Heavy quark production and elliptic flow at RHIC and LHC

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Outline

- **Motivation**
- **Charm processes in BAMPS**
- **Box calculation: chemical equilibration**
- **Heavy quark production in heavy-ion collisions**
- **Elliptic flow of charm**
- **Summary**

Motivation

Large heavy quark mass

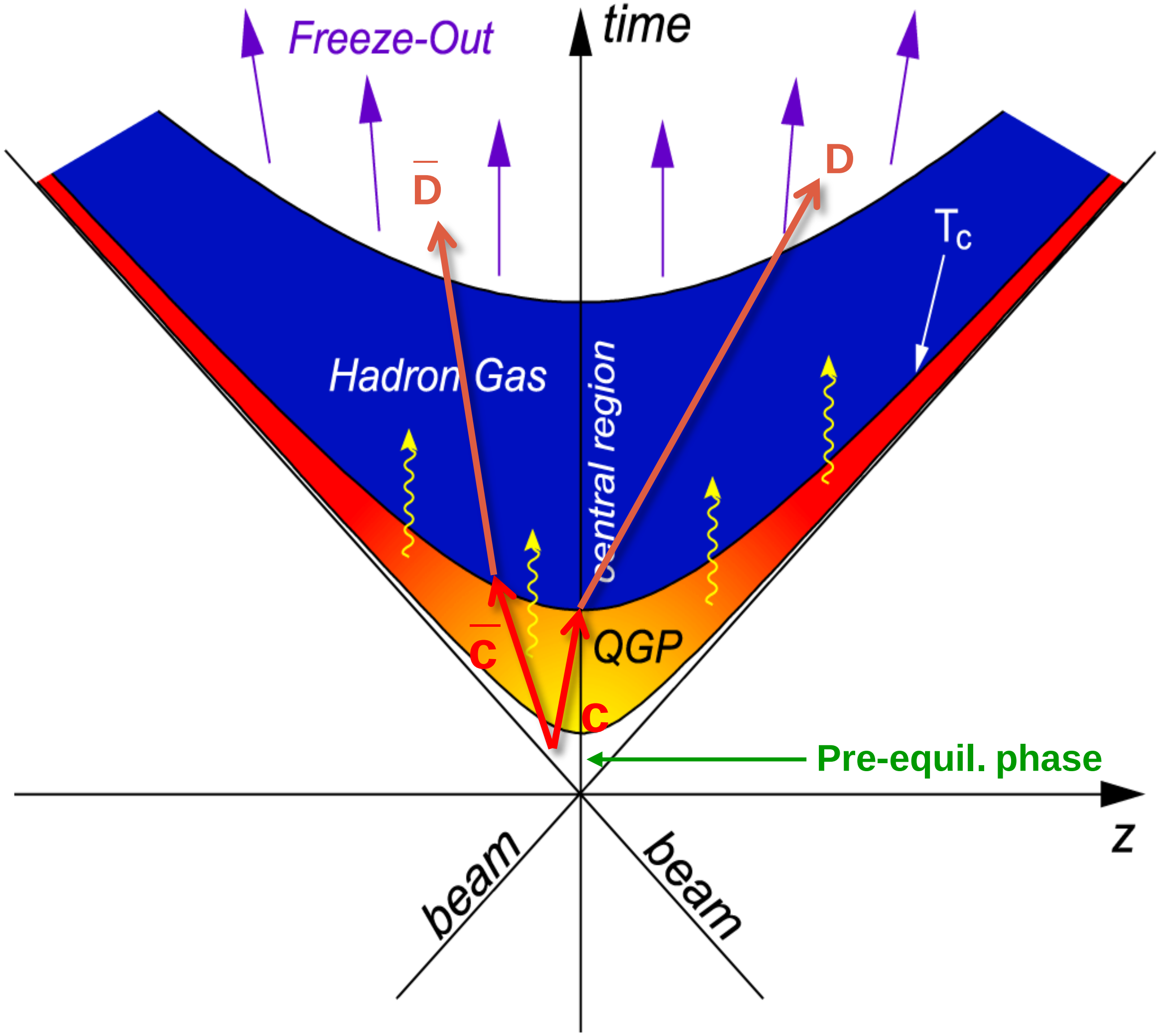
>> Λ_{QCD}

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**



BAMPS

BAMPS: Boltzmann Approach of MultiParton Scatterings

Transport algorithm solving the Boltzmann equations for on-shell partons with pQCD interactions

$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}_1}{E_1}\frac{\partial}{\partial \mathbf{r}}\right) f_1(\mathbf{r}, \mathbf{p}_1, t) = \mathcal{C}_{22} + \mathcal{C}_{23} + \cdots$$

Z. Xu & C. Greiner,
Phys. Rev. C 71 (2005) 064901

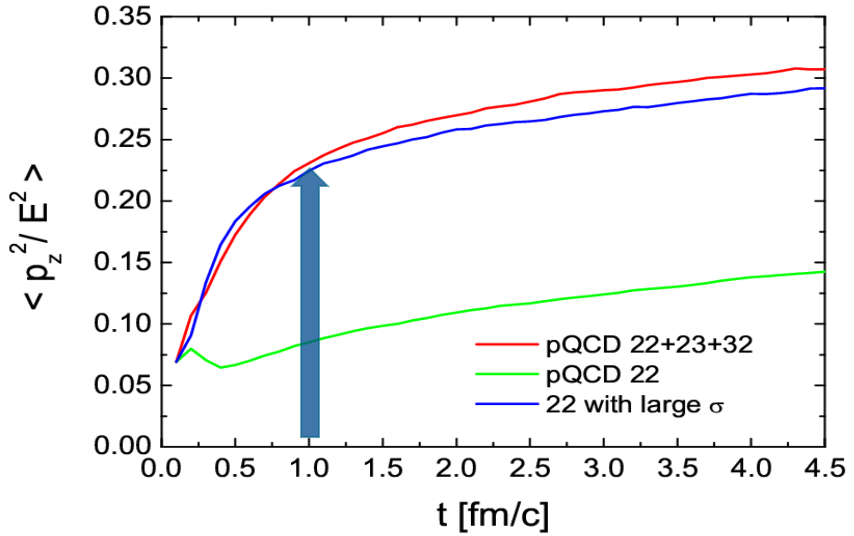
Implemented processes:

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

(no light quarks yet)

$$g + g \rightarrow c + \bar{c}$$
$$c + \bar{c} \rightarrow g + g$$
$$g + c \rightarrow g + c$$
$$g + \bar{c} \rightarrow g + \bar{c}$$

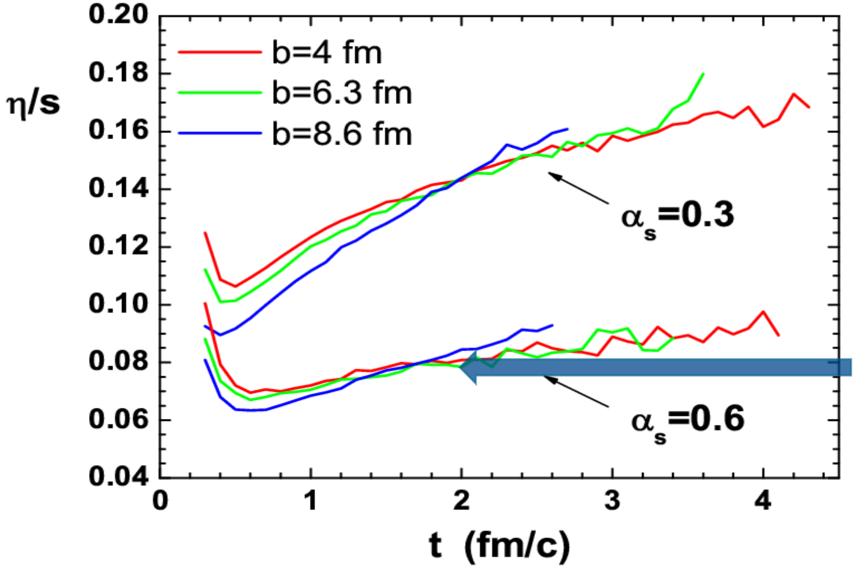
BAMPS



Rapid thermalization

$$\tau_{eq} \approx 1\,\mathrm{fm/c}$$

Z. Xu & C. Greiner,
Phys. Rev. C 76 (2007)



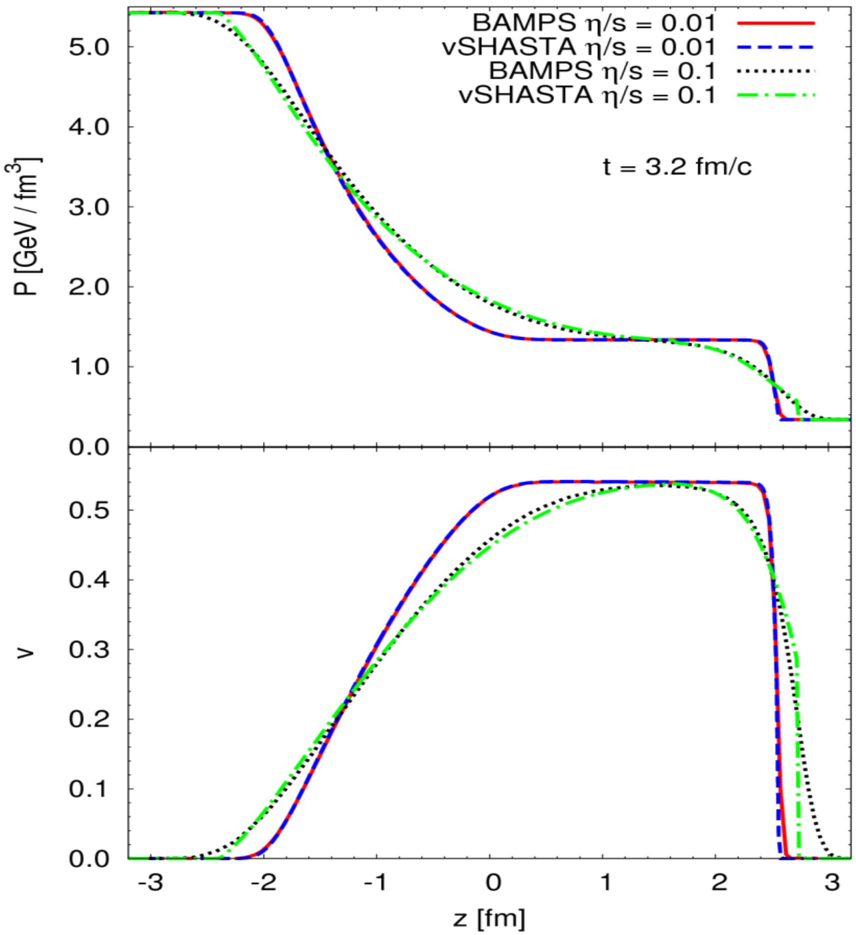
η/s extraction

$$\eta / s \approx 0.08$$

Z. Xu, C. Greiner & H. Stöcker,
Phys. Rev. Lett. 101 (2008)

BAMPS ⟷ Hydro

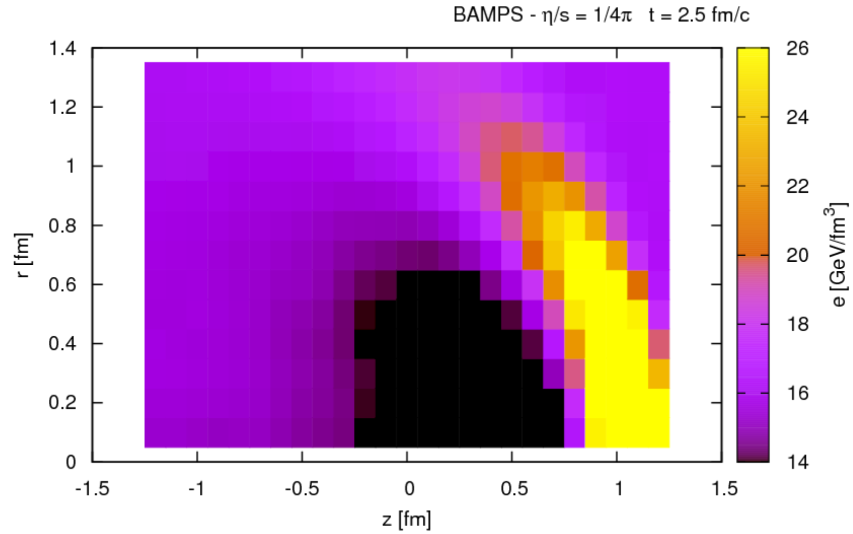
Solving the Riemann problem



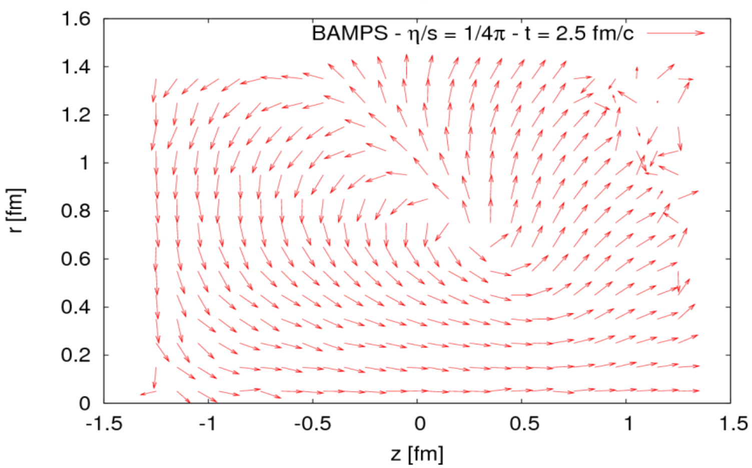
I. Bouras et al.,
Phys. Rev. Lett. 103 (2009)

Shock waves

by F. Lauciello & I. Bouras



Velocity field



Time scale of chemical equilibration

Toy model: consider box of gluons with just two processes

$$g + g \rightarrow c + \bar{c}$$

$$c + \bar{c} \rightarrow g + g$$

Initial conditions:

thermally distributed gluons

Rate equation:

$$\partial_\mu \left(n_c u^\mu \right) = R_{gg \rightarrow c\bar{c}} - R_{c\bar{c} \rightarrow gg}$$

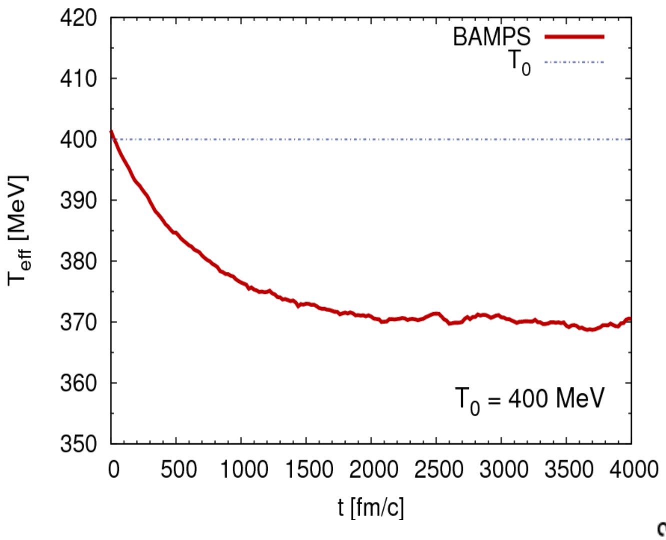
with

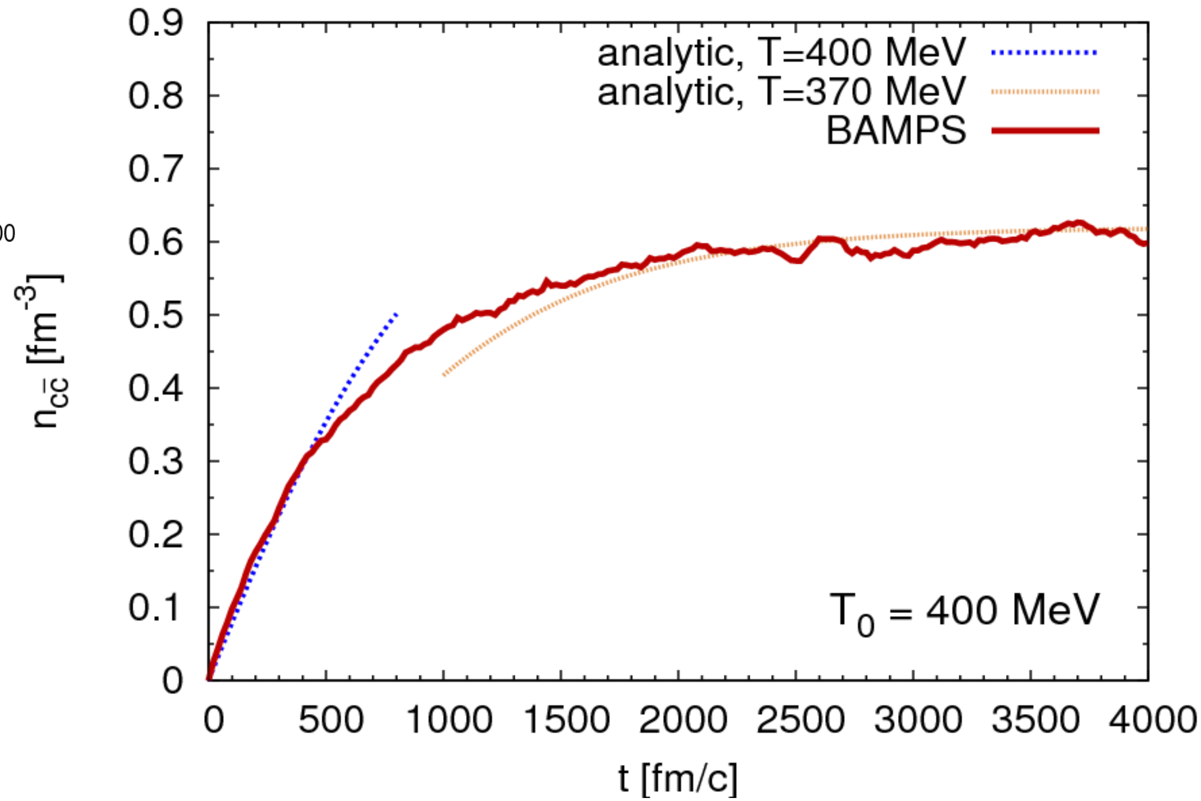
$$R_{gg \rightarrow c\bar{c}} = \frac{1}{2} < \sigma_{gg \rightarrow c\bar{c}} v_{rel} > n_g^2$$

$$R_{c\bar{c} \rightarrow gg} = < \sigma_{c\bar{c} \rightarrow gg} v_{rel} > n_c n_{\bar{c}}$$

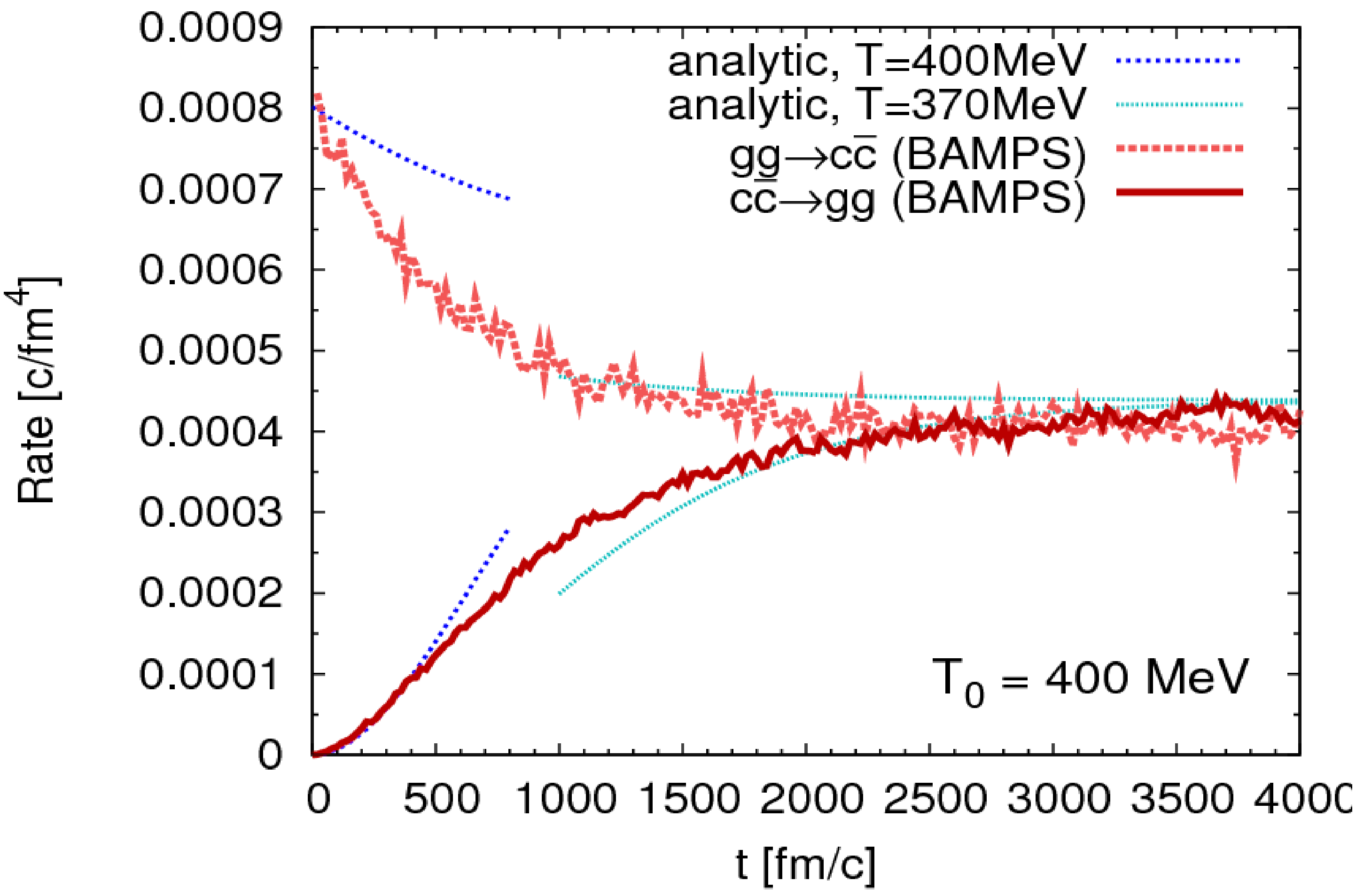
Matsui, Svetitsky, McLerran, Phys. Rev. D (1986)
Biro, van Doorn, Müller, Thoma, Wang, Phys. Rev. C (1993)

