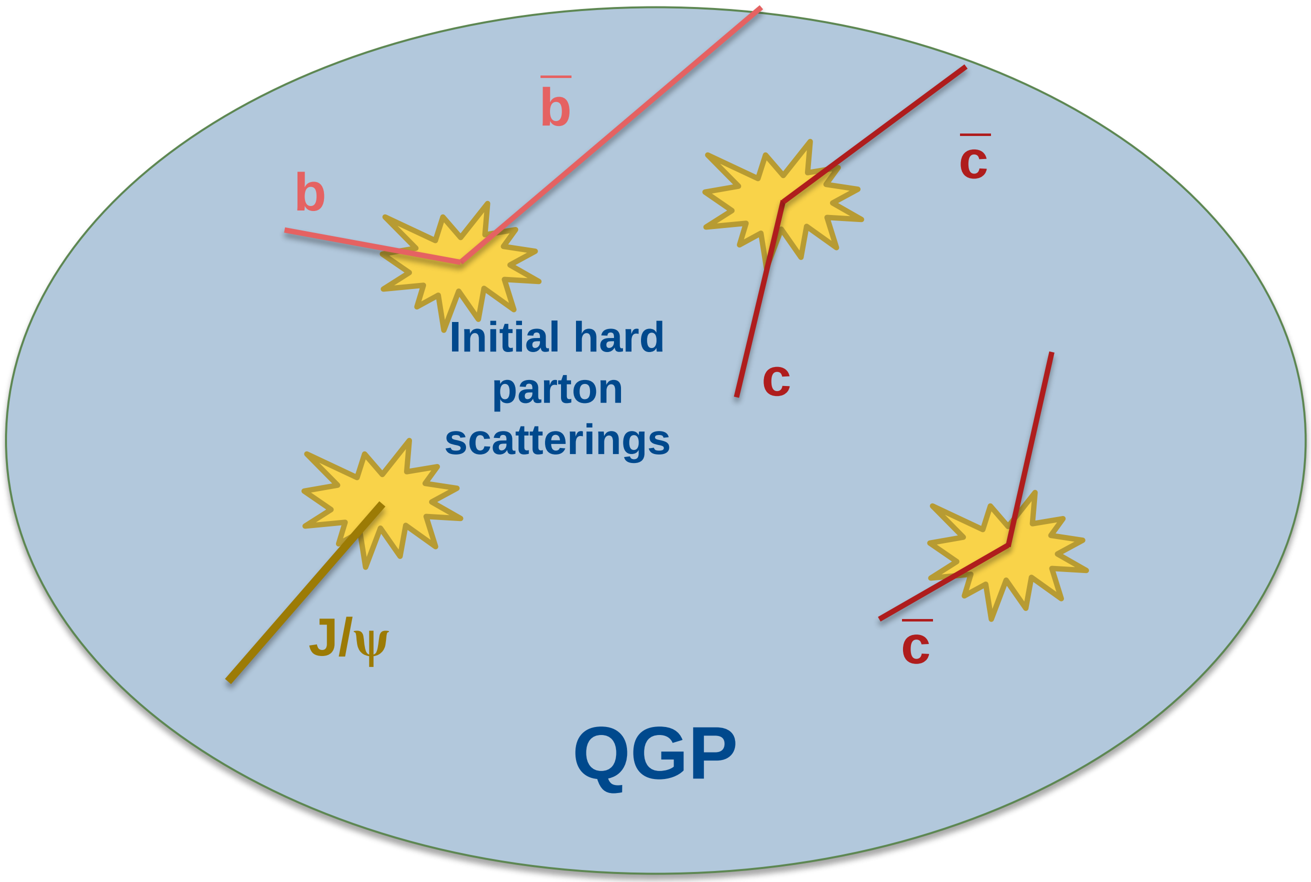
Heavy flavor in BAMPS



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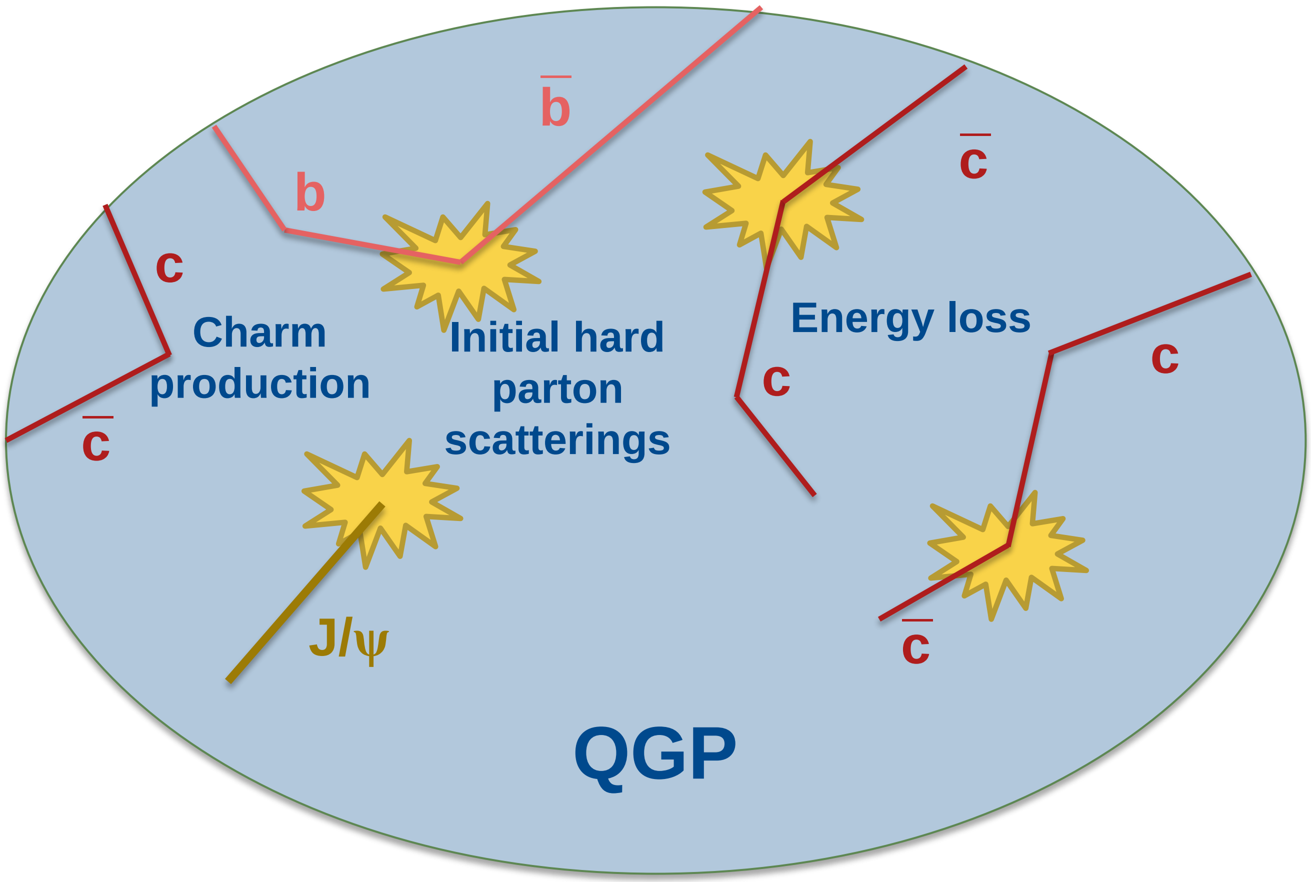

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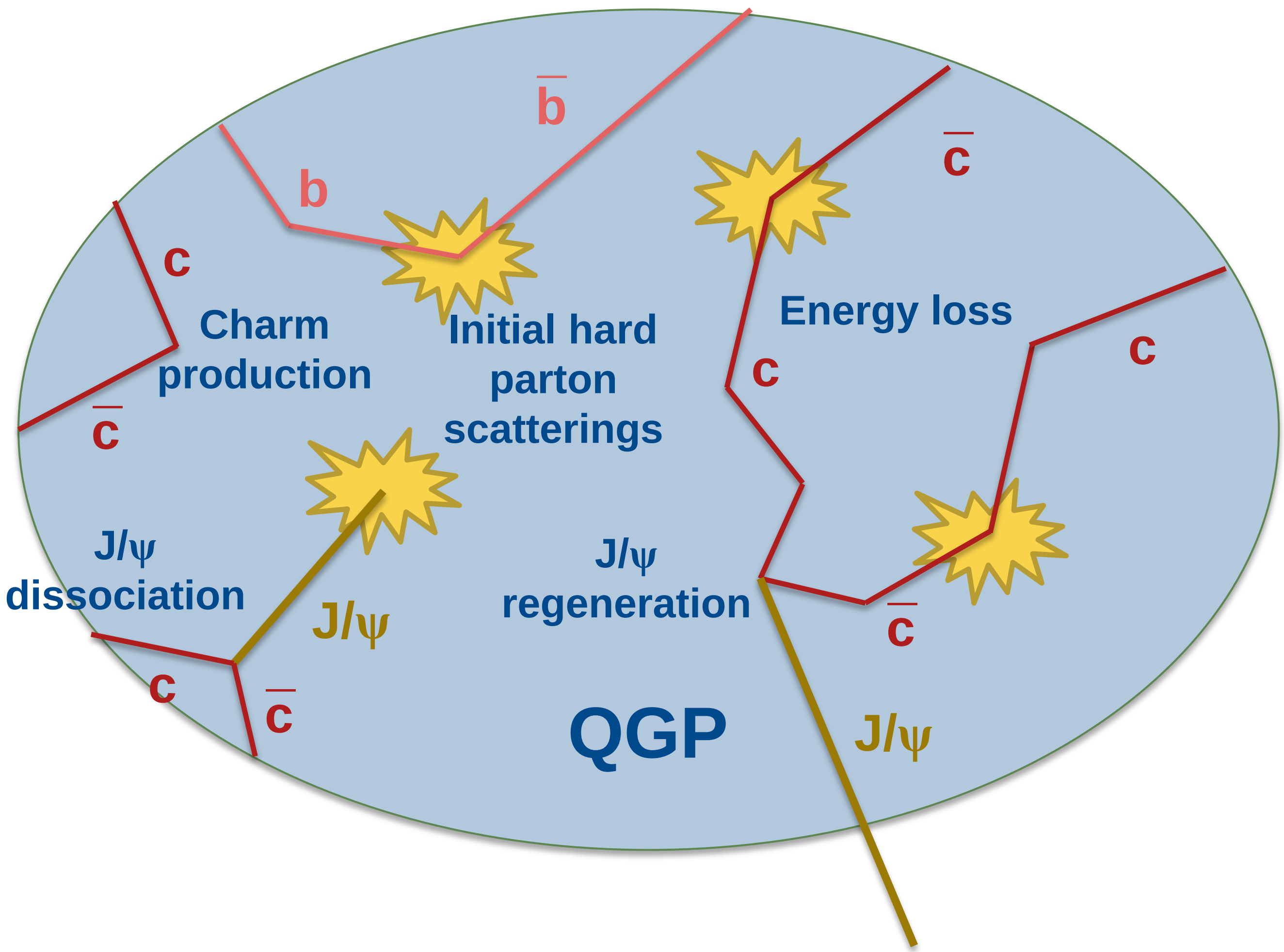
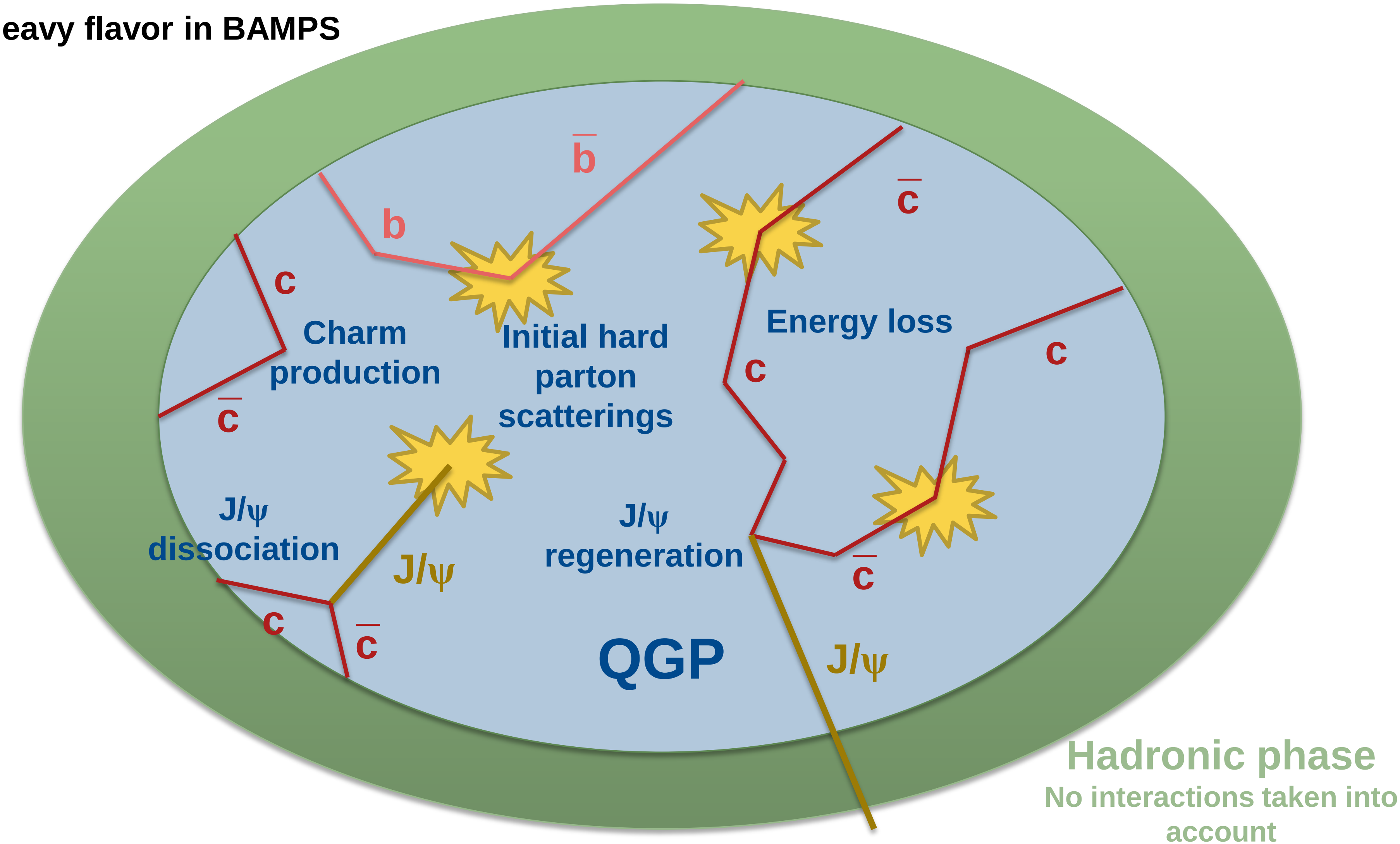
Heavy flavor in BAMPS

