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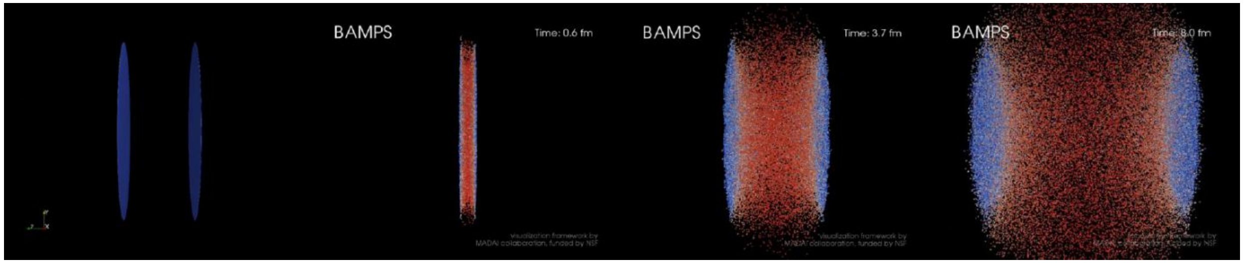
Heavy vs. light quark energy loss in ultra-relativistic heavy-ion collisions

Jan Uphoff

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

Based on Phys. Lett. B 717, 430 (2012)
and Phys. Rev. D88 (2013)



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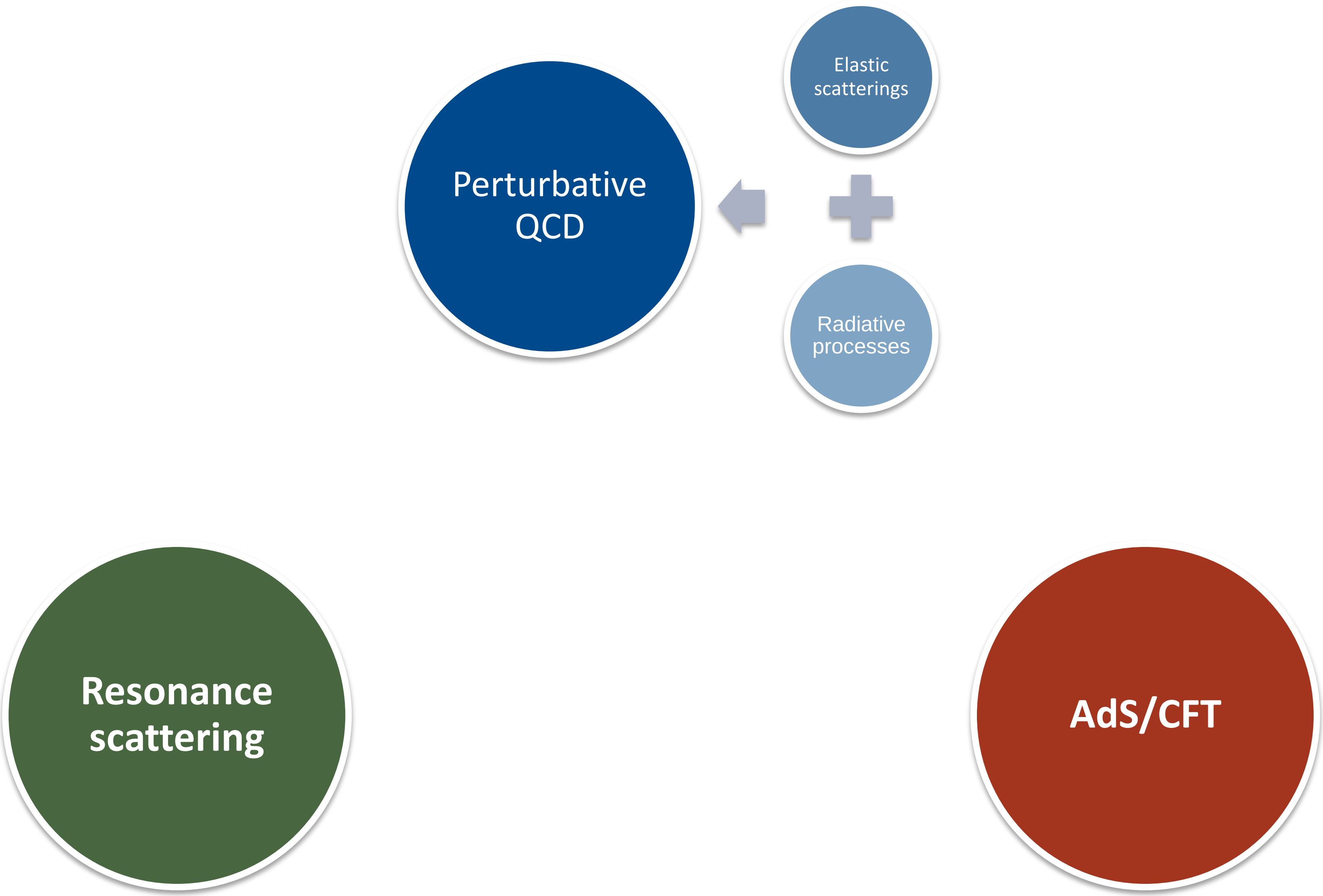
H-QM Helmholtz Research School
Quark Matter Studies

Hard Probes, Stellenbosch
5 November 2013

Heavy quark energy loss mechanism



Heavy quark energy loss mechanism

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Perturbative QCD

- Djordjevic, Gyulassy
- Buzatti, Gyulassy
- Sharma, Vitev
- Armesto, Cacciari, Dainese, Salgado, Wiedemann
- Nahrgang, Gossiaux, Aichelin
- Cao, Bass
- Mazumder, Bhattacharyya, Alam, Das
- **JU, Fochler, Xu, Greiner**
- …

Elastic scatterings

- Moore, Teaney
- Gossiaux, Aichelin
- Alberico, Beraudo, et al.
- **JU, Fochler, Xu, Greiner**
- Meistrenko, JU, Greiner, Peshier
- Young, Schenke, Gale
- …

Radiative processes

- Abir, Jamil, Mustafa, Srivastava
- …

Resonance scattering

- v.Hees, Greco, Rapp
- He, Fries, Rapp
- Lang, v.Hees, Bleicher
- …

AdS/CFT

- Horowitz, Gyulassy
- Chesler, Lekaveckas, Rajagopal
- …

BAMPS

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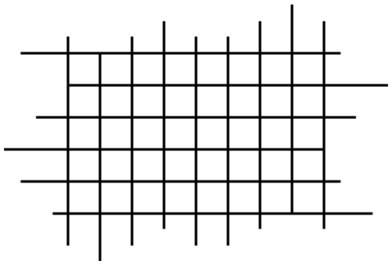
BAMPS: Boltzmann Approach to MultiParton Scatterings

- **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**

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

Interactions in BAMPS with $N_{flavor} = 3+2$

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Light flavors

Heavy flavors

binary

Light flavors:

$$g\,g \to g\,g$$
$$g\,g \to q\,\bar{q}$$
$$q\,\bar{q} \to g\,g \quad \text{and} \quad q\,\bar{q} \to q'\,\bar{q}'$$
$$q\,g \to q\,g \quad \text{and} \quad \bar{q}\,g \to \bar{q}\,g$$
$$q\,\bar{q} \to q\,\bar{q}$$
$$q\,q \to q\,q \quad \text{and} \quad \bar{q}\,\bar{q} \to \bar{q}\,\bar{q}$$
$$q\,q' \to q\,q' \quad \text{and} \quad q\,\bar{q}' \to q\,\bar{q}'$$

Heavy flavors:

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

inelastic

Light flavors:

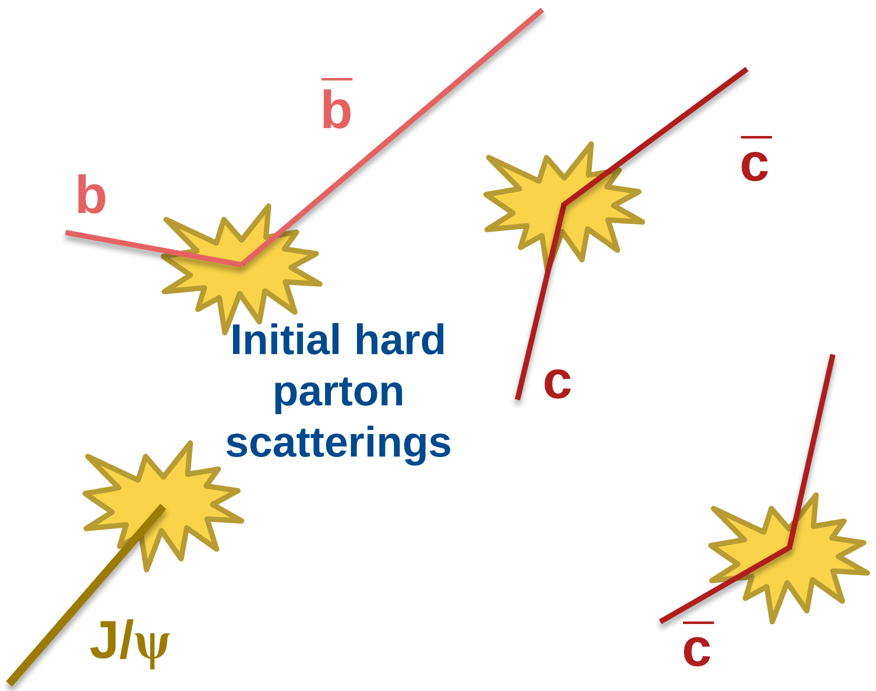
$$g\,g \leftrightarrow g\,g\,g$$
$$q\,g \leftrightarrow q\,g\,g \quad \text{and} \quad \bar{q}\,g \leftrightarrow \bar{q}\,g\,g$$
$$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$$
$$q\,q \leftrightarrow q\,q\,g \quad \text{and} \quad \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$$
$$q\,q' \leftrightarrow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

Heavy flavors:

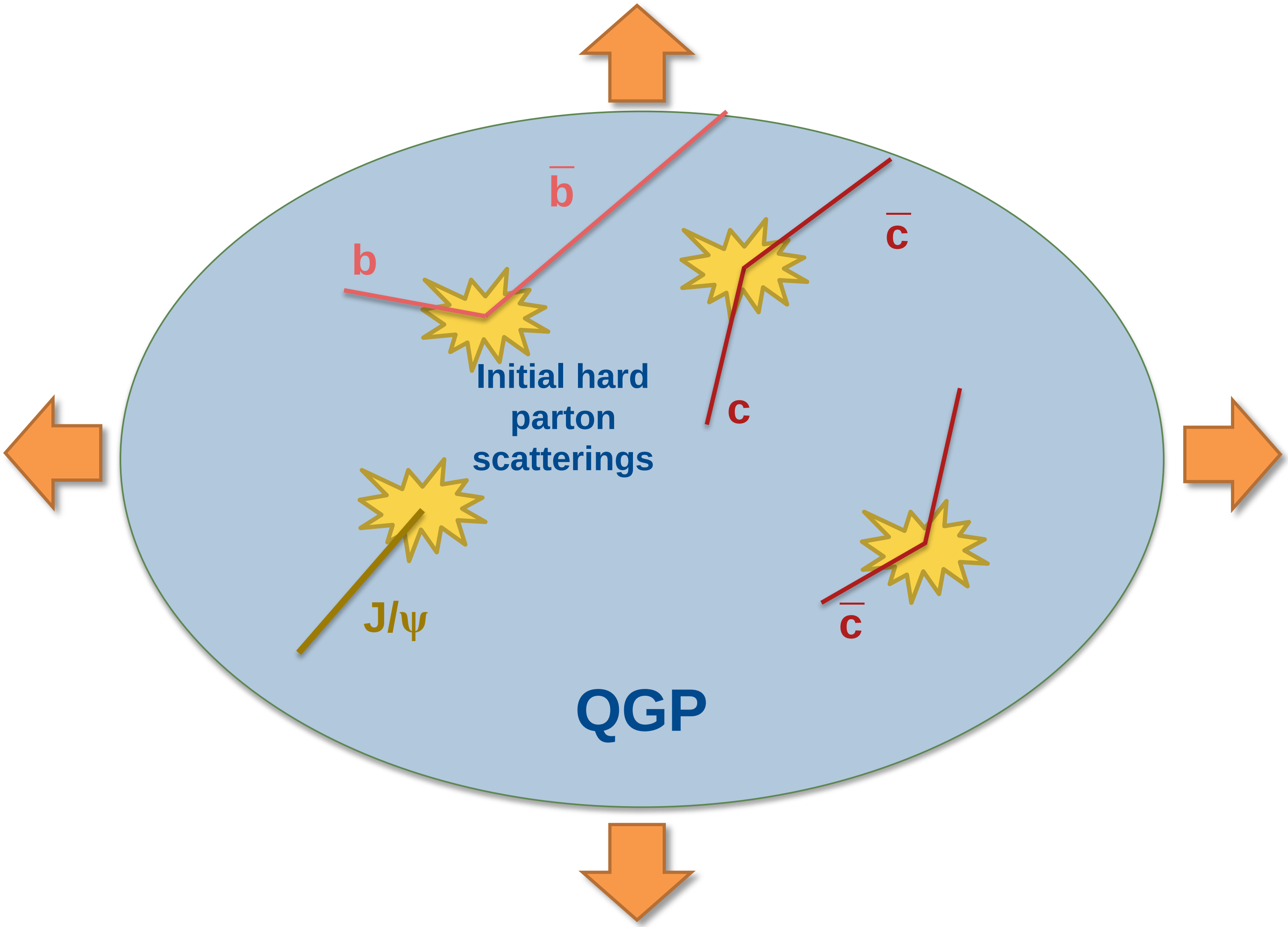
$$g + Q \to g + Q + g$$
$$q + Q \to q + Q + g$$

