# Heavy quark production and elliptic flow at RHIC and LHC

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**Winter Workshop on Nuclear Dynamics**

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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

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**Large heavy quark mass**

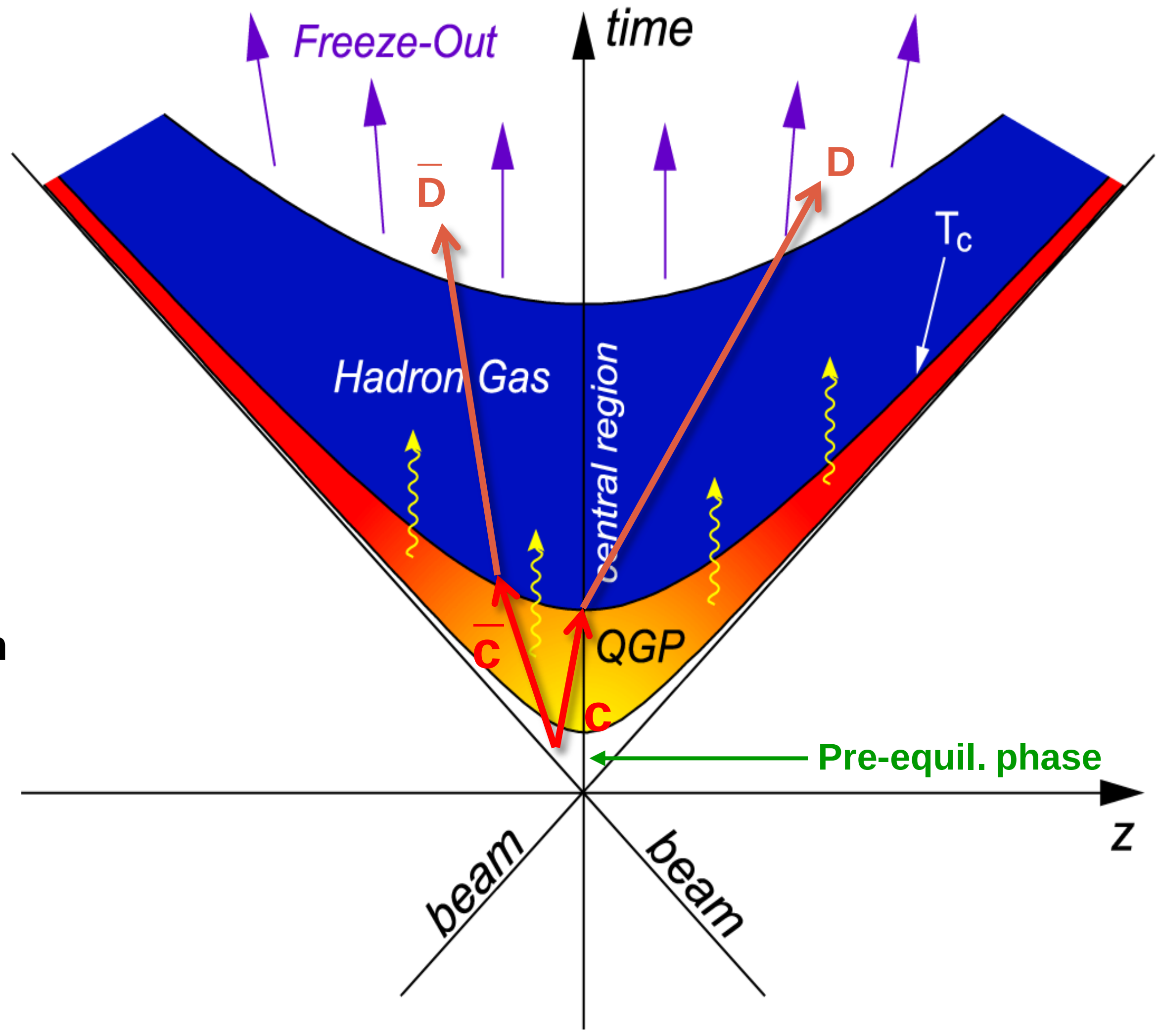
**>> $\Lambda_{QCD}$**

**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**



# Our model: 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:**

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

(no light quarks yet)

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

# 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:**

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

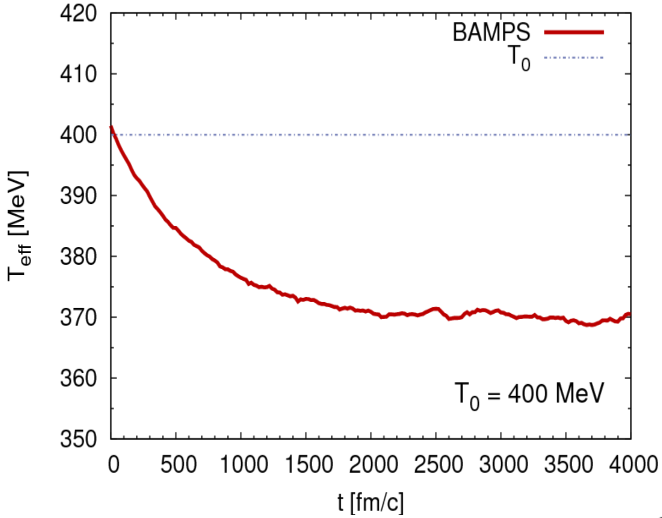
**with**

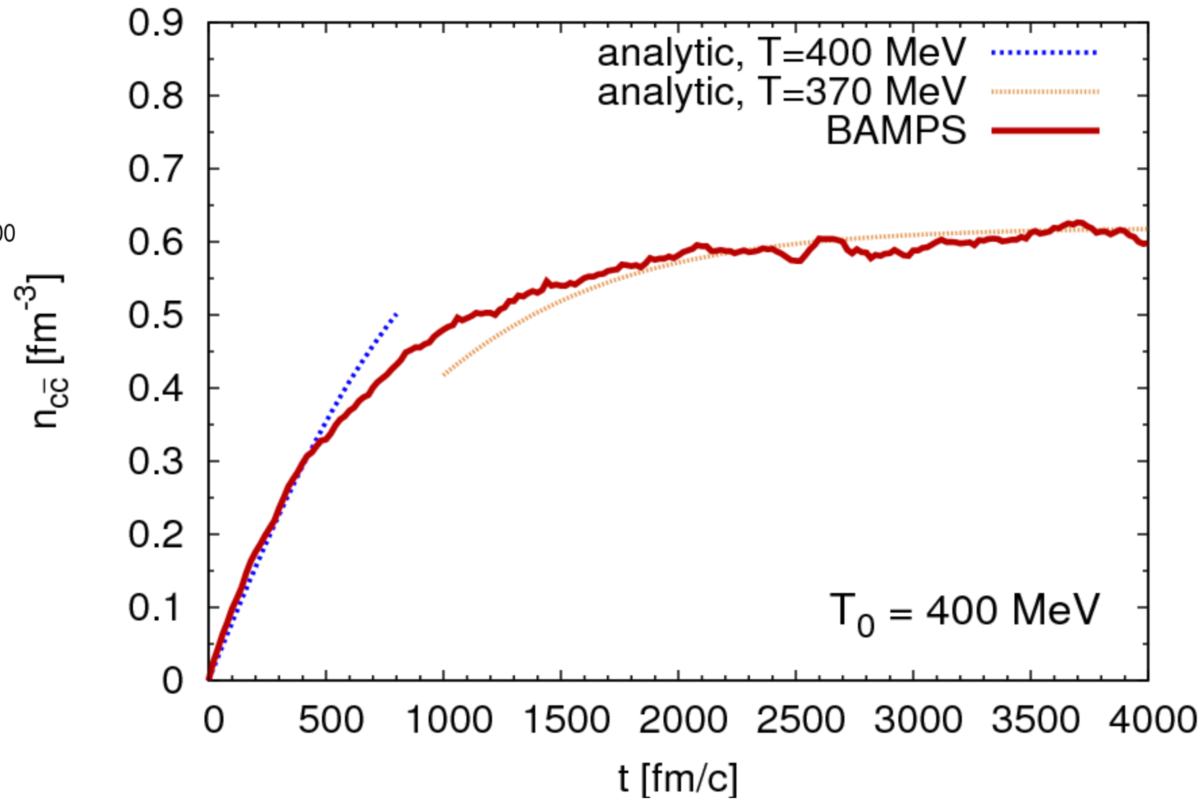
$$R_{gg\rightarrow c\bar{c}} = \frac{1}{2} < \sigma_{gg\rightarrow c\bar{c}} v_{rel} > n_g^2$$

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

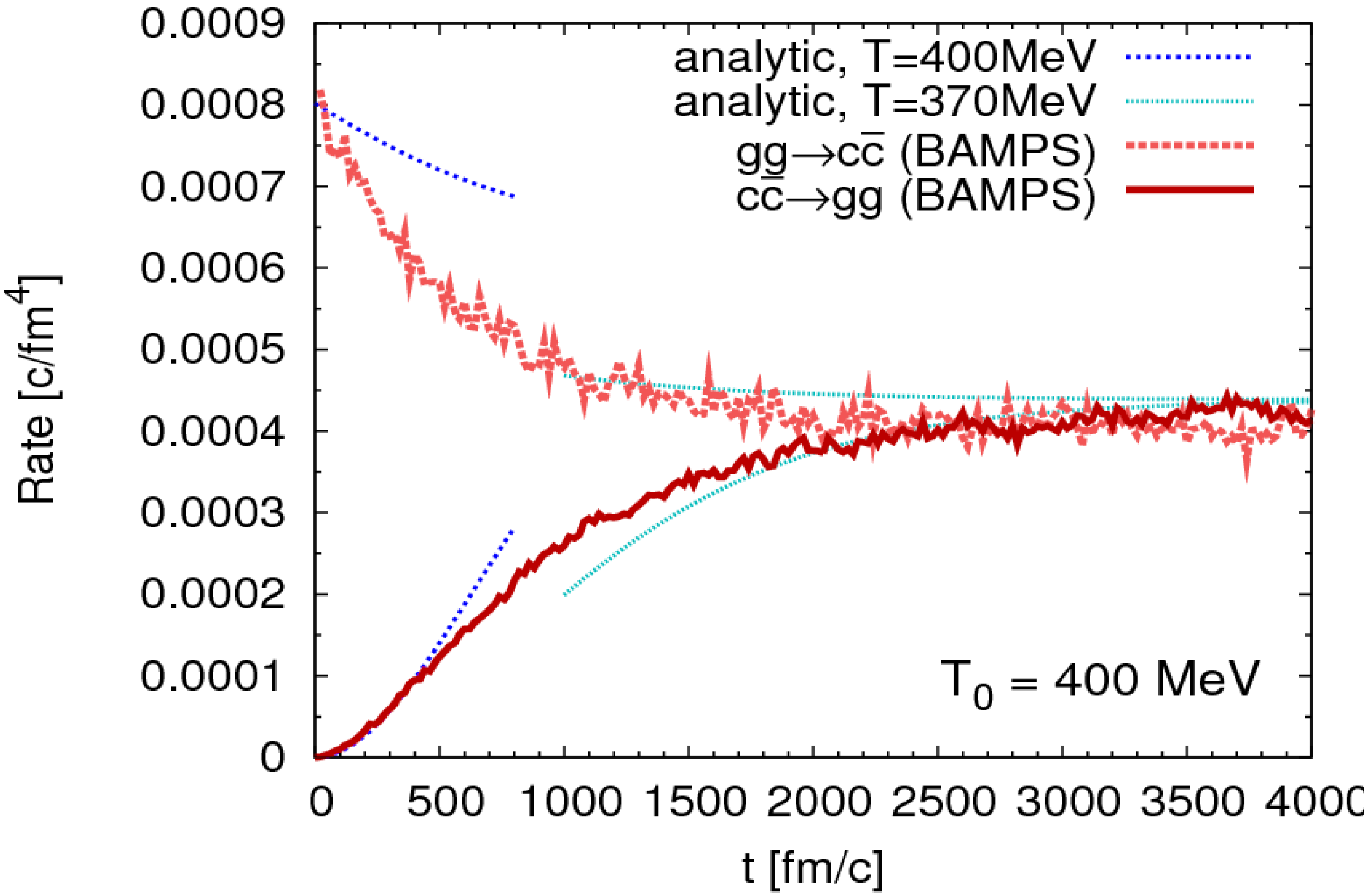
Matsui, Svetitsky, McLerran, Phys. Rev. D (1986)
Biro, van Doorn, Müller, Thoma, Wang, Phys. Rev. C (1993)

