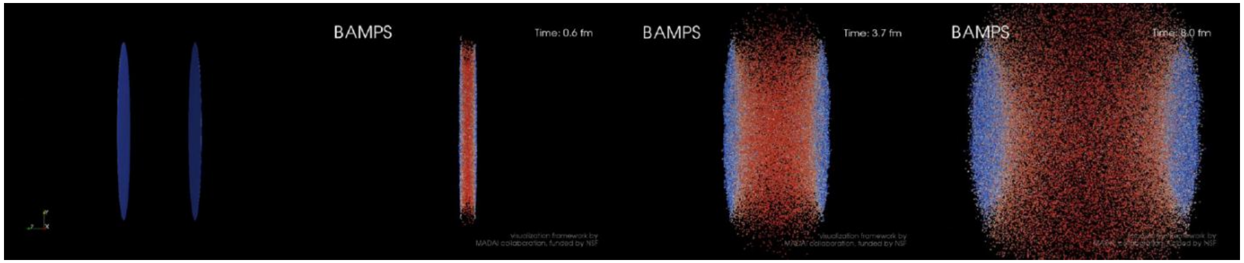
Open heavy flavor with BAMPS

Jan Uphoff

with Z. Xu and C. Greiner

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



Open heavy flavor at CBM, Frankfurt
28 May 2014

Motivation

Large heavy quark mass

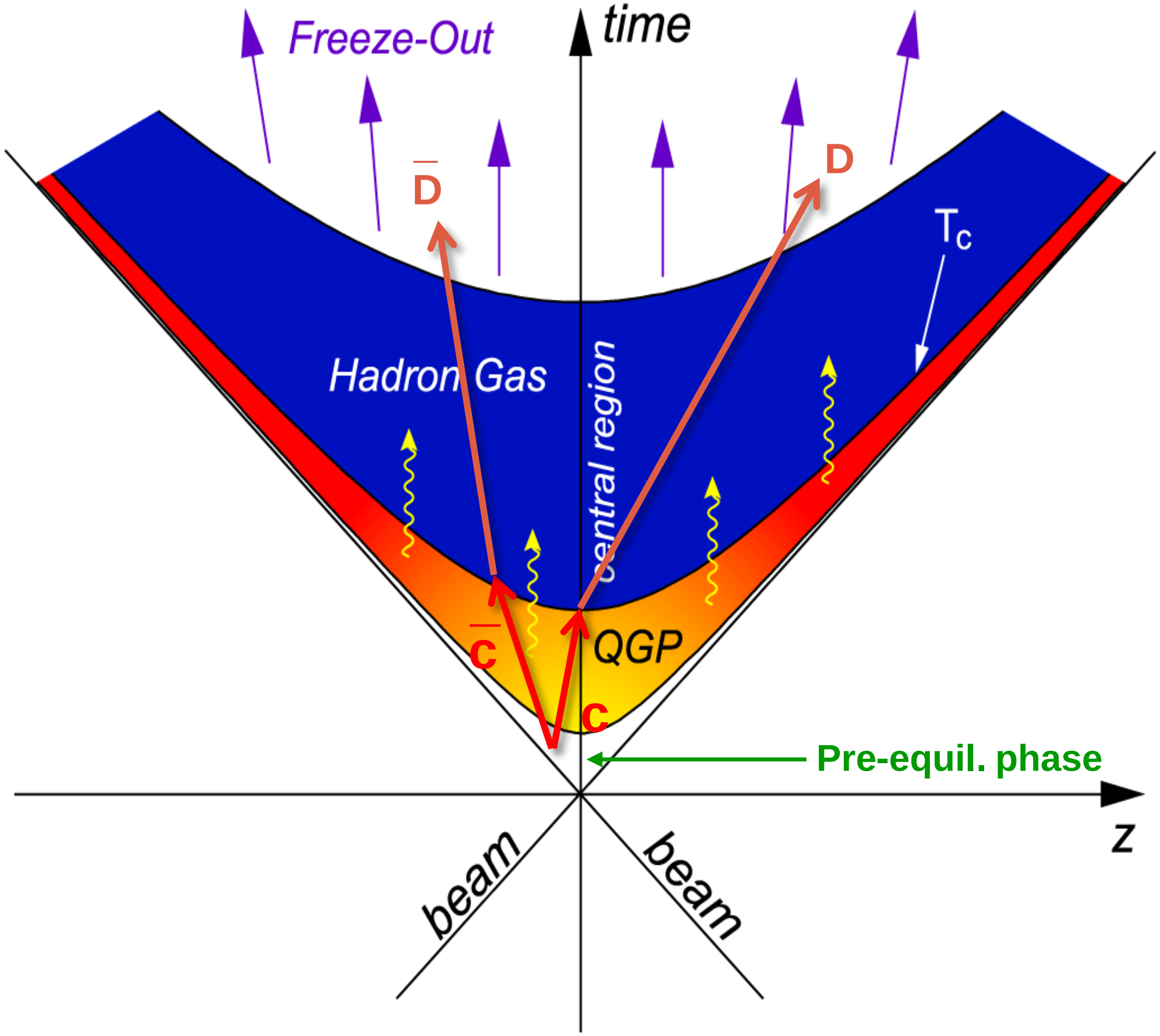
$\gg \Lambda_{QCD}$

Charm: $M_c \approx 1.5$ GeV

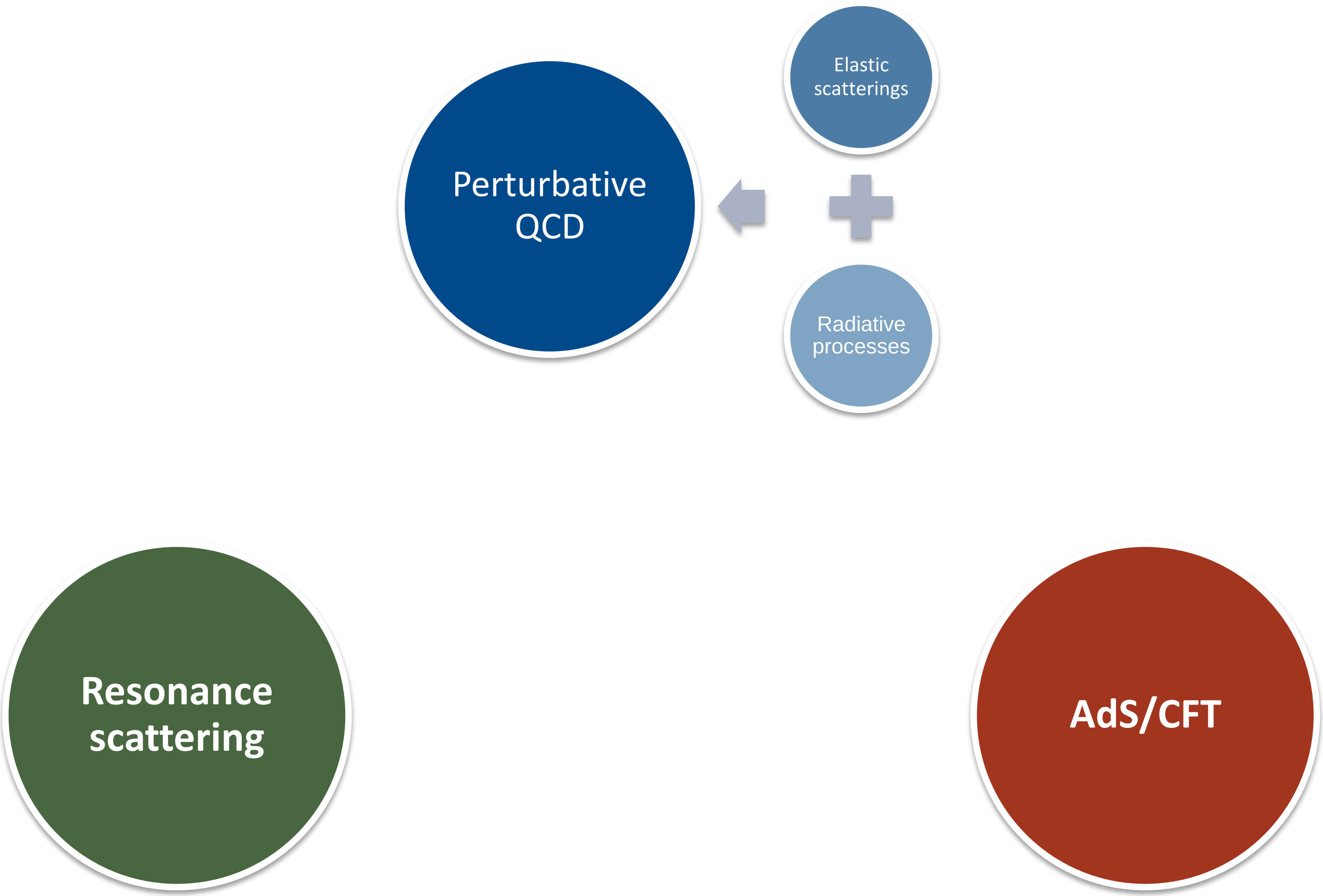
Bottom: $M_b \approx 4.75$ GeV

➡ charm production at early stage of collision

➡ ideal probe for this stage



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

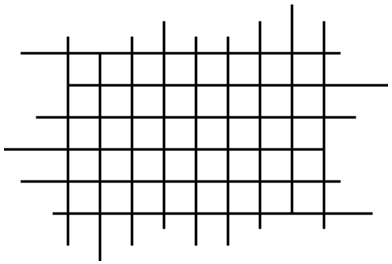
BAMPS: Boltzmann Approach to MultiParton Scatterings

- **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**

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

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

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Light flavors

Heavy flavors

binary

Light flavors:

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

Heavy flavors:

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

inelastic

Light flavors:

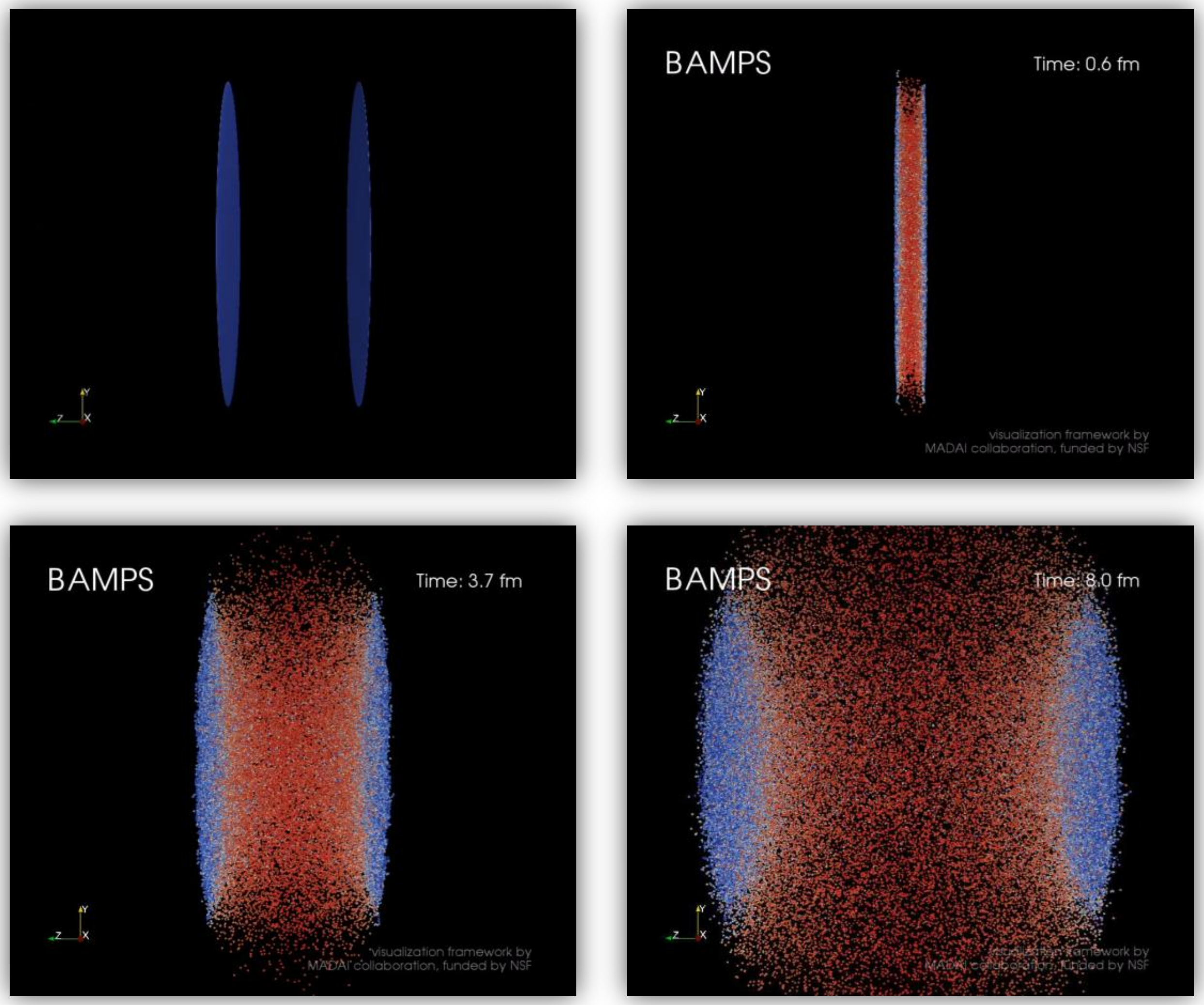
$$g\,g \leftrightarrow g\,g\,g$$
$$q\,g \leftrightarrow q\,g\,g \quad \text{and} \quad \bar{q}\,g \leftrightarrow \bar{q}\,g\,g$$
$$q\,\bar{q} \leftrightarrow q\,\bar{q}\,g$$
$$q\,q \leftrightarrow q\,q\,g \quad \text{and} \quad \bar{q}\,\bar{q} \leftrightarrow \bar{q}\,\bar{q}\,g$$
$$q\,q' \leftrightarrow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

Heavy flavors:

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

Heavy-ion collision at LHC

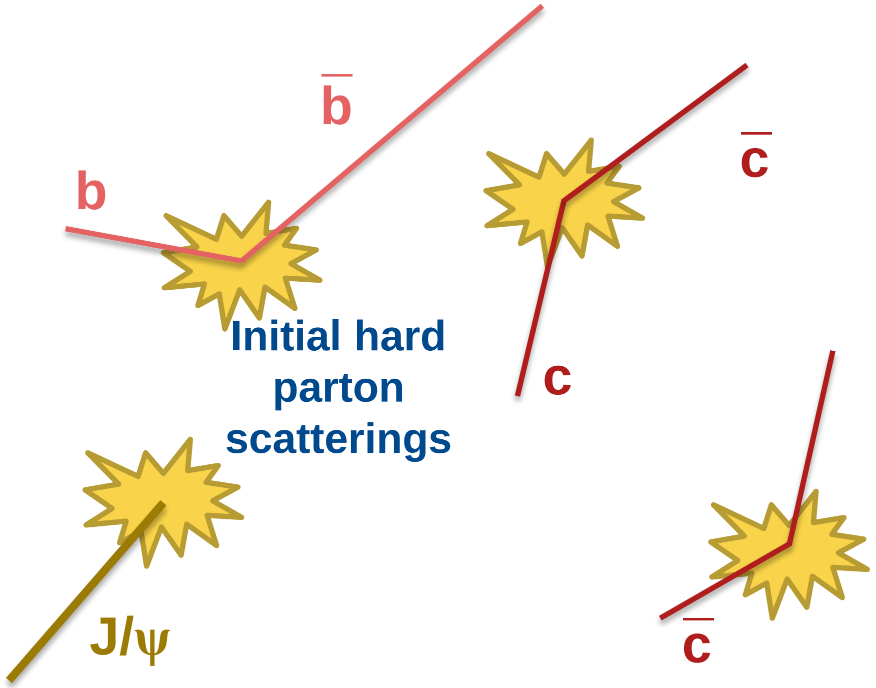
BAMPS simulation of QGP phase at LHC at $\sqrt{s_{NN}}$ = 2.76 TeV



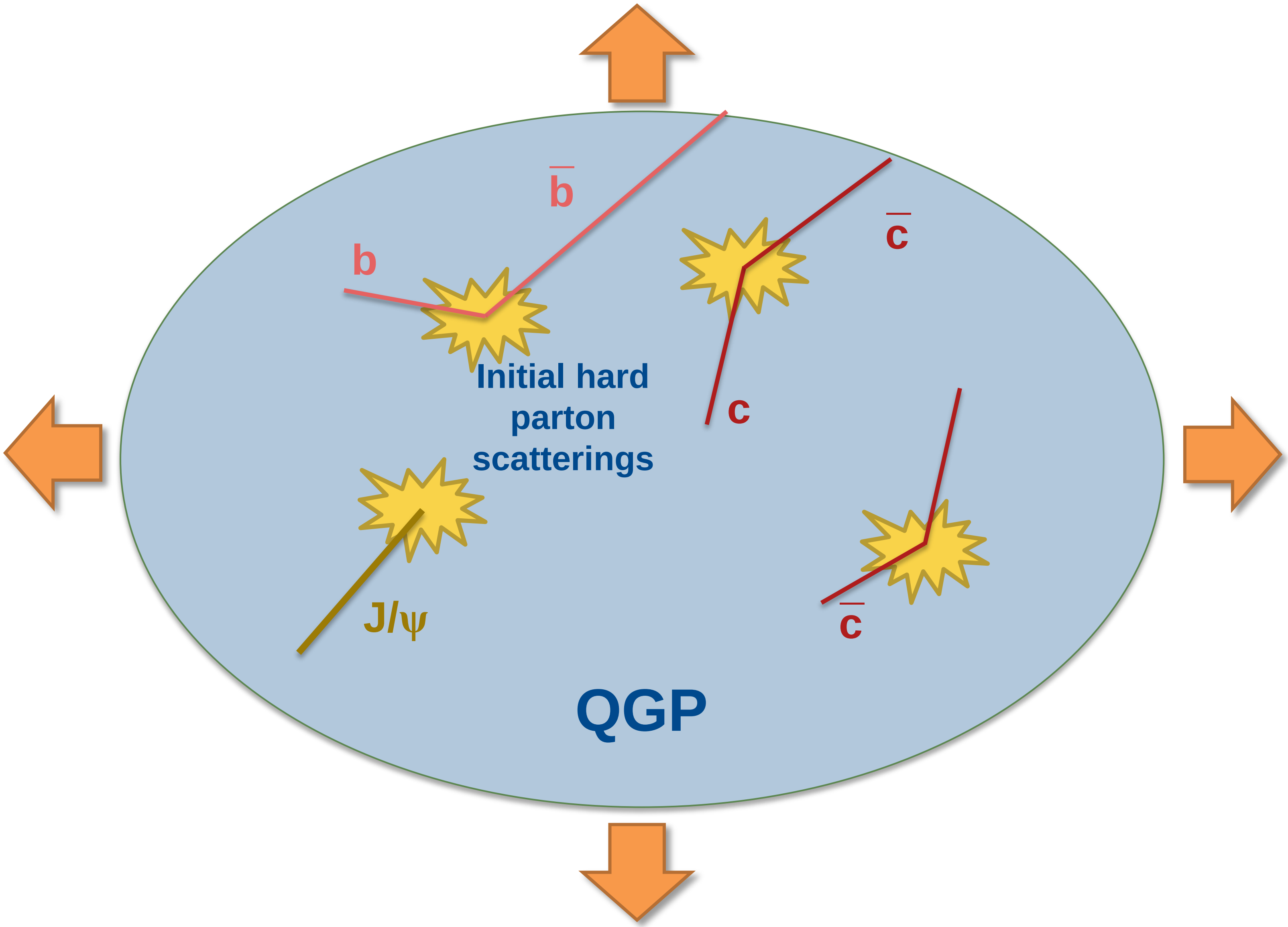
Visualization framework courtesy MADAI collaboration, funded by the NSF under grant# NSF-PHY-09-41373