Sketch of heavy flavor in HIC

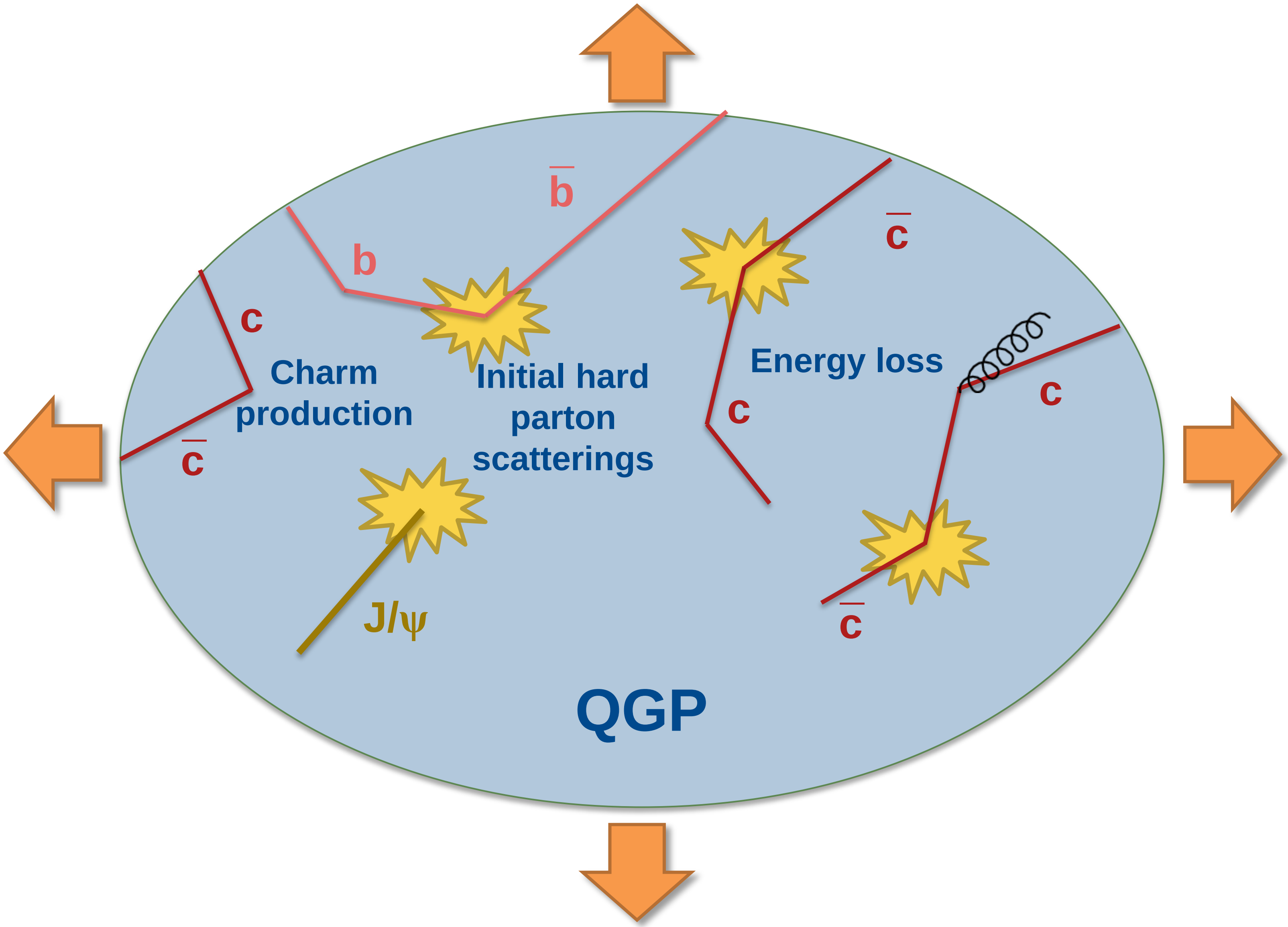
Sketch of heavy flavor in HIC



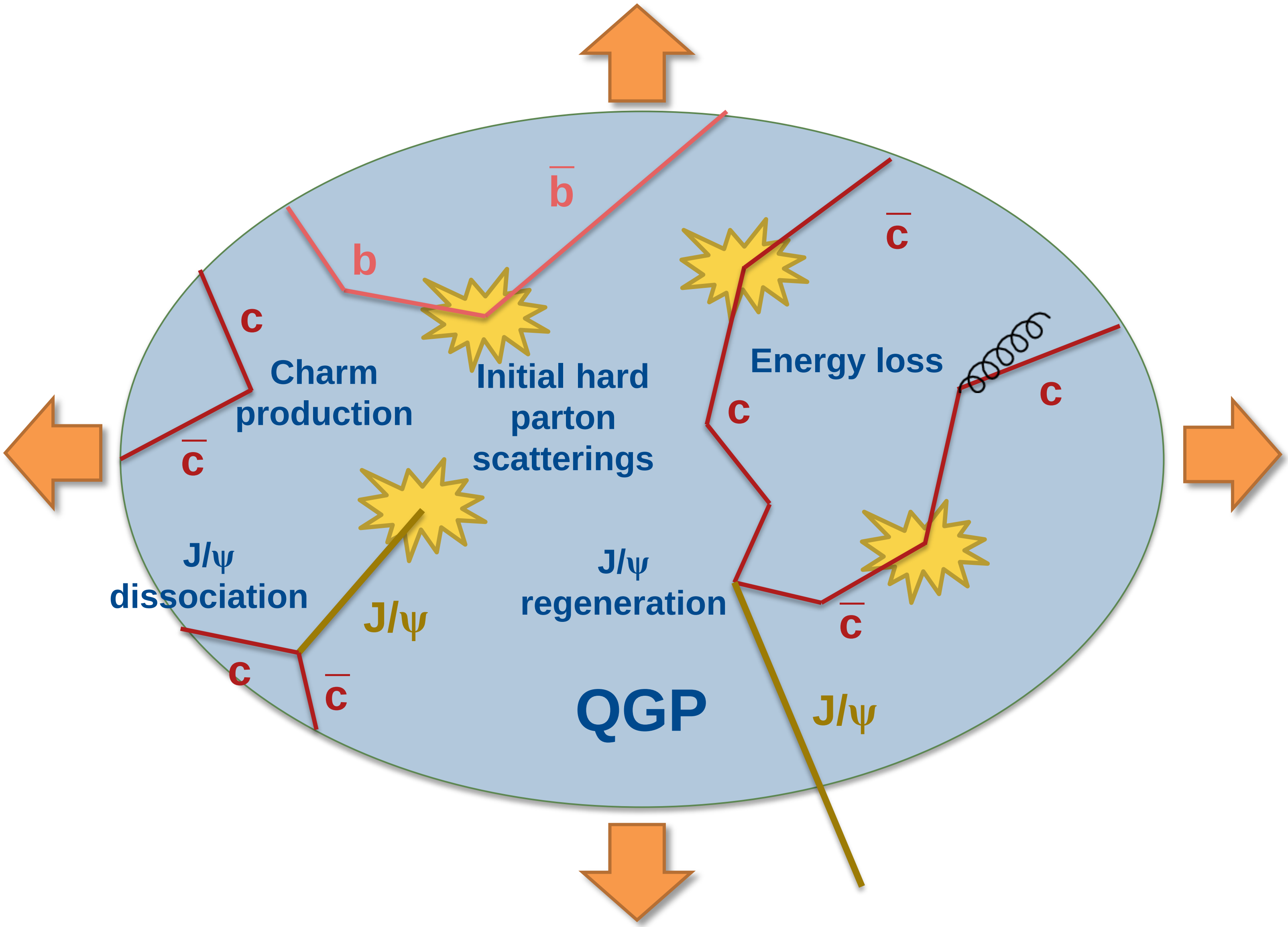
Sketch of heavy flavor in HIC



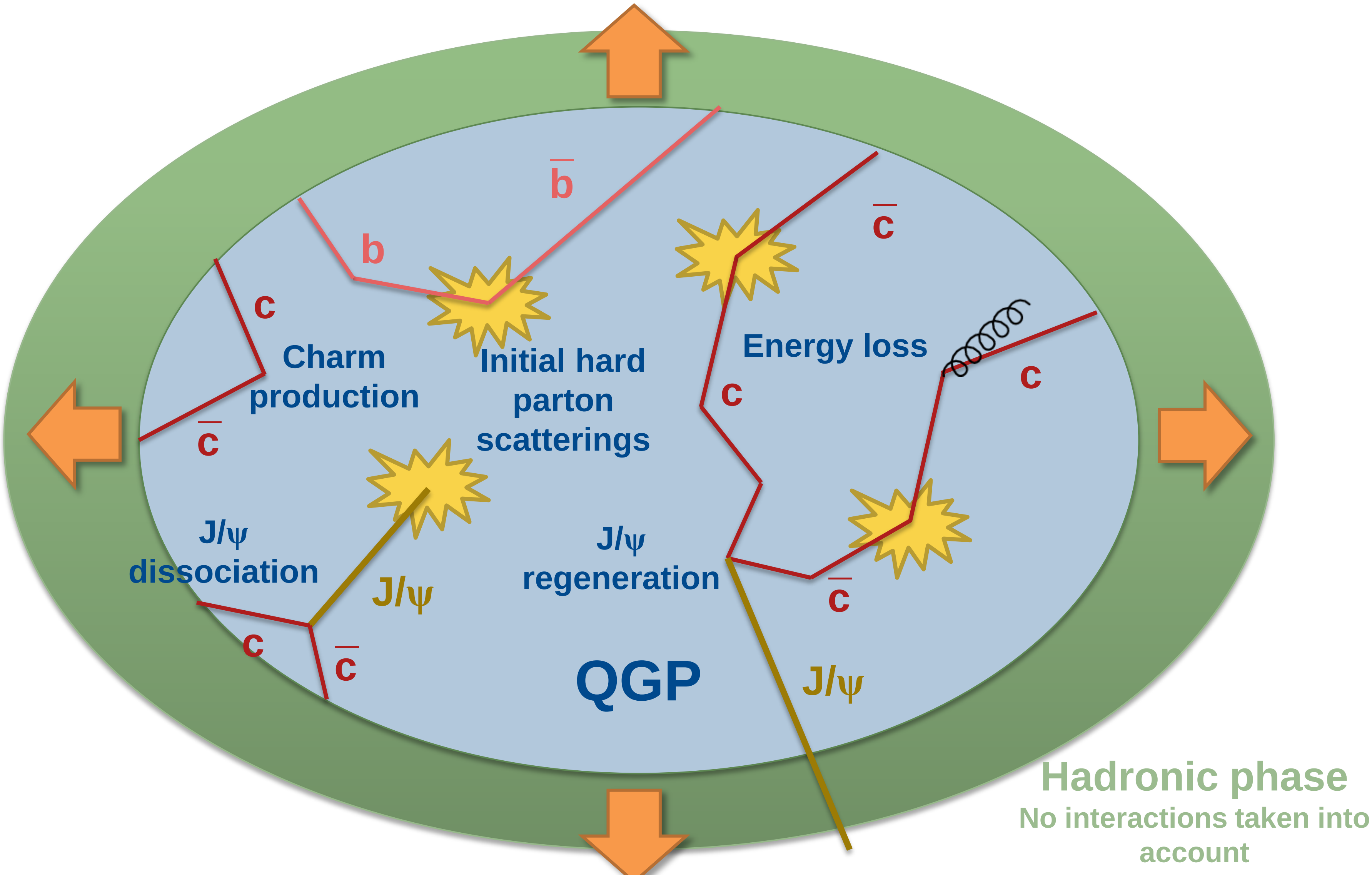
Sketch of heavy flavor in HIC



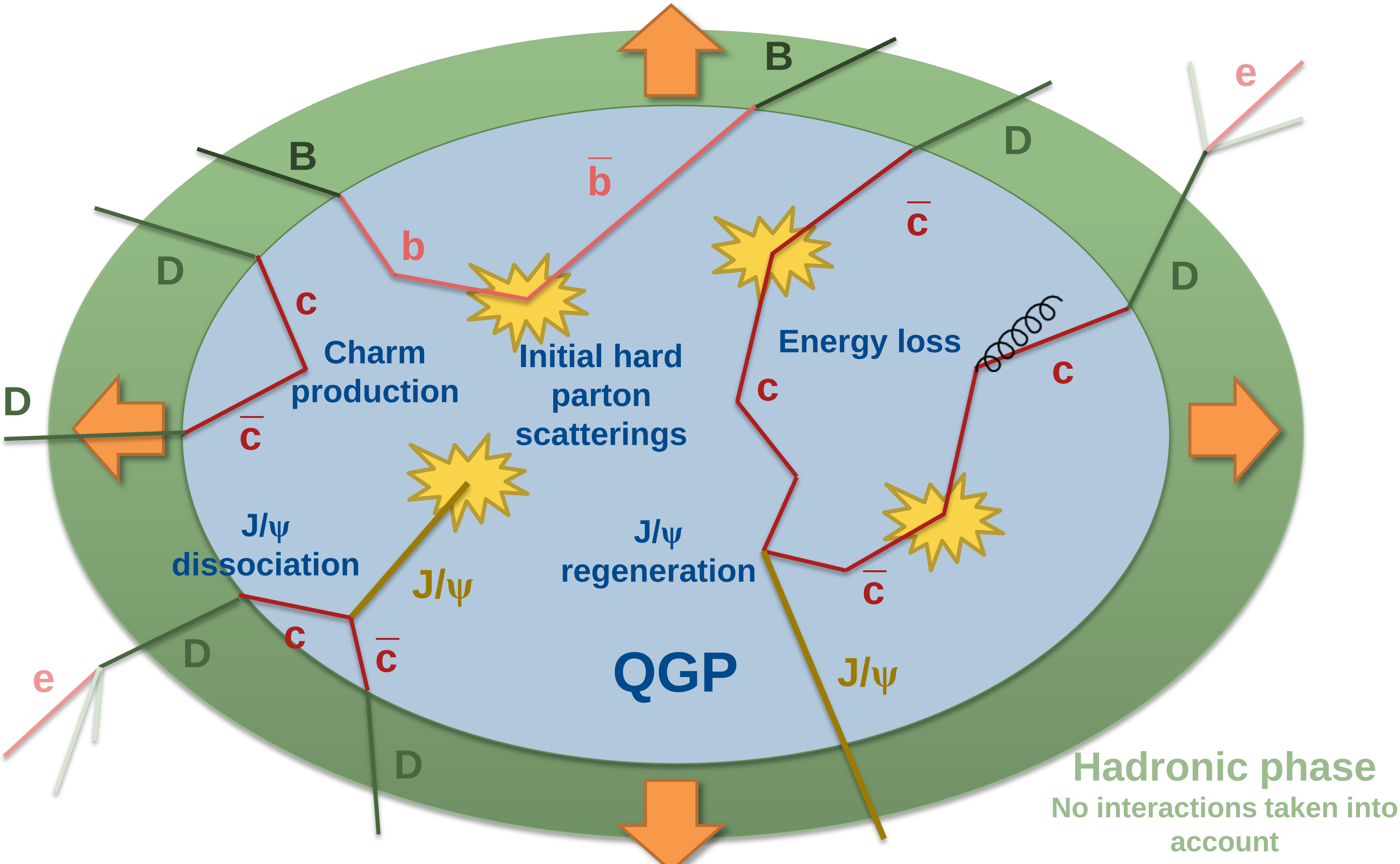
Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC



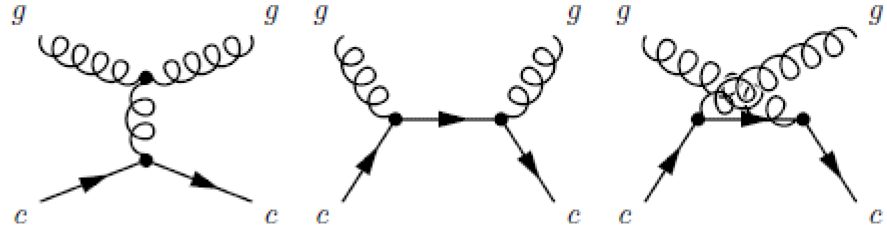
Sketch of heavy flavor in HIC



Heavy quark scattering

Leading order perturbative QCD:

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



Improved Debye screening by comparing to HTL

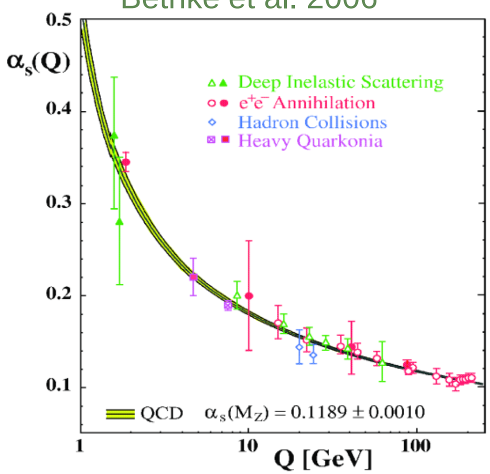
$$\frac{1}{t} \to \frac{1}{t - \kappa\, m_D^2}$$

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

A. Peshier,
Nucl.Phys. A888 (2012)

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

Bethke et al. 2006



Running coupling

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

Heavy quark v_2 and R_{AA} at RHIC

RHIC

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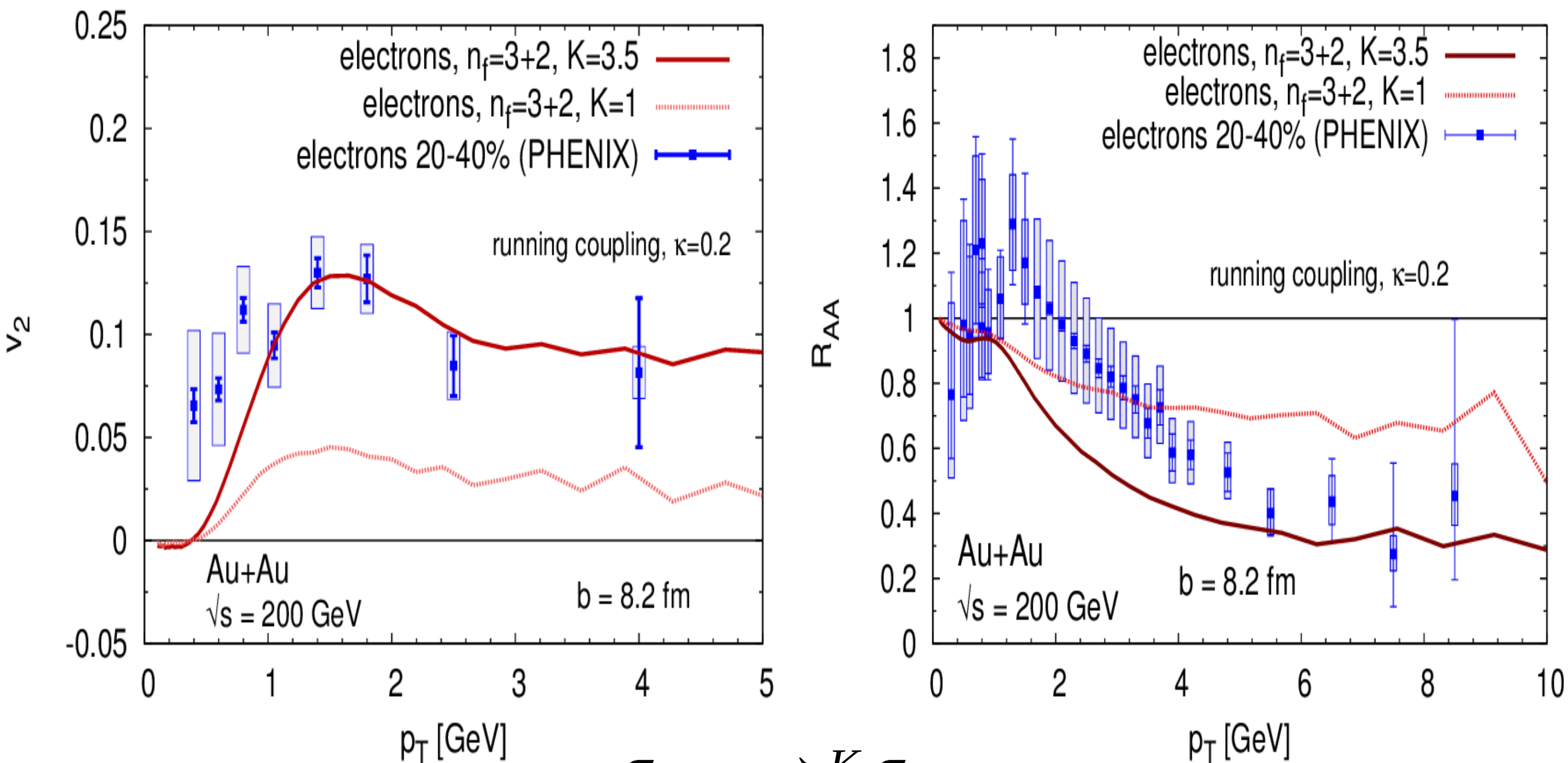

$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

only elastic heavy quark processes

JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

PHENIX data,
Phys.Rev. C84 (2011)

D meson R_{AA} and electron v_2 at LHC

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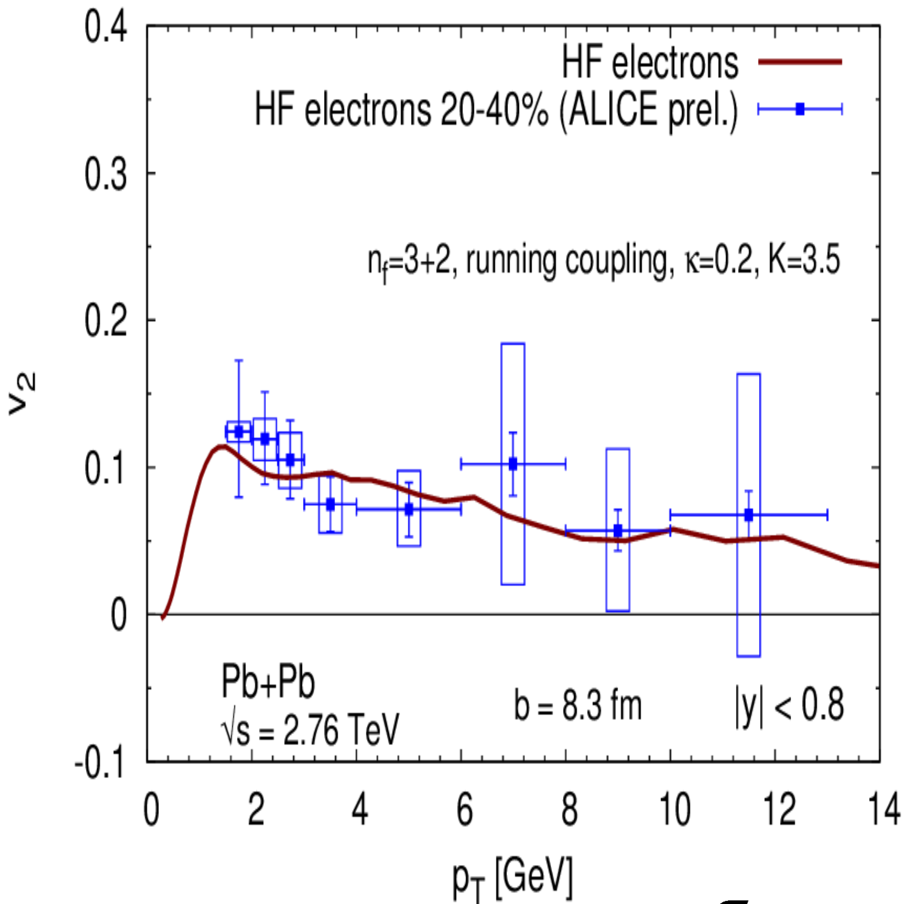
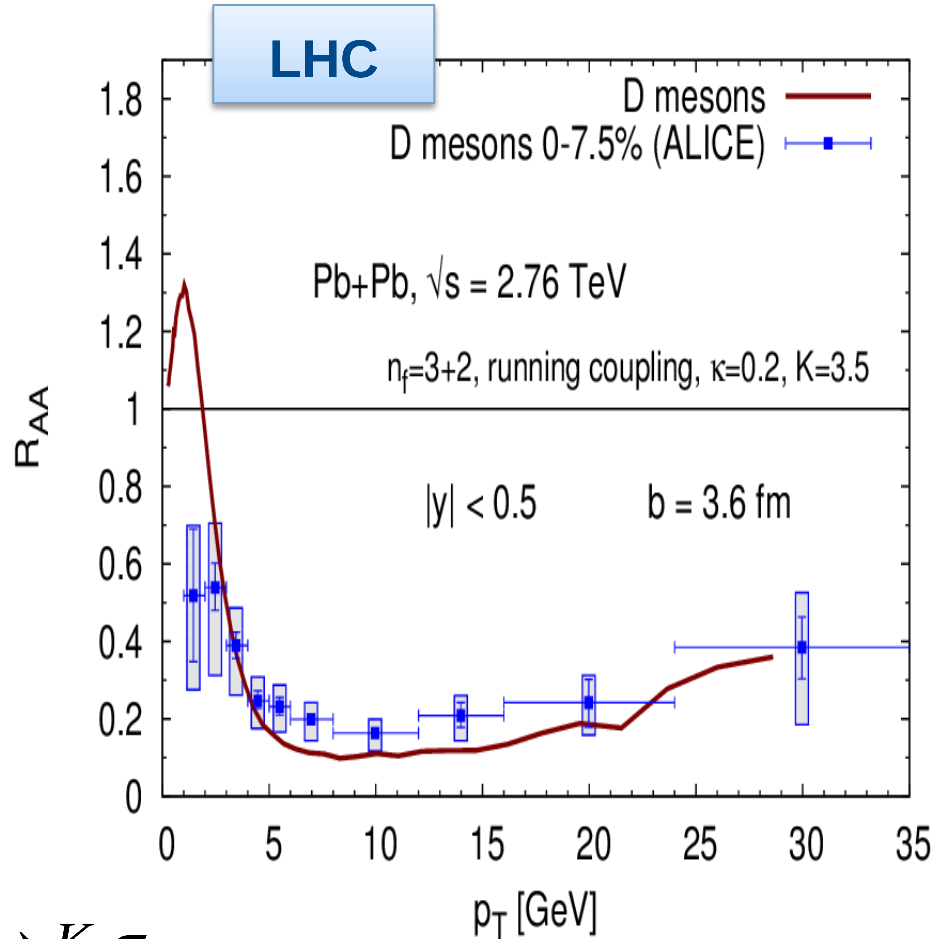