# Box calculation $T_0$ = 400 MeV

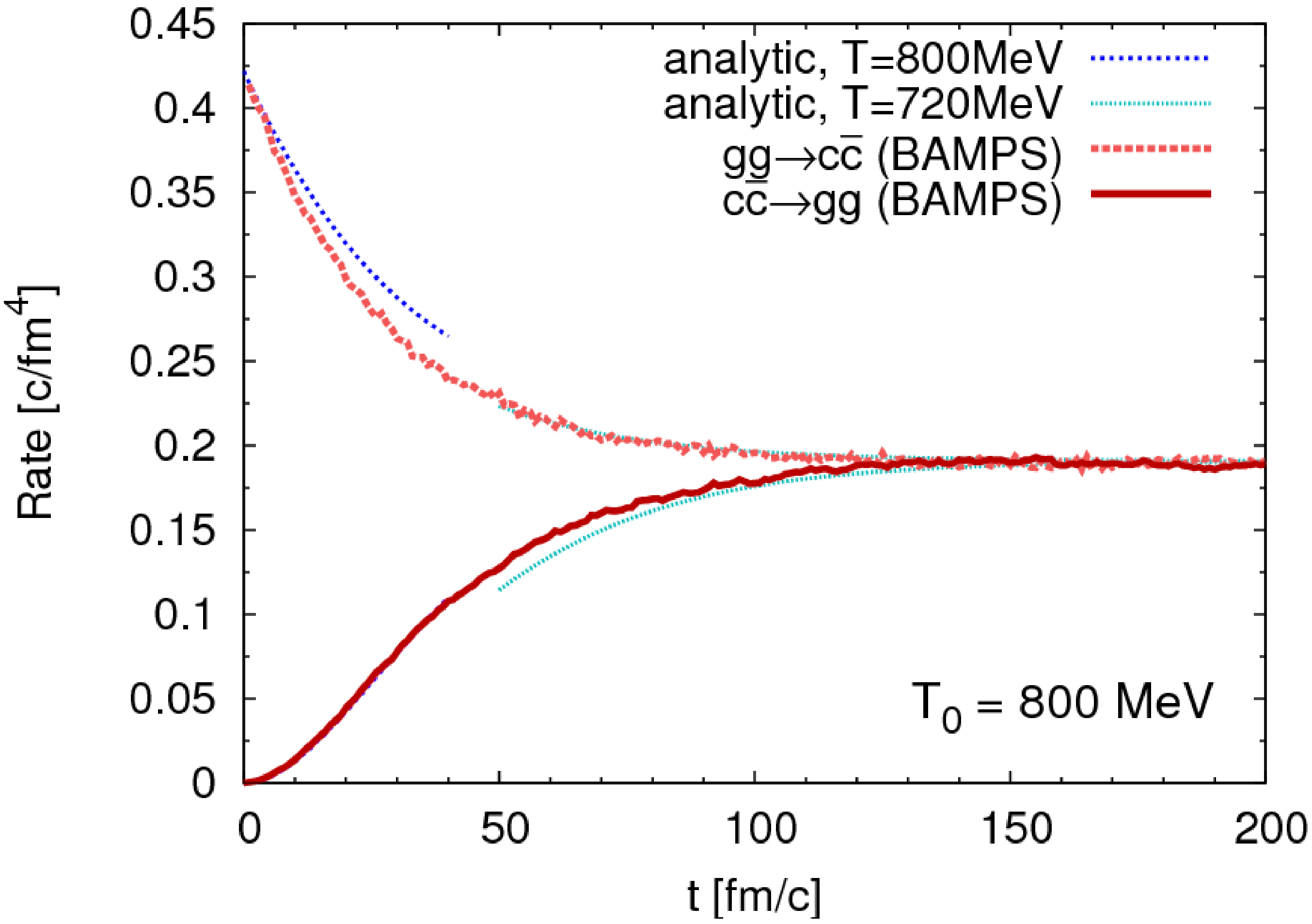


# Box calculation $T_0$ = 400 MeV



# Box calculation $T_0$ = 800 MeV



# Initial charm in hard parton scatterings

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**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 $\mu_R$

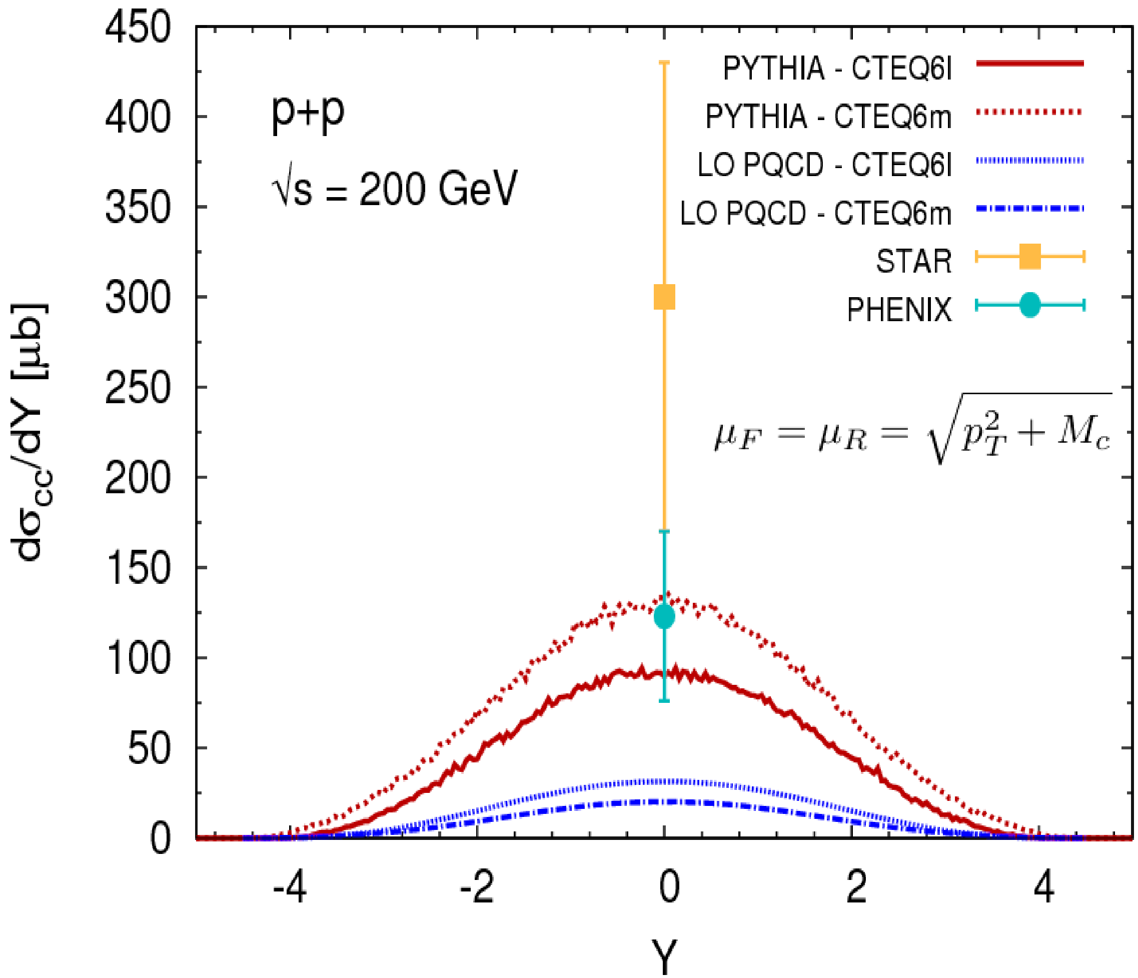
$$C(x_1,x_2) = f_g^A(x_1)\, f_g^B(x_2)\, \frac{\mathrm{d}\hat{\sigma}_{gg\to c\bar{c}}}{\mathrm{d}\hat{t}} + \sum_q \left[f_q^A(x_1)\, f_{\bar{q}}^B(x_2) + f_{\bar{q}}^A(x_1)\, f_q^B(x_2)\right] \frac{\mathrm{d}\hat{\sigma}_{q\bar{q}\to c\bar{c}}}{\mathrm{d}\hat{t}}$$

depend on factorization scale $\mu_F$

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



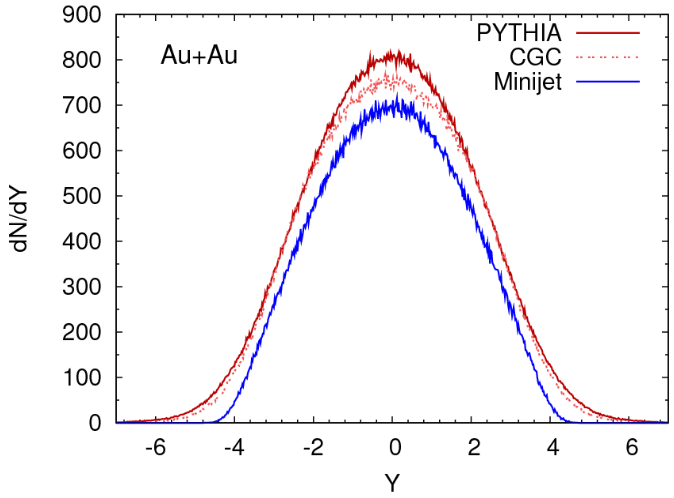

**PYTHIA closer to data**

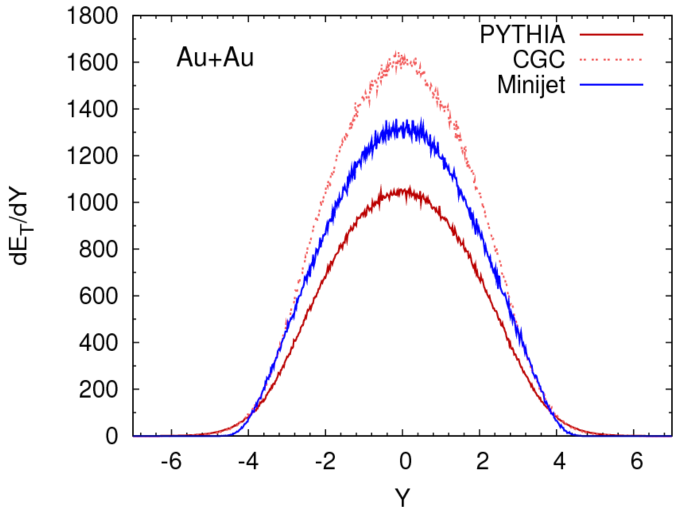
**Total initial charm yield in central Au+Au collisions @ RHIC:**

