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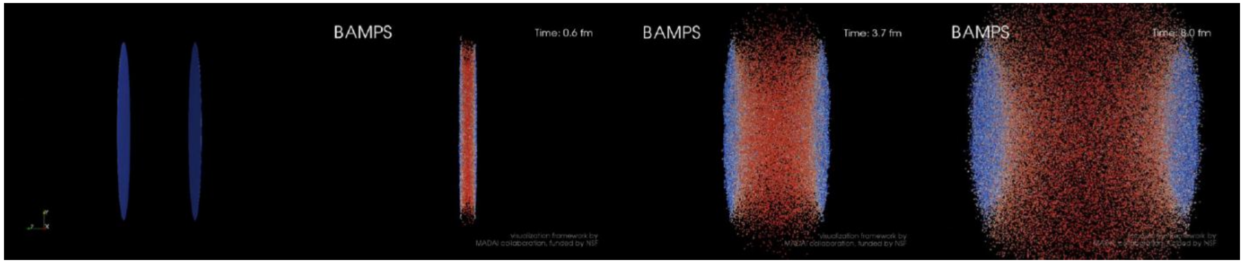
Heavy vs. light quark energy loss in ultra-relativistic heavy-ion collisions

Jan Uphoff

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

Based on Phys. Lett. B 717, 430 (2012)
and arXiv:1302.5250



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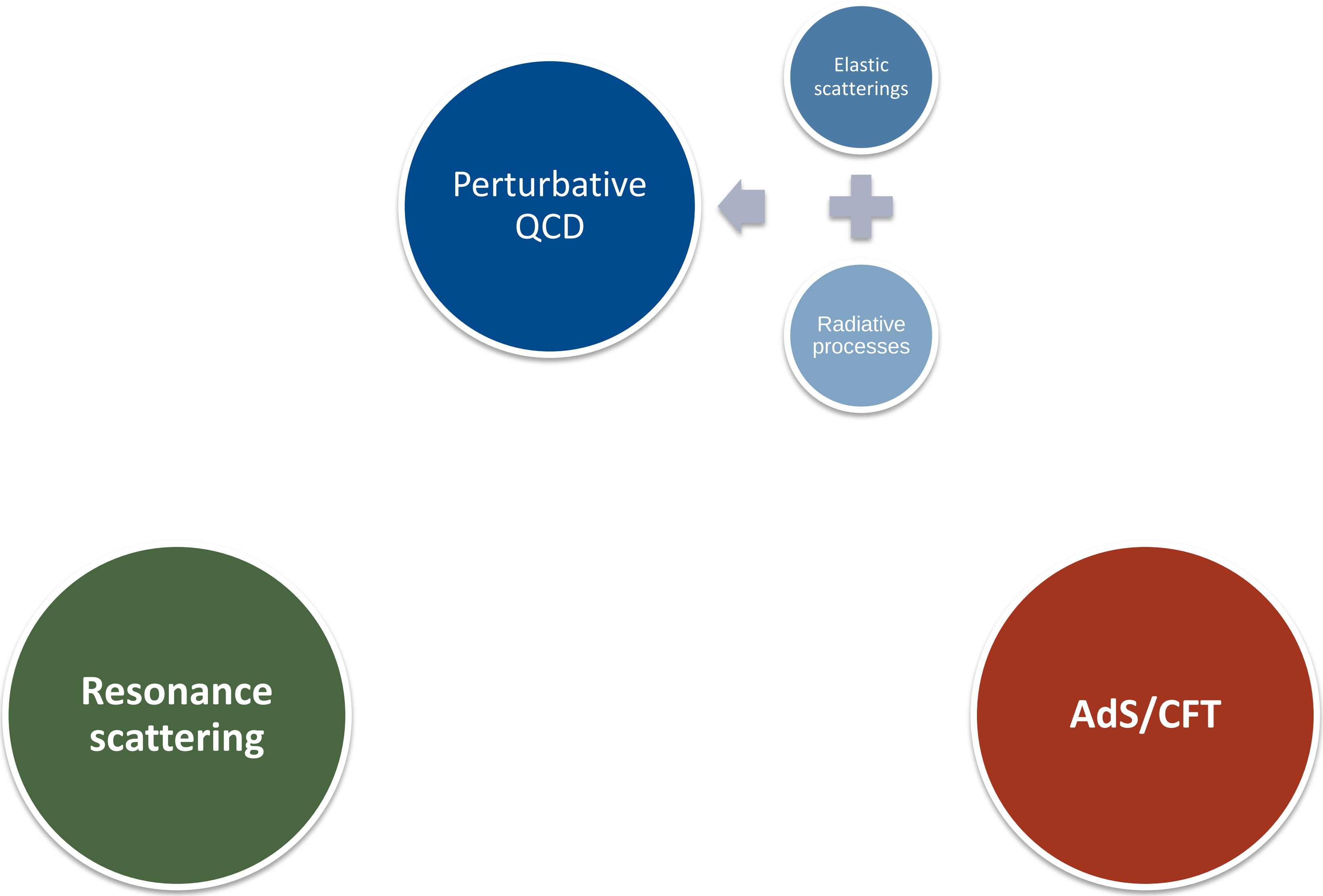
H-QM Helmholtz Research School Quark Matter Studies

SQM, Birmingham
25 July 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
- 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

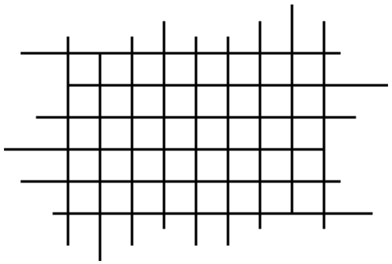
BAMPS: Boltzmann Approach to MultiParton Scatterings

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

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

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

- **Divide collision zone into cells**

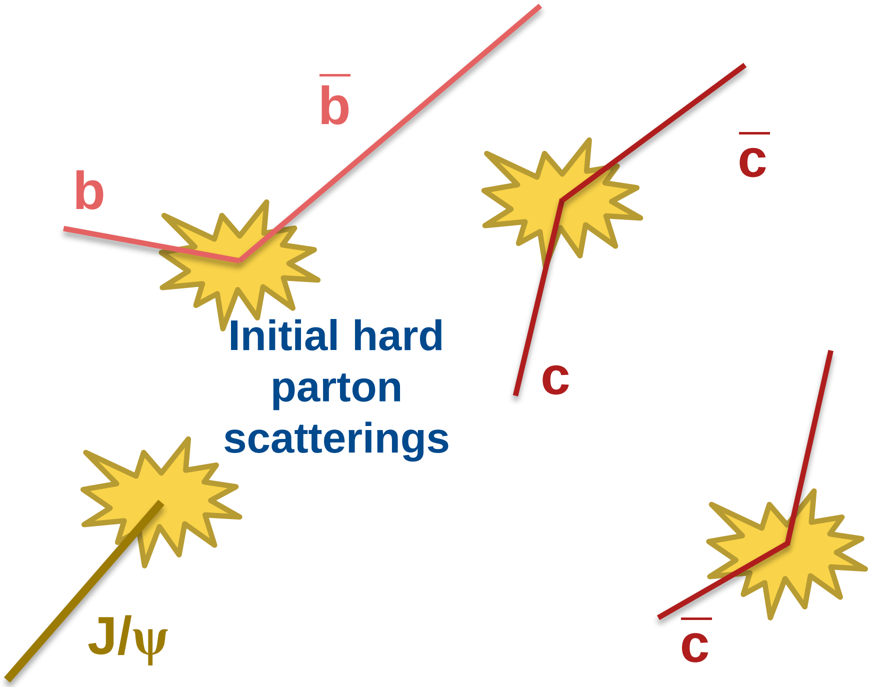


- **Using stochastic method**

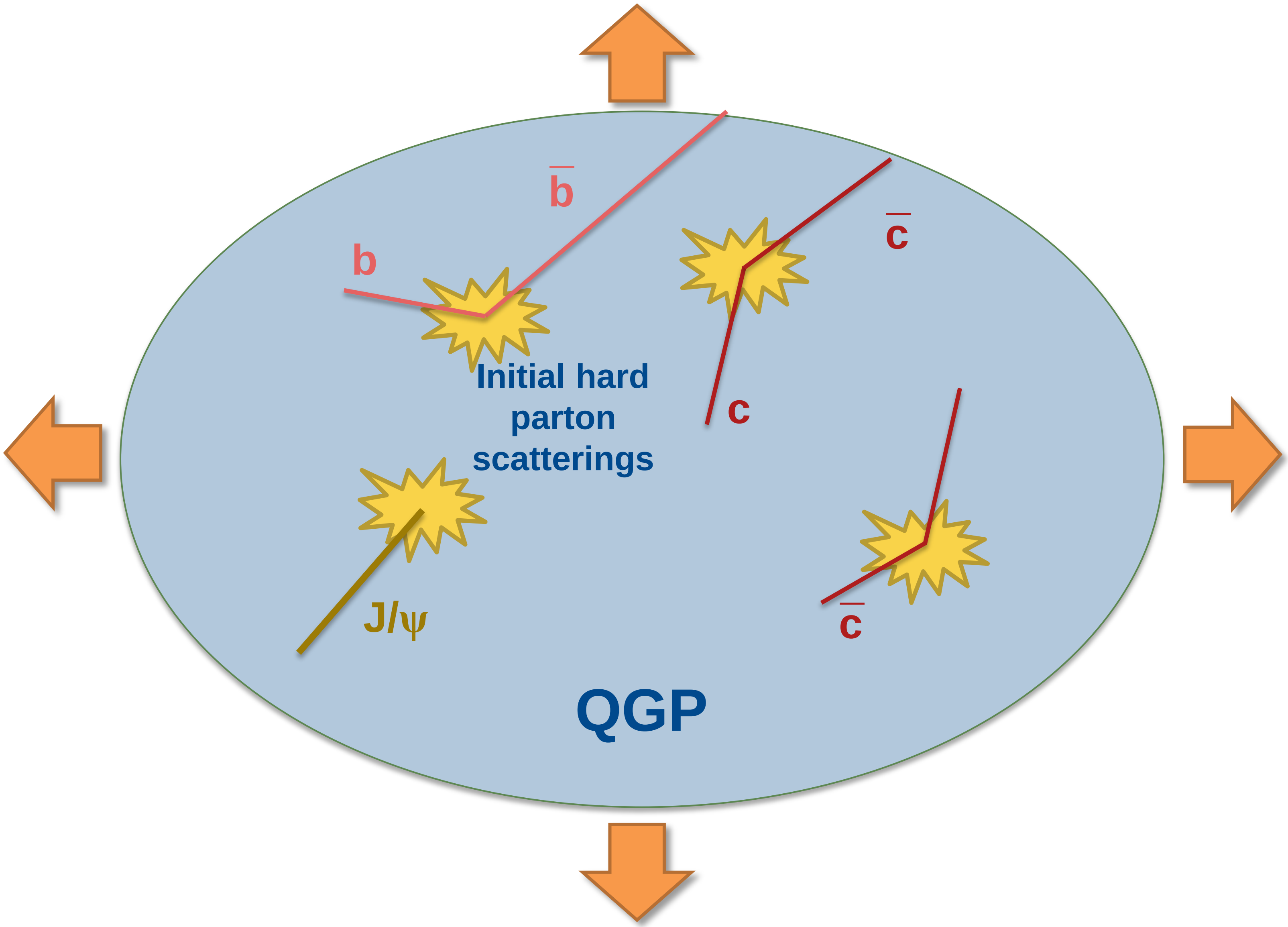
$$P_{2\to 2} = v_{\text{rel}} \frac{\sigma_{2\to 2}}{N_{\text{test}}} \frac{\Delta t}{\Delta^3 x}$$

Sketch of heavy flavor in HIC

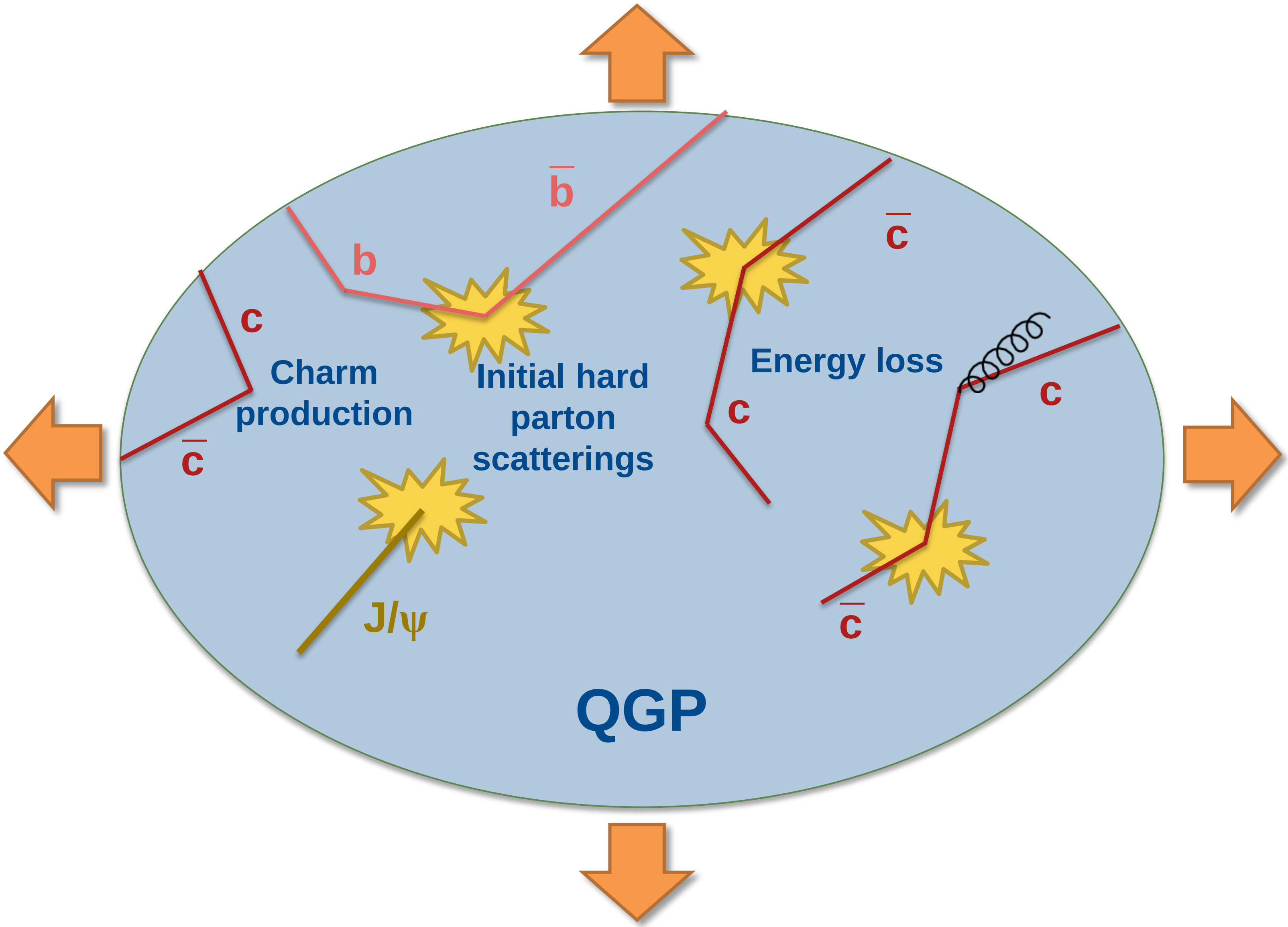
Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC



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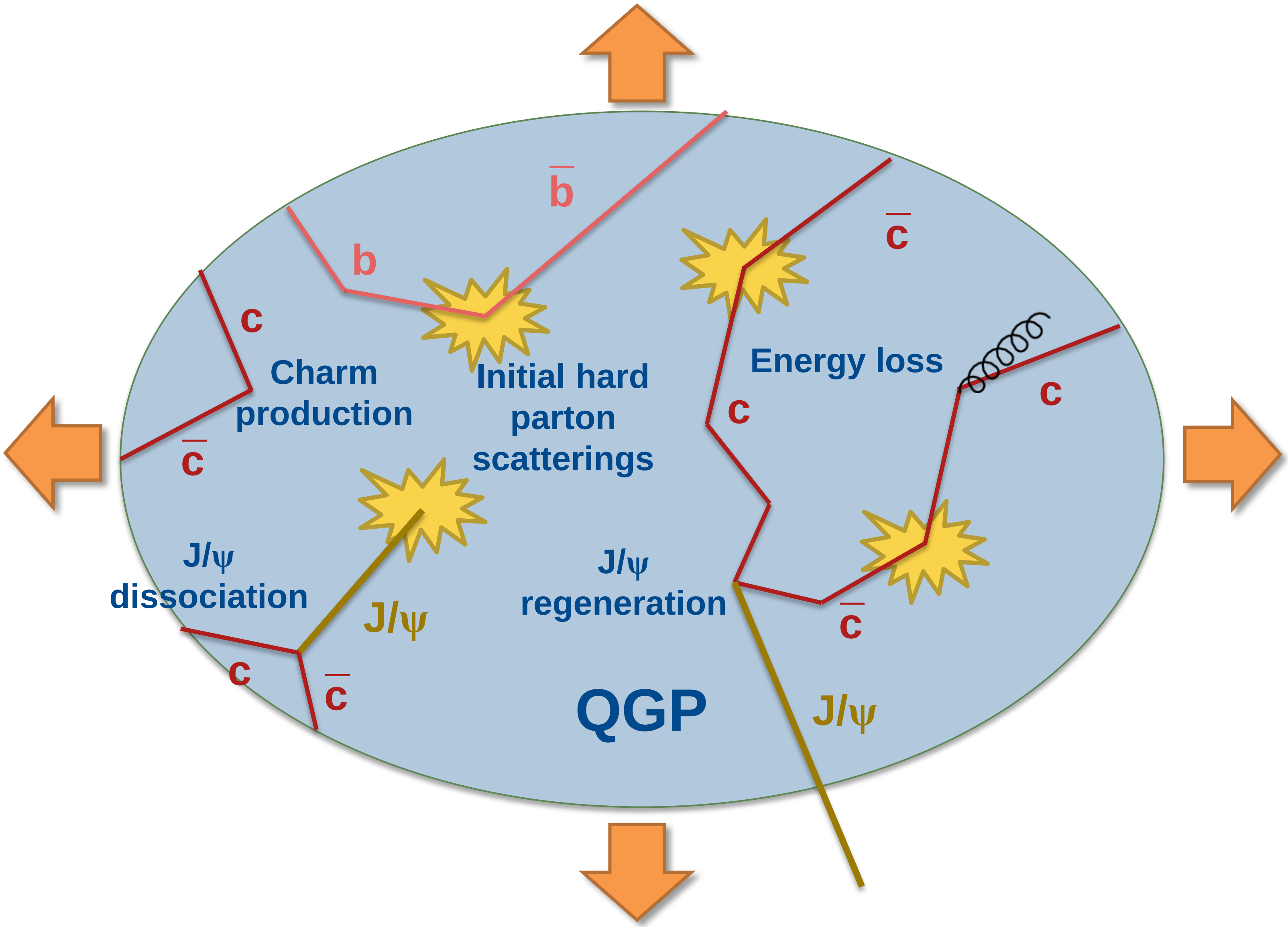
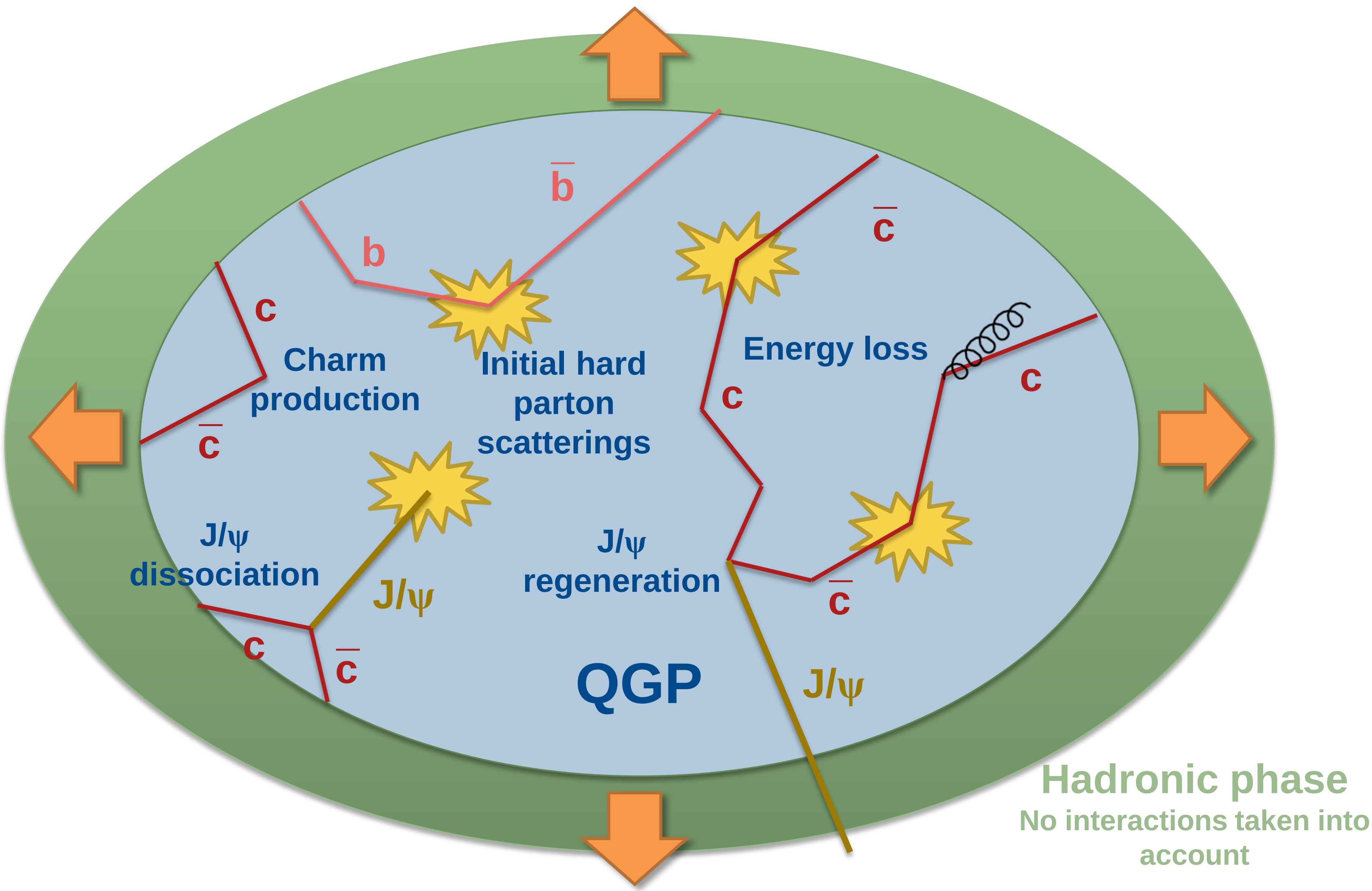
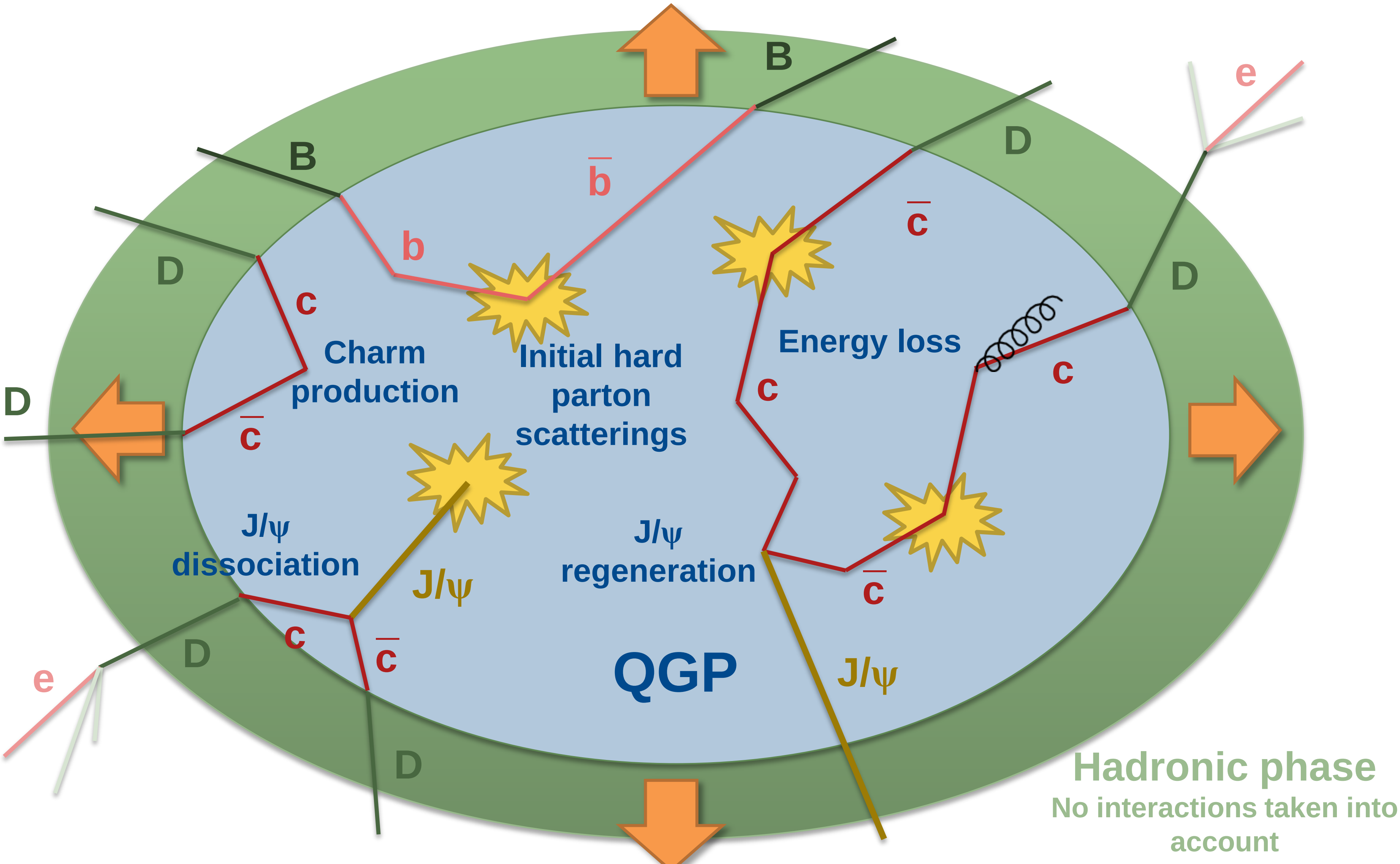


Sketch of heavy flavor in HIC



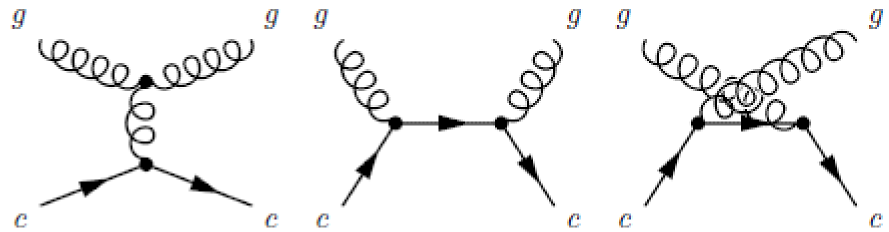
Sketch of heavy flavor in HIC



Heavy quark scattering

Leading order perturbative QCD:

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



Improved Debye screening by comparing to HTL

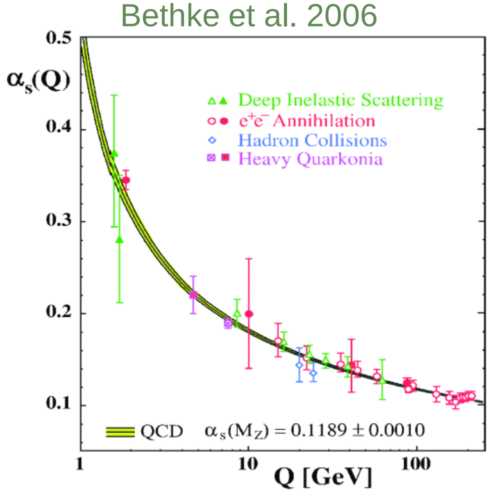
$$\frac{1}{t} \to \frac{1}{t - \kappa\, m_D^2}$$

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

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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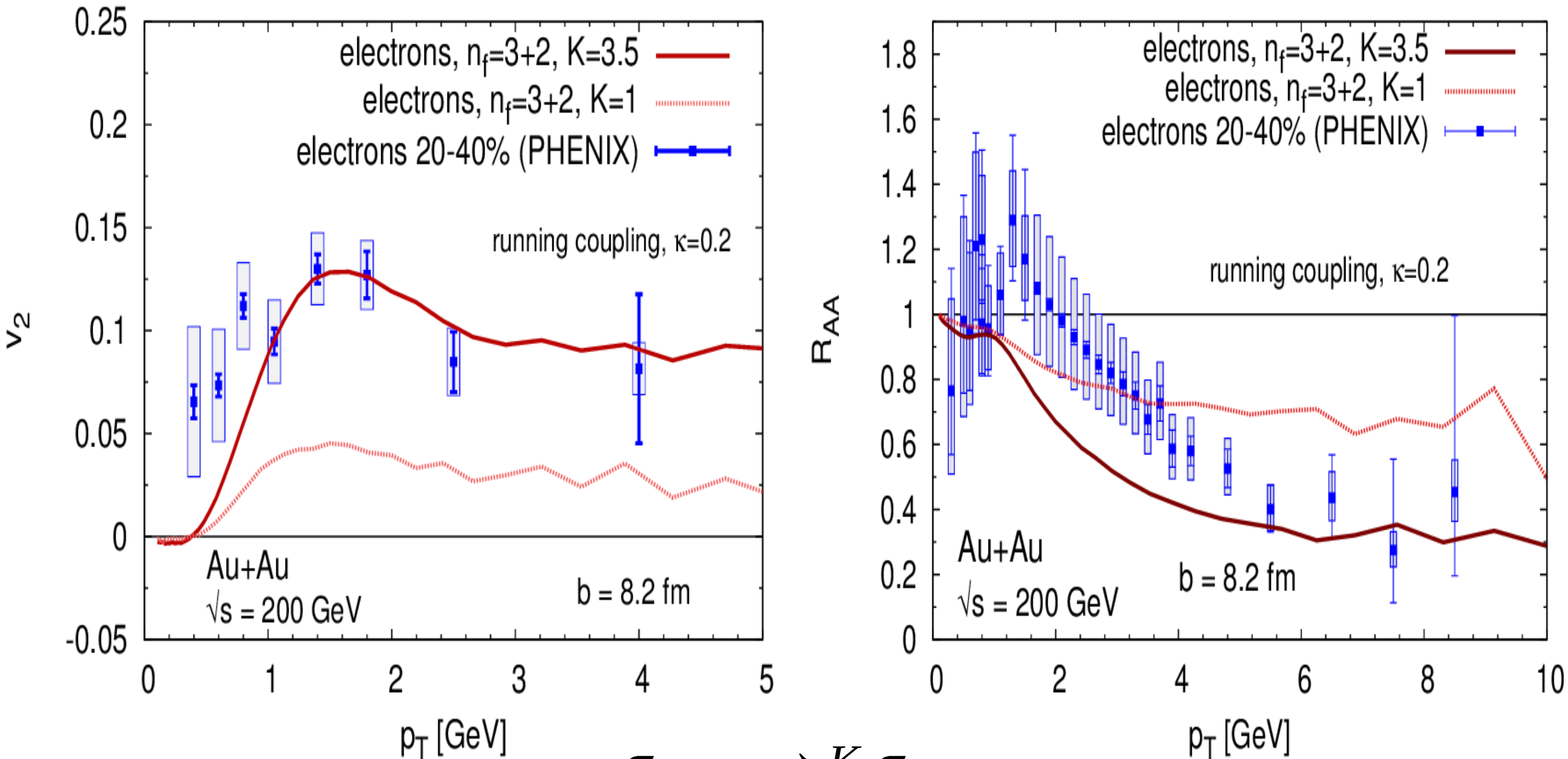