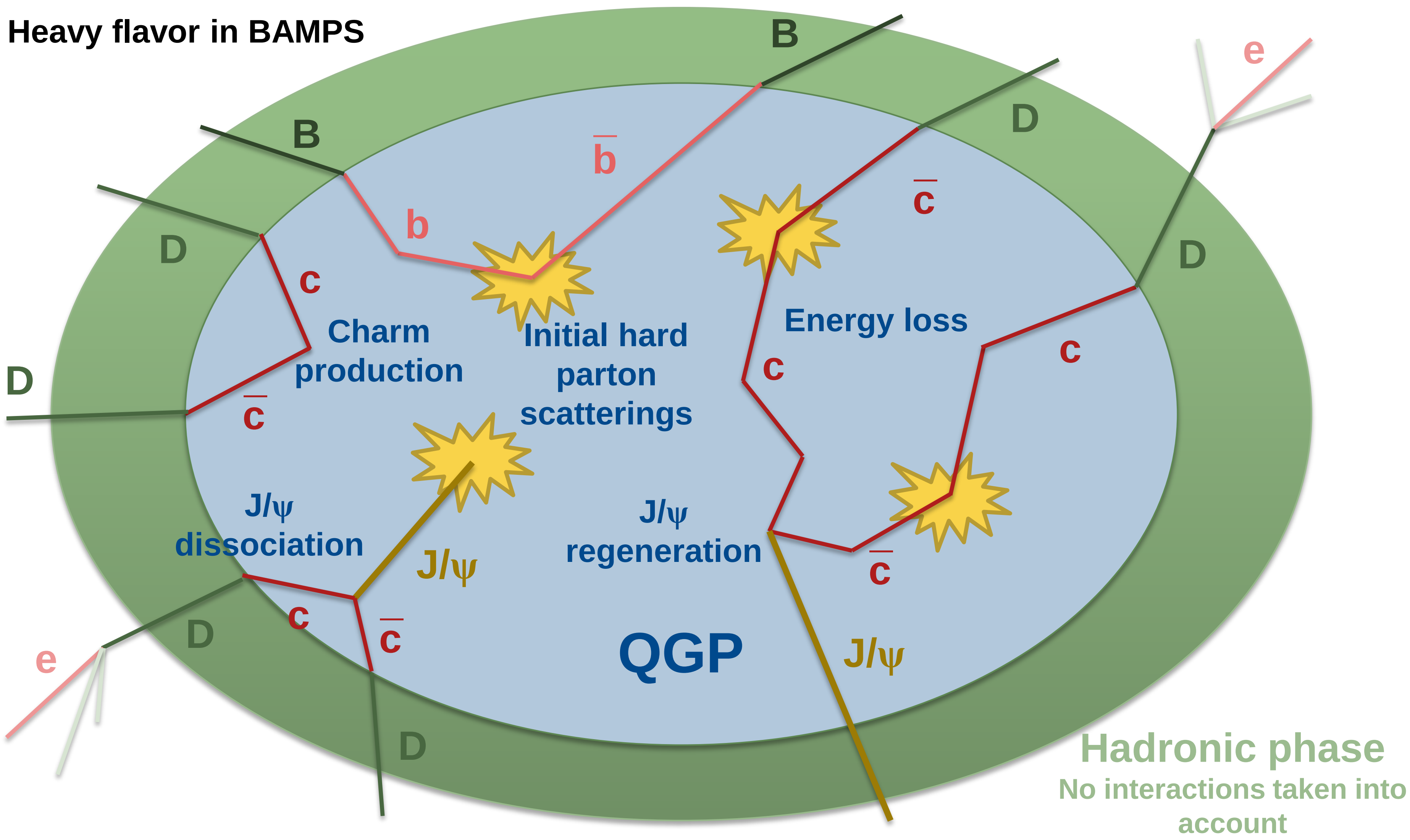


Sketch of heavy-ion collision in BAMPS

Heavy flavor in BAMPS



Sketch of heavy-ion collision in BAMPS



Heavy quark scattering

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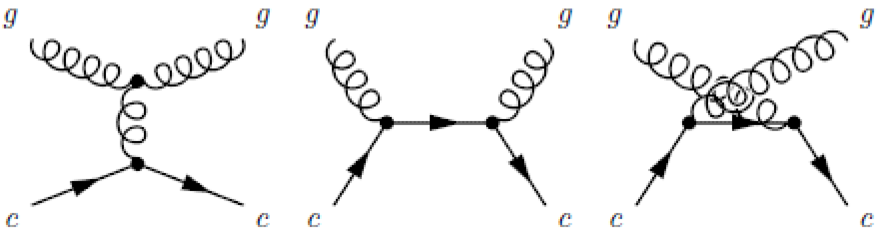
Leading order perturbative QCD:

$$g + Q \to g + Q$$
$$q + Q \to q + Q$$



t channel is divergent for small t

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

κ **can be fixed to**

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

by comparing dE/dx to HTL result beyond logarithmic accuracy

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

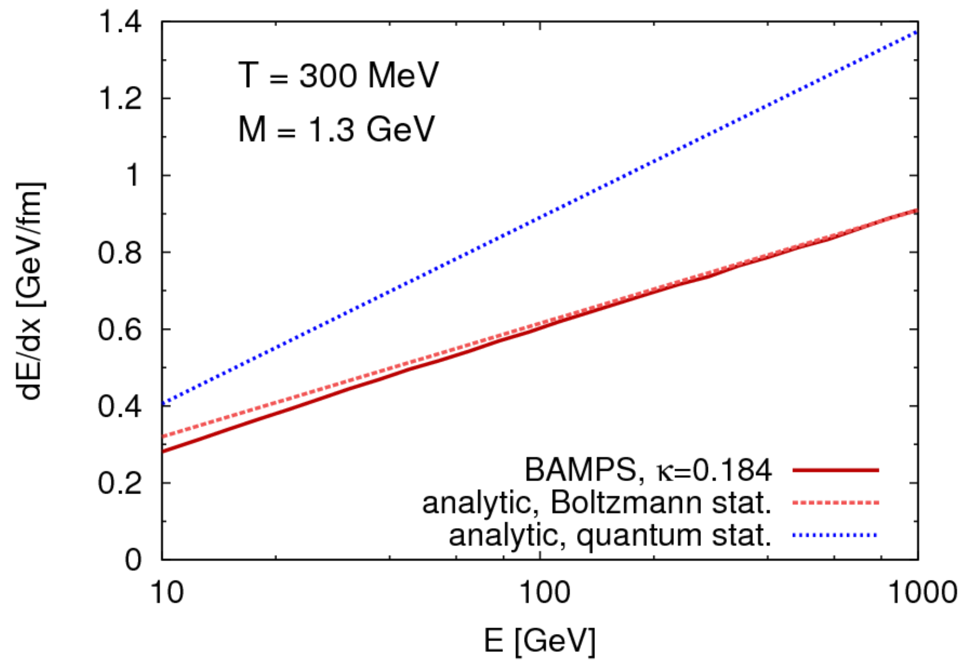
P.B. Gossiaux,
J. Aichelin,
Phys.Rev.C78 (2008)

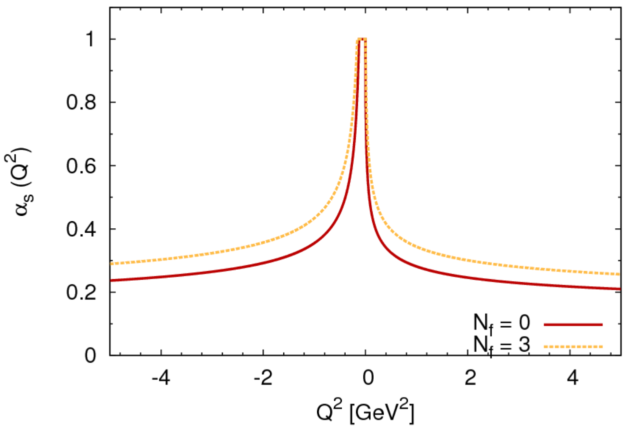
Heavy quark scattering

Compare to analytic formula

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

Details: - Peigne & Peshier (2008)
- JU, Fochler, Xu, Greiner
Phys. Rev. C 84 (2011)





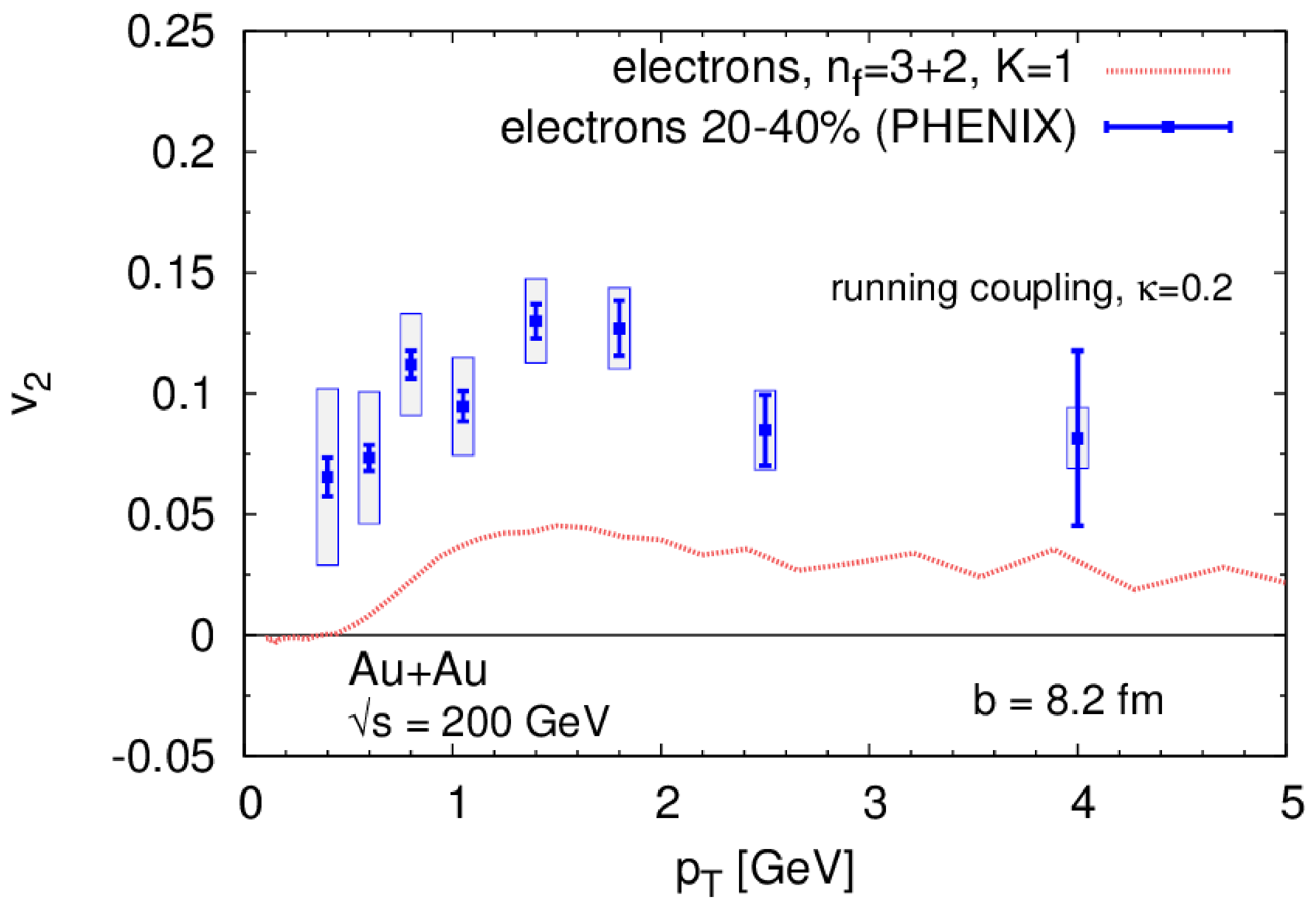
Introduce a running coupling constant for all channels

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

RHIC results

Heavy quark elliptic flow v_2 at RHIC

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



RHIC

What is missing:

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

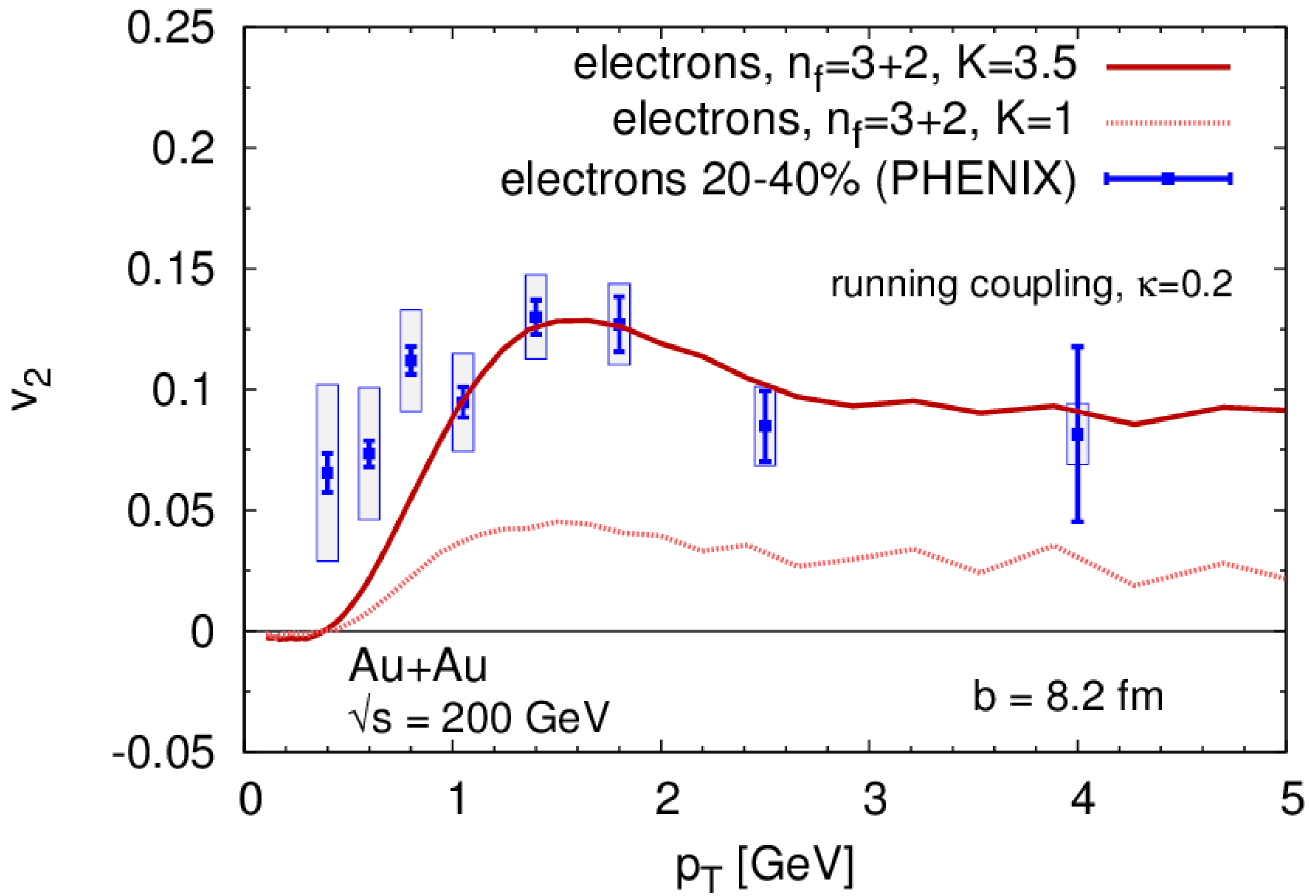
PHENIX, arXiv:1005.1627

only elastic heavy quark processes

JU, Fochler, Xu, Greiner
arXiv:1205.4945

Heavy quark elliptic flow v_2 at RHIC

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



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JU, Fochler, Xu, Greiner
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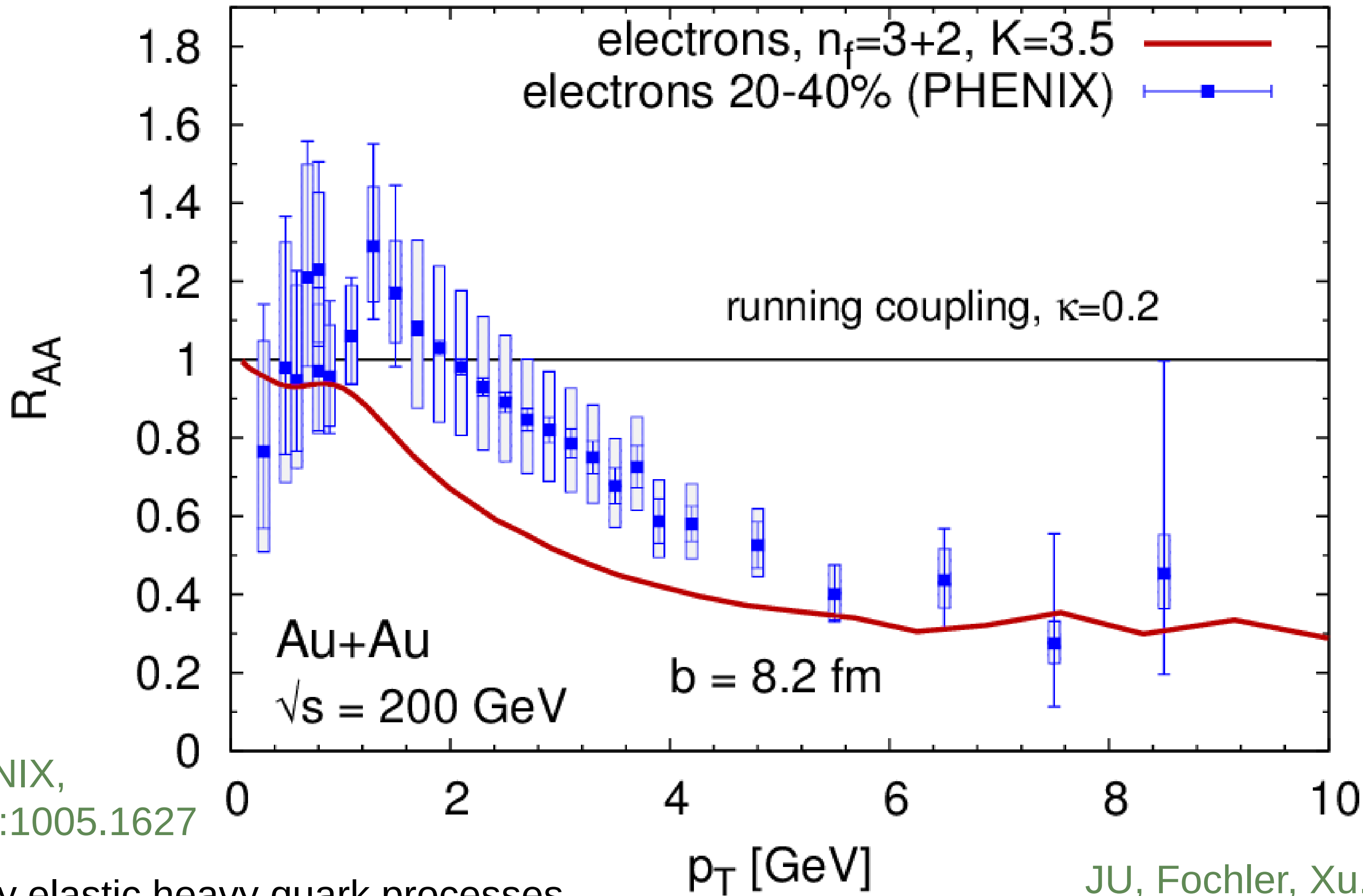
Heavy quark R_{AA} at RHIC