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

# 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**
- **Color glass condensate**

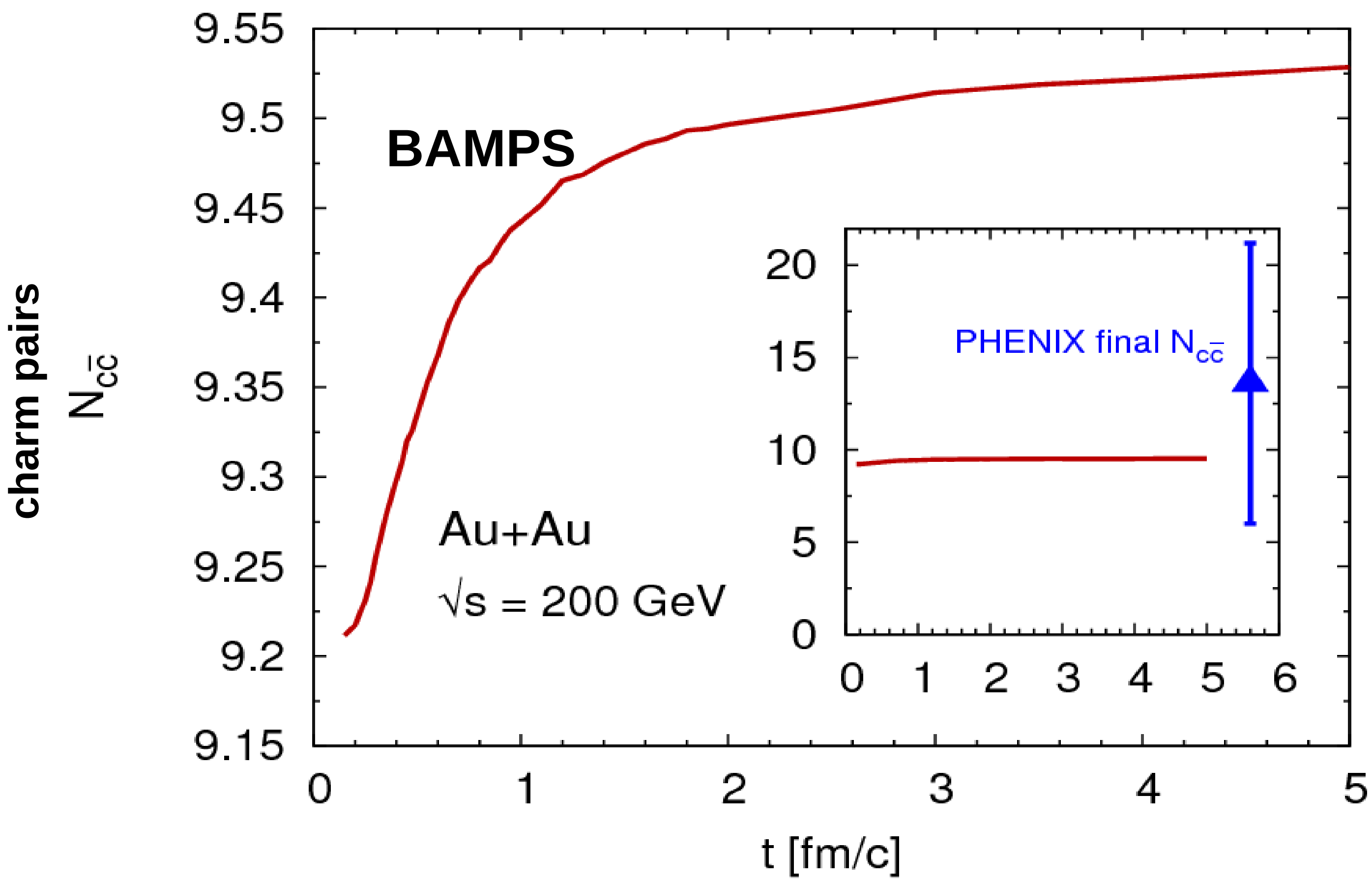


# Charm production in the QGP at RHIC

RHIC

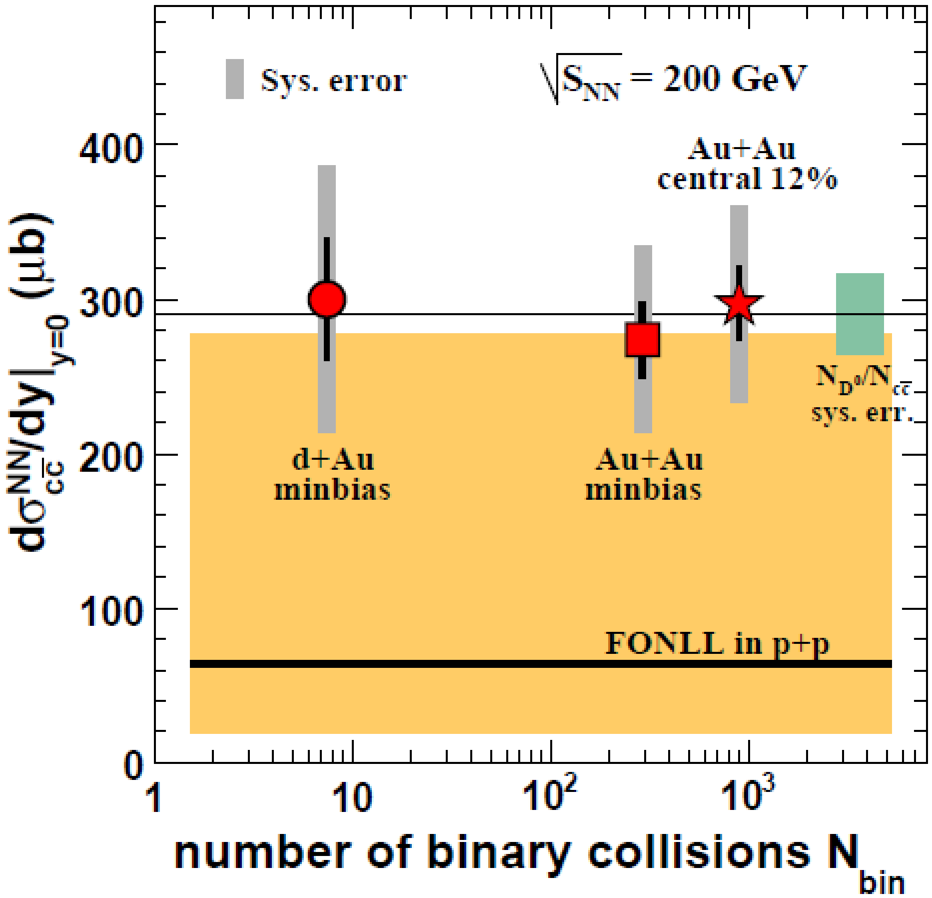
**PYTHIA initial conditions**




**Only 0.3 charm pairs are produced during the QGP phase**

➡ **3 % of total charm**

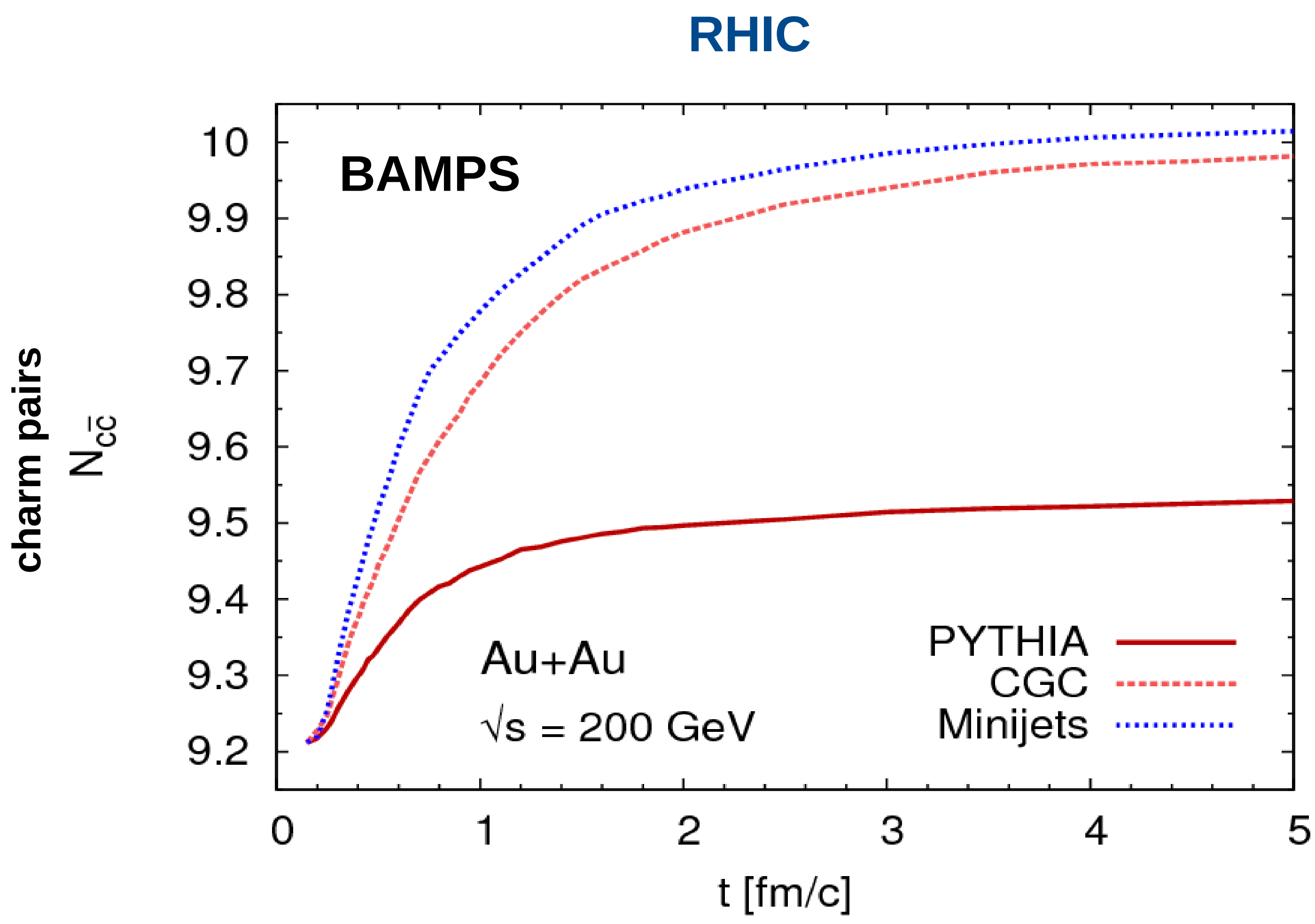
# Charm scales with number of bin. coll.




**STAR data**

arXiv:0805.0364 [nucl-ex]