Box calculation T_0 = 400 MeV

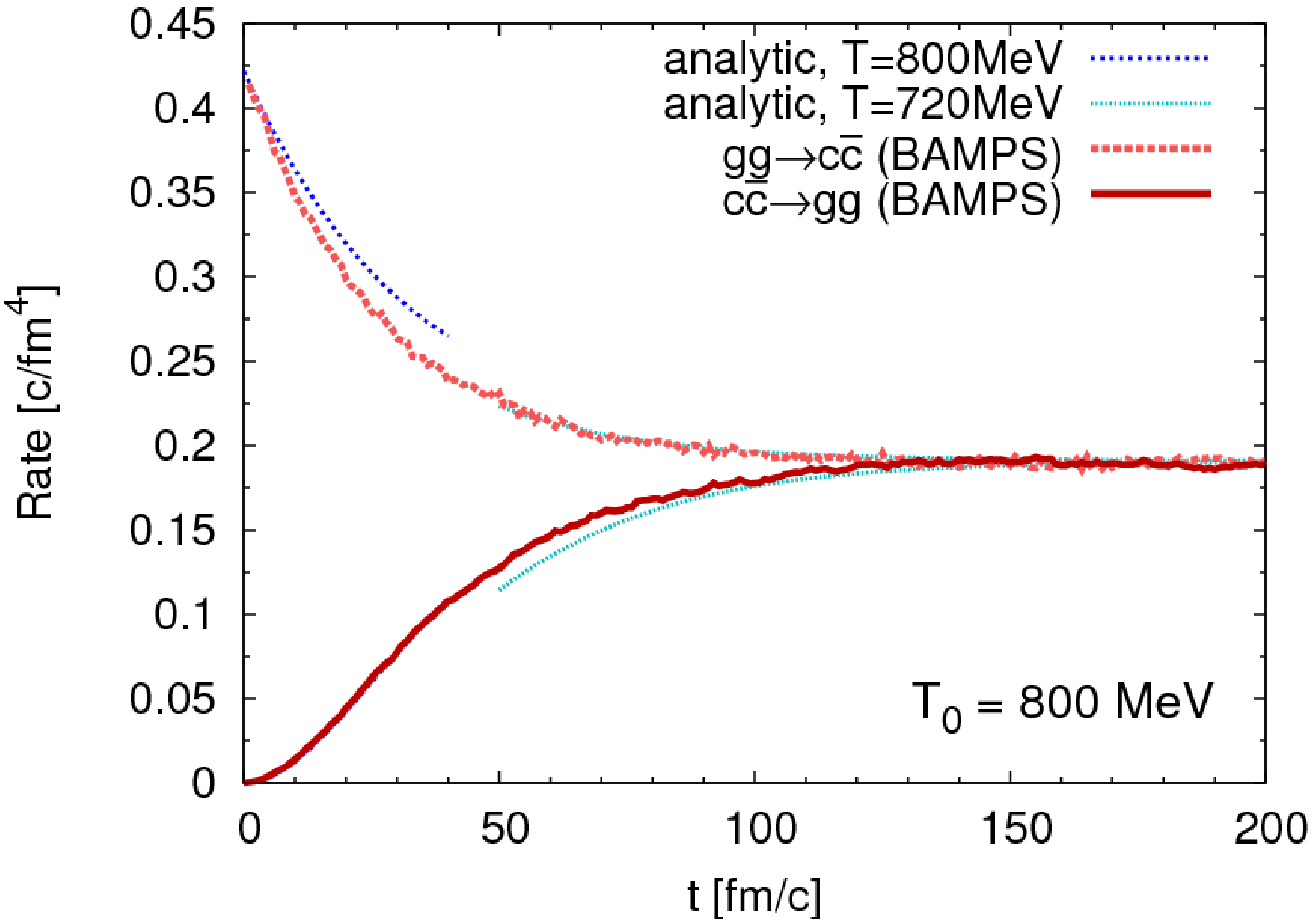




Box calculation T_0 = 400 MeV



Box calculation T_0 = 800 MeV



Initial charm in hard parton scatterings

Two approaches:

1. **LO pQCD: mini-jets**

$$\frac{\mathrm{d}\sigma^{AB}_{c\bar{c}}}{\mathrm{d}p_T^2\mathrm{d}y_c\mathrm{d}y_{\bar{c}}} = x_1 x_2 C(x_1, x_2)$$

depend on renormalization scale μ_R

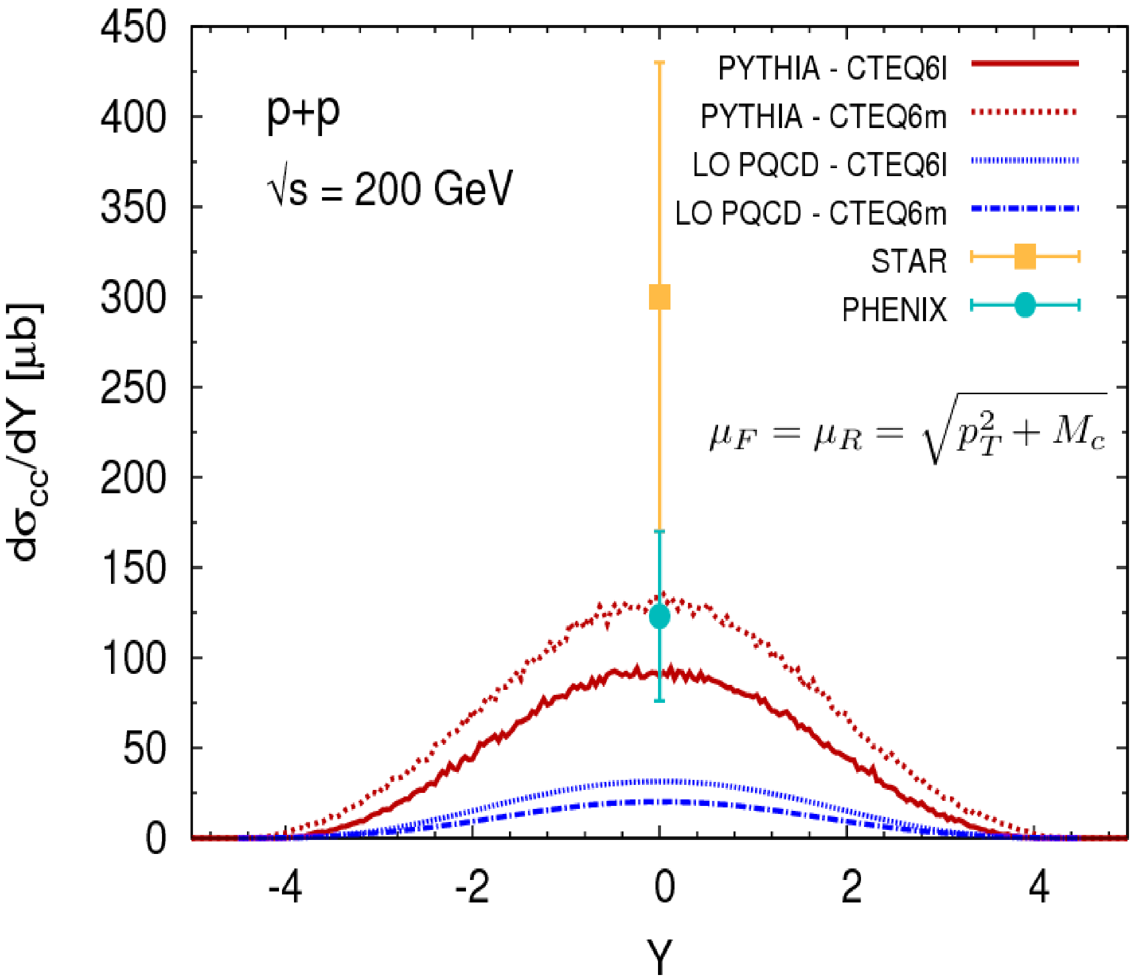
$$C(x_1,x_2) = f_g^A(x_1)\, f_g^B(x_2)\, \frac{\mathrm{d}\hat{\sigma}_{gg\to c\bar{c}}}{\mathrm{d}\hat{t}} + \sum_q \left[f_q^A(x_1)\, f_{\bar{q}}^B(x_2) + f_{\bar{q}}^A(x_1)\, f_q^B(x_2) \right] \frac{\mathrm{d}\hat{\sigma}_{q\bar{q}\to c\bar{c}}}{\mathrm{d}\hat{t}}$$

depend on factorization scale μ_F

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

both very sensitive on
- **parton distribution functions**
- **factorization scale**
- **renormalization scale**
- **charm mass**

Initial charm in hard parton scatterings



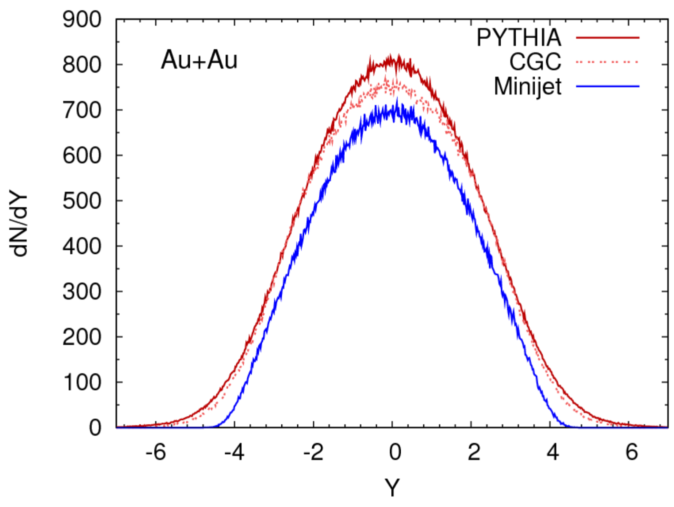
Total initial charm yield in central Au+Au collisions @ RHIC:

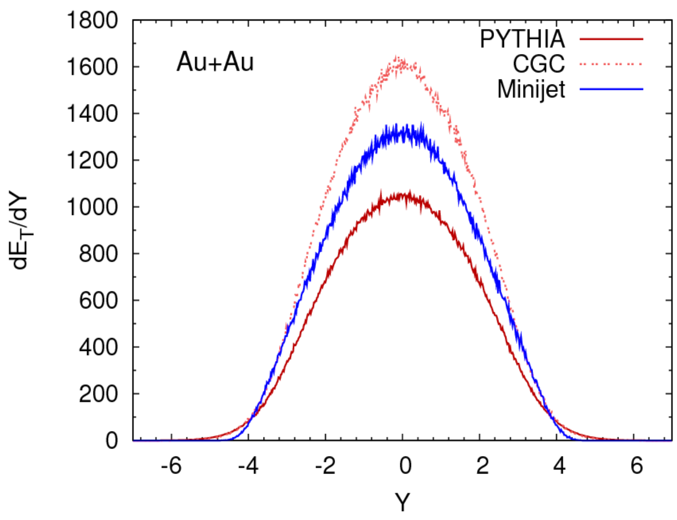
- **PYTHIA:**
  8 – 14 charm pairs
- **LO pQCD:**
  2 – 4 charm pairs

PYTHIA closer to data

Initial gluon distribution for parton cascade

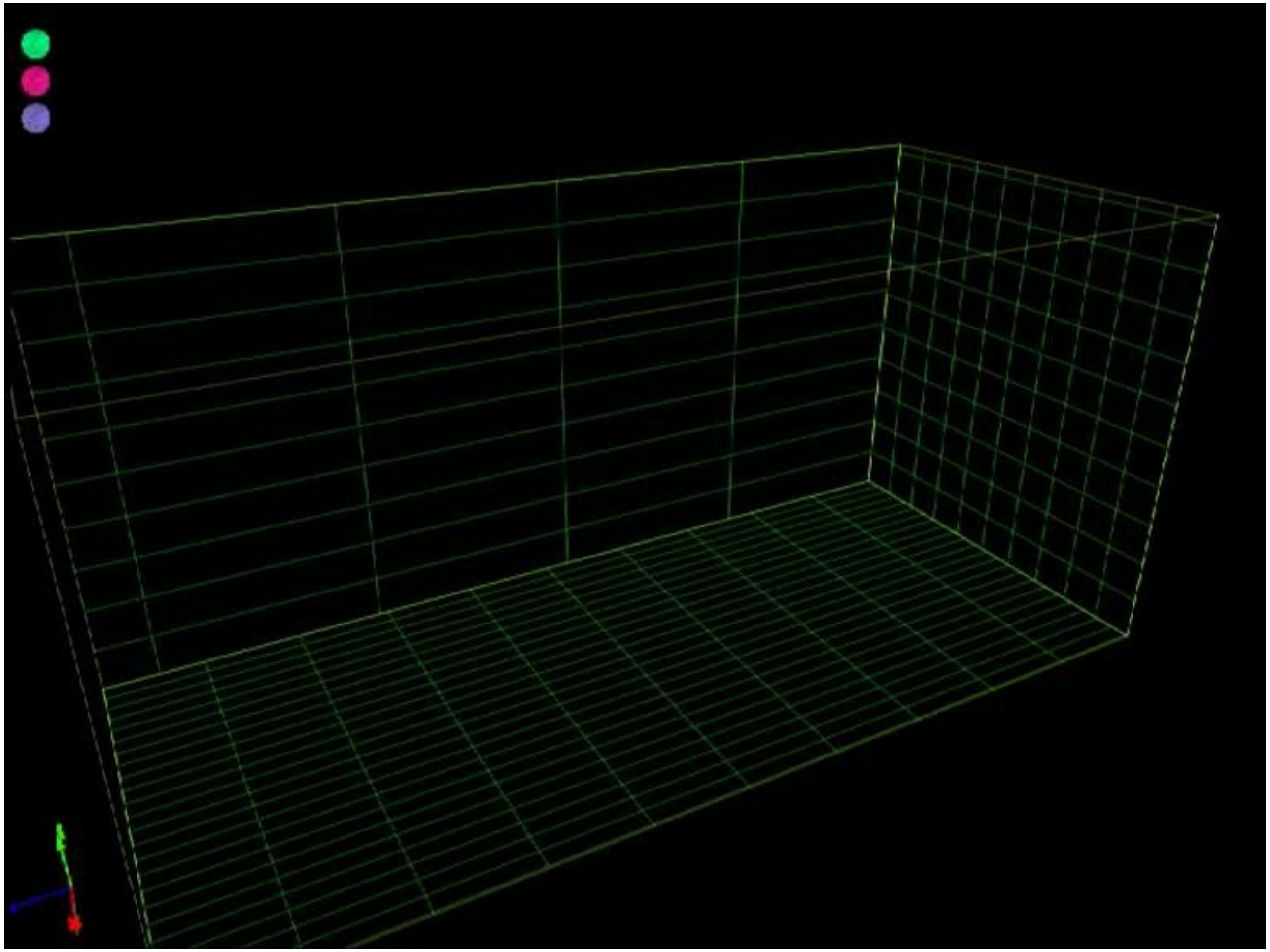
- **PYTHIA**
  scaling to heavy-ion collisions with Glauber model (considering shadowing) and energy conservation
  - **hard partons ~ N_{bin}: number of binary collision**
  - **soft partons ~ A: number of nucleons in one nuclei**
- **Minijets (low p_T cut-off at 1.4 GeV)**
- **Color glass condensate** H.J. Drescher & Y. Nara, Phys. Rev. C75 (2007)





Charm production in the QGP

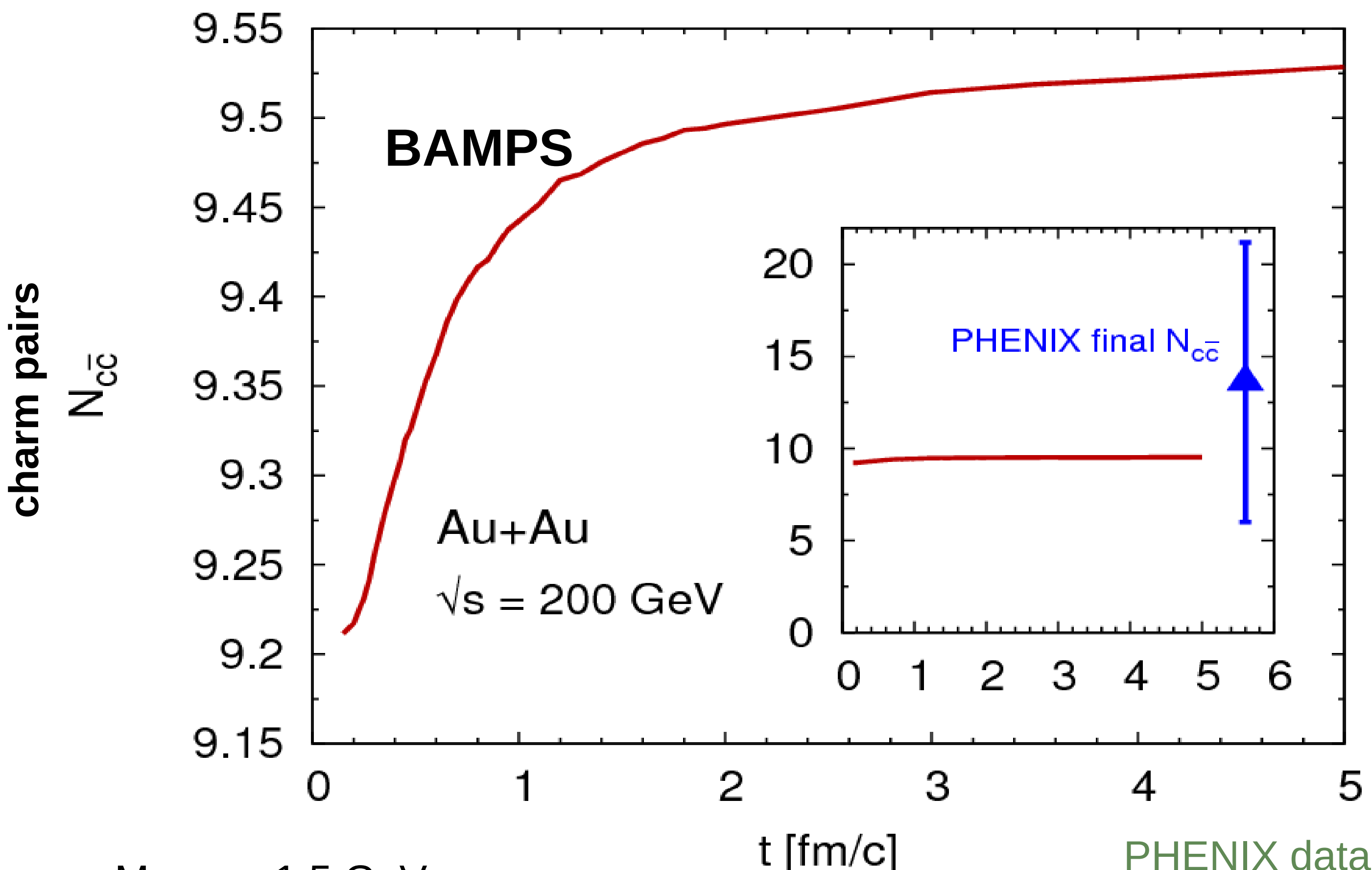
BAMPS simulation of QGP phase at RHIC



Charm production in the QGP at RHIC

RHIC

PYTHIA initial conditions



Only 0.3 charm pairs are produced during the QGP phase

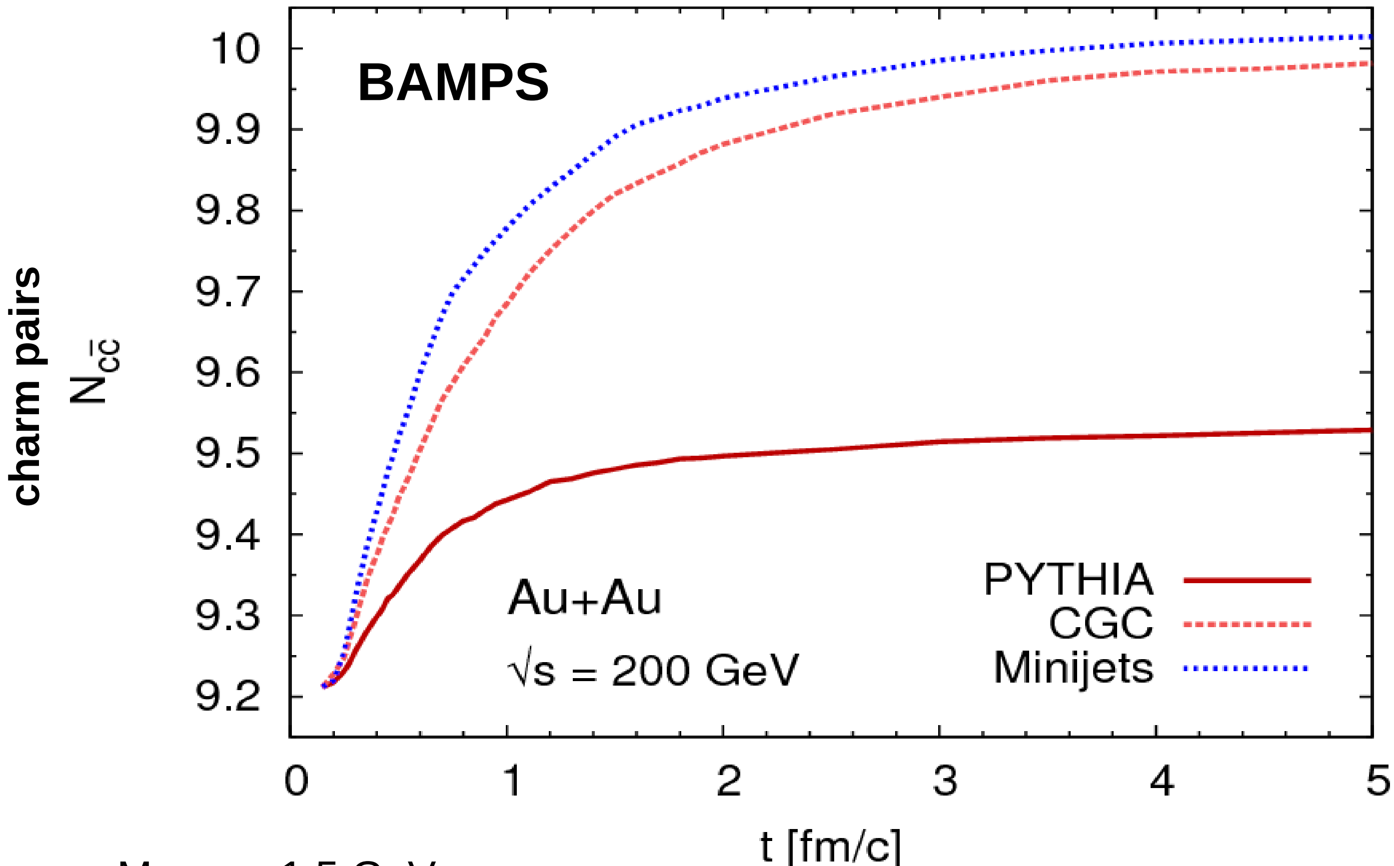
➡ **3 % of total charm**

M_{charm} = 1.5 GeV

PHENIX data,
Phys. Rev. Lett. 94 (2005)