Sketch of heavy flavor in HIC

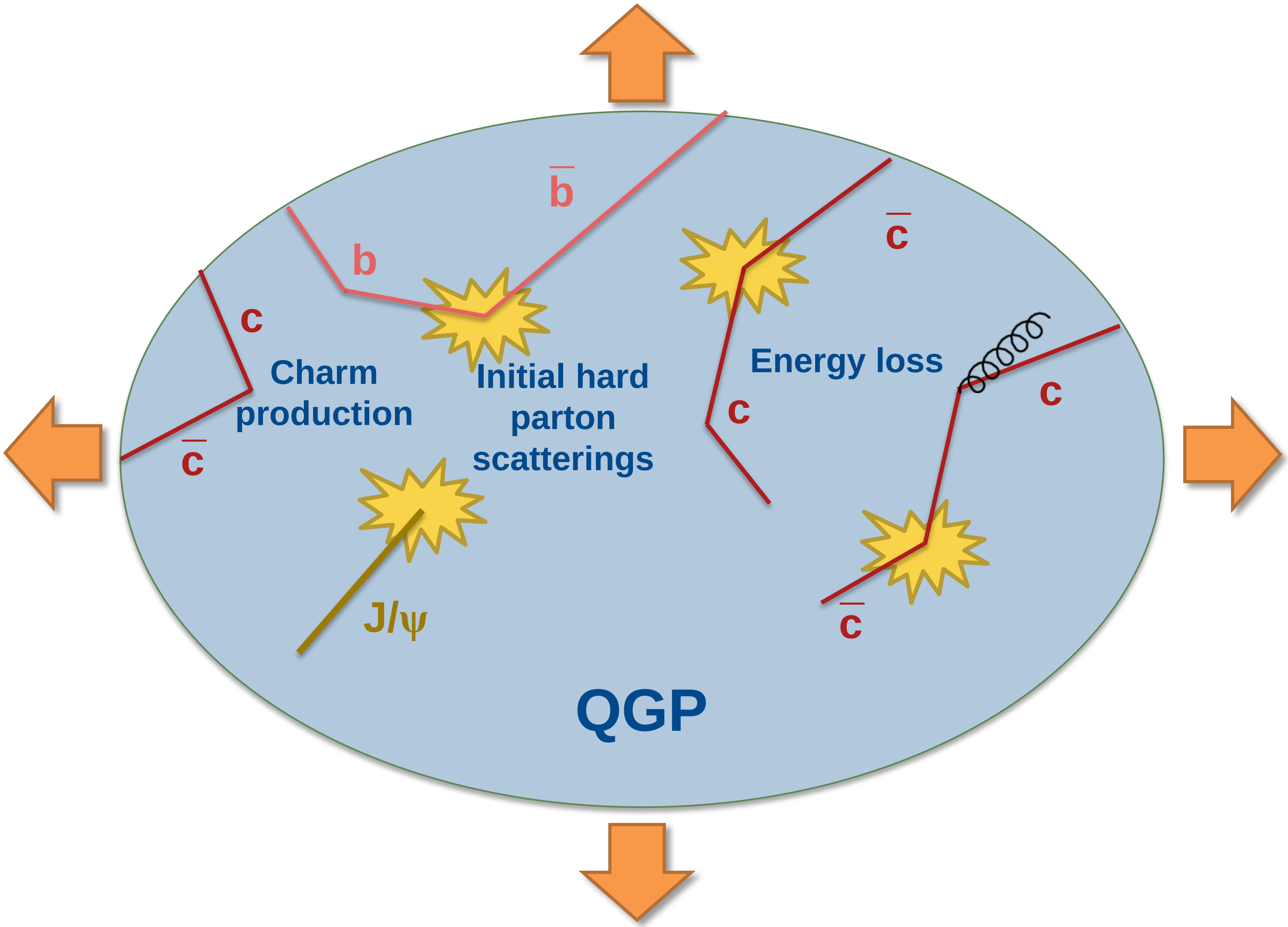
Sketch of heavy flavor in HIC



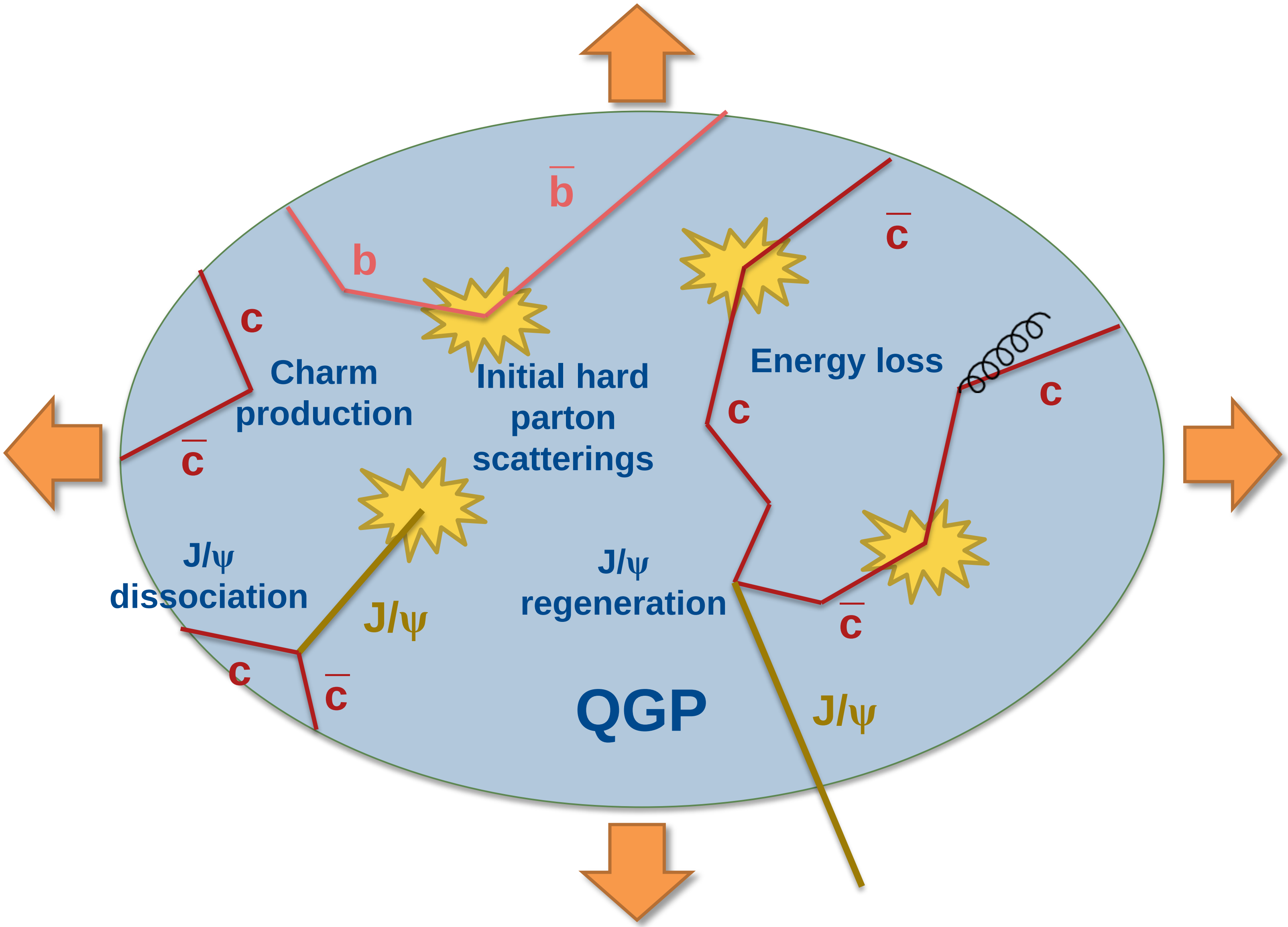
Sketch of heavy flavor in HIC



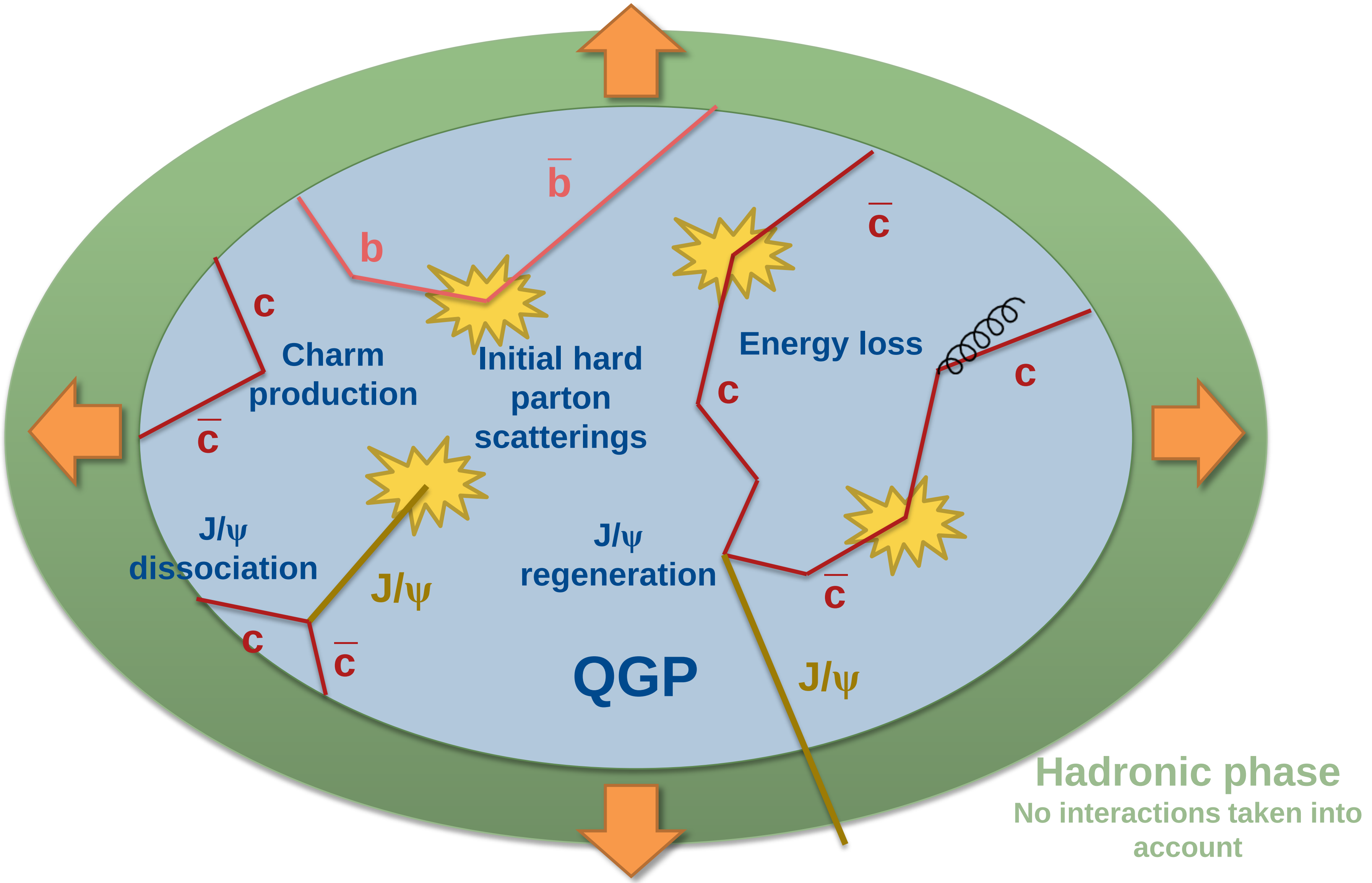
Sketch of heavy flavor in HIC



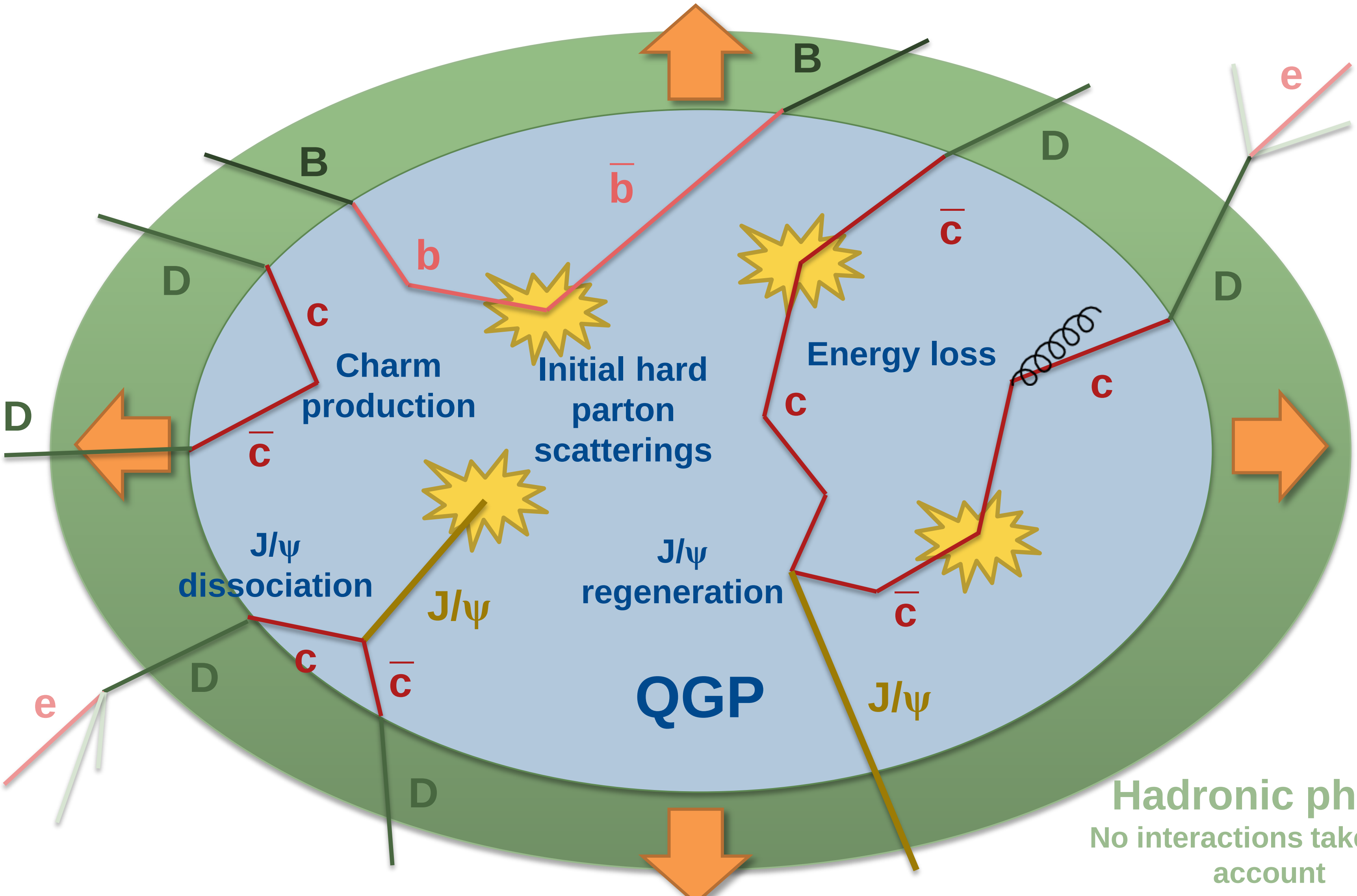
Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC

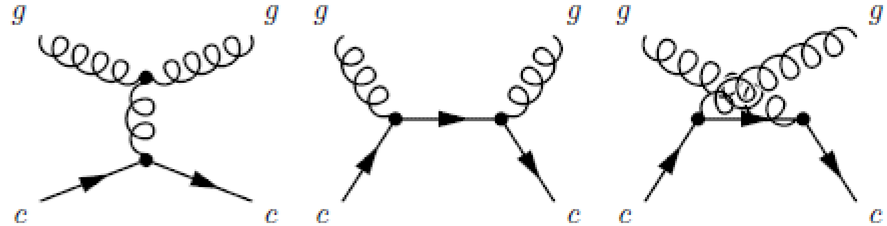


Hadronic phase
No interactions taken into account

Heavy quark scattering

Leading order perturbative QCD:

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



Improved Debye screening by comparing to HTL

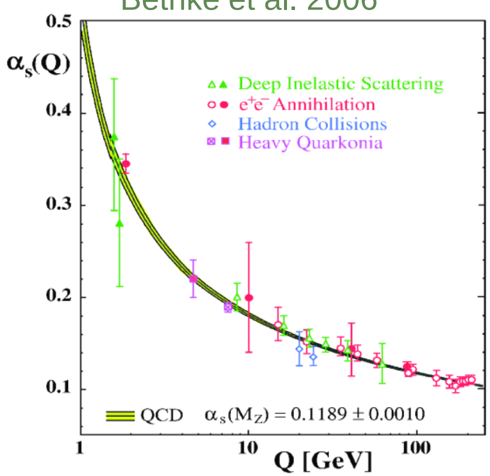
$$\frac{1}{t} \to \frac{1}{t - \kappa\, m_D^2}$$

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

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)

Radiative processes: Improved Gunion-Bertsch matrix element

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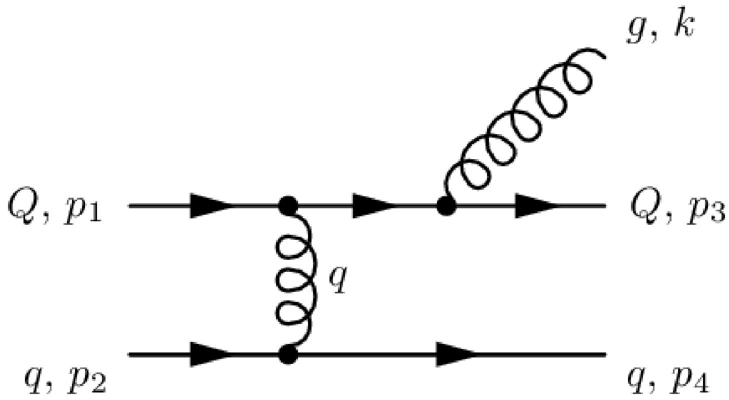
$$g + Q \to g + Q + g$$

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



Improved Gunion-Bertsch matrix element generalized to heavy quarks:

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

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)

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

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

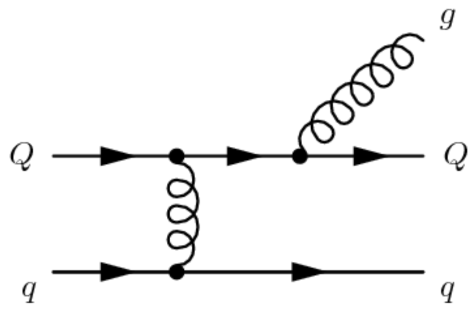
$$D=\begin{pmatrix} x_{31}^2 x_{54}^2, & 2x_{23}x_{31}x_{54}^2, & 4s_{12}x_{31}x_{54}^2, & 2s_{12}x_{31}x_{43}x_{54}, & 2s_{12}x_{31}x_{53}x_{54} \\ & x_{23}^2 x_{54}^2, & 4s_{12}x_{23}x_{54}^2, & 2s_{12}x_{23}x_{43}x_{54}, & 2s_{12}x_{23}x_{53}x_{54} \\ & & 4s_{12}^2 x_{54}^2, & 4s_{12}^2 x_{43}x_{54},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

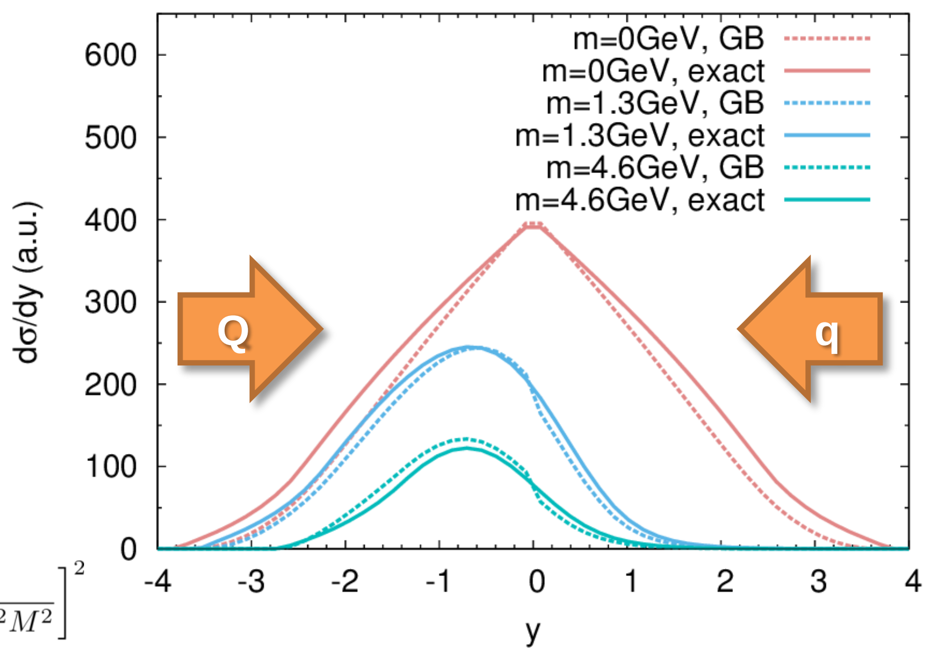
$$\begin{aligned}
N_{11} &= x_{31}(-x_{42}x_{53} - x_{43}x_{52} + 2m_Q^2 x_{54}) + 2m_Q^2(x_{41}x_{52} + x_{42}x_{51} + x_{42}x_{53} + x_{43}x_{52} + 2m_Q^2 x_{54}), \\
N_{12} &= x_{12}[x_{41}(2x_{52} + x_{53}) + x_{42}(2x_{51} + x_{53}) + x_{43}(x_{51} + x_{52}) + 4m_Q^2 x_{54}] \\
&\quad + x_{23}[x_{41}(-2x_{51} + x_{52}) + x_{42}x_{51} + 2m_Q^2 x_{54}] \\
&\quad + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52}) + 2m_Q^2 x_{54}] - 4m_Q^2 x_{43}x_{53}, \\
N_{13} &= x_{12}[-2x_{31}x_{54} + x_{41}(4x_{52} + 3x_{53}) + x_{42}(4x_{51} + 3x_{53}) + x_{43}(3x_{51} + 3x_{52} + 2x_{53}) + 8m_Q^2 x_{54}] \\
&\quad + x_{23}[x_{41}(-6x_{51} + x_{52} - x_{53}) + (x_{42} - x_{43})x_{51} + 4m_Q^2 x_{54}] \\
&\quad + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 2x_{52} - 3x_{53}) - 3x_{43}x_{52}] \\
&\quad + 2m_Q^2[x_{41}(2x_{51} + 4x_{52} + 3x_{53}) + x_{42}(4x_{51} - 2x_{52} + 5x_{53}) + x_{43}(3x_{51} + 5x_{52}) + 8m_Q^2 x_{54}], \\
N_{14} &= x_{51}(-x_{12}x_{43} + x_{23}x_{41} + x_{42}x_{43}) + x_{31}[2x_{41}x_{52} + x_{42}(x_{51} - x_{54}) + 2x_{43}x_{52} + 2m_Q^2 x_{54}] \\
&\quad + x_{41}[2(x_{41} + x_{43})x_{52} + x_{42}(2x_{51} + x_{53}) + 2m_Q^2(x_{53} + 2x_{54})] + 2m_Q^2 x_{43}(x_{53} + x_{54} - x_{51} - x_{52}),
\end{aligned}$$

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

$$\begin{aligned}
N_{33} &= x_{12}[2x_{54}(x_{12} - x_{23} - x_{31}) + x_{41}(-2x_{51} + 6x_{52} + 5x_{53}) + x_{42}(-2x_{52} + 6x_{51} + 5x_{53}) \\
&\qquad + x_{43}(5x_{51} + 5x_{52} + 4x_{53}) + 28m_Q^2 x_{54}] \\
&\quad + x_{23}[-2x_{31}x_{54} + x_{41}(-6x_{51} + x_{52} - 3x_{53}) + (x_{42} - 3x_{43})x_{51}] \\
&\quad + x_{31}[x_{41}x_{52} + x_{42}(x_{51} - 6x_{52} - 3x_{53}) - 3x_{43}x_{52}] \\
&\quad + 2m_Q^2[x_{41}(-4x_{51} + 4x_{52} + 7x_{53}) + x_{42}(4x_{51} - 4x_{52} + 7x_{53}) + x_{43}(7x_{51} + 7x_{52} + 2x_{53}) + 24m_Q^2 x_{54}], \\
N_{34} &= x_{12}[x_{54}(x_{23} + x_{31} + x_{42} + x_{41}) - 2x_{43}(x_{51} + x_{52})] \\
&\quad + x_{23}[2x_{31}x_{54} + x_{41}(x_{52} - x_{53} - x_{54}) + 3x_{51}(x_{42} + x_{43}) + 8m_Q^2 x_{54}] \\
&\quad + x_{31}[x_{42}(x_{51} - x_{53} - x_{54}) + 3x_{52}(x_{41} + x_{43}) + 8m_Q^2 x_{54}] \\
&\quad + x_{41}[3(x_{41} + x_{43})x_{52} + x_{42}(x_{51} + x_{52} + 2x_{53}) + 2m_Q^2(x_{53} + 5x_{54})] \\
&\quad + x_{42}[3(x_{42} + x_{43})x_{51} + 2m_Q^2(x_{53} + 5x_{54})] + 2m_Q^2 x_{43}(2x_{53} + 2x_{54} - 5x_{51} - 5x_{52}), \\
N_{44} &= x_{43}(-x_{23}x_{51} - x_{31}x_{52} - 2m_Q^2 x_{53}), \\
N_{45} &= x_{54}[x_{23}(x_{41} + x_{51}) + x_{31}(x_{42} + x_{52}) + 4m_Q^2(x_{53} + x_{54} + x_{43})] \\
&\quad + x_{41}[x_{52}(x_{43} + 2x_{54}) + x_{53}(x_{52} - 2x_{42})] + x_{51}[-2x_{43}x_{52} + x_{42}(x_{53} + 2x_{54} + x_{43})],
\end{aligned}$$

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





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 can be seen in BAMPS

Heavy quark suppression factor

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

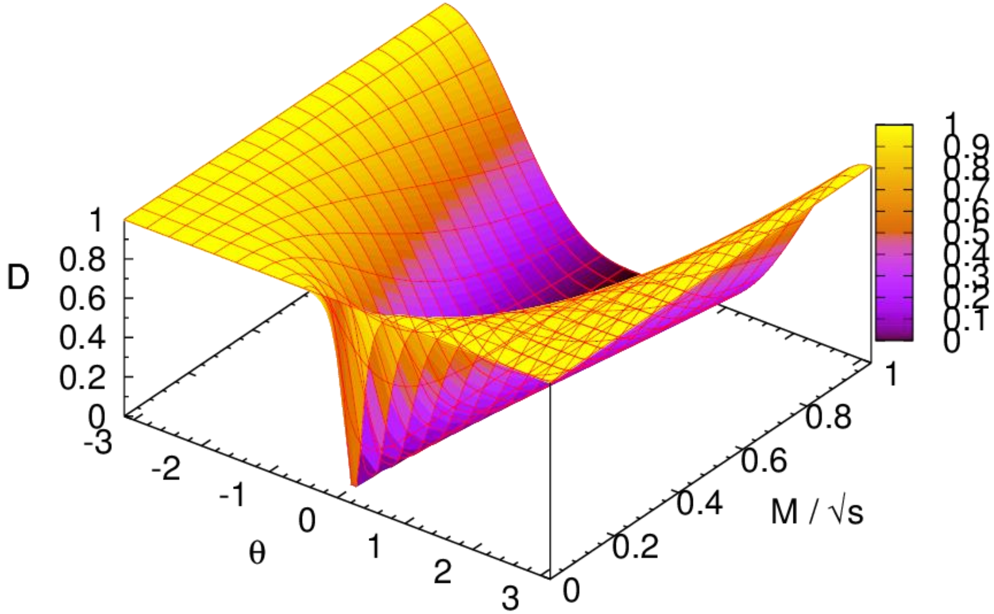
Dokshitzer, Kharzeev,
Phys.Lett. B519 (2001)