# Charm production in the QGP at RHIC



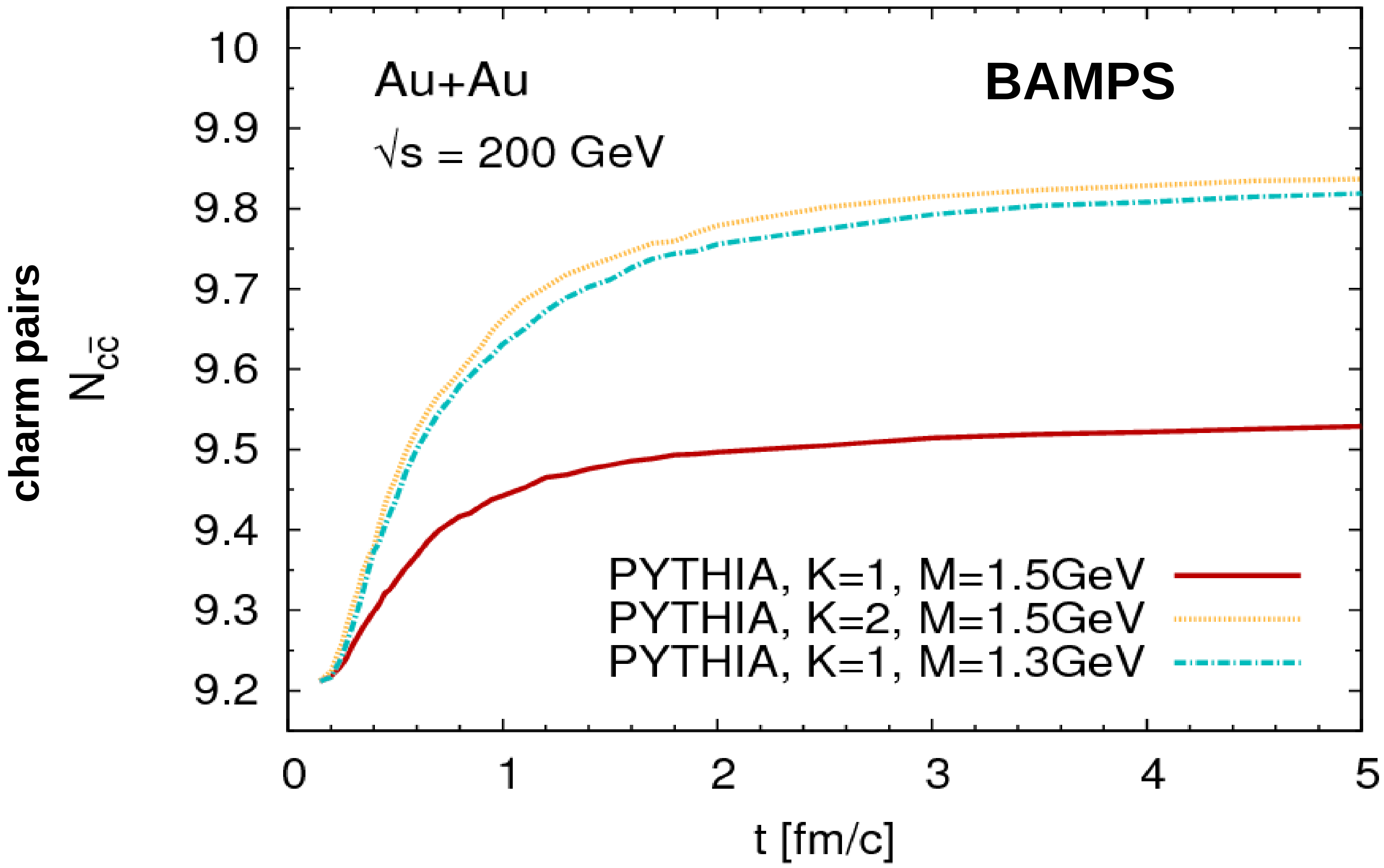

Different initial conditions

➡ factor 2.5 difference in charm production during QGP phase

# Charm production in the QGP at RHIC



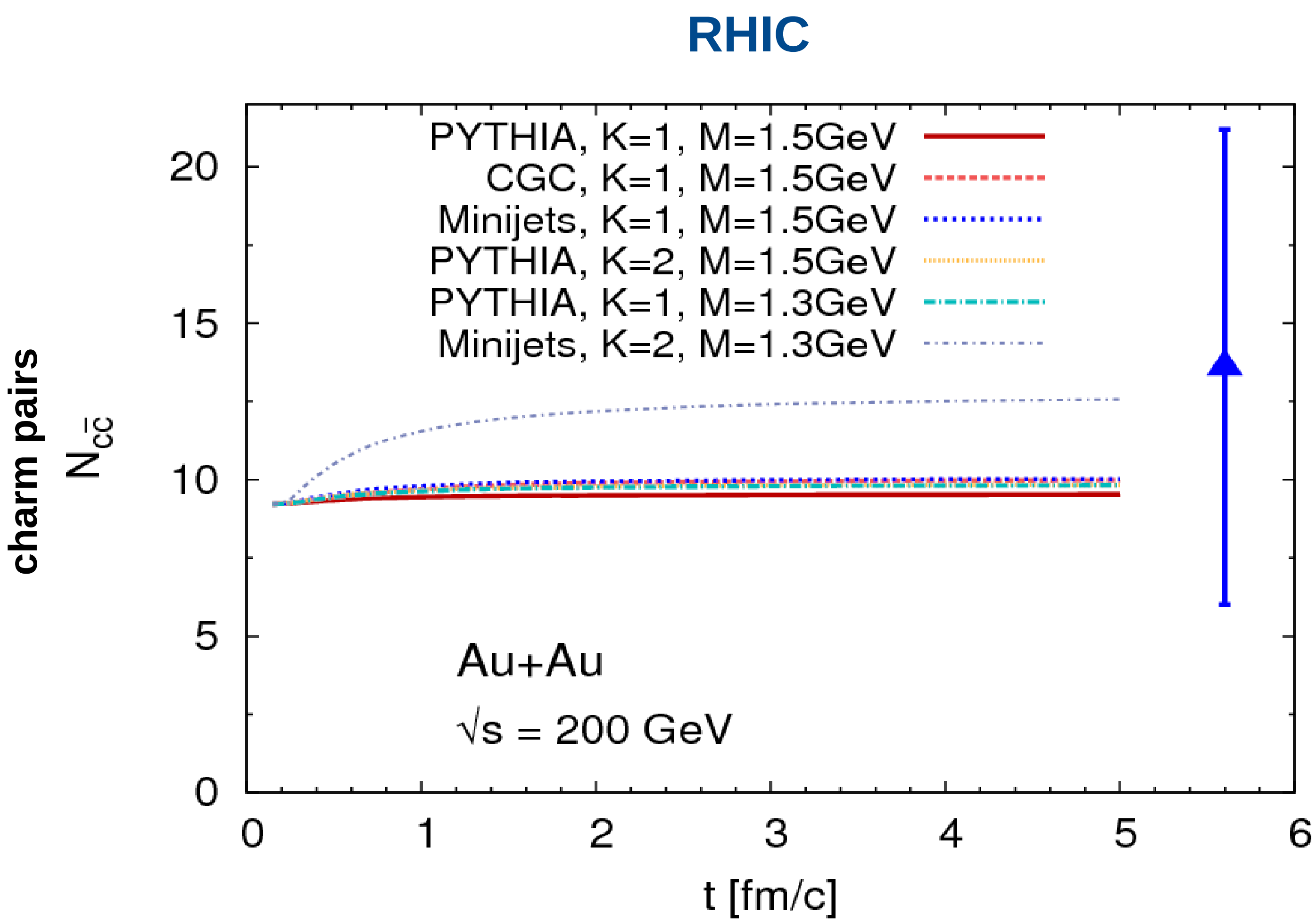
**RHIC**




**K factor or different charm mass**

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

# Charm production in the QGP at RHIC



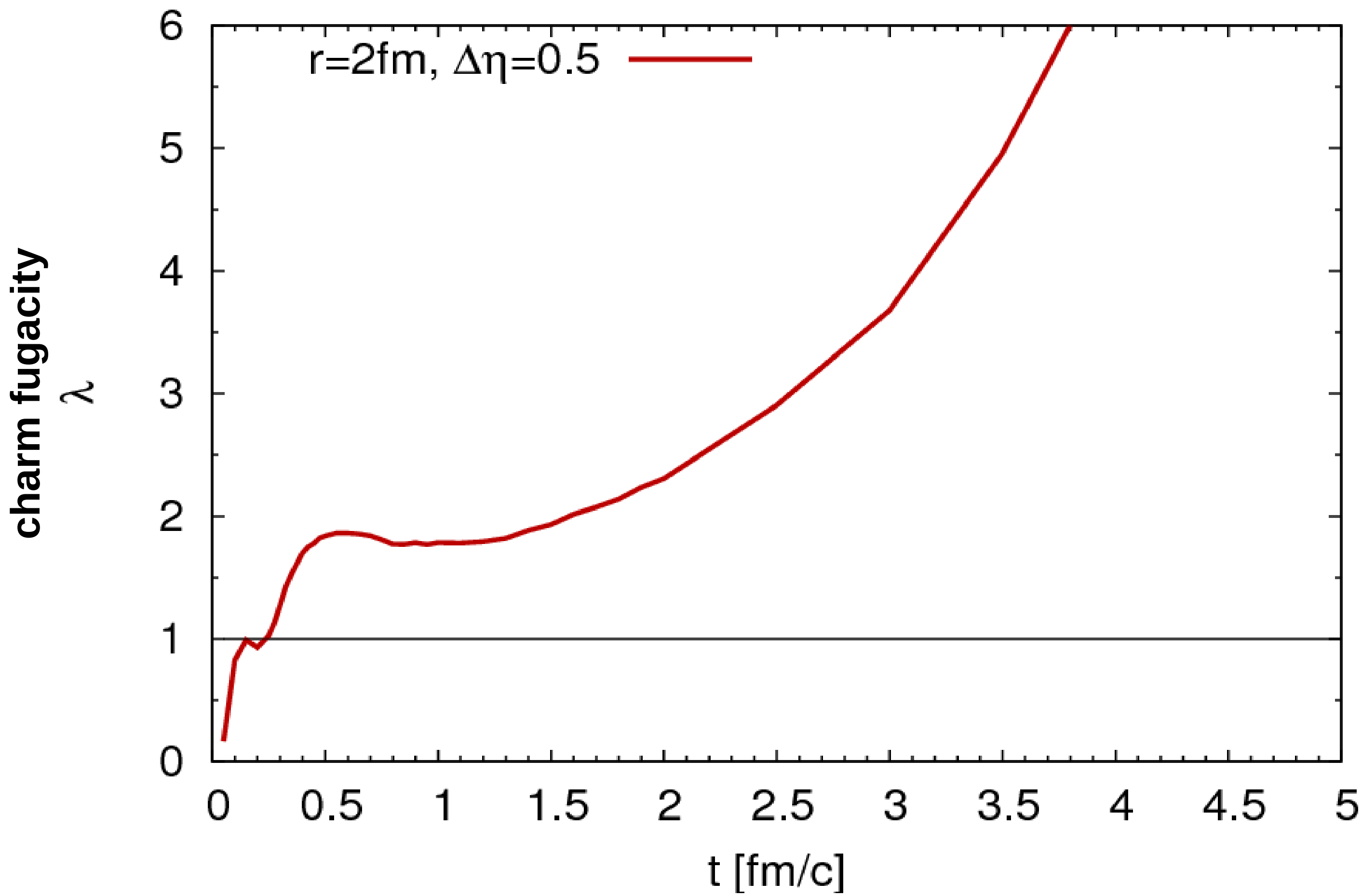

**Maximum charm production of 3.4 pairs**

➡ **27 % of total charm**