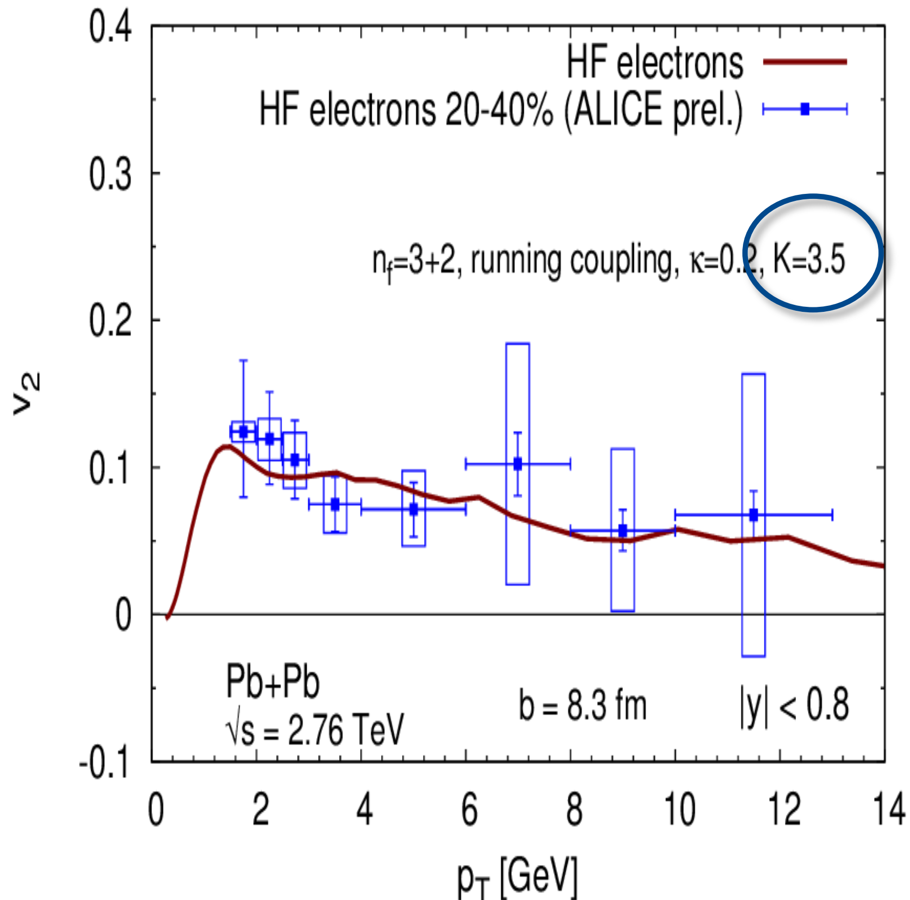
$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

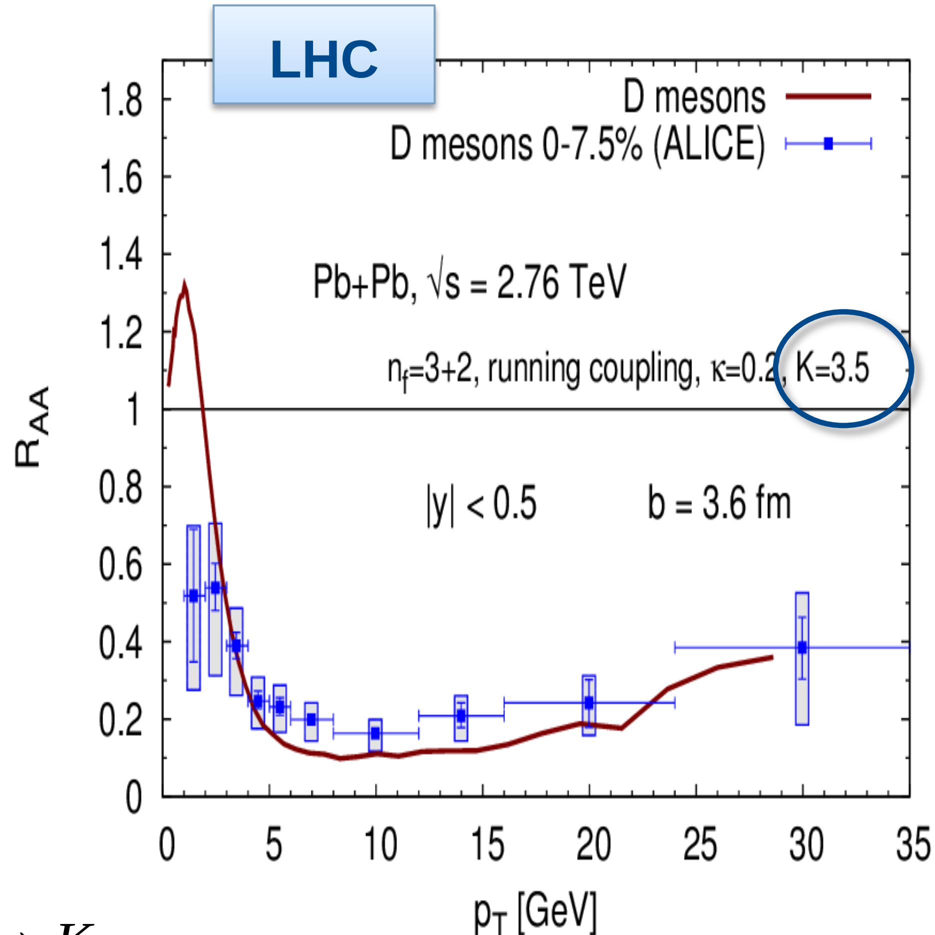
only elastic heavy quark processes

JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

ALICE data, QM12

D meson R_{AA} and electron v_2 at LHC





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

only elastic heavy quark processes

JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

ALICE data, QM12

Radiative processes: Improved Gunion-Bertsch matrix element

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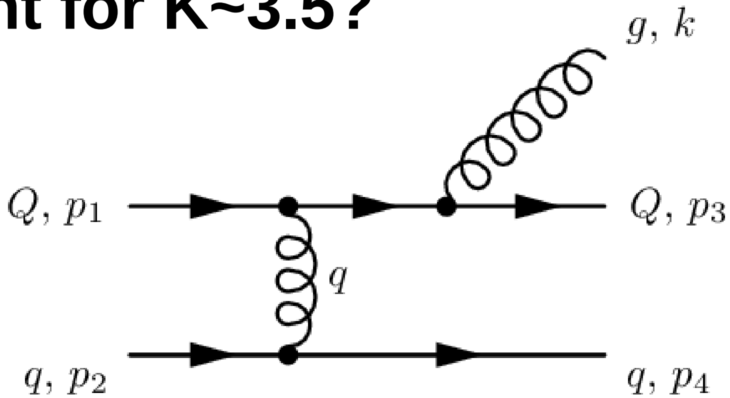
Can radiative processes account for K~3.5?

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

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



Improved Gunion-Bertsch matrix element generalized to heavy quarks:

$$\left|\overline{\mathcal{M}}_{qQ\rightarrow qQg}\right|^2 = 12g^2(1-\bar{x})^2 \left|\overline{\mathcal{M}}_0^{qQ}\right|^2 \left[\frac{\mathbf{k}_\perp}{k_\perp^2 + x^2M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + x^2M^2}\right]^2$$

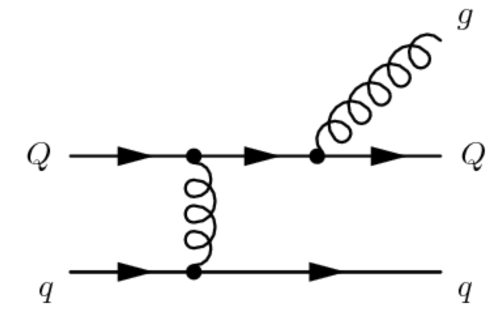
Fochler, JU, Xu, Greiner, Phys. Rev. D88 (2013)

In accordance to scalar QCD result at mid- and forward rapidity from
Gossiaux, Aichelin, Gousset, Guiho, J.Phys.G37 (2010)

Radiative pQCD processes

Exact matrix element

Kunszt, Pietarinen, Reya, Phys.Rev. D21 (1980)



$$\left|\overline{\mathcal{M}}\right|^2 = -16 \sum_{i,j=1}^{5} C_{ij} \frac{N_{ij}}{D_{ij}}$$

$$C = \frac{1}{3}\begin{pmatrix} 8 & 1 & 9 & -2 & -7 \\ & 8 & 9 & -7 & -2 \\ & & 18 & -9 & -9 \\ & & & 8 & 1 \\ & & & & 8 \end{pmatrix}$$

$$D = \begin{pmatrix} x_{31}^2 x_{54}^2, & 2x_{23}x_{31}x_{54}^2, & 4s_{12}x_{31}x_{54}^2, & 2s_{12}x_{31}x_{43}x_{54}, & 2s_{12}x_{31}x_{53}x_{54} \\ & x_{23}^2 x_{54}^2, & 4s_{12}x_{23}x_{54}^2, & 2s_{12}x_{23}x_{43}x_{54}, & 2s_{12}x_{23}x_{53}x_{54} \\ & & 4s_{12}^2 x_{54}^2, & 4s_{12}^2 x_{43}x_{54}, & 4s_{12}^2 x_{53}x_{54} \\ & & & s_{12}^2 x_{43}^2, & 2s_{12}^2 x_{43}x_{53} \\ & & & & s_{12}^2 x_{53}^2 \end{pmatrix}$$

$$N_{11} = x_{31}(-x_{42}x_{53} - x_{43}x_{52} + 2m_Q^2 x_{54}) + 2m_Q^2(x_{41}x_{52} + x_{42}x_{51} + x_{42}x_{53} + x_{43}x_{52} + 2m_Q^2 x_{54}),$$

$$N_{12} = x_{12}[x_{41}(2x_{52} + x_{53}) + x_{42}(2x_{51} + x_{53}) + x_{43}(x_{51} + x_{52}) + 4m_Q^2 x_{54}] + x_{23}[x_{41}(-2x_{51} + x_{52}) + x_{42}x_{51} + 2m_Q^2 x_{54}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52}) + 2m_Q^2 x_{54}] - 4m_Q^2 x_{43}x_{53},$$

$$N_{13} = x_{12}[-2x_{31}x_{54} + x_{41}(4x_{52} + 3x_{53}) + x_{42}(4x_{51} + 3x_{53}) + x_{43}(3x_{51} + 3x_{52} + 2x_{53}) + 8m_Q^2 x_{54}] + x_{23}[x_{41}(-6x_{51} + x_{52} - x_{53}) + (x_{42} - x_{43})x_{51} + 4m_Q^2 x_{54}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52} - 3x_{53}) - 3x_{43}x_{52}] + 2m_Q^2[x_{41}(2x_{51} + 4x_{52} + 3x_{53}) + x_{42}(4x_{51} - 2x_{52} + 5x_{53}) + x_{43}(3x_{51} + 5x_{52}) + 8m_Q^2 x_{54}],$$

$$N_{14} = x_{51}(-x_{12}x_{43} + x_{23}x_{41} + x_{42}x_{43}) + x_{31}[2x_{41}x_{52} + x_{42}(x_{51} - x_{54}) + 2x_{43}x_{52} + 2m_Q^2 x_{54}] + x_{41}[2(x_{41} + x_{43})x_{52} + x_{42}(2x_{51} + x_{53}) + 2m_Q^2(x_{53} + 2x_{54})] + 2m_Q^2 x_{43}(x_{53} + x_{54} - x_{51} - x_{52}),$$

$$N_{15} = N_{14}(4 \leftrightarrow 5), \quad N_{22} = N_{11}(1 \leftrightarrow 2), \quad N_{23} = N_{13}(1 \leftrightarrow 2), \quad N_{24} = N_{14}(1 \leftrightarrow 2), \quad N_{25} = N_{24}(4 \leftrightarrow 5),$$

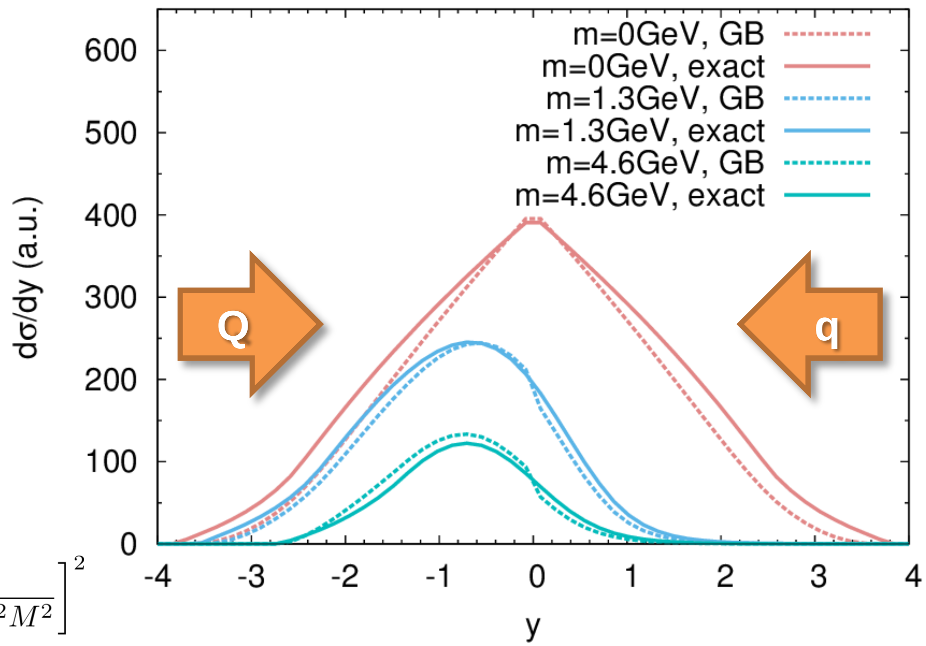
$$N_{33} = x_{12}[2x_{54}(x_{12} - x_{23} - x_{31}) + x_{41}(-2x_{51} + 6x_{52} + 5x_{53}) + x_{42}(-2x_{52} + 6x_{51} + 5x_{53}) + x_{43}(5x_{51} + 5x_{52} + 4x_{53}) + 28m_Q^2 x_{54}] + x_{23}[-2x_{31}x_{54} + x_{41}(-6x_{51} + x_{52} - 3x_{53}) + (x_{42} - 3x_{43})x_{51}] + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 6x_{52} - 3x_{53}) - 3x_{43}x_{52}] + 2m_Q^2[x_{41}(-4x_{51} + 4x_{52} + 7x_{53}) + x_{42}(4x_{51} - 4x_{52} + 7x_{53}) + x_{43}(7x_{51} + 7x_{52} + 2x_{53}) + 24m_Q^2 x_{54}],$$

$$N_{34} = x_{12}[x_{54}(x_{23} + x_{31} + x_{42} + x_{41}) - 2x_{43}(x_{51} + x_{52})] + x_{23}[2x_{31}x_{54} + x_{41}(x_{52} - x_{53} - x_{54}) + 3x_{51}(x_{42} + x_{43}) + 8m_Q^2 x_{54}] + x_{31}[x_{42}(x_{51} - x_{53} - x_{54}) + 3x_{52}(x_{41} + x_{43}) + 8m_Q^2 x_{54}] + x_{41}[3(x_{41} + x_{43})x_{52} + x_{42}(x_{51} + x_{52} + 2x_{53}) + 2m_Q^2(x_{53} + 5x_{54})] + x_{42}[3(x_{42} + x_{43})x_{51} + 2m_Q^2(x_{53} + 5x_{54})] + 2m_Q^2 x_{43}(2x_{53} + 2x_{54} - 5x_{51} - 5x_{52}),$$

$$N_{44} = x_{43}(-x_{23}x_{51} - x_{31}x_{52} - 2m_Q^2 x_{53}),$$

$$N_{45} = x_{54}[x_{23}(x_{41} + x_{51}) + x_{31}(x_{42} + x_{52}) + 4m_Q^2(x_{53} + x_{54} + x_{43})] + x_{41}[x_{52}(x_{43} + 2x_{54}) + x_{53}(x_{52} - 2x_{42})] + x_{51}[-2x_{43}x_{52} + x_{42}(x_{53} + 2x_{54} + x_{43})],$$

$$N_{35} = N_{34}(4 \leftrightarrow 5), \quad N_{55} = N_{44}(4 \leftrightarrow 5).$$



Gunion Bertsch (GB) approximation

$$\left|\overline{\mathcal{M}}_{qQ\to qQg}\right|^2 = 12g^2(1-\bar{x})^2 \left|\overline{\mathcal{M}}_0^{qQ}\right|^2 \left[\frac{\mathbf{k}_\perp}{k_\perp^2 + x^2M^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + x^2M^2}\right]^2$$

Fochler, JU, Xu, Greiner, Phys. Rev. D88 (2013)

Dead cone effect

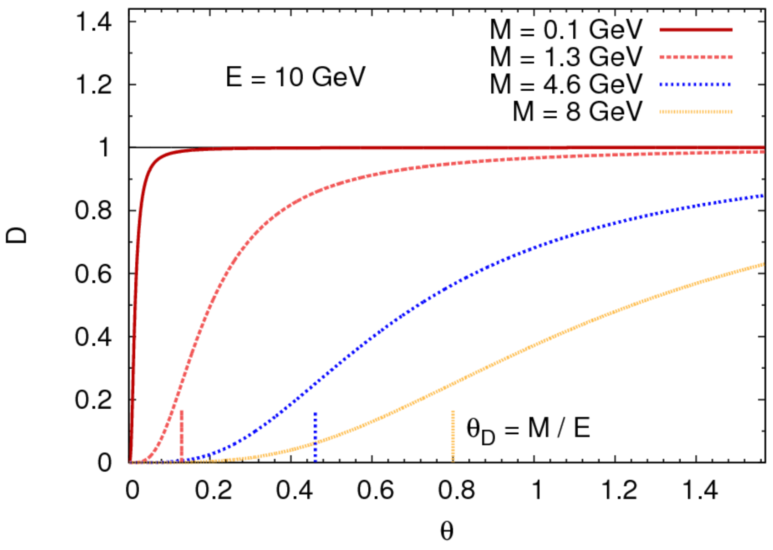
$$\left|\overline{\mathcal{M}}_{qQ\to qQg}\right|^2 = \left|\overline{\mathcal{M}}_{qq\to qqg}\right|^2 \mathcal{D}$$

Heavy quark suppression factor

$$\mathcal{D} = \frac{1}{\left(1+\frac{M^2}{\theta^2 E^2}\right)^2} = \frac{1}{\left(1+\frac{\theta_D^2}{\theta^2}\right)^2}$$

Dokshitzer, Kharzeev,
Phys.Lett. B519 (2001)

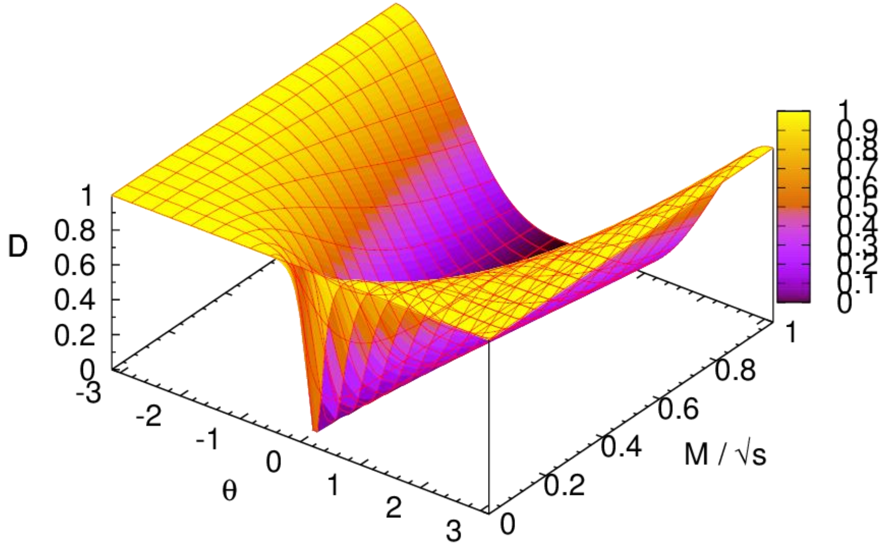
$$\theta_D = \frac{M}{E}$$



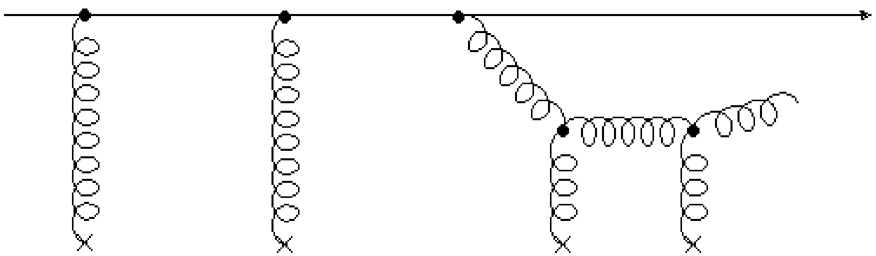
More accurate: valid for all order of mass M and also for large angles

$$\mathcal{D} = \frac{1}{1+\frac{M^2}{s\tan^2(\frac{\theta}{2})}}$$

Abir, Greiner, Martinez, Mustafa, JU,
Phys.Rev. D85 (2012)