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

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

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

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



LPM cut-off

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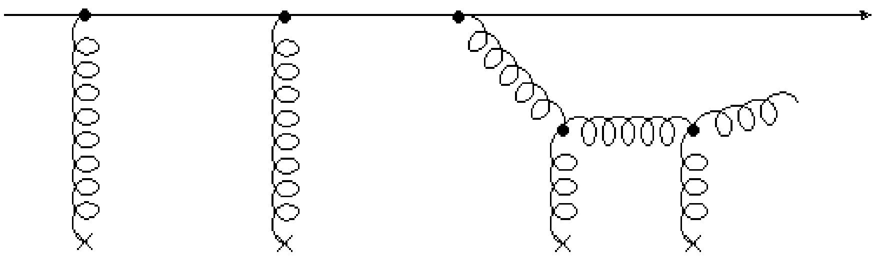


Mean free path $\lambda > X \, \tau$ **Formation time**

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

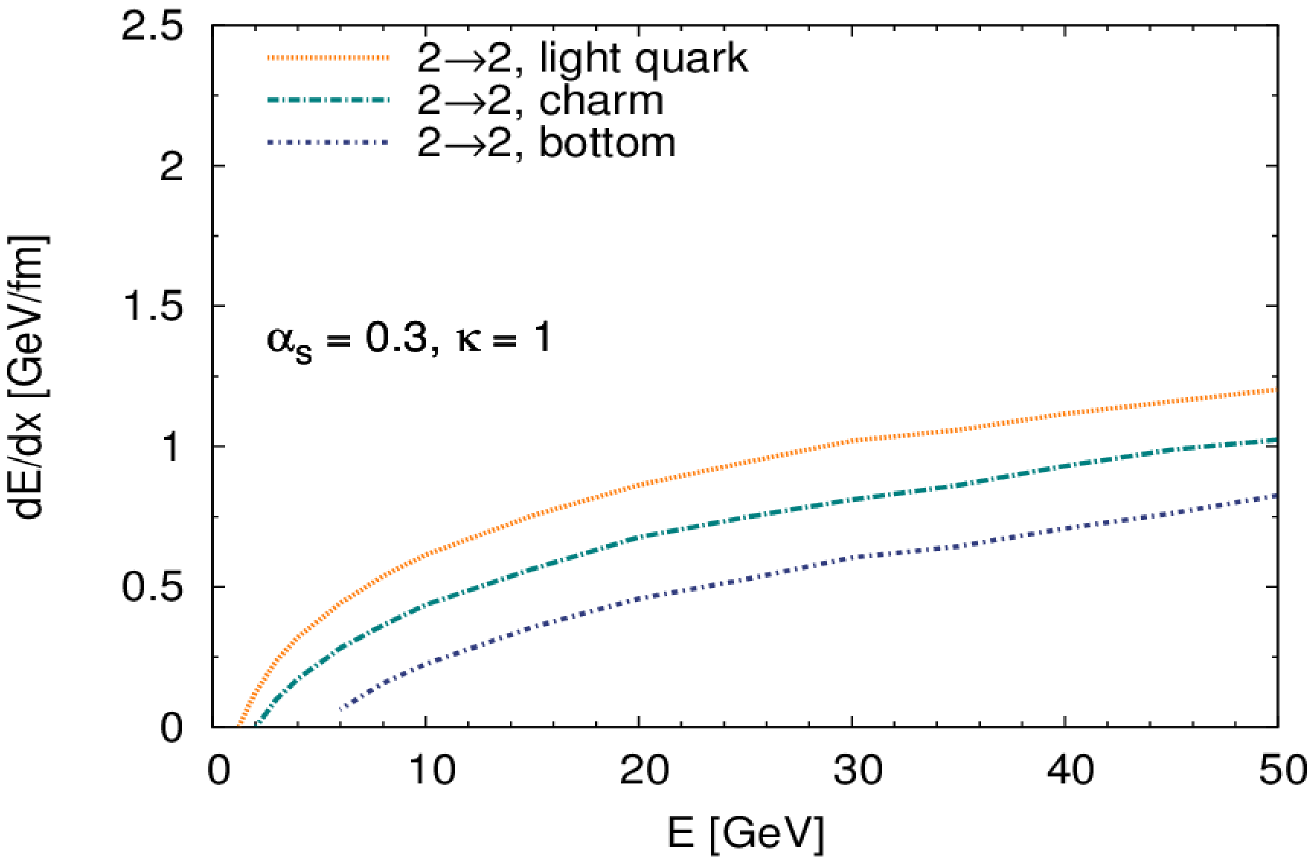
$X = 0$ **No LPM effect**

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

$0 < X < 1$ **Allows effectively some interference effects**

Radiative energy loss

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

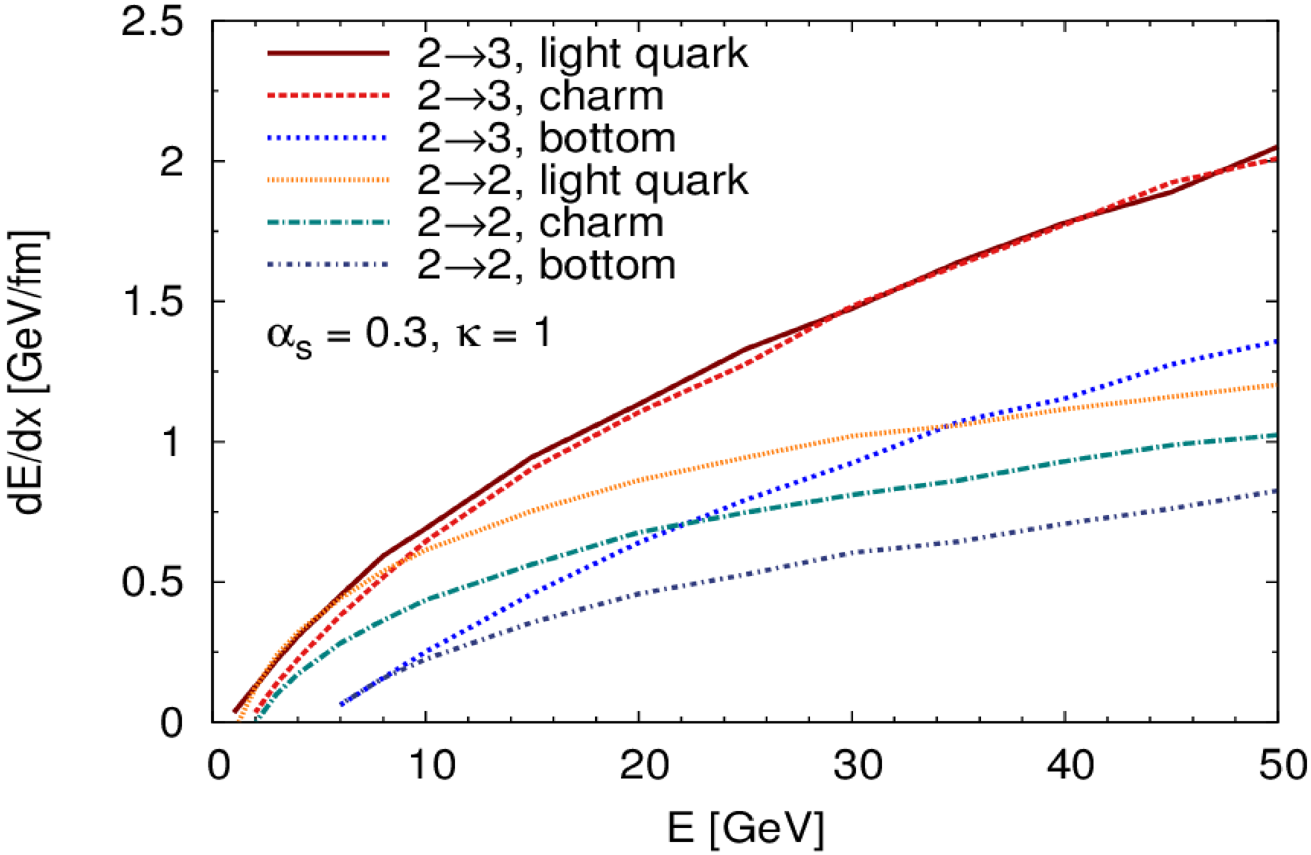


$\alpha_s = 0.3$

$X_{LPM} = 1$

Radiative energy loss

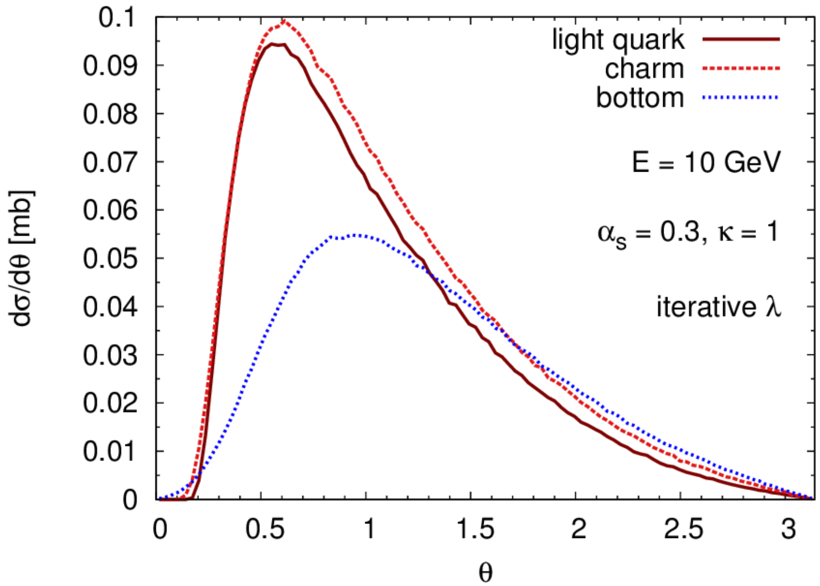
$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{light quark}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{charm}} > \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{bottom}}$$