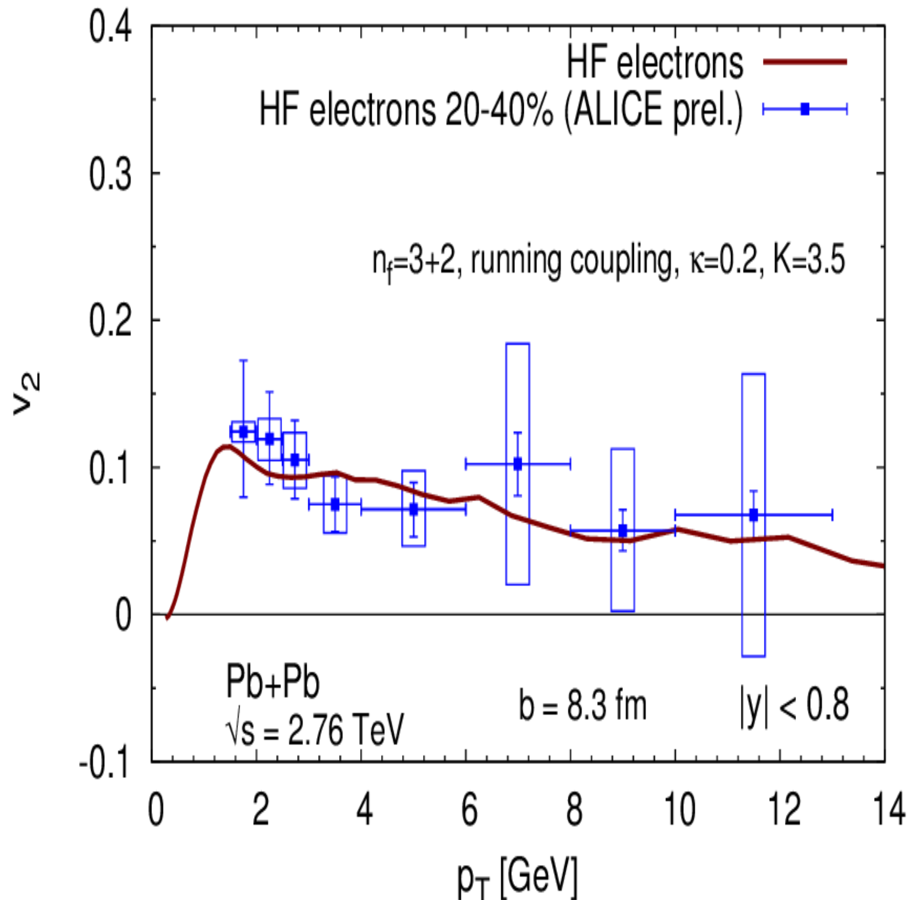
$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

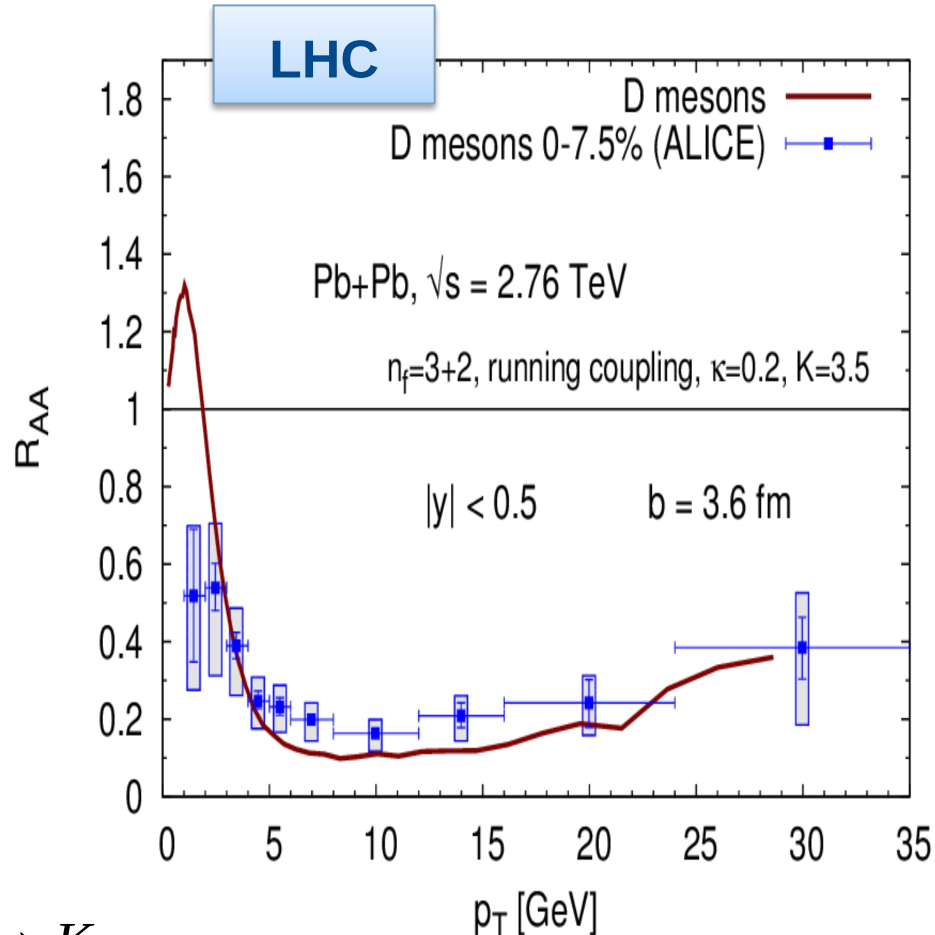
only elastic heavy quark processes

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





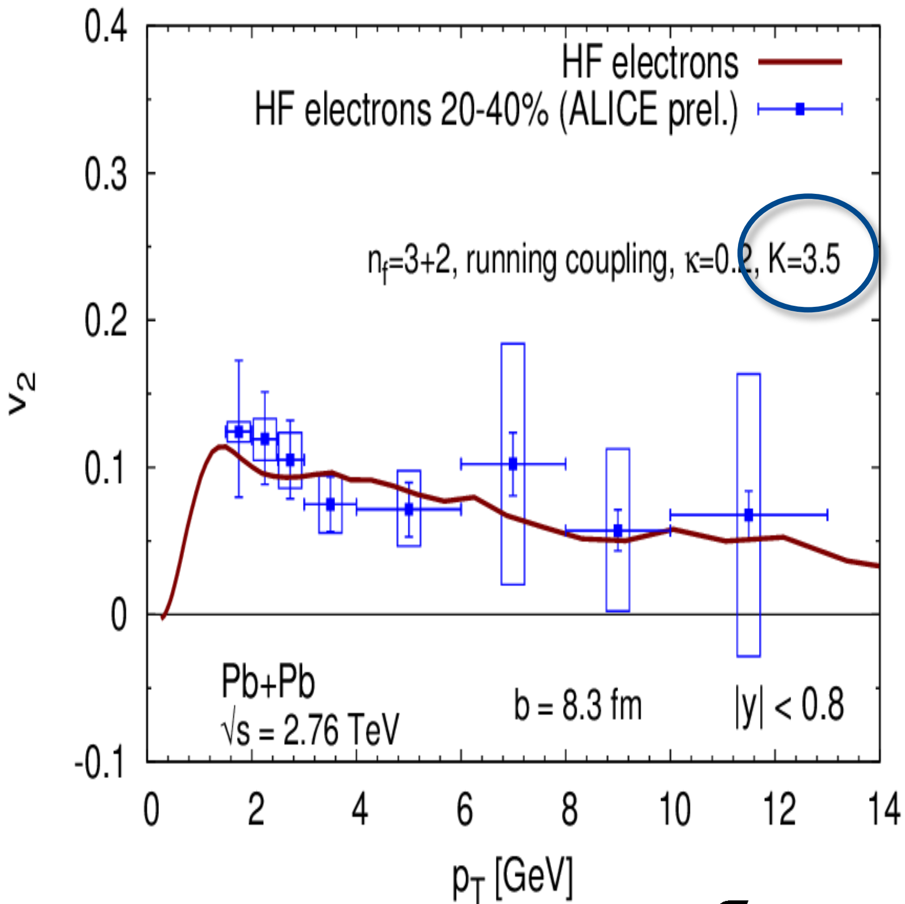
$$\sigma_{gQ\to gQ} \to K\, \sigma_{gQ\to gQ}$$

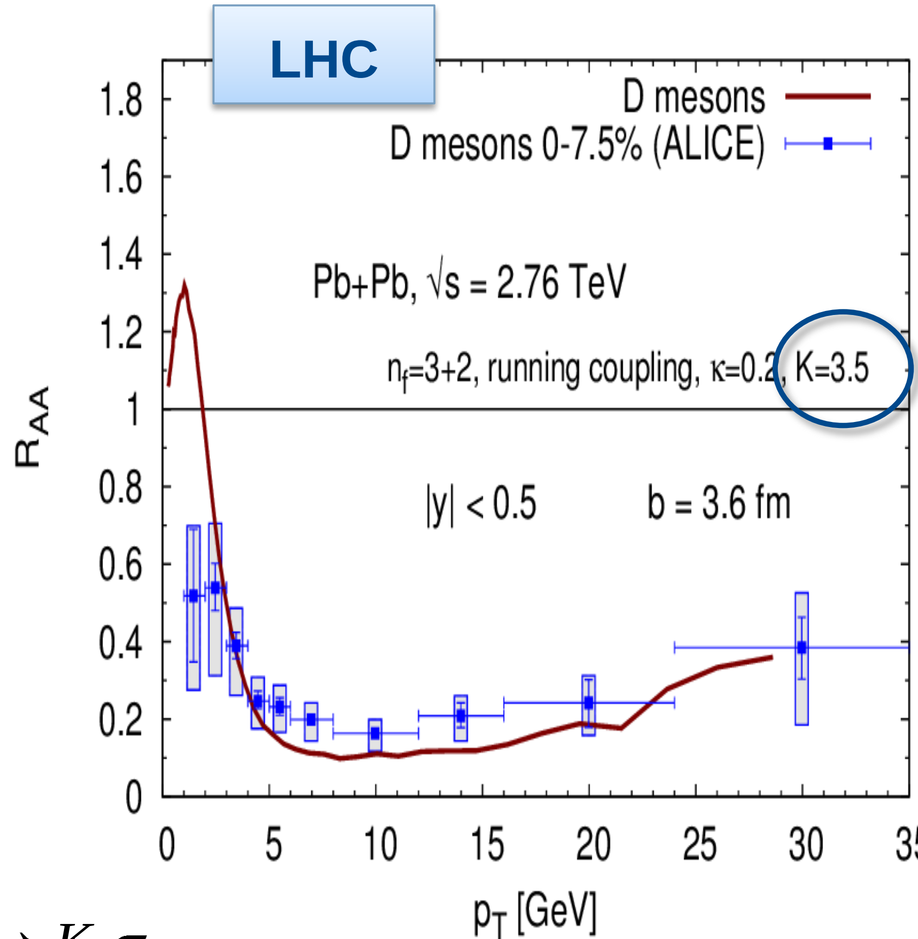
only elastic heavy quark processes

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

ALICE data, QM12

D meson R_{AA} and electron v_2 at LHC





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

only elastic heavy quark processes

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

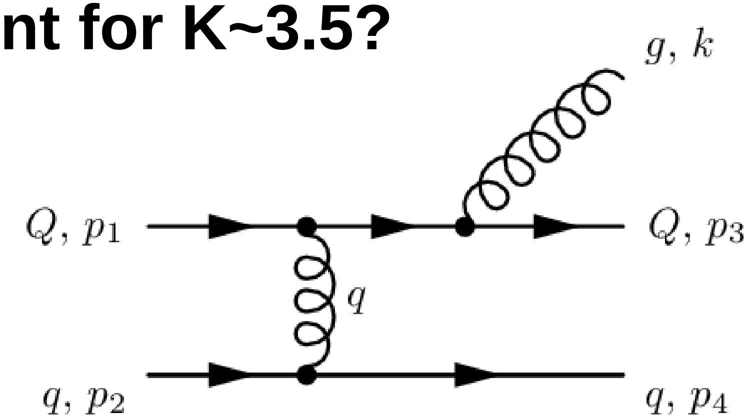
ALICE data, QM12

Radiative processes: Improved Gunion-Bertsch matrix element

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, arXiv:1302.5250, to appear in PRD

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

Radiative pQCD processes

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Exact matrix element

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

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

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

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

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

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

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

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

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

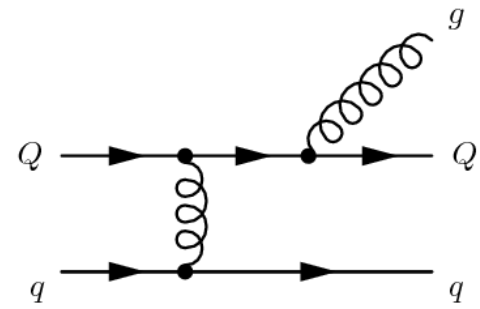
$$N_{33} = x_{12}[2x_{54}(x_{12} - x_{23} - x_{31}) + x_{41}(-2x_{51} + 6x_{52} + 5x_{53}) + x_{42}(-2x_{52} + 6x_{51} + 5x_{53})$$
$$+ x_{43}(5x_{51} + 5x_{52} + 4x_{53}) + 28m_Q^2 x_{54}]$$
$$+ x_{23}[-2x_{31}x_{54} + x_{41}(-6x_{51} + x_{52} - 3x_{53}) + (x_{42} - 3x_{43})x_{51}]$$
$$+ x_{31}[x_{41}x_{52}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

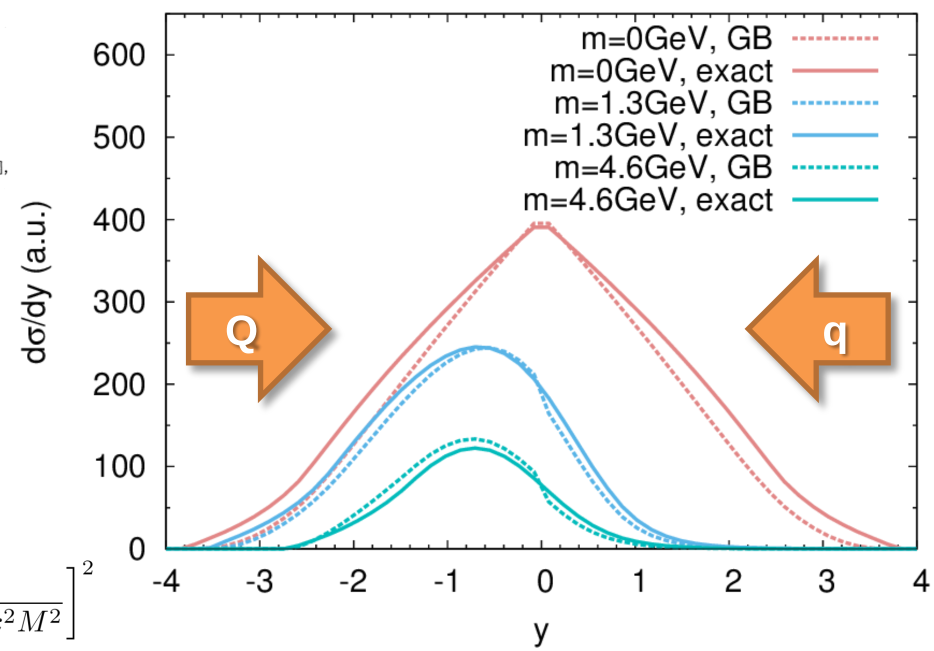
$$N_{34} = x_{12}[x_{54}(x_{23} + x_{31} + x_{42} + x_{41}) - 2x_{43}(x_{51} + x_{52})]$$
$$+ x_{23}[2x_{31}x_{54} + x_{41}(x_{52} - x_{53} - x_{54}) + 3x_{51}(x_{42} + x_{43}) + 8m_Q^2 x_{54}]$$
$$+ x_{31}[x_{42}(x_{51} - x_{53} - x_{54}) + 3x_{52}(x_{41} + x_{43}) + 8m_Q^2 x_{54}]$$
$$+ x_{41}[3(x_{41}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