LPM cut-off



Mean free path $\lambda > X \tau$ **Formation time**

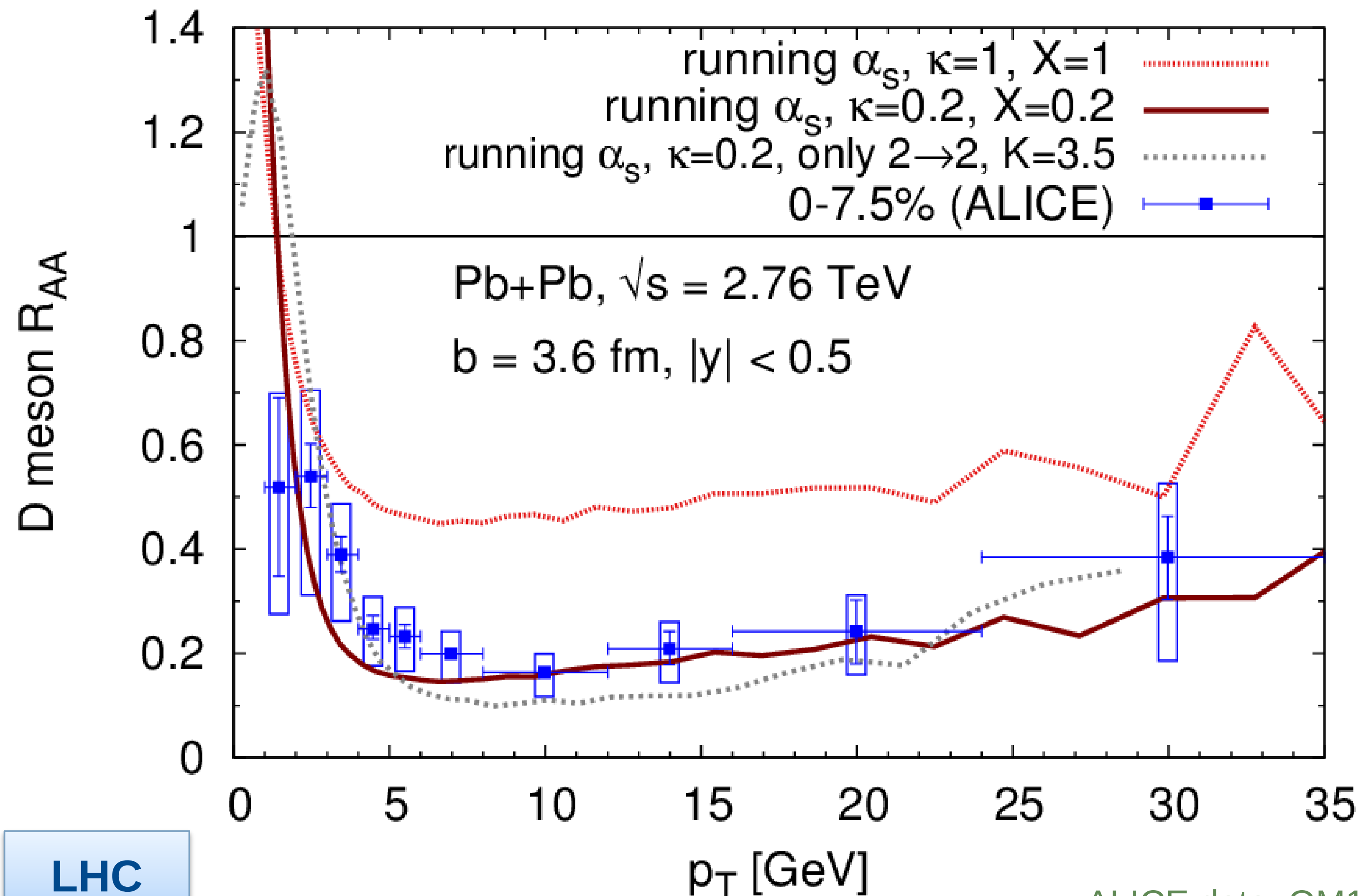
$2 \rightarrow 3$ process only allowed if mean free path of jet larger than formation time of radiated gluon

$X = 0$ **No LPM**

$X = 1$ **Only completely independent scatterings (forbids too many interactions)**

$X < 1$ **Allows effectively some interference effects**

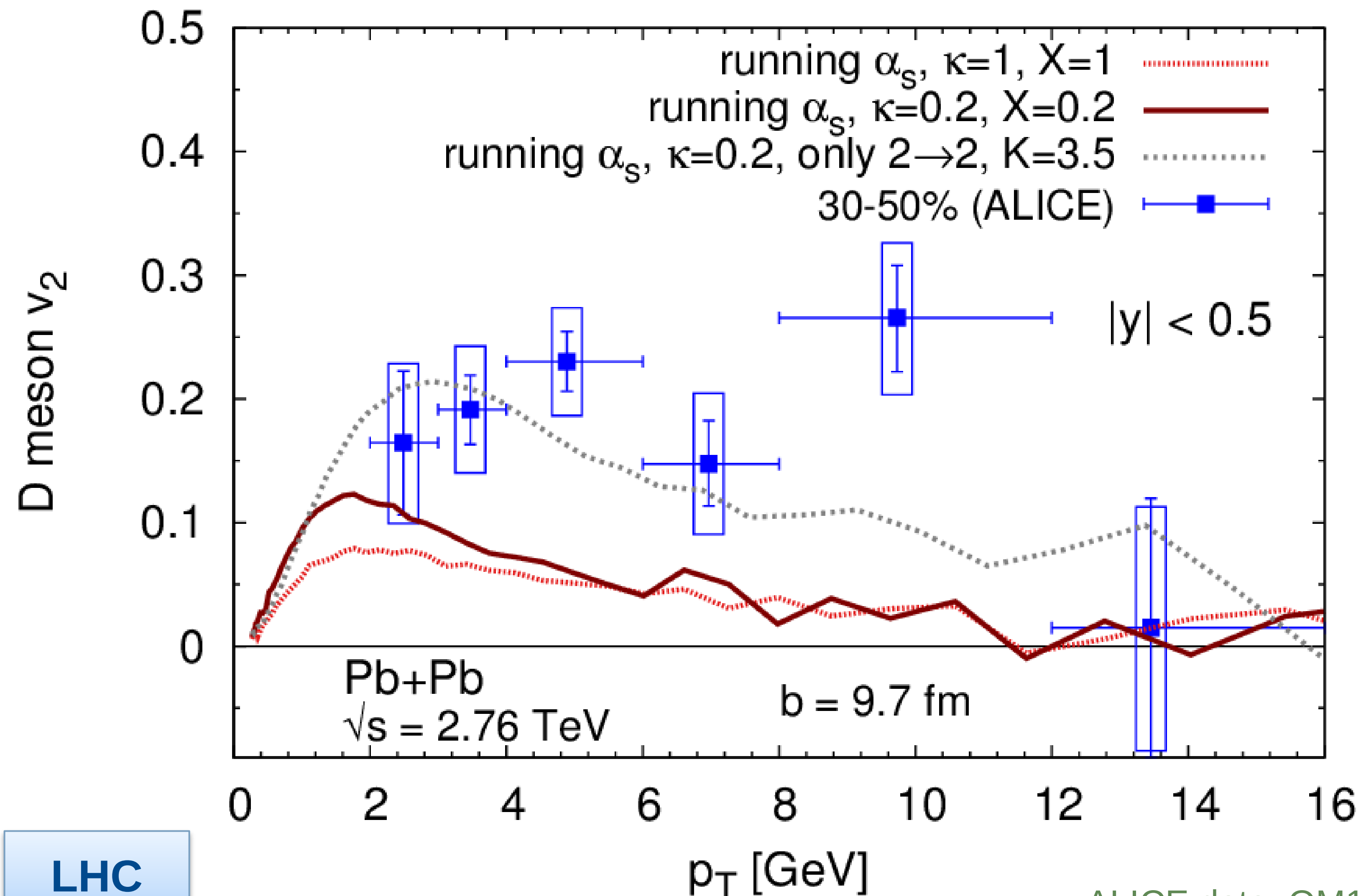
With improved screening: D meson R_{AA} at LHC



LHC

ALICE data, QM12

D meson v_2 at LHC



LHC

ALICE data, QM12

Energy loss and transport cross section

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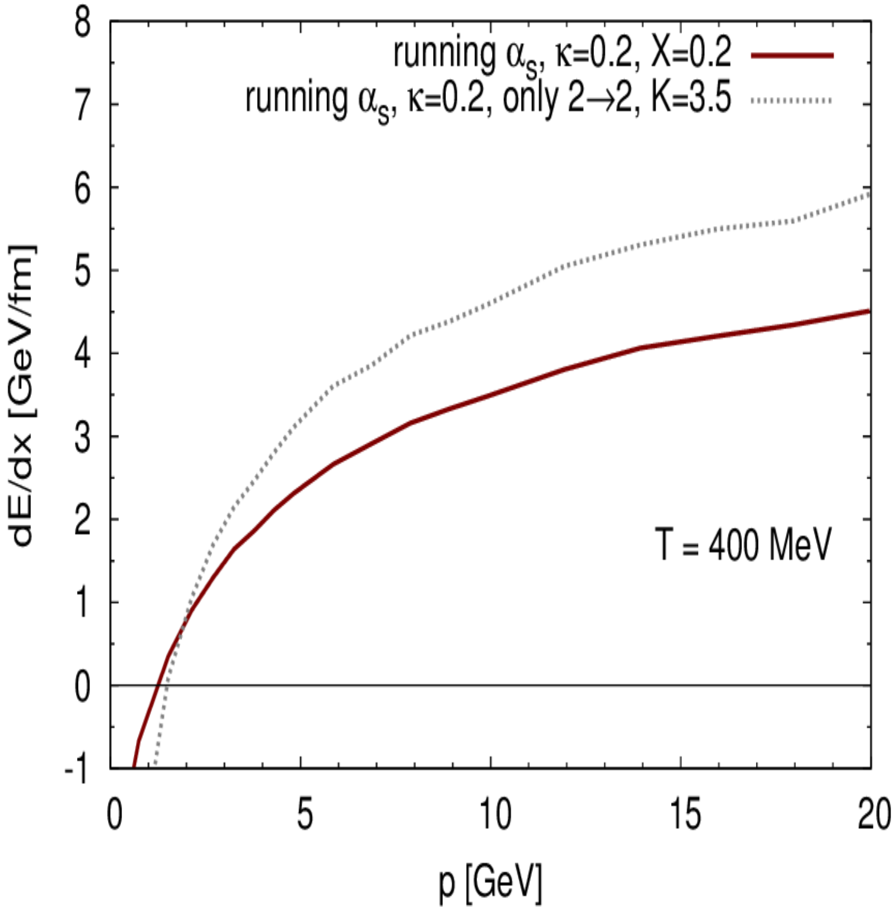
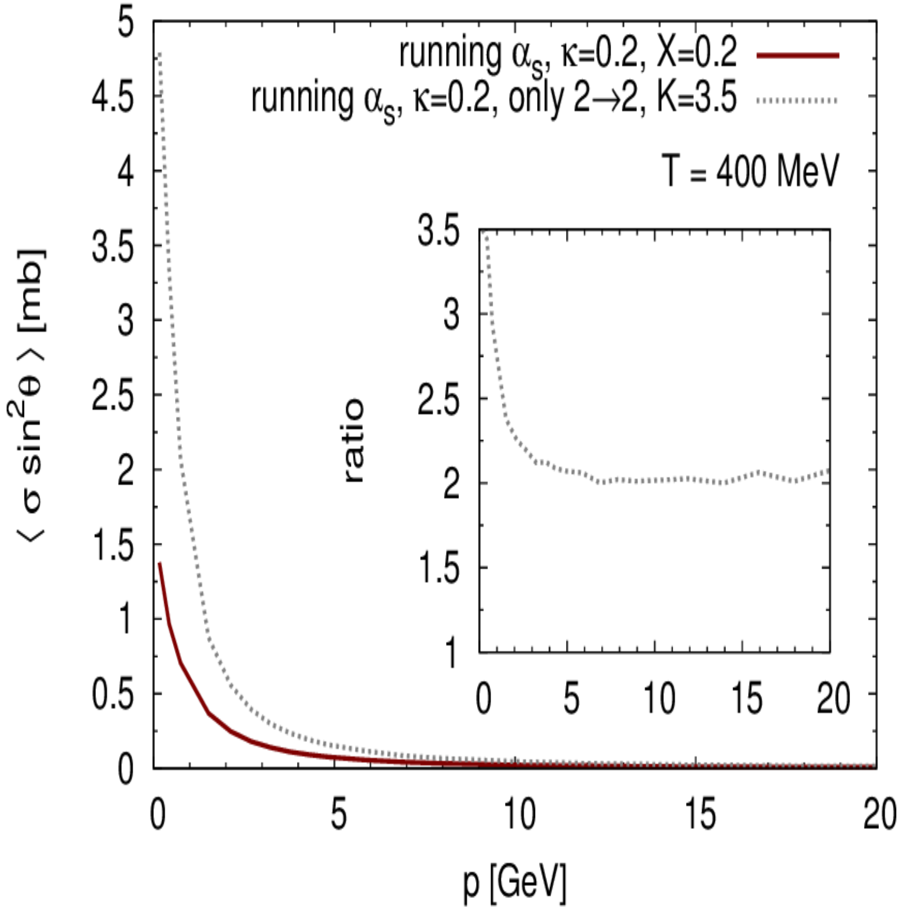
Energy loss
in static medium



Transport cross section
in static medium



Radiative energy loss

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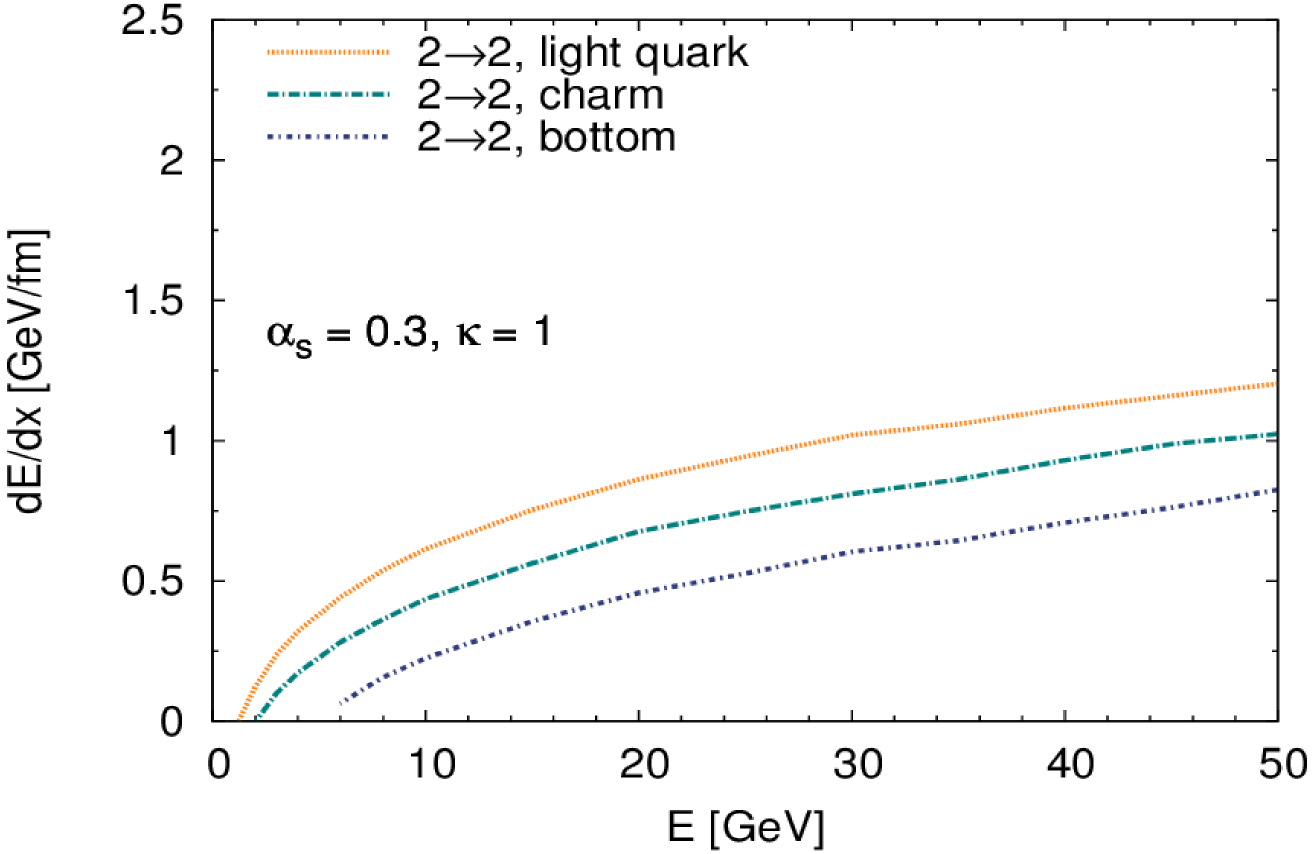
$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{light quark}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{charm}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{bottom}}$$