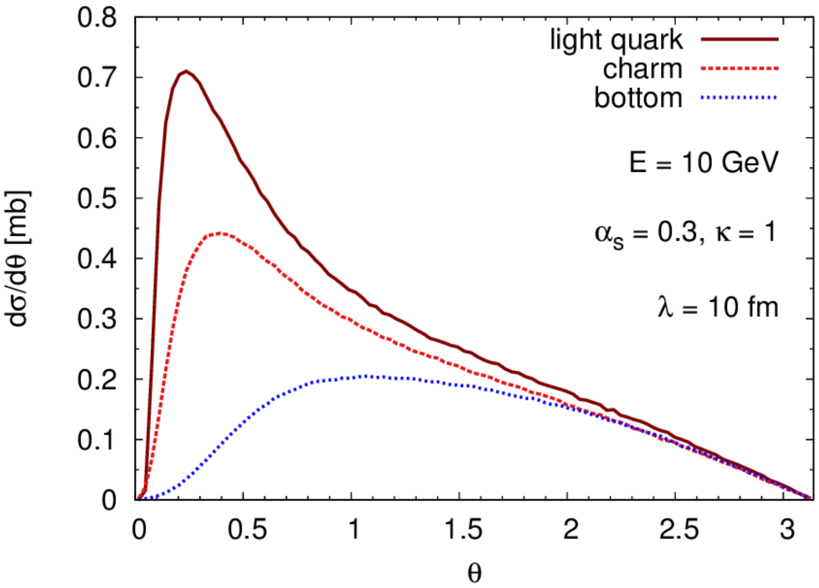


$\alpha_s = 0.3$

$X_{LPM} = 1$

Angle distribution in lab frame





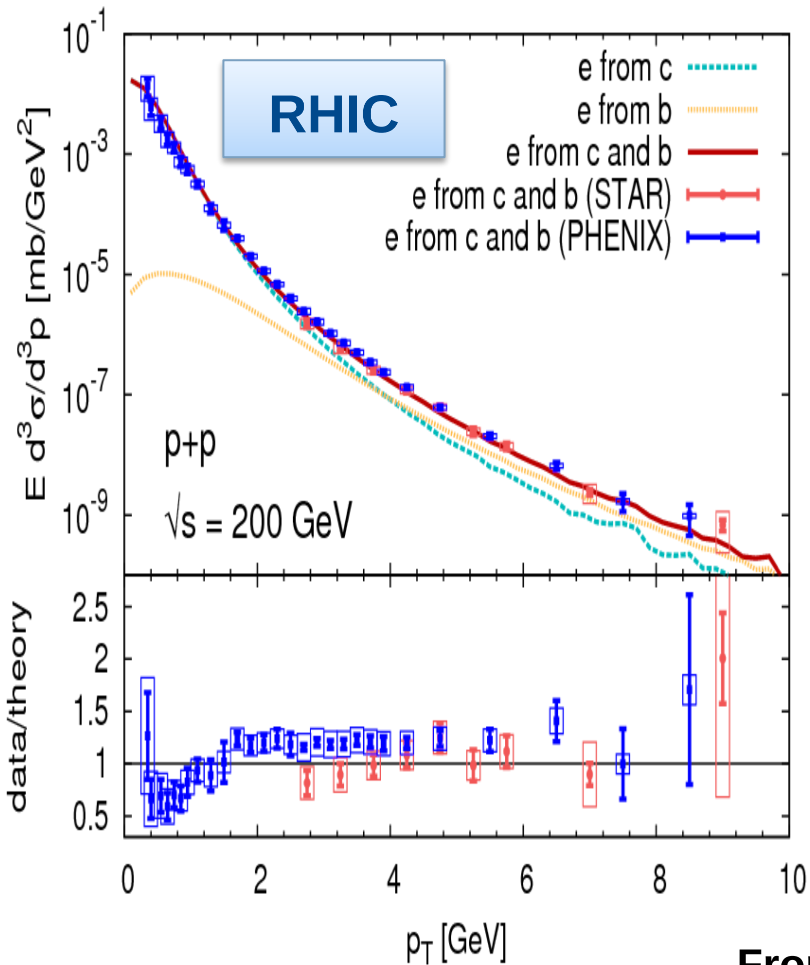
With LPM

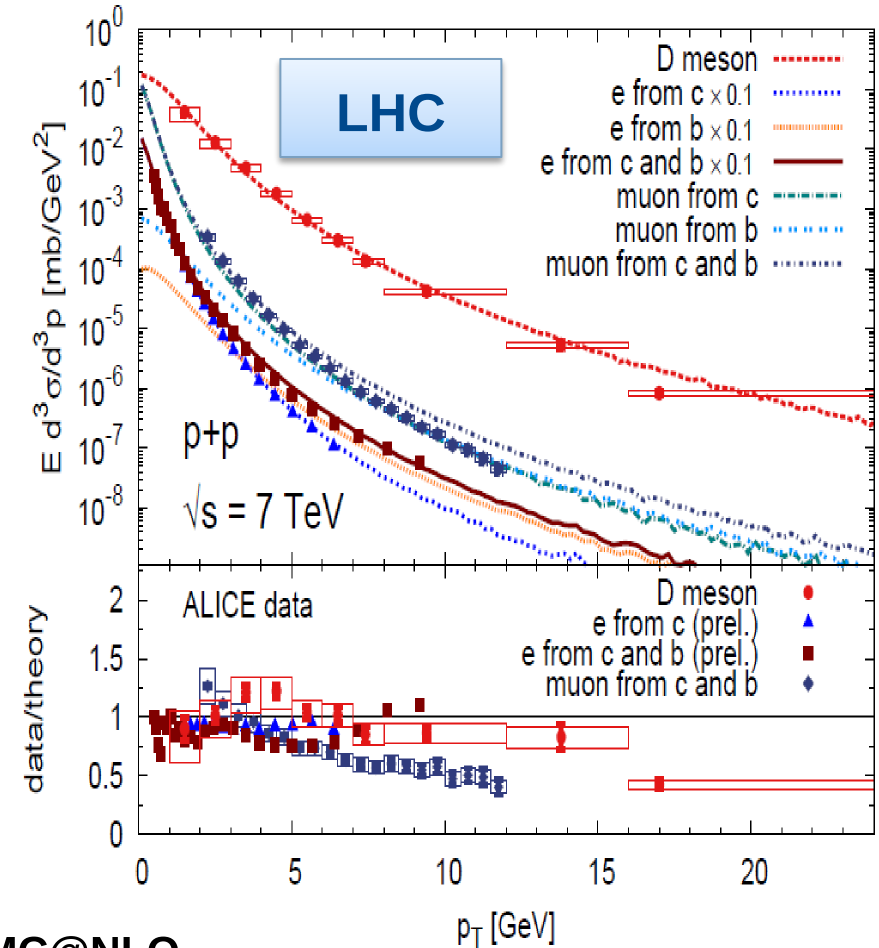
Without LPM

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

Dead cone due to mass is visible

Initial heavy flavor spectrum



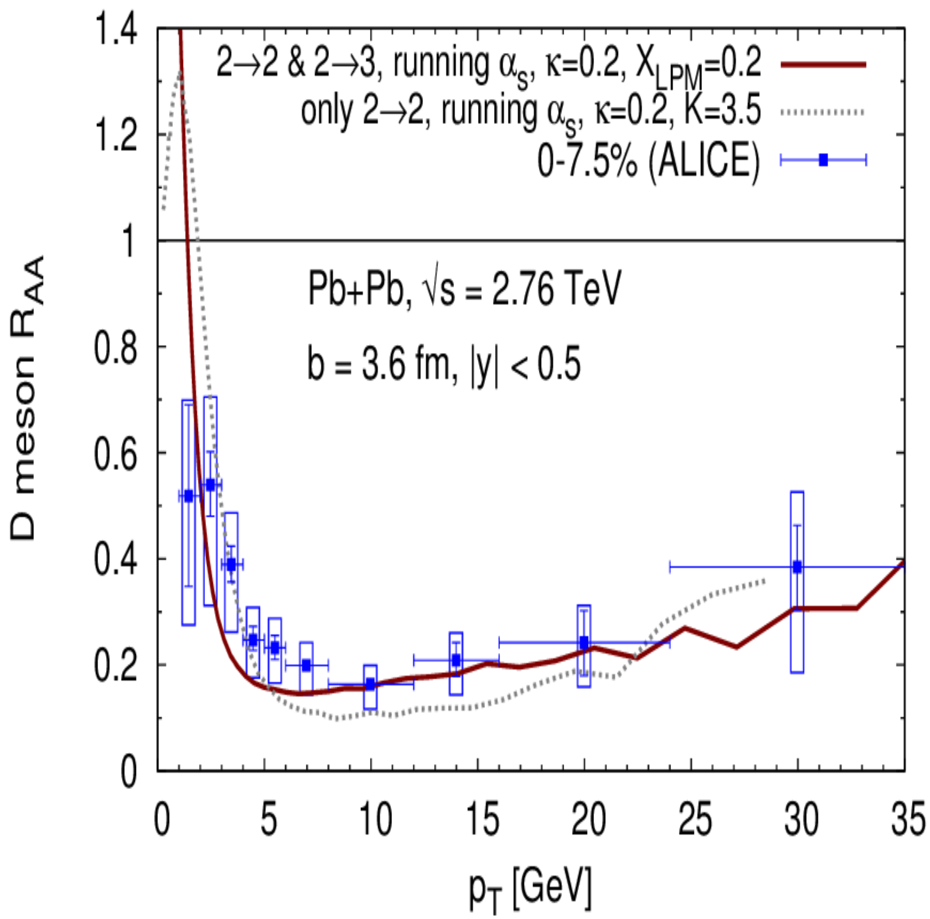


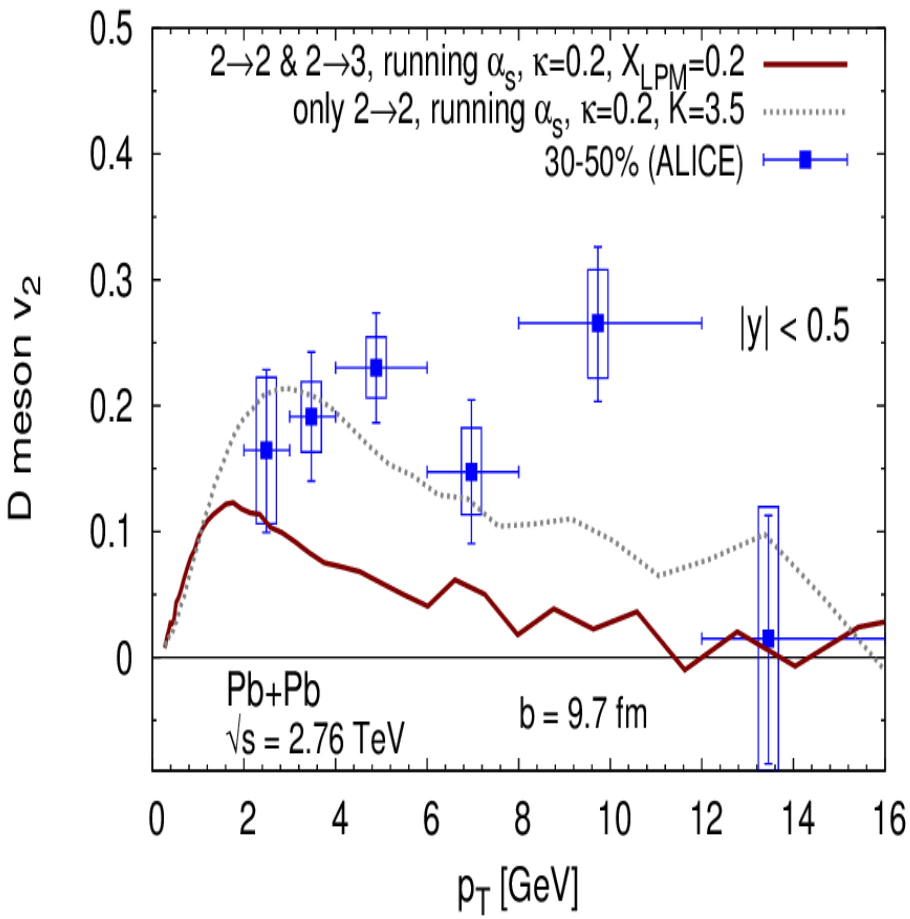
From MC@NLO

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

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

D meson R_{AA} and v_2 at LHC



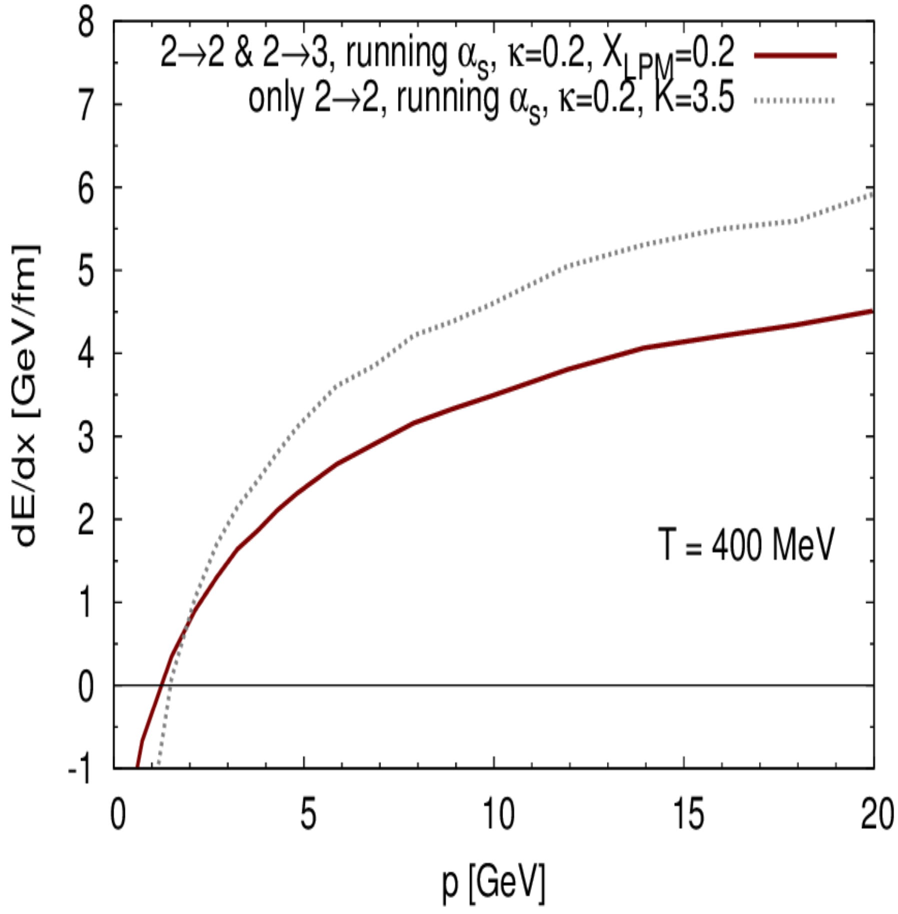


LHC

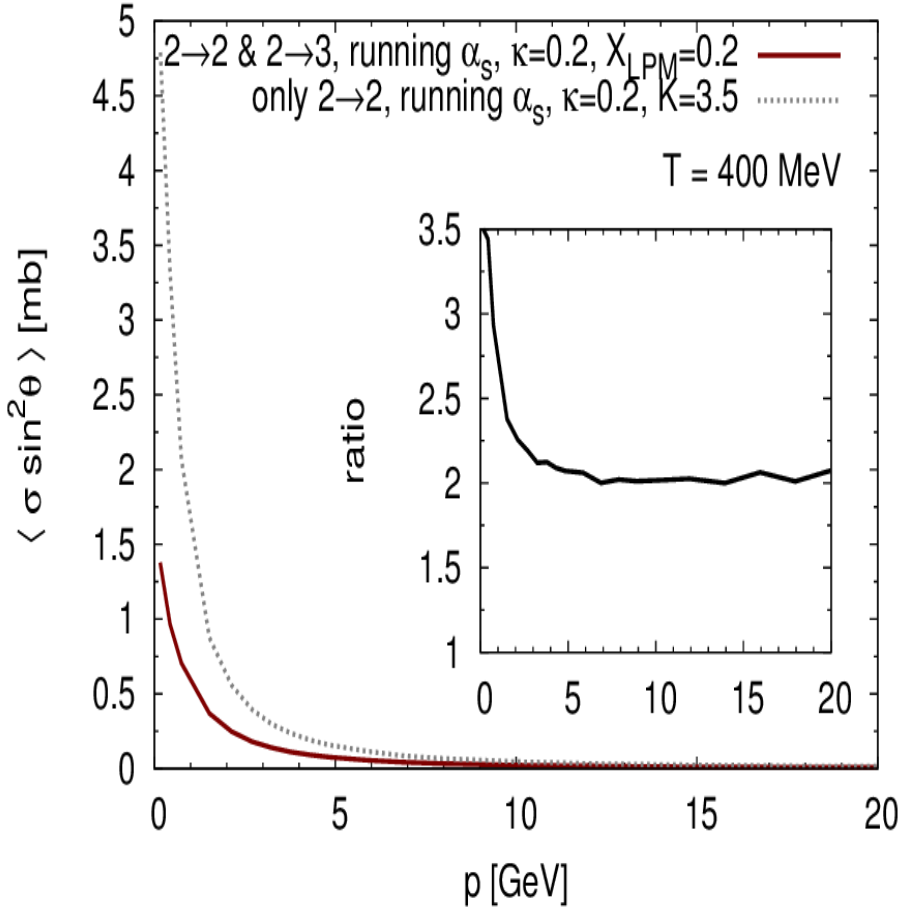
ALICE data, QM12

Energy loss and transport cross section

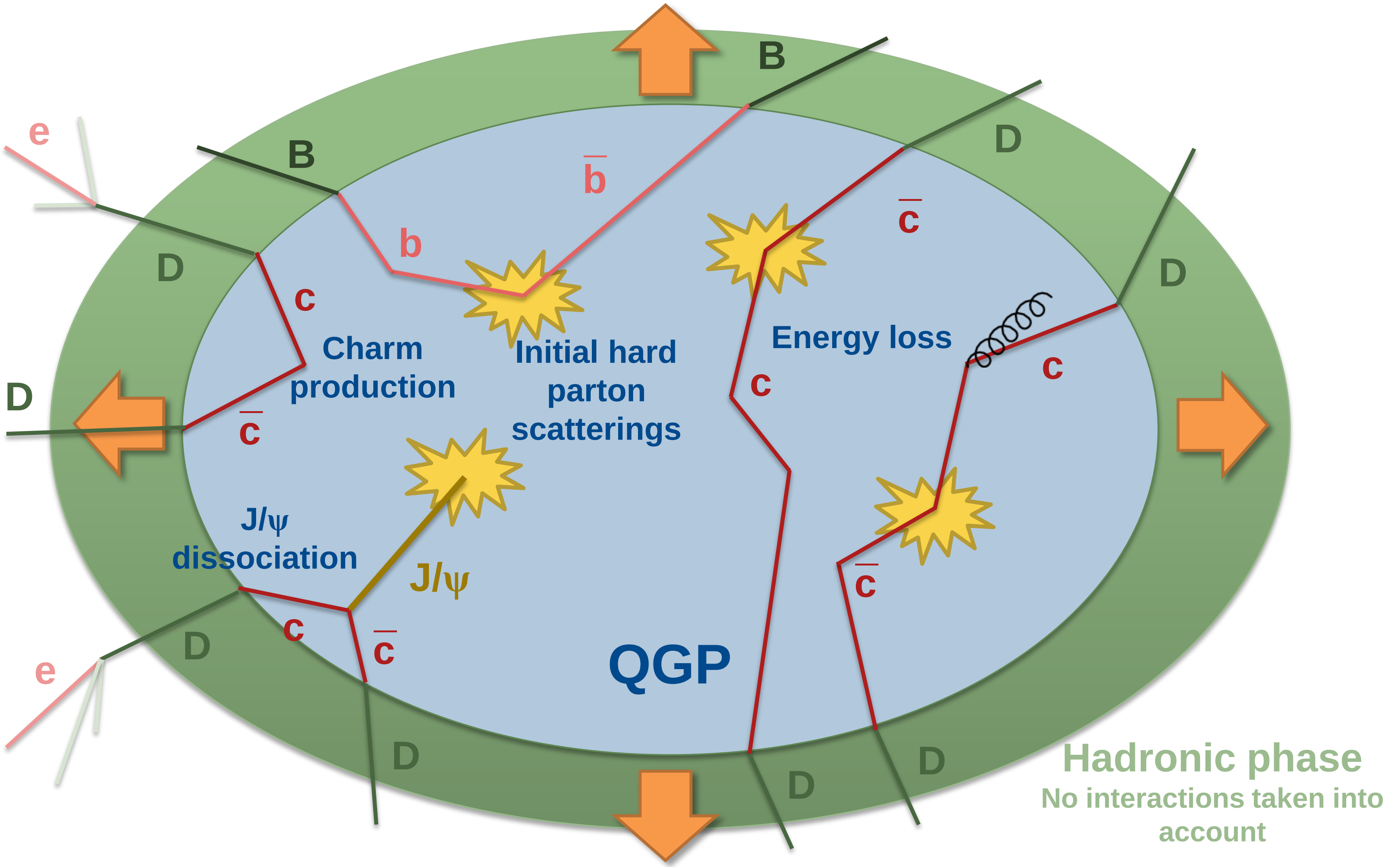
Energy loss
in static medium



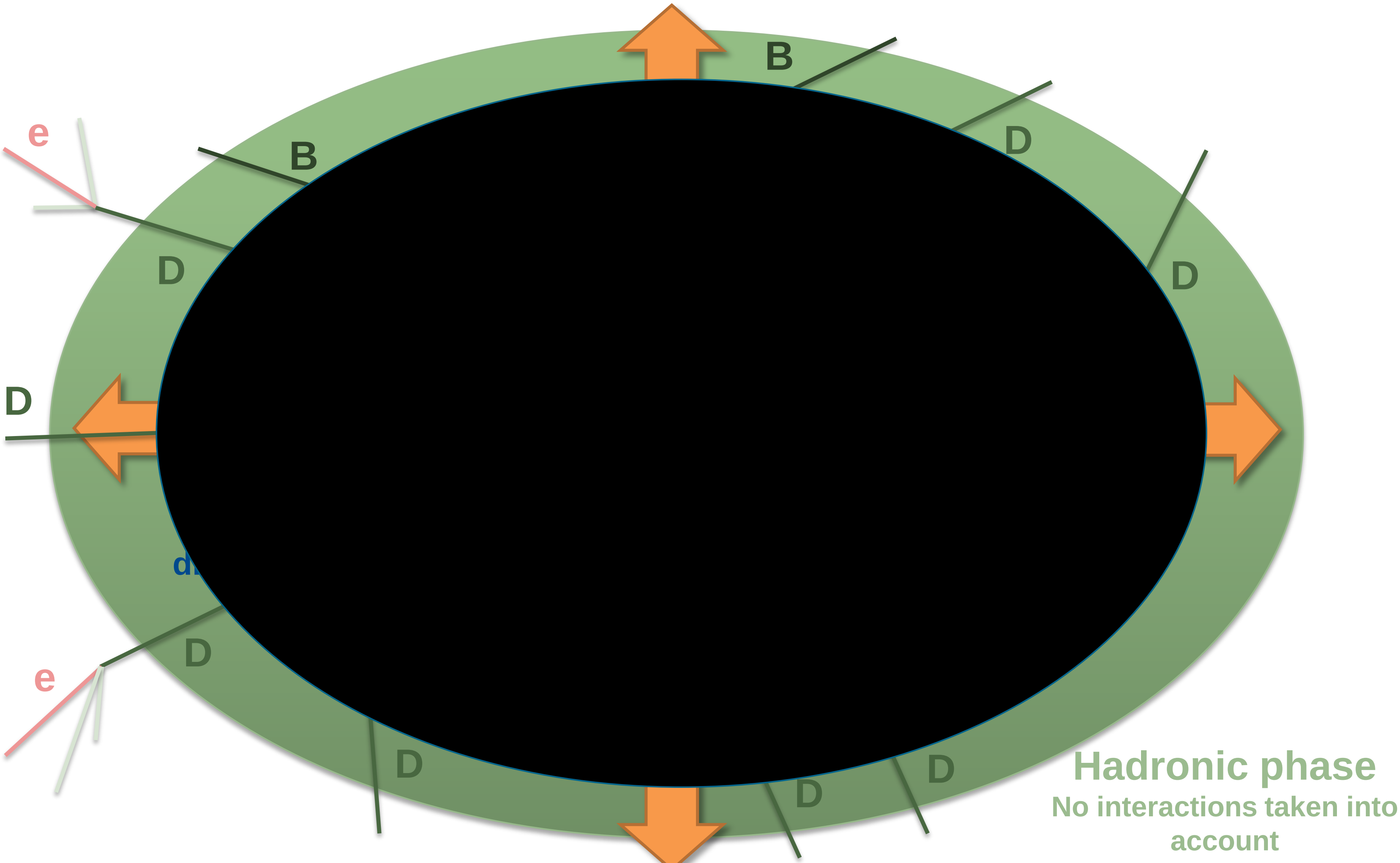
Transport cross section
in static medium



Sketch of heavy flavor in HIC



Sketch of heavy flavor in HIC



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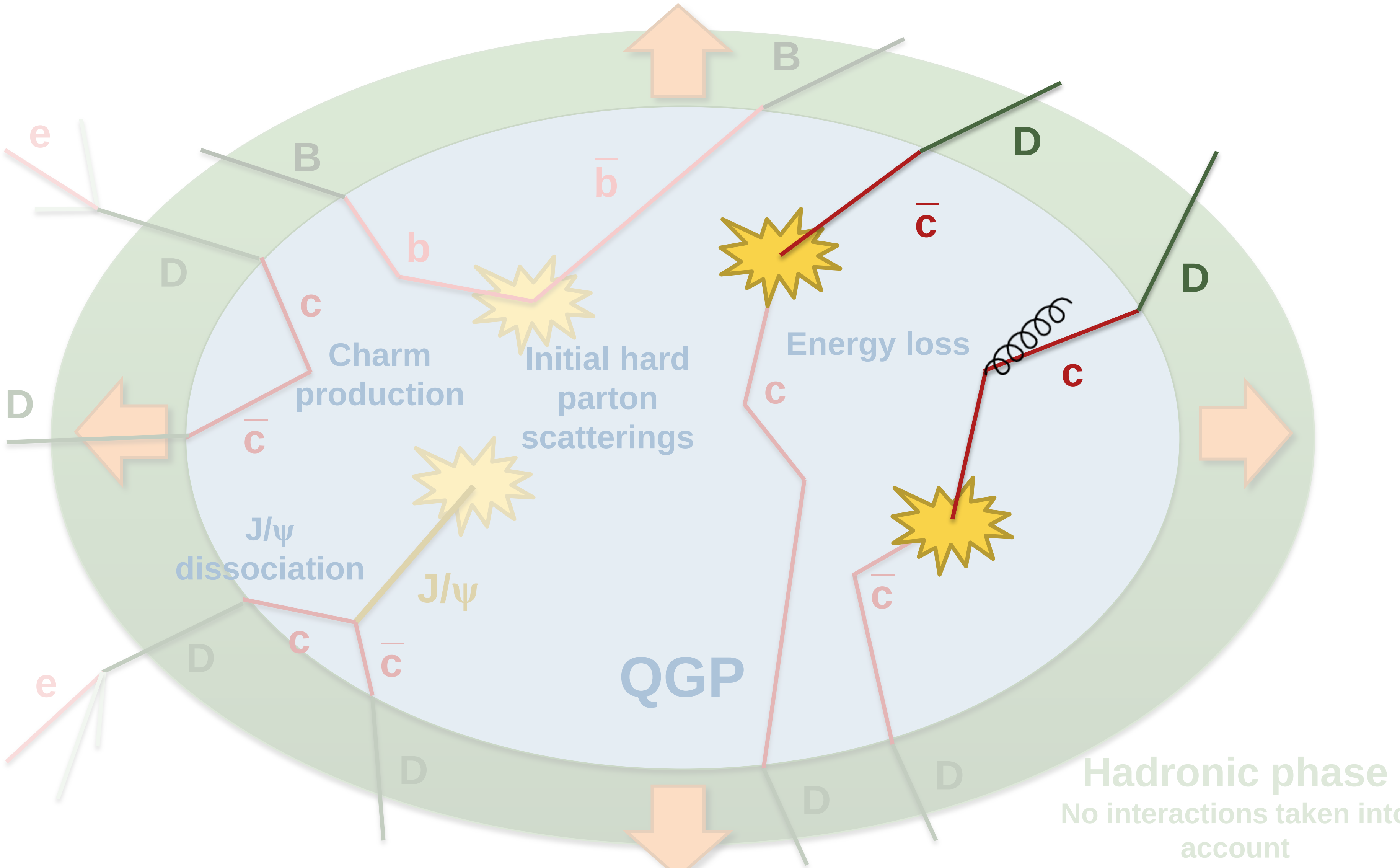
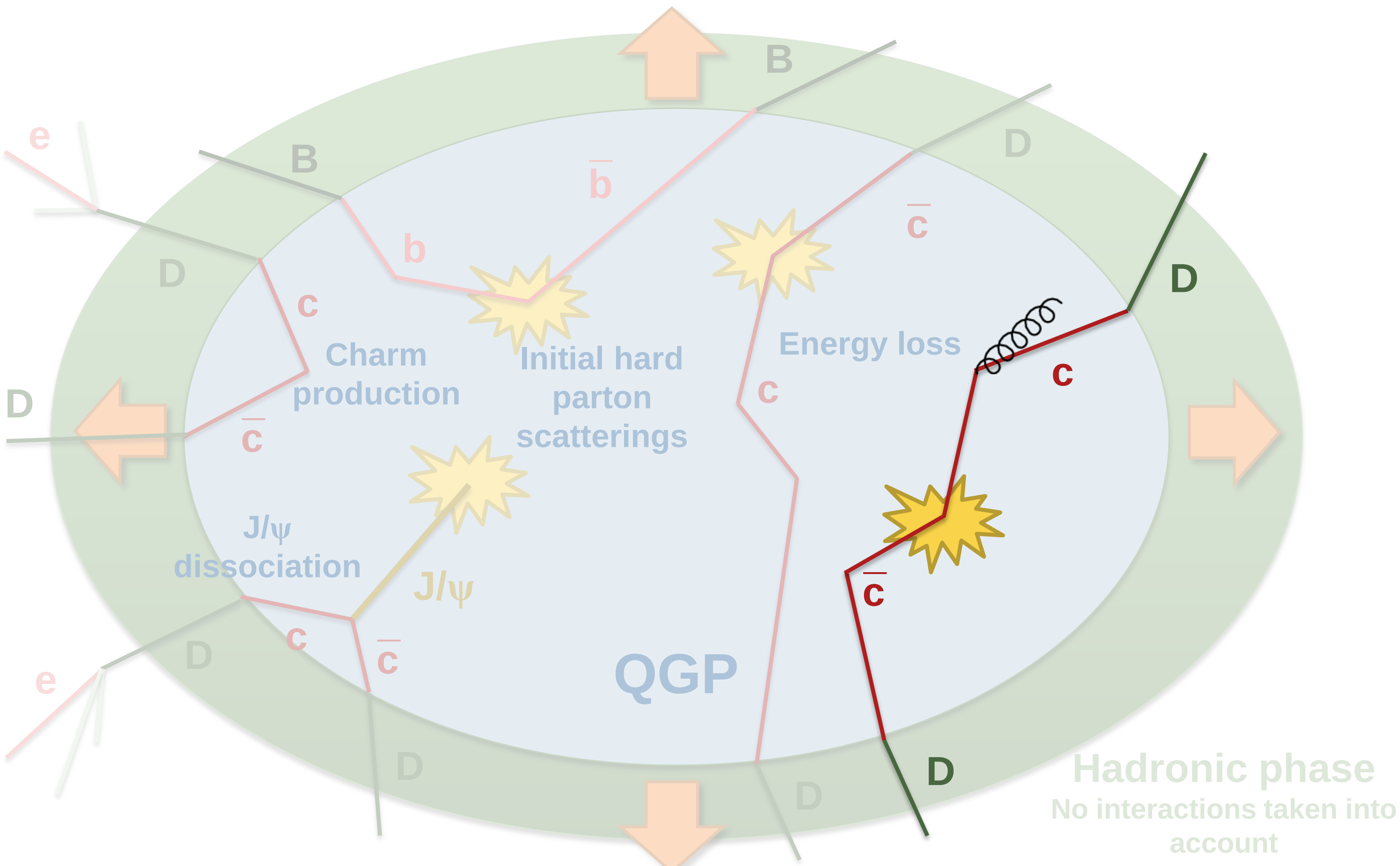
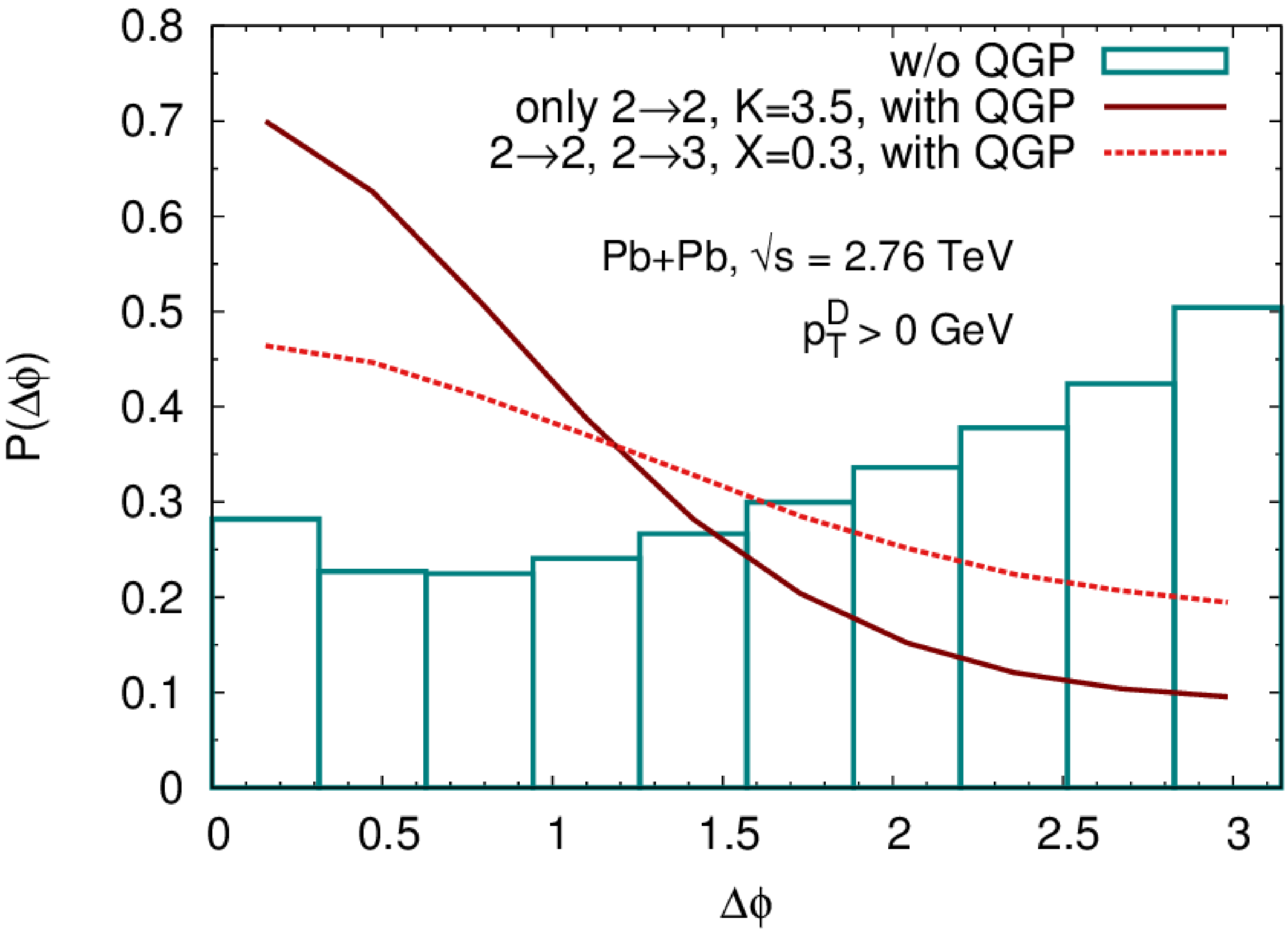