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

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

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





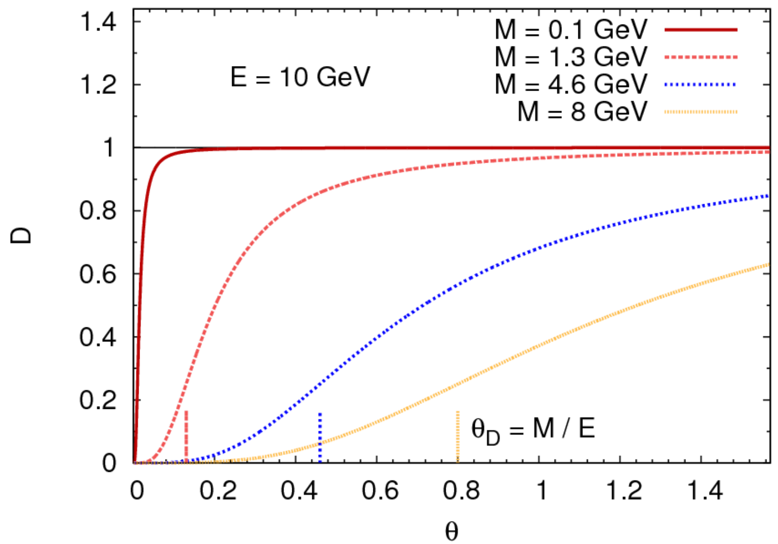
Gunion Bertsch (GB) approximation

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

Fochler, JU, Xu, Greiner, arXiv:1302.5250

Dead cone effect

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

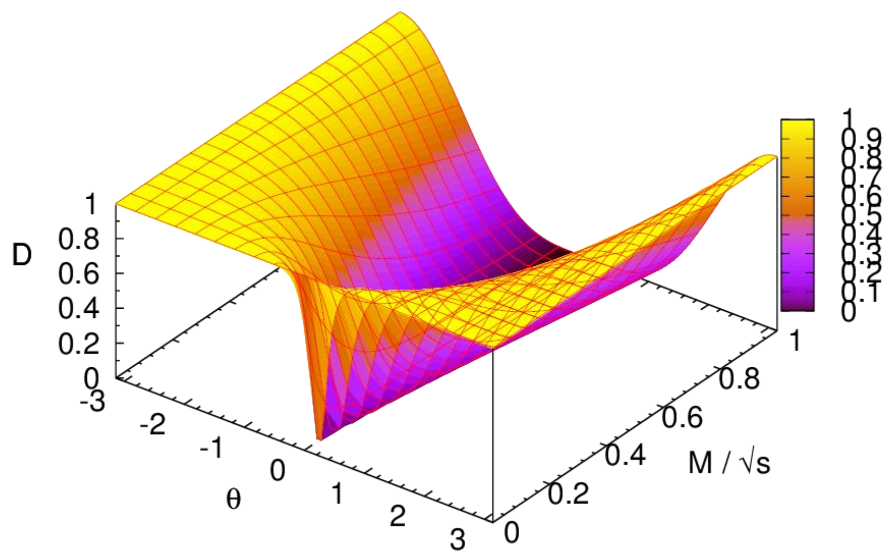


Heavy quark suppression factor

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

Y.L. Dokshitzer and D.E. Kharzeev, Phys.Lett. B519 (2001)