$\alpha_s = 0.3$

Radiative energy loss

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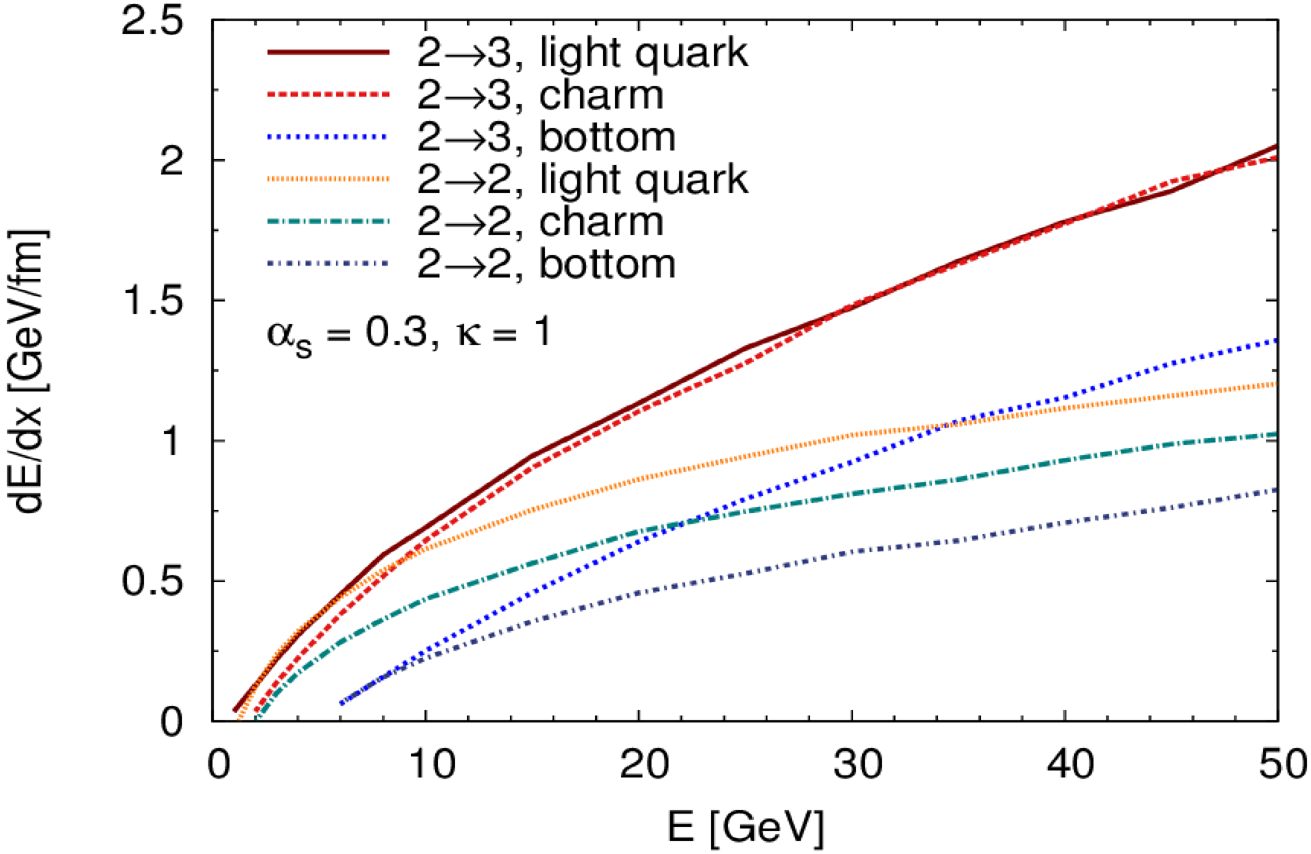
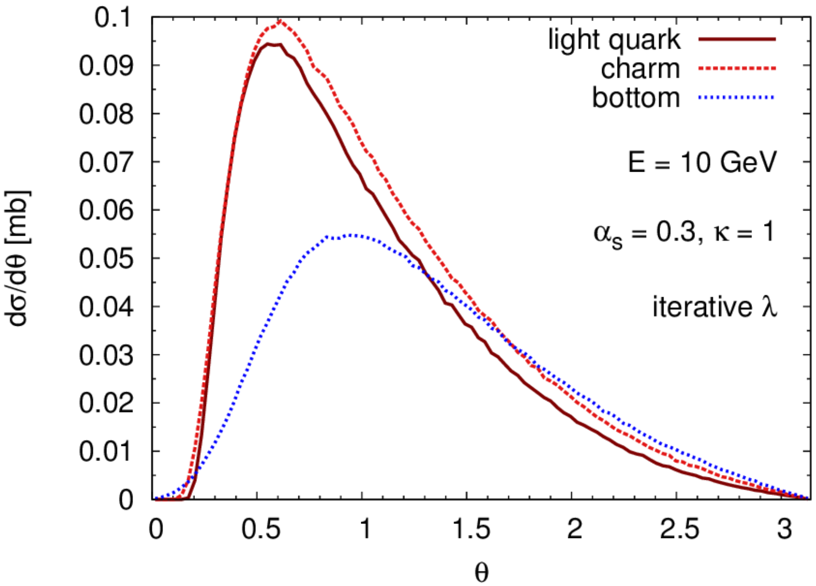
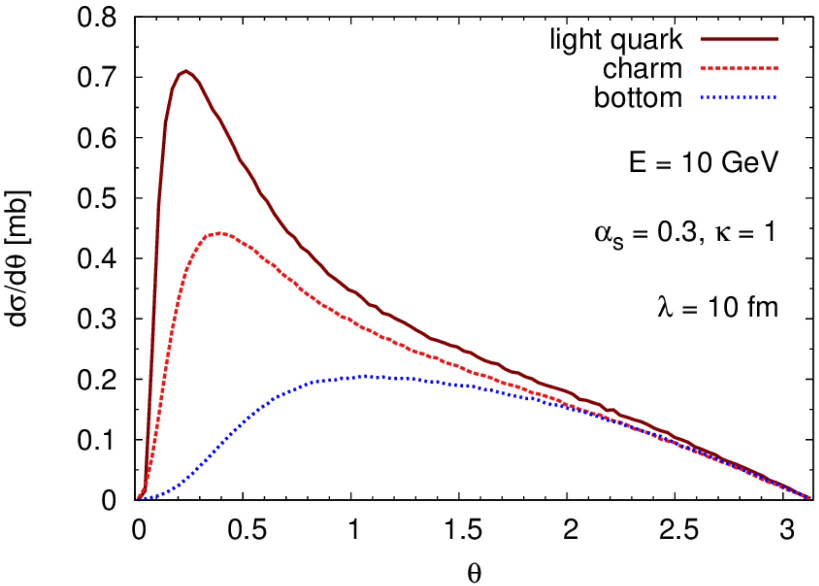
$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{light quark}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{charm}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{bottom}}$$



$$\alpha_s = 0.3$$

Angle distribution in lab frame





With LPM

Without LPM

Dead cone due to mass is overlayed by second dead cone from LPM cut-off

Dead cone due to mass is visible

Heavy flavor and charged hadron R_{AA} at LHC

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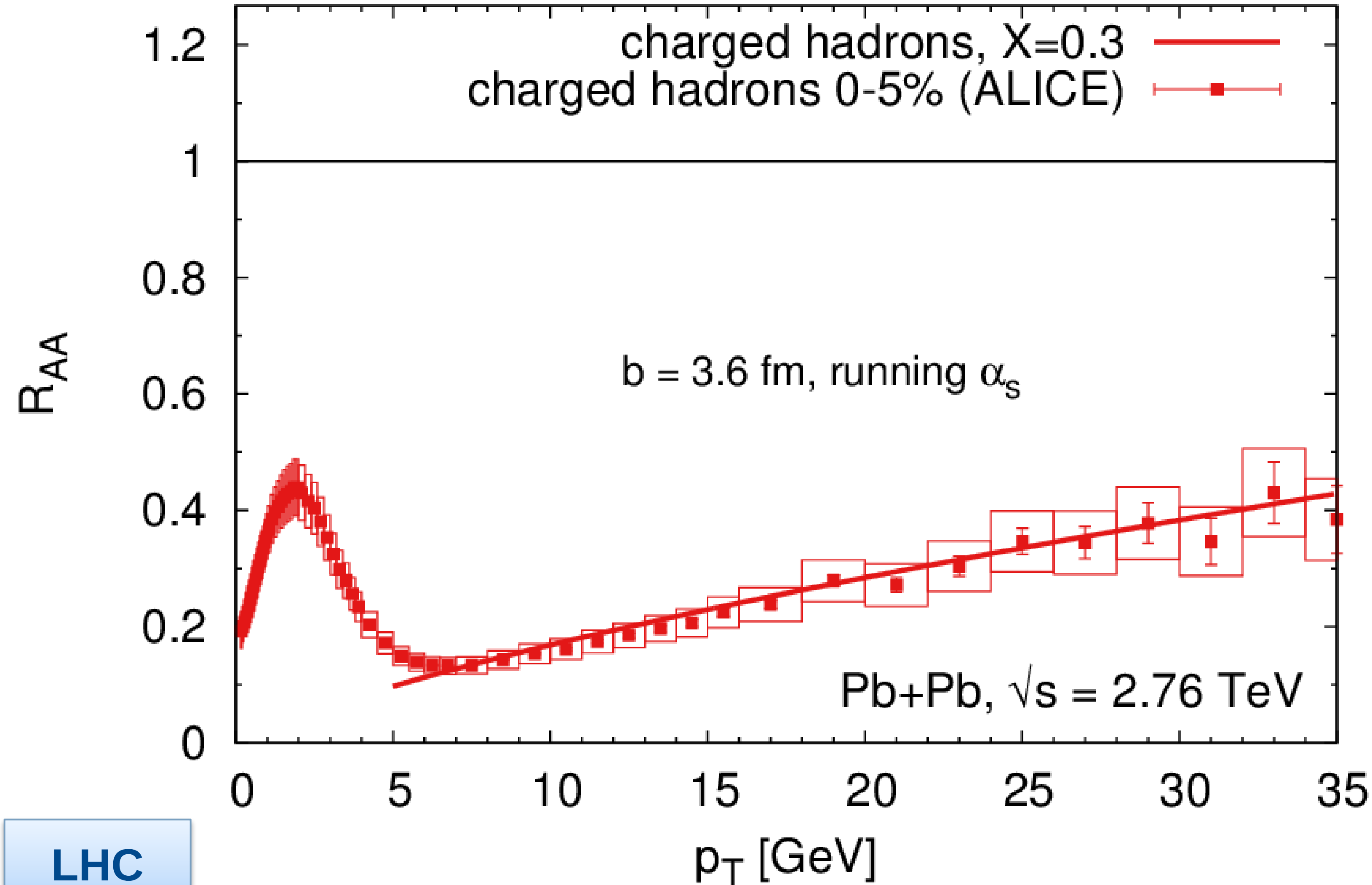

LHC

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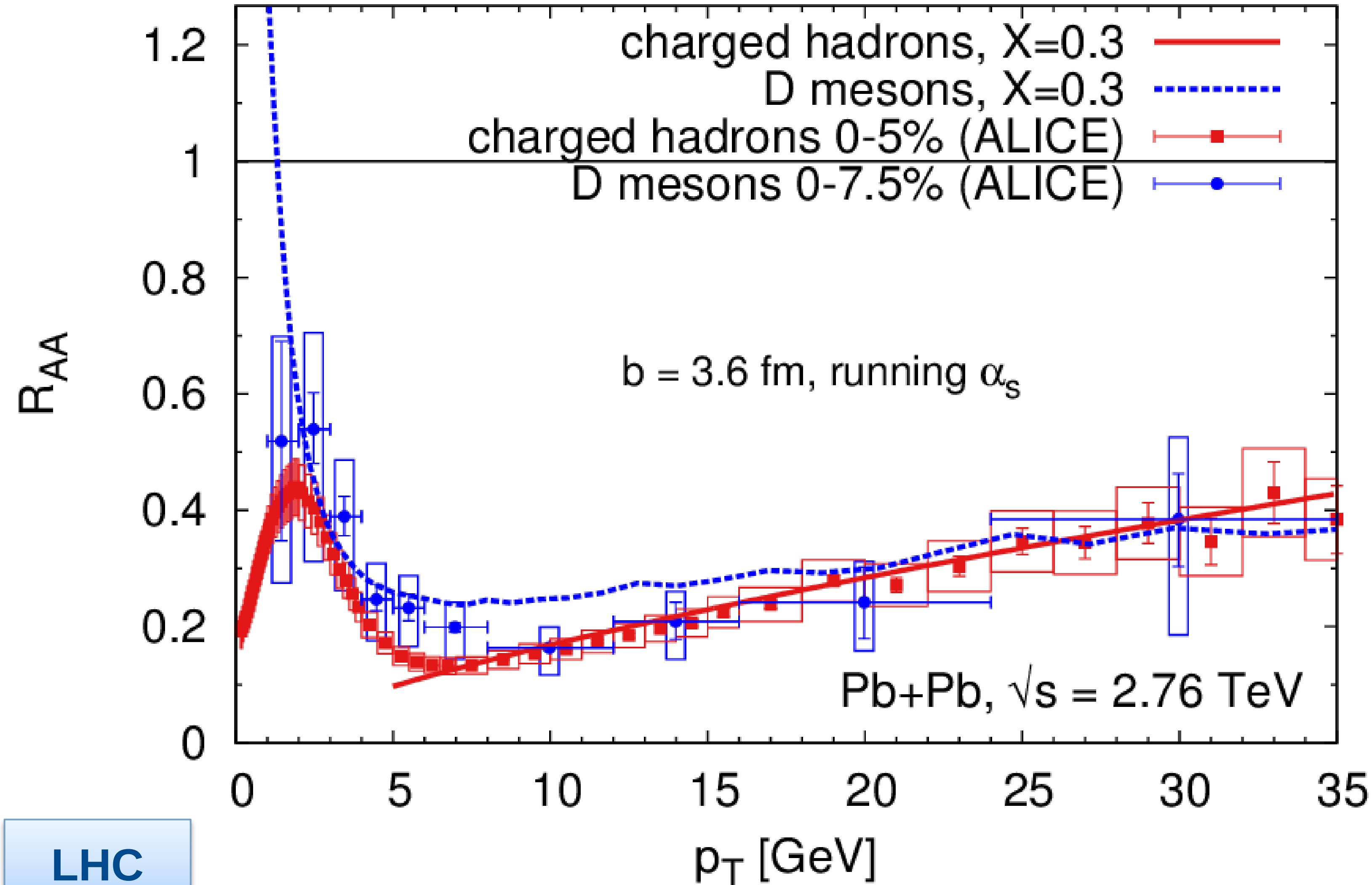

LHC

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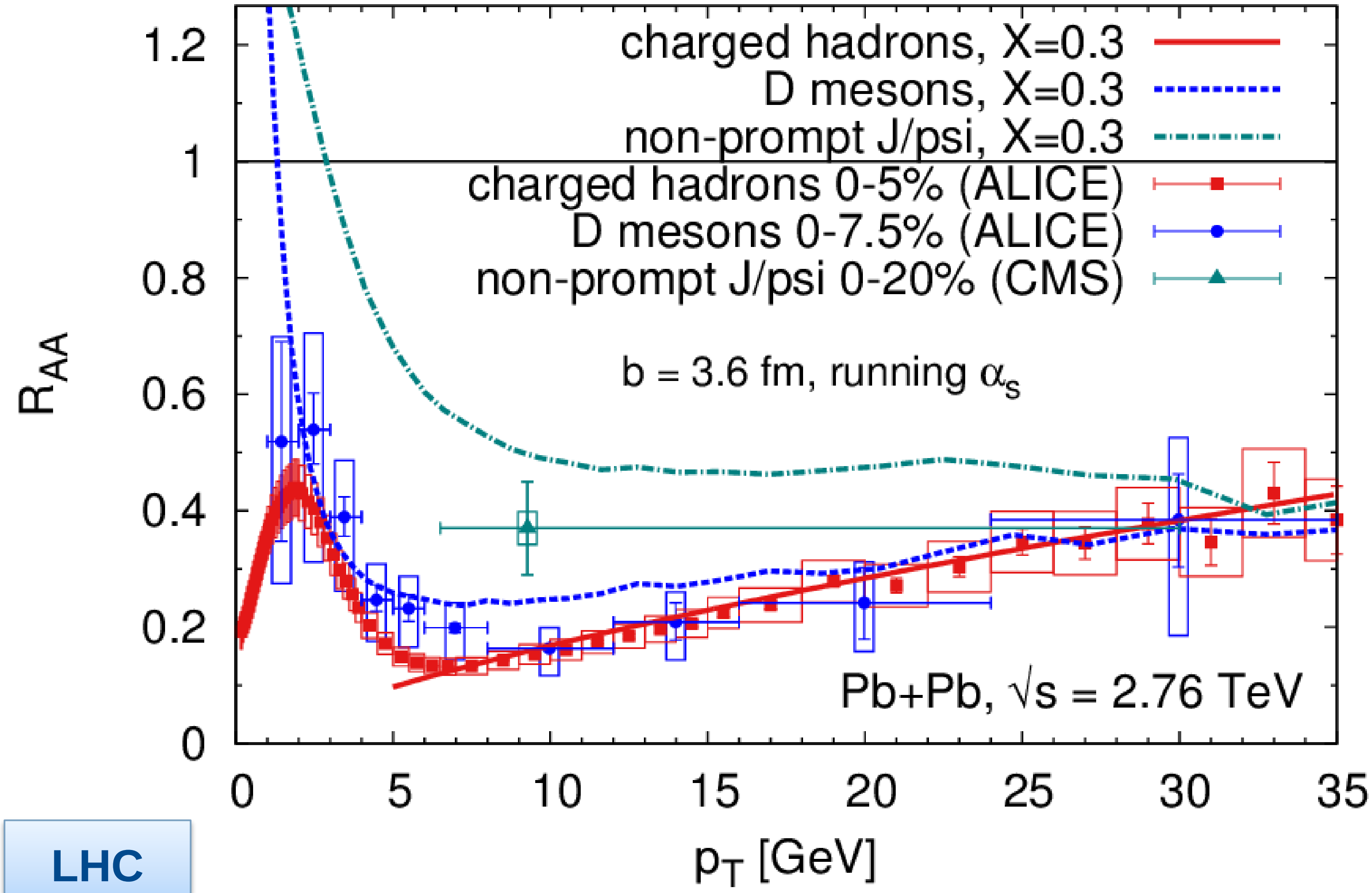

LHC

Conclusions & outlook

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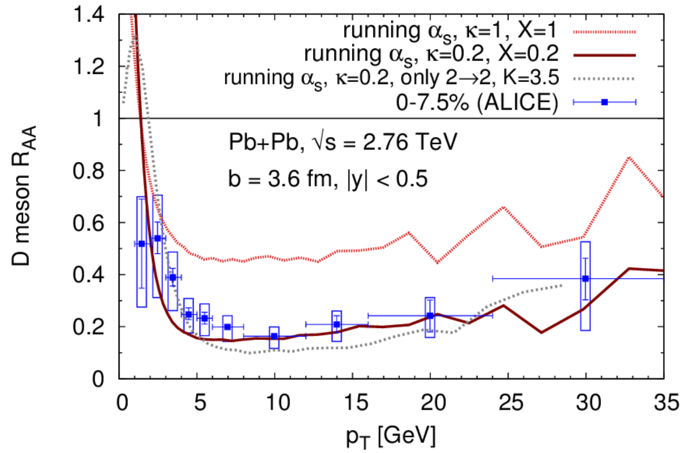
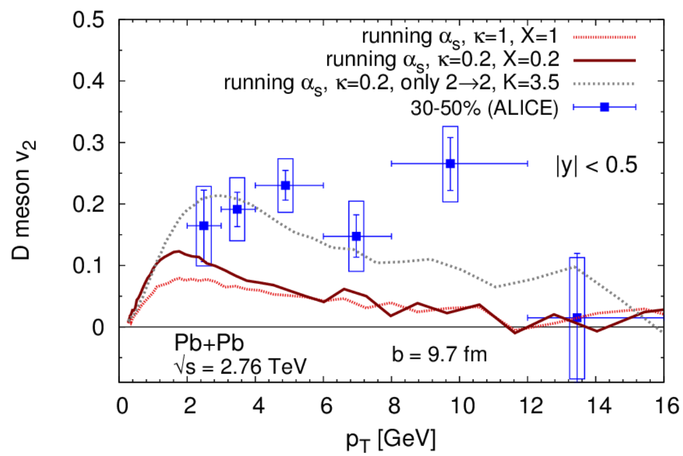
Full space-time evolution of QGP with charm and bottom quarks

- **Only binary collisions:**
  With running coupling and improved Debye screening, v_2 and R_{AA} agreement only with K=3.5

- **Radiative and binary collisions:**
  - Not enough energy loss
    → improvement of LPM
  - R_{AA} and v_2 simultaneously seems difficult
  - R_{AA} of light and heavy hadrons can be described

Further details in Phys. Lett. B 717, 430 (2012)
and Phys. Rev. D88 (2013)



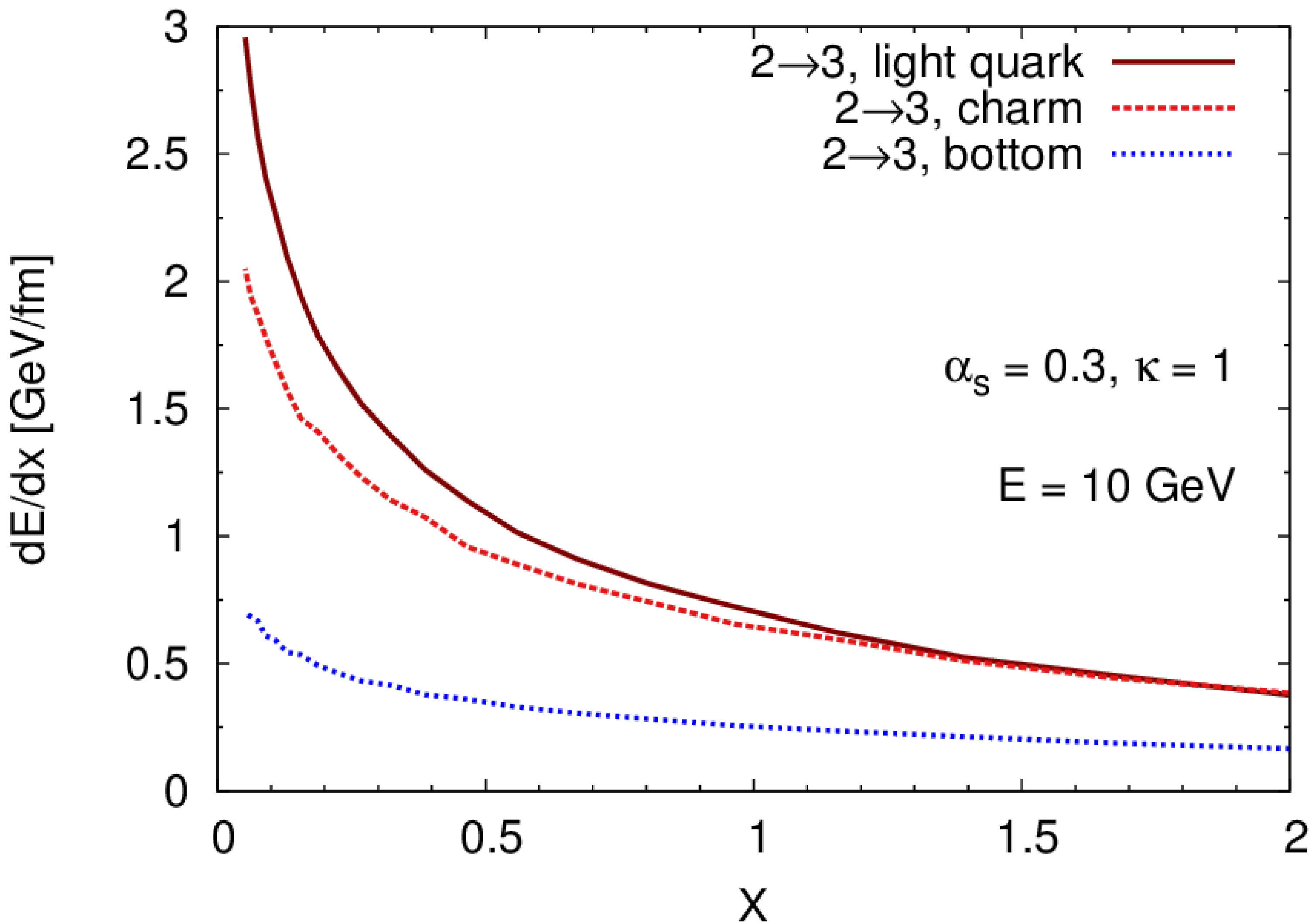


Future tasks:

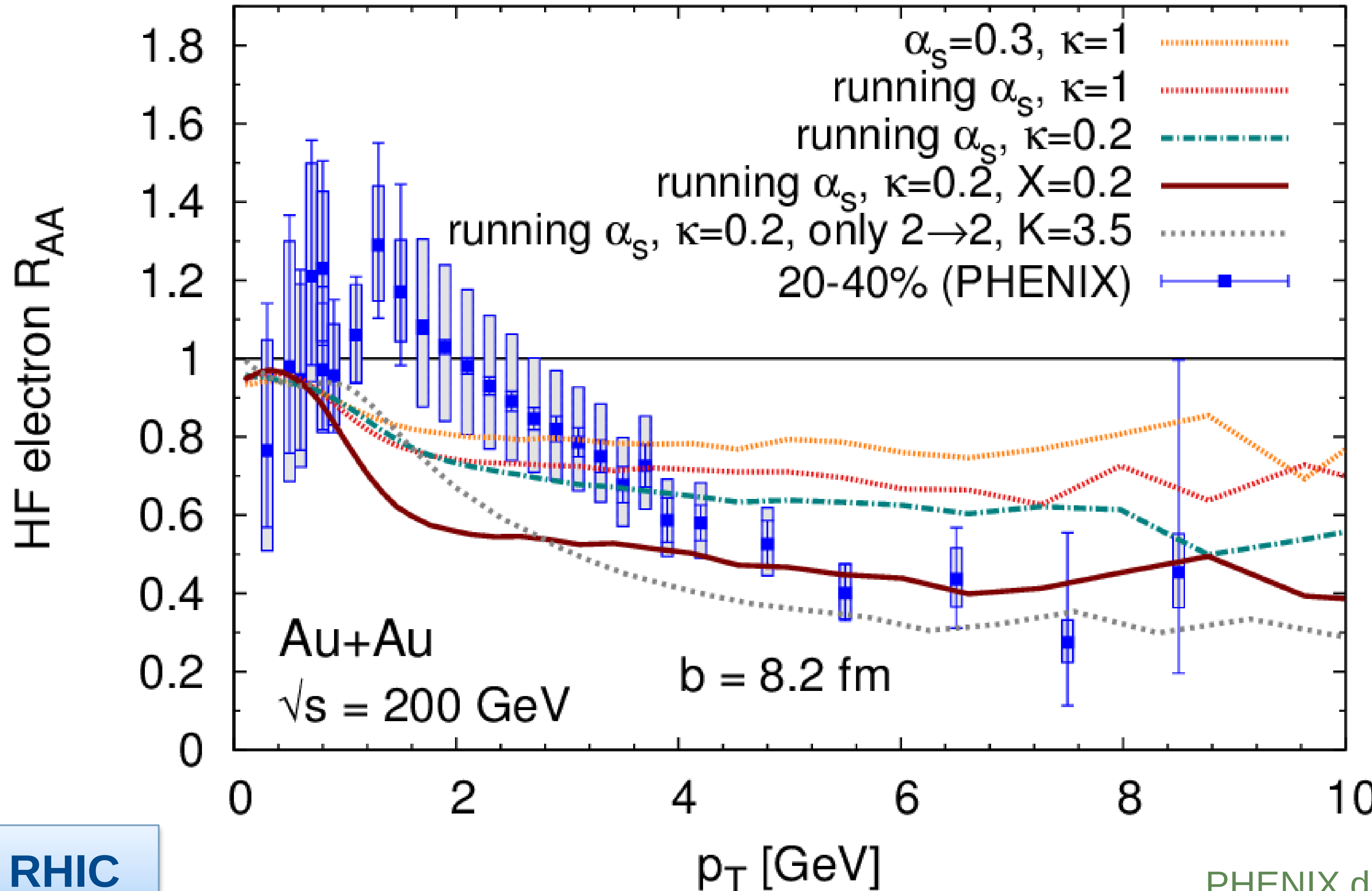
- Improvement of LPM effect

Thank you for your attention.

LPM: X dependence



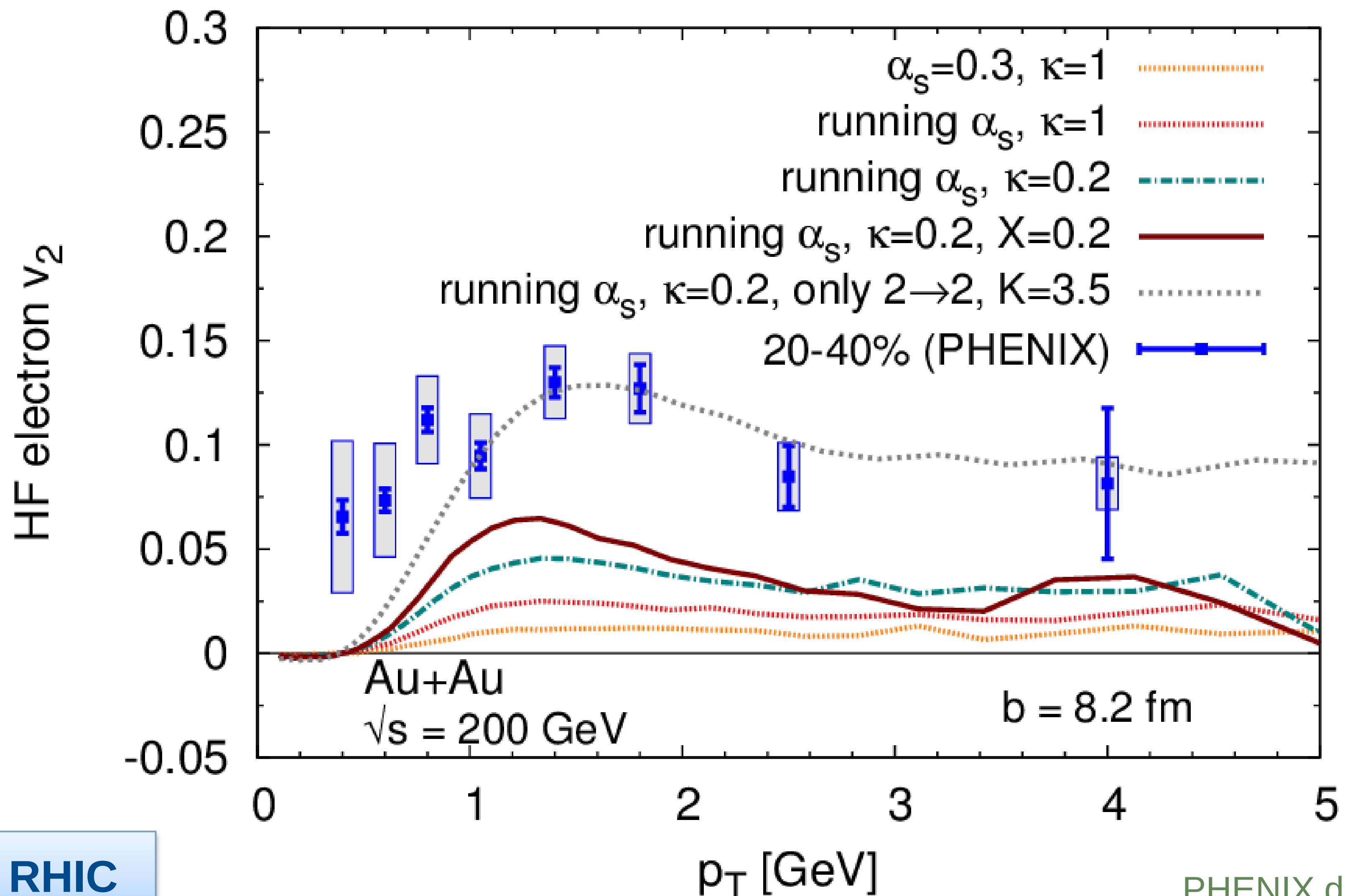
Heavy quark R_{AA} at RHIC



RHIC

PHENIX data,
Phys.Rev. C84 (2011)

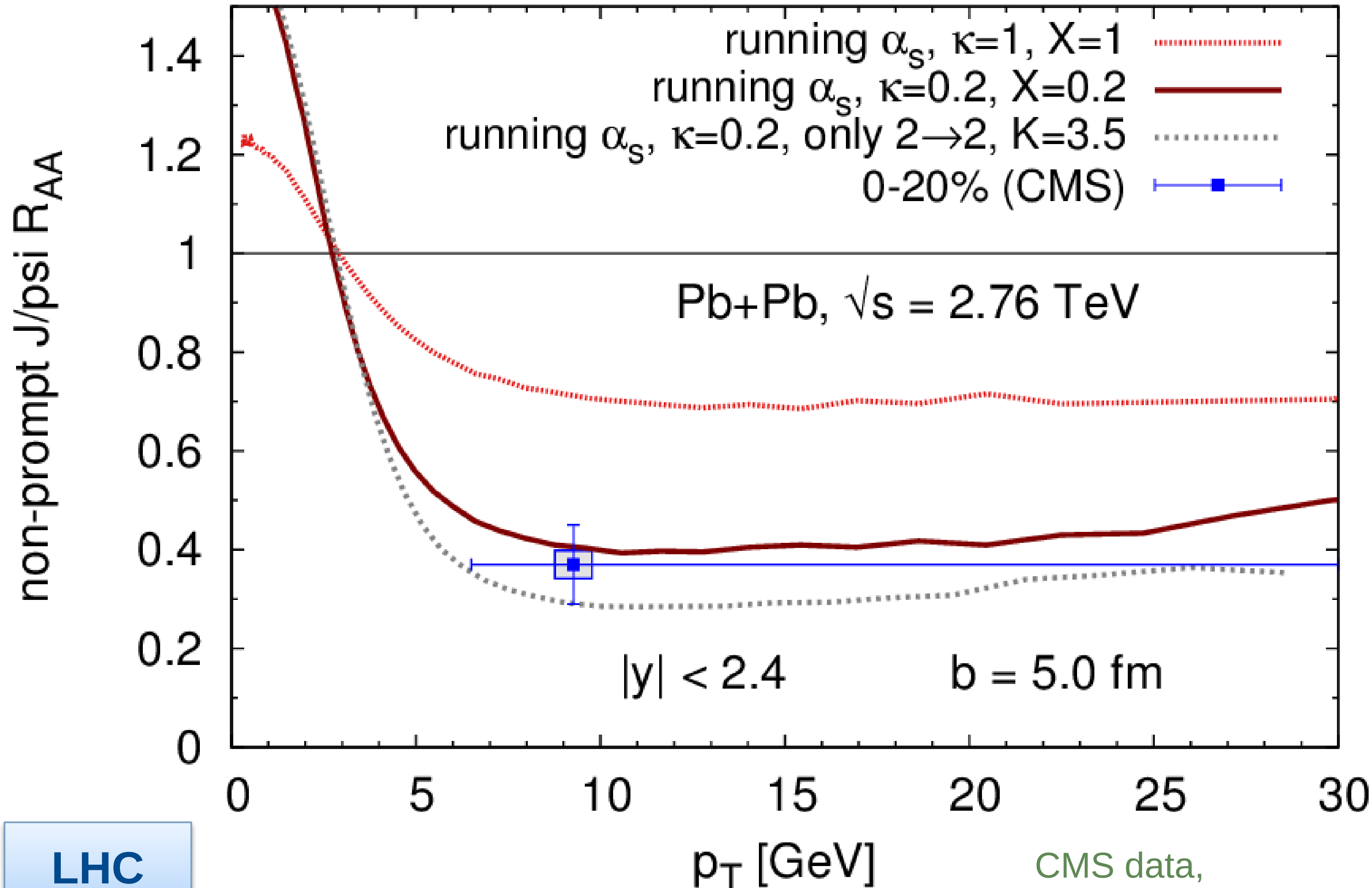
Heavy quark v_2 at RHIC



RHIC

PHENIX data,
Phys.Rev. C84 (2011)

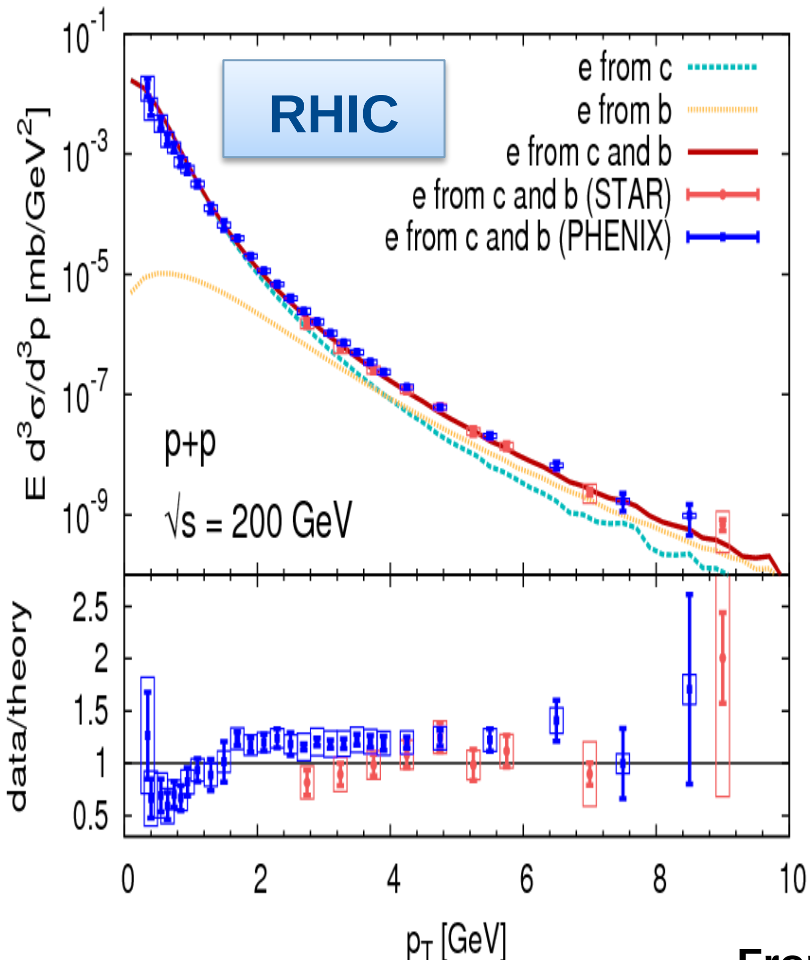
Non-prompt J/psi R_{AA} at LHC

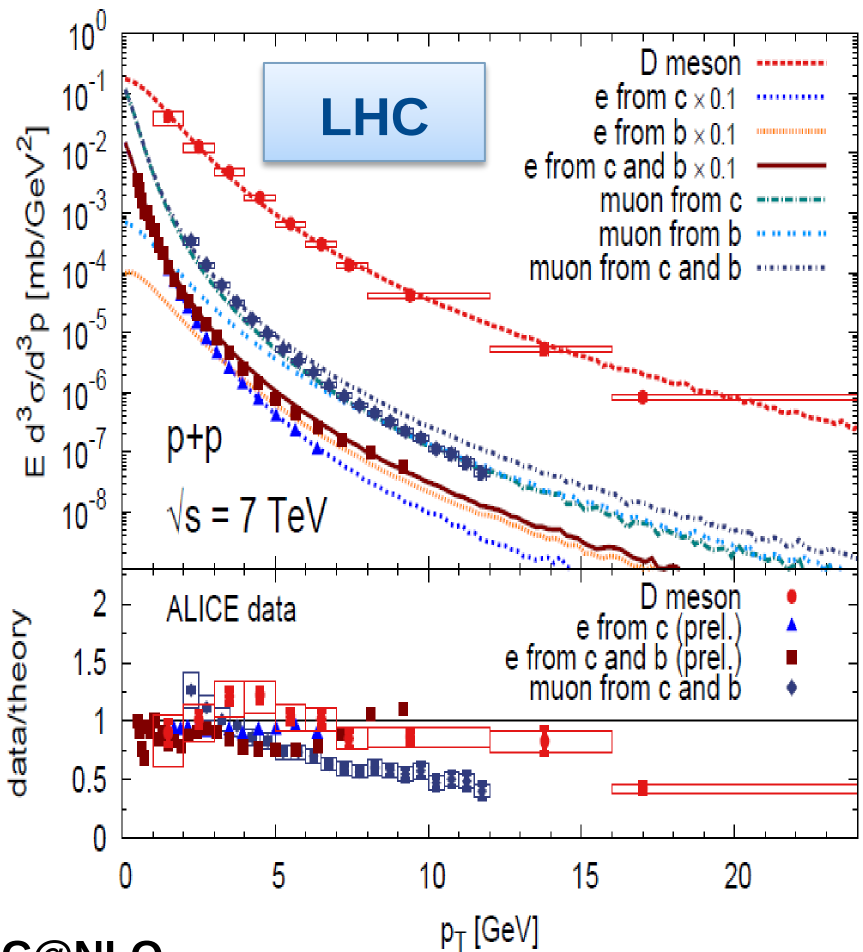


LHC

CMS data, arXiv:1201.5069

Initial heavy flavor spectrum





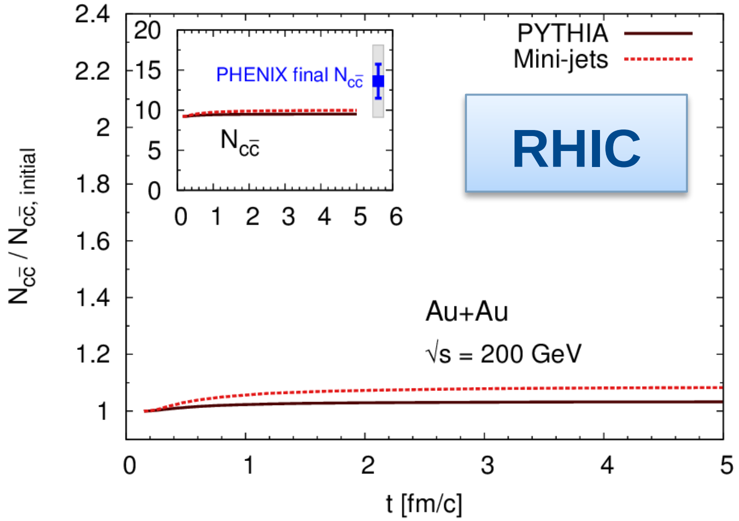
From MC@NLO

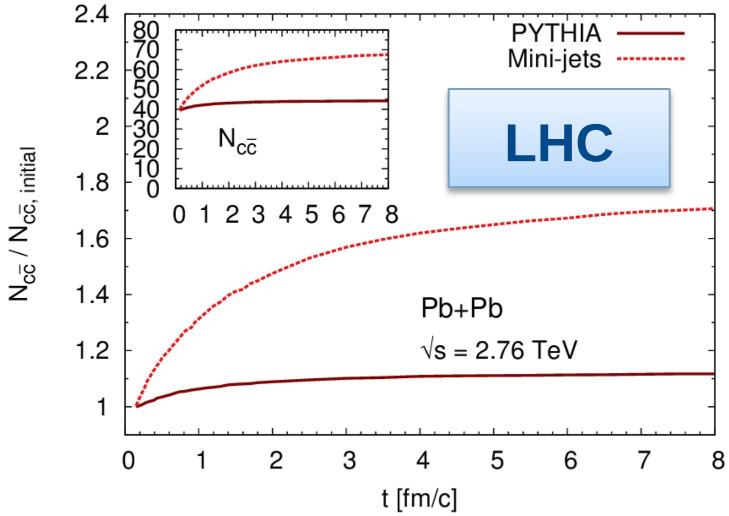
JU, Fochler, Xu, Greiner
Phys. Rev. C84 (2011)