Charm production in the QGP at RHIC

RHIC



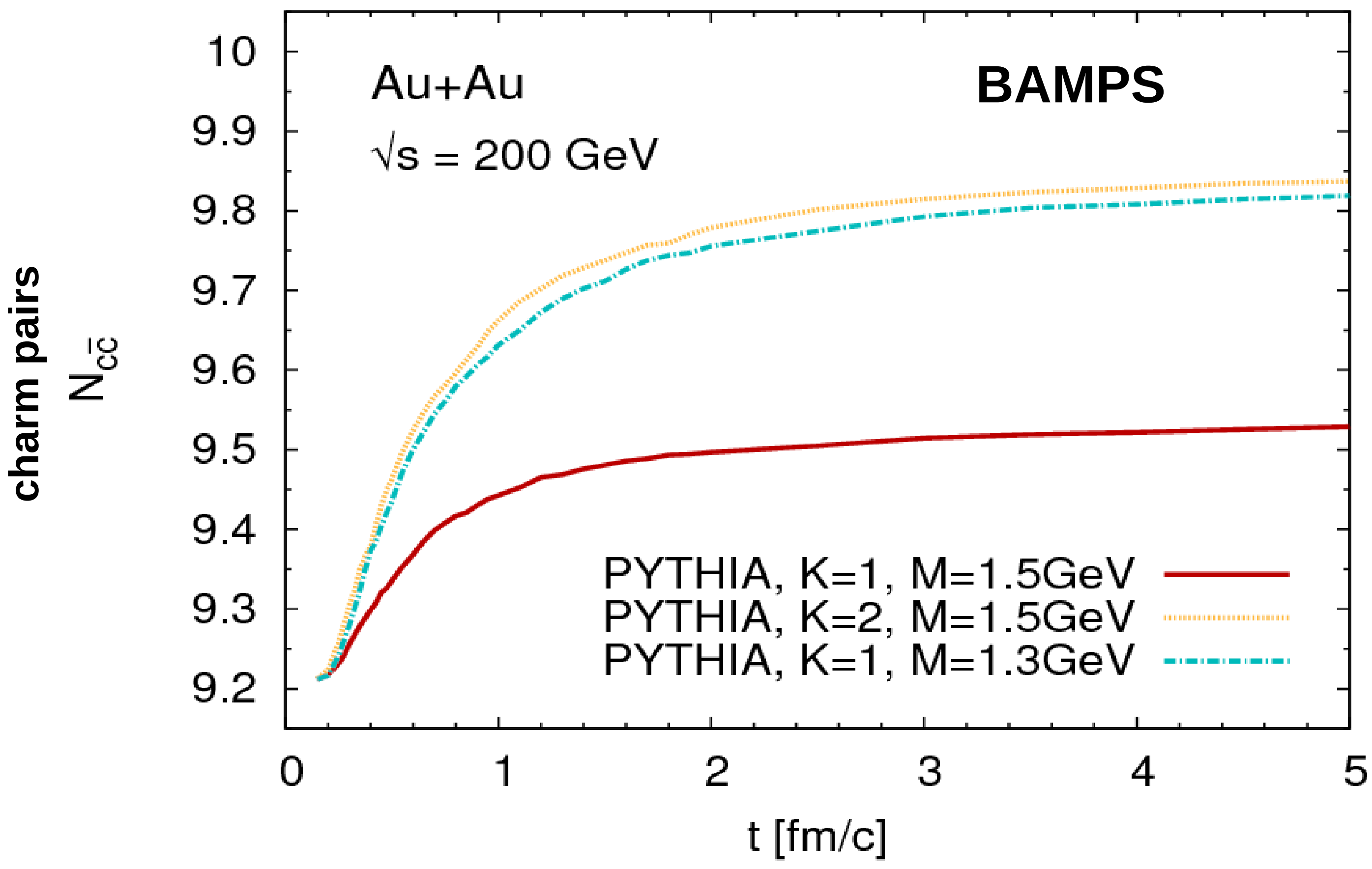
M_{charm} = 1.5 GeV

Different initial conditions

➡ **factor 2.5 difference in charm production during QGP phase**

Charm production in the QGP at RHIC

RHIC

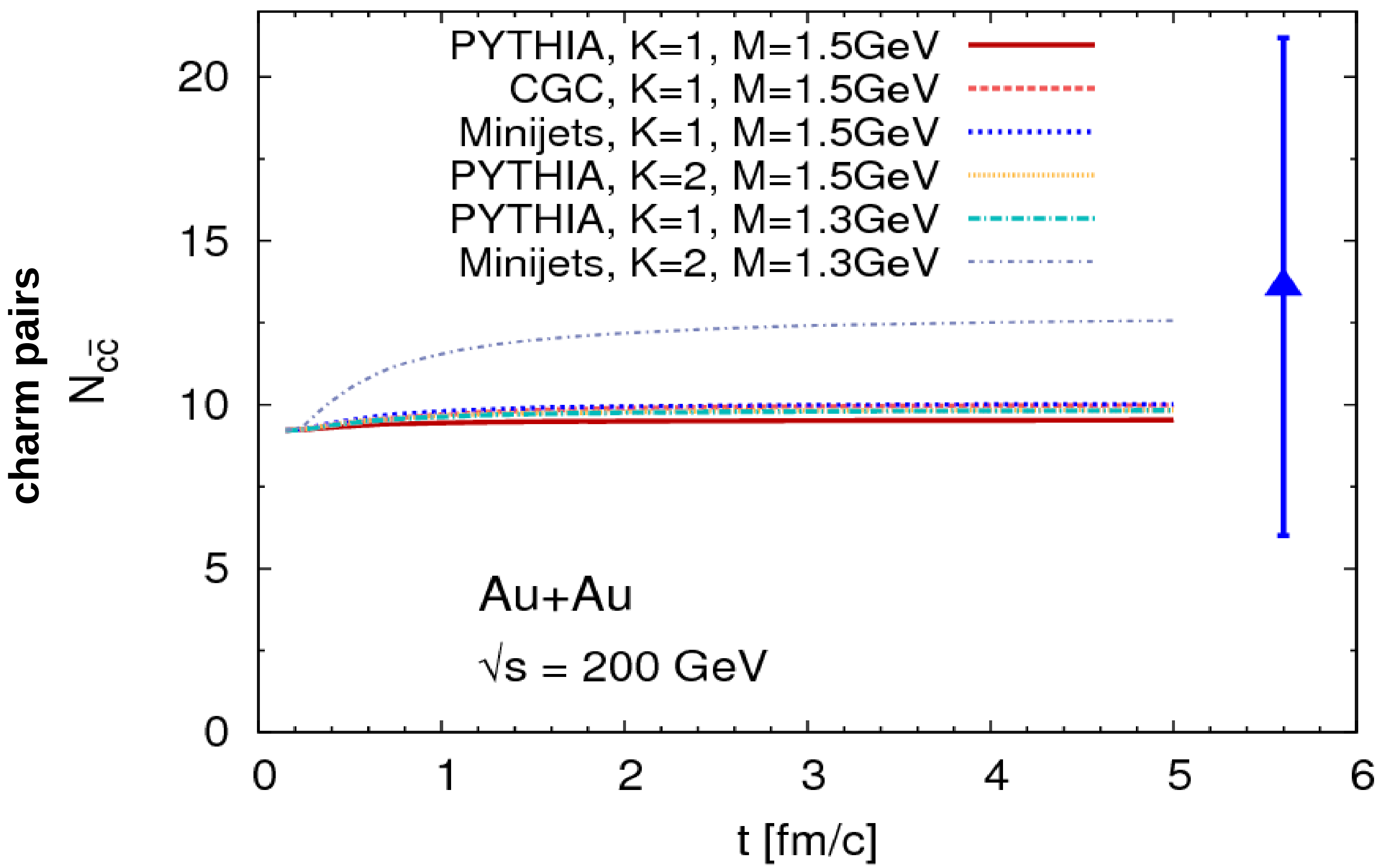


K factor or different charm mass

➡ **factor 2 difference in charm production during QGP phase**

Charm production in the QGP at RHIC

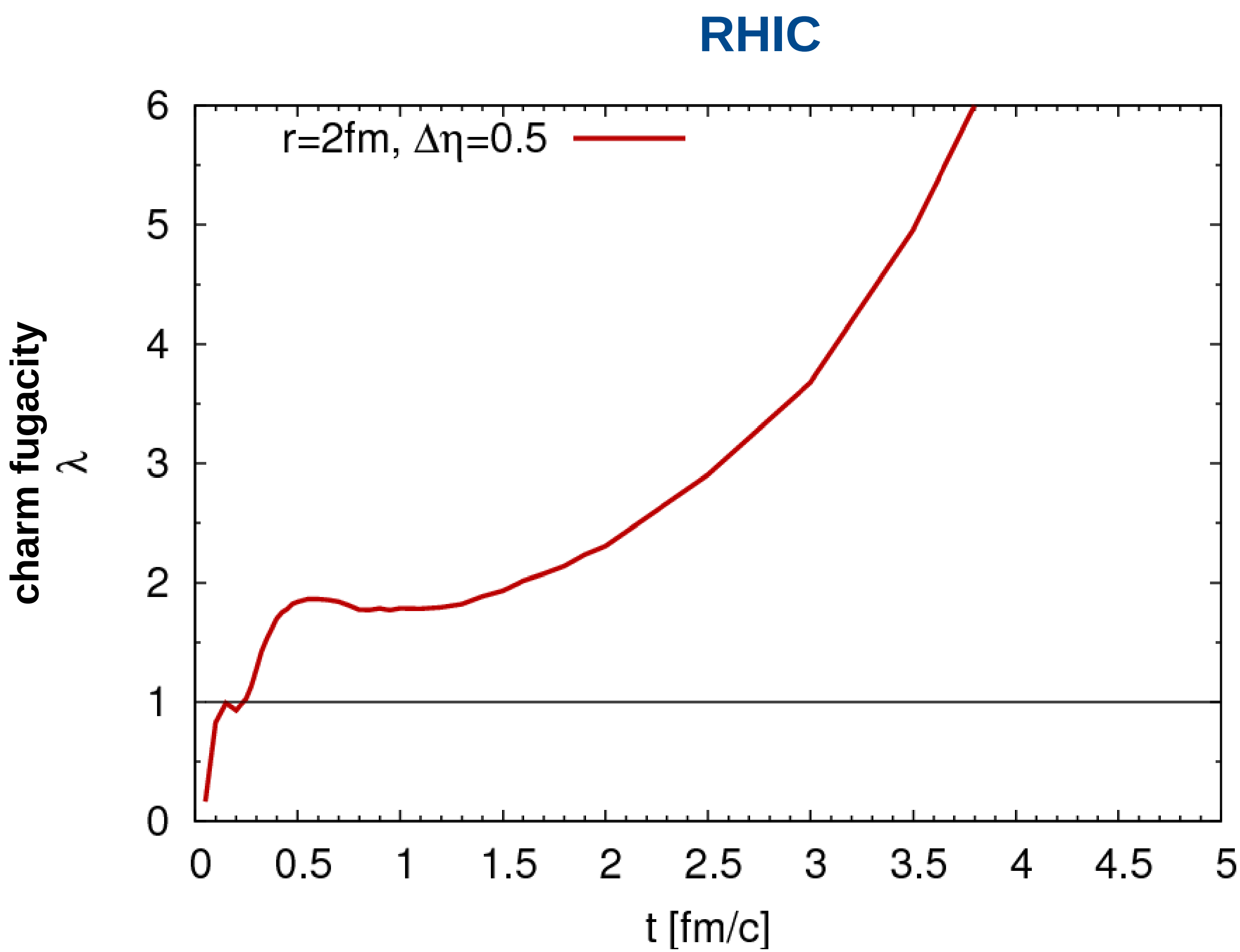
RHIC



Maximum charm production of 3.4 pairs

➡ **27 % of total charm**

Charm production in the QGP at RHIC

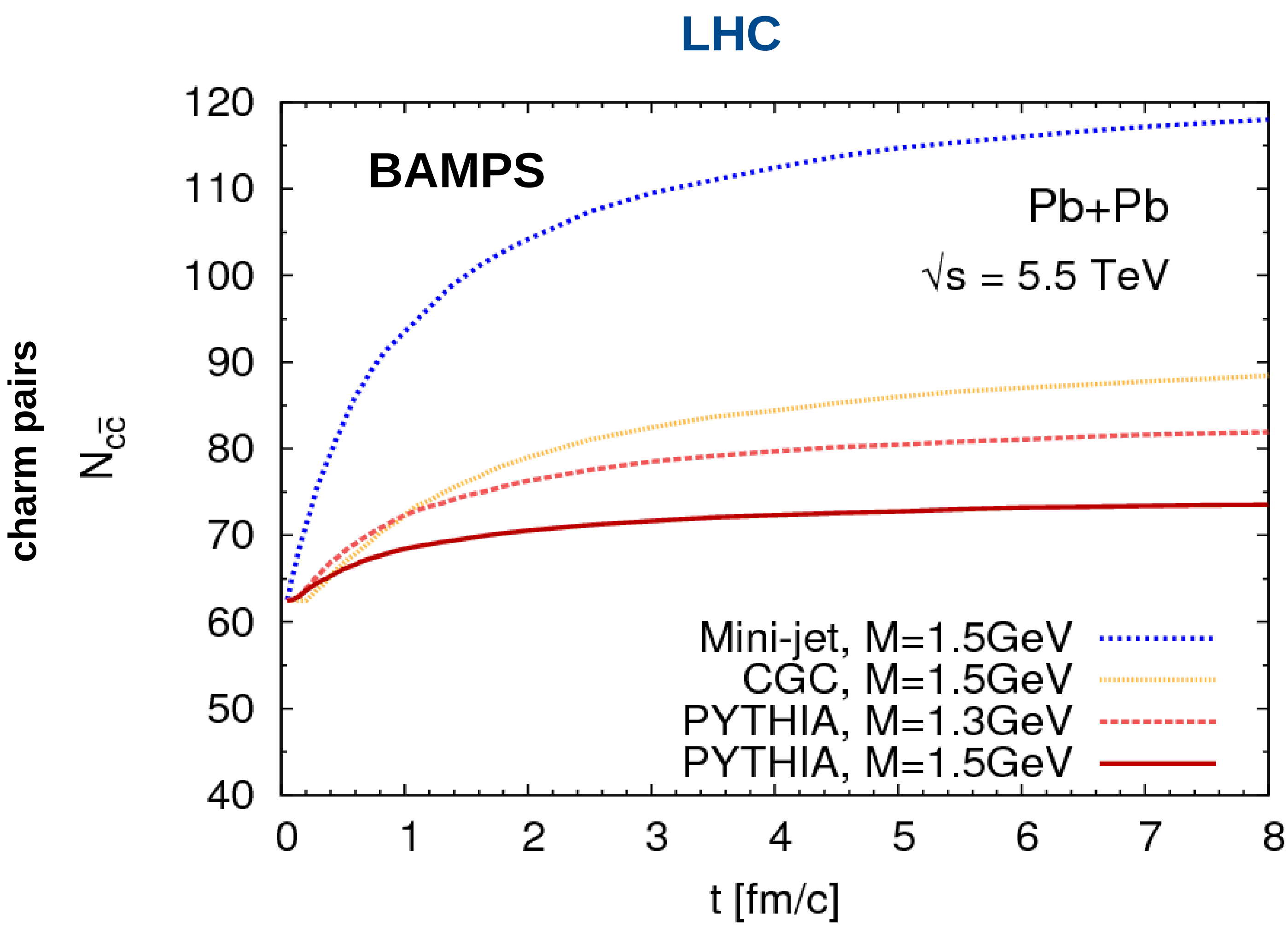


Extract temperature, compute n^{eq}

$$\Rightarrow \lambda_{c\bar{c}}(t) = \frac{n_{c\bar{c}}(t)}{n_{c\bar{c}}^{\mathrm{eq}}}$$

Number of charm quarks in center of collision far above equilibrium value

Charm production in the QGP at LHC

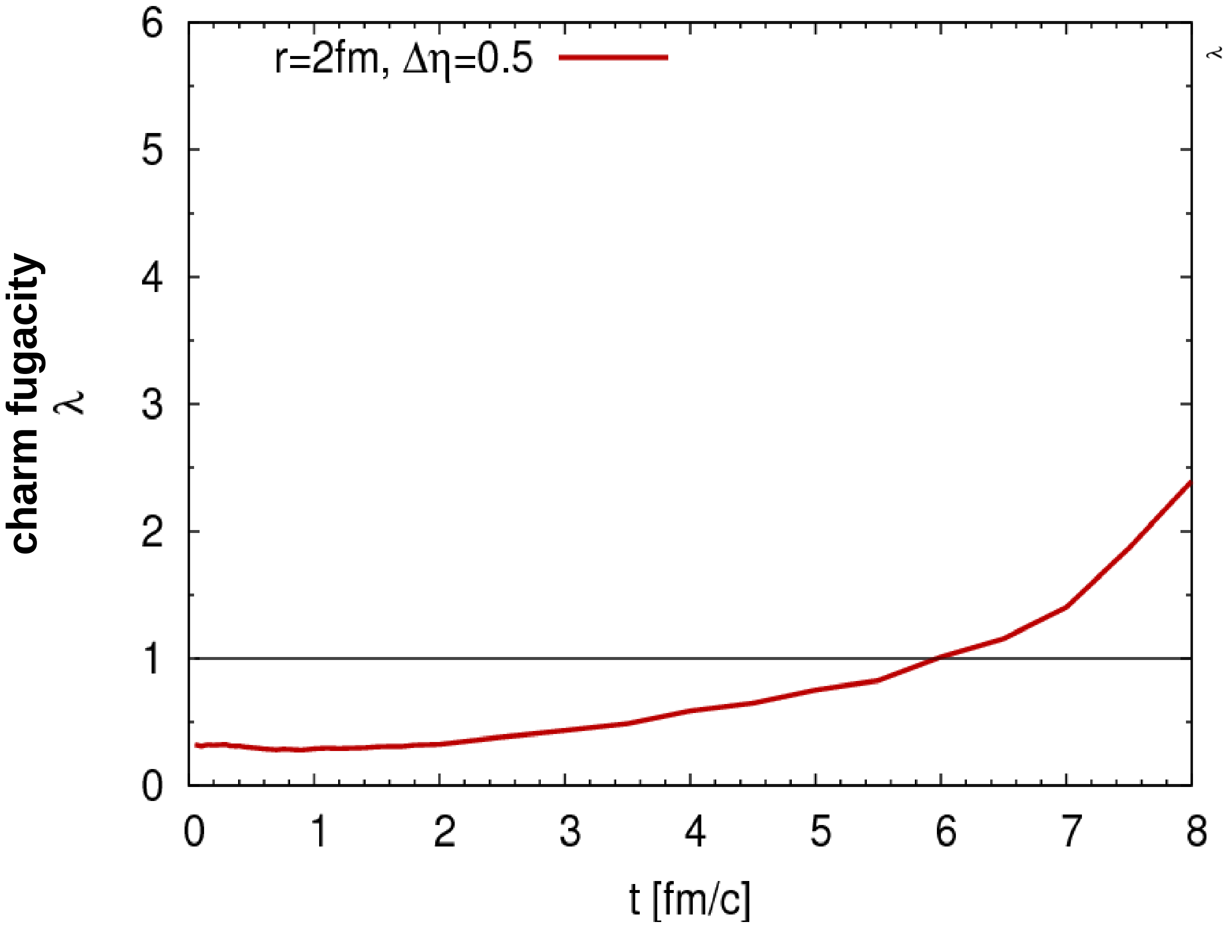


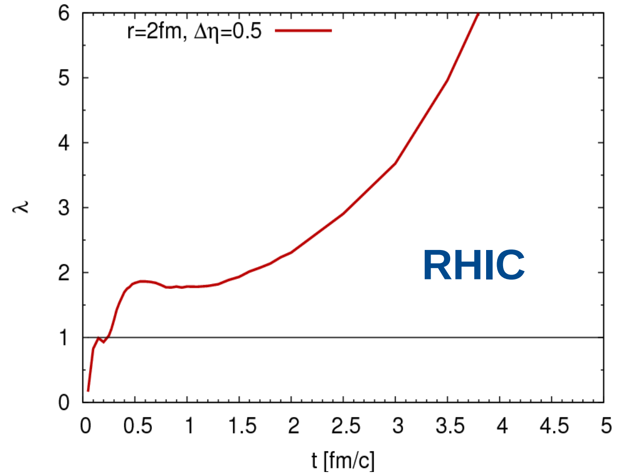
11 - 50 charm pairs are produced in the QGP