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

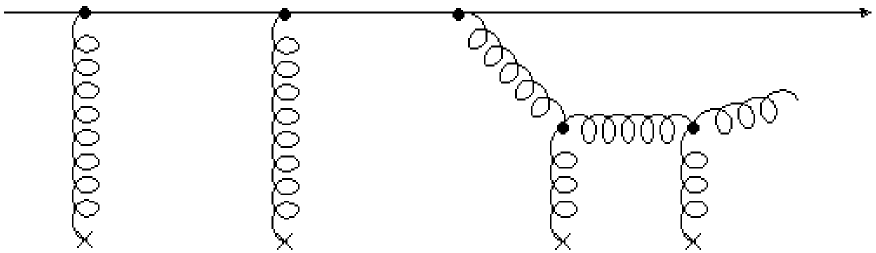


More accurate: valid for all order of mass M and also for large angles

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

R. Abir, C. Greiner, M. Martinez, M.G. Mustafa, JU, Phys.Rev. D85 (2012)

LPM effect

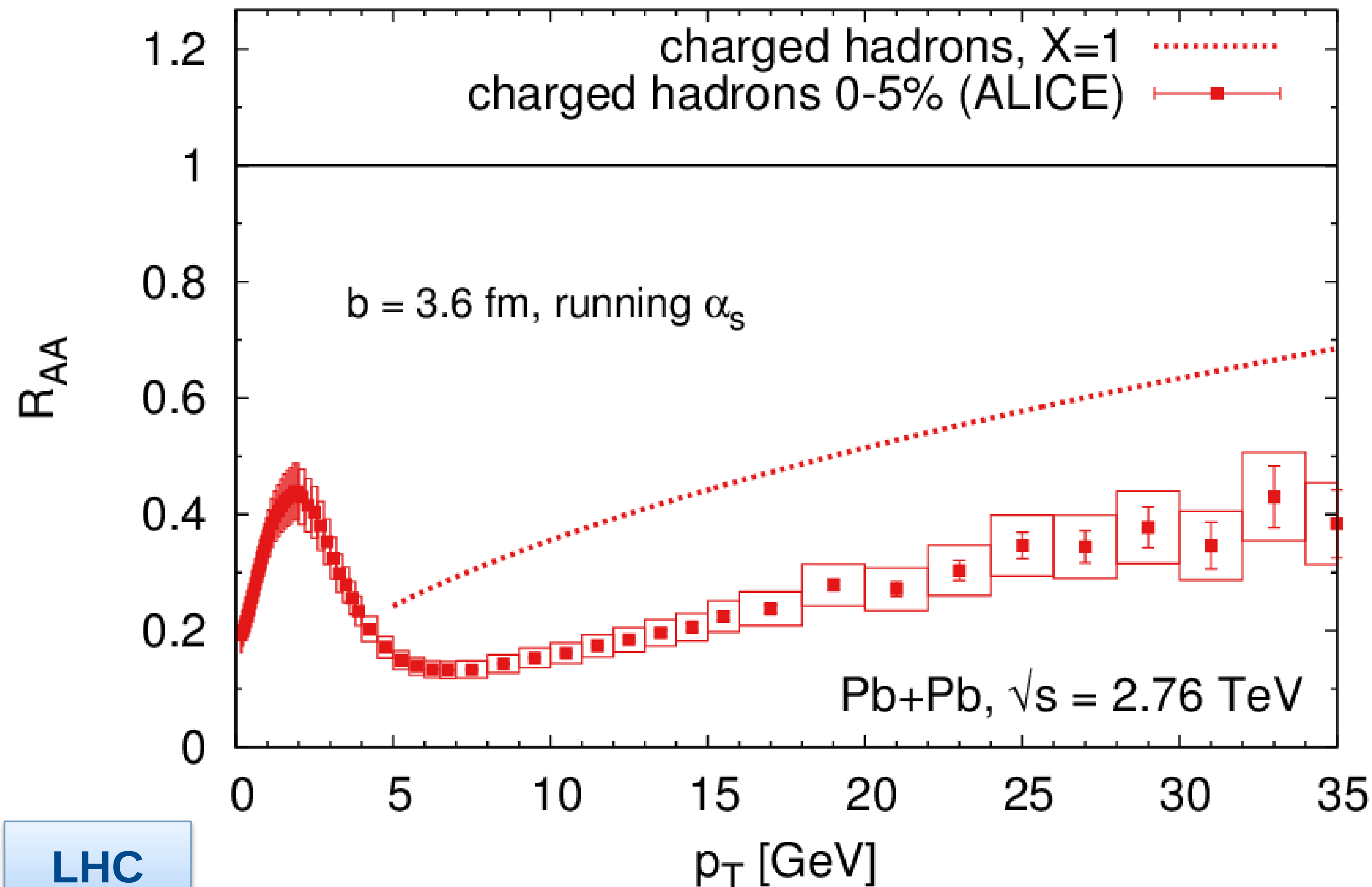


$$\lambda > \tau$$

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

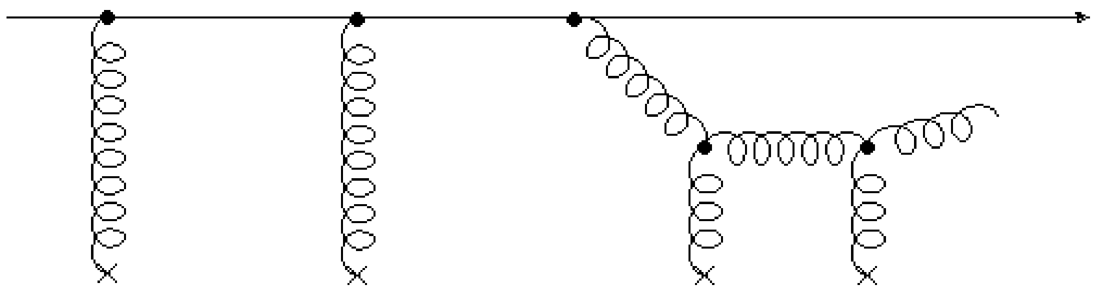
➡ Independent scatterings

Charged hadron R_{AA} at LHC



LHC

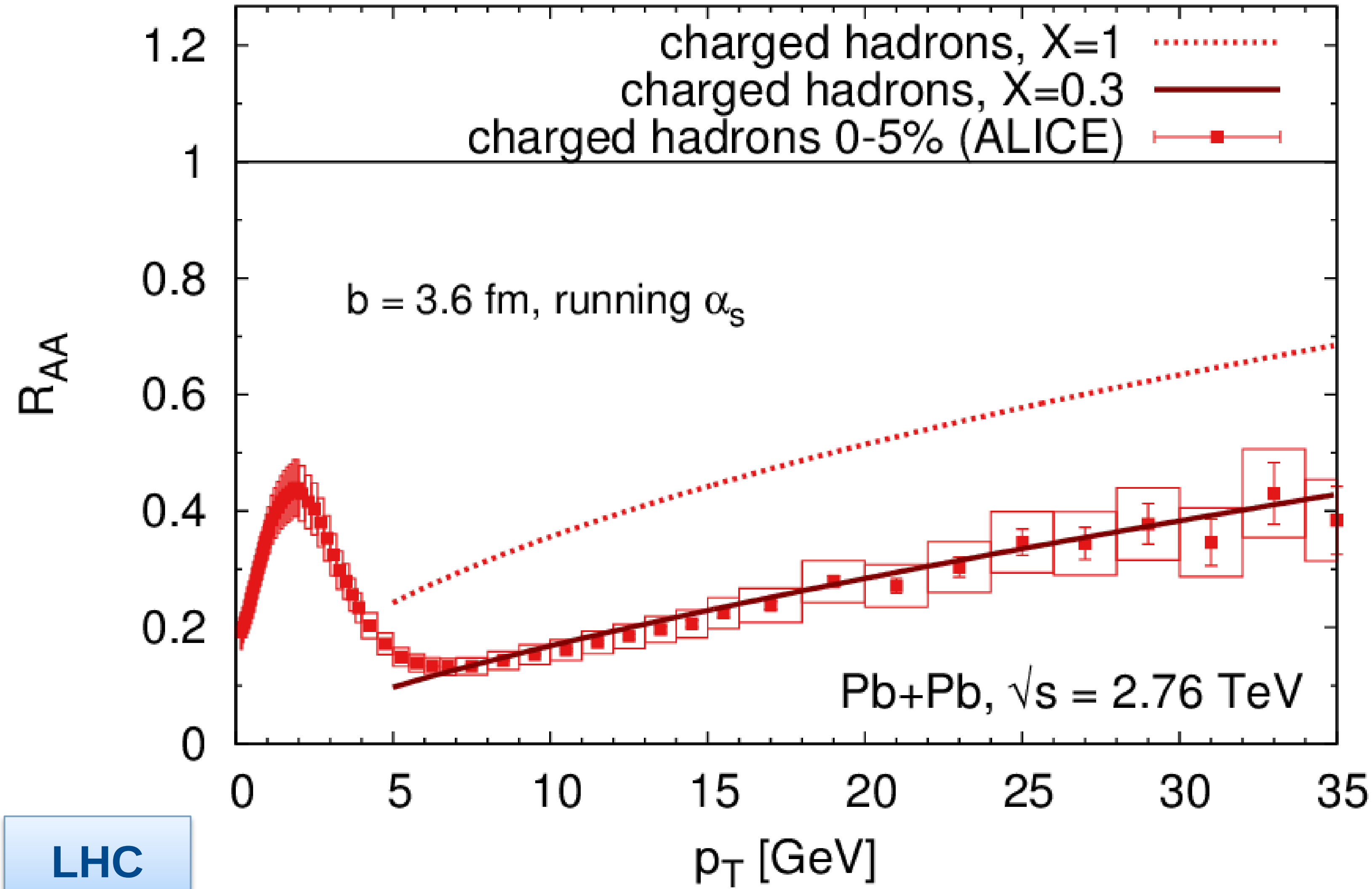
LPM effect



Only completely independent scatterings $\lambda > \tau$

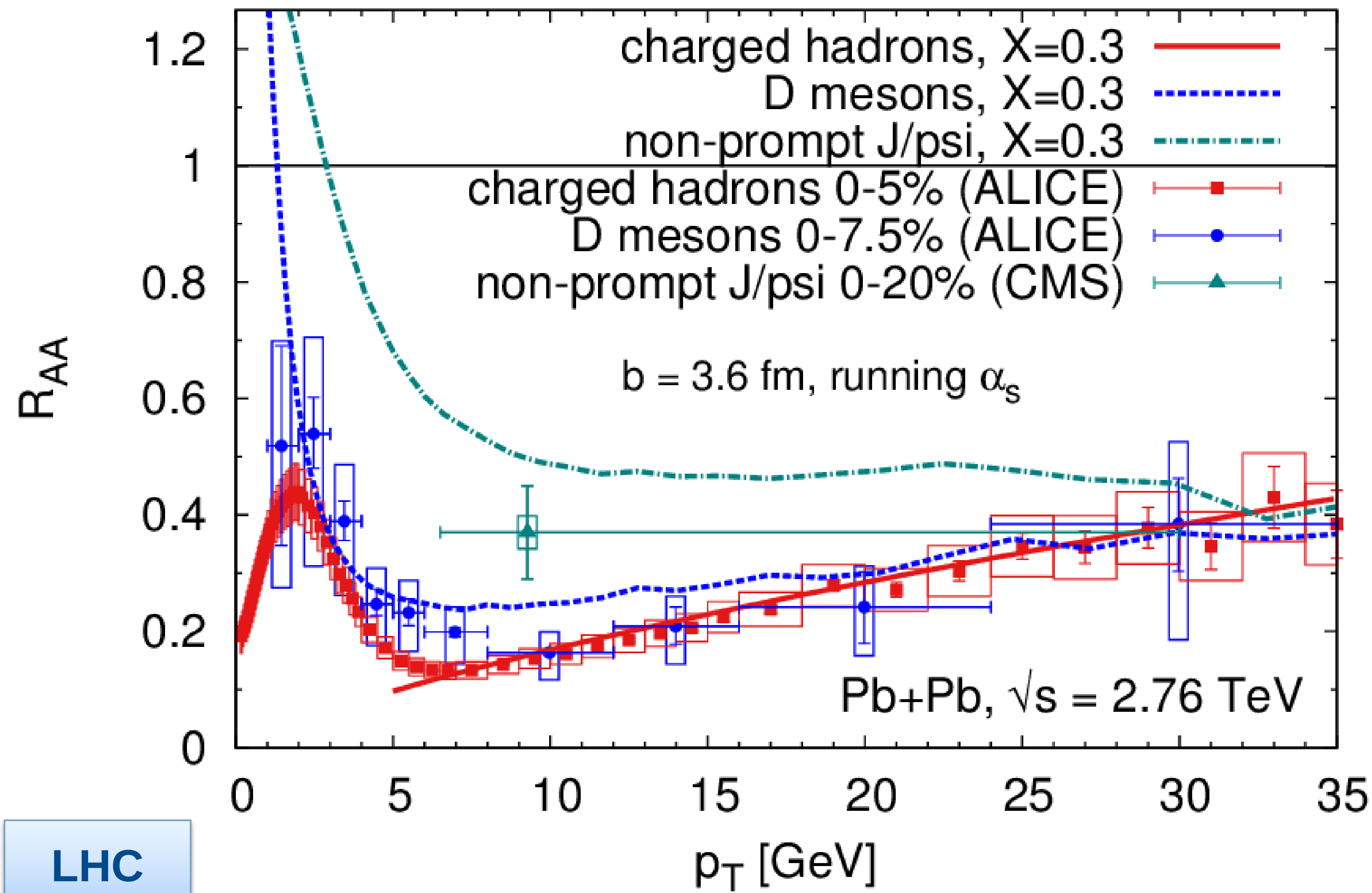
Interference effects: X < 1 expected $\lambda > X\,\tau$

Charged hadron R_{AA} at LHC



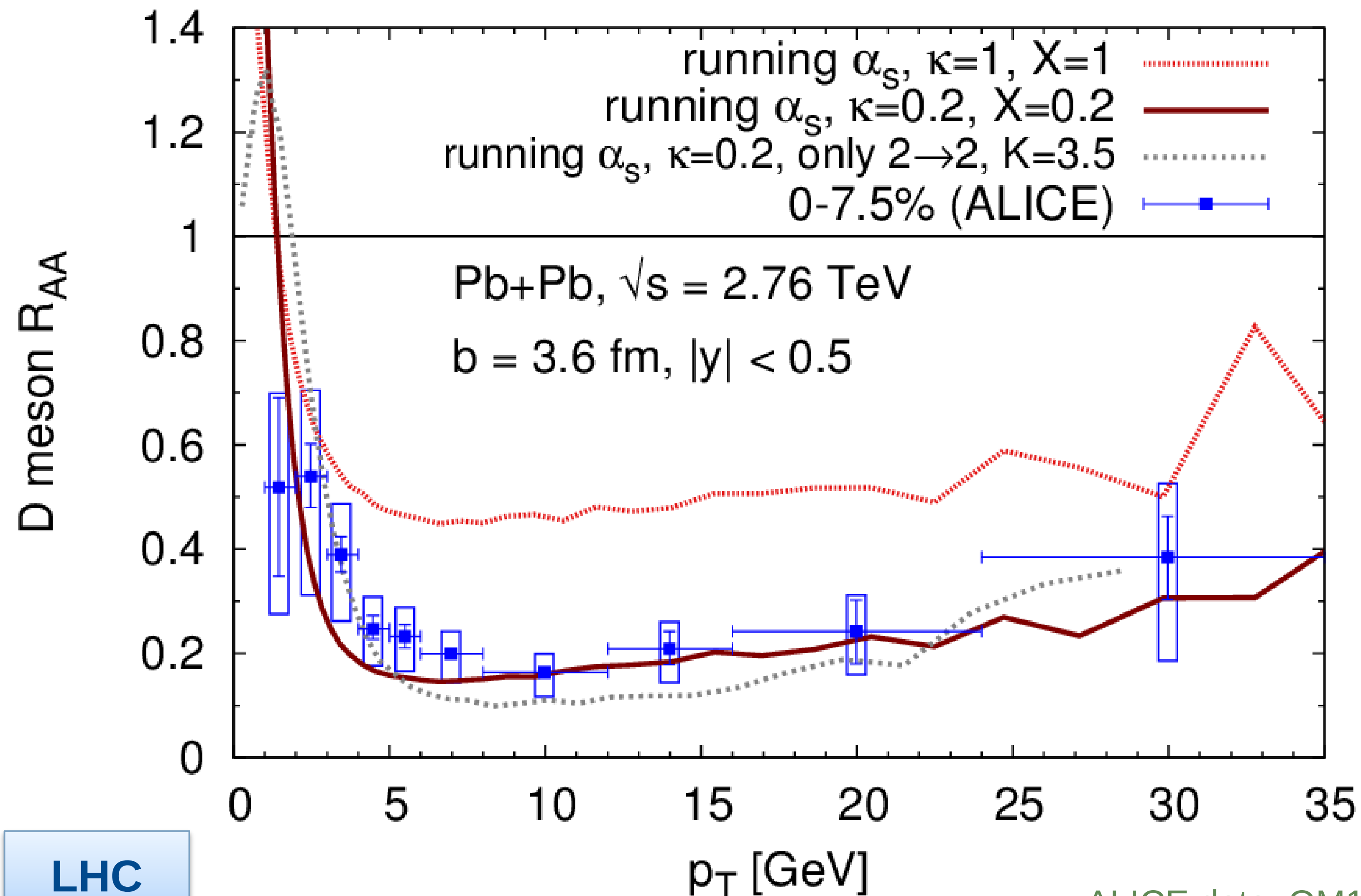
LHC

Heavy flavor and charged hadron R_{AA} at LHC



LHC

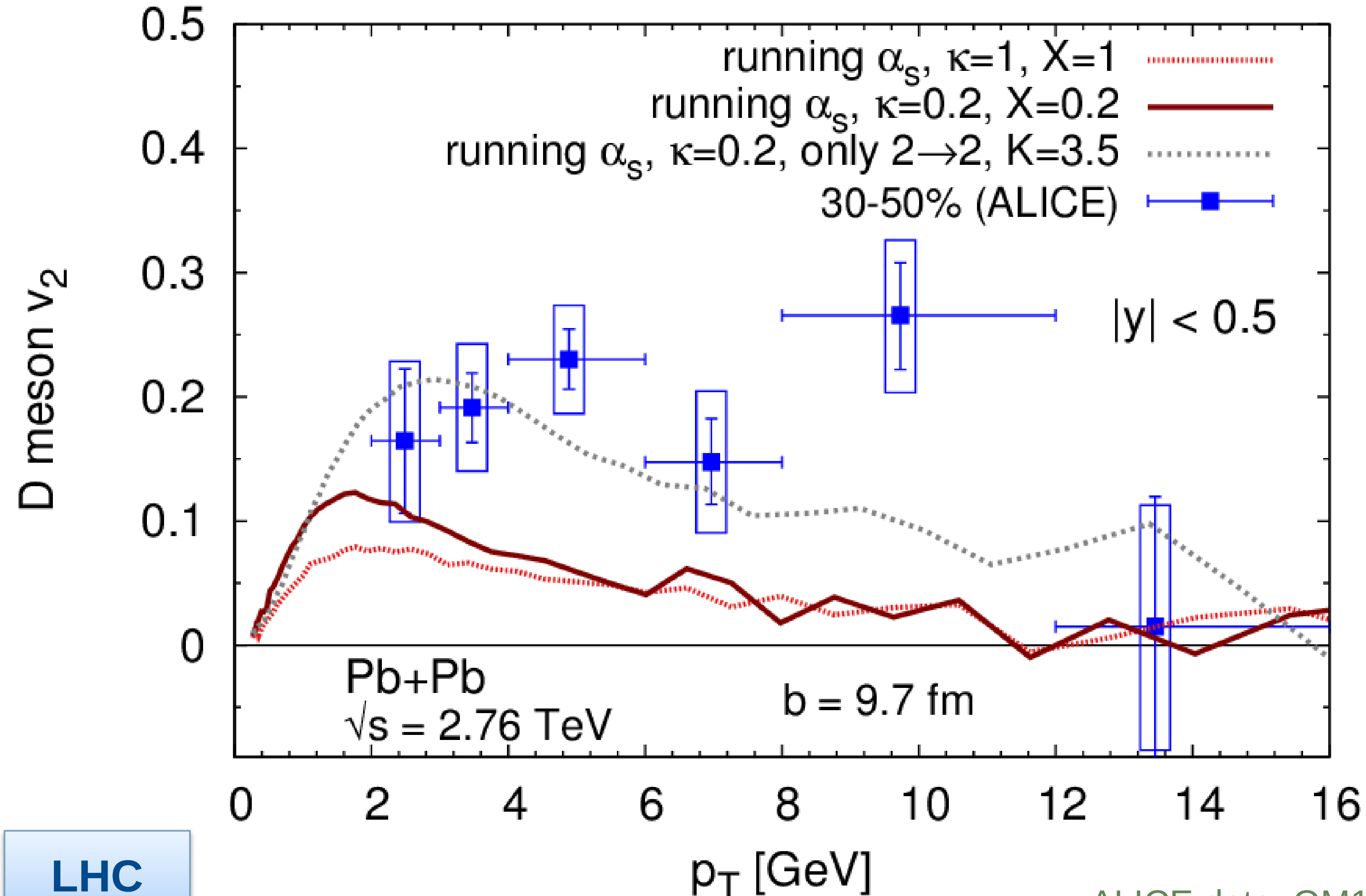
With improved screening: D meson R_{AA} at LHC



LHC

ALICE data, QM12

D meson v_2 at LHC

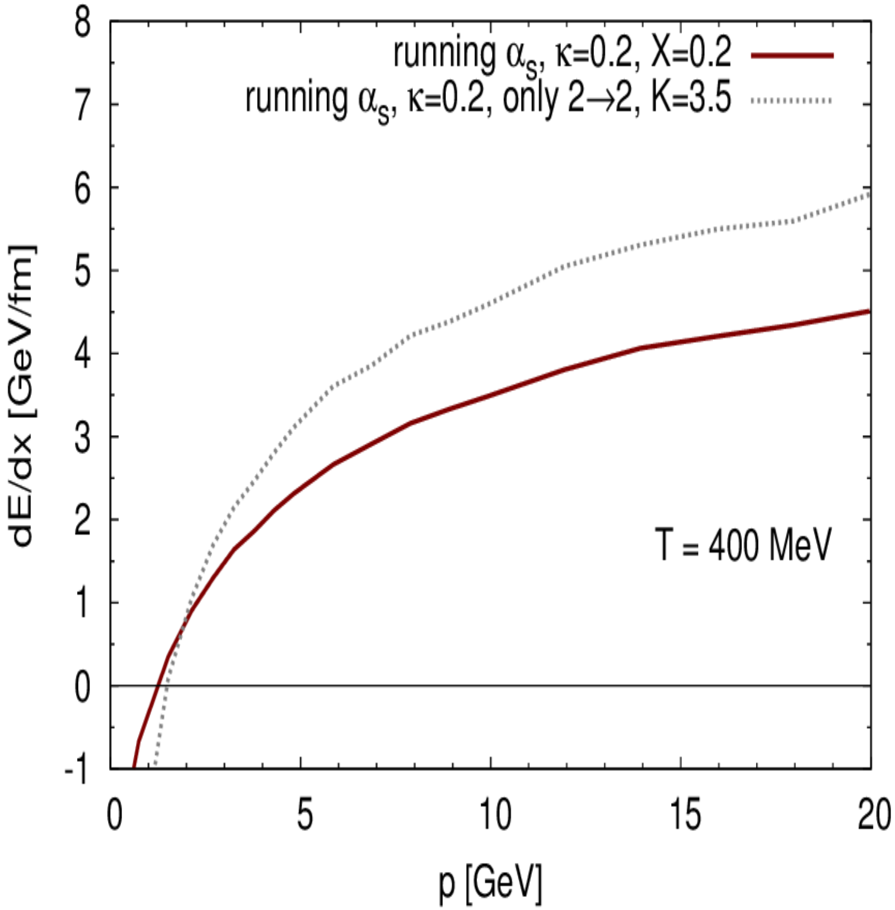


LHC

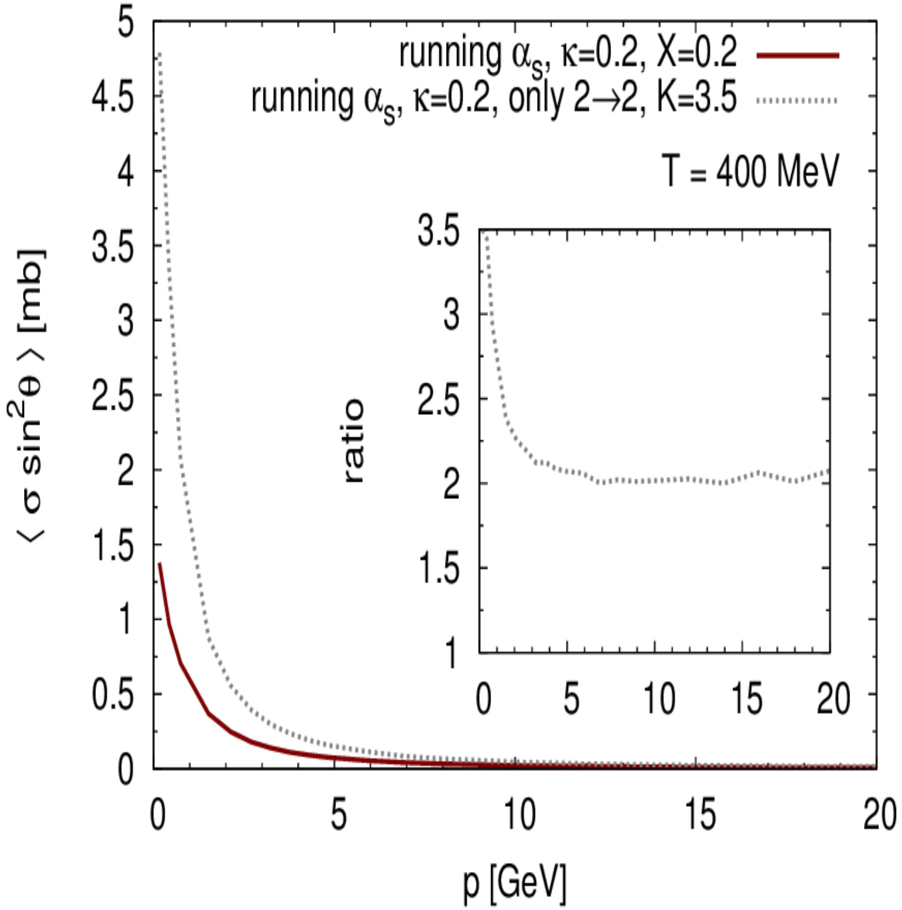
ALICE data, QM12

Energy loss and transport cross section

Energy loss
in static medium



Transport cross section
in static medium



What can the models explain?