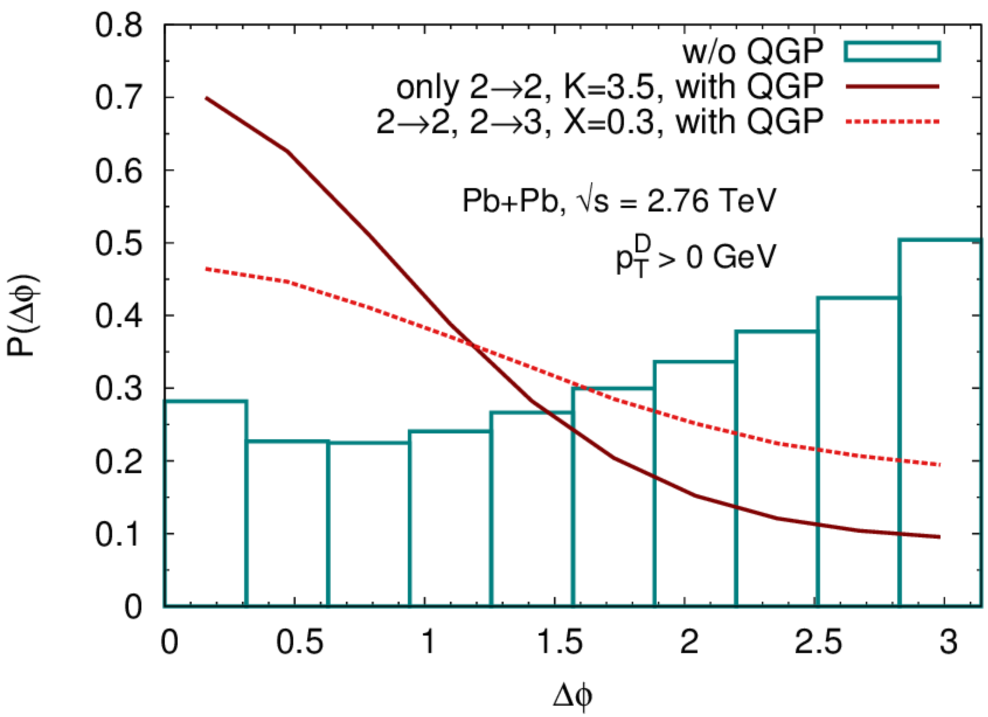
Sketch of heavy flavor in HIC

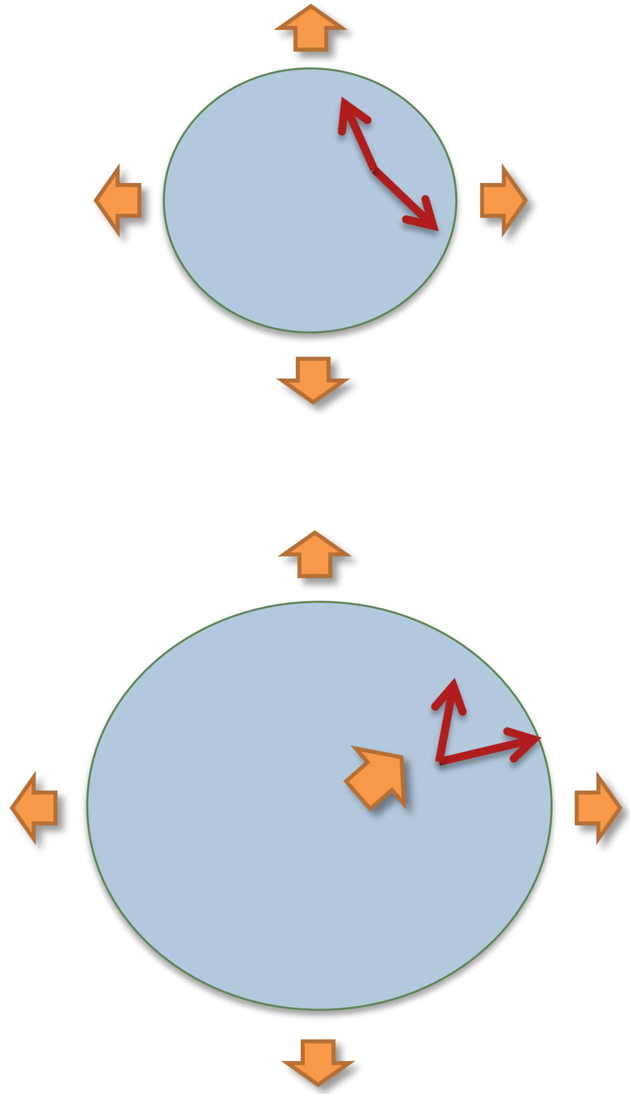


D meson angle correlations

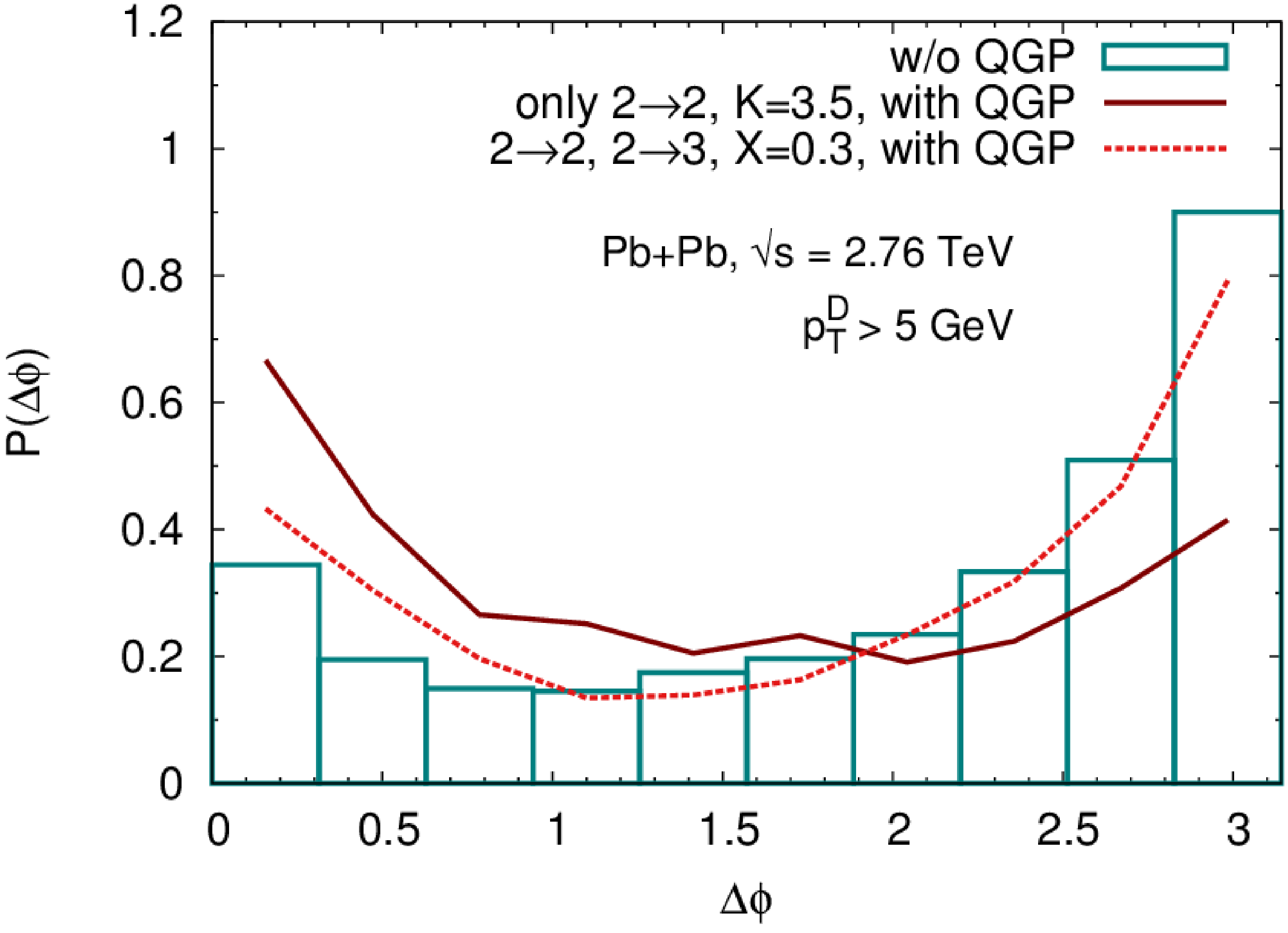


D meson angle correlations



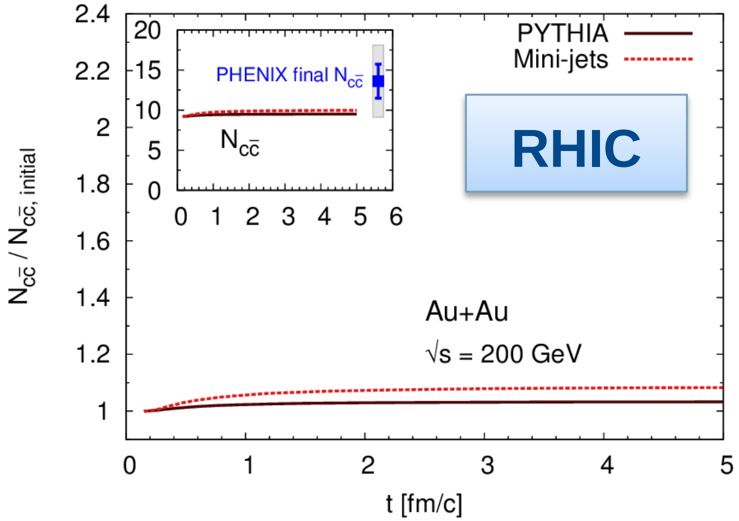


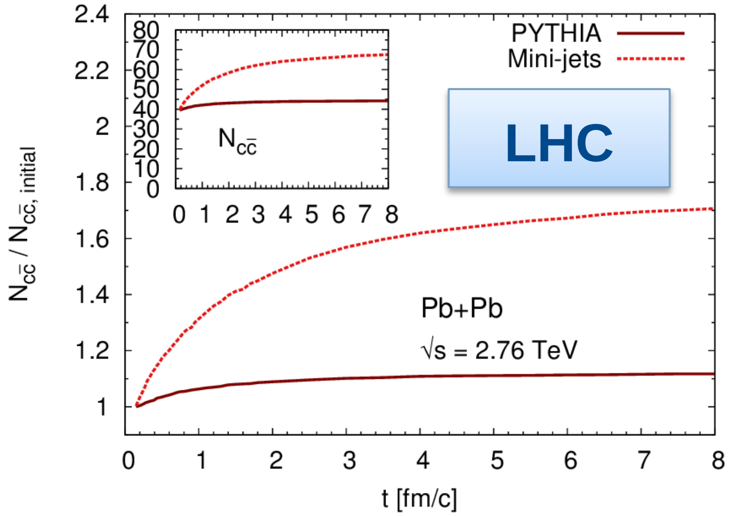
D meson angle correlations

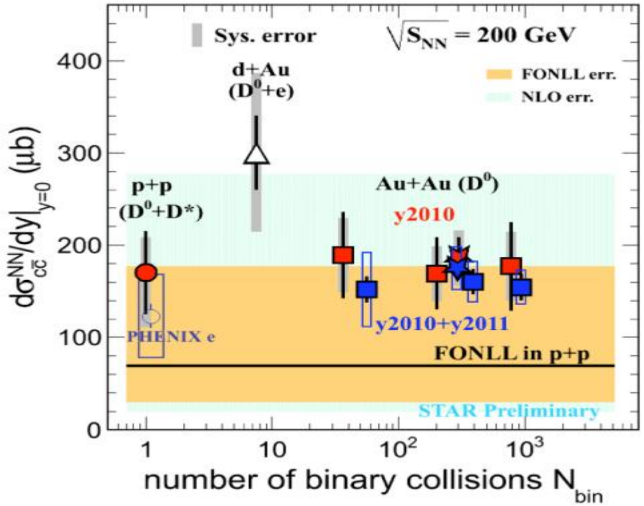


Total charm production

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





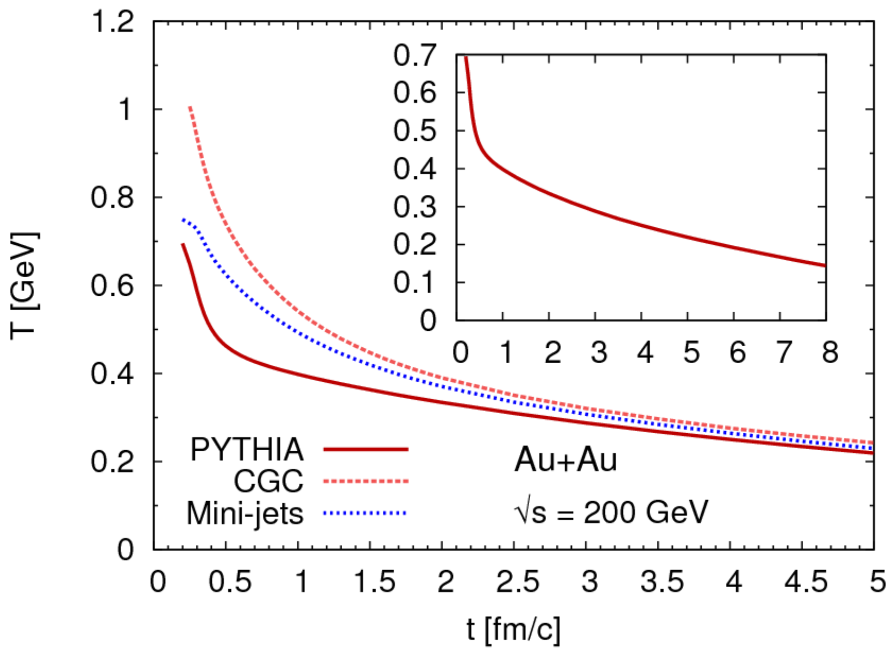


STAR, QM12

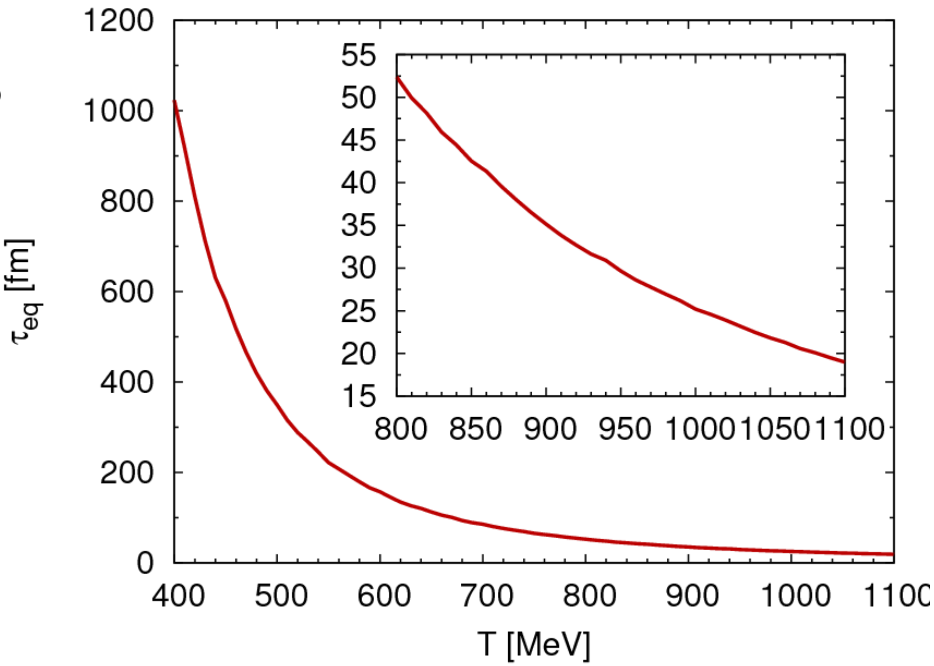
Sizeable charm production in QGP at LHC

Experiment ?

Charm production in the QGP at RHIC

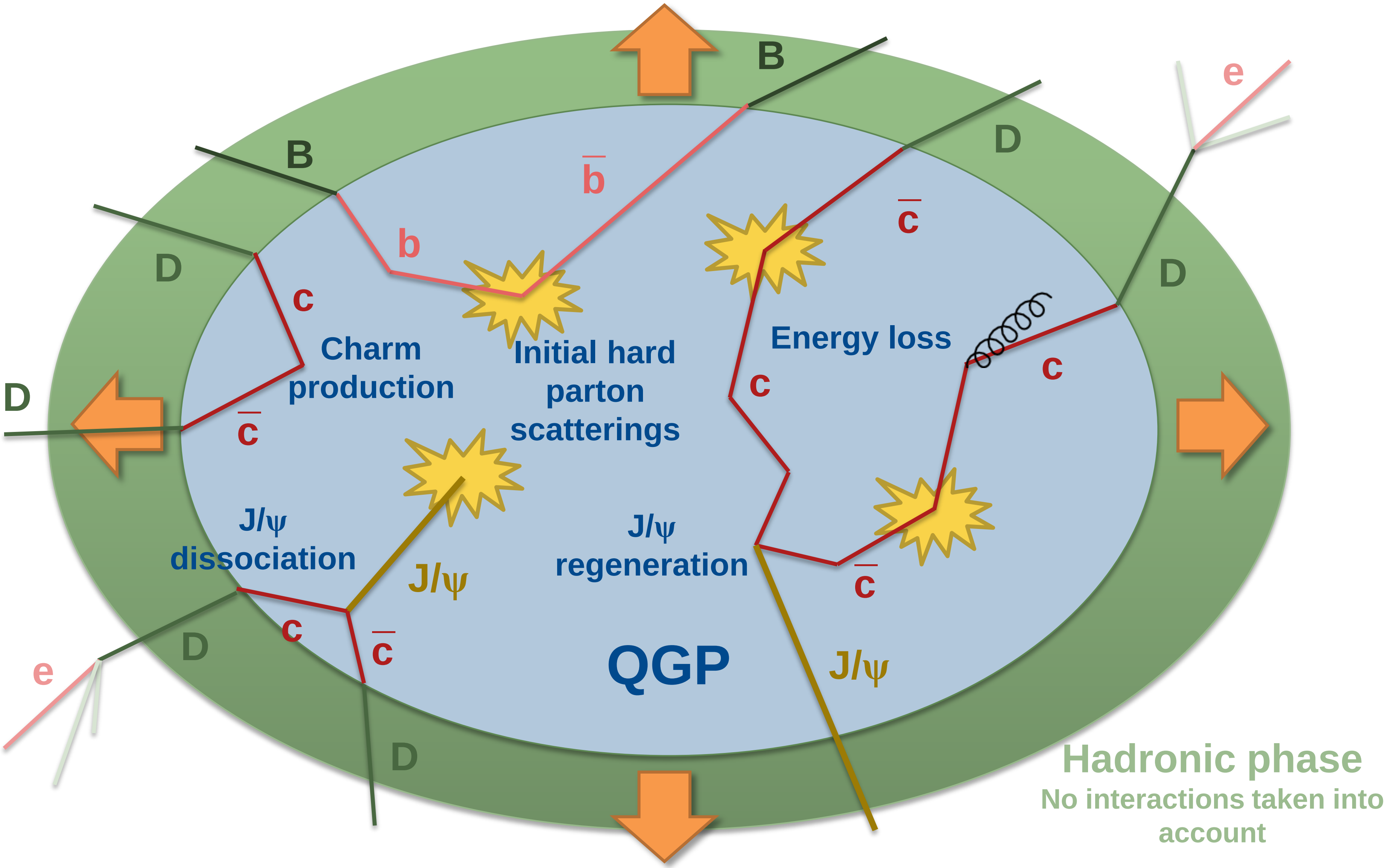


200 GeV

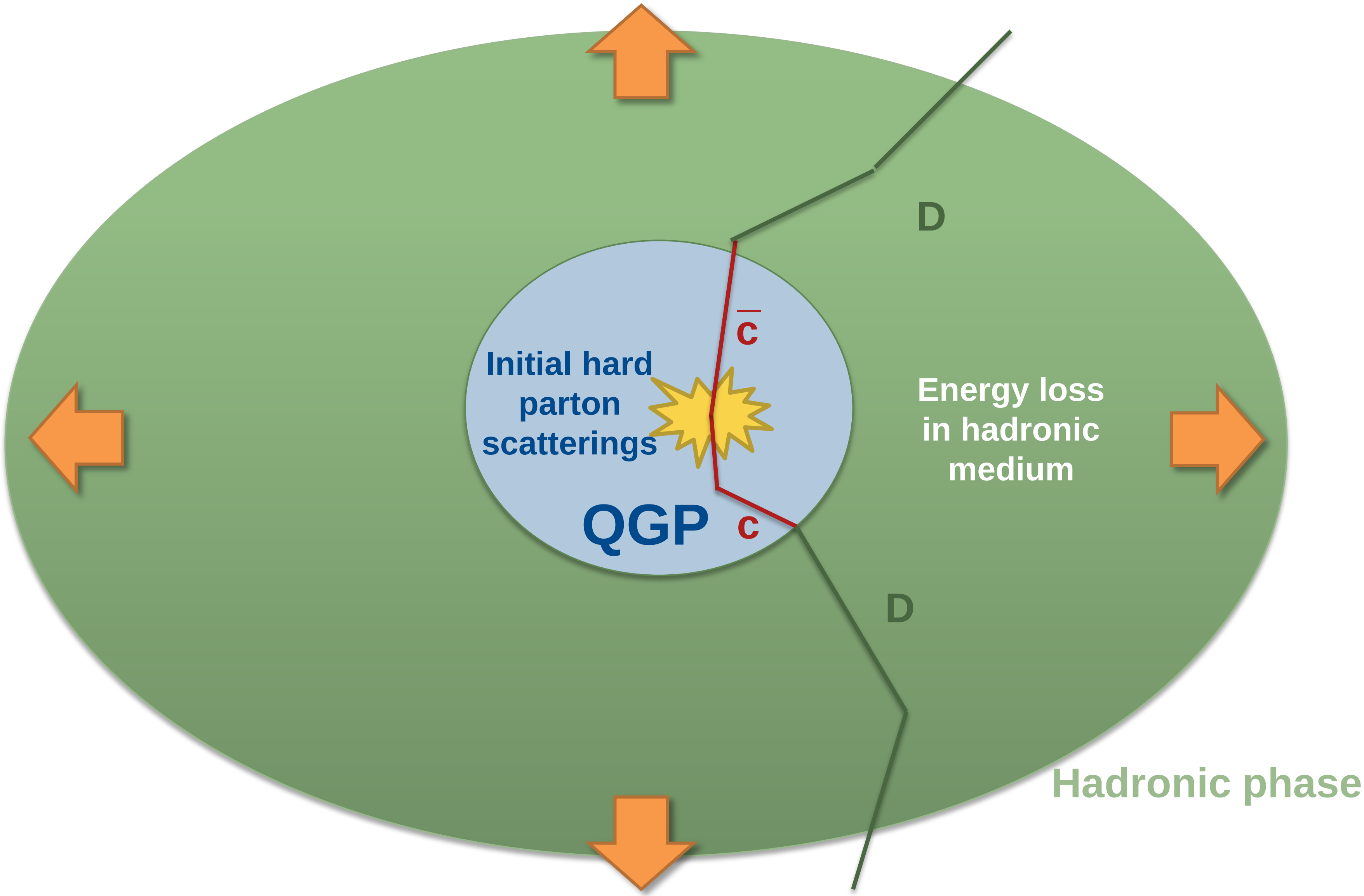


Application to FAIR physics

Sketch of heavy flavor at RHIC/LHC



Sketch of heavy flavor at FAIR



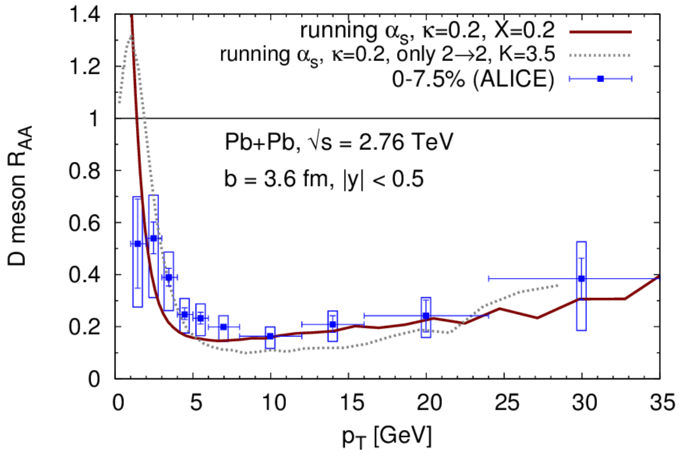
Some questions

- **What are the initial conditions?** Scaled p+p? CNM?
  - All partons → PYTHIA?
  - Charm quarks → MC@NLO? PYTHIA?
- **Is BAMPS applicable?**
  - Is there a QGP?
  - Does the major contribution comes from energy loss in QGP?
  - Are radiative or elastic processes more important? Or even other processes?
- **Is there secondary charm production?** → no
- **What about correlations?** → very promising (~ one pair, mostly back-to-back)