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



RHIC

PHENIX, arXiv:1005.1627

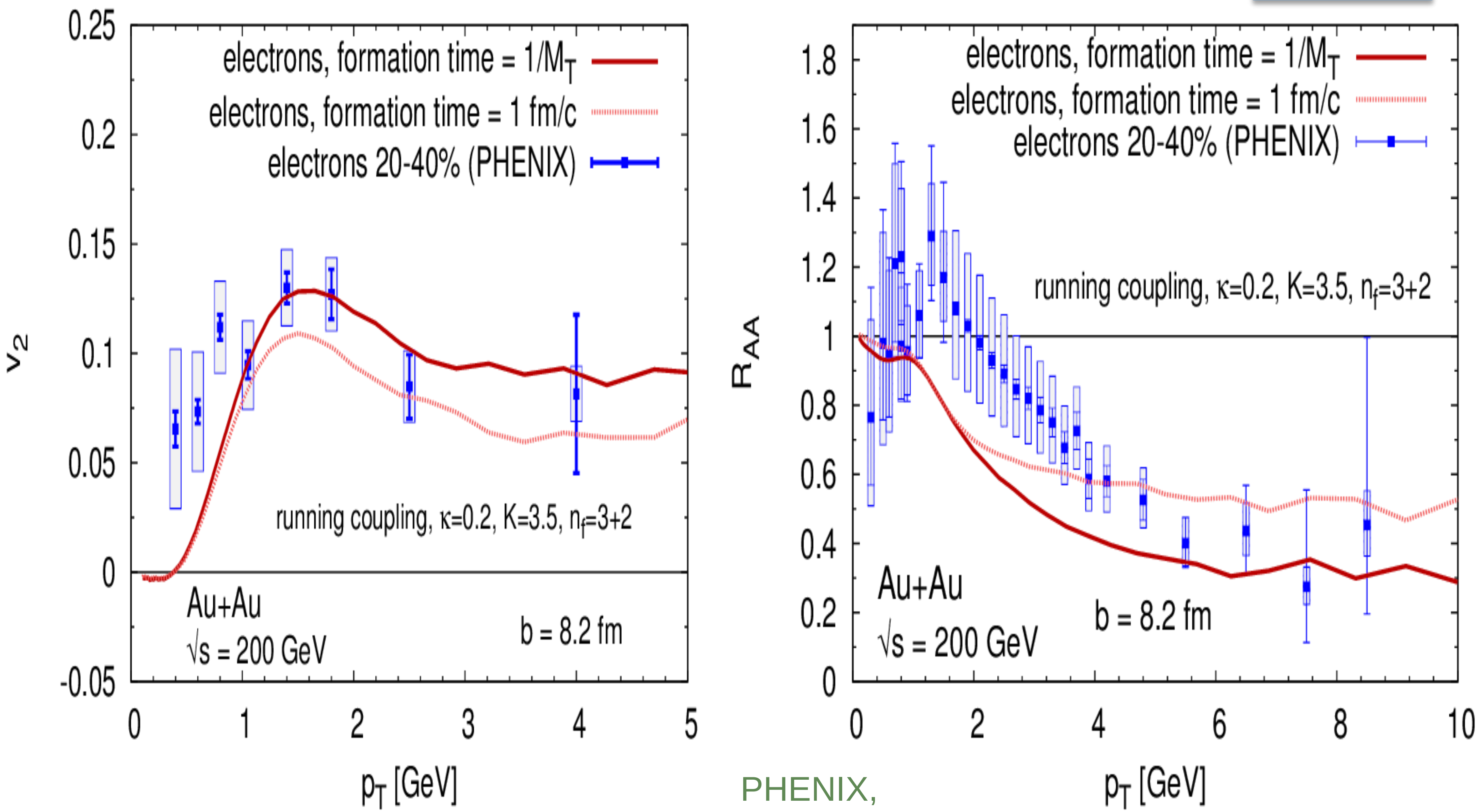
only elastic heavy quark processes

JU, Fochler, Xu, Greiner
arXiv:1205.4945

Influence of formation time

RHIC

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



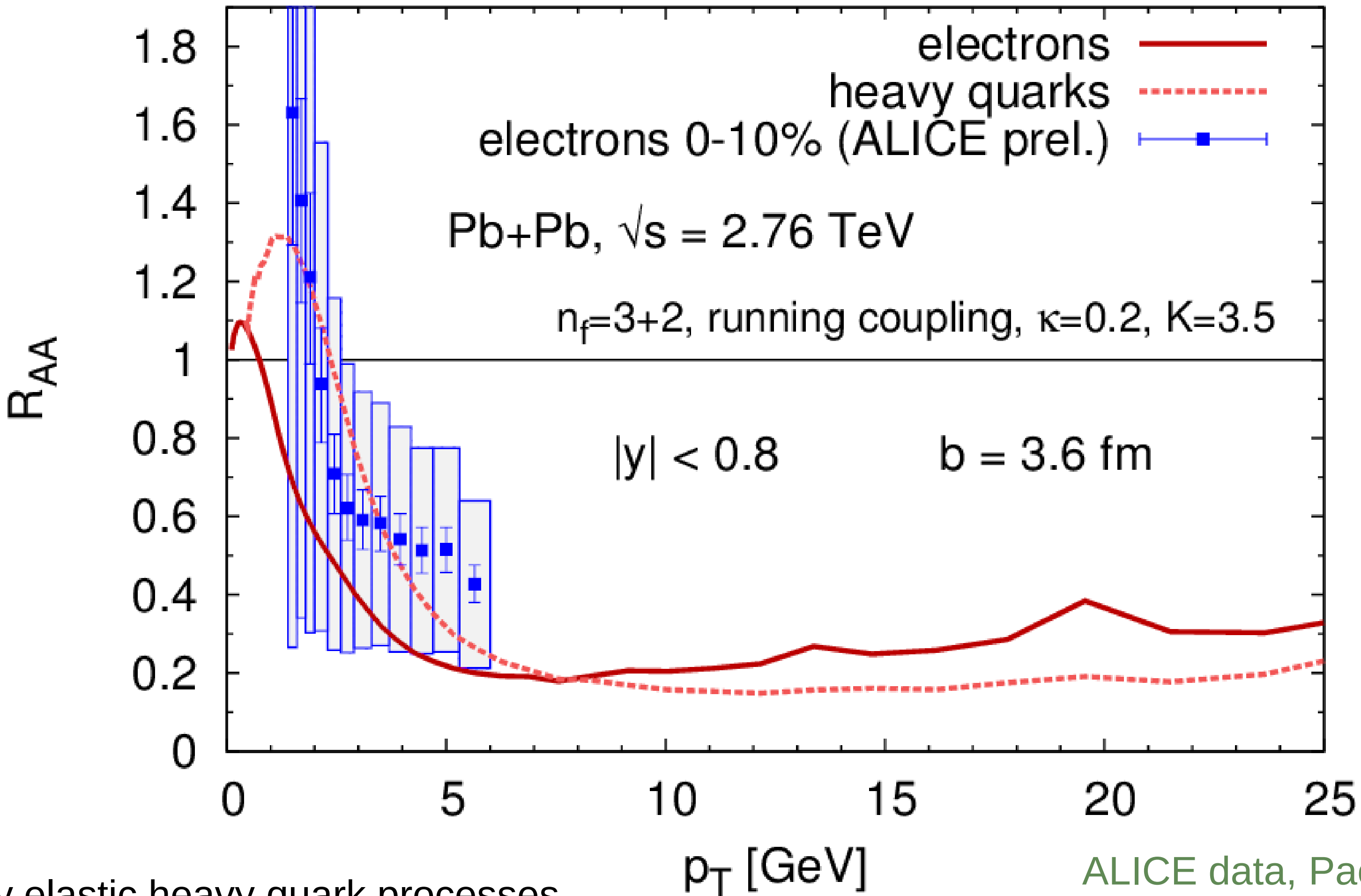
PHENIX, arXiv:1005.1627

only elastic heavy quark processes

LHC results

Heavy flavor electron R_{AA} at LHC

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



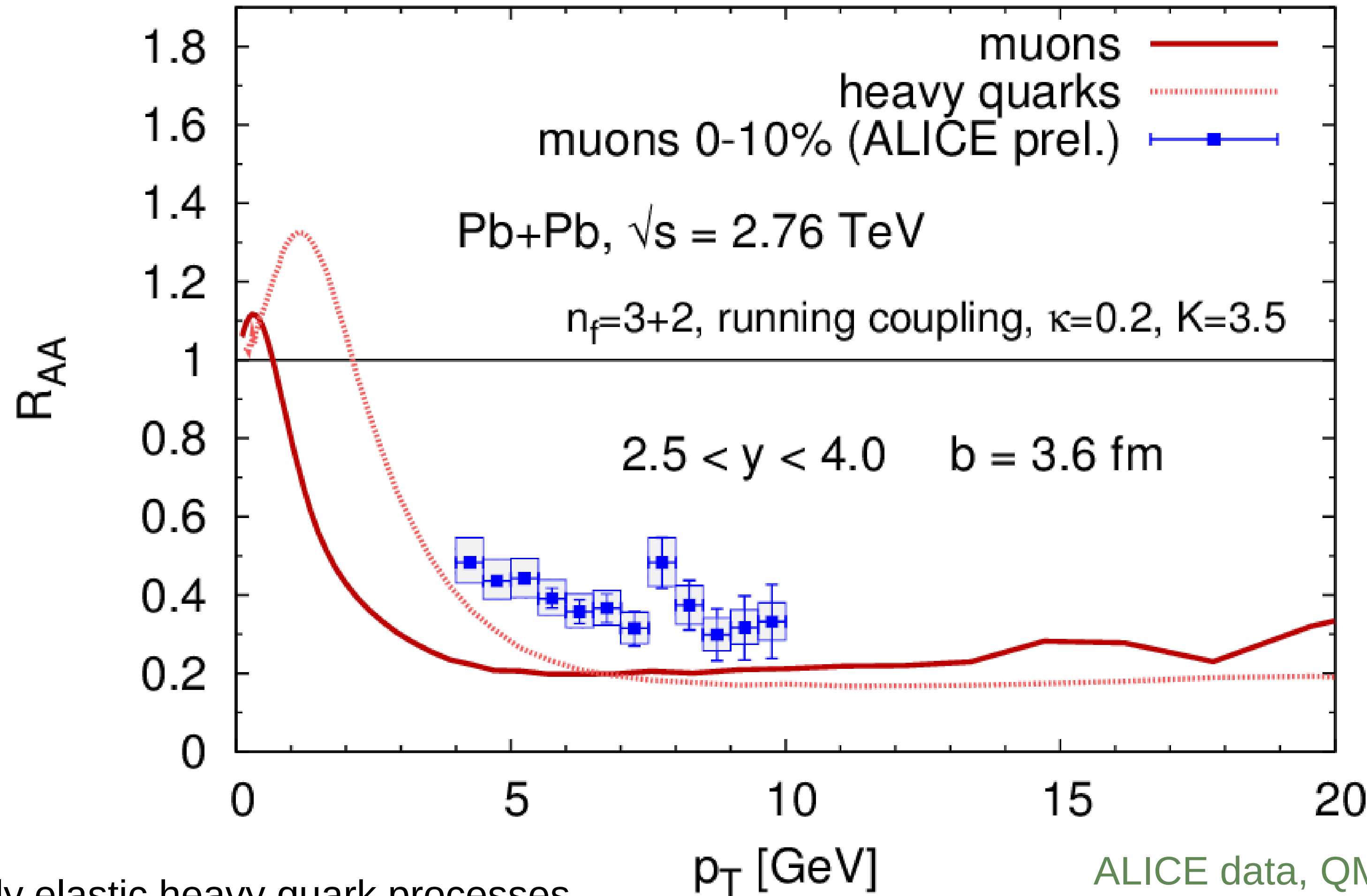
LHC

only elastic heavy quark processes

ALICE data, Pachmayer, QM 2011

Muon R_{AA} at forward rapidity at LHC

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



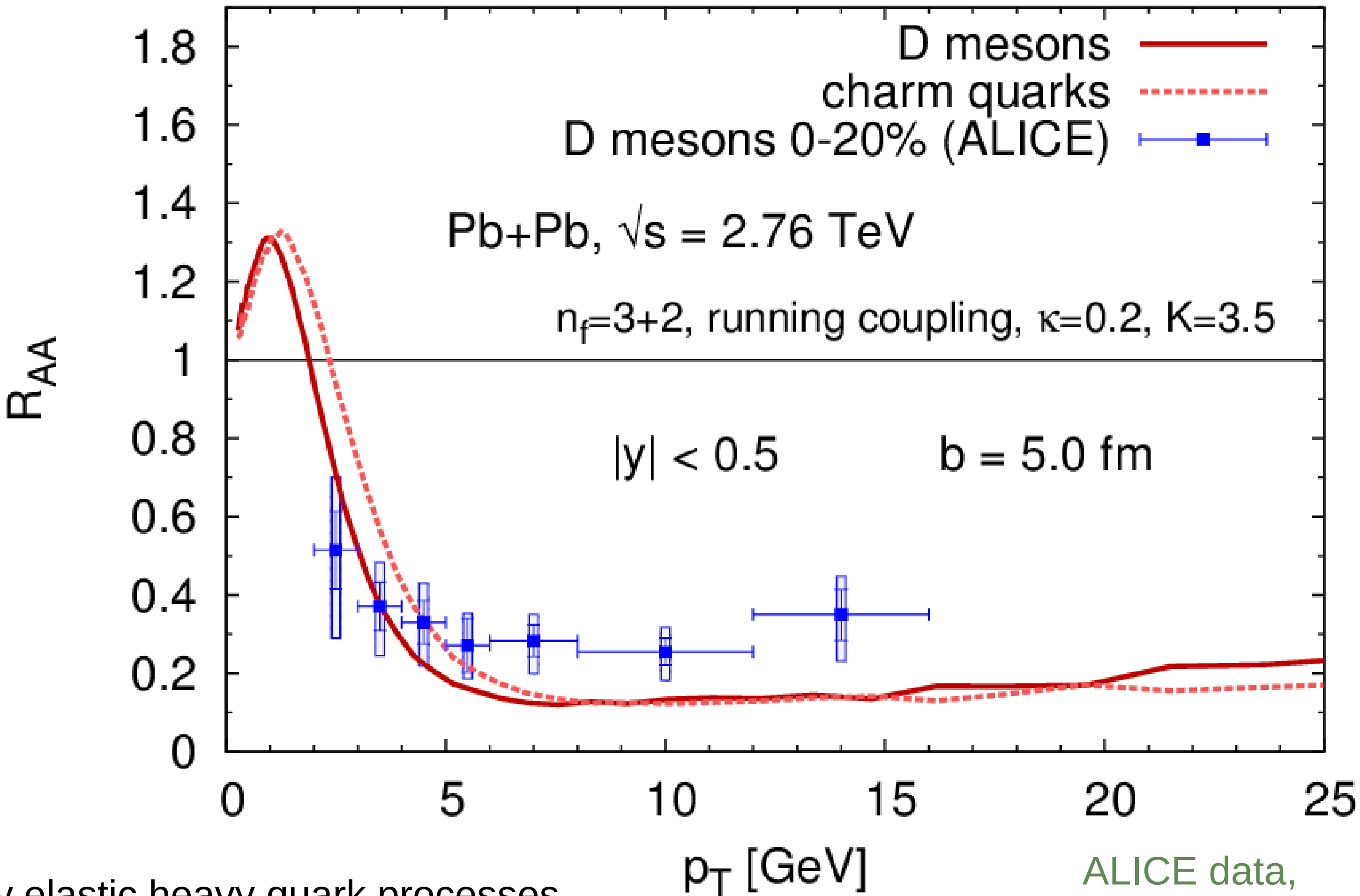
LHC

only elastic heavy quark processes

ALICE data, QM 2011, arXiv:1106.4042

D meson R_{AA} at LHC

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



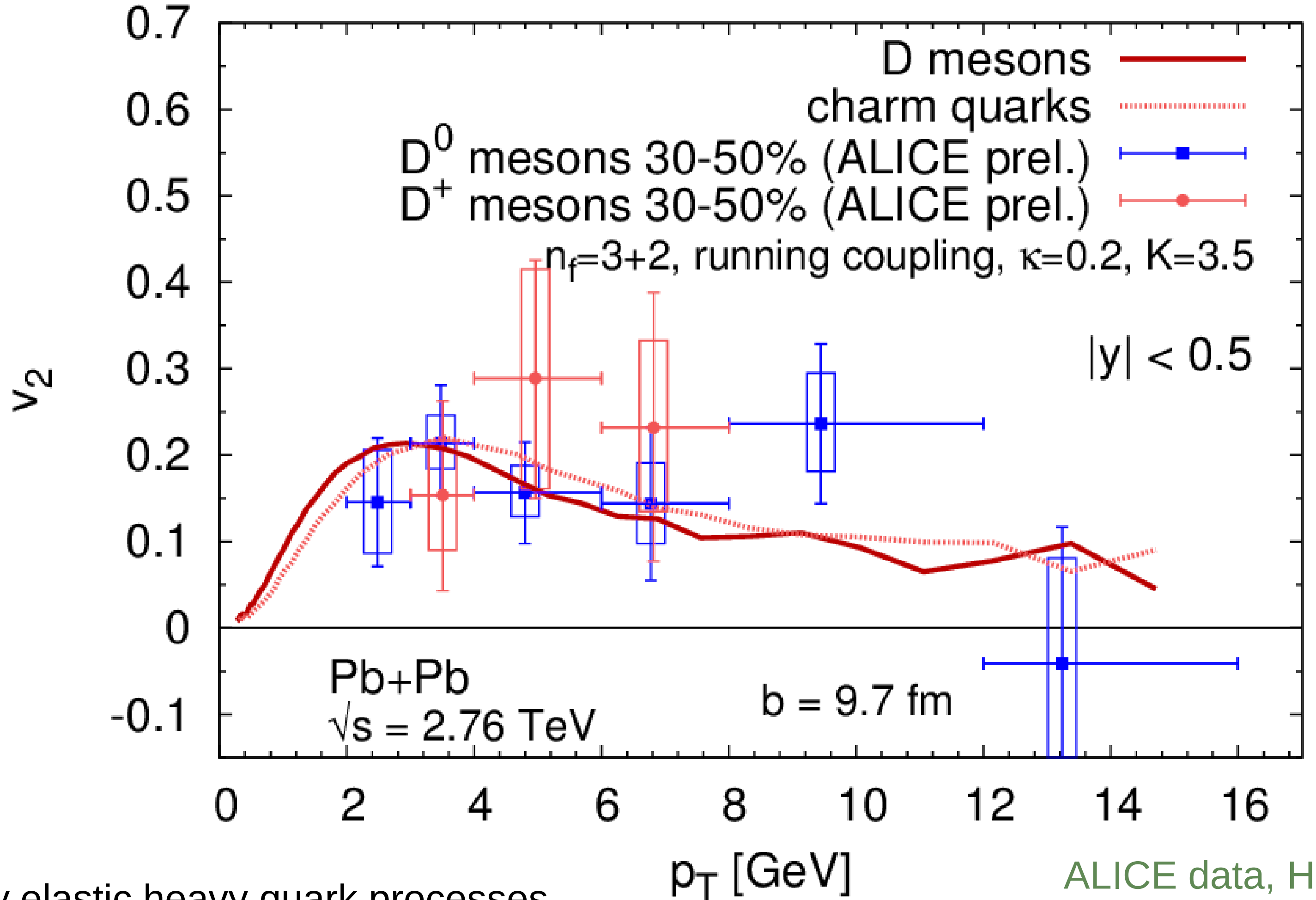
LHC

only elastic heavy quark processes