➡ **15 - 45 % of total charm**

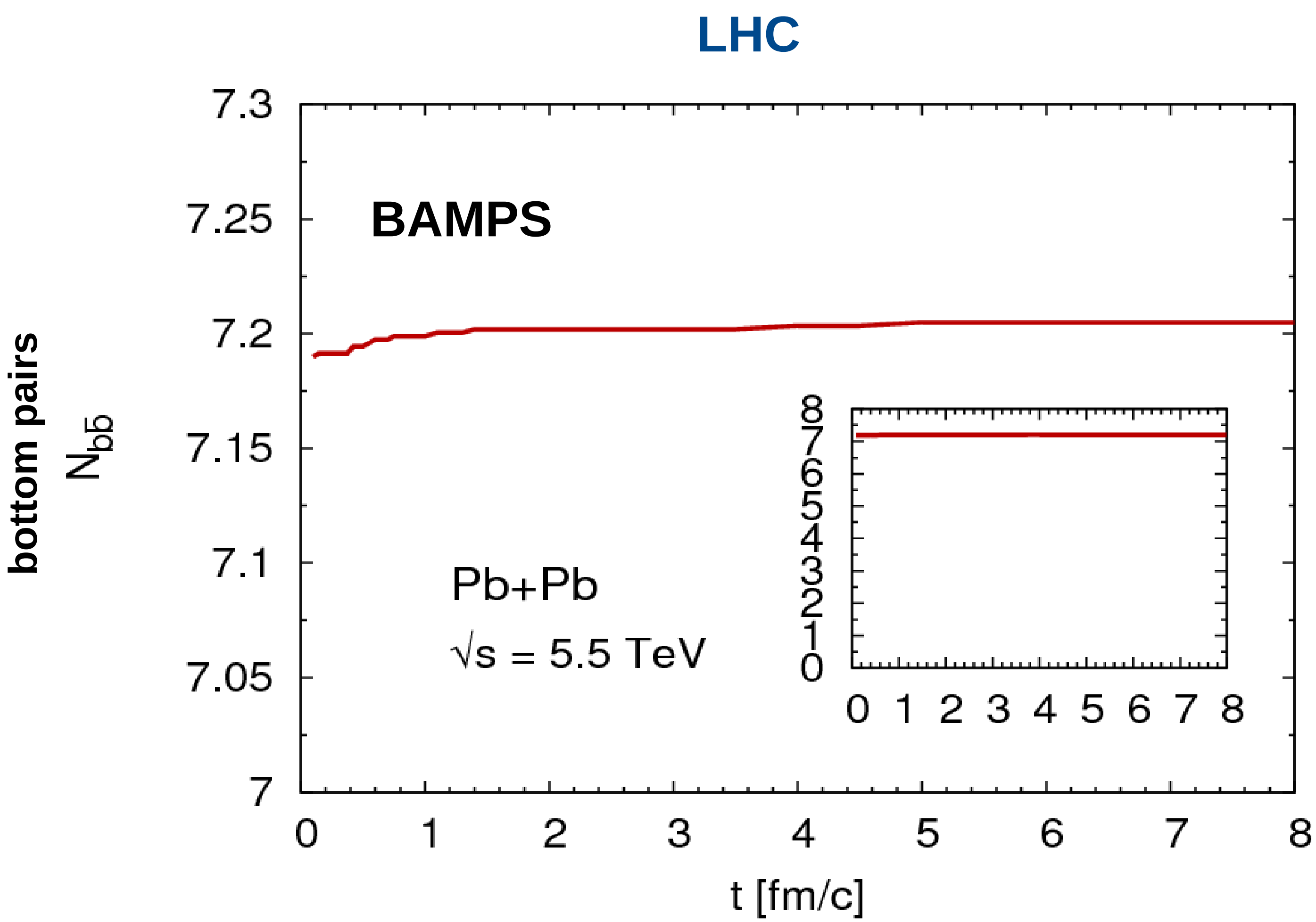
Charm production in the QGP at LHC

LHC





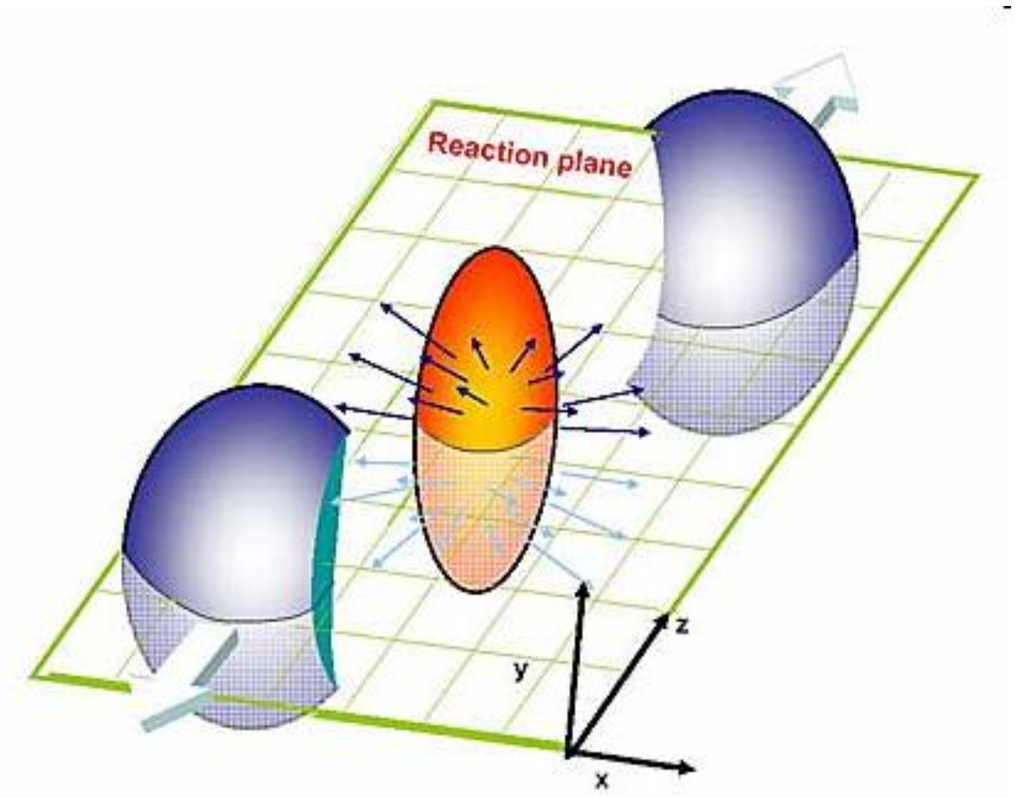
Bottom production in the QGP at LHC

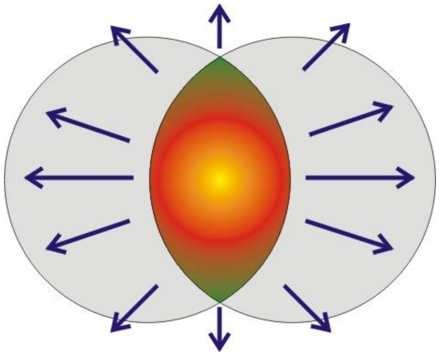


0.01 bottom pairs are produced in the QGP

➡ **0.2 % of total bottom**

Elliptic flow v_2

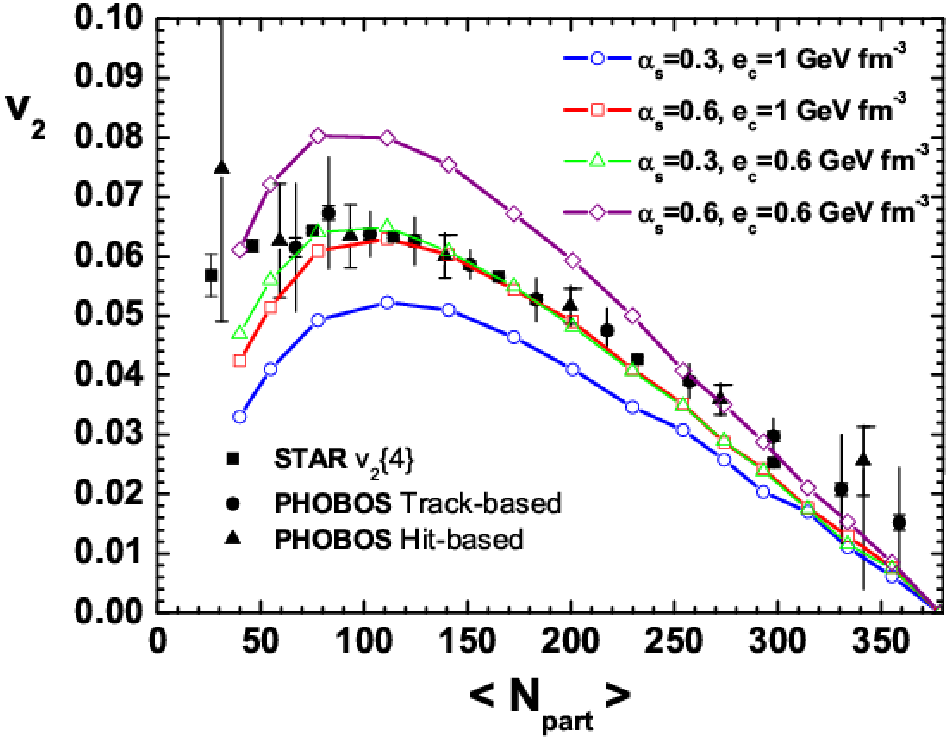




$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

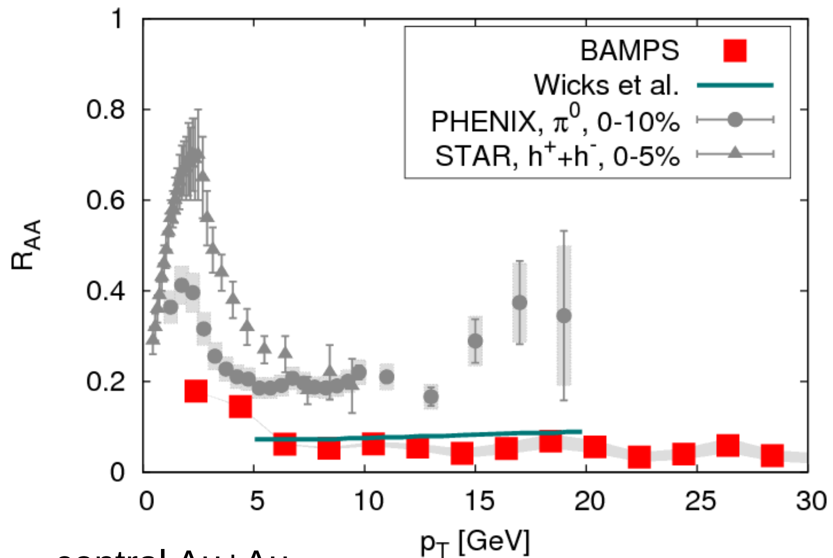
$$\frac{\mathrm{d}^3 N}{p_T \mathrm{d}p_T \mathrm{d}y \mathrm{d}\phi}(p_T, y, \phi) = \frac{1}{2\pi} \frac{\mathrm{d}^2 N}{p_T \mathrm{d}p_T \mathrm{d}y} \left[1 + 2 v_2(p_T, y) \cos(2\phi) + \ldots\right]$$

Elliptic flow v_2 for gluons



Z. Xu & C. Greiner,
Phys. Rev. C 79 (2009)

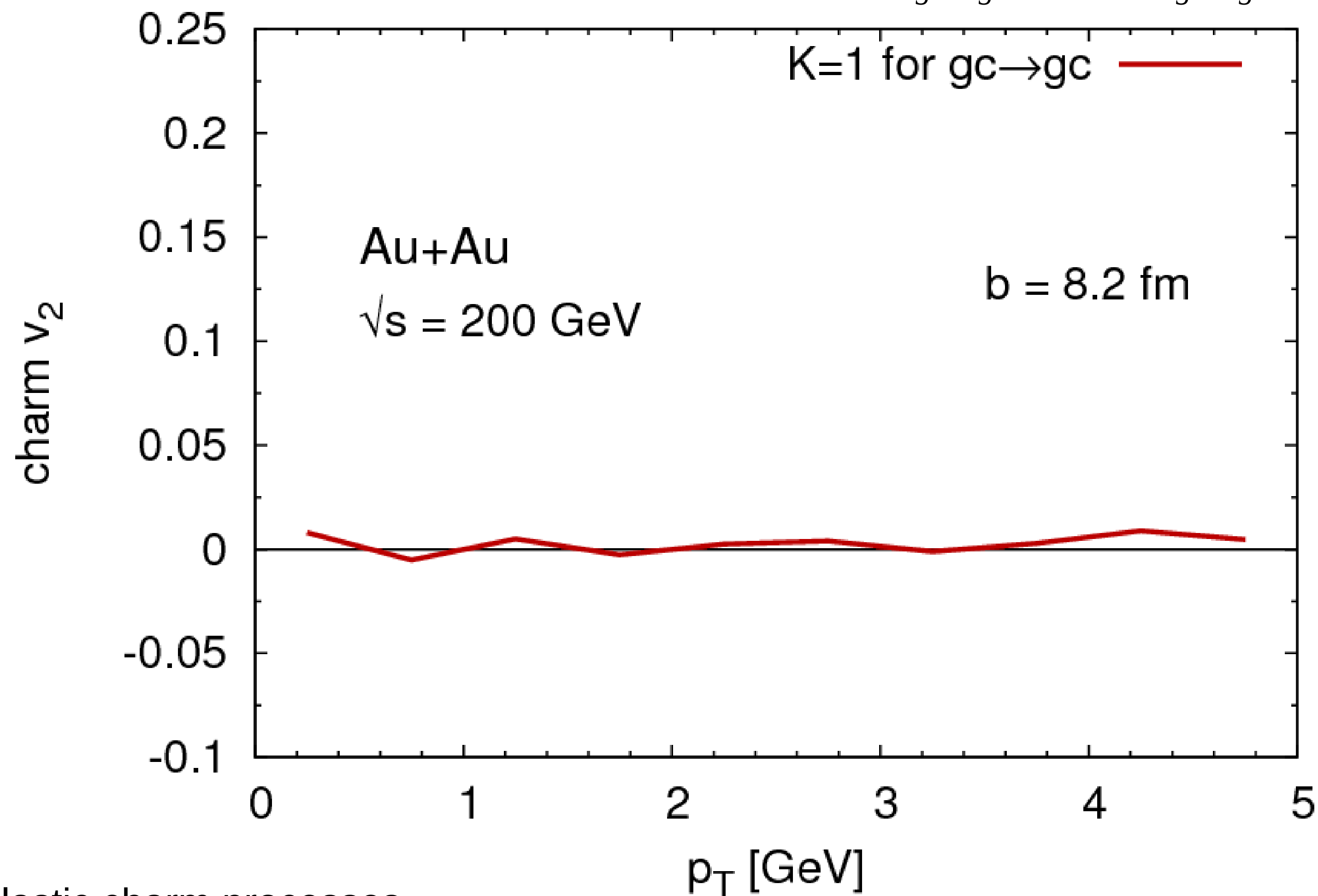
O. Fochler, Z. Xu & C. Greiner,
Phys.Rev.Lett.102 (2009)



central Au+Au

Elliptic flow v_2 for charm at RHIC

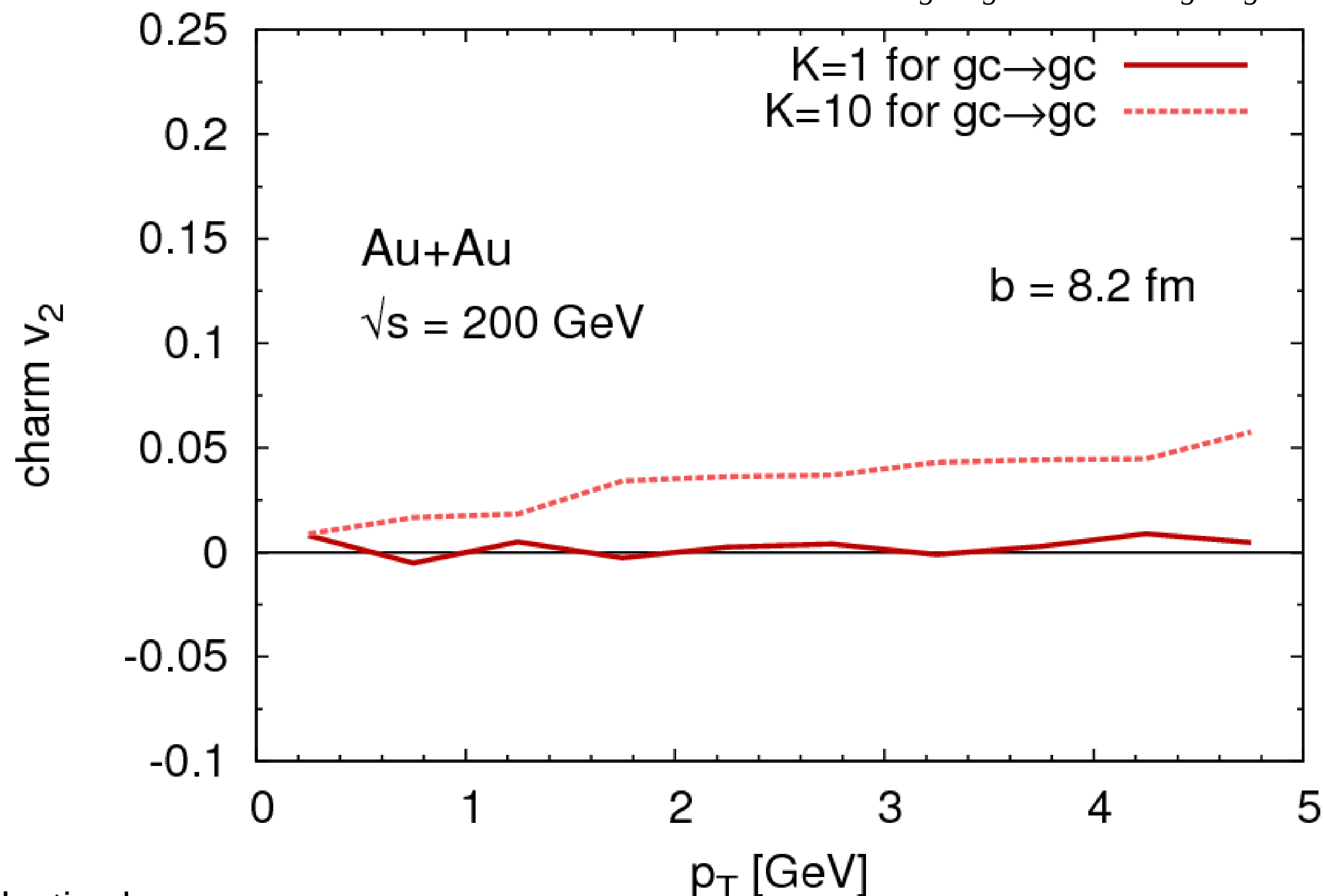
$$\sigma_{gc\to gc} \to K\,\sigma_{gc\to gc}$$