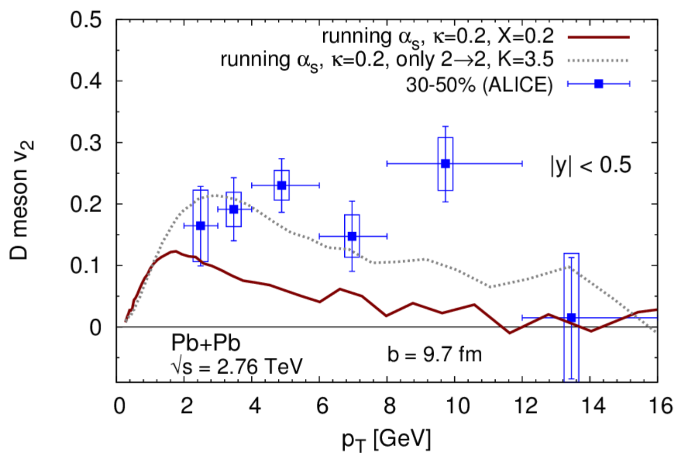
Conclusions

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

- **Radiative and binary collisions:**
  - Sensitivity on LPM implementation
  - R_{AA} and v_2 simultaneously seems difficult
  - Correlations can shed light on radiative processes



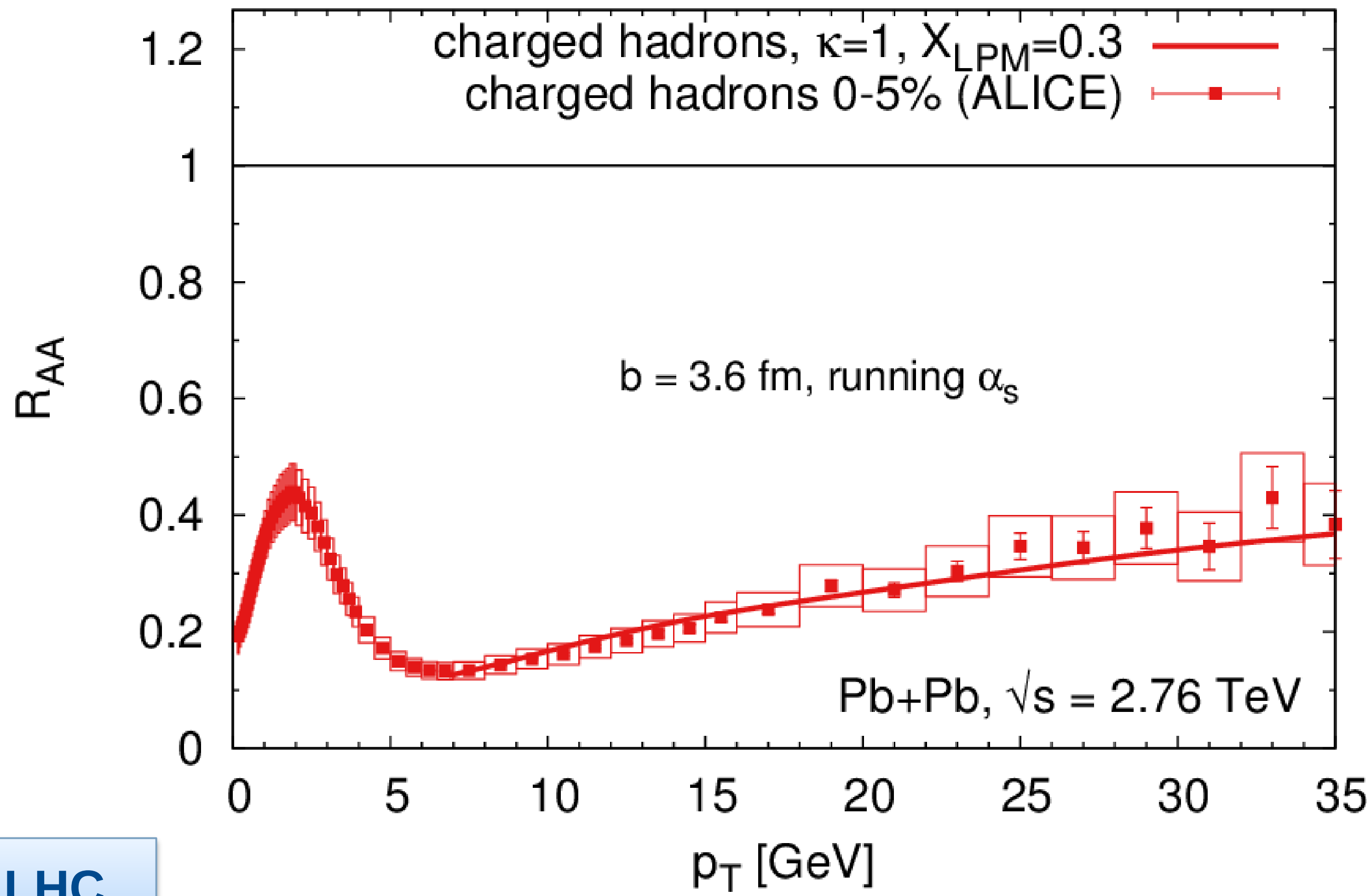
- **Heavy flavor at FAIR:**
  - BAMPS difficult to apply
  - p+p reference important
  - Heavy flavor correlations promising



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

Thank you for your attention.

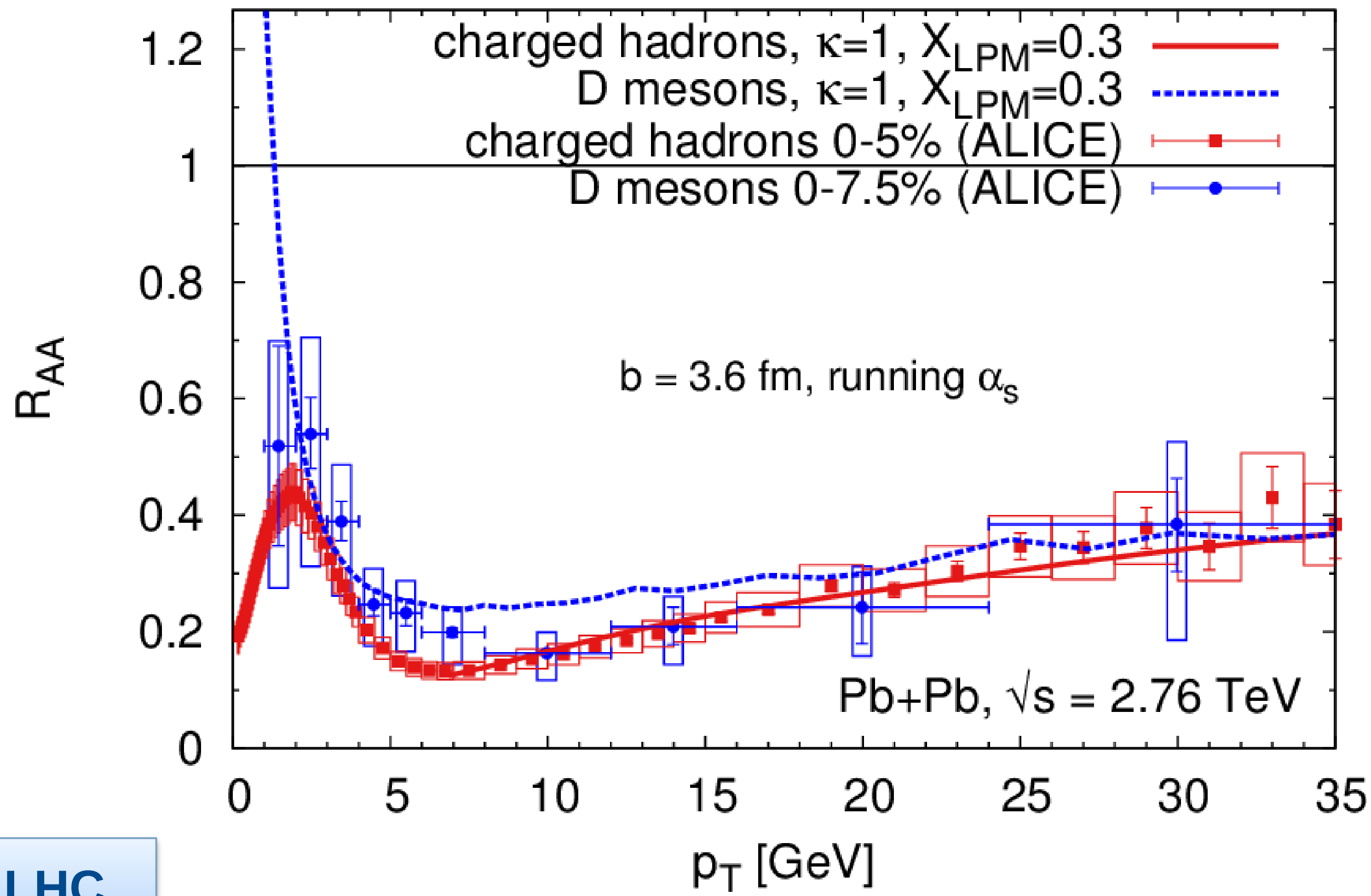
Heavy flavor and charged hadron R_{AA} at LHC



LHC

for more BAMPS results on light particles
see talk by Florian Senzel, Monday 5:30 pm, europium

Heavy flavor and charged hadron R_{AA} at LHC



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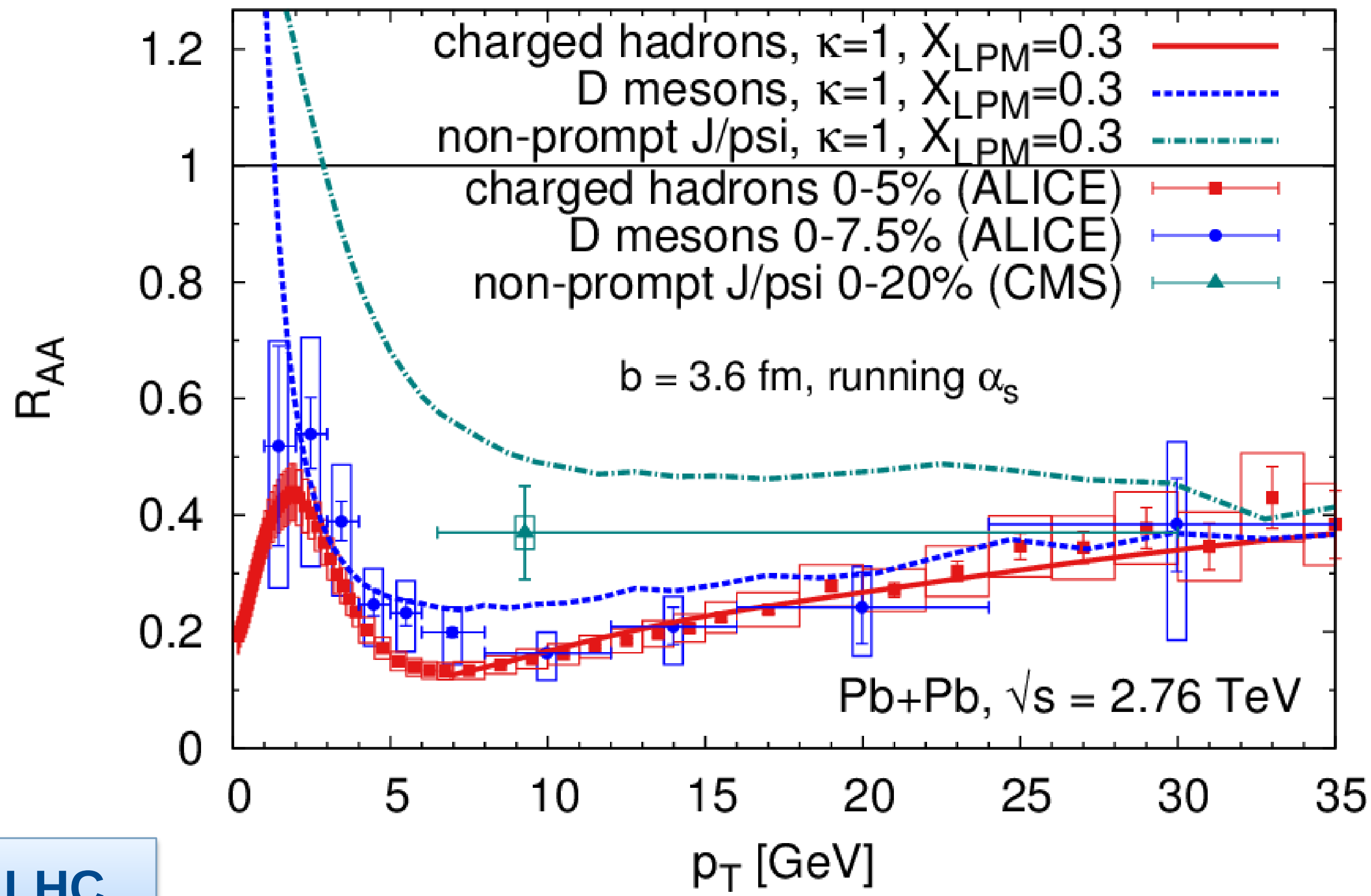

LHC

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Heavy quark v_2 and R_{AA} at RHIC

RHIC

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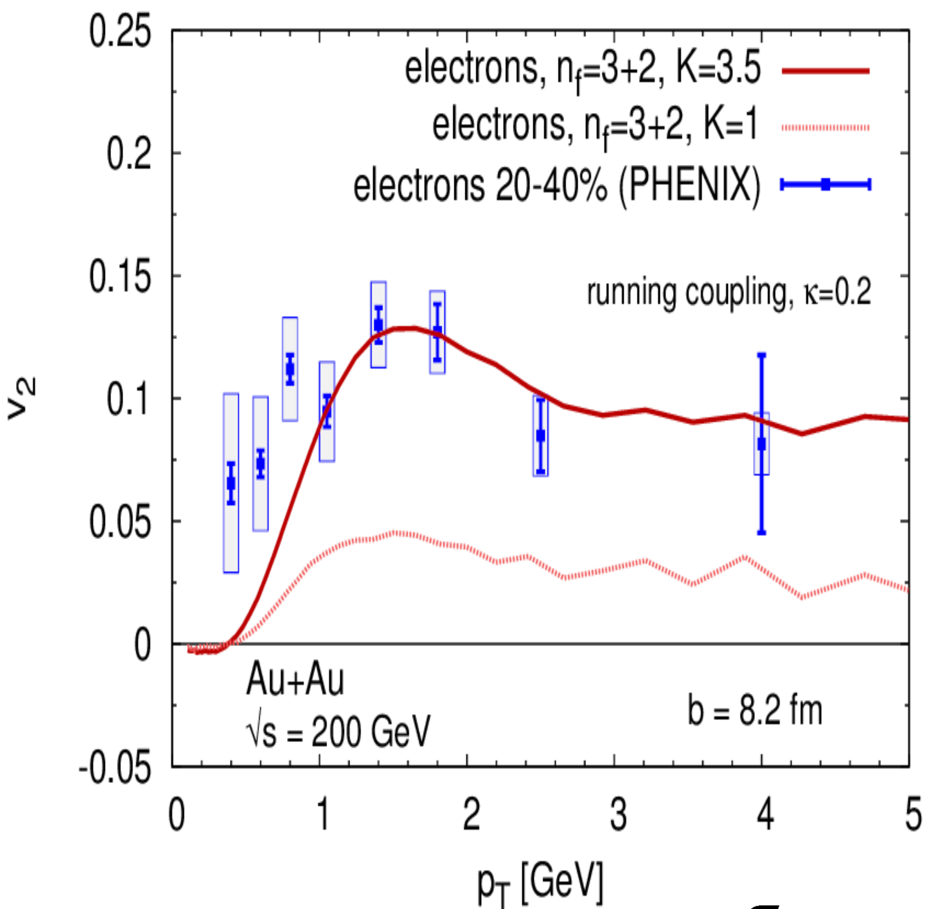
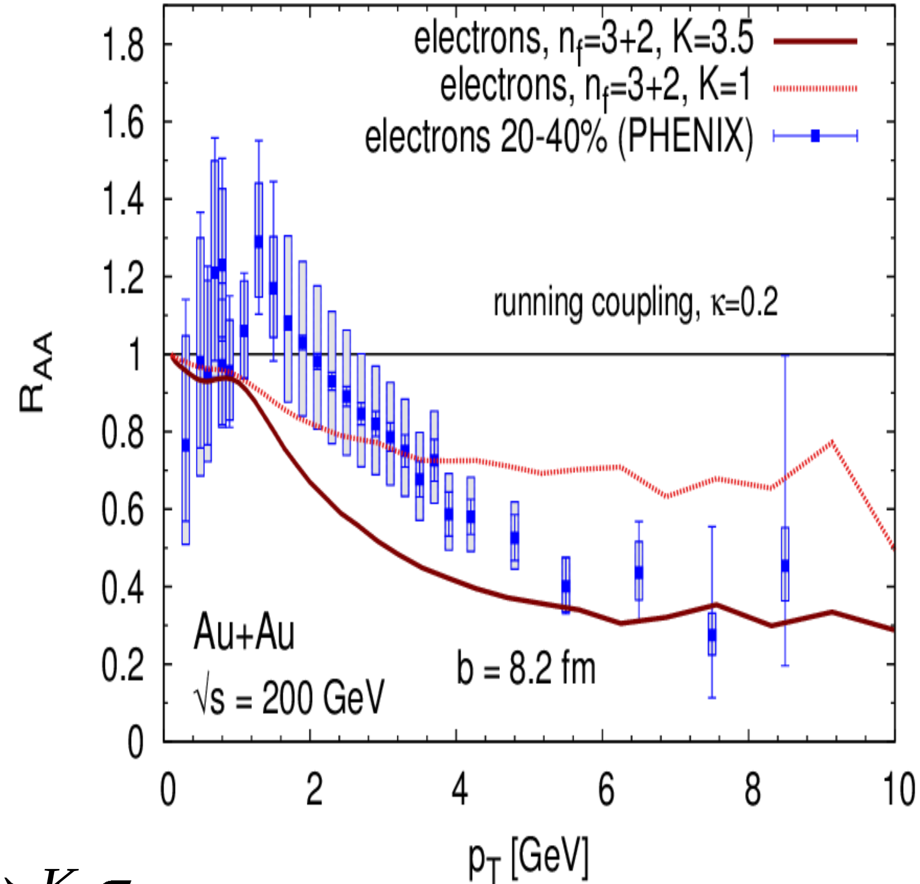




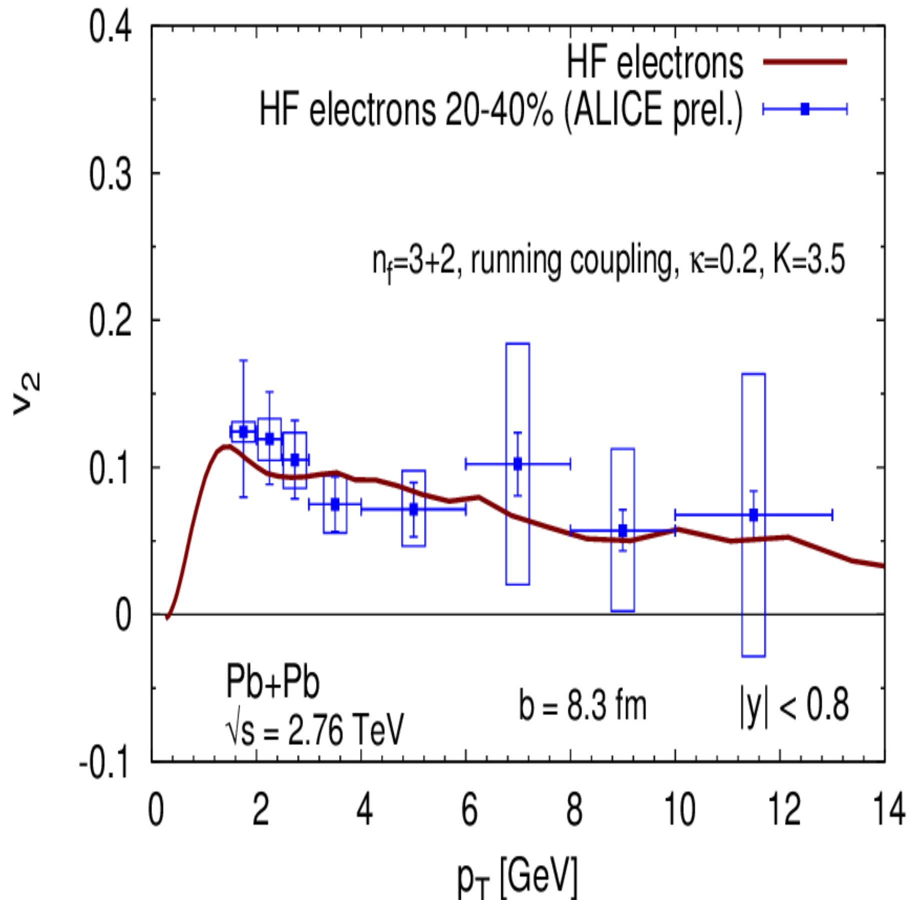
$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