ALICE data, arXiv:1203.2160

D meson v_2 at LHC

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



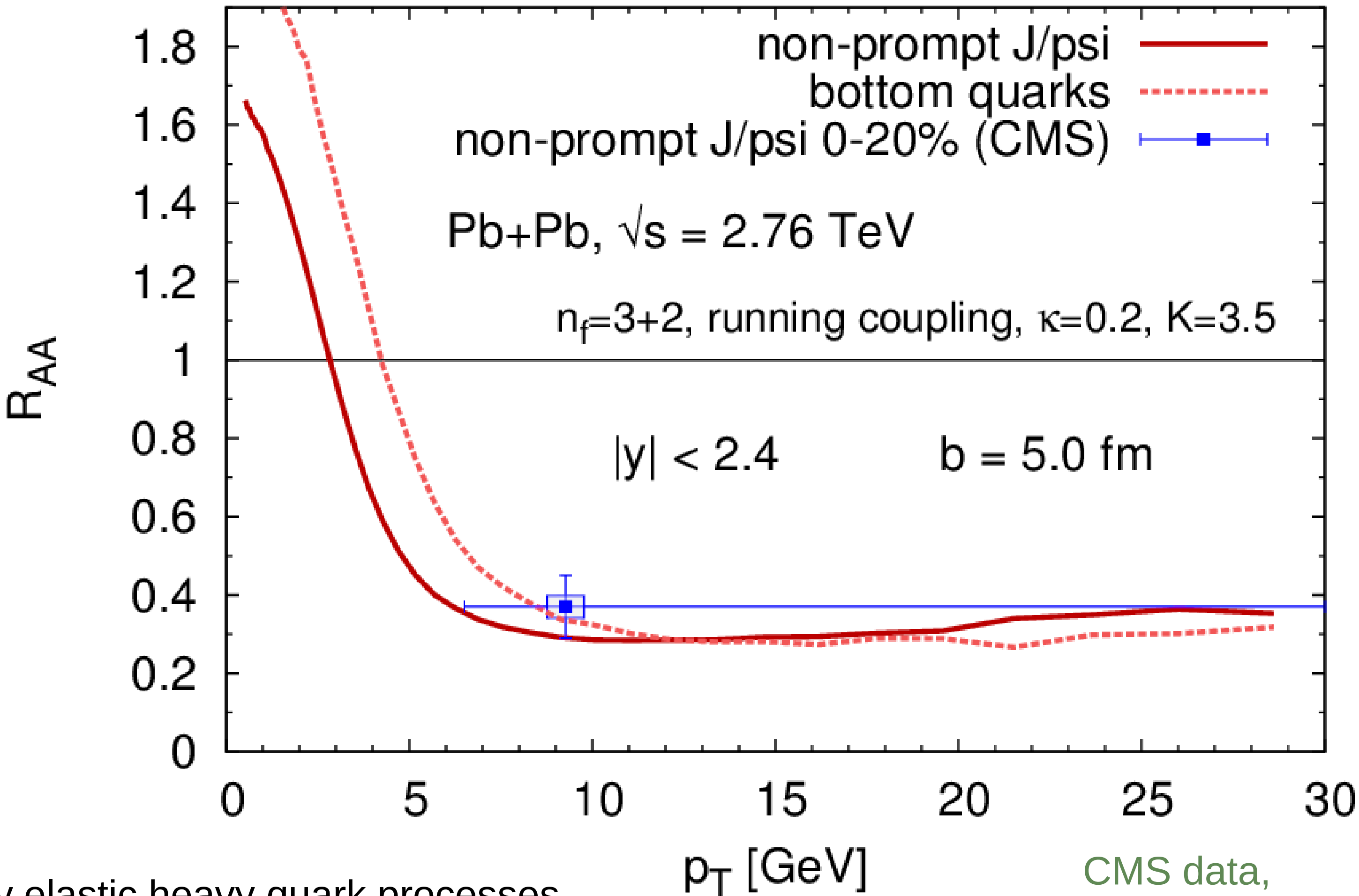
LHC

only elastic heavy quark processes

ALICE data, Hard Probes 2012

Non-prompt J/psi R_{AA} at LHC

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



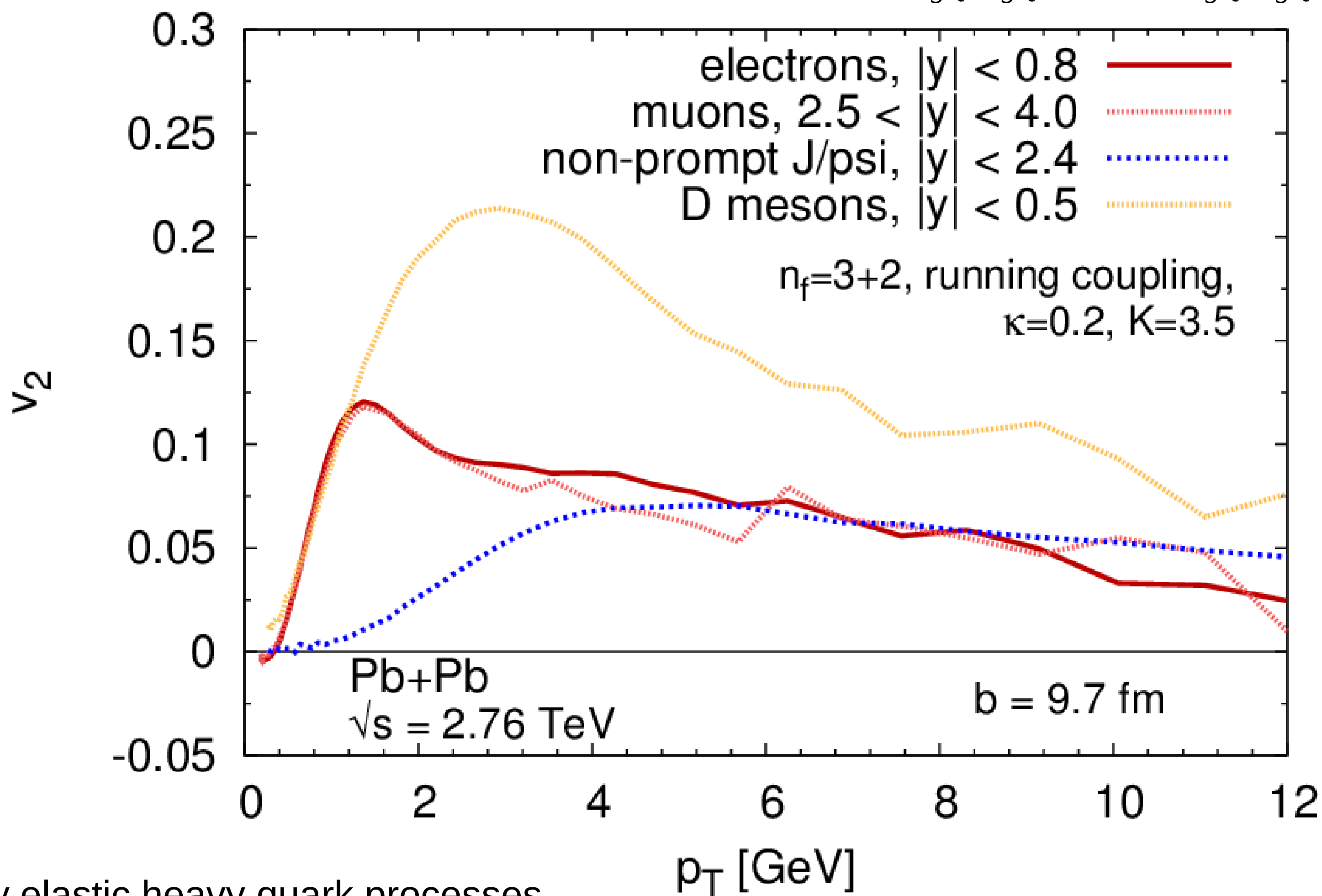
LHC

only elastic heavy quark processes

CMS data, arXiv:1201.5069

v_2 predictions for the LHC

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



LHC

only elastic heavy quark processes

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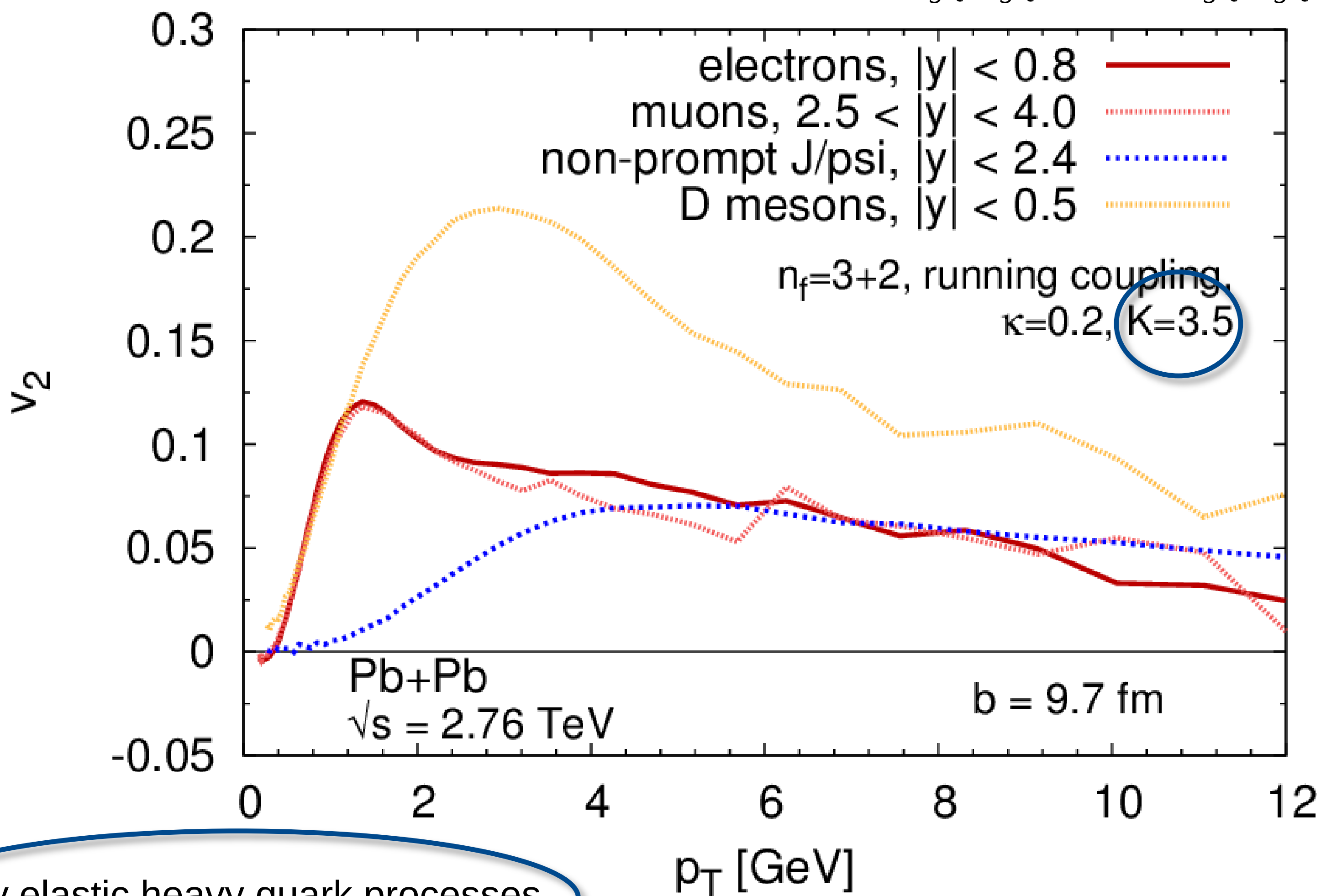


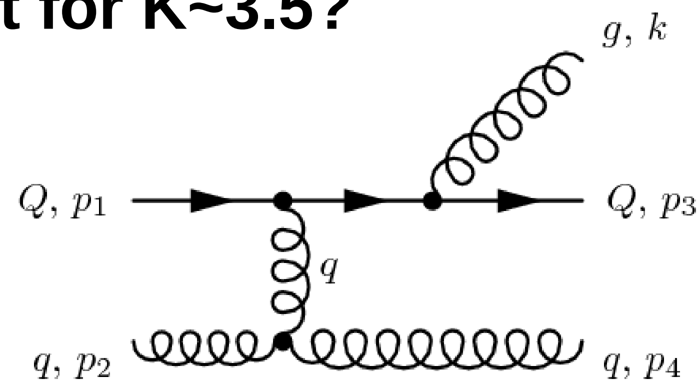
LHC

only elastic heavy quark processes

Radiative processes

Can radiative processes account for K~3.5?

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

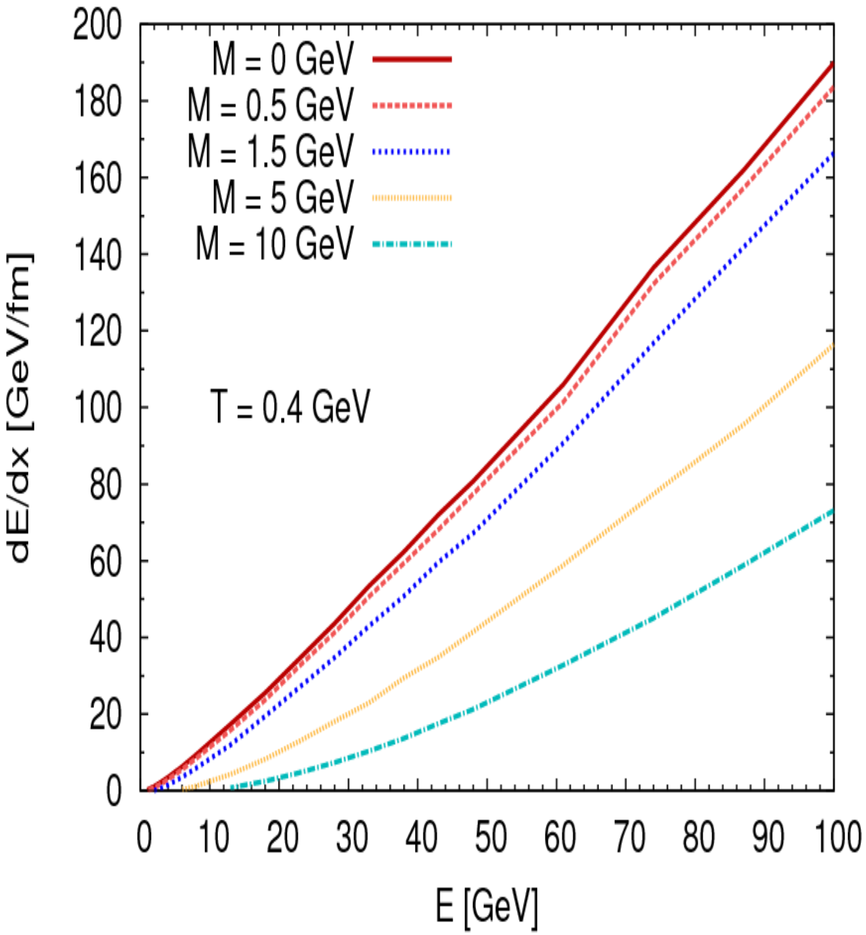


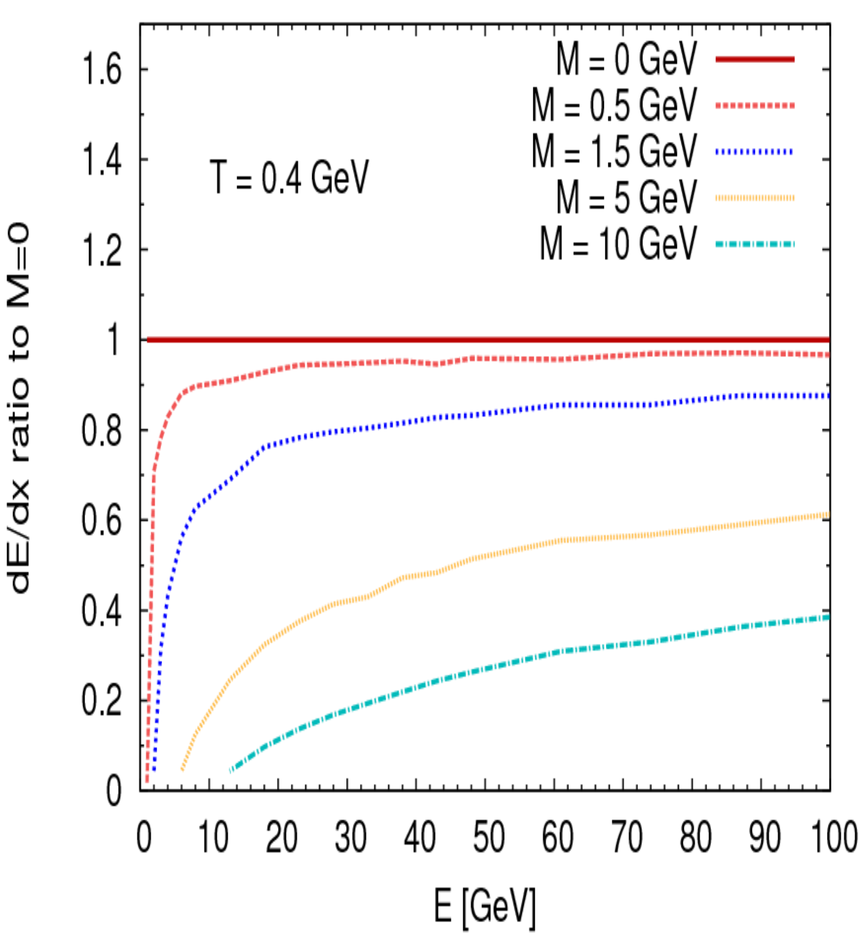
Gunion-Bertsch matrix element generalized to heavy quarks:

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

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

Energy loss in static medium

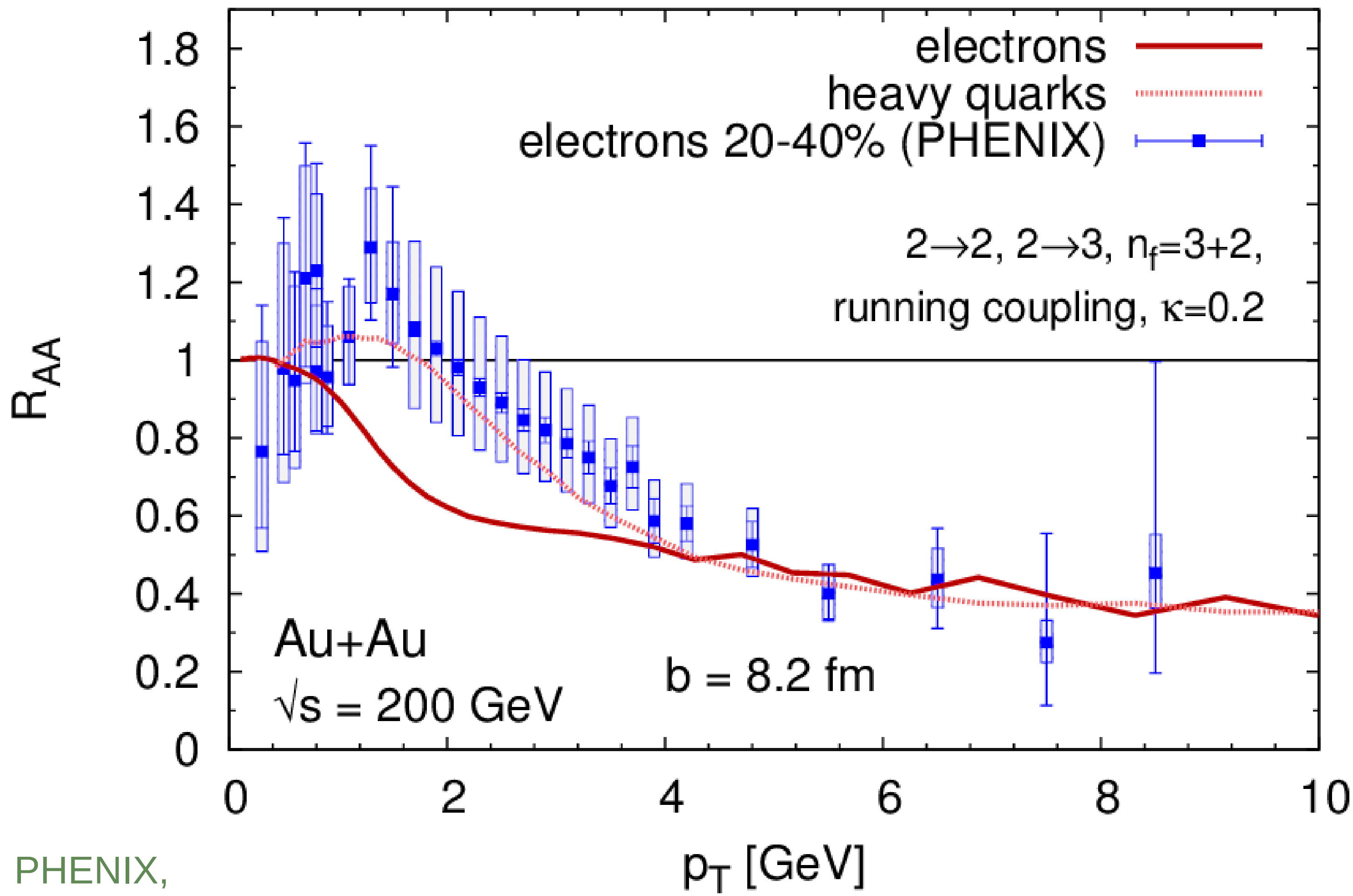




Fixed coupling, without LPM effect

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

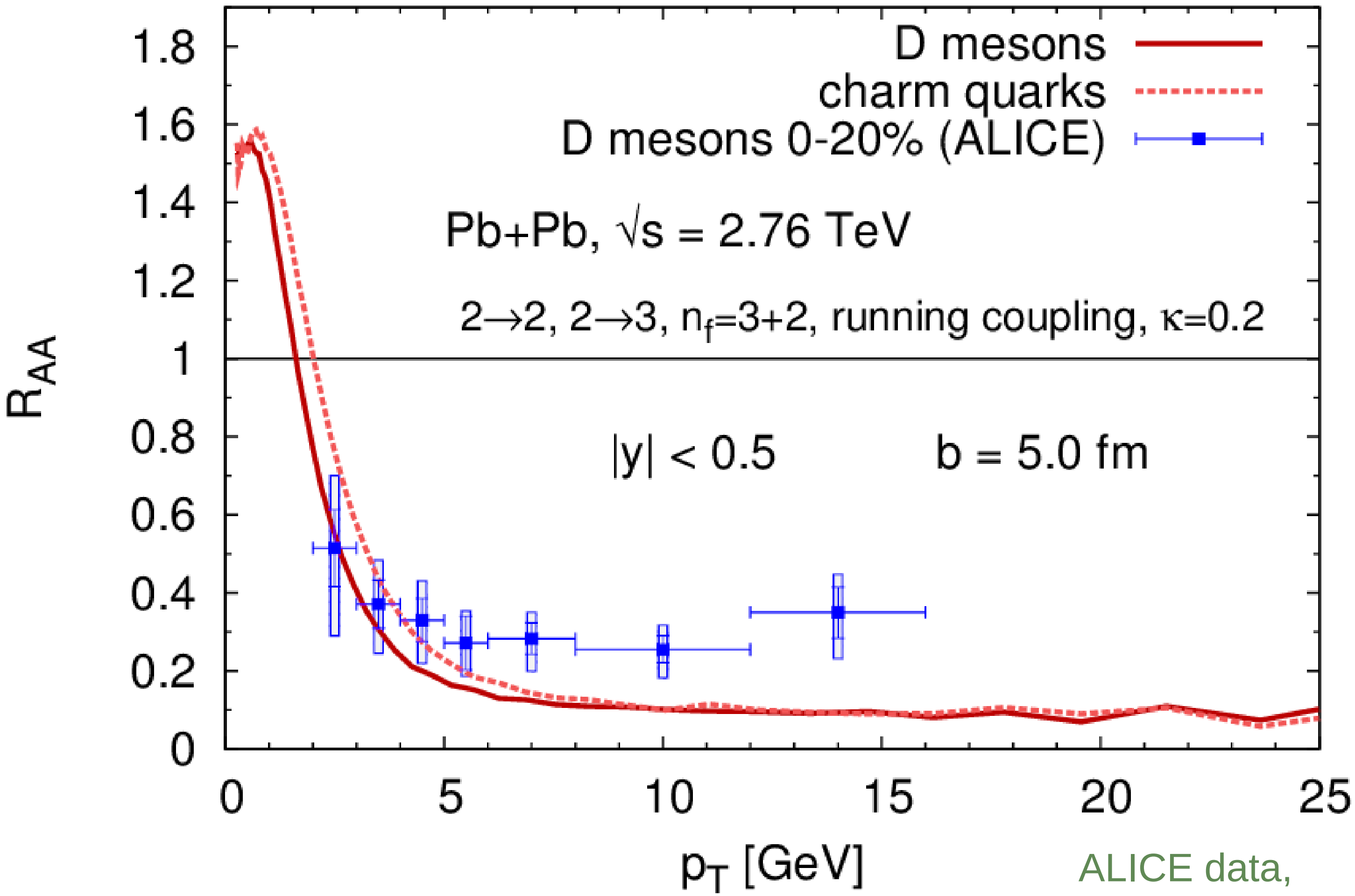
preliminary



RHIC

PHENIX, arXiv:1005.1627

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



LHC

ALICE data, arXiv:1203.2160

Conclusions & outlook

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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 if K=3.5 is introduced**
- **Good agreement with D meson v_2 at LHC**
- **RAA of D mesons, non-prompt J/psi and muon at LHC underestimated**
- **Preliminary results with $2 \rightarrow 3$ in full cascade are promising**

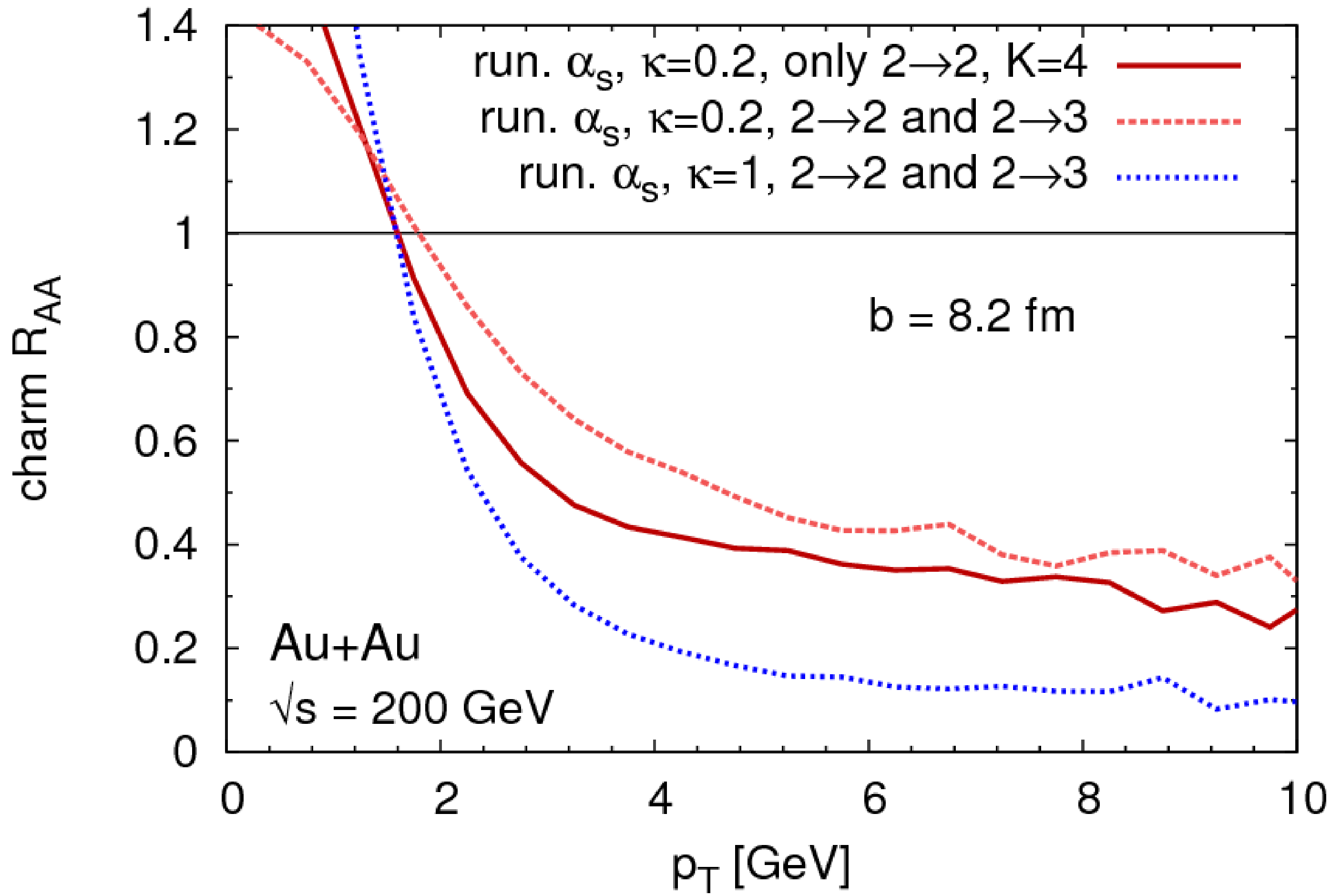
Further details in Phys. Rev. C 84, 024908 (2011) and arXiv:1205.4945

Future tasks:

- **Further study of radiative heavy quark scattering in full cascade**
- **J/ψ calculations at RHIC and LHC**

Thank you for your attention.