# Charm production in the QGP at RHIC



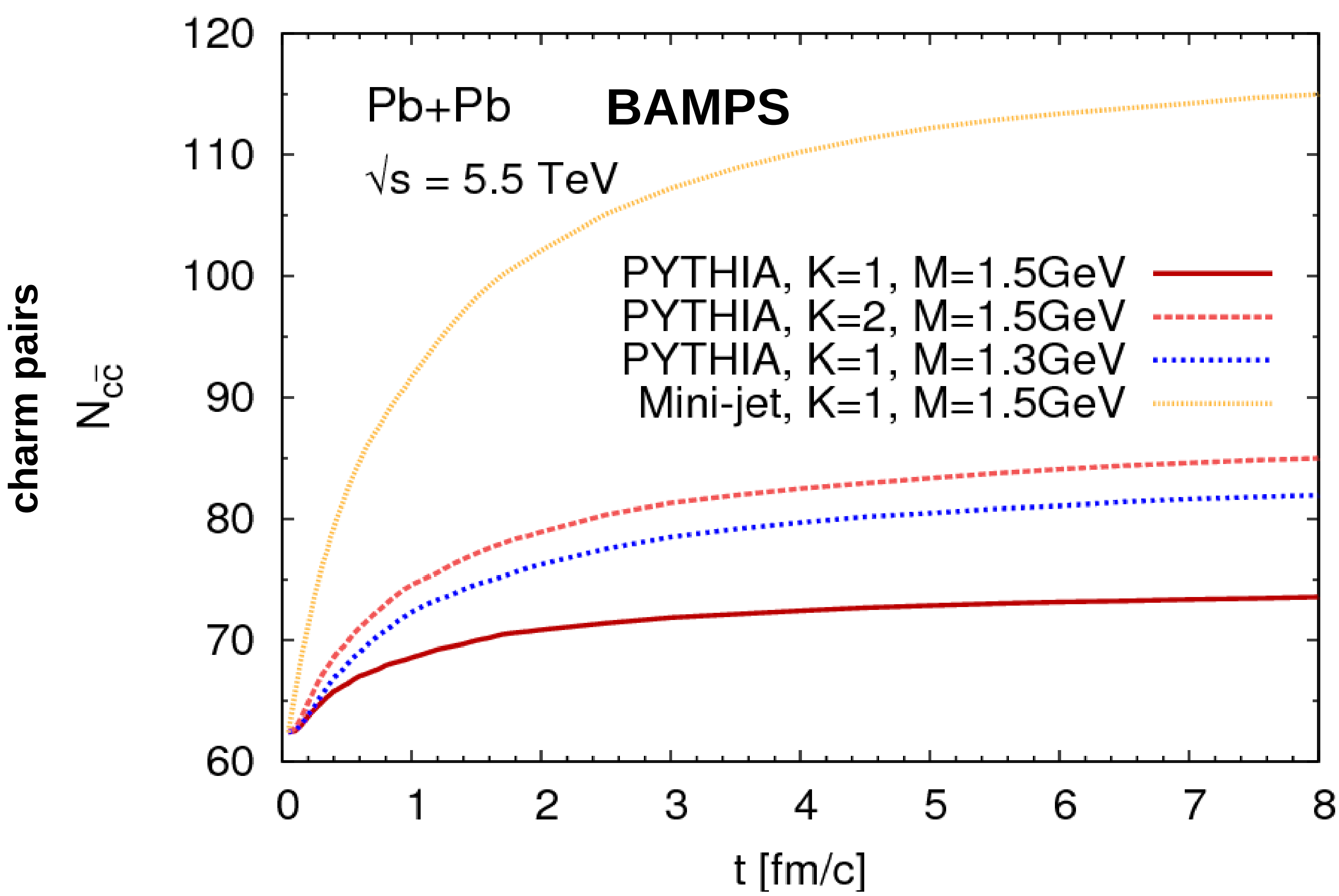
## RHIC




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

# Charm production in the QGP at LHC

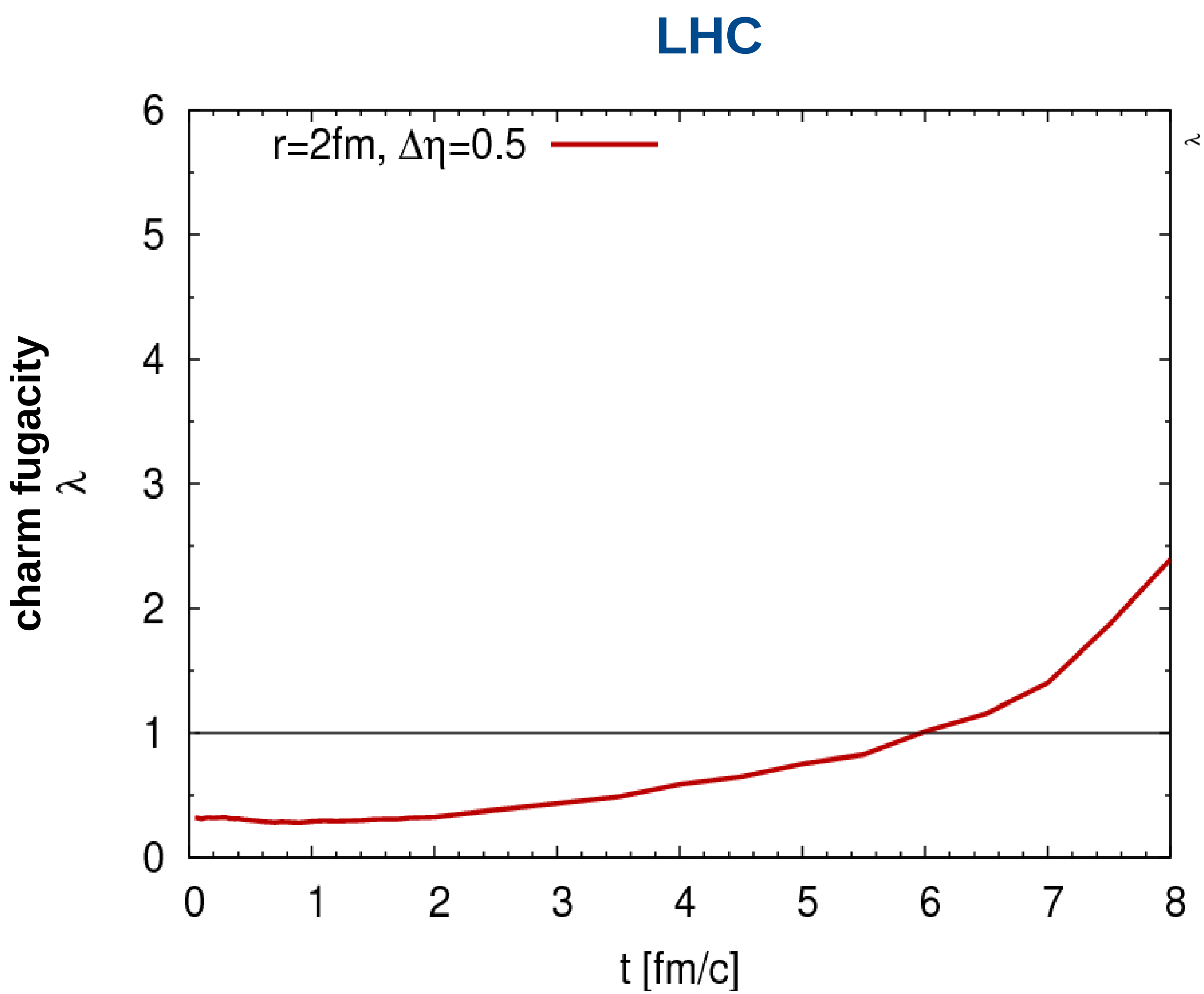
## LHC

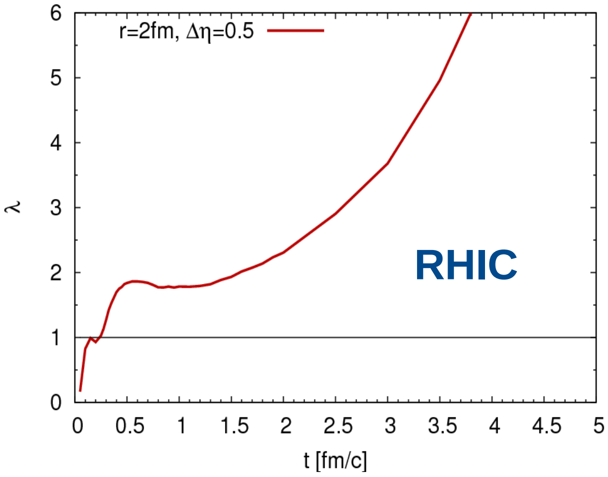



**11 - 50 charm pairs are produced in the QGP**

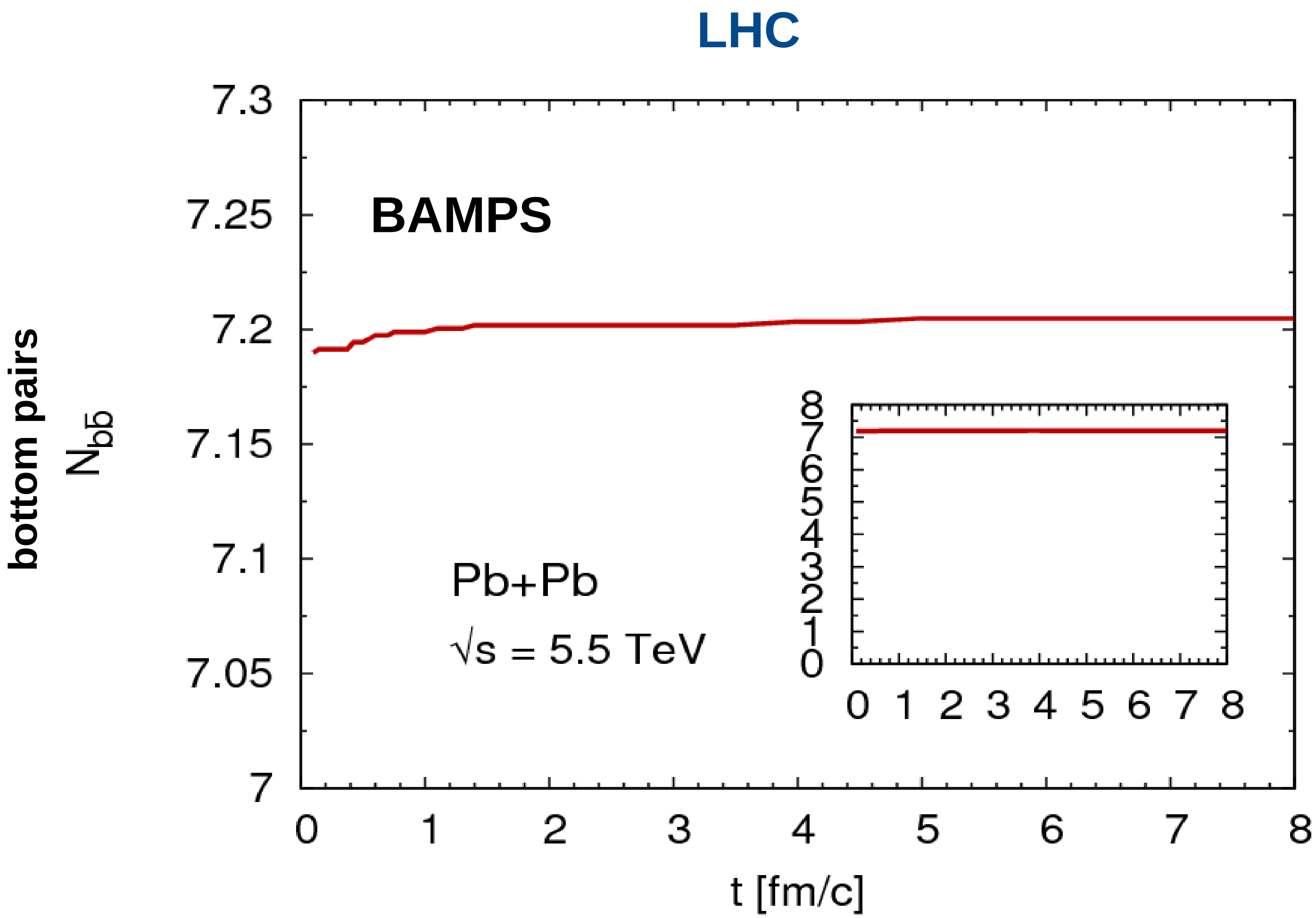
**➡ 15 - 45 % of total charm**

# Charm production in the QGP at LHC



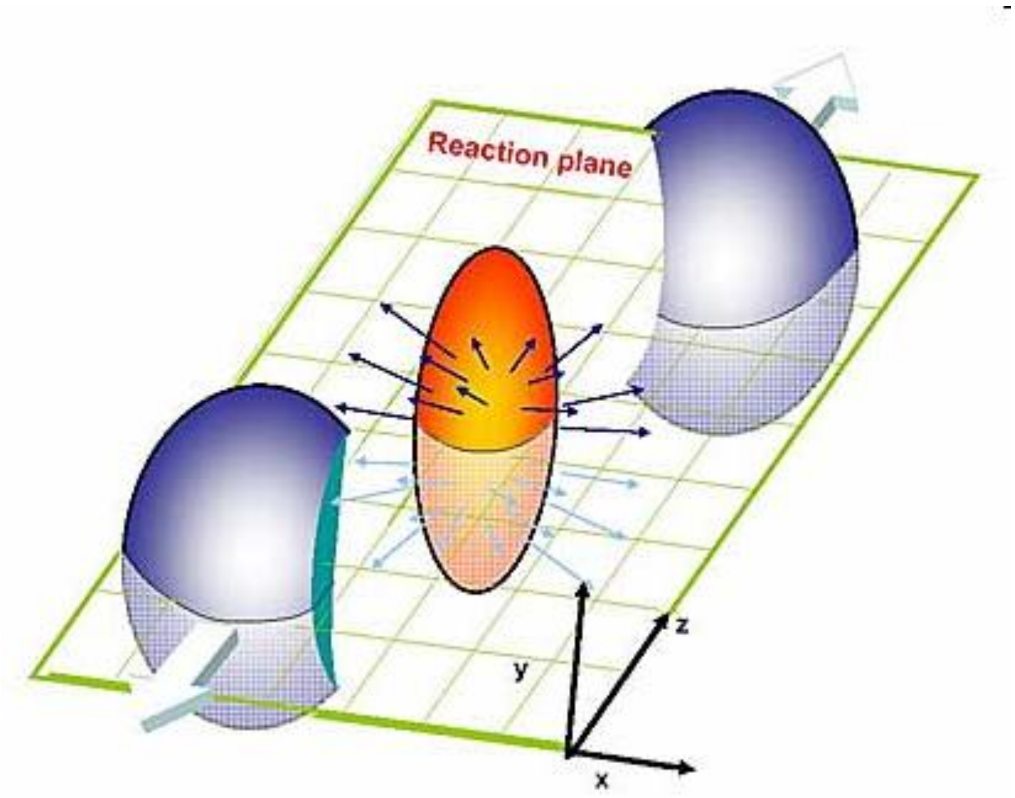
# Bottom production in the QGP at LHC

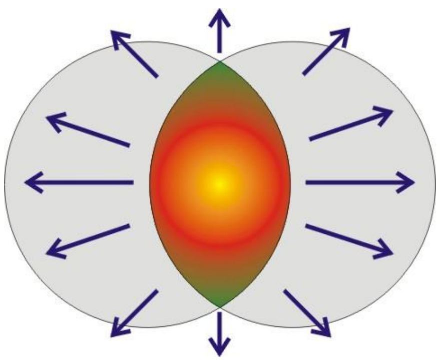