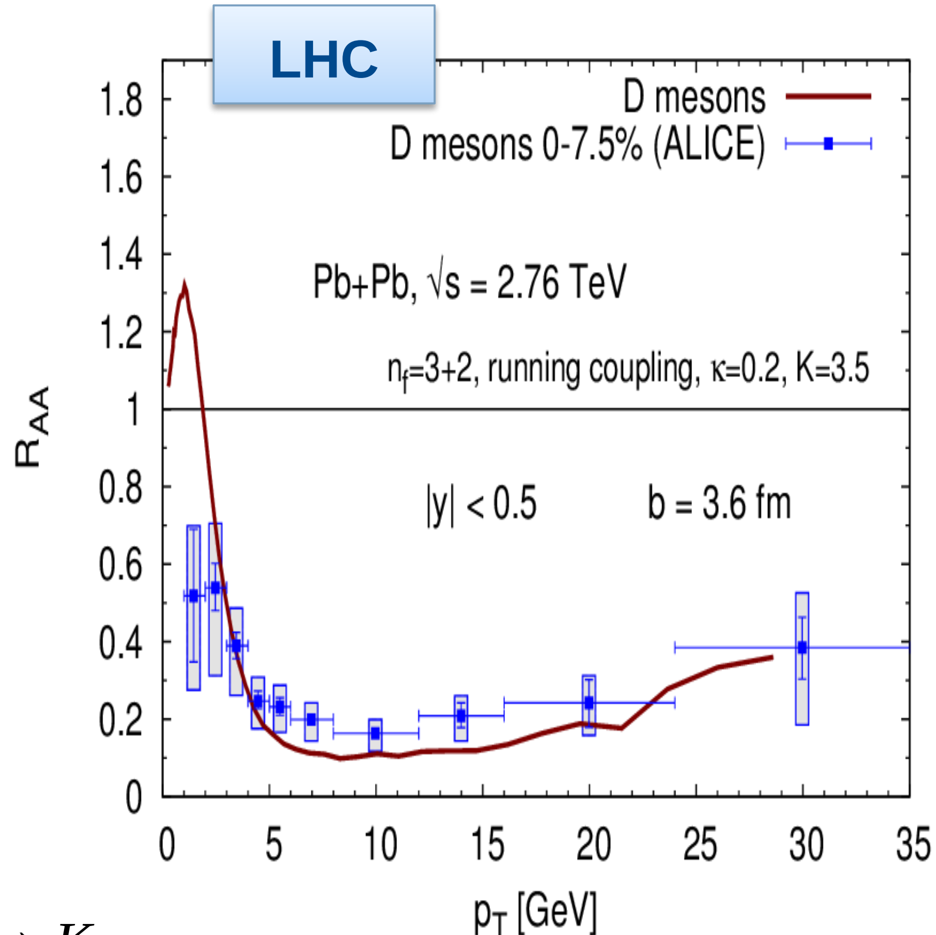
only elastic heavy quark processes

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





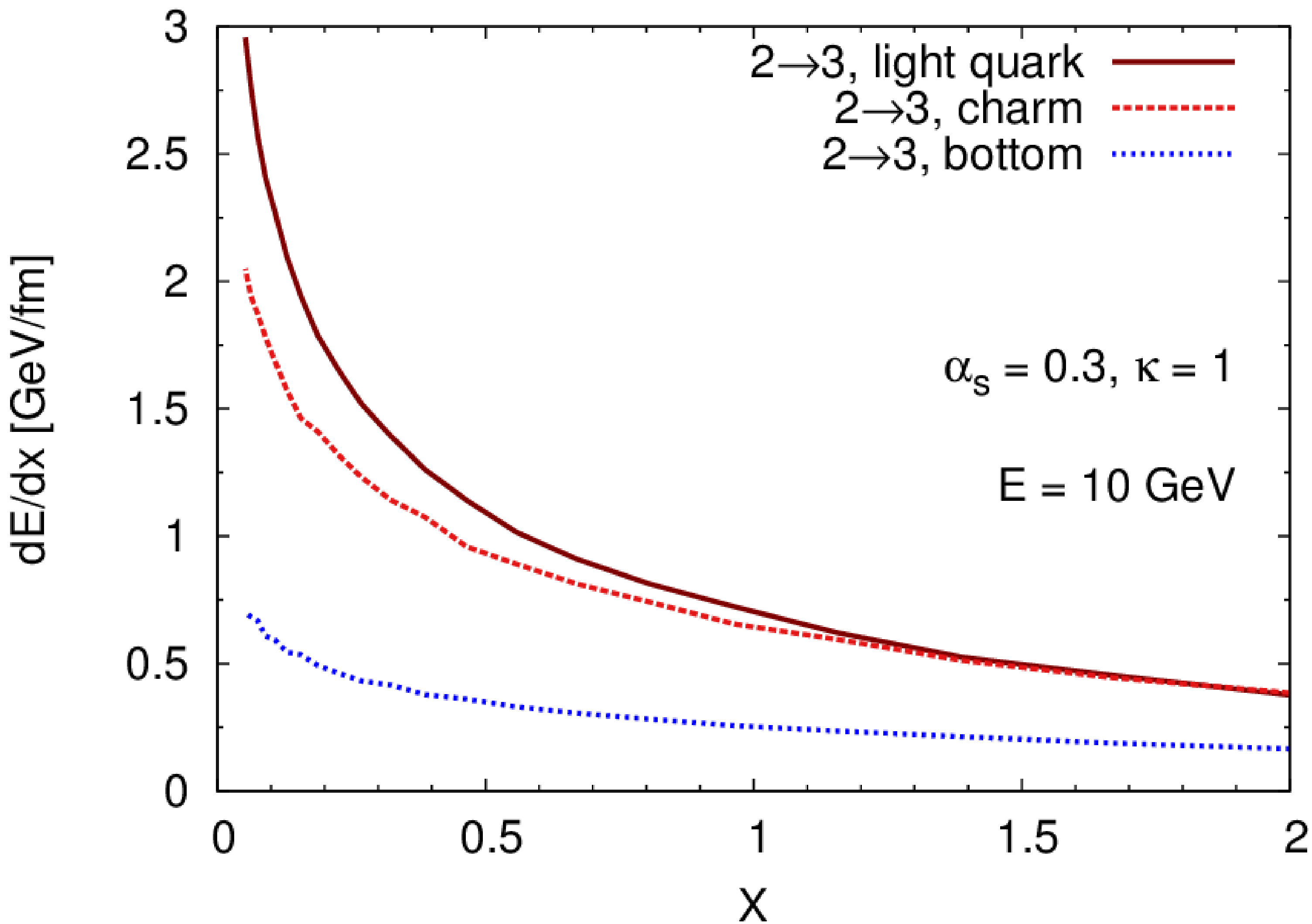
$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

only elastic heavy quark processes

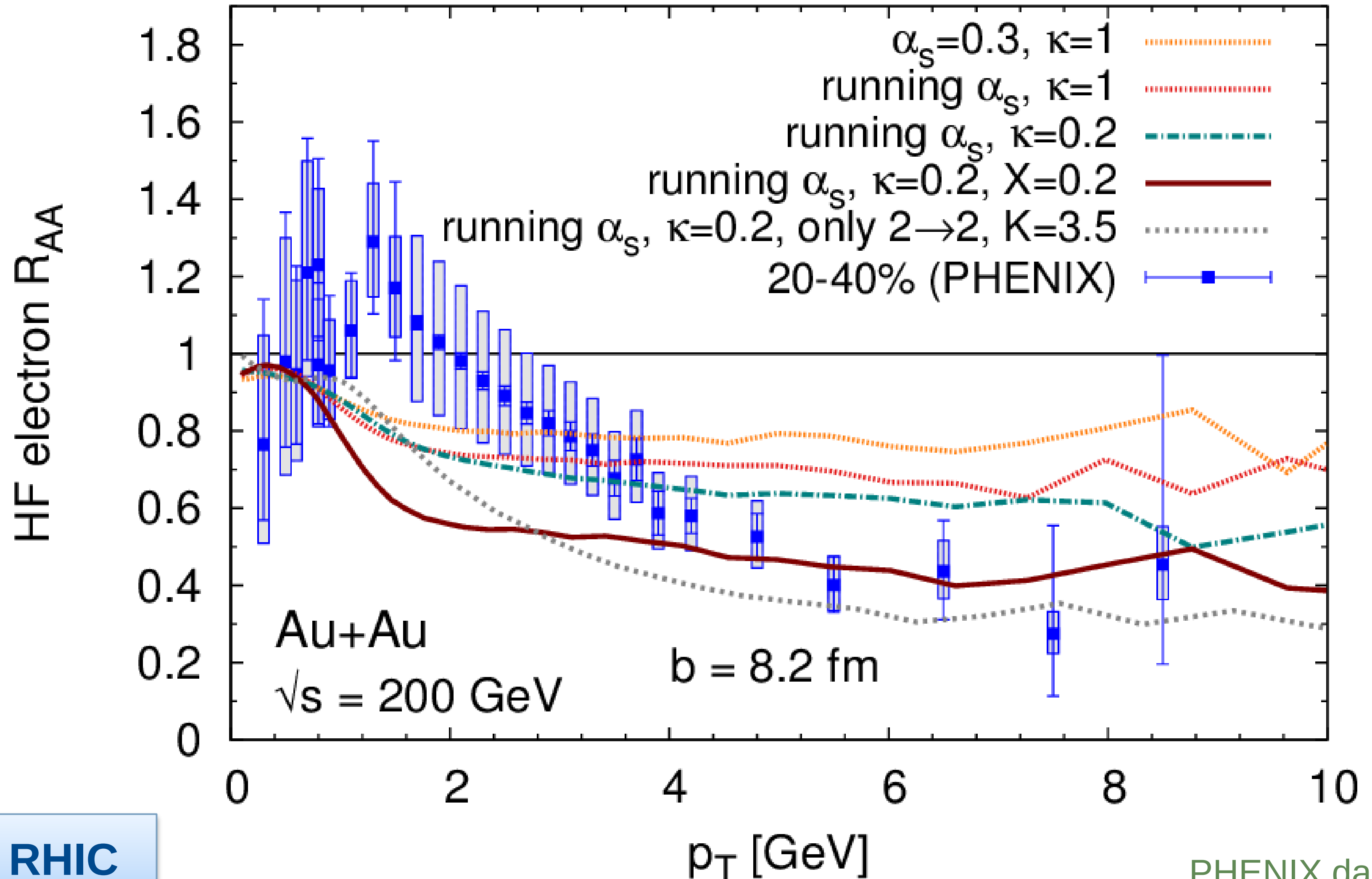
JU, Fochler, Xu, Greiner
Phys. Lett. B 717 (2012)

ALICE data, QM12

LPM: X dependence



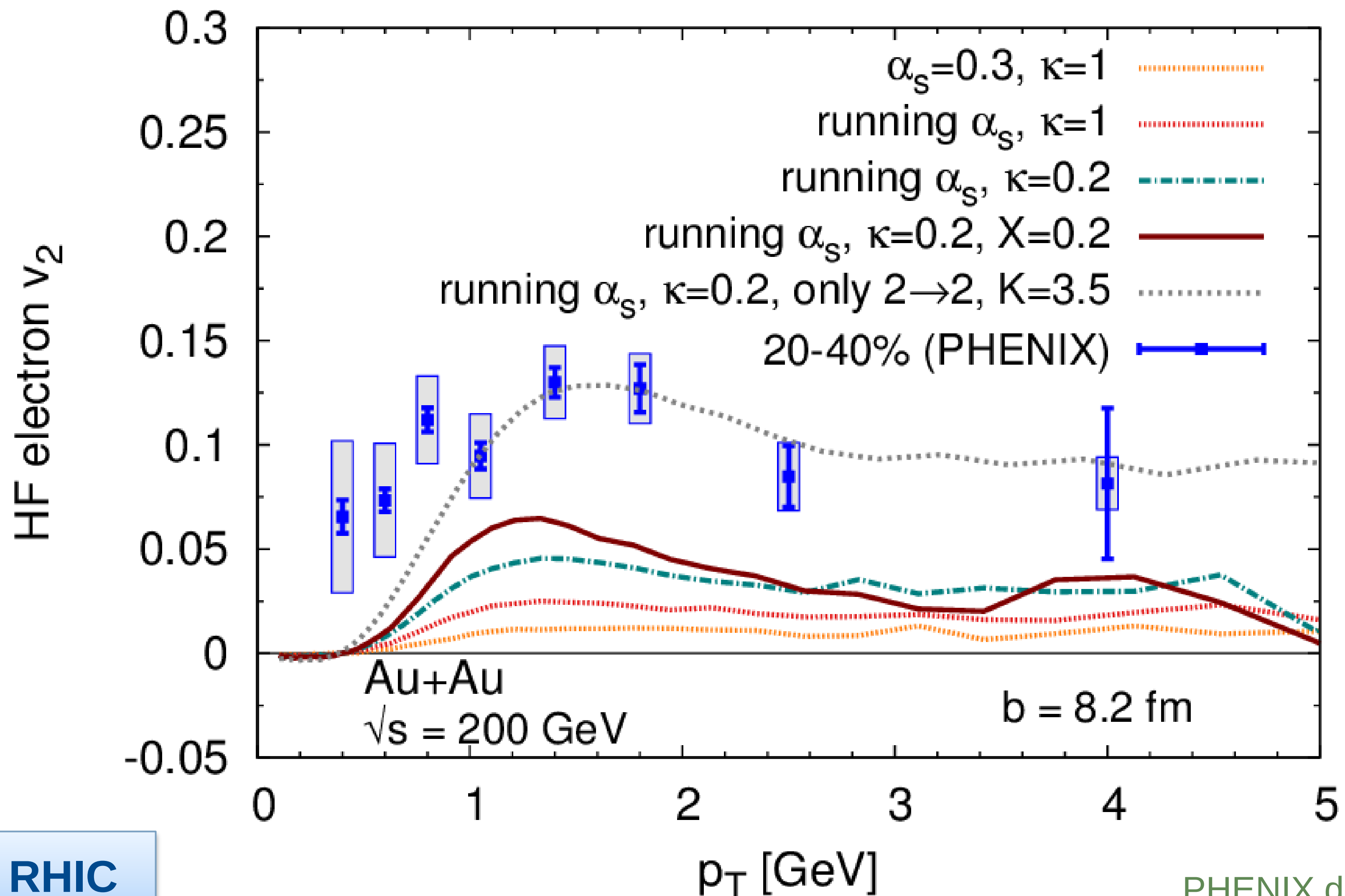
Heavy quark R_{AA} at RHIC



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

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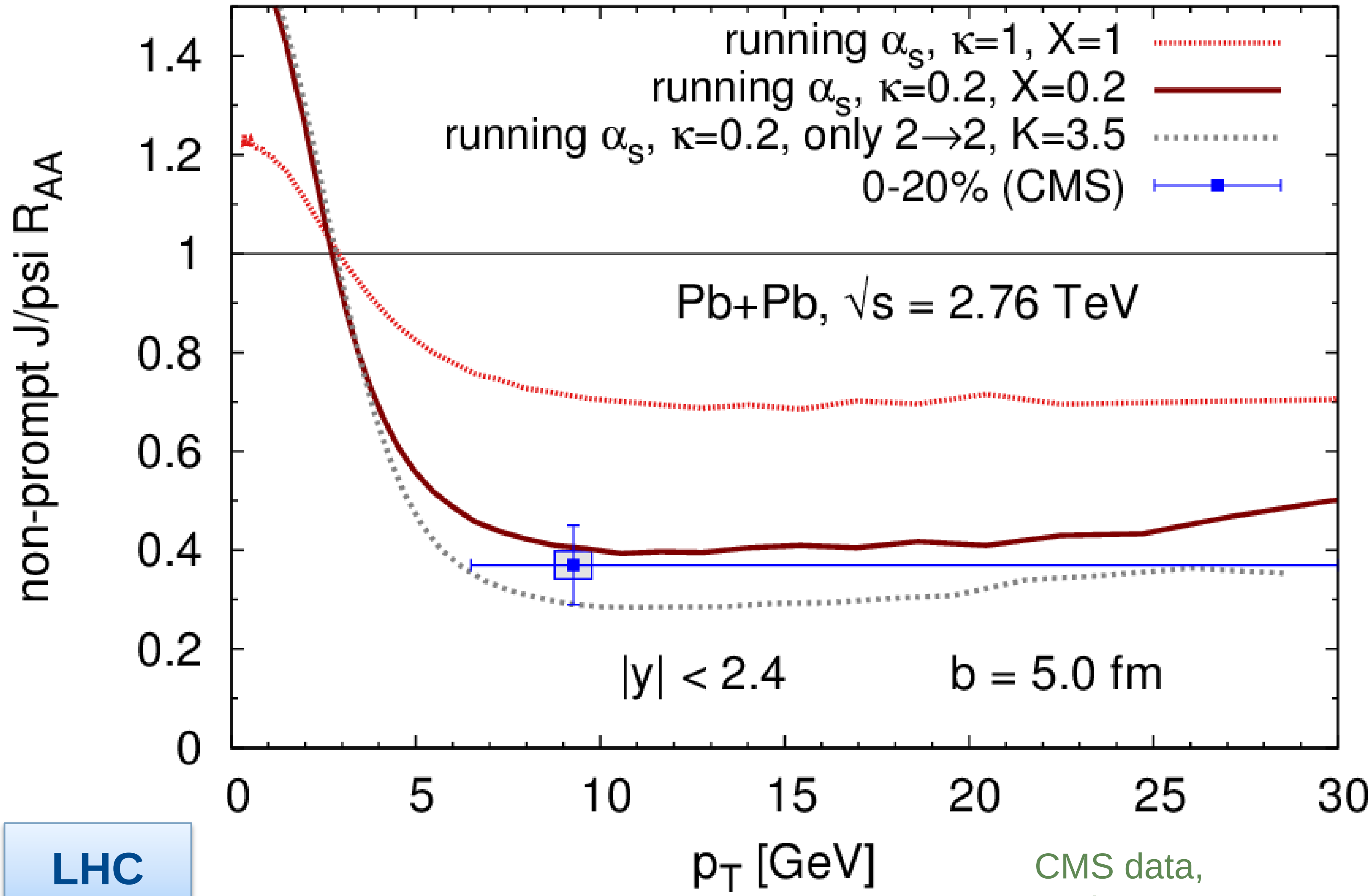
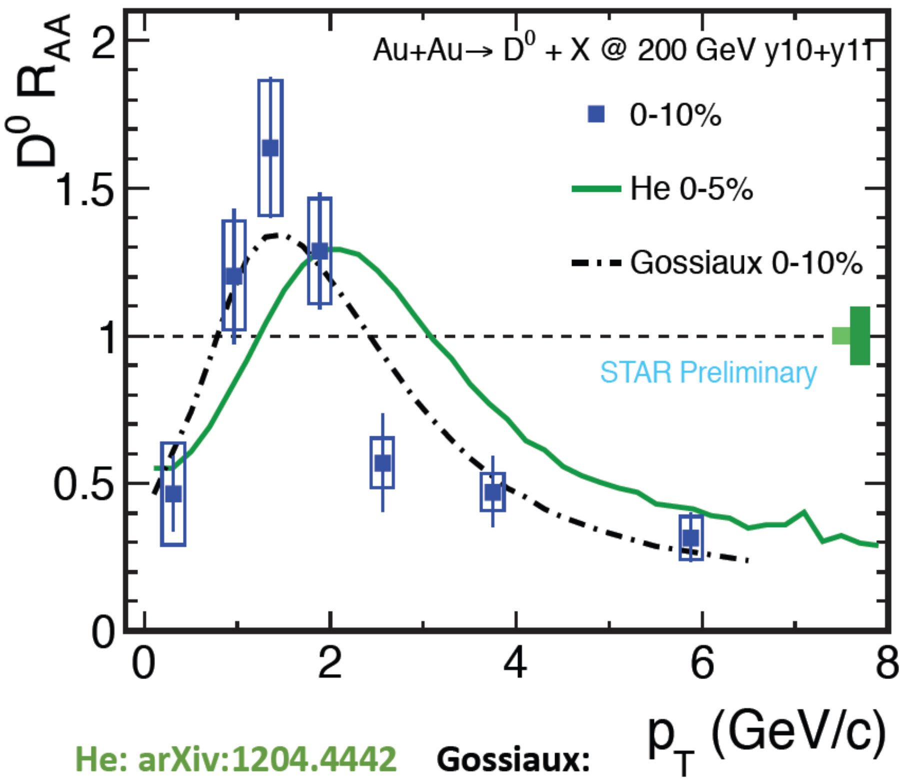


LHC

CMS data, arXiv:1201.5069

D meson R_{AA} from STAR

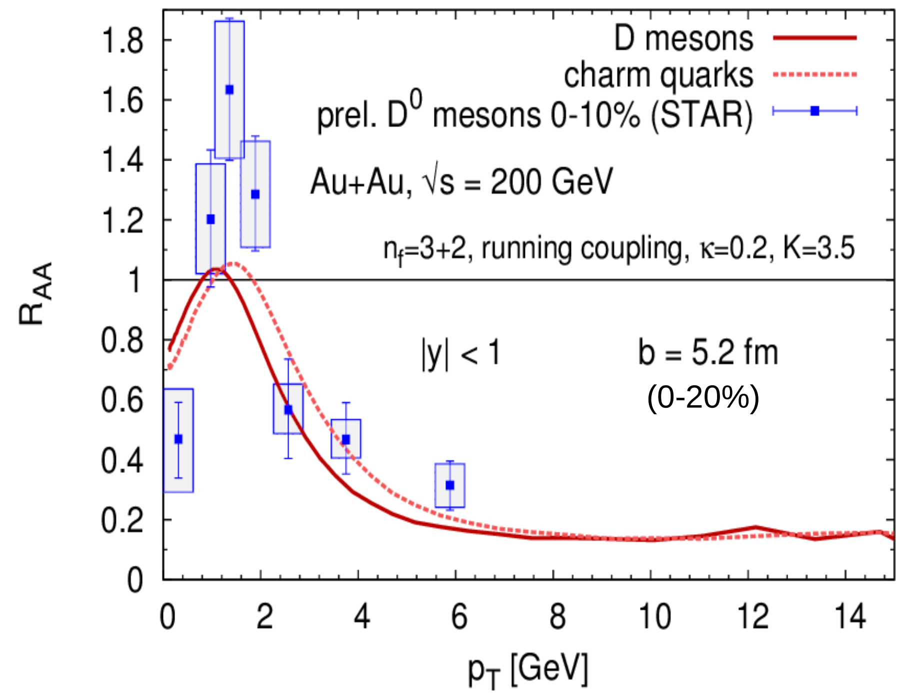


He: arXiv:1204.4442
Focker-Planck
Resonance
recombination

Gossiaux:
arXiv:1207.5445
Boltzmann
pQCD with running coupling

STAR data, QM 2012

RHIC



JU, Fochler, Xu, Greiner

Fragmentation and Decay

- **Peterson fragmentation**

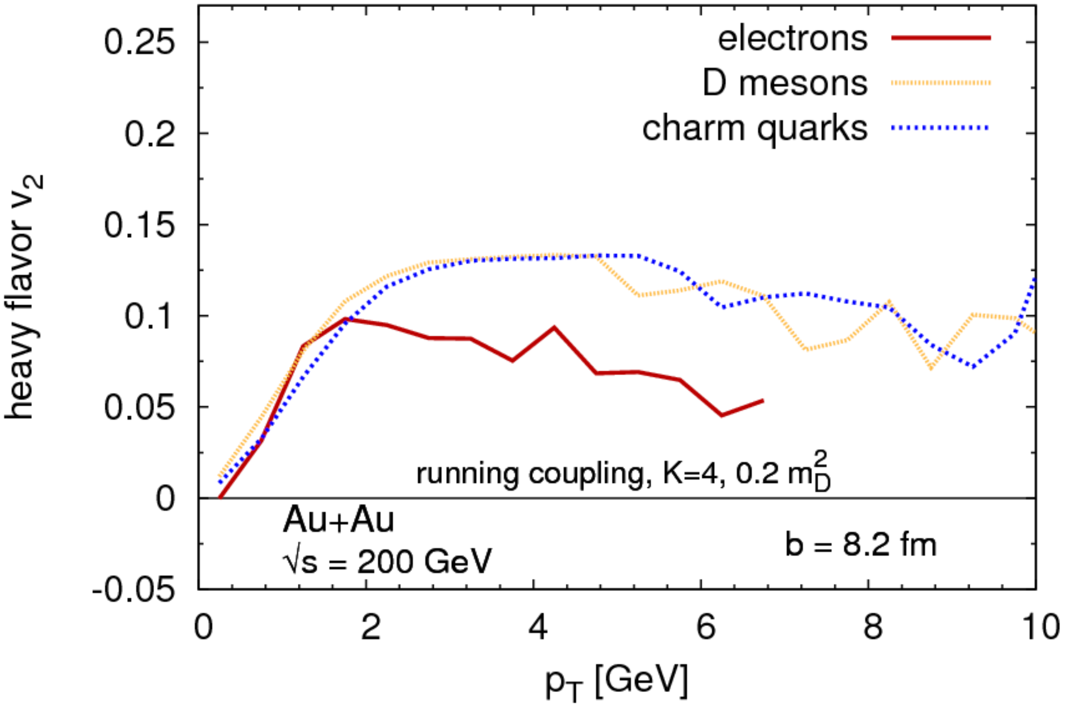
Peterson et al., Phys. Rev. D27 (1983)