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Perturbative QCD

- Djordjevic, Gyulassy
- Buzatti, Gyulassy
- Sharma, Vitev
- Armesto, Cacciari, Dainese, Salgado, Wiedemann
- 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
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+

Radiative processes

- Abir, Jamil, Mustafa, Srivastava
- …

Resonance scattering

- v.Hees, Greco, Rapp
- He, Fries, Rapp
- Lang, v.Hees, Bleicher
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AdS/CFT

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

Can explain R_{AA}

Perturbative QCD

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Can explain R_{AA} and v_2

With scaled cross sections

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Elastic scatterings

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- …

Resonance scattering

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

AdS/CFT

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

Conclusions & outlook

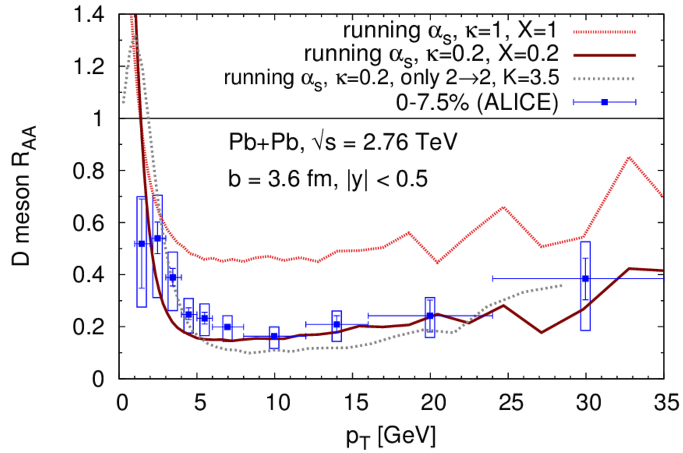
Full space-time evolution of QGP with charm and bottom quarks

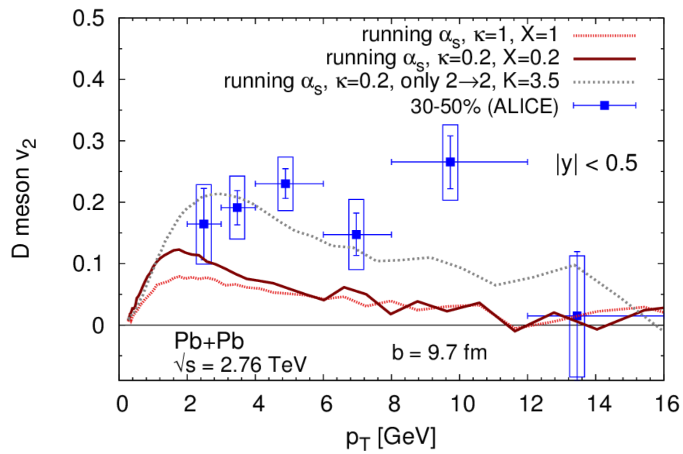
- **Only binary collisions:**

  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

Further details in Phys. Lett. B 717, 430 (2012) and arXiv:1302.5250





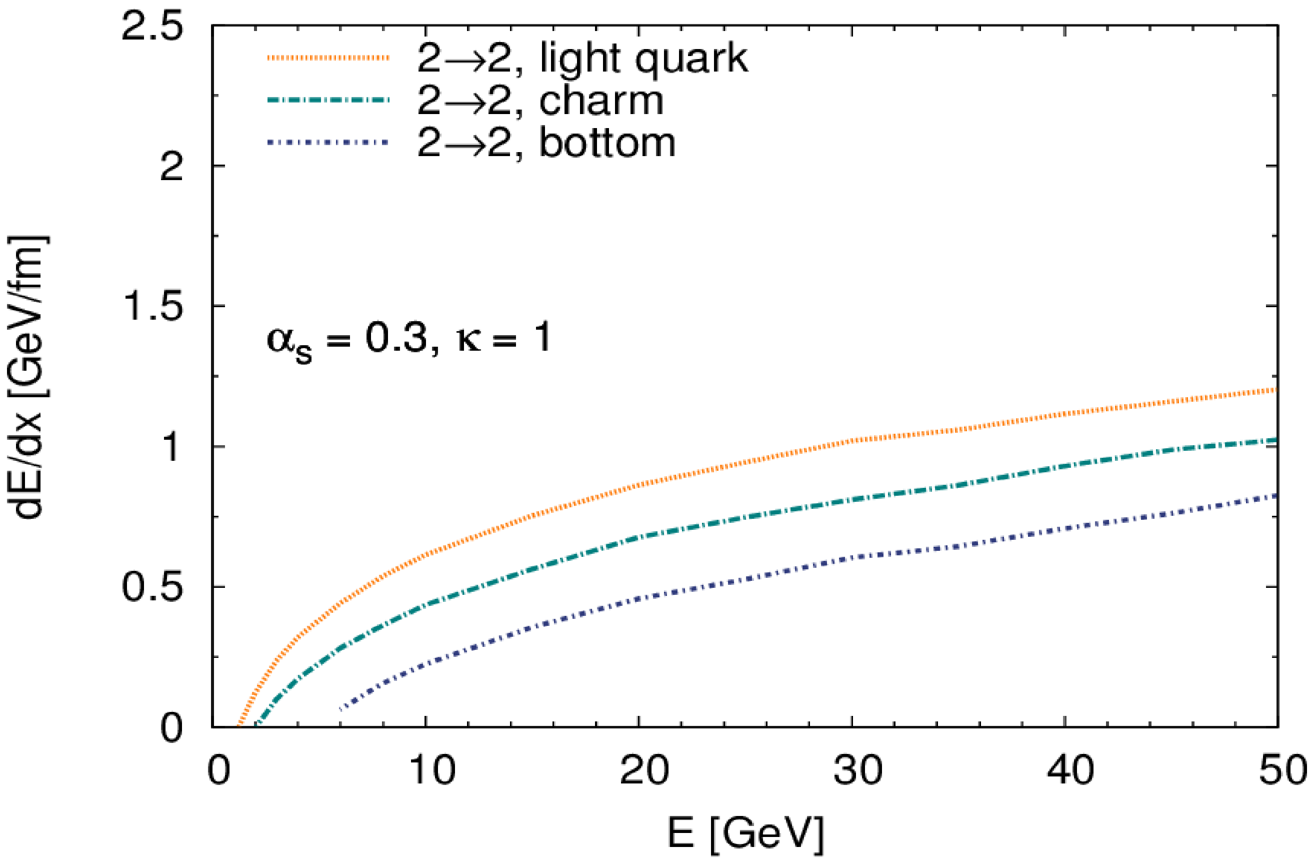
Future tasks:

- Improvement of LPM effect

Thank you for your attention.

Radiative energy loss

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

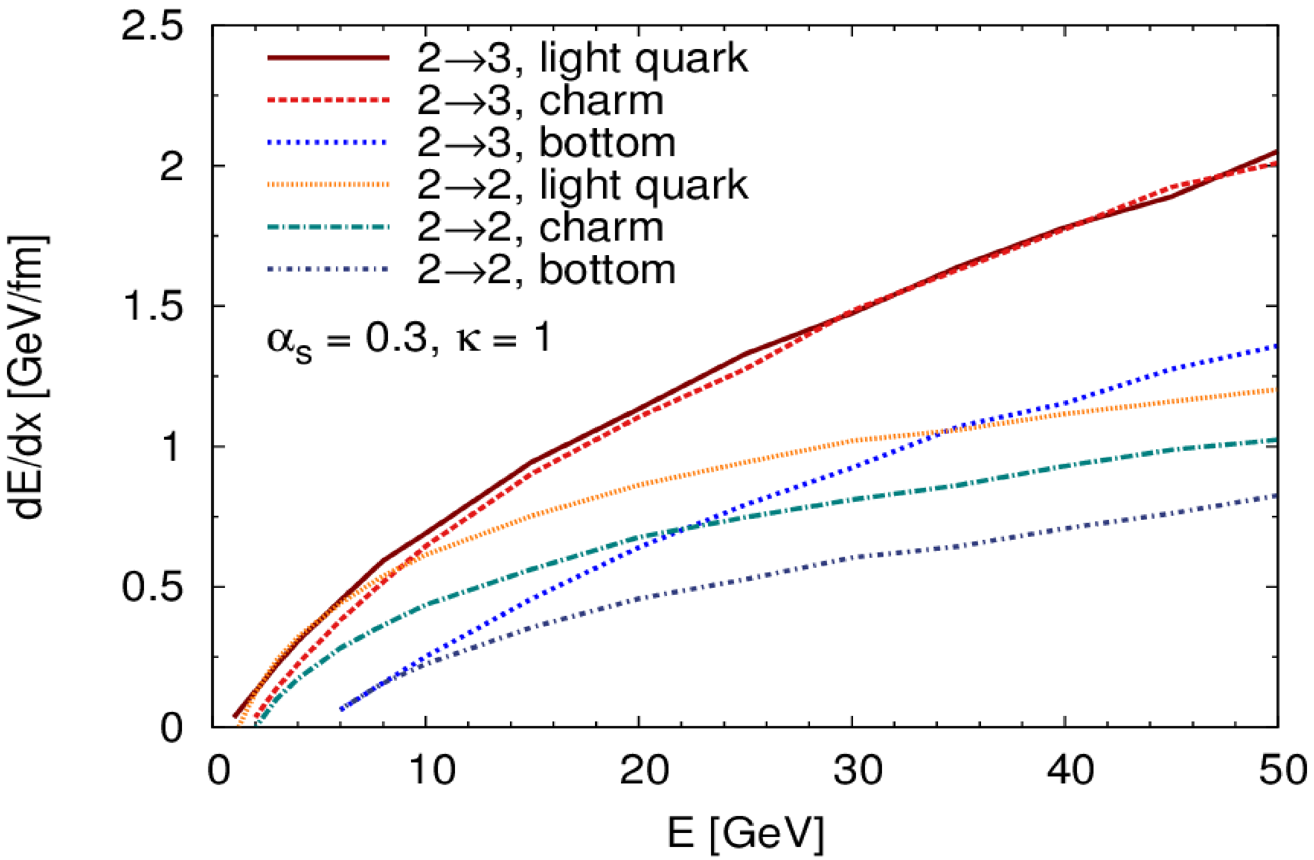


$\alpha_s = 0.3$

However, does not have to hold for RAA → pp spectrum shape also important

Radiative energy loss

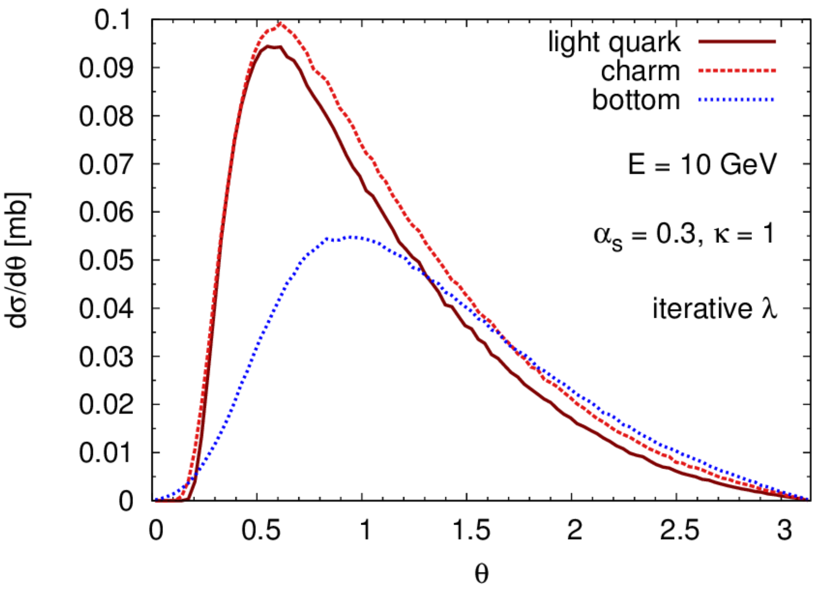
$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{light quark}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{charm}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{bottom}}$$

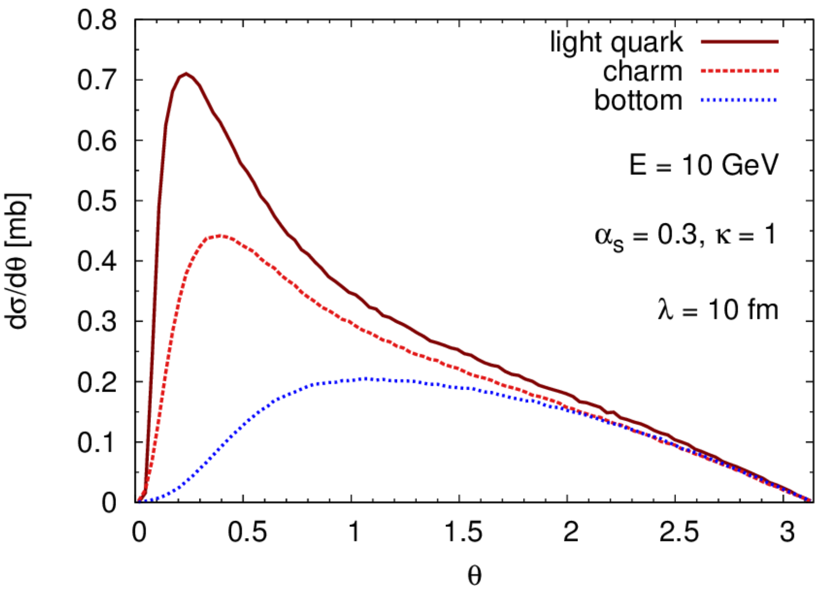


$$\alpha_s = 0.3$$

However, does not have to hold for RAA → pp spectrum shape also important

Angle distribution in lab frame





With LPM

Without LPM

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

Light flavors

binary

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

inelastic

$g\,g \leftrightarrow g\,g\,g$		
$q\,g \leftrightarrow q\,g\,g$	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 flavors