only elastic charm processes

Elliptic flow v_2 for charm at RHIC

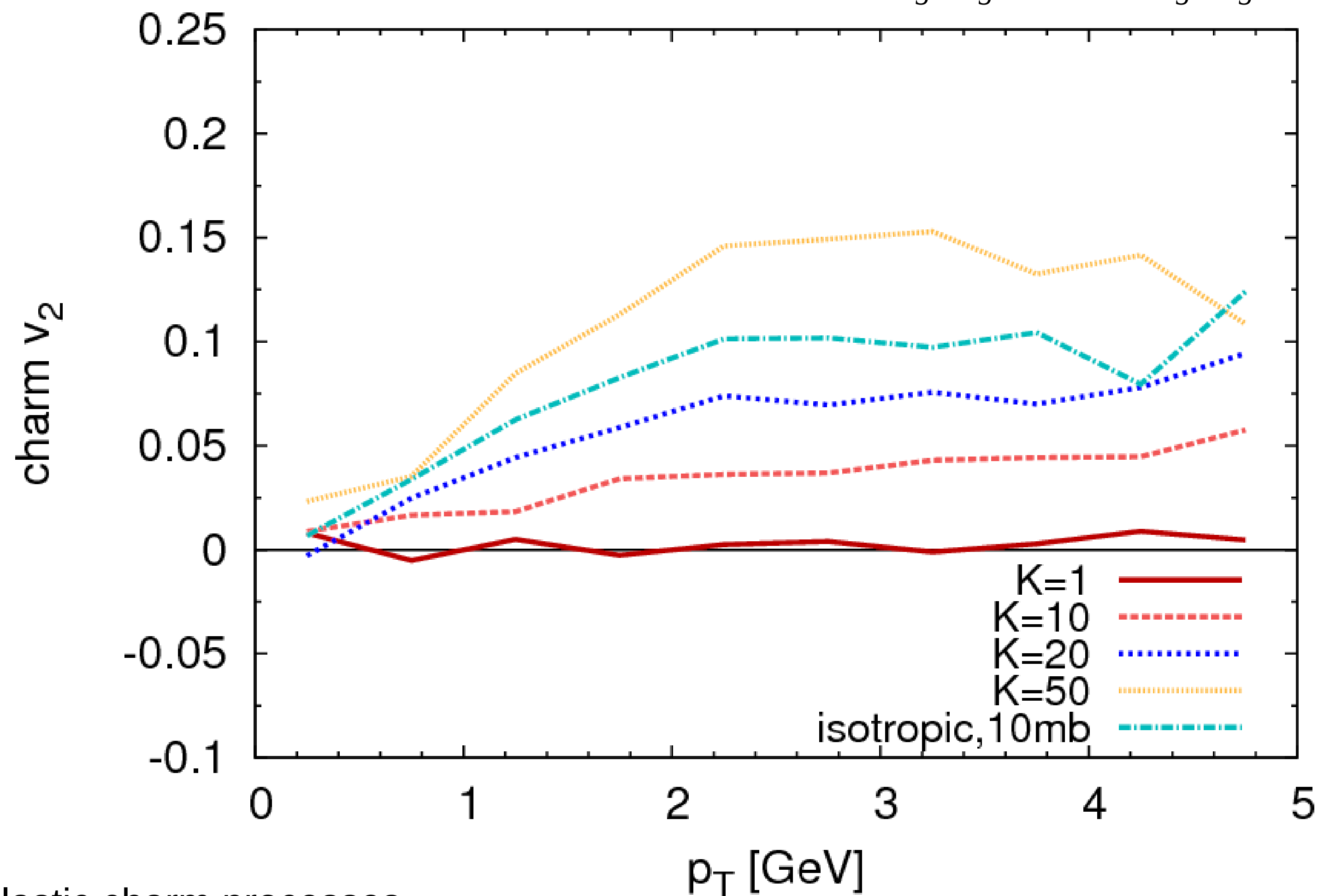
$$\sigma_{gc\to gc} \to K\,\sigma_{gc\to gc}$$



only elastic charm processes

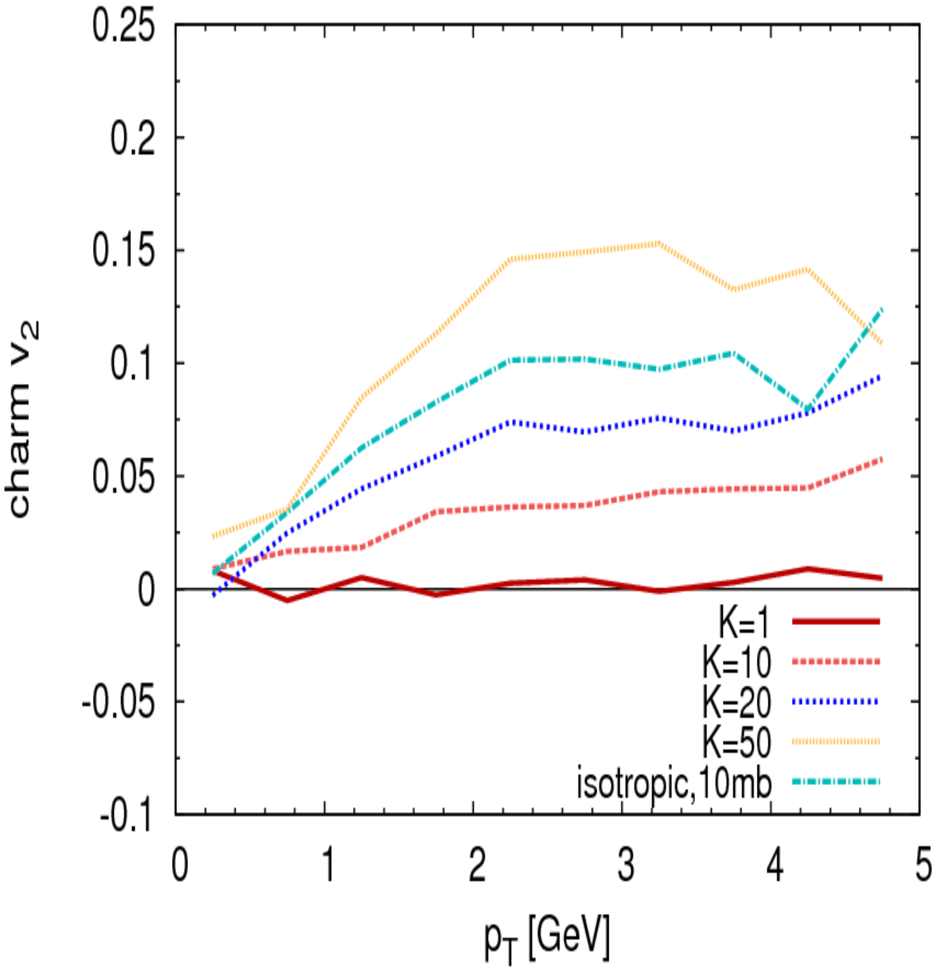
Elliptic flow v_2 for charm at RHIC

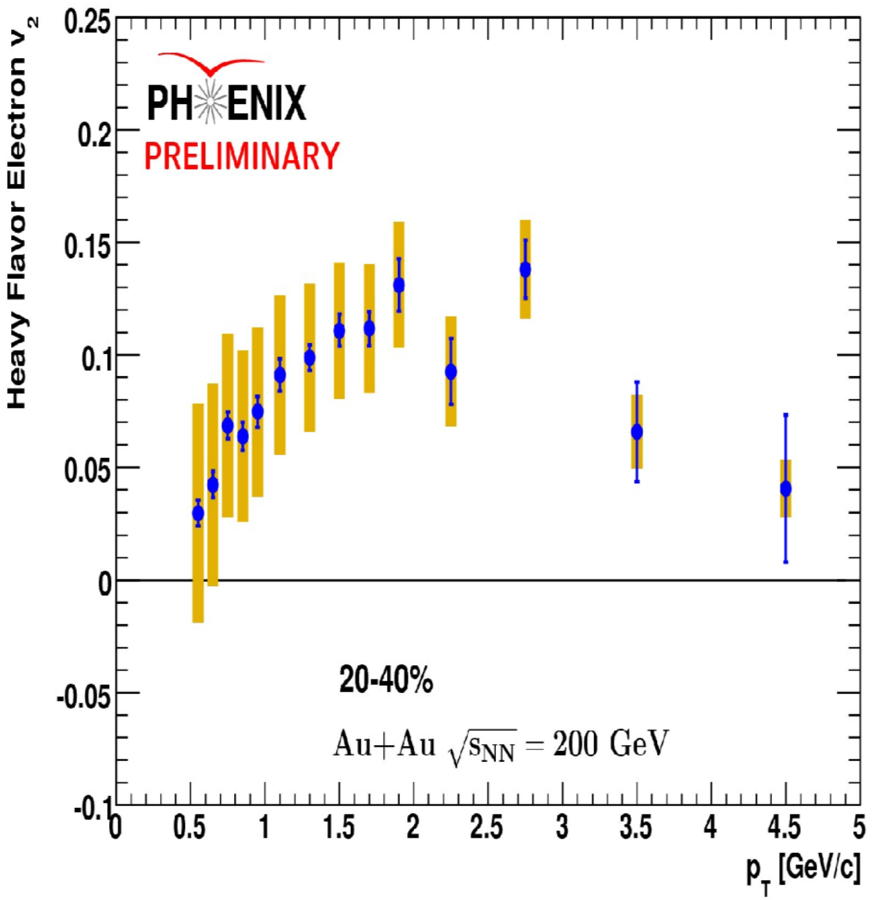
$$\sigma_{gc\to gc} \to K\,\sigma_{gc\to gc}$$



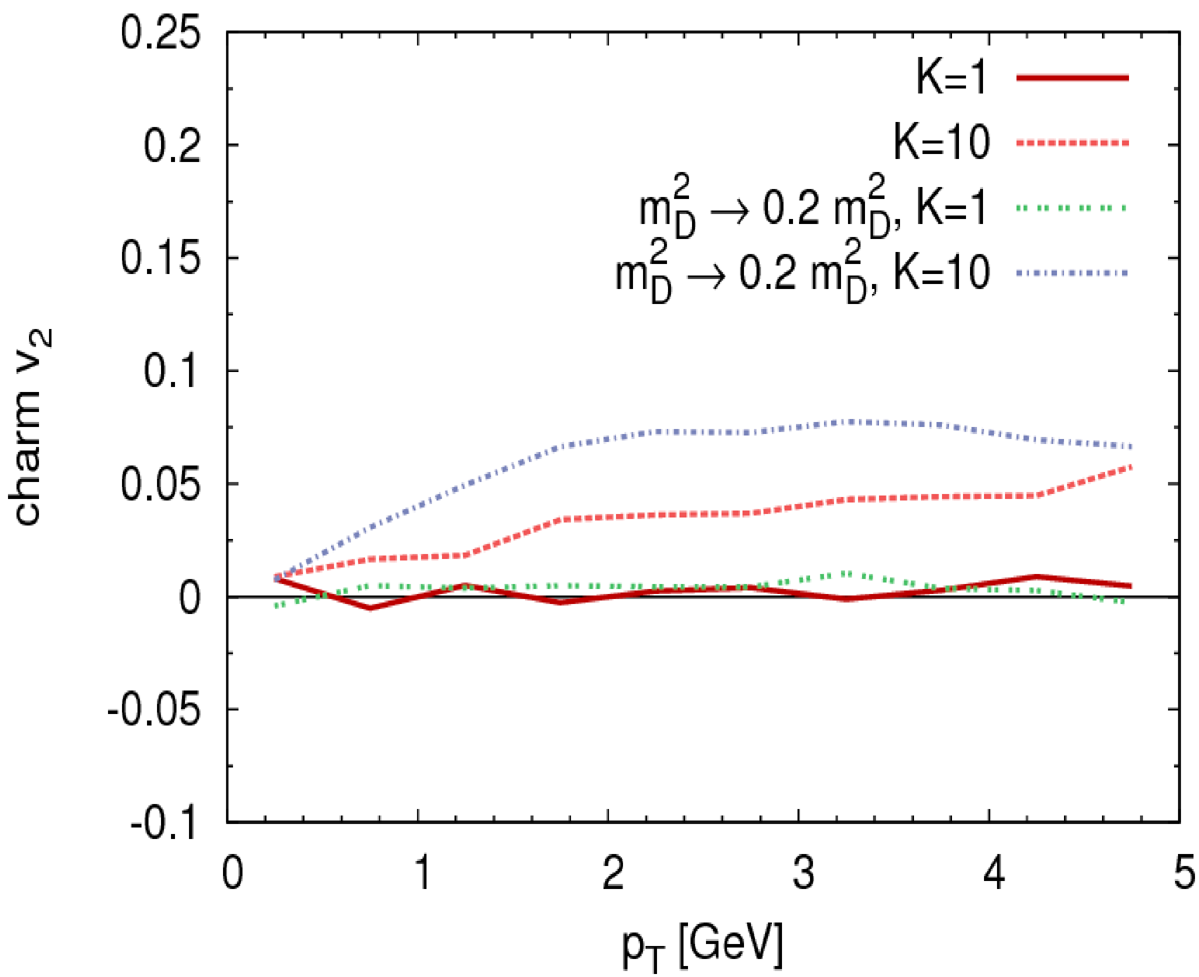
only elastic charm processes

Elliptic flow v_2 for charm at RHIC





Elliptic flow v_2 for charm at RHIC



Debye mass with a prefactor κ = 0.2, proposed by

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

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

only elastic charm processes

$$\sigma_{gc\to gc} \to K\ \sigma_{gc\to gc}$$

Conclusion & outlook

- Chemical equilibration time for charm very large
- Huge uncertainty on initial charm yield due to PDF and scale dependencies
  ➡ LO calculations cannot explain data

Full space-time evolution of charm and bottom quarks

- Small charm yield during QGP phase
  - RHIC: 3 - 27 % of final charm are produced in QGP
  - LHC: 15 - 45 % of final charm are produced in QGP
- Negligible bottom yield during QGP phase at LHC
- LO gluon charm scattering is not sufficient to build up collective flow

Future tasks:

- Light quarks
- Higher order corrections, gluon radiation for charm scattering
- Energy loss of charm quarks ➡ R_{AA}

Thank you for your attention.

Backup

BAMPS

- **3+1 dimensional Monte Carlo cascade**

- **Divides collision zone into cells**

Z. Xu & C. Greiner,
Phys. Rev. C 71 (2005) 064901

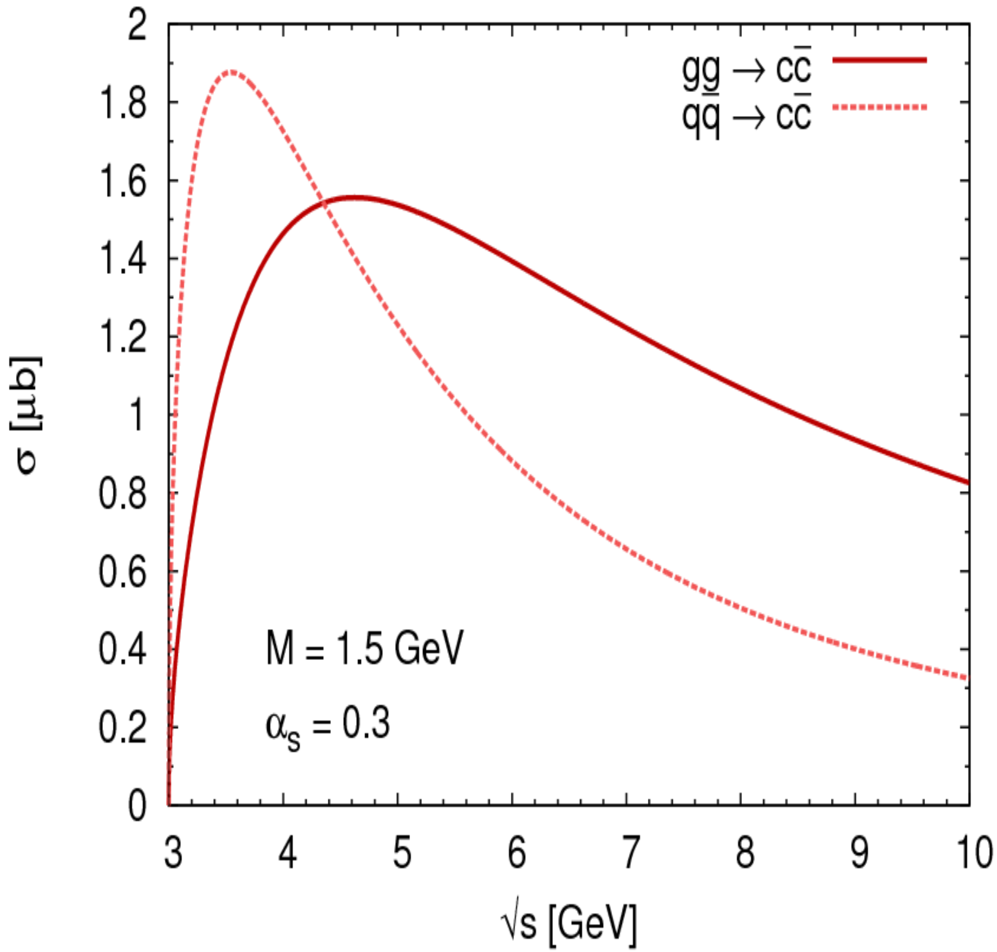
- **Using stochastic method:**

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

$$v_{\rm rel} = \frac{\sqrt{(P_1^\mu P_{2\mu})^2 - m_1^2 m_2^2}}{E_1 E_2}$$

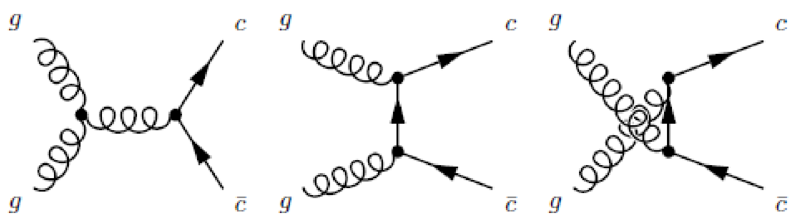
- **Testparticles to increase statistics**

Partonic cross sections



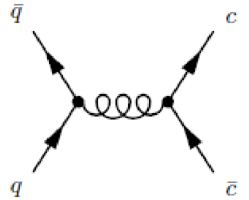
Dominant process for charm production:

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



Other possible process:

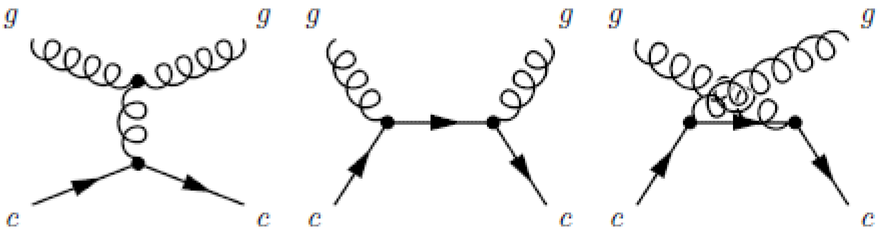
$$q + \bar{q} \to c + \bar{c}$$

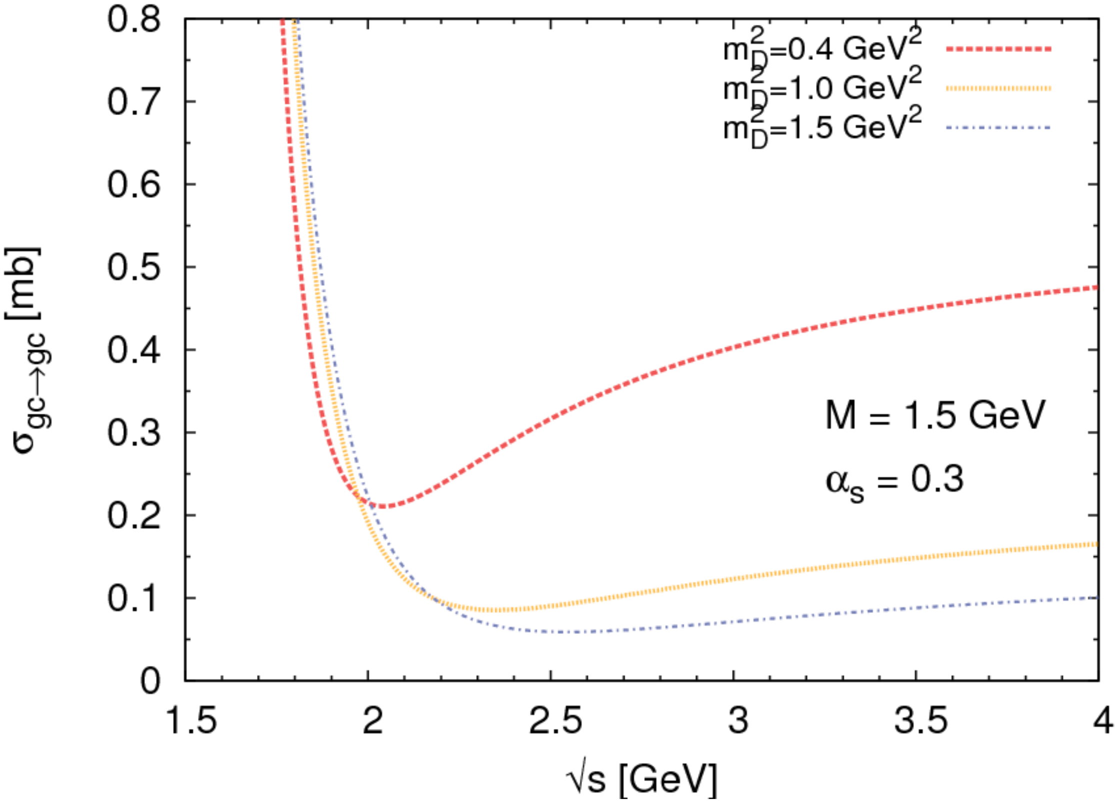


Charm quark scattering

LO pQCD:

$$g + c \rightarrow g + c$$
$$g + \bar{c} \rightarrow g + \bar{c}$$





Debye screening

Partonic cross sections

Back reaction

$$c + \bar{c} \rightarrow g + g$$

through detailed balance

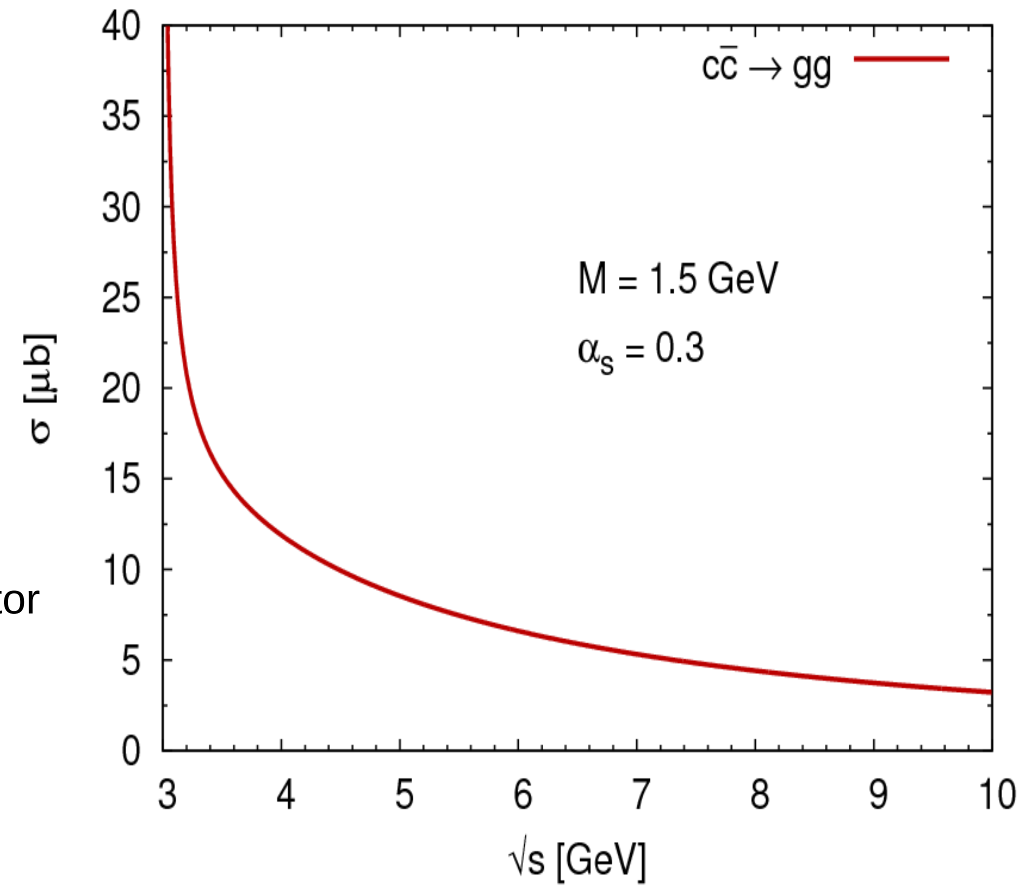
$$\sigma_{c\bar{c}\rightarrow gg} = \frac{1}{2}\,\frac{64}{9}\,\frac{1}{\chi}\,\sigma_{gg\rightarrow c\bar{c}}$$

gluons identical particles

color averaging

kinematical factor

$$\chi = \sqrt{1 - \frac{4M^2}{s}}$$



Solution of rate equation

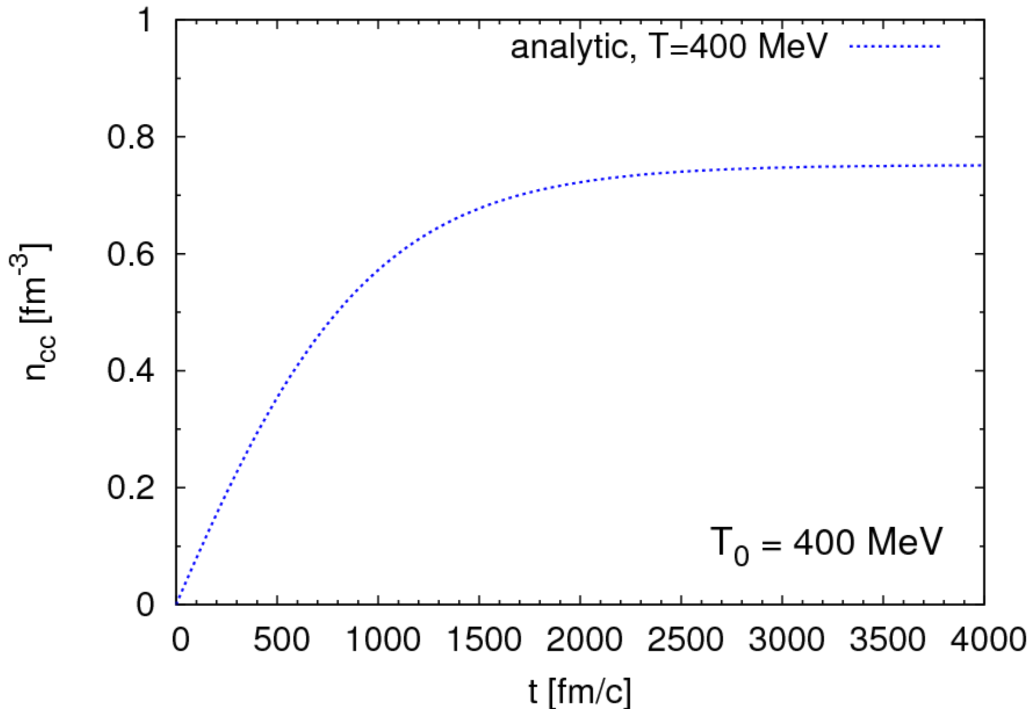
Number of charm quarks for fixed temperature and fixed number of particles:

$$n_{c+\bar{c}}(t) = \frac{n_{tot}}{1-\zeta^2}\left[1 - \frac{e^{2t/\tau}(\zeta+1)-\zeta+1}{e^{2t/\tau}\left(\frac{1}{\zeta}+1\right)-\frac{1}{\zeta}+1}\right]$$

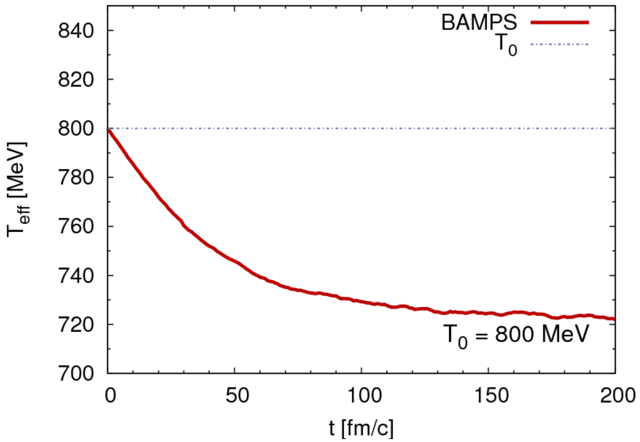
$$\zeta = \frac{n_g^{eq}}{n_{c+\bar{c}}^{eq}} = \frac{n_{tot}-n_{c+\bar{c}}^{eq}}{n_{c+\bar{c}}^{eq}}$$

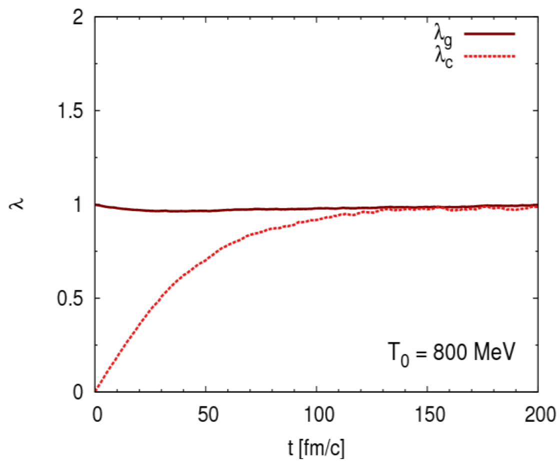
$$\tau = \frac{n_{c+\bar{c}}^{eq}}{\sigma_g n_{tot} n_g^{eq}} = \frac{n_{c+\bar{c}}^{eq}}{\sigma_g(n_{tot}^2 - n_{tot}n_{c+\bar{c}}^{eq})}$$

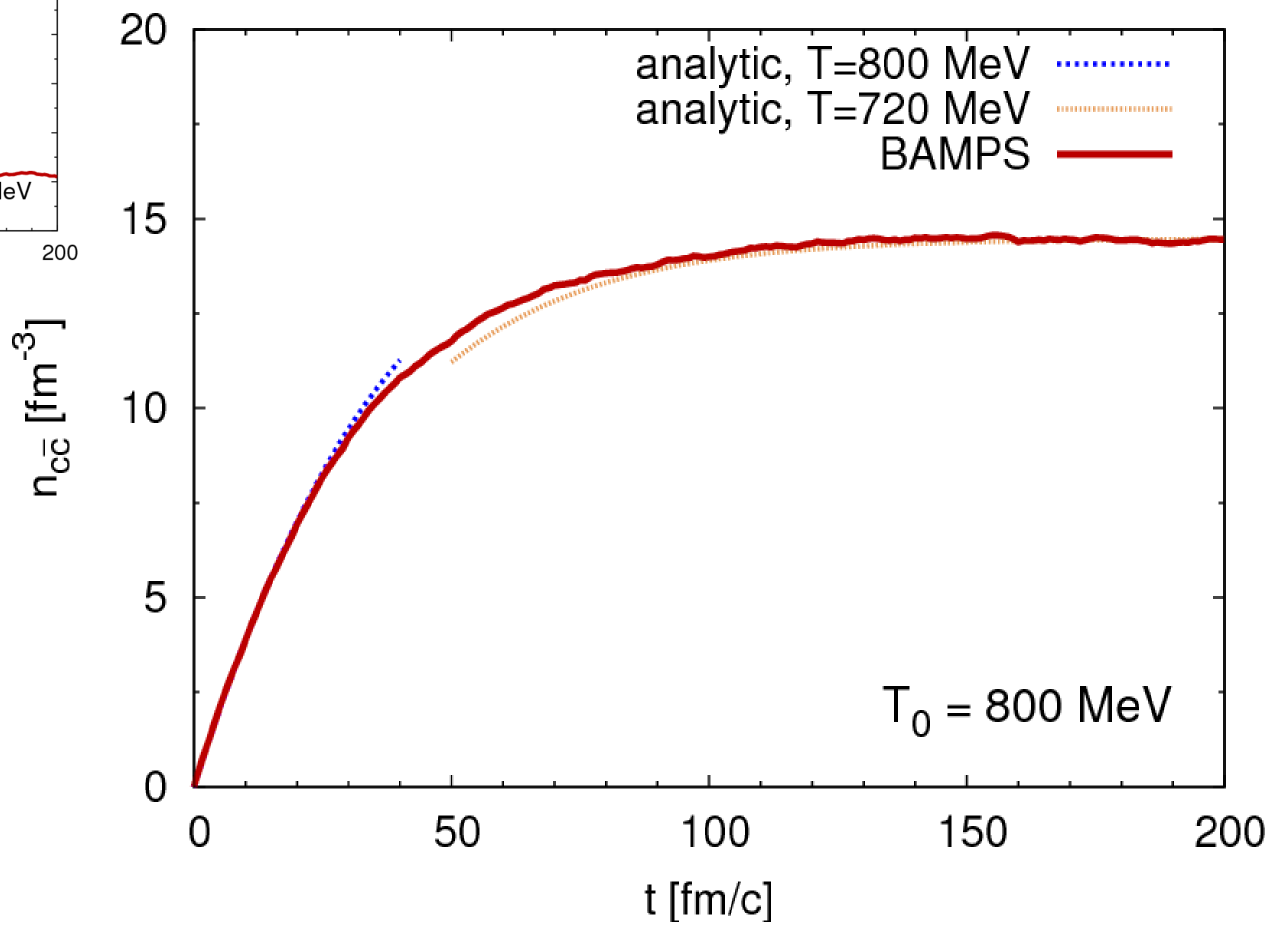
$$n_{c+\bar{c}}^{eq} = \frac{n_{tot}}{\frac{1}{\sqrt{2R}}+1}$$



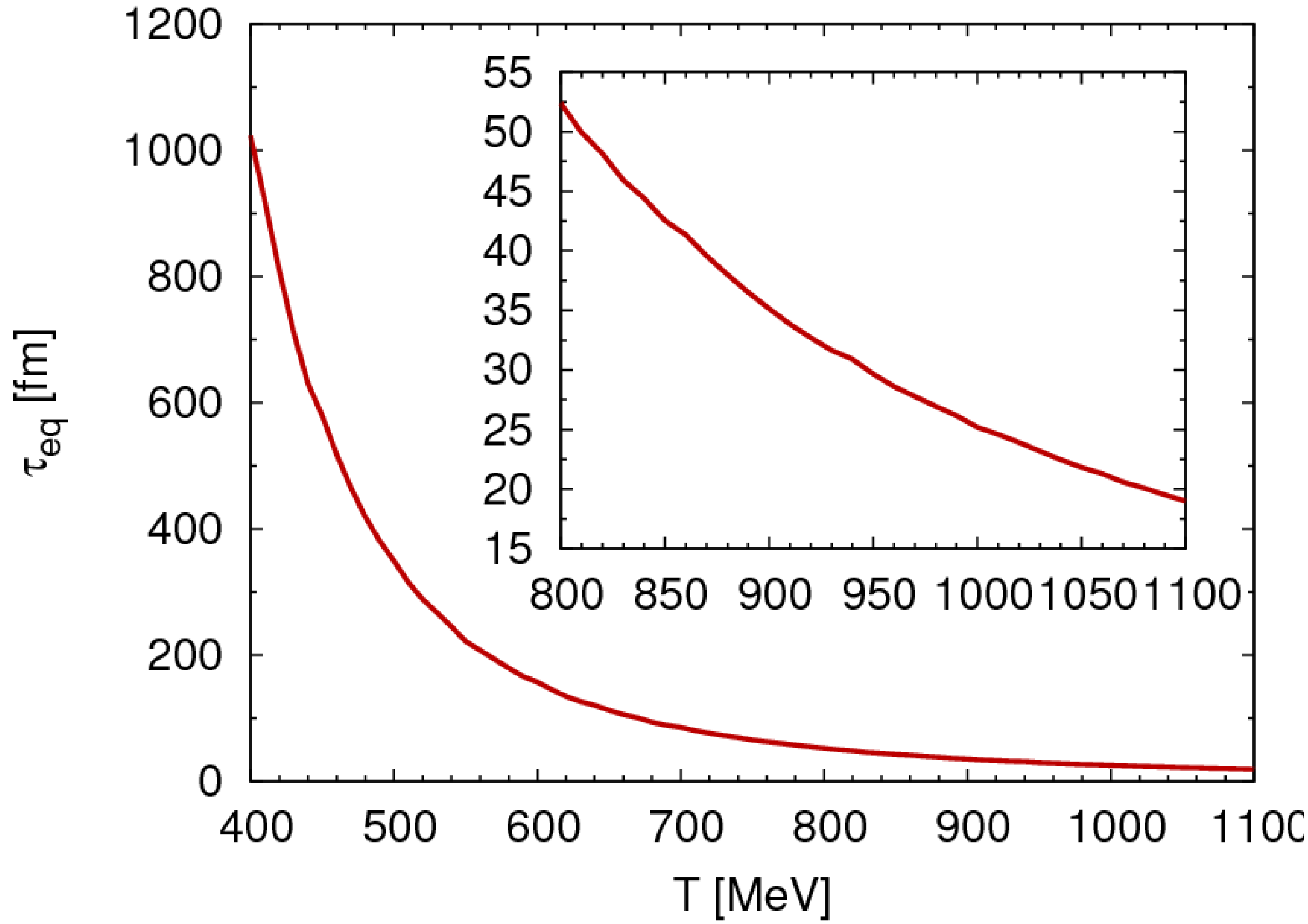
Box calculation T_0 = 800 MeV







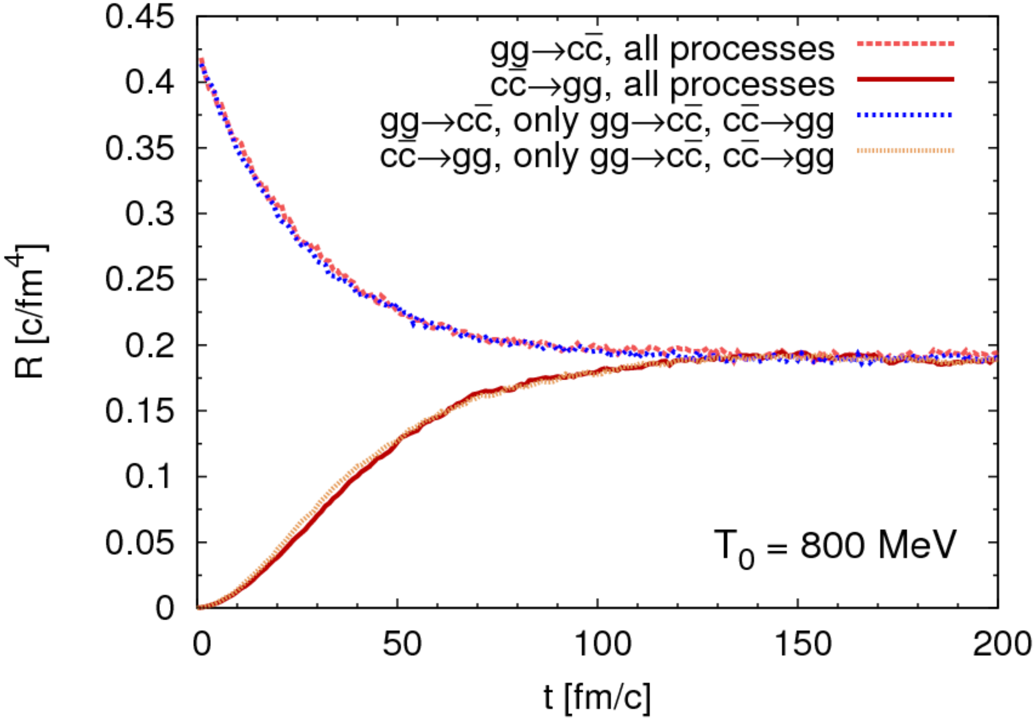
Time scale of chemical equilibration

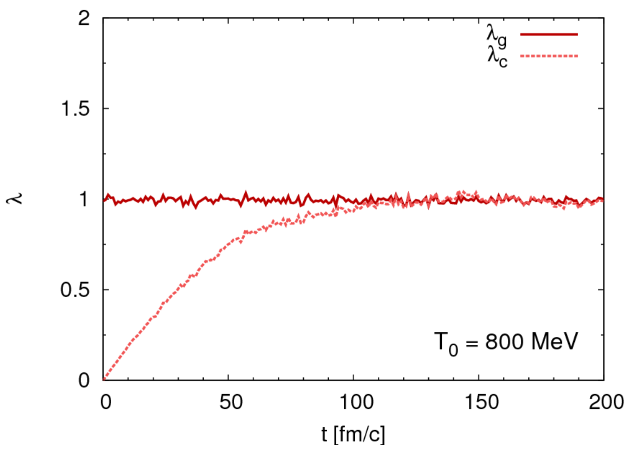


Time scale of chemical equilibration

Considering all processes

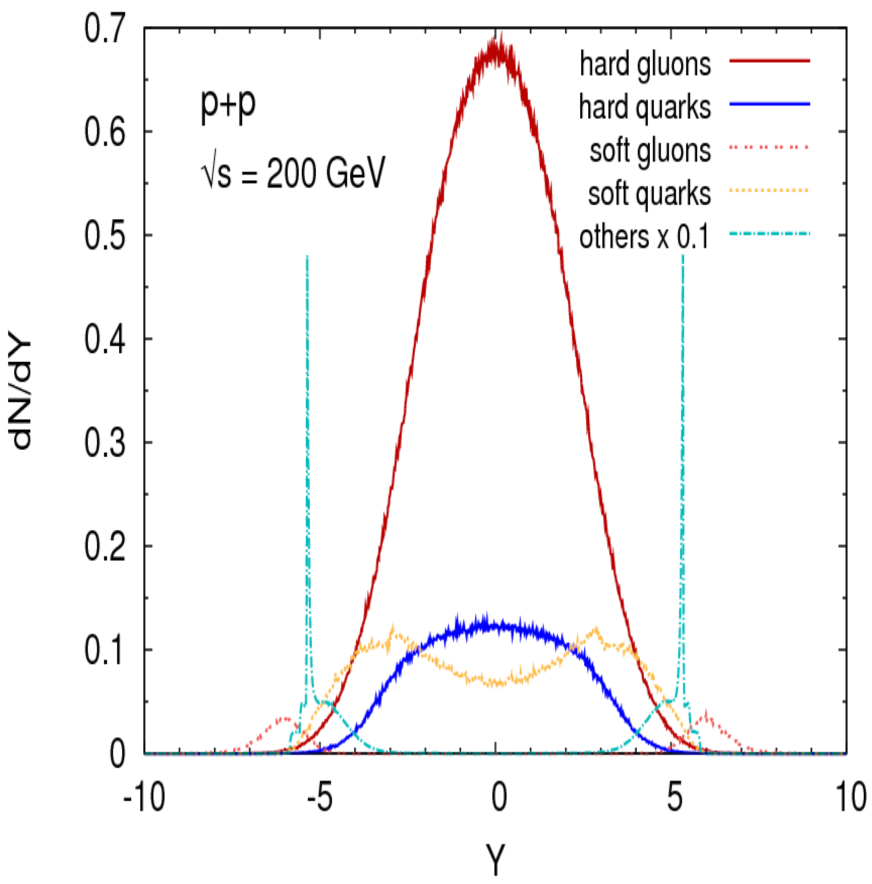
$$g+g \rightarrow g+g \qquad g+g \rightarrow c+\bar{c}$$
$$g+g \rightarrow g+g+g \qquad c+\bar{c} \rightarrow g+g$$
$$g+g+g \rightarrow g+g \qquad g+c \rightarrow g+c$$
$$g+\bar{c} \rightarrow g+\bar{c}$$