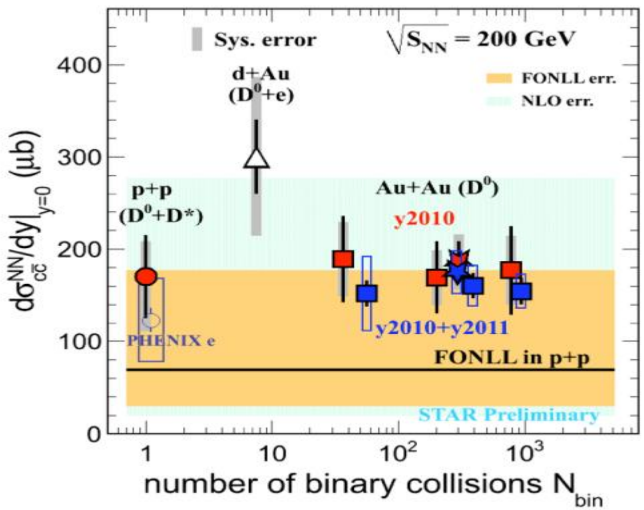
JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

Total charm production

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







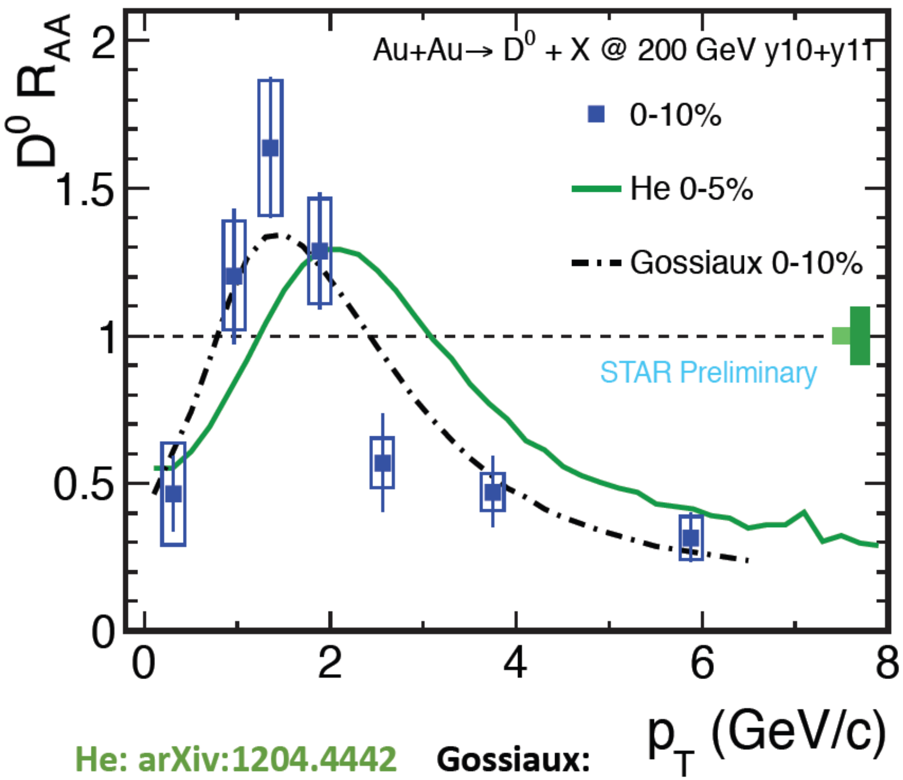
STAR, QM12

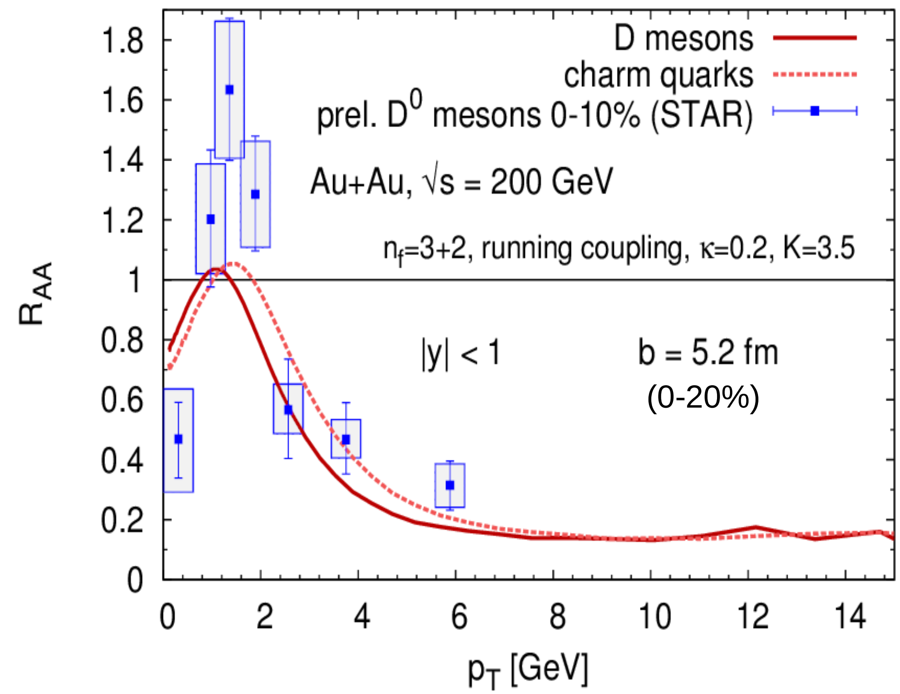
Sizeable charm production in QGP at LHC

Experiment ?

D meson R_{AA} from STAR

RHIC





He: arXiv:1204.4442
Focker-Planck
Resonance
recombination

Gossiaux:
arXiv:1207.5445
Boltzmann
pQCD with running coupling

JU, Fochler, Xu, Greiner

STAR data, QM 2012

Fragmentation and Decay

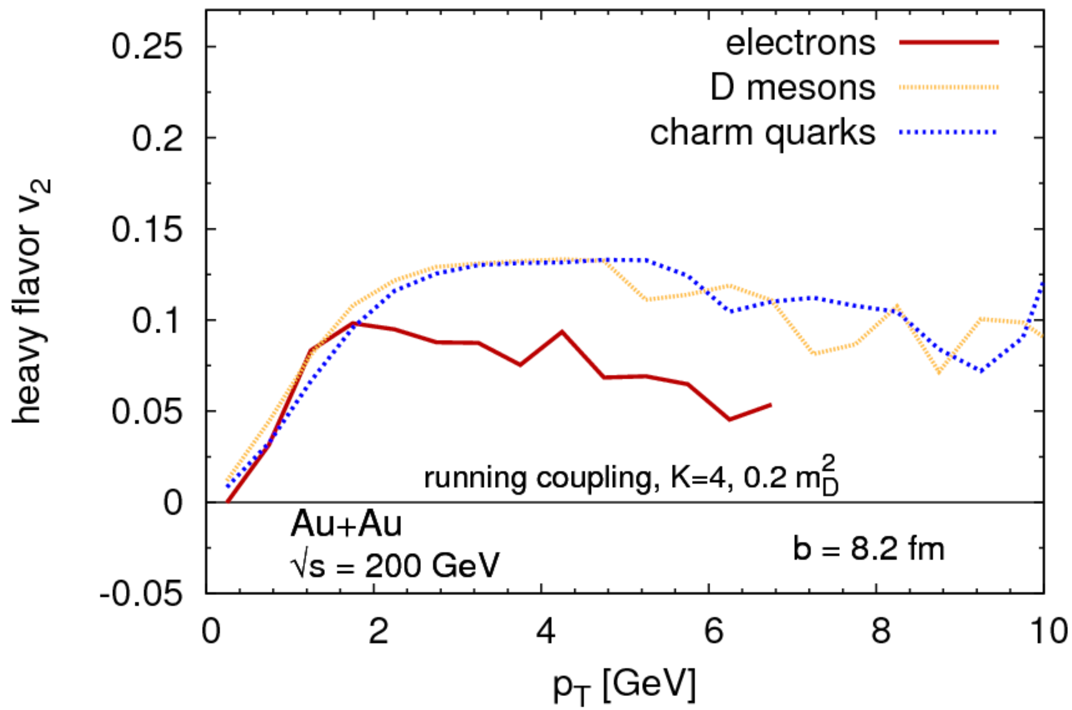
- **Peterson fragmentation**

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

$$D_{H/Q}(z) = \frac{N}{z\left(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right)^2} \qquad z = \frac{|\vec{p}_H|}{|\vec{p}_Q|}$$

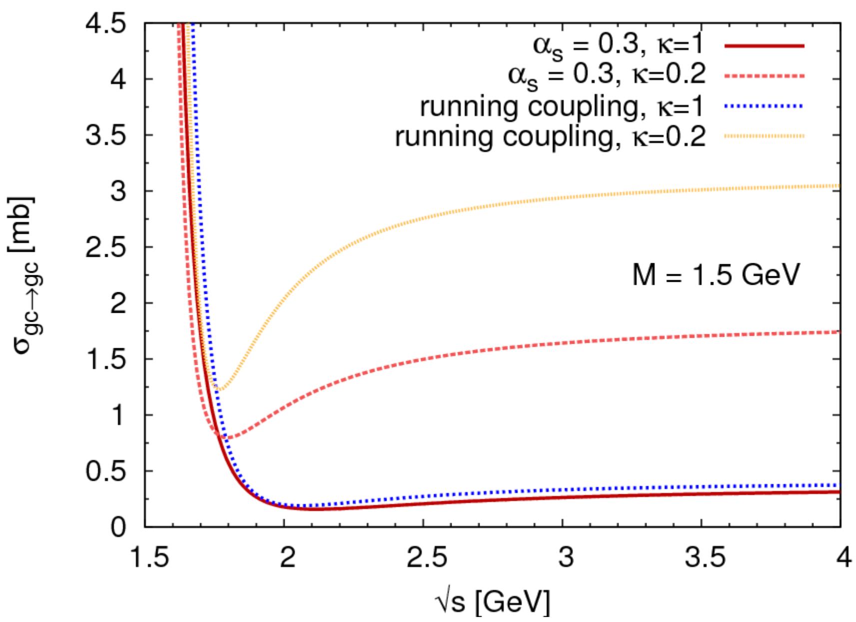
$$\epsilon_c = 0.05$$
$$\epsilon_b = 0.005$$

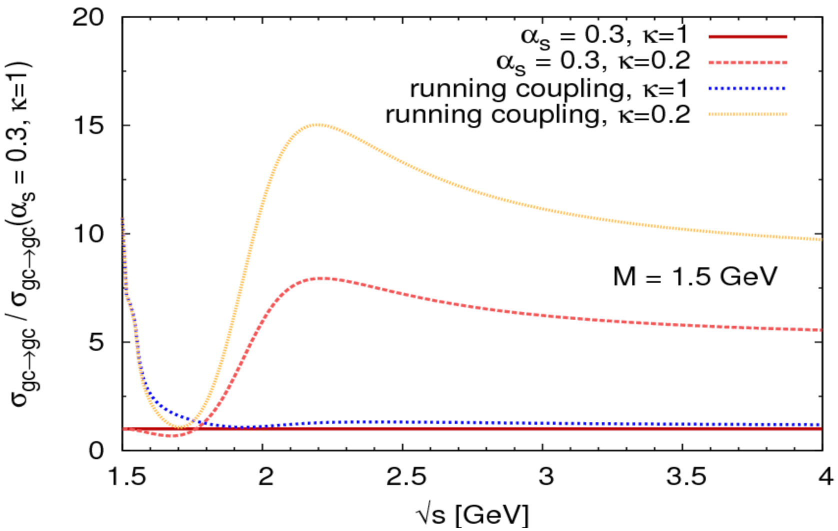
- **Decay to electrons with PYTHIA**

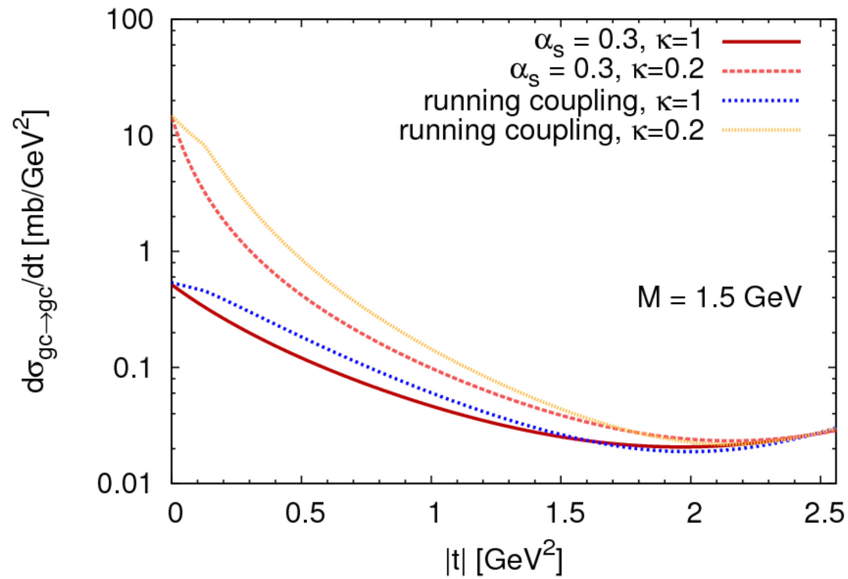


Impact of hadronization and decay small

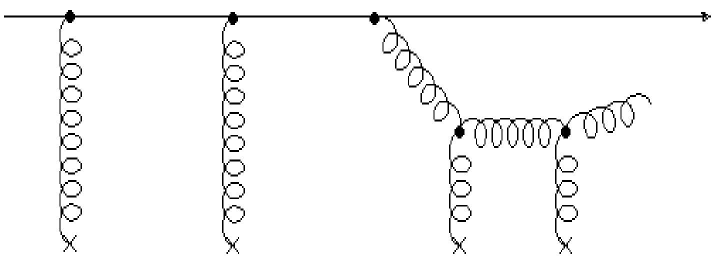
Heavy quark scattering cross section







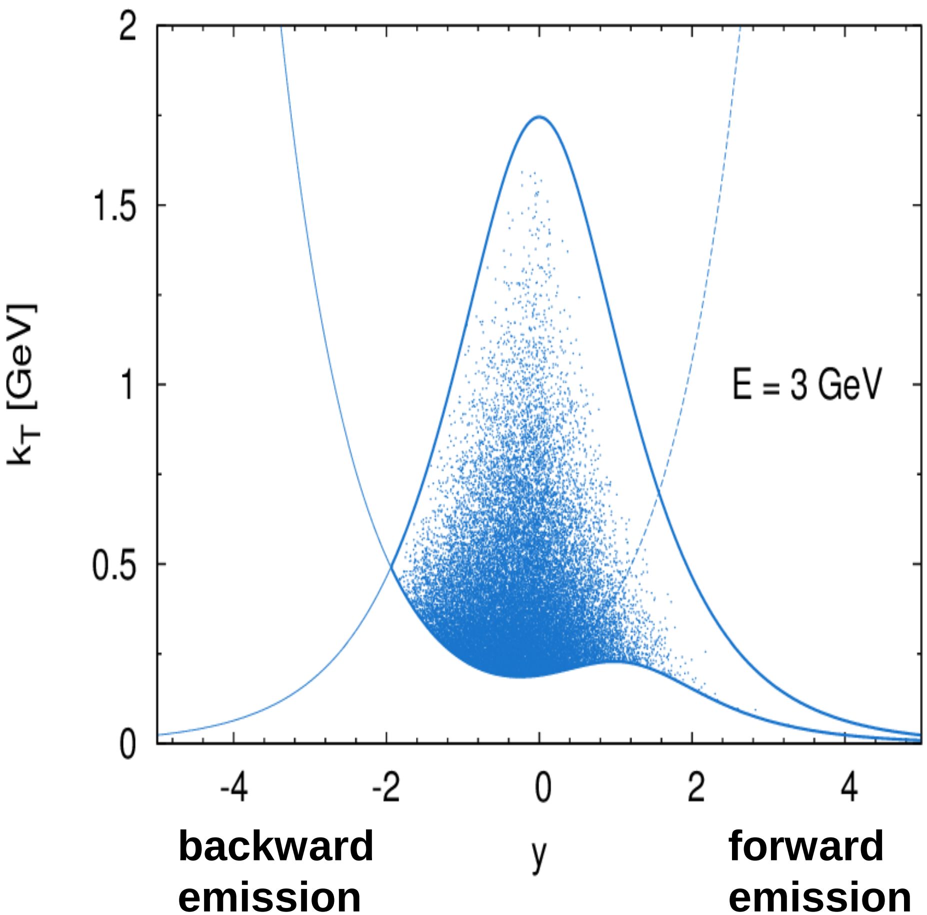
LPM effect vs. dead cone effect



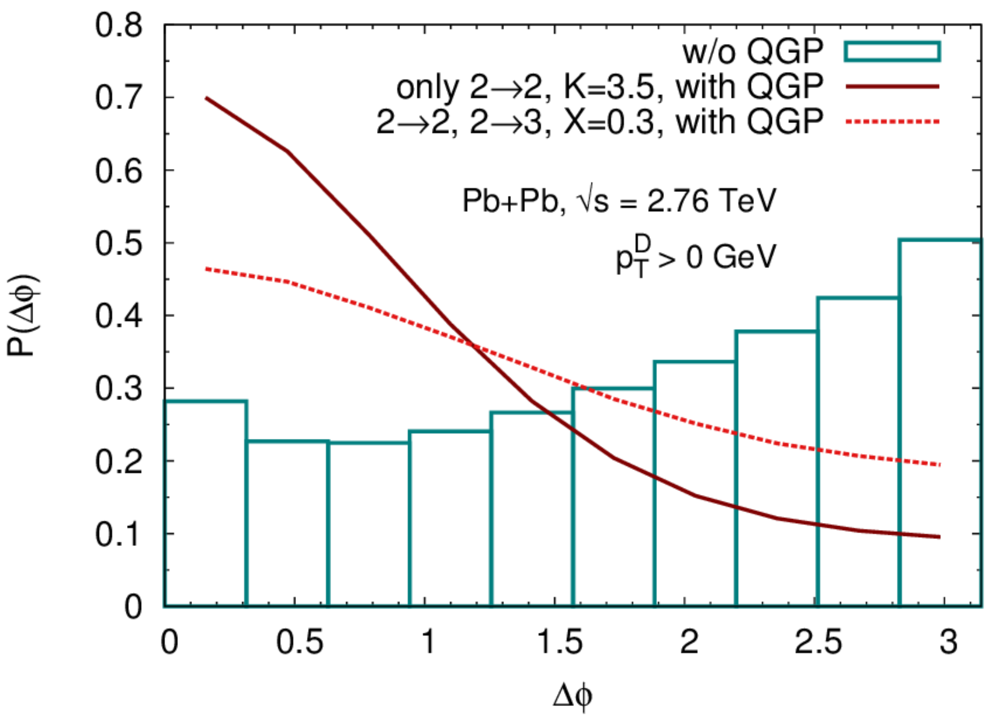
$$\lambda > \tau$$

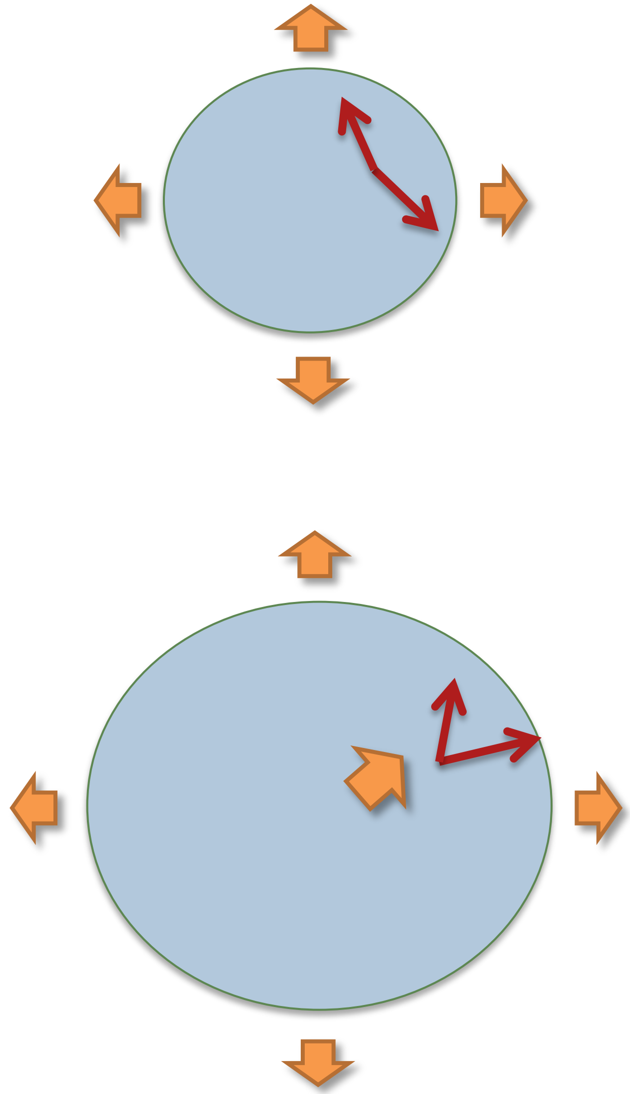
2 → 3 process only allowed if mean free path of jet larger than formation time of radiated gluon