**0.01 bottom pairs are produced in the QGP**

➡ **0.2 % of total bottom**

# Elliptic flow $v_2$

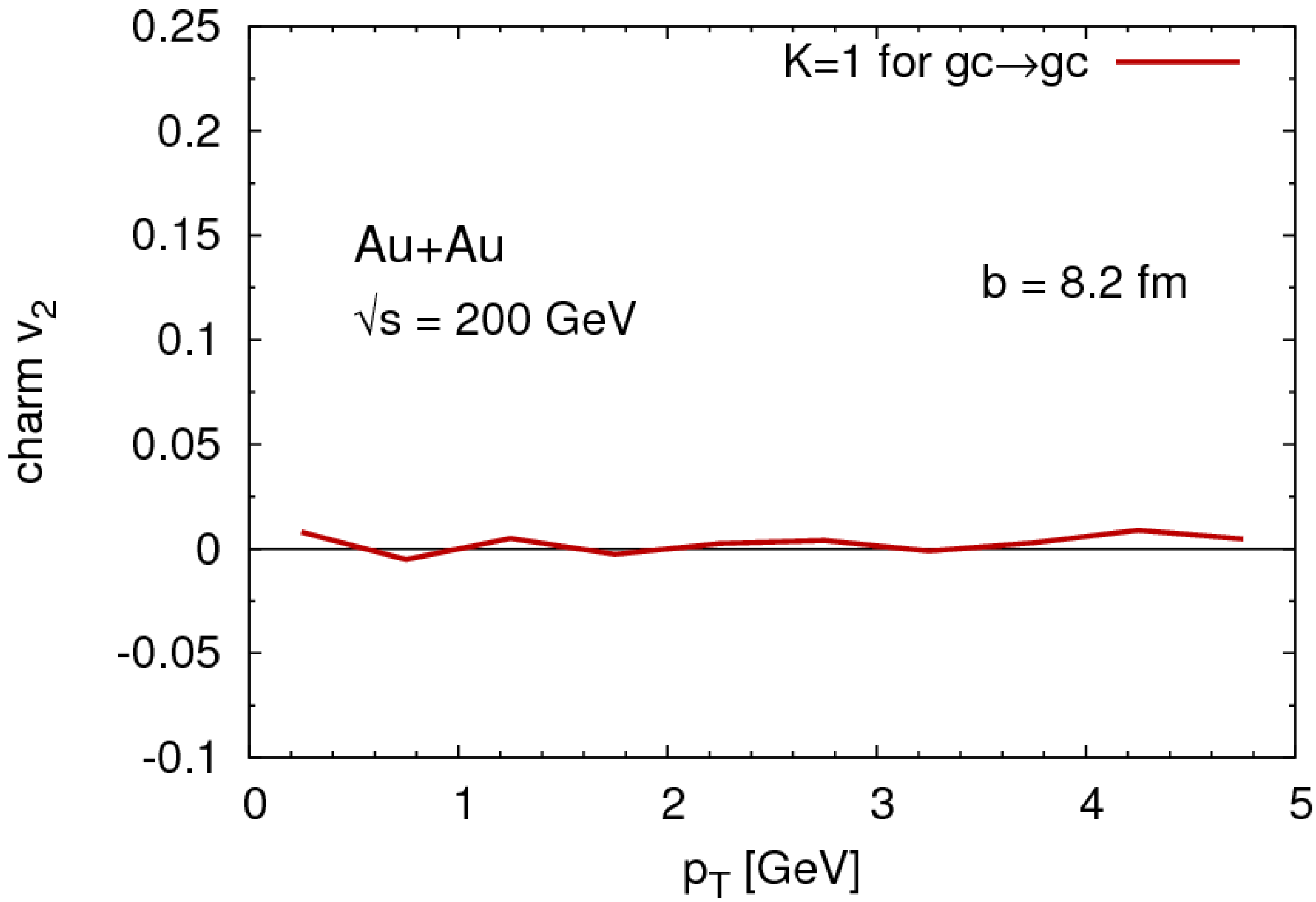


$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

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

# Elliptic flow $v_2$ for charm at RHIC



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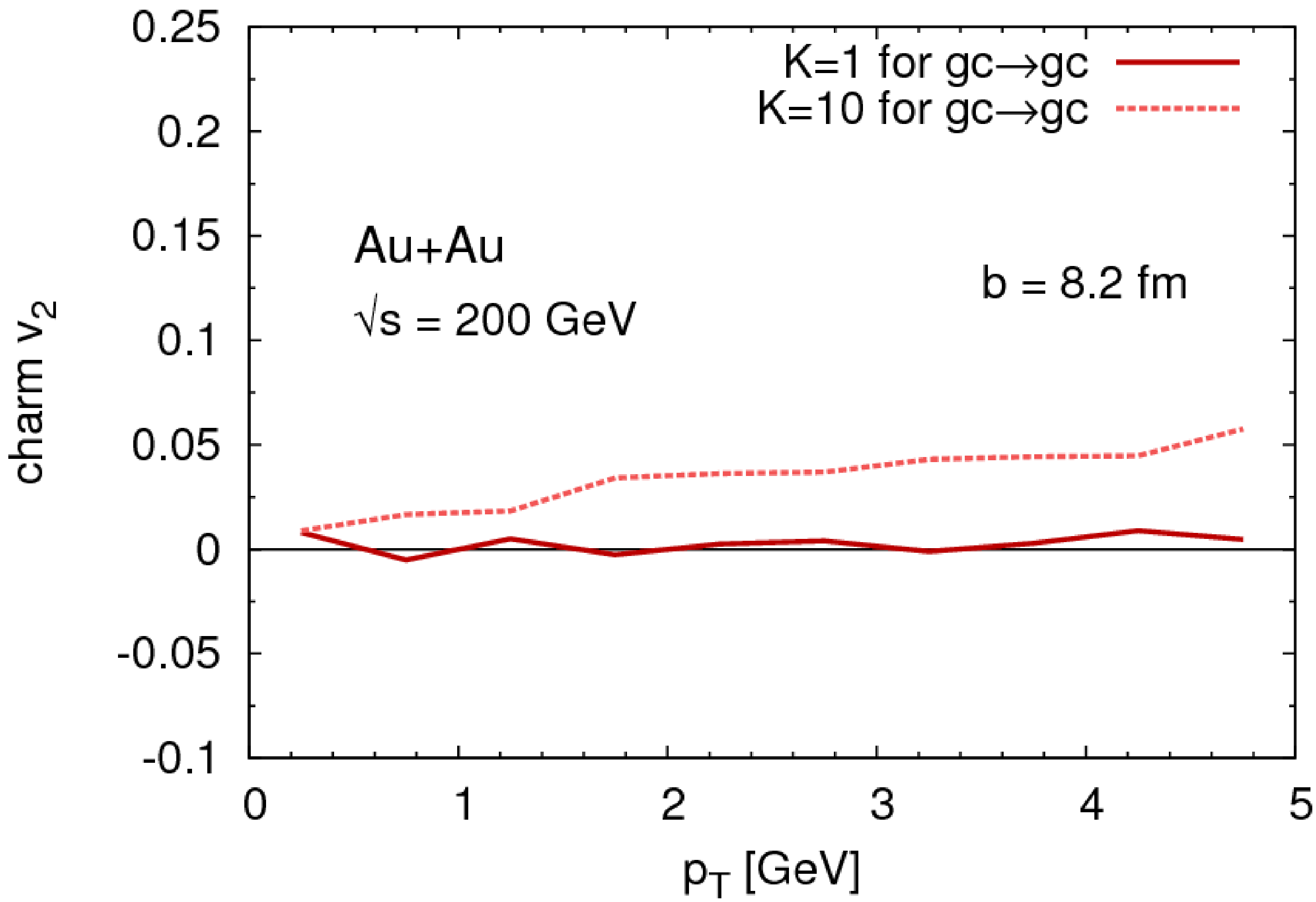
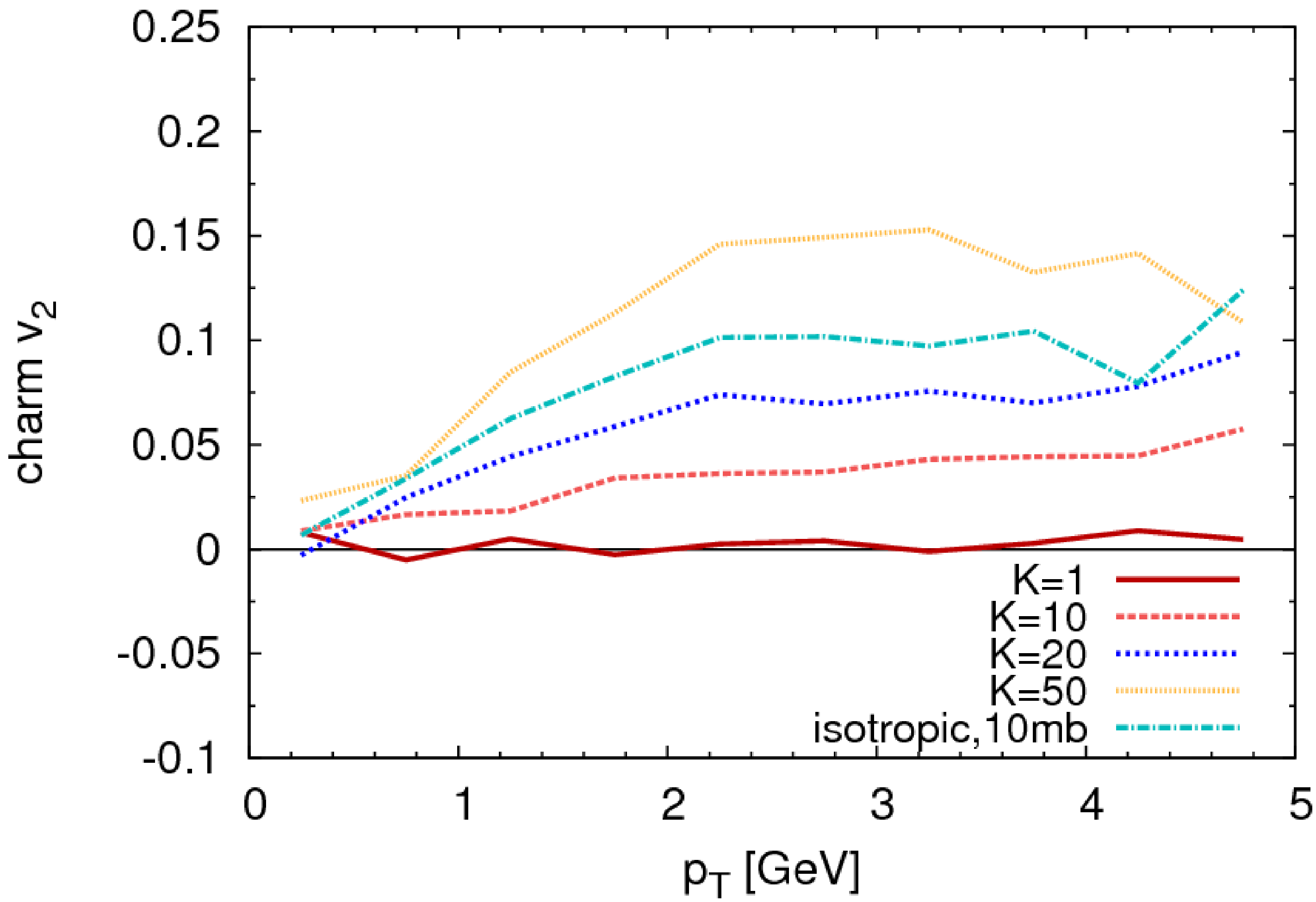
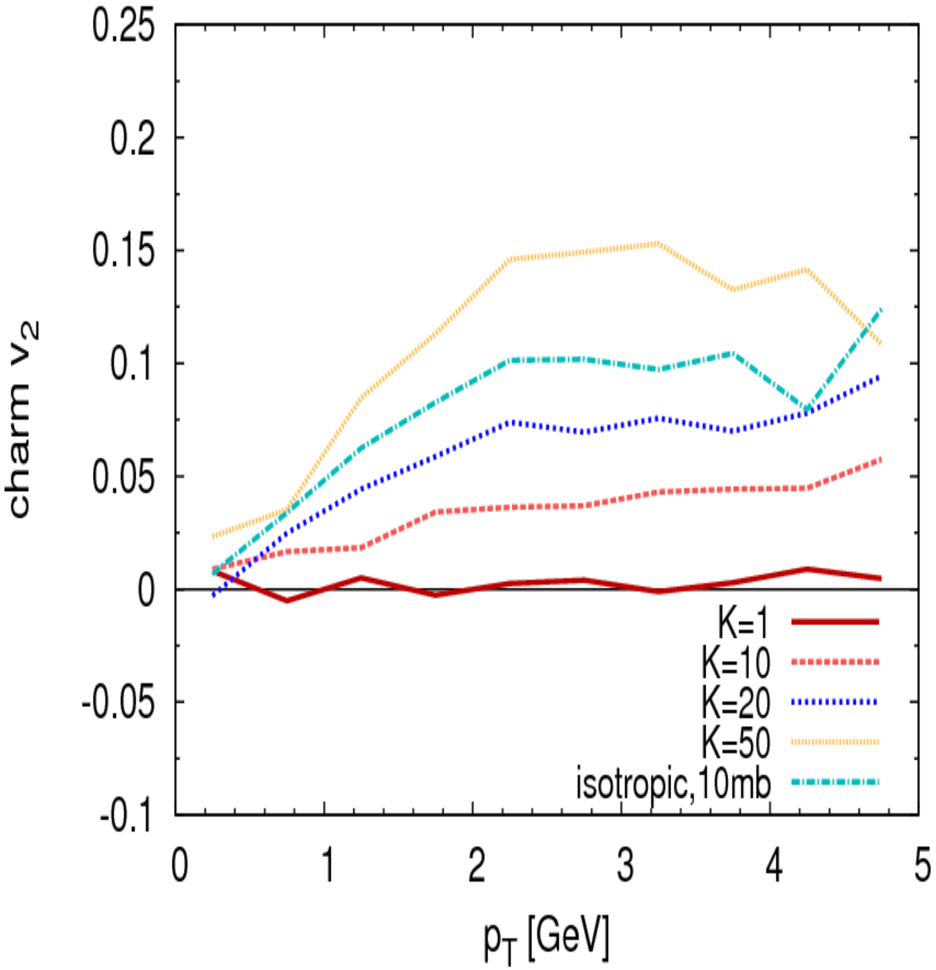
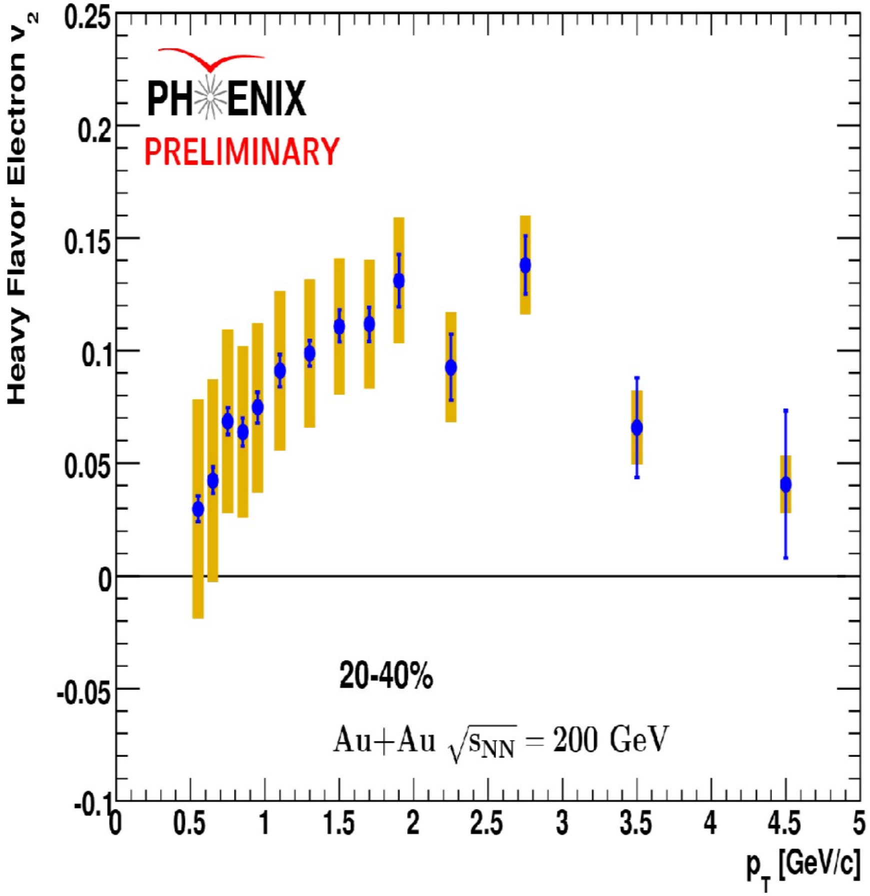