binary

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

inelastic

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

Heavy quark R_{AA} at RHIC

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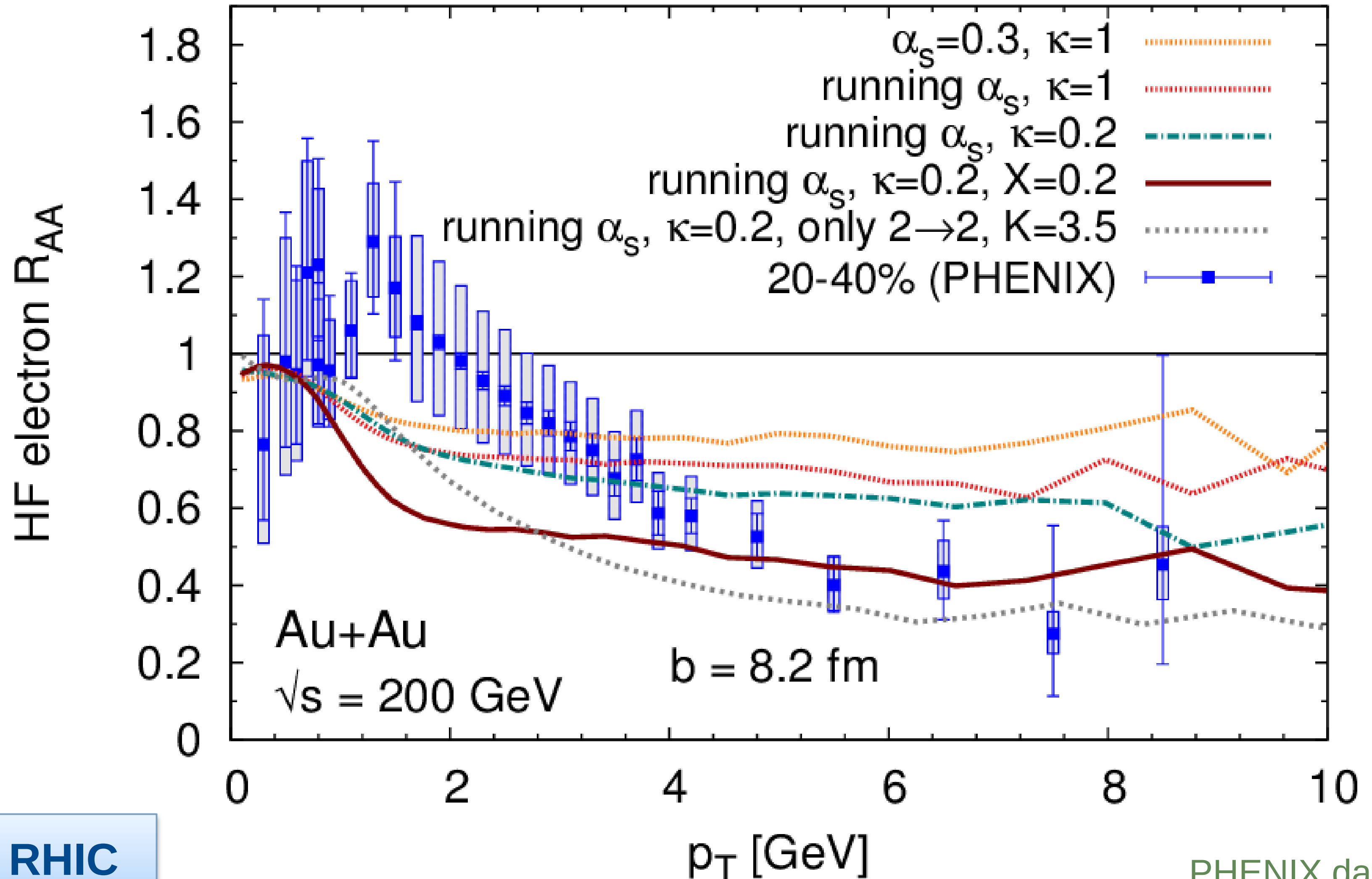
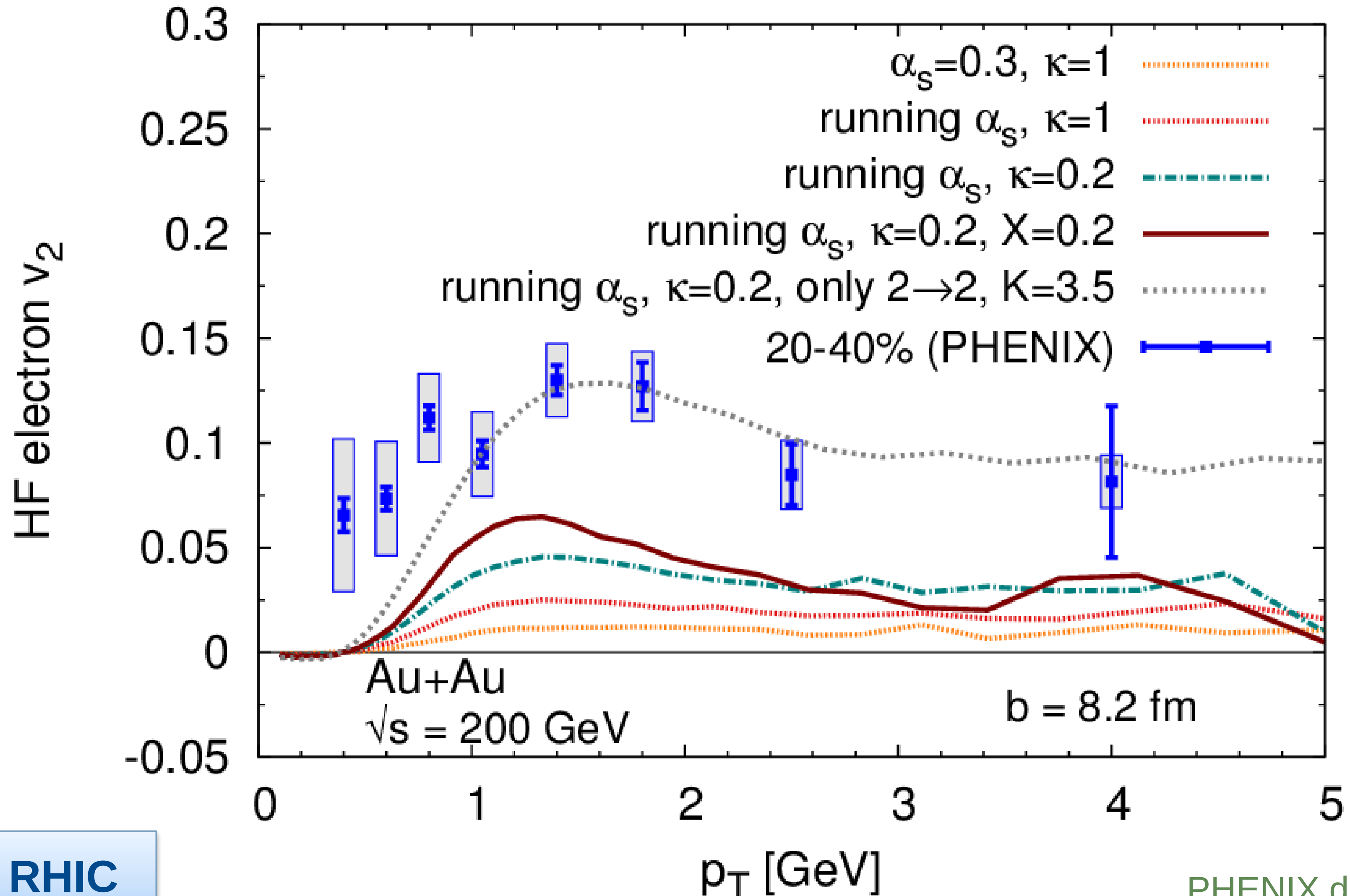


RHIC

PHENIX data,
Phys.Rev. C84 (2011)

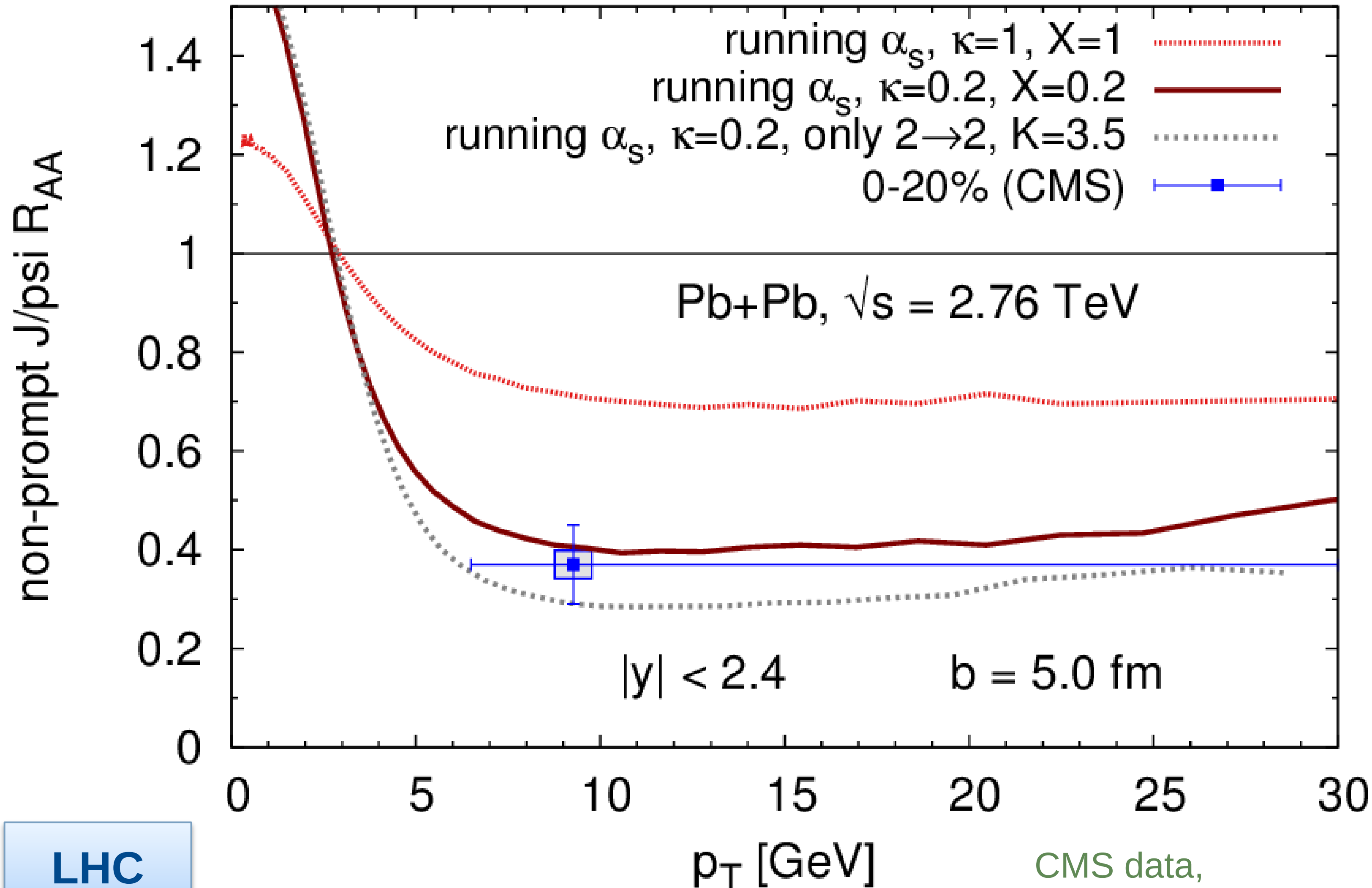
Heavy quark v_2 at RHIC



RHIC

PHENIX data,
Phys.Rev. C84 (2011)

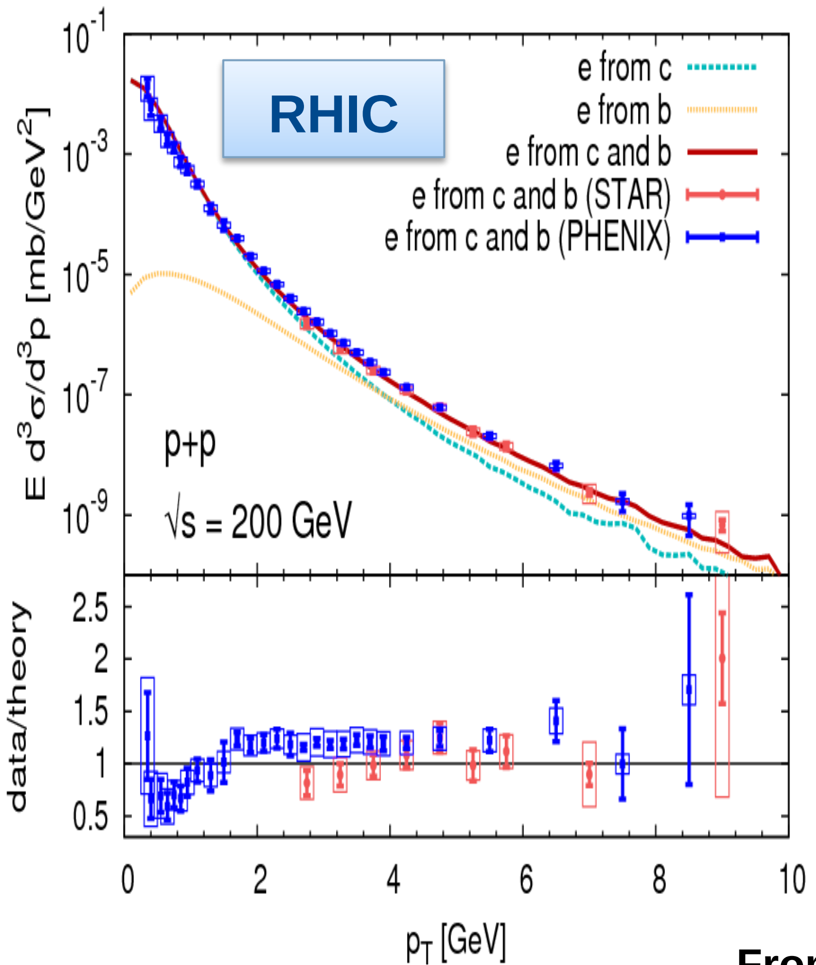
Non-prompt J/psi R_{AA} at LHC

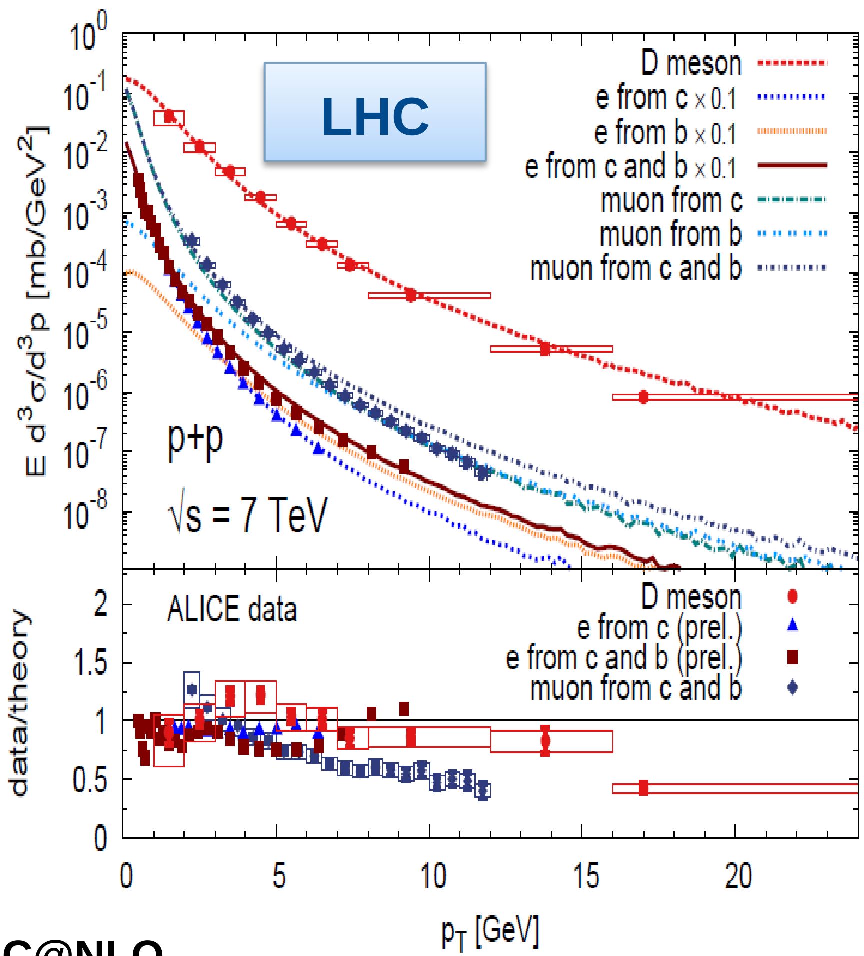


LHC

CMS data,
arXiv:1201.5069

Initial heavy flavor spectrum





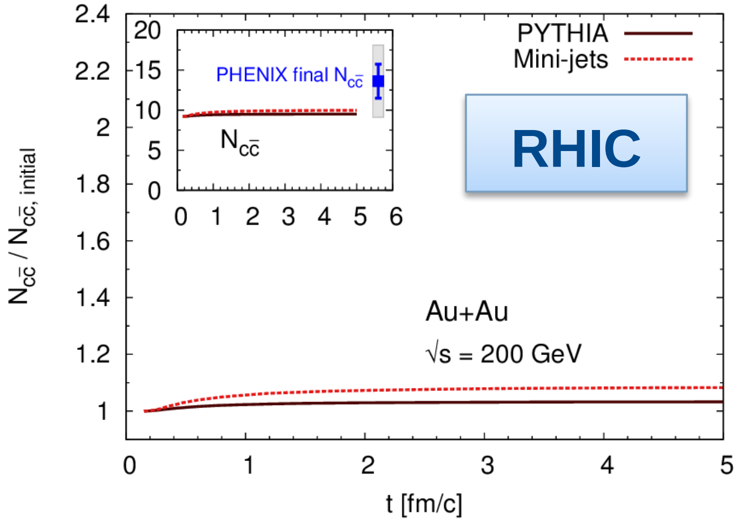
From MC@NLO

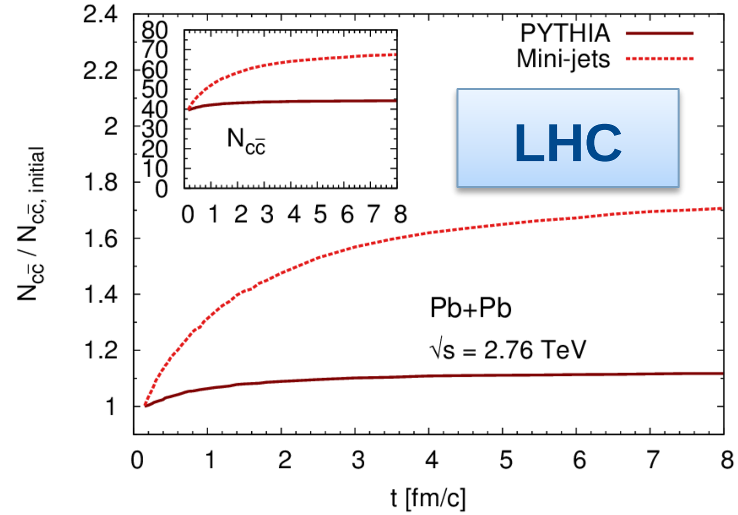
JU, Fochler, Xu, Greiner
Phys. Rev. C84 (2011)