➡ Independent scatterings



D meson angle correlations





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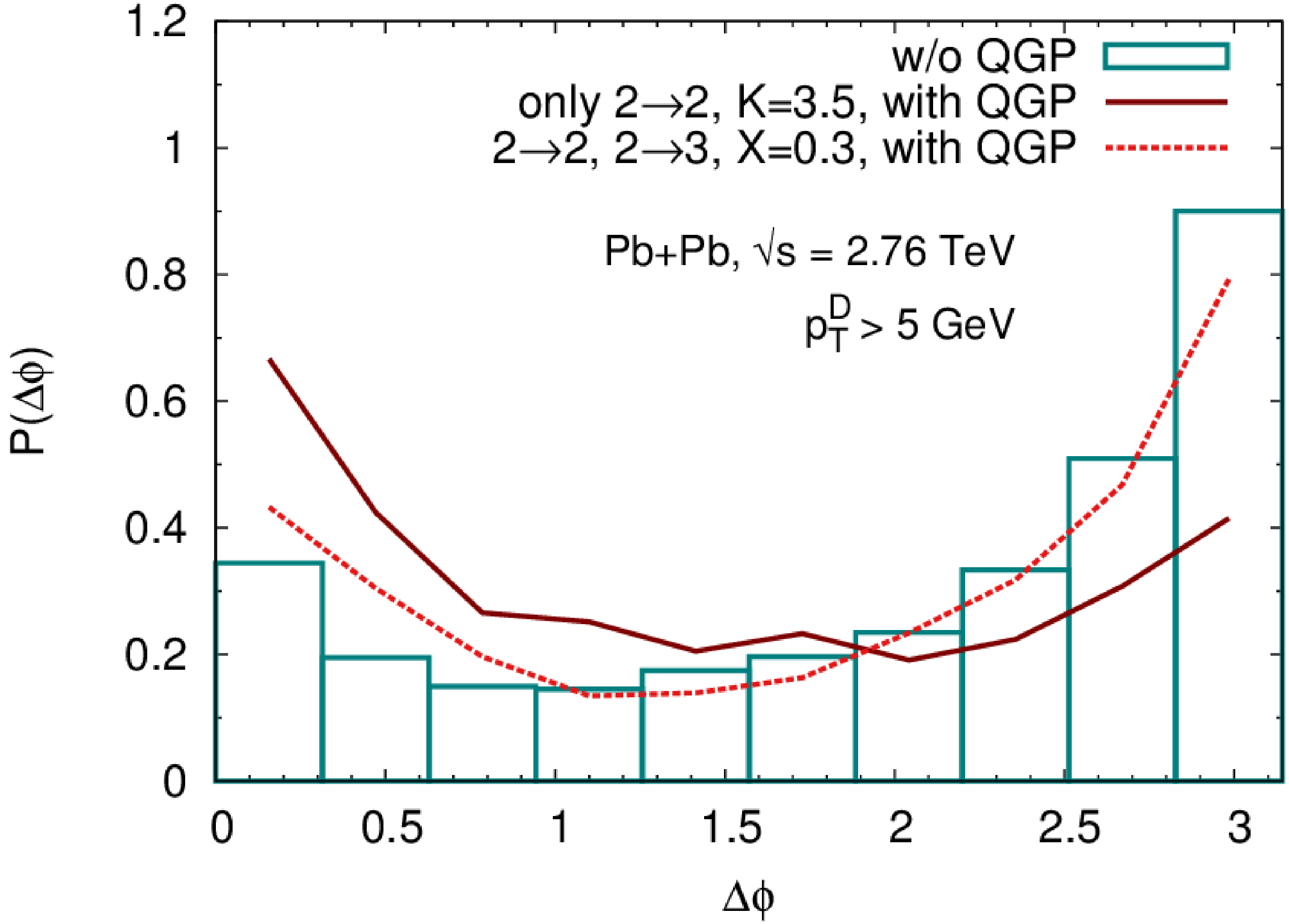


Momentum imbalance A_D

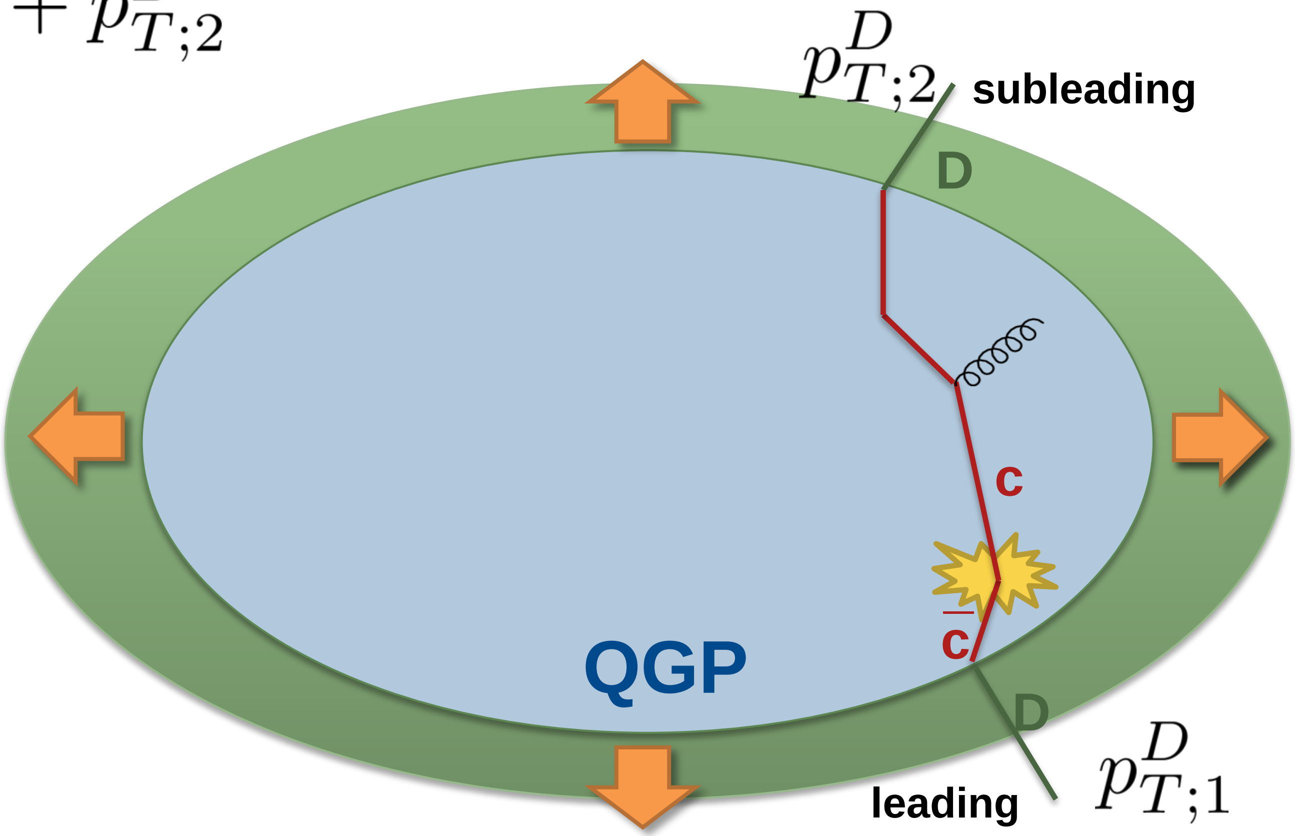
D meson momentum imbalance

$$A_D = \frac{p_{T;1}^D - p_{T;2}^D}{p_{T;1}^D + p_{T;2}^D}$$

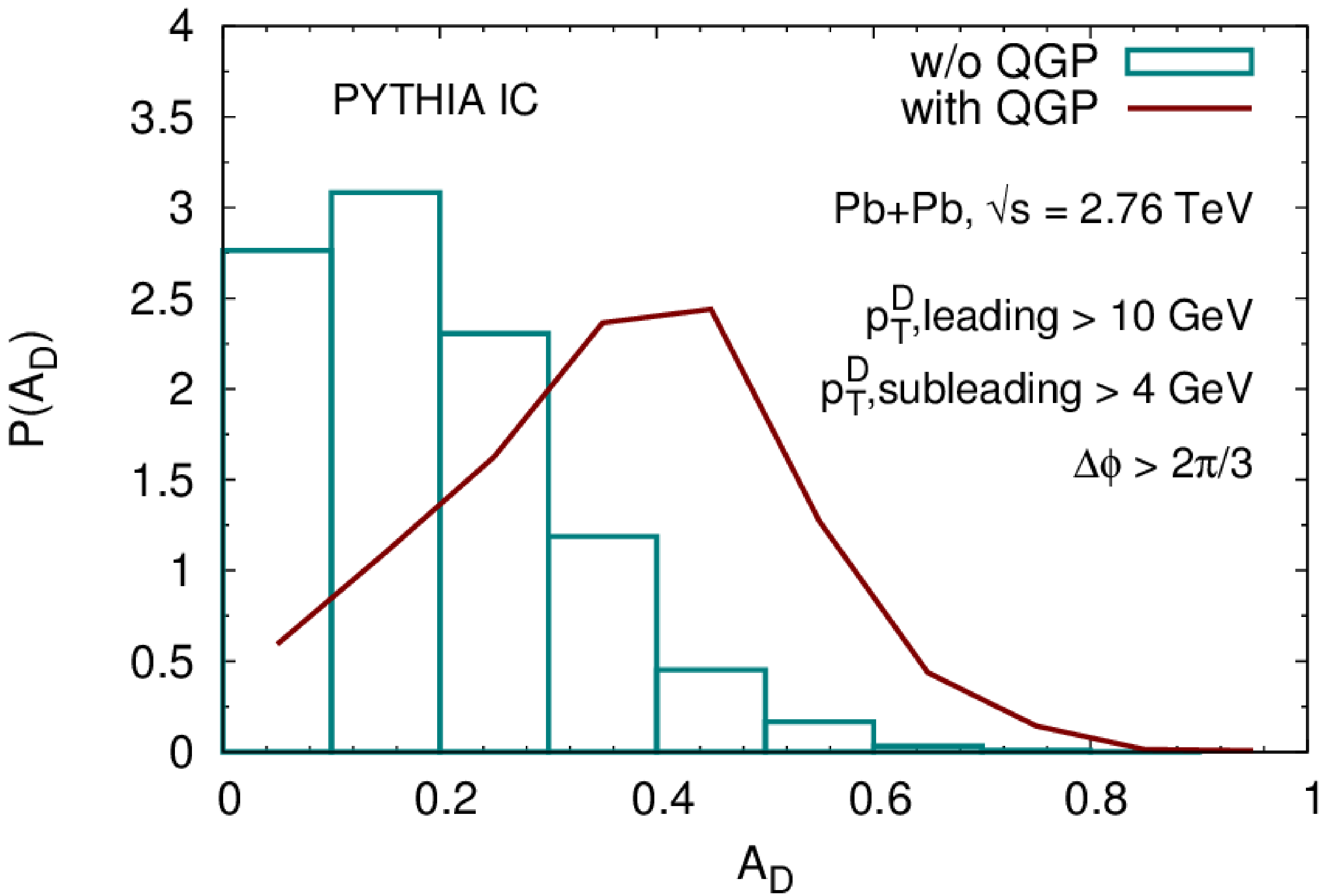
No jet reconstruction necessary

Analogous to

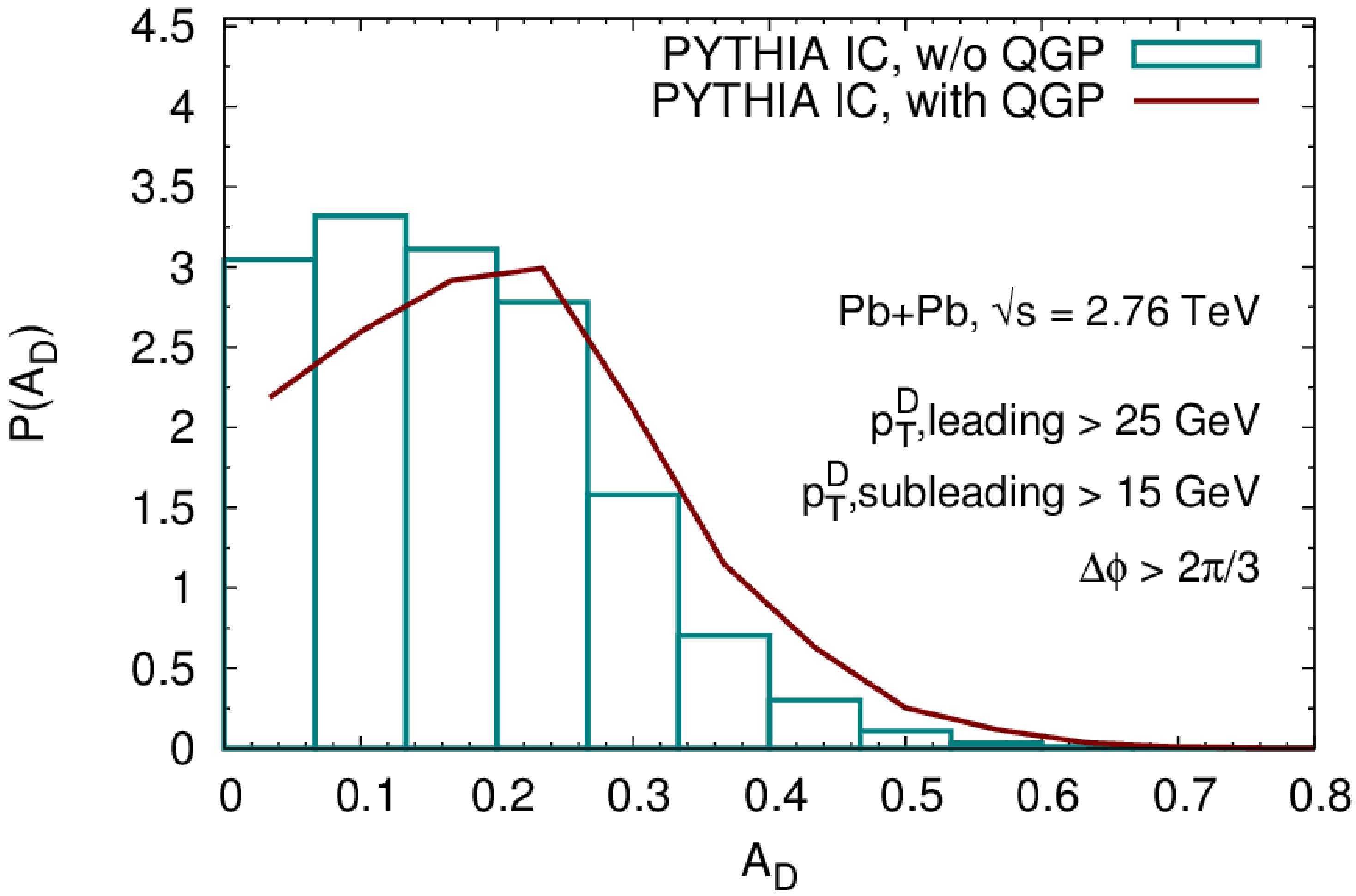
$$A_J = \frac{p_{T;1}^J - p_{T;2}^J}{p_{T;1}^J + p_{T;2}^J}$$



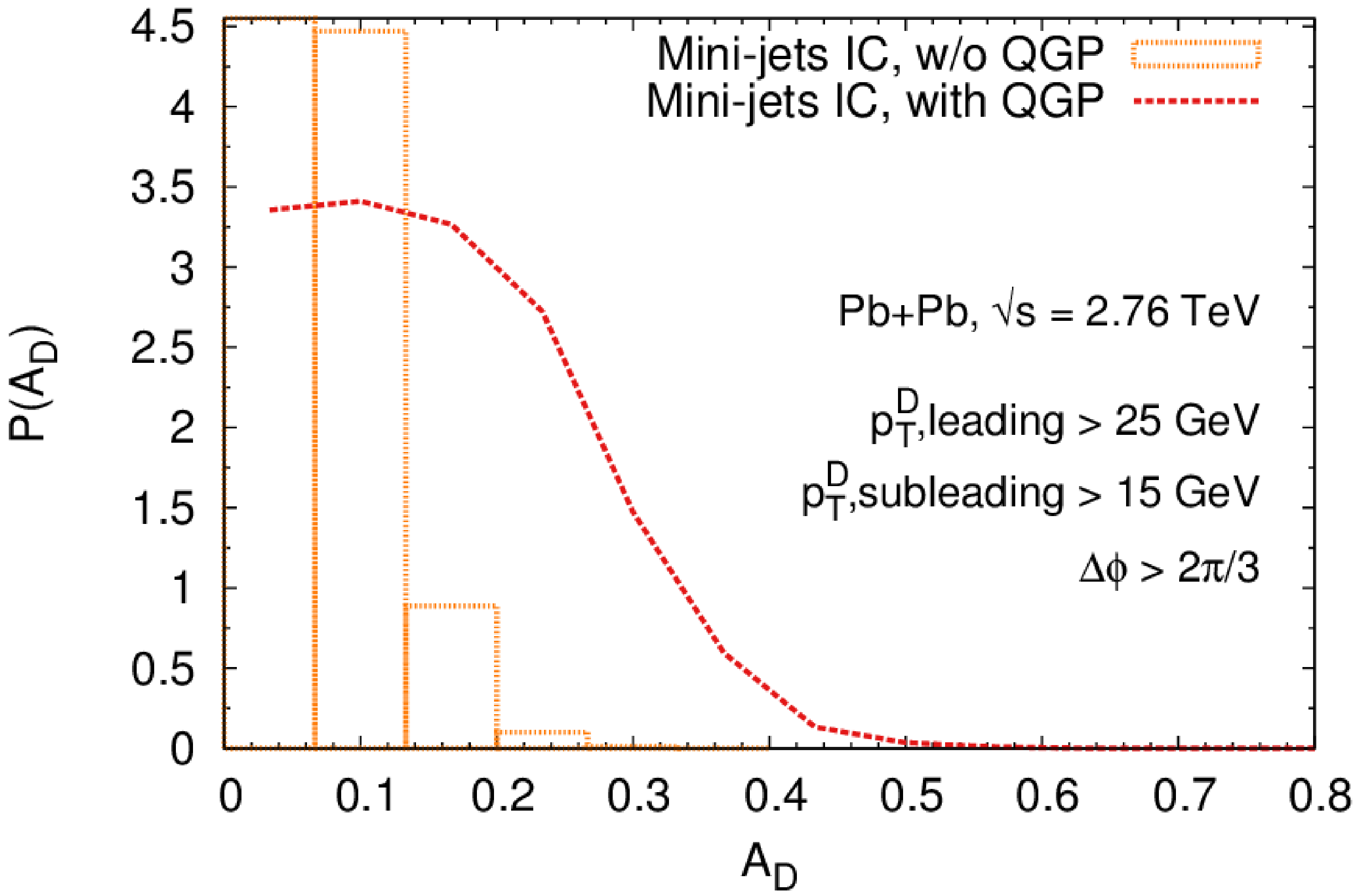
Momentum imbalance A_D for low triggers



A_D for high triggers – PYTHIA



A_D for high triggers – Mini-jets



Length imbalance