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

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

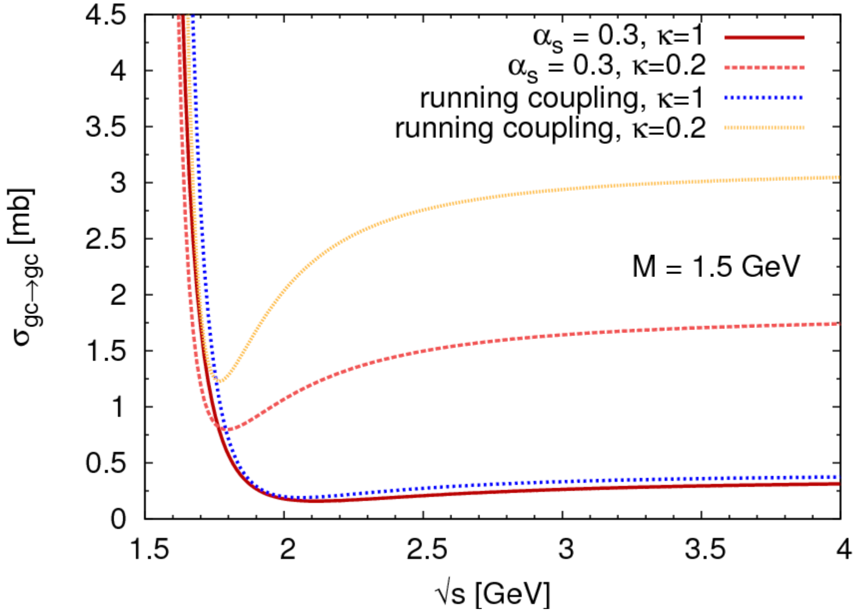
$$\epsilon_c = 0.05$$
$$\epsilon_b = 0.005$$

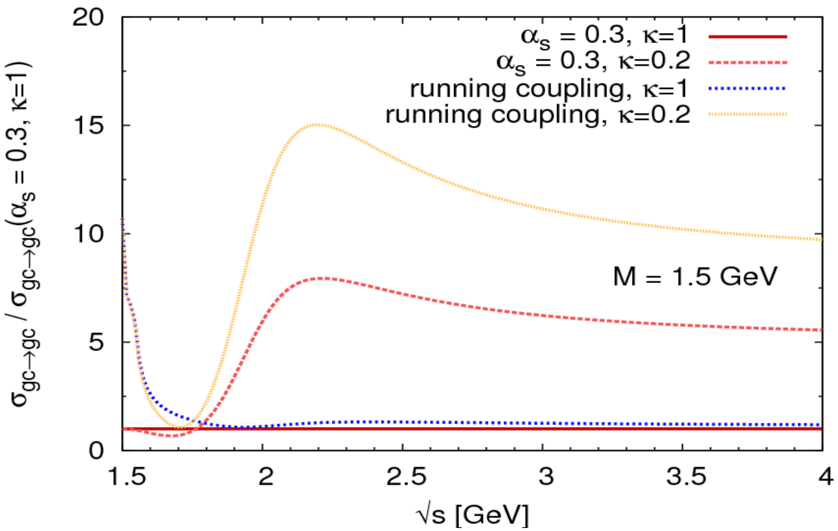
- **Decay to electrons with PYTHIA**

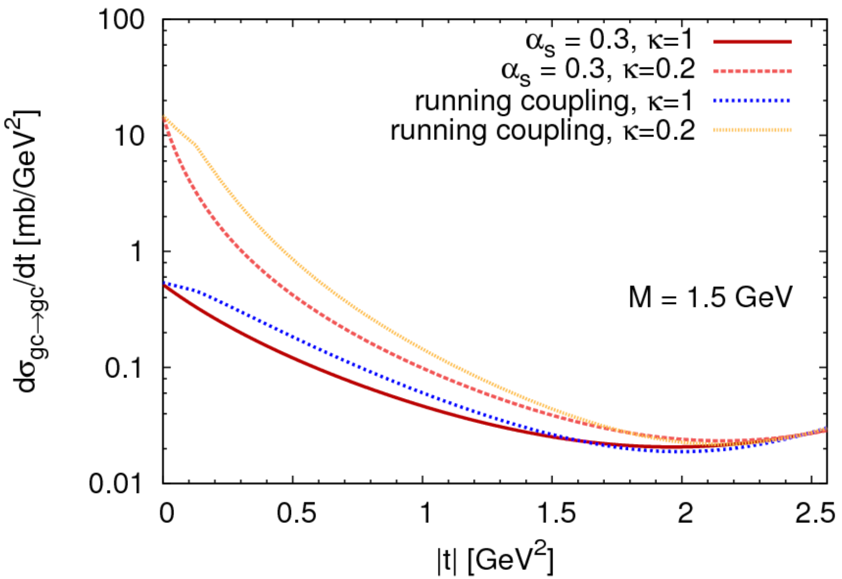


Impact of hadronization and decay small

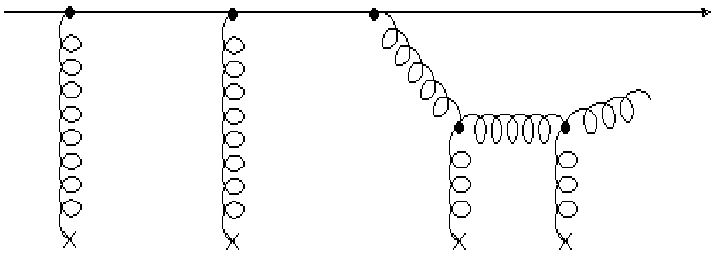
Heavy quark scattering cross section







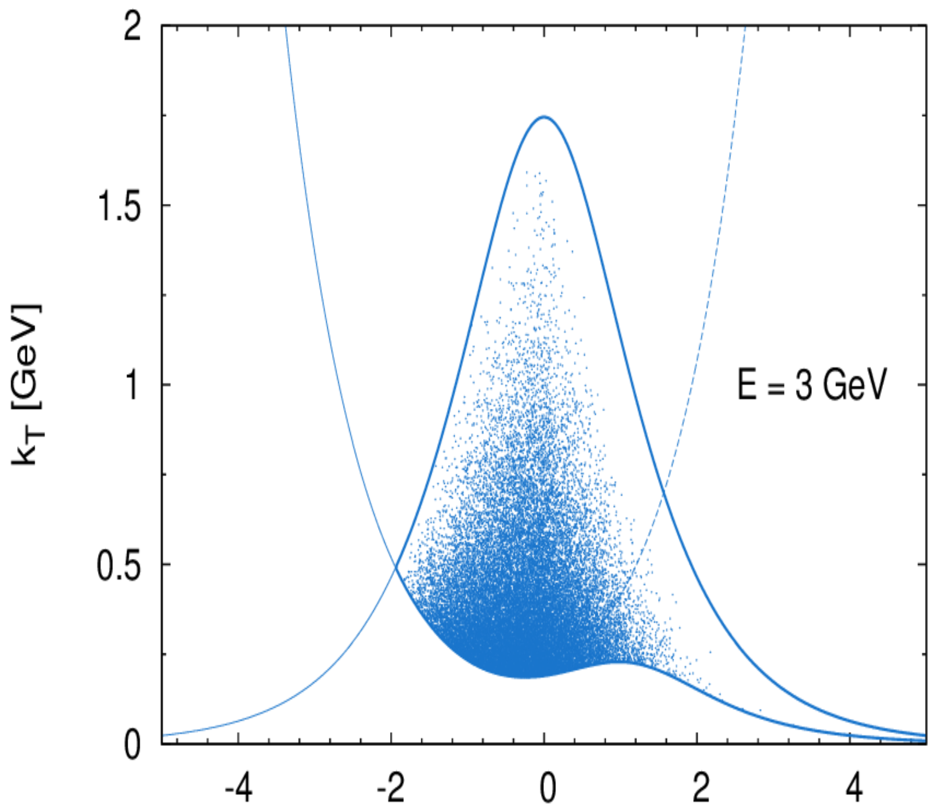
LPM effect vs. dead cone effect



$$\lambda > \tau$$

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

➡ Independent scatterings



backward emission

forward emission

Momentum imbalance A_D

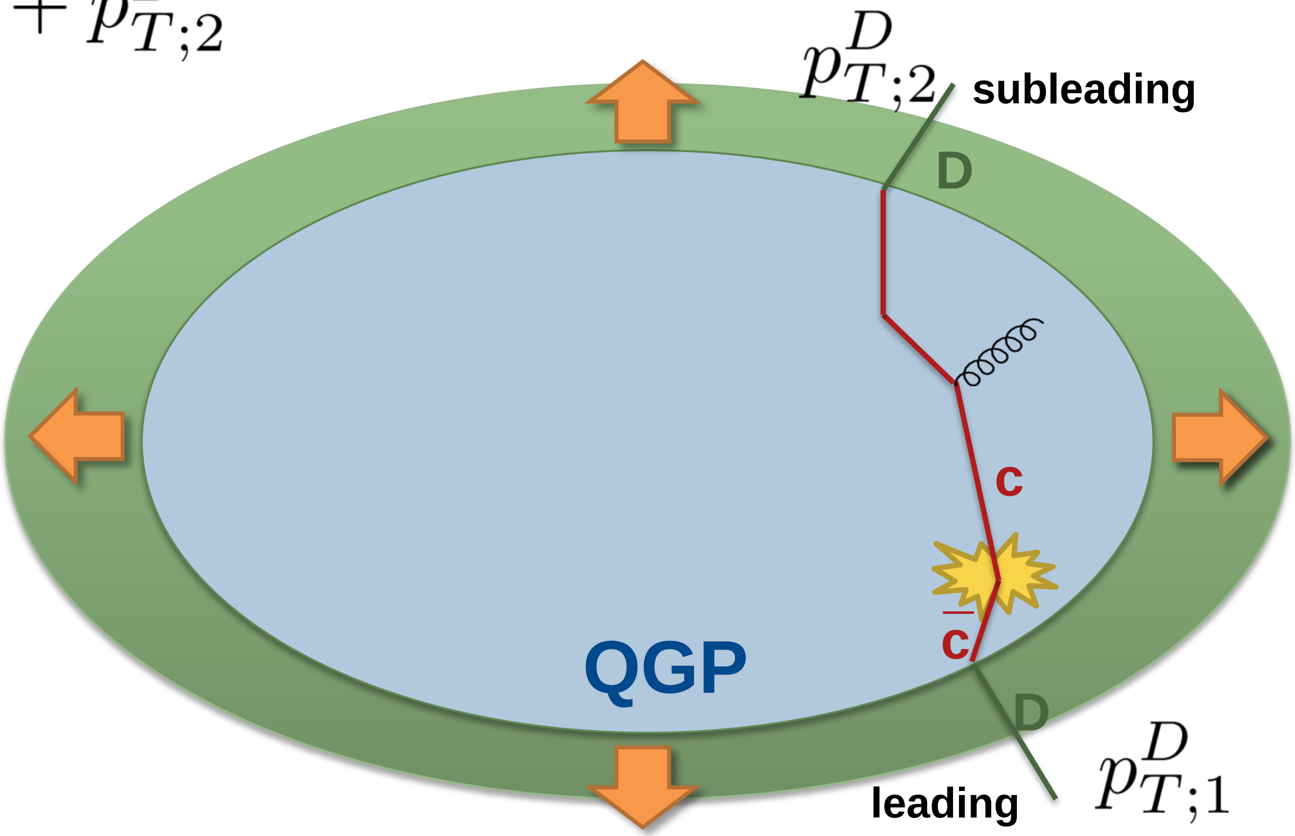
D meson momentum imbalance

$$A_D = \frac{p^D_{T;1} - p^D_{T;2}}{p^D_{T;1} + p^D_{T;2}}$$

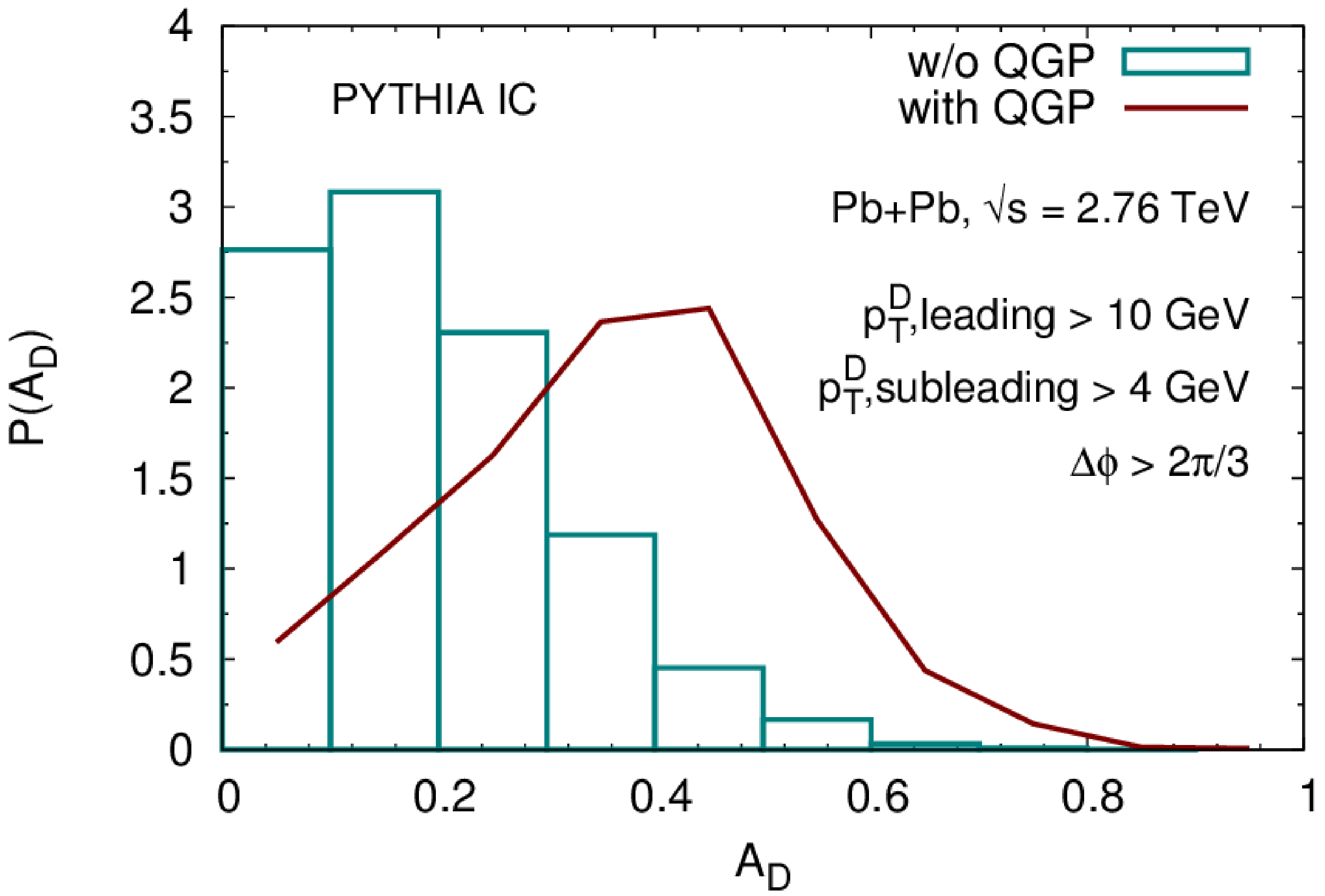
Analogous to

$$A_J = \frac{p^J_{T;1} - p^J_{T;2}}{p^J_{T;1} + p^J_{T;2}}$$

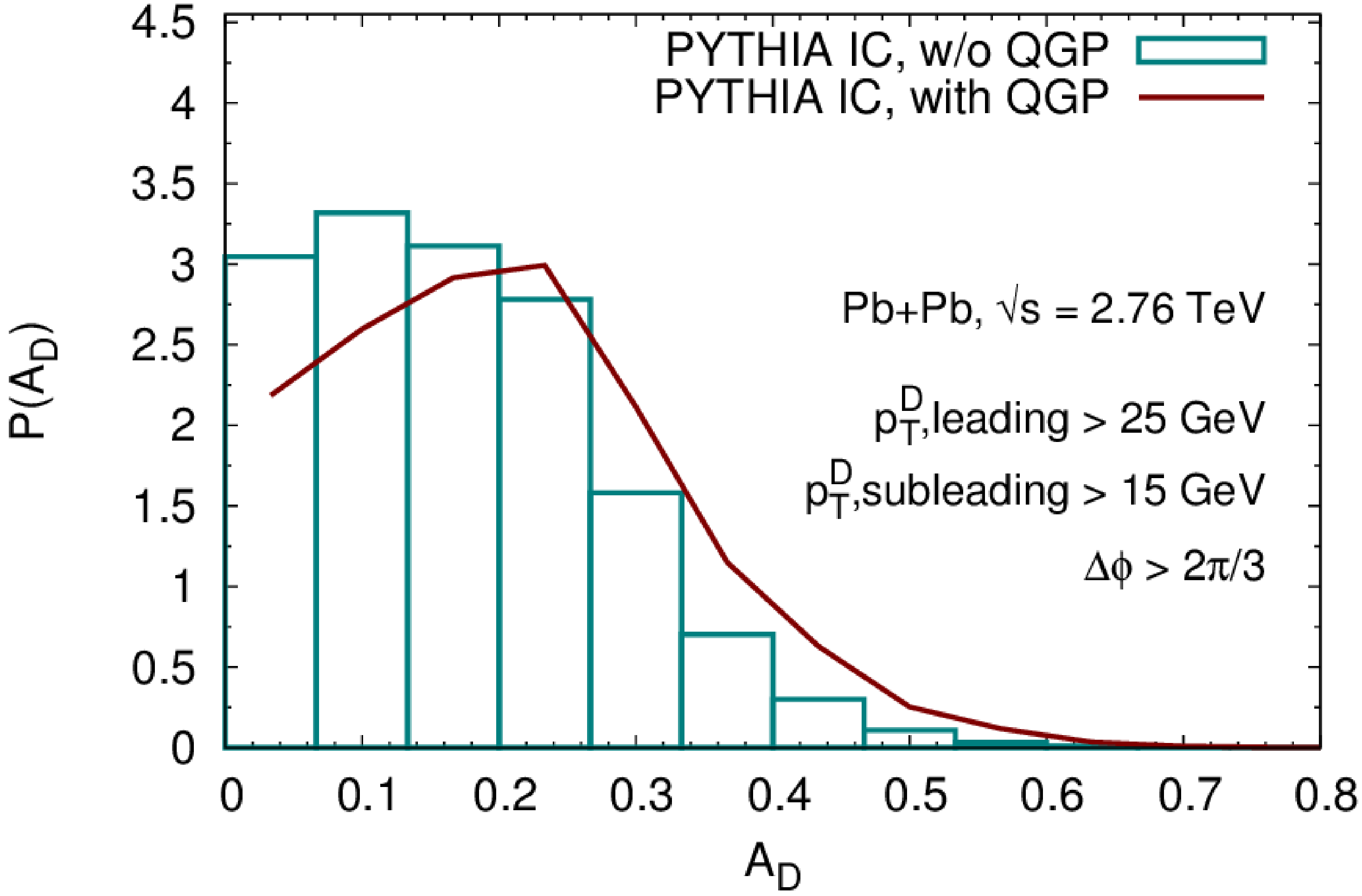
No jet reconstruction necessary



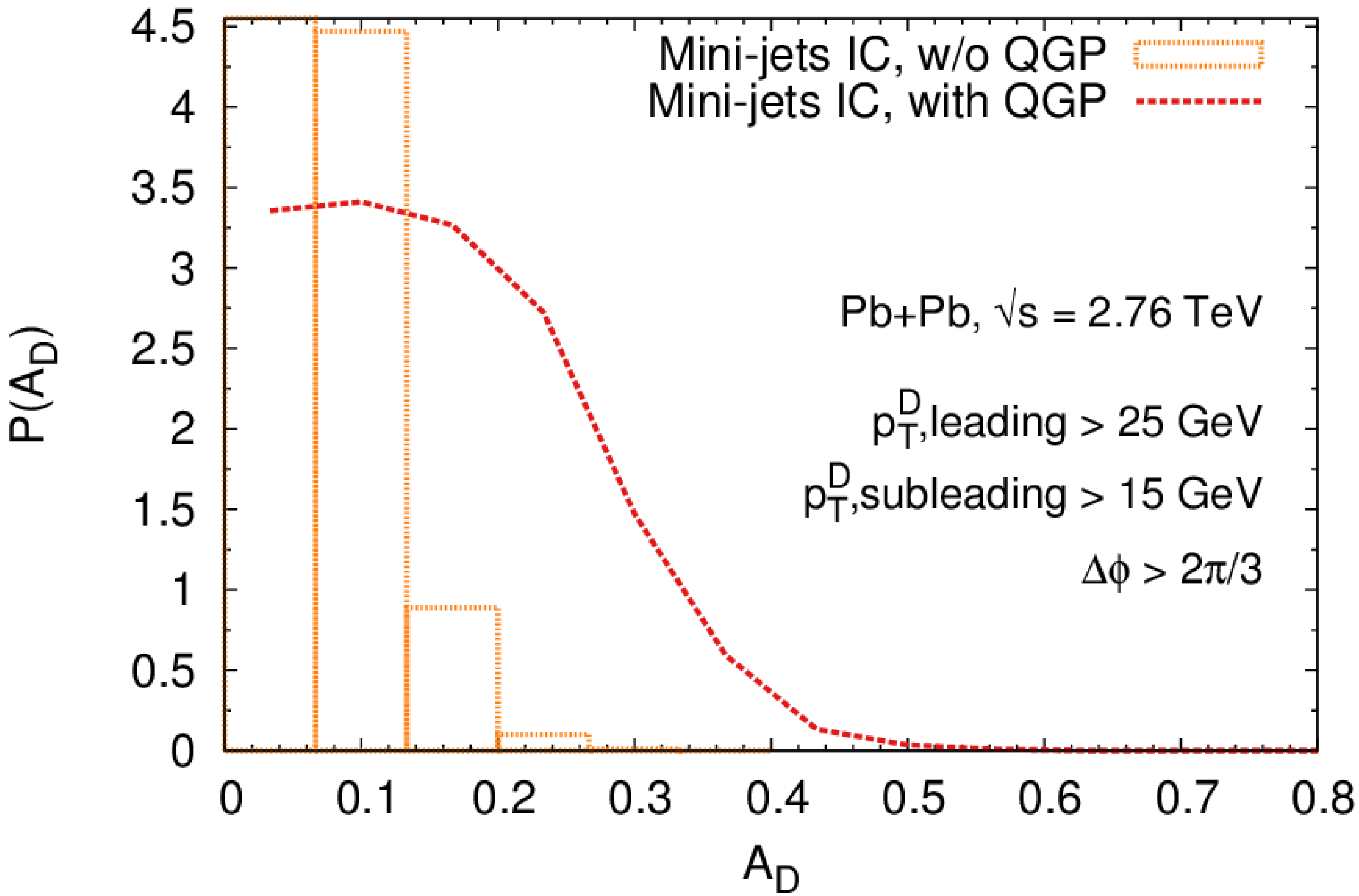
Momentum imbalance A_D for low triggers



A_D for high triggers – PYTHIA



A_D for high triggers – Mini-jets



Length imbalance