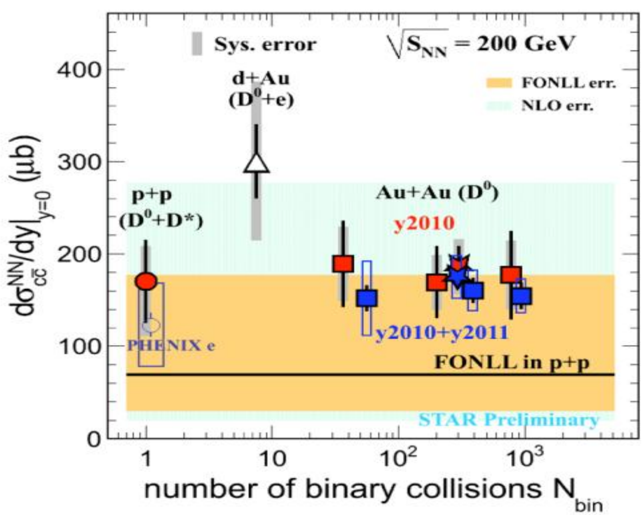
JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

Total charm production

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





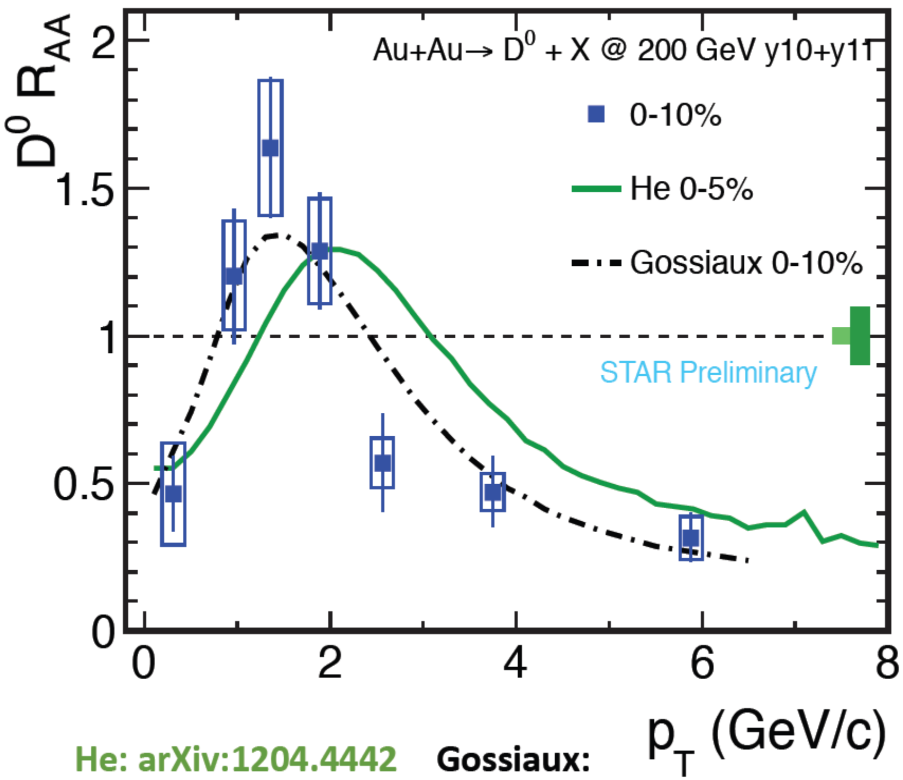


STAR, QM12

Sizeable charm production in QGP at LHC

Experiment ?

D meson R_{AA} from STAR

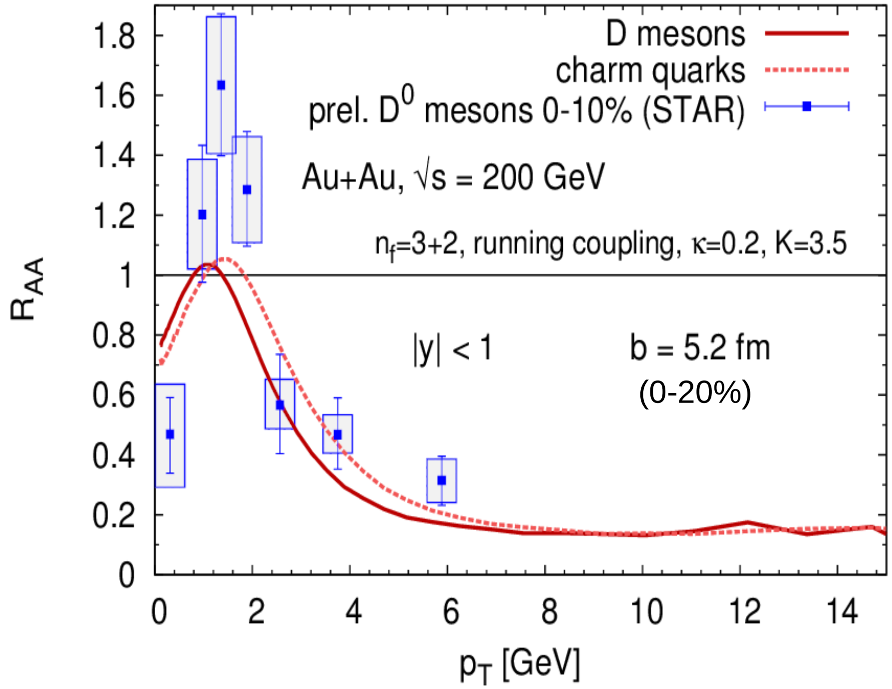


He: arXiv:1204.4442
Focker-Planck
Resonance
recombination

Gossiaux:
arXiv:1207.5445
Boltzmann
pQCD with running coupling

STAR data, QM 2012

RHIC



JU, Fochler, Xu, Greiner

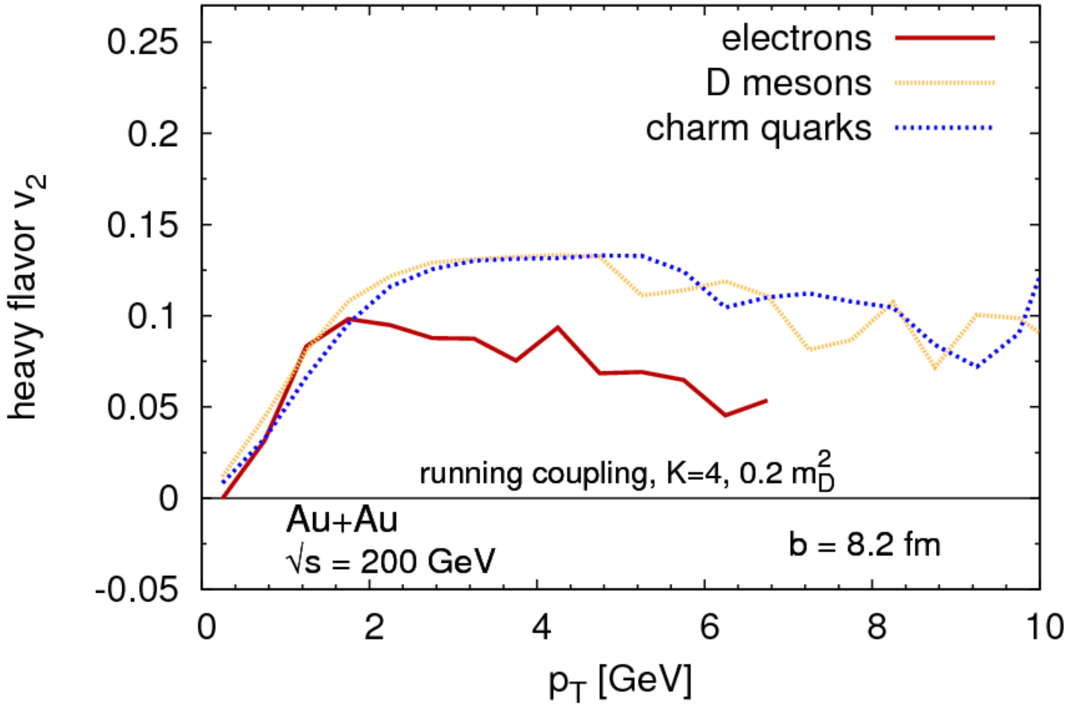
Fragmentation and Decay

- **Peterson fragmentation**

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

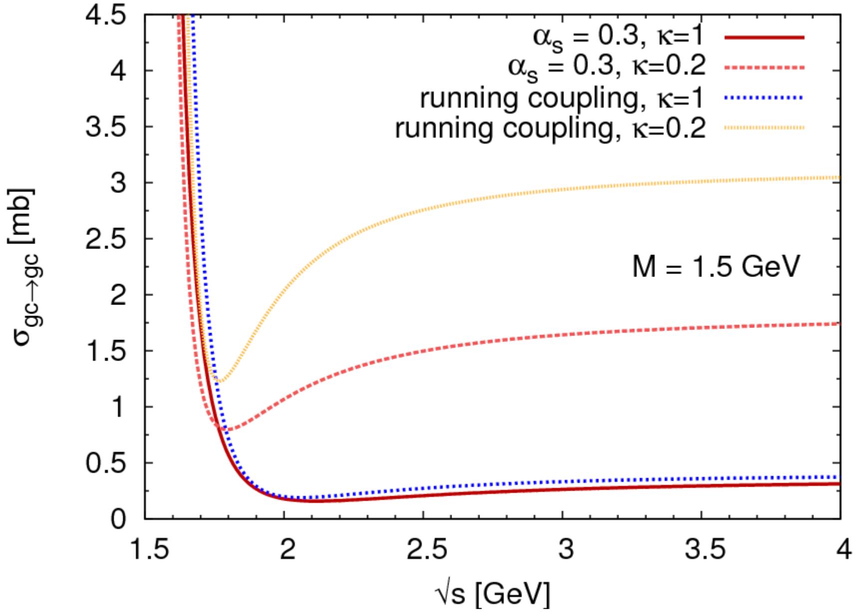
$$D_{H/Q}(z) = \frac{N}{z\left(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right)^2} \qquad z = \frac{|\vec{p}_H|}{|\vec{p}_Q|} \qquad \begin{aligned}\epsilon_c &= 0.05 \\ \epsilon_b &= 0.005\end{aligned}$$

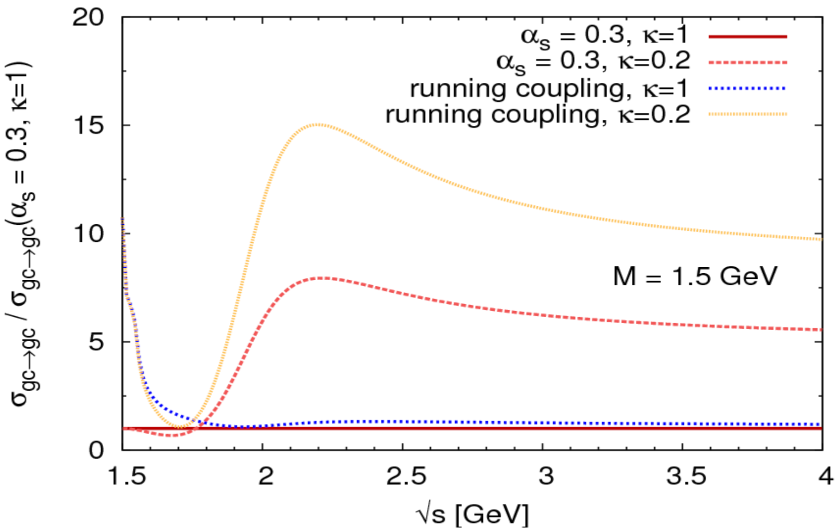
- **Decay to electrons with PYTHIA**

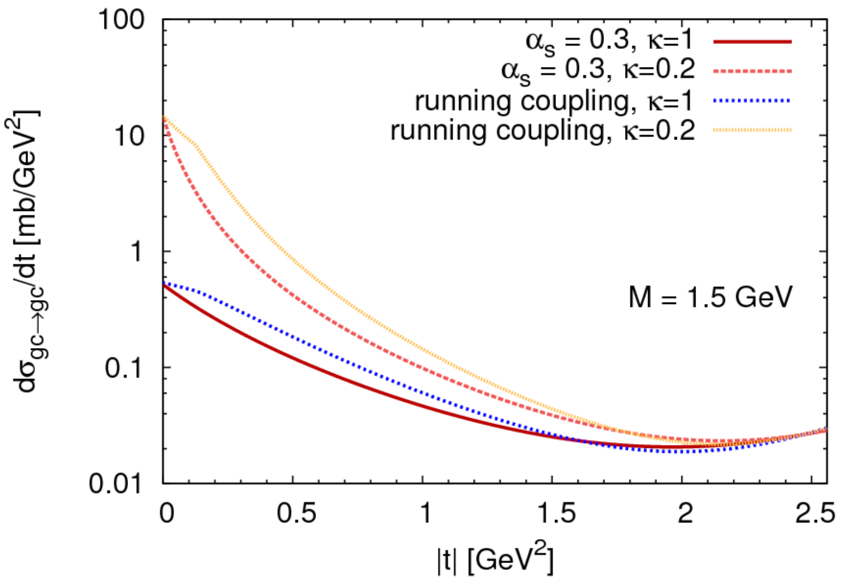


Impact of hadronization and decay small

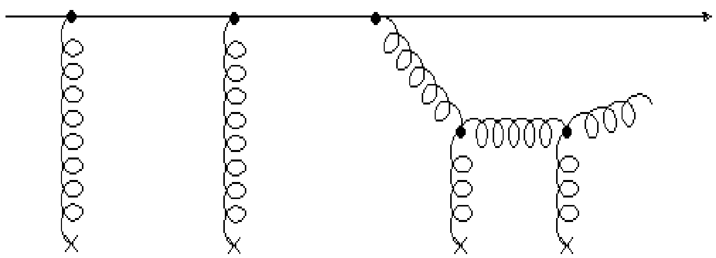
Heavy quark scattering cross section







LPM effect vs. dead cone effect



$$\lambda > \tau$$

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

➡ Independent scatterings