No change of chemical equilibration time scale

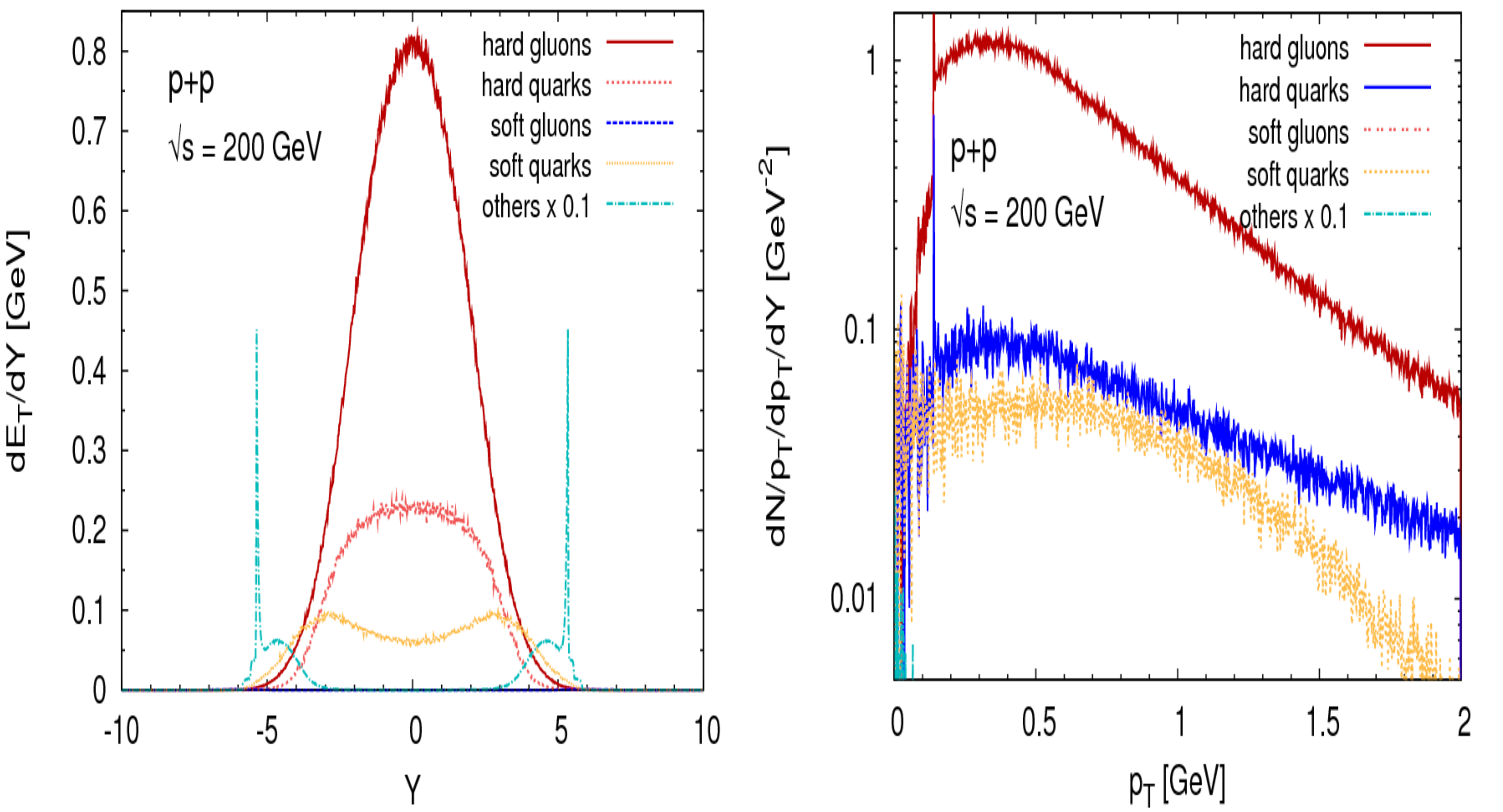
PYTHIA simulates only nucleon-nucleon collisions



Distinguish between particles from soft and hard events

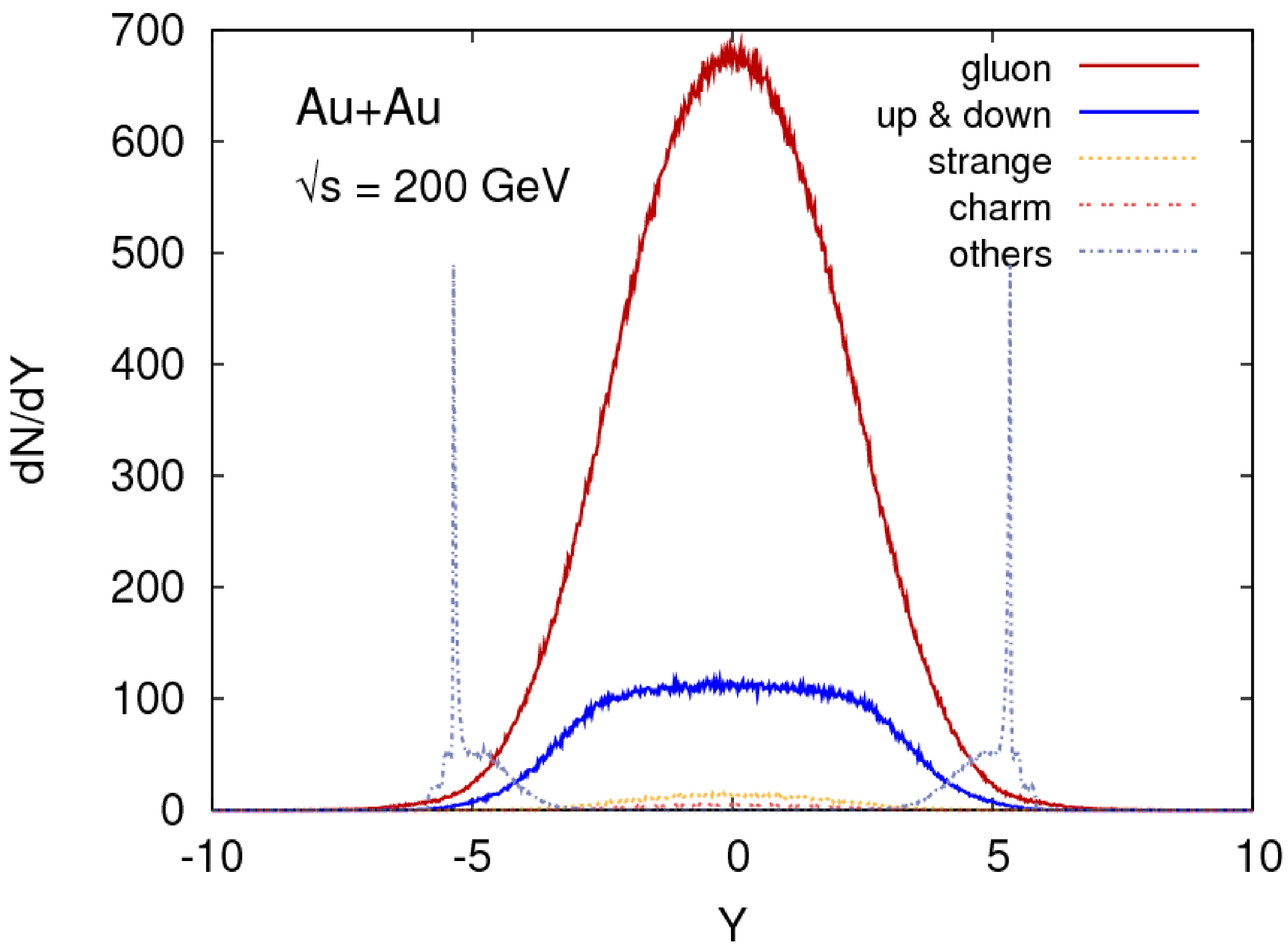
hard parton scatterings	soft scatterings
$q_i q_j \to q_i q_j$	elastic
$q_i \bar{q}_i \to q_k \bar{q}_k$	single diffractive
$q_i \bar{q}_i \to gg$	double diffractive
$q_i g \to q_i g$	low-$p_\perp$ production
$gg \to q_k \bar{q}_k$	
$gg \to gg$	

PYTHIA

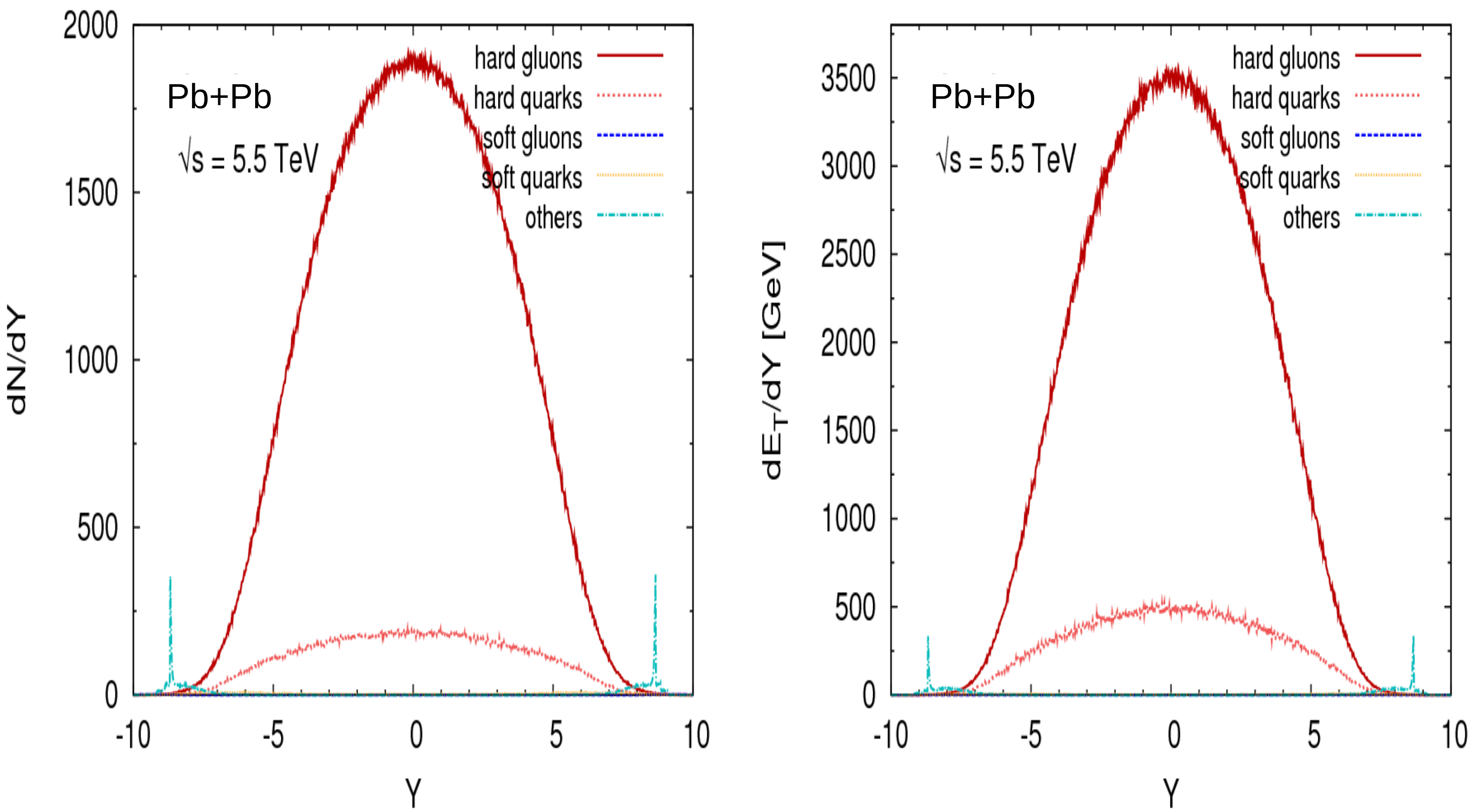


p+p
√s = 200 GeV
hard gluons
hard quarks
soft gluons
soft quarks
others x 0.1
dE_T/dY [GeV]
Y
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-10
-5
0
5
10
p+p
√s = 200 GeV
hard gluons
hard quarks
soft gluons
soft quarks
others x 0.1
dN/p_T/dp_T/dY [GeV^-2]
p_T [GeV]
1
0.1
0.01
0
0.5
1
1.5
2

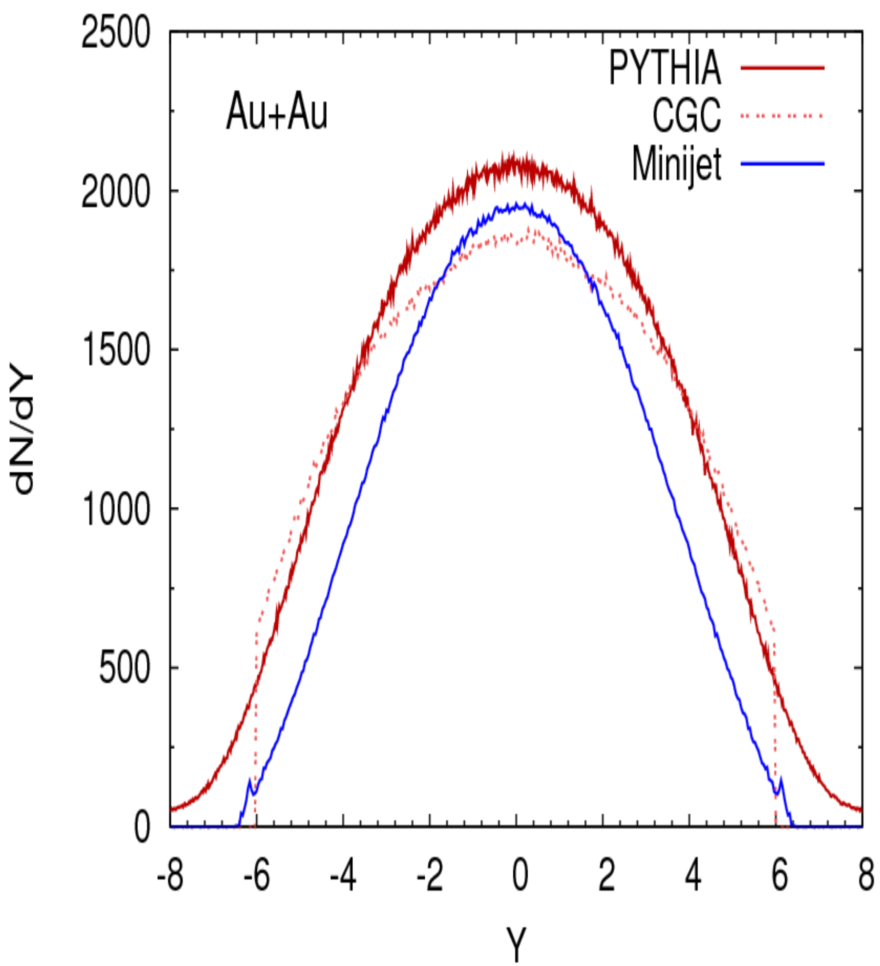
Initial conditions for parton cascade

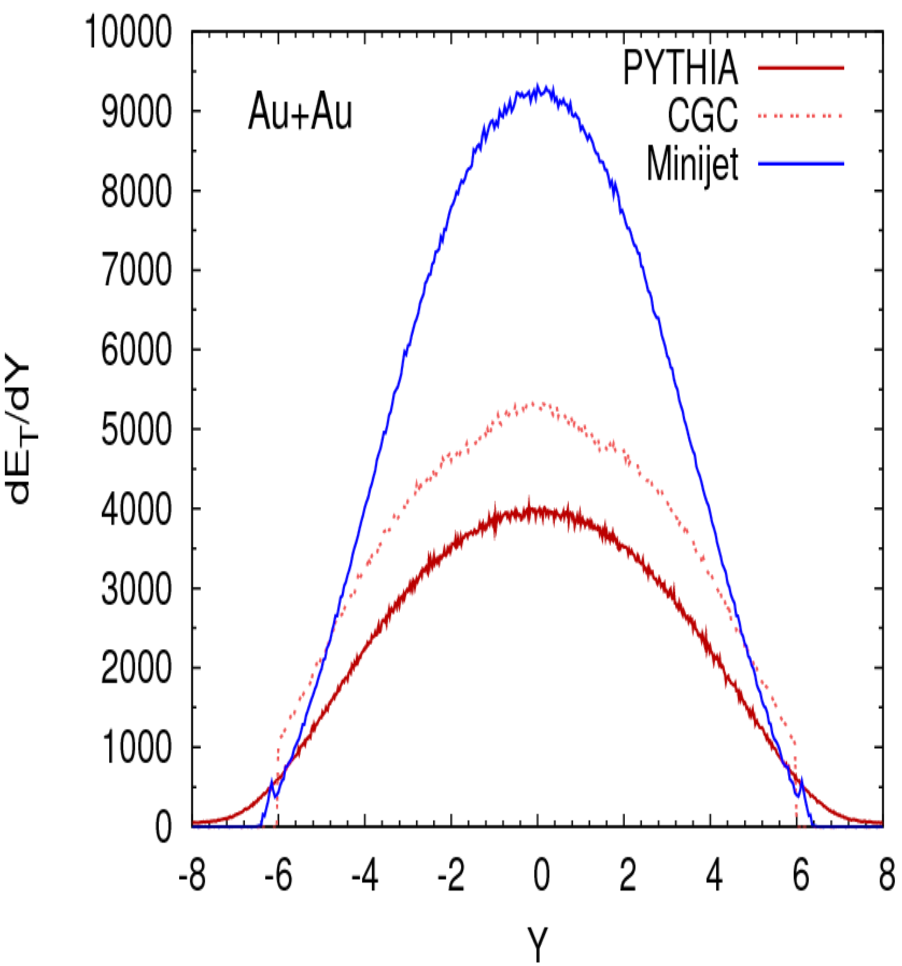


Initial conditions for cascade at LHC



Initial conditions for cascade at LHC





In agreement with most of LHC predictions
(cf. N. Armesto, J.Phys.G35 (2008)

Charm yield from PYTHIA

Total initial charm yield in central Au+Au collisions @ RHIC:

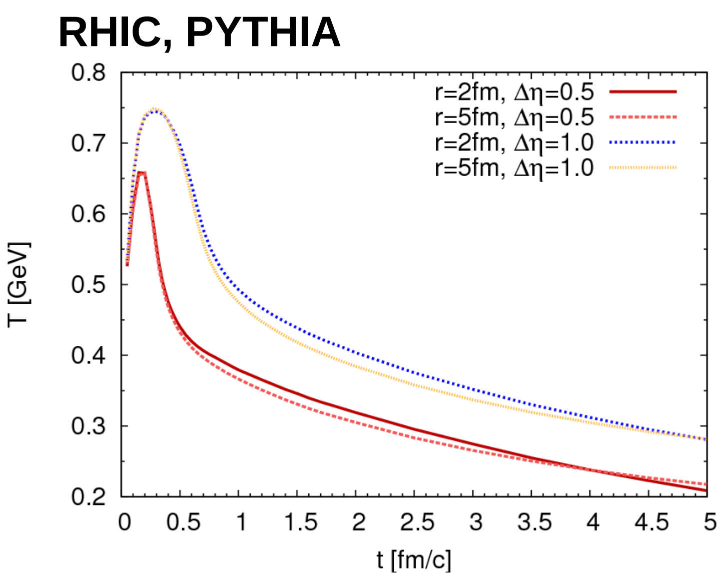
- **PYTHIA:**
  3 – 14 charm pairs
- **LO pQCD:**
  2 – 4 charm pairs