# Elliptic flow $v_2$ for charm at RHIC



# Elliptic flow $v_2$ for charm at RHIC



# 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
- Small charm yield during QGP phase
  - RHIC: 3 - 27 % of final charm are produced in QGP
  - LHC: 15 % 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, essentially
  gluon radiation for charm scattering
- Energy loss of charm quarks

# 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

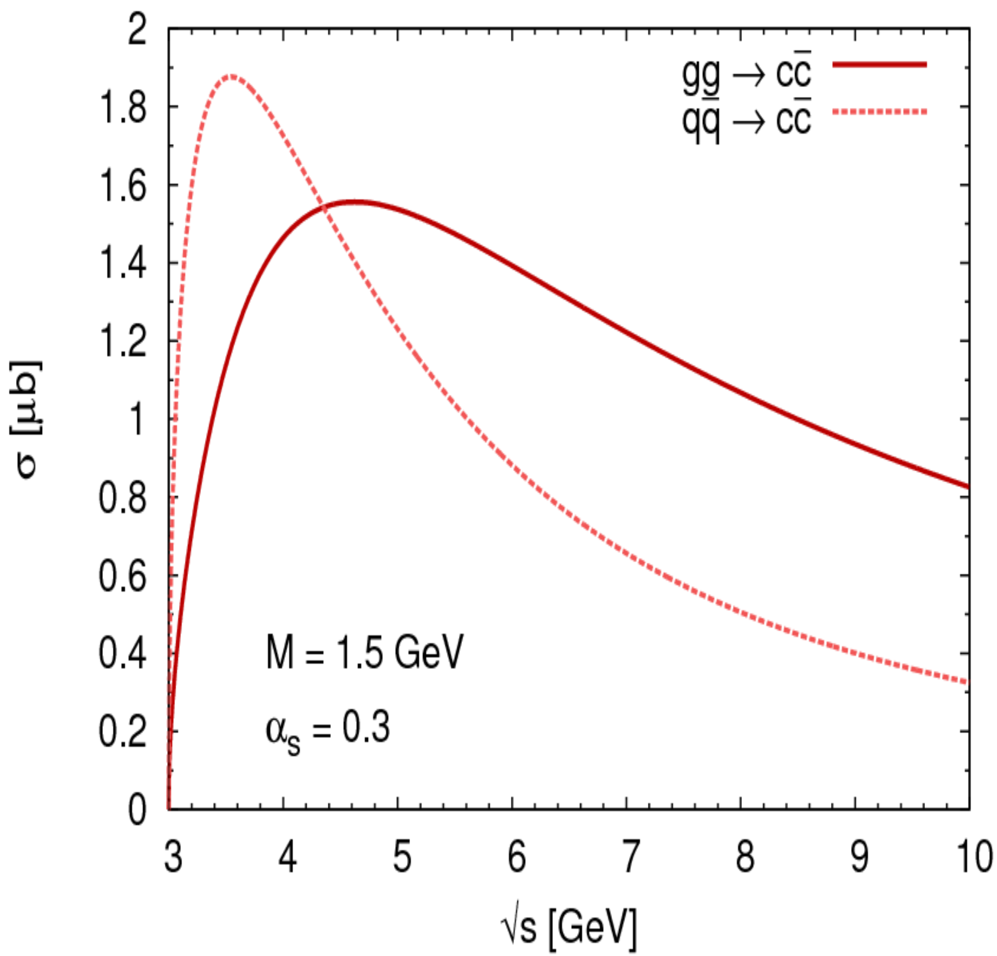
- **Using stochastic method:**

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

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

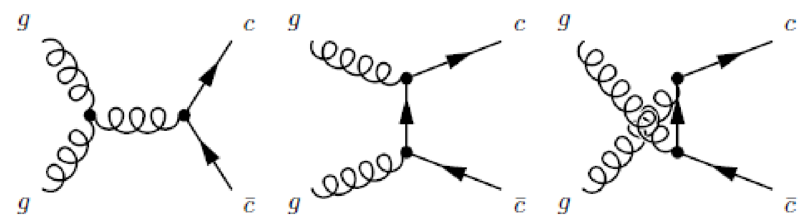
- **Testparticles to increase statistics**