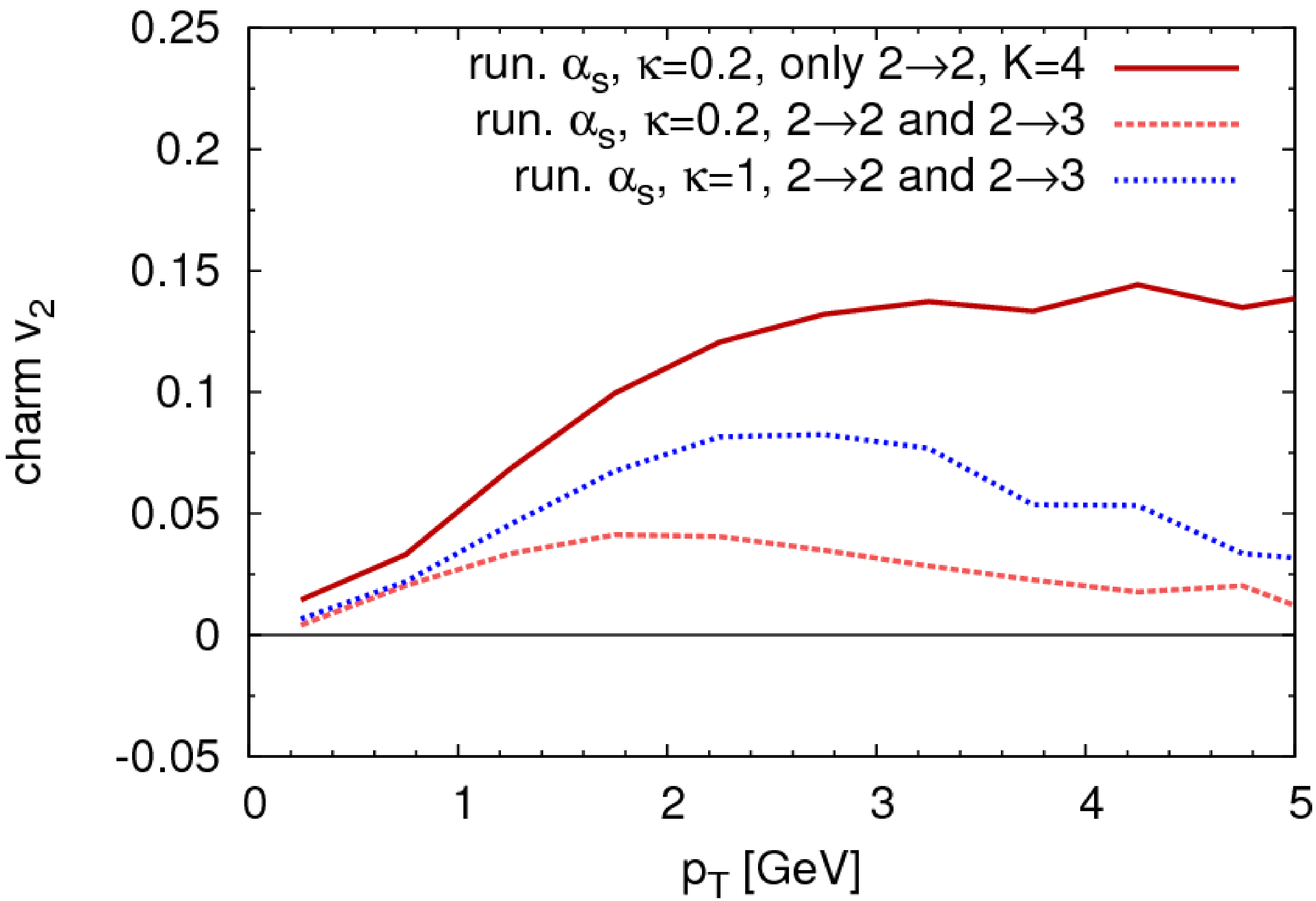
Charm R_{AA} at RHIC



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}

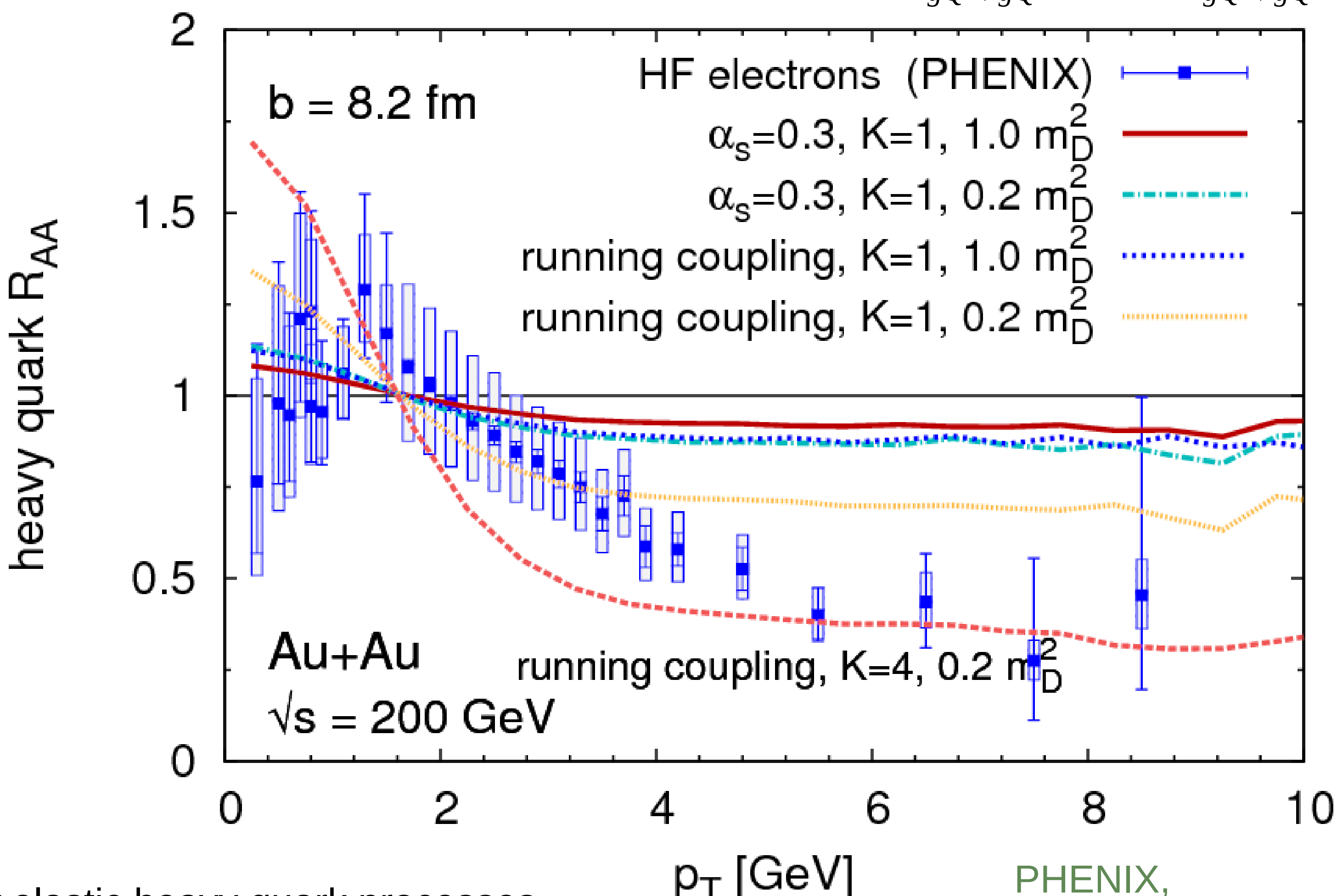
Reason: LPM effect

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

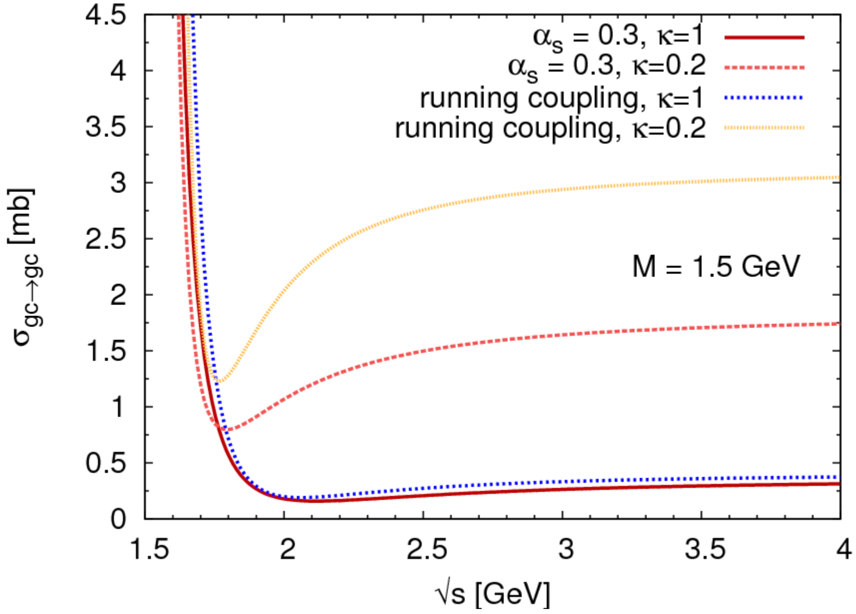
$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

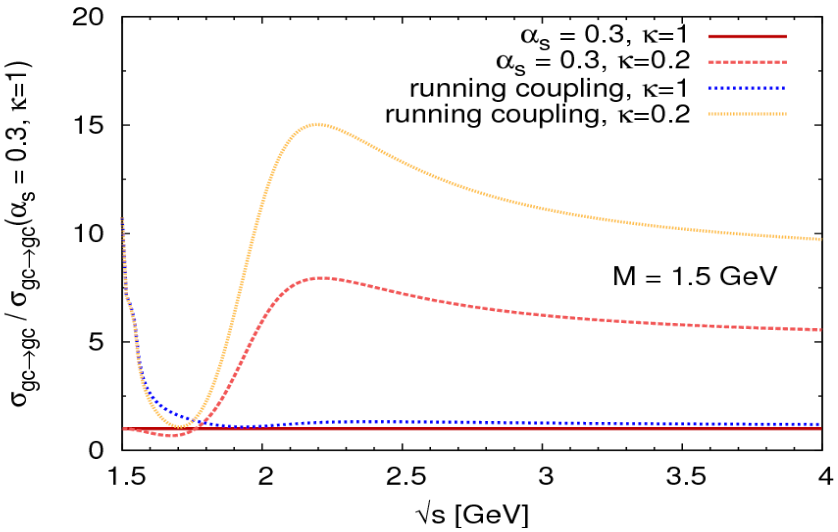


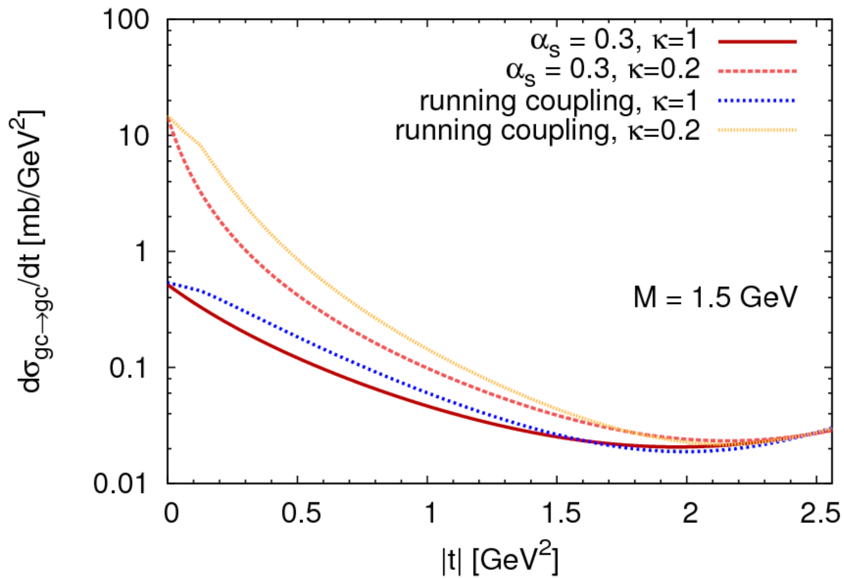
only elastic heavy quark processes

PHENIX, arXiv:1005.1627

Heavy quark scattering cross section



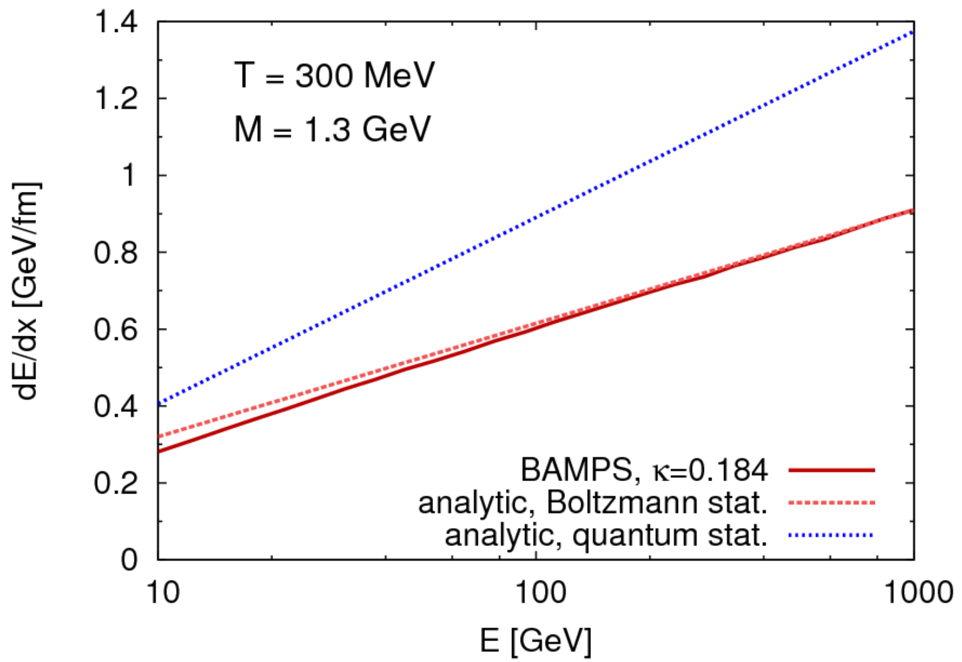




Heavy quark scattering

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

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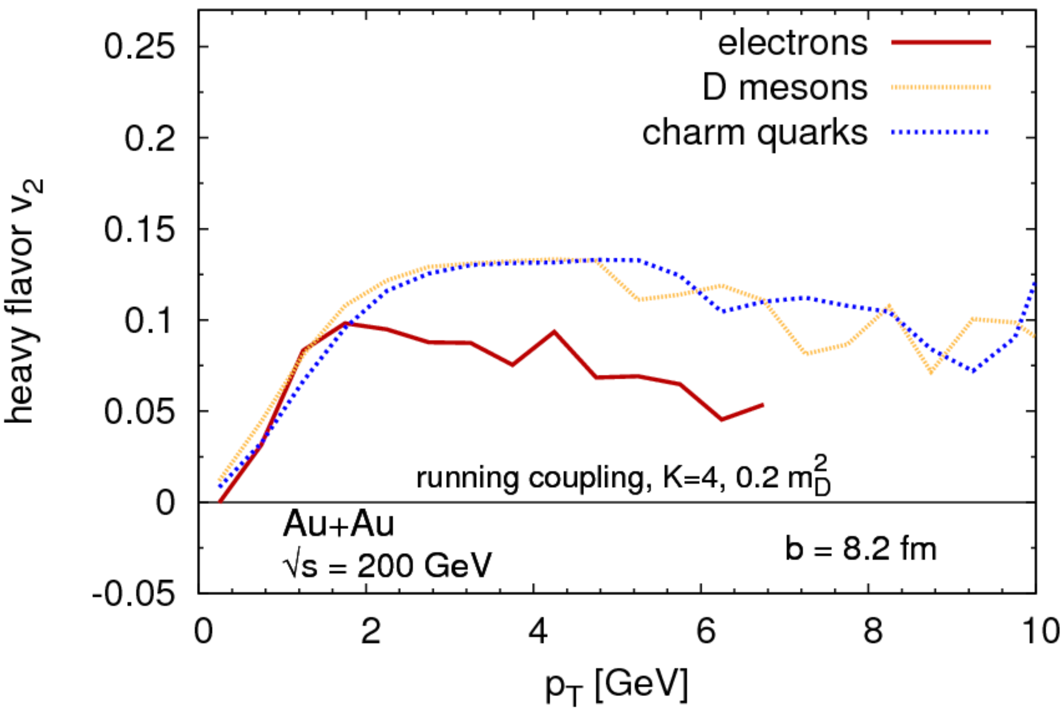
- **Peterson fragmentation**