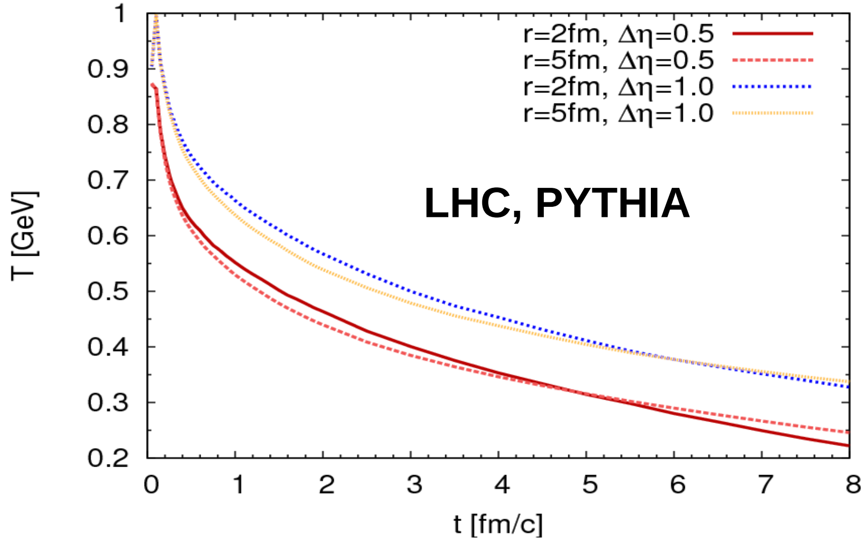
Parton distribution functions	charm quark pairs
CTEQ5l (LO) (Standard)	8.9
CTEQ6l (LO)	9.2
CTEQ6m ($\overline{MS}$)	13.6
MRST2001LO	9.6
MRST2007LOmod	9.2
HERAPDF01	12.3
GJR08 (FF LO)	3.0
GRV98 (LO)	3.0

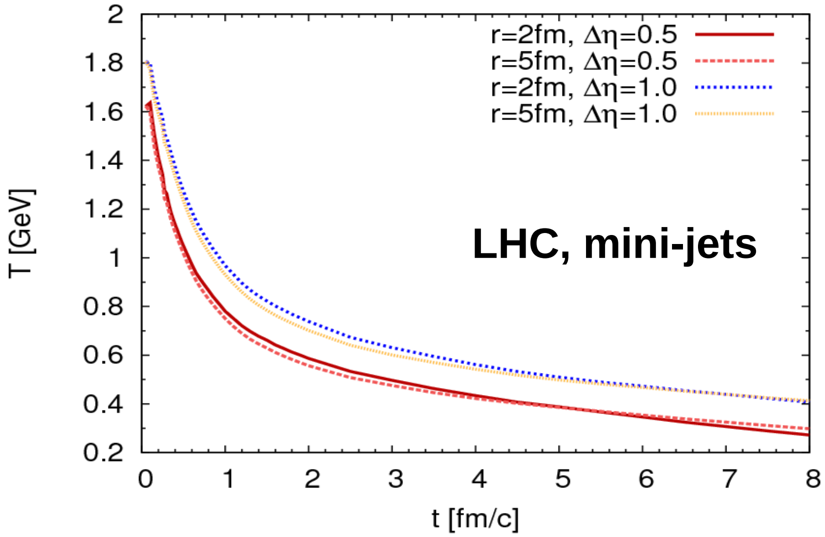
Choose CTEQ6l as standard parton distribution function, although its charm yield is farer from data than CTEQ6m

➡ **Reason: Designed for LO event generators**

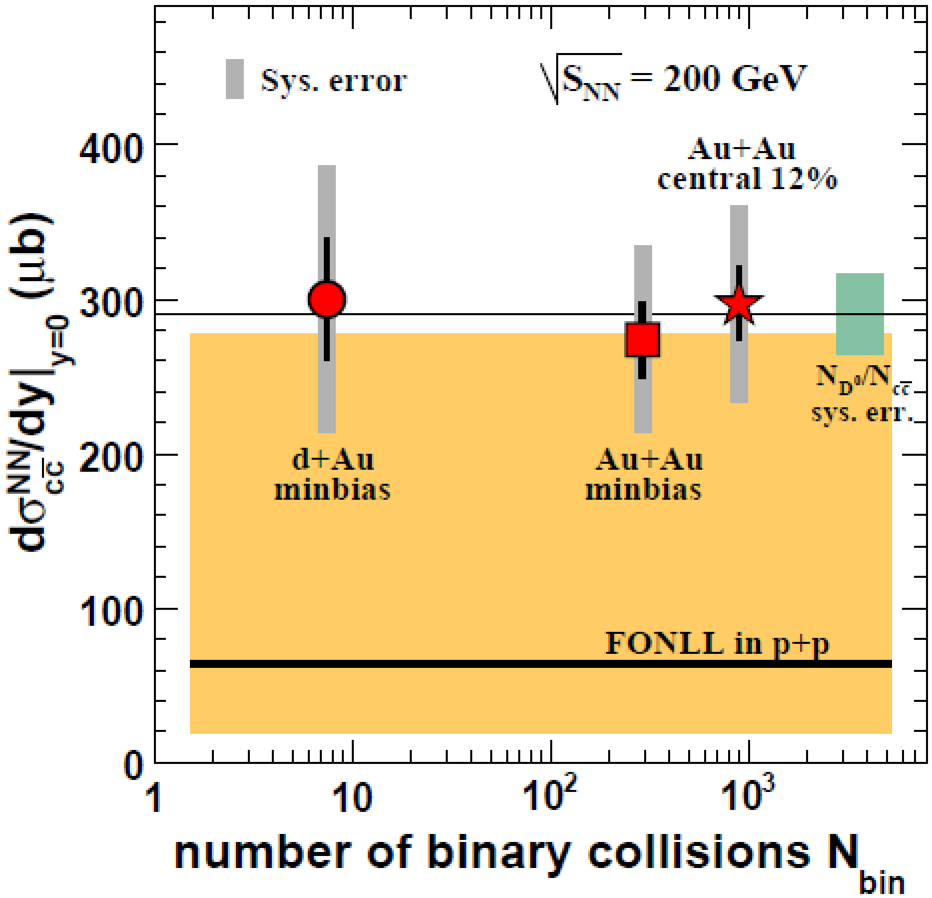
Temperature at RHIC and LHC







Charm scales with number of bin. coll.



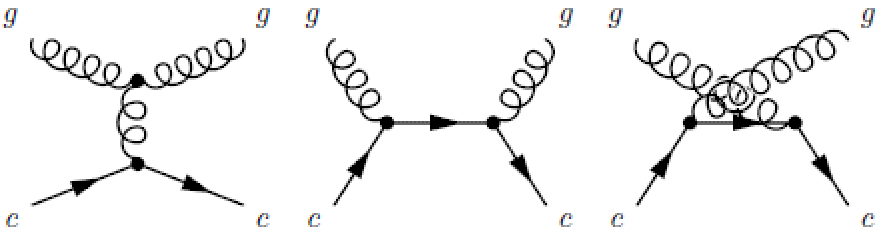
STAR data

arXiv:0805.0364 [nucl-ex]

Charm quark scattering

LO pQCD:

$$g + c \rightarrow g + c$$
$$g + \bar{c} \rightarrow g + \bar{c}$$



Cross section:

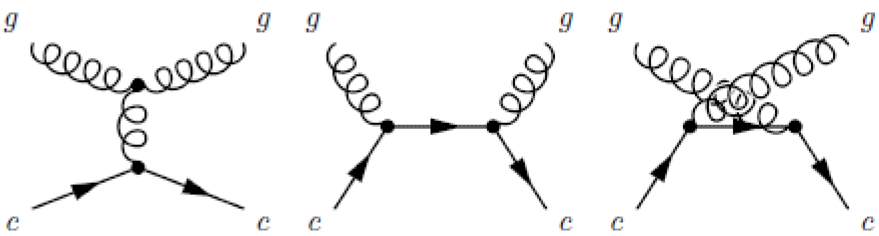
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\left|\overline{\mathcal{M}}_{gc\rightarrow gc}\right|^2}{16\pi\left(s - M^2\right)^2}$$

$$\frac{\left|\overline{\mathcal{M}}_{gc\rightarrow gc}\right|^2}{\pi^2\alpha_s^2} = \frac{32(s-M^2)(M^2-u)}{t^2} + \frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2}$$
$$+ \frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(u+M^2)}{(M^2-u)^2} + \frac{16}{9}\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)}$$
$$+ 16\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t(s-M^2)} - 16\frac{(s-M^2)(M^2-u)-M^2(s-u)}{t(M^2-u)}$$

Charm quark scattering

LO pQCD:

$$g + c \rightarrow g + c$$
$$g + \bar{c} \rightarrow g + \bar{c}$$



Cross section:

$$\frac{d\sigma}{dt} = \frac{\left|\overline{\mathcal{M}}_{gc\rightarrow gc}\right|^2}{16\pi\left(s - M^2\right)^2}$$

$$\frac{\left|\overline{\mathcal{M}}_{gc\rightarrow gc}\right|^2}{\pi^2\alpha_s^2} = \frac{32(s-M^2)(M^2-u)}{t^2} + \frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2}$$
$$+ \frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(u+M^2)}{(M^2-u)^2} + \frac{16}{9}\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)}$$
$$+ 16\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t(s-M^2)} - 16\frac{(s-M^2)(M^2-u)-M^2(s-u)}{t(M^2-u)}$$

divergent for t=0

Charm quark scattering

$$\sigma_{gc\to gc}(s) = \int_{t_{min}}^{t_{max}} \frac{\mathrm{d}\sigma}{\mathrm{d}t}\mathrm{d}t$$

$$t_{max} = 0$$

$$t_{min} = -\frac{(s-M^2)^2}{s}$$

Solutions:

1. **Cut-off for t_{max}**
2. **Debye screening**

$$t \to t - m_D^2$$

$$m_D^2 = 16\pi\alpha_s \int \frac{\mathrm{d}^3p}{(2\pi)^3}\frac{1}{p}(N_c f_g + N_f f_q)$$

Charm quark scattering

$$\sigma_{gc\to gc}(s) = \int_{t_{min}}^{t_{max}} \frac{\mathrm{d}\sigma}{\mathrm{d}t}\mathrm{d}t$$

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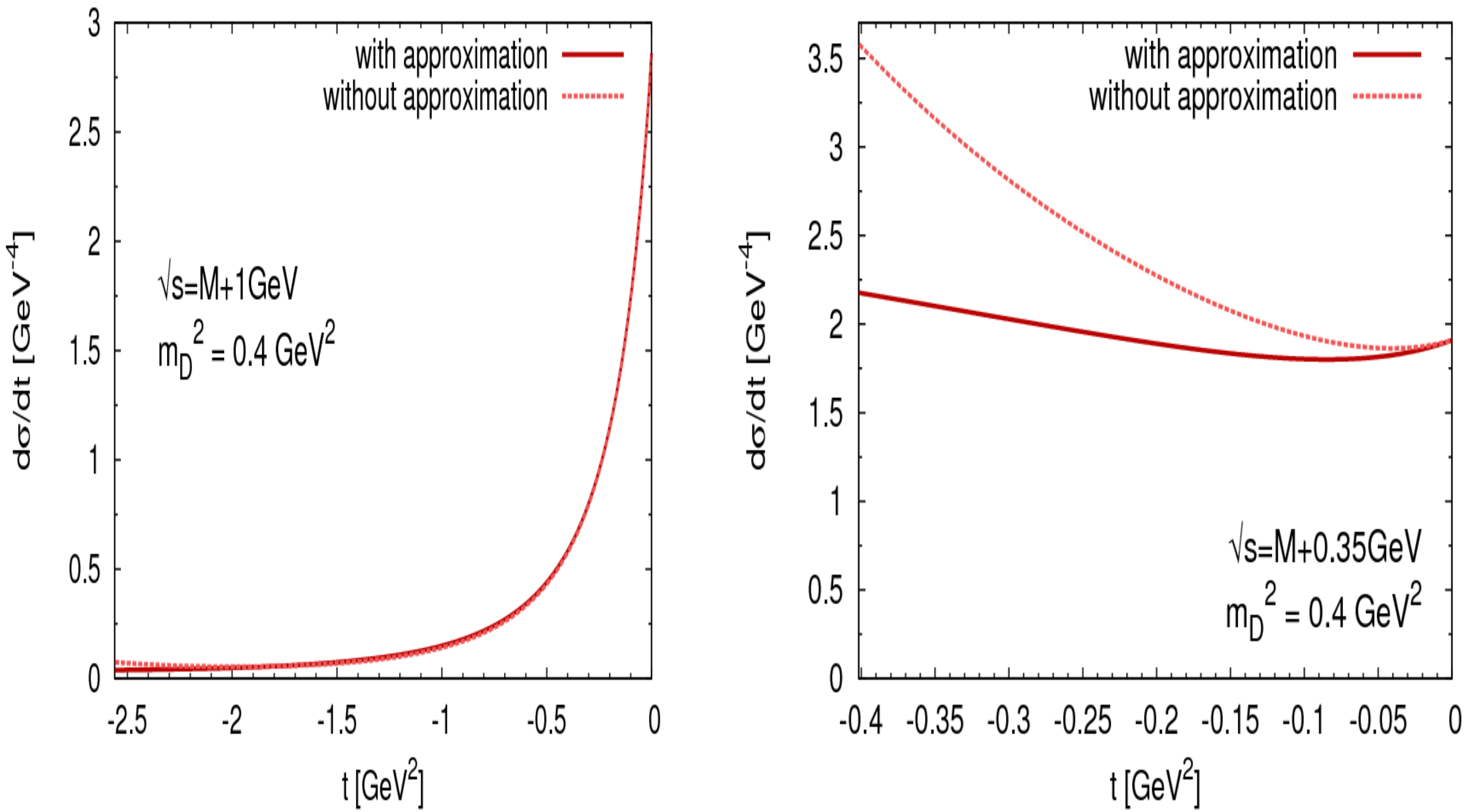
$$m_D^2 = 16\pi\alpha_s \int \frac{\mathrm{d}^3p}{(2\pi)^3}\frac{1}{p}(N_c f_g + N_f f_q)$$

Total cross section:

$$\sigma_{gc\to gc}(s) = \pi\alpha_s^2 \left\{ \frac{2}{m_D^2} - \frac{2s}{(s-M^2)^2 + s\,m_D^2} + 2\frac{s+M^2}{(s-M^2)^2}\ln\left[\frac{s\,m_D^2}{(s-M^2)^2 + s\,m_D^2}\right] + \frac{17}{9s} + \frac{2M^2}{s(s-M^2)} + \frac{4M^4}{s(s-M^2)^2} \right\}$$

Charm quark scattering

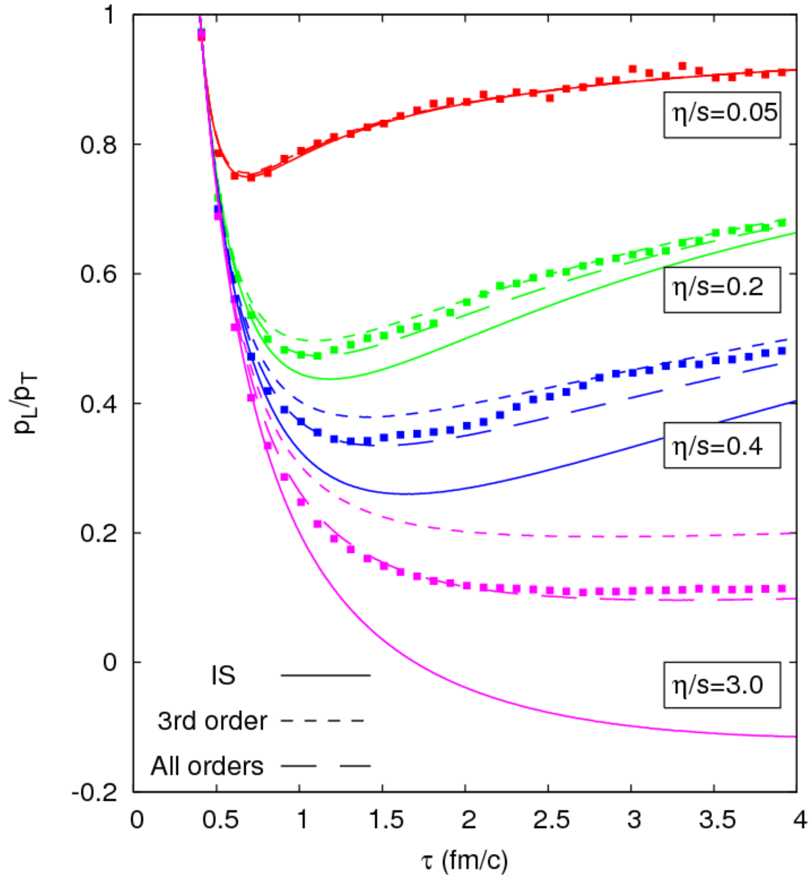


LO pQCD: mini-jets

p+p
Sqrt(s)=
200 GeV

PDF	Skala $\mu_F = \mu_R$	M_c [GeV]	σ [μb]	$d\sigma/dY\|_{Y=0}$ [μb]
CTEQ6m	$2M_c$	1.2	160	38
		1.5	72	19
	$\sqrt{p_T^2 + M_c^2}$	1.2	140	36
		1.5	79	20
	PYTHIA		540	130
CTEQ6l	$2M_c$	1.2	230	57
		1.5	90	25
	$\sqrt{p_T^2 + M_c^2}$	1.2	280	68
		1.5	120	31
	PYTHIA		370	91
GRV98lo	$2M_c$	1.2	190	38
		1.5	78	17
	$\sqrt{p_T^2 + M_c^2}$	1.2	220	43
		1.5	97	20
	PYTHIA		120	30
PHENIX			544 ± 381	123 ± 47
STAR			1400 ± 600	300 ± 130

Comparison with Hydro



A. El, Z. Xu and C. Greiner, arXiv: 0907.4500 [hep-ph]

Eta/s extraction

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ZX and C.Greiner, PRL 100, 172301, (2008)

$$\eta_{NS} \cong \frac{1}{5} n \frac{\left\langle E\left(\frac{1}{3}-\frac{p_z^2}{E^2}\right)\right\rangle}{\frac{1}{3}-\left\langle\frac{p_z^2}{E^2}\right\rangle} \frac{1}{R^{tr}[f]+\frac{3}{n}\int dw\, C[f]}$$

transport rate

$$R^{tr} = \frac{\int dw \frac{p_z^2}{E^2} C[f] - \left\langle\frac{p_z^2}{E^2}\right\rangle \int dw\, C[f]}{n\left(\frac{1}{3}-\left\langle\frac{p_z^2}{E^2}\right\rangle\right)} \sim n\sigma^{tr} = n\int d\theta \frac{d\sigma}{d\theta}\sin^2\theta$$

$$s = 4n - n\ln\lambda$$

Partonic cross sections

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\left|\overline{\mathcal{M}}_{gg\to c\bar{c}}\right|^2}{16\pi s^2}$$

$$\frac{\left|\overline{\mathcal{M}}_{gg\to c\bar{c}}\right|^2}{\pi^2\alpha_s^2} = \frac{12}{s^2}(M^2-t)(M^2-u) + \frac{8}{3}\left(\frac{M^2-u}{M^2-t} + \frac{M^2-t}{M^2-u}\right)$$
$$- \frac{16M^2}{3}\left[\frac{M^2+t}{(M^2-t)^2} + \frac{M^2+u}{(M^2-u)^2}\right] - \frac{6}{s}(2M^2-t-u)$$
$$+ \frac{6}{s}\frac{M^2(t-u)^2}{(M^2-t)(M^2-u)} - \frac{2}{3}\frac{M^2(s-4M^2)}{(M^2-t)(M^2-u)}$$

Partonic cross sections

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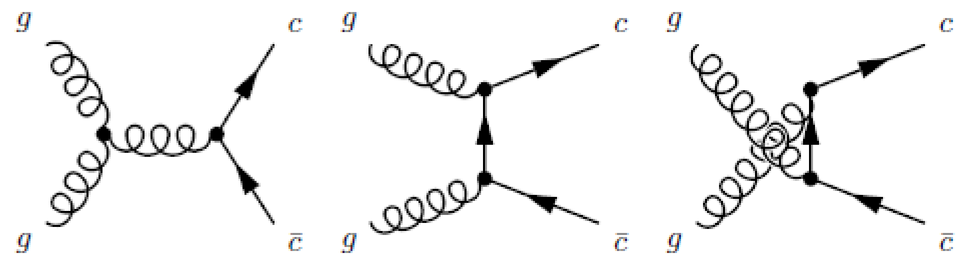
$$g + g \rightarrow c + \bar{c}$$



$$\sigma_{gg\rightarrow c\bar{c}}(s) = \frac{\pi\alpha_s^2}{3s}\left[\left(1+\frac{4M^2}{s}+\frac{M^4}{s^2}\right)\log\left(\frac{1+\chi}{1-\chi}\right) - \left(\frac{7}{4}+\frac{31M^2}{4s}\right)\chi\right]$$

$$\chi = \sqrt{1-\frac{4M^2}{s}}$$

$$q + \bar{q} \rightarrow c + \bar{c}$$

$$\sigma_{q\bar{q}\rightarrow c\bar{c}}(s) = \frac{8\pi\alpha_s^2}{27s}\left(s+2M^2\right)\chi$$