# Partonic cross sections



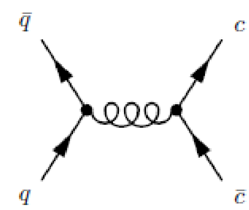

**Dominant process for charm production:**

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




**Other possible process:**

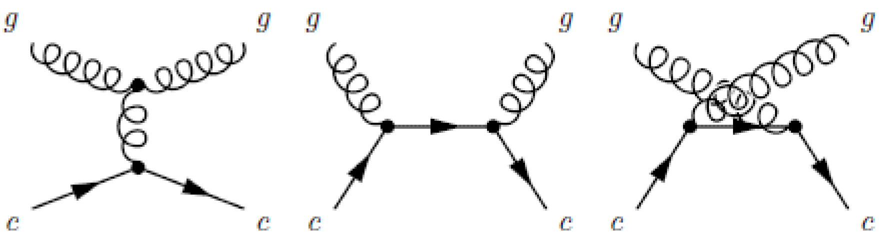
$$q + \bar{q} \rightarrow c + \bar{c}$$

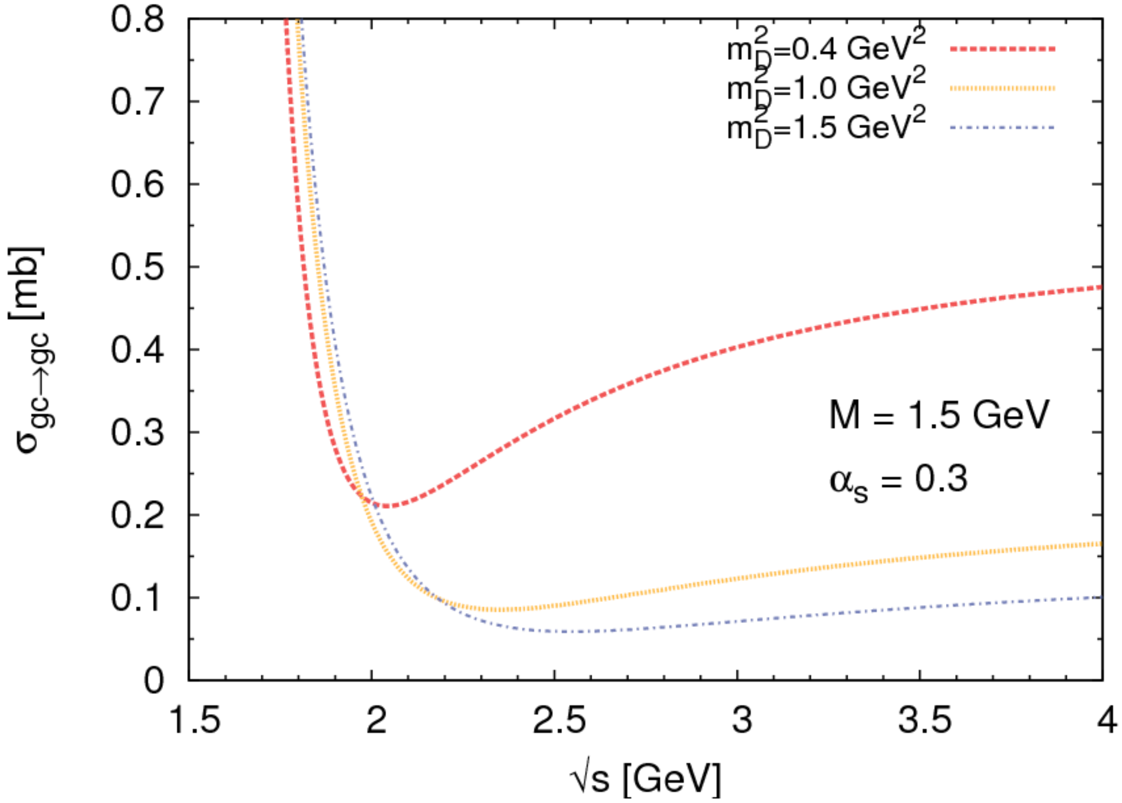


# Charm quark scattering

**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**

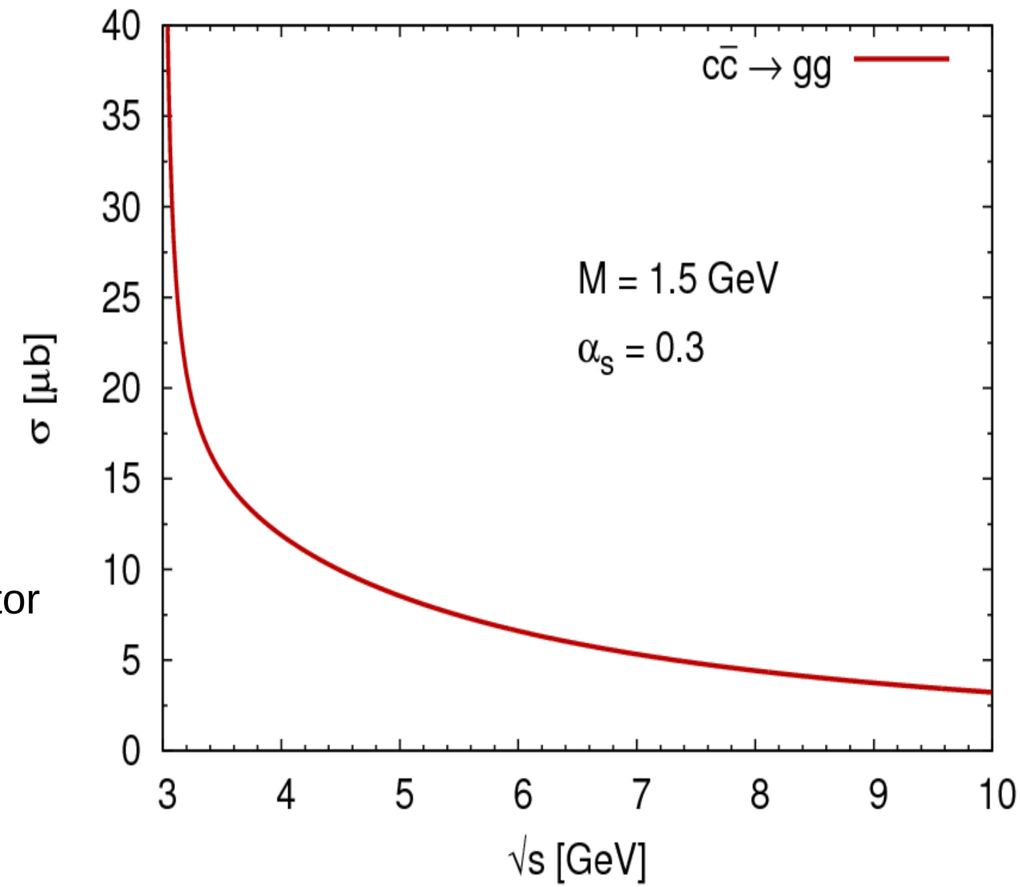
$$\sigma_{c\bar{c}\rightarrow gg} = \frac{1}{2}\,\frac{64}{9}\,\frac{1}{\chi}\,\sigma_{gg\rightarrow c\bar{c}}$$

gluons identical particles

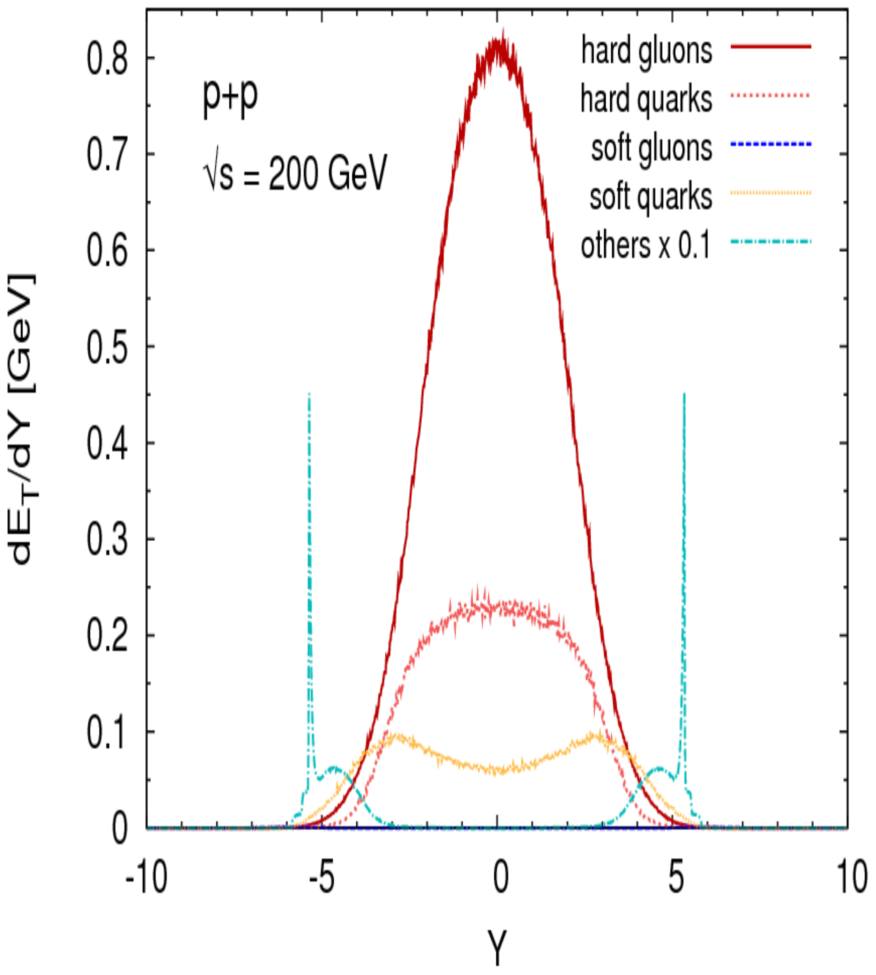
color averaging

kinematical factor

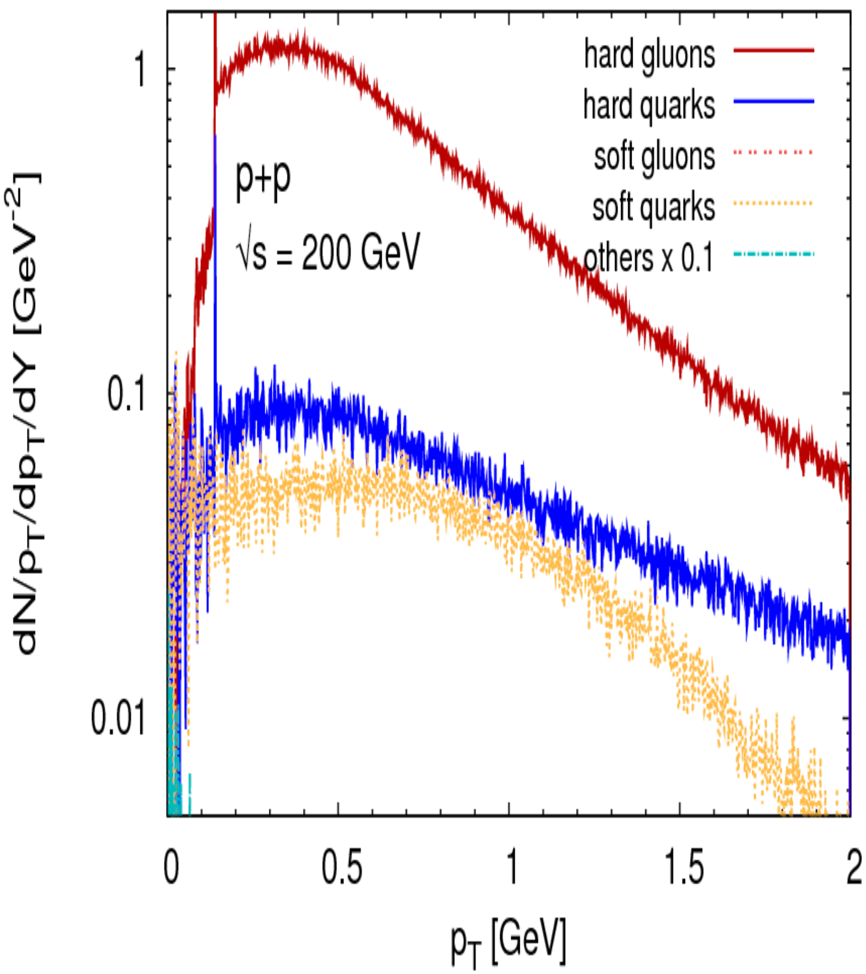
$$\chi = \sqrt{1 - \frac{4M^2}{s}}$$



# PYTHIA



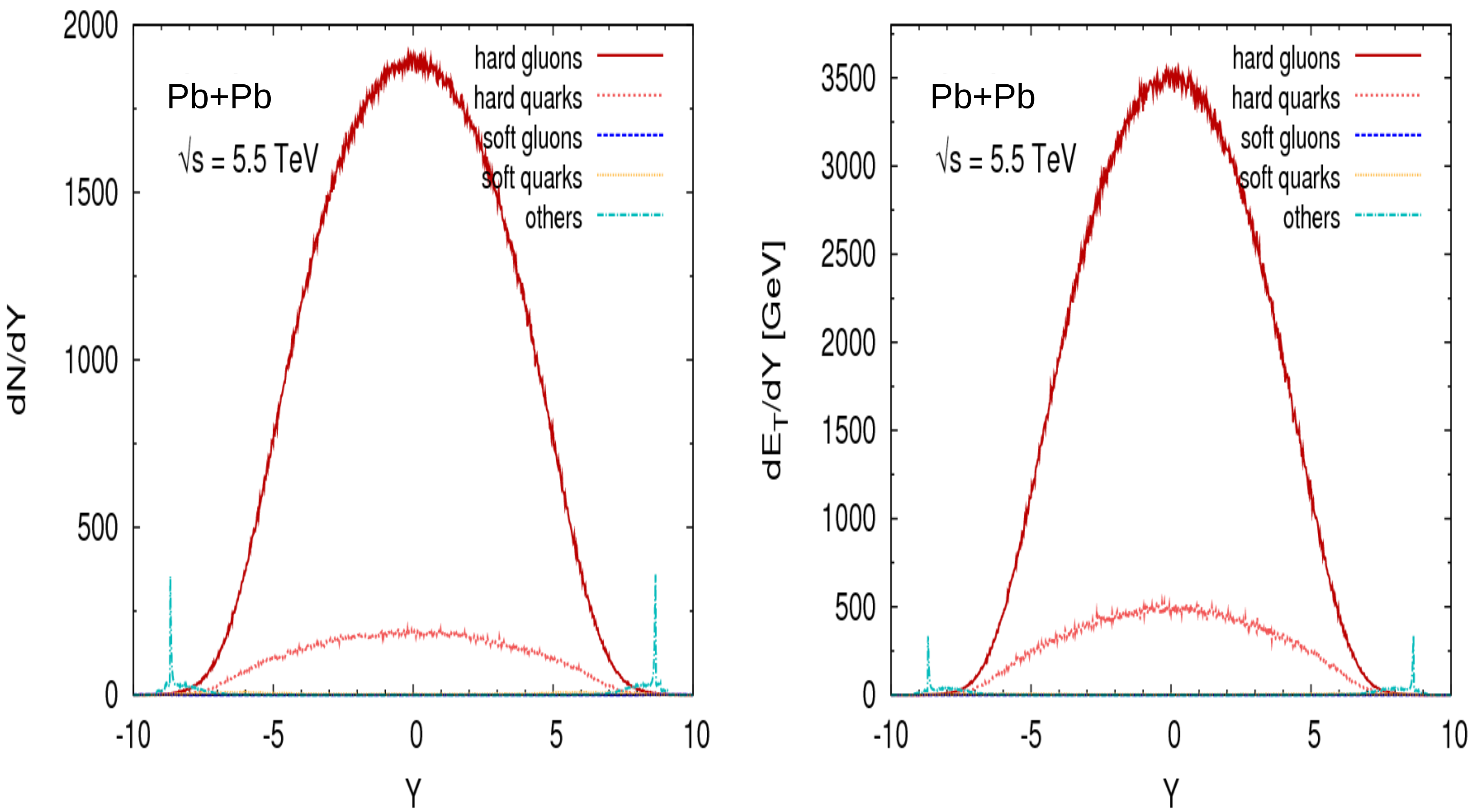
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-10
-5
0
5
10
Y
$dE_T/dY$ [GeV]
p+p
$\sqrt{s}$ = 200 GeV
hard gluons
hard quarks
soft gluons
soft quarks
others x 0.1

1
0.1
0.01
0
0.5
1
1.5
2
$p_T$ [GeV]
$dN/p_T/dp_T/dY$ [$GeV^{-2}$]
p+p
$\sqrt{s}$ = 200 GeV
hard gluons
hard quarks
soft gluons
soft quarks
others x 0.1

# Initial conditions for cascade at LHC





# Elliptic flow $v_2$ for charm at RHIC