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

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

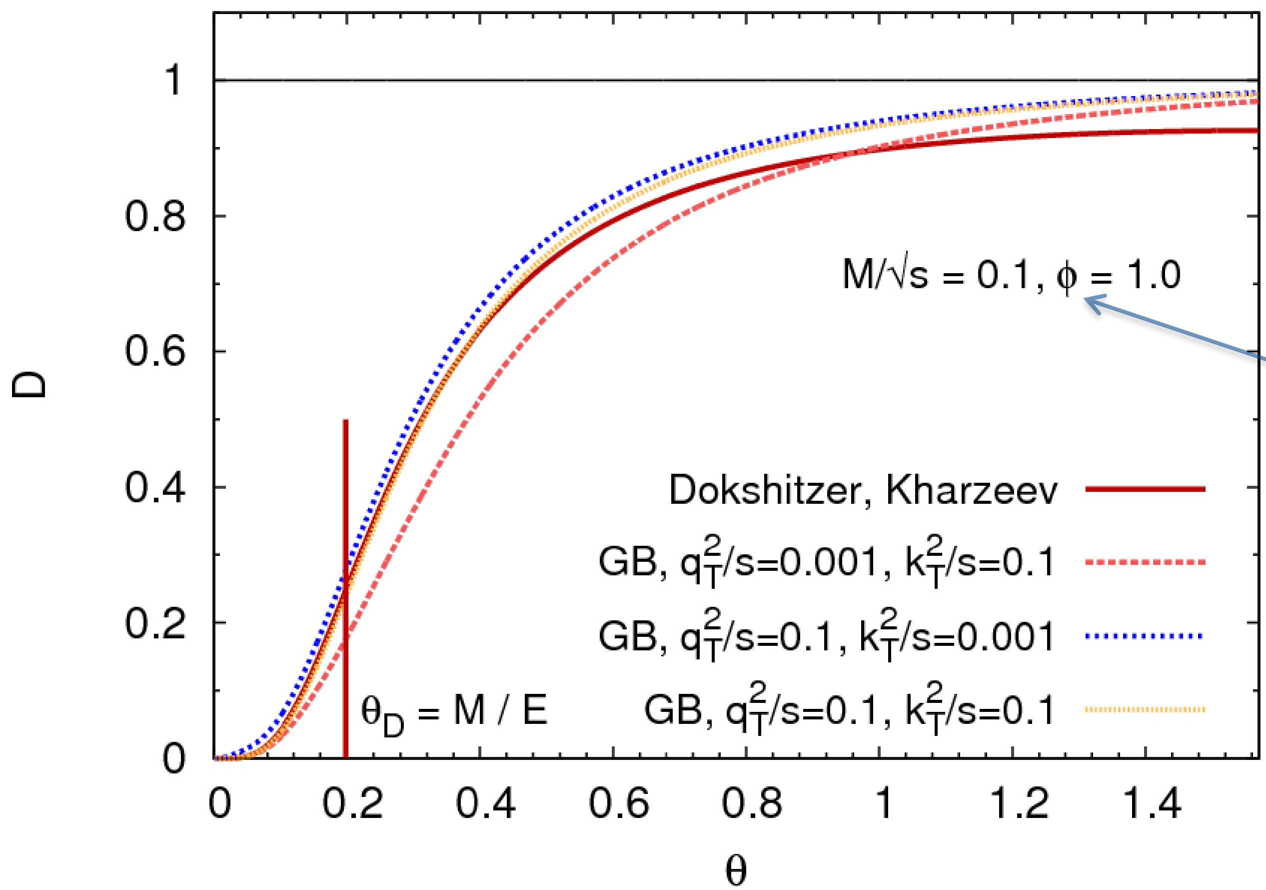
- **Decay to electrons with PYTHIA**



Impact of hadronization and decay small

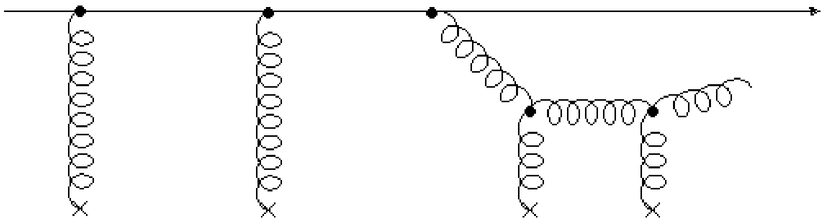
Dead cone effect

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



Angle between q_T^2 & k_T^2

LPM effect

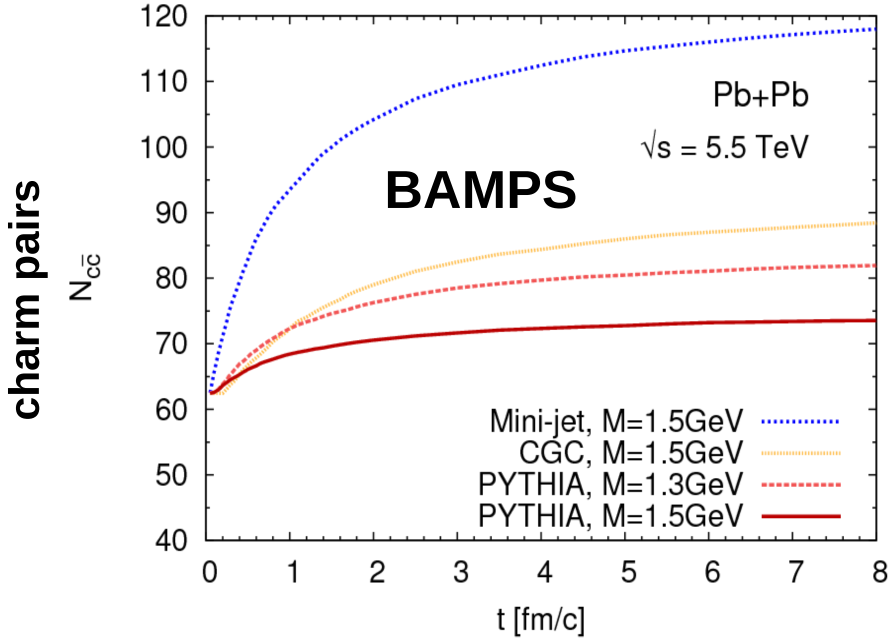


$$\lambda > \tau$$

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

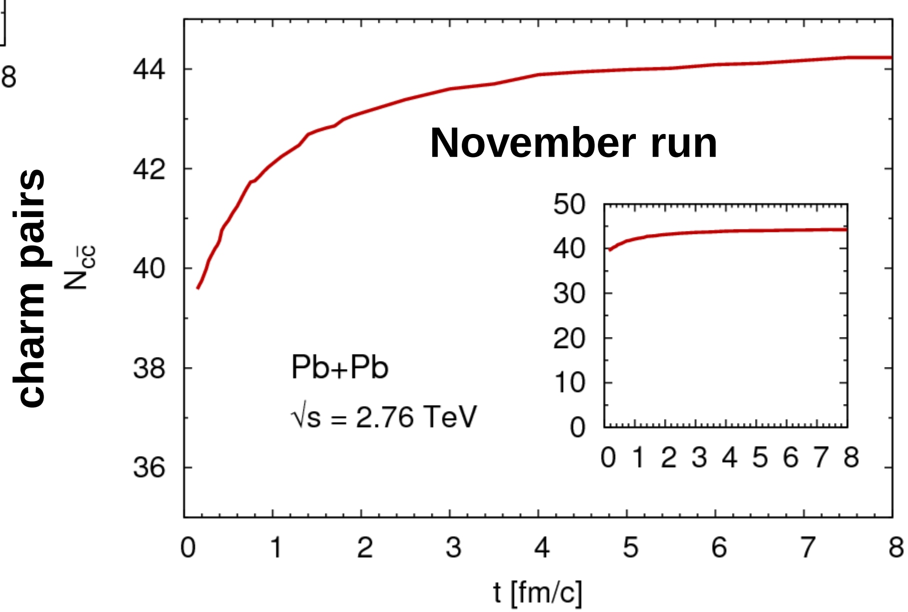
➡ Bethe-Heitler regime, independent scatterings

Charm production in the QGP at LHC



LHC

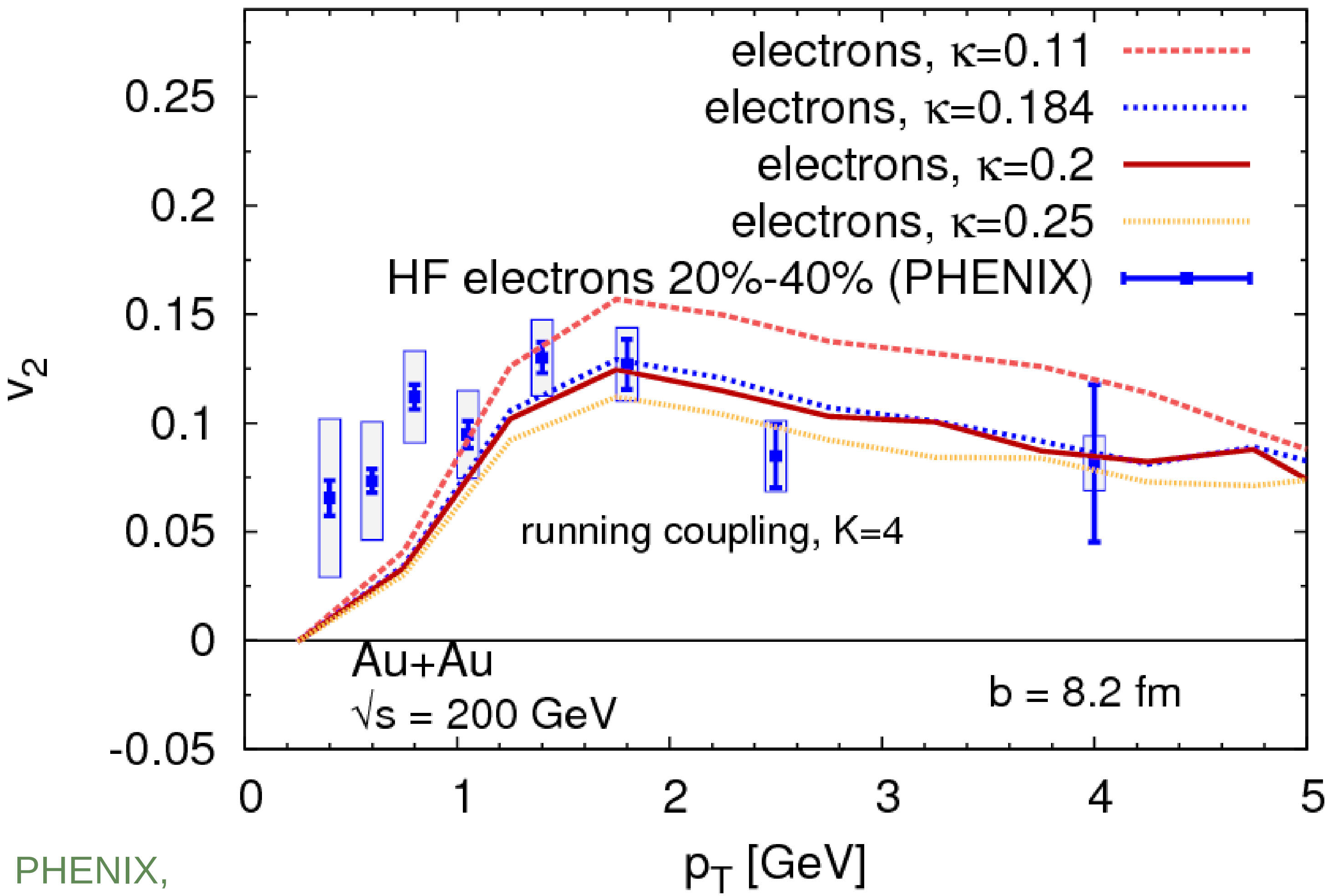
Large secondary production → Can even be comparable to initial production



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

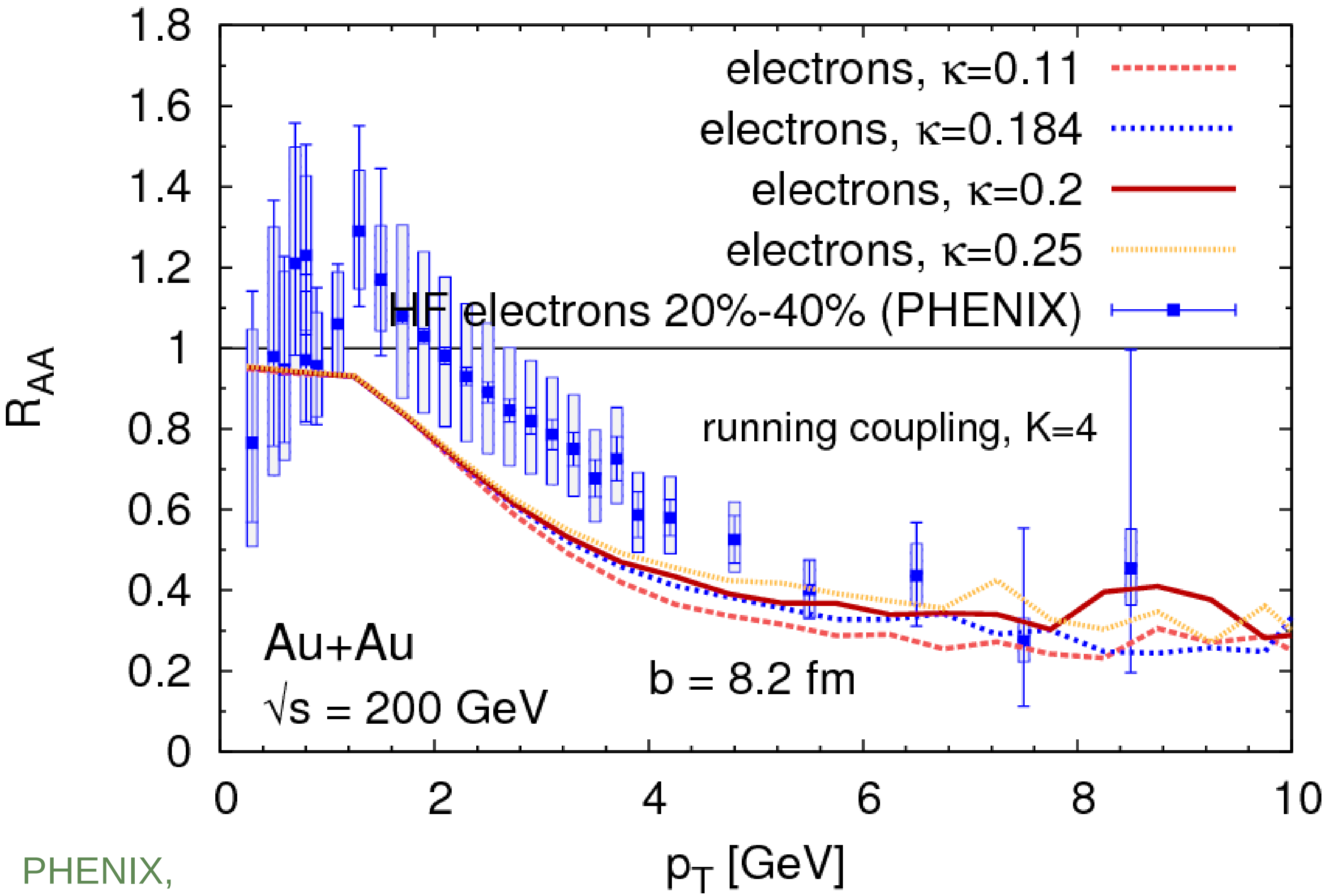
Heavy quark elliptic flow v_2 at RHIC

RHIC



PHENIX, arXiv:1005.1627

Heavy quark elliptic flow v_2 at RHIC

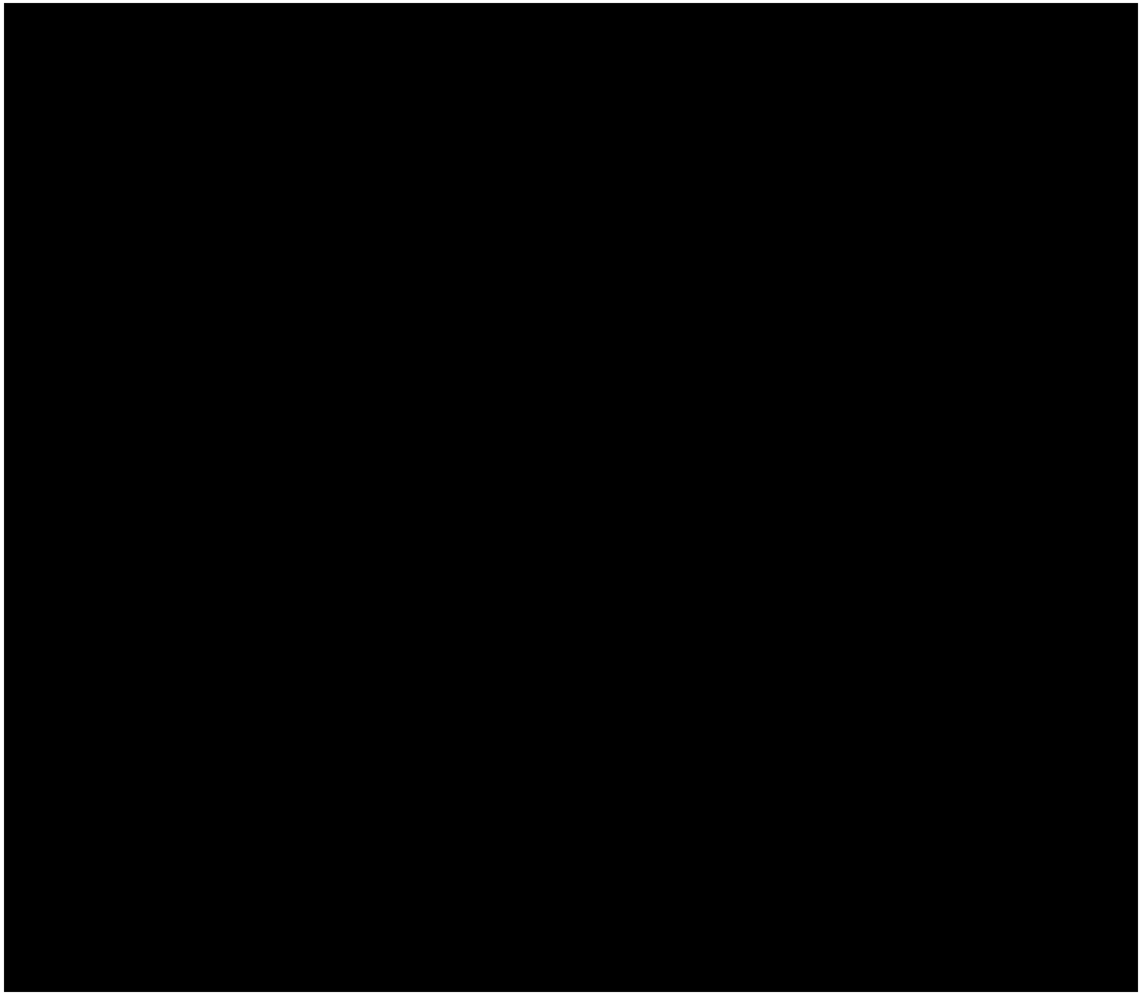


RHIC

PHENIX, arXiv:1005.1627

Heavy-ion collision at LHC

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



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