Thermal Charm production at LHC

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- Introduction
- Charm production
  - in QCD
  - in QGP
  - at LHC
  - from three-gluon interaction
- Summary

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Supported by National Science Foundation and The Welch Foundation

Why is understanding charm production important in HIC?

- Charmonium production: Braun-Munzinger, Thews, Greco ….
  - Yield depends quadratically on the charm quark number in statistical, kinetic, and coalescence models
  - Enhanced charm production would lead to possible charmonium enhancement instead of suppression, which was proposed as a signal for QGP (Matsui and Satz)
  - Expect charmonium suppression at RHIC but enhancement at LHC

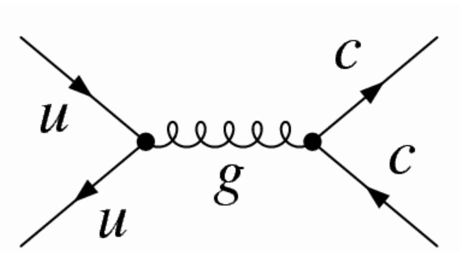
- Charmed exotics production: Lee, Yasui, Liu & Ko (hep-ph/0707.1747)
  - Consideration of the color-spin interaction leads to possible stable charmed tetraquark meson $T_{cc}(ud\bar{c}\bar{c})$ and pentaquark baryon $\Theta_{sc}(uds\bar{c})$
  - Enhanced charm production at LHC makes the latter a possible factory for studying charmed exotics

Four stages of charm production in HIC

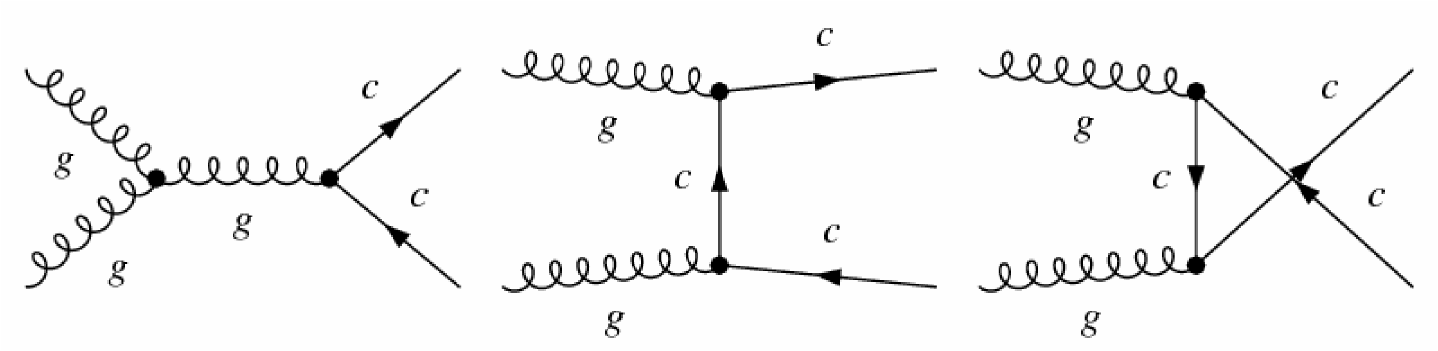
- Direct production: Meuller, Wang (92); Vogt (94); Gavin (96) …..
  - Mainly from initial gluon fusions
  - About 3 pairs in mid-rapidity at RHIC (from STAR collaboration)
  - About 20 pairs in mid-rapidity at LHC
- Pre-thermal production: Lin, Gyulassy (95), Levai, Meuller, Wang (95)…..
  - Not important based on minijet gluons
  - Production from initial strong color field?
- Thermal production from QGP: Levai, Vogt (97) …..
  - Based on leading-order calculations
  - Important if initial temperature of QGP is high
- Thermal production from hadronic matter: Cassing et al. (99), Liu & Ko (02)
  - Such as $\pi N \rightarrow \Lambda_c D$ and $\rho N \rightarrow \Lambda_c D$
  - Expect small effect on charm production in HIC

Leading-order diagrams for charm production

1) $q\bar{q} \rightarrow c\bar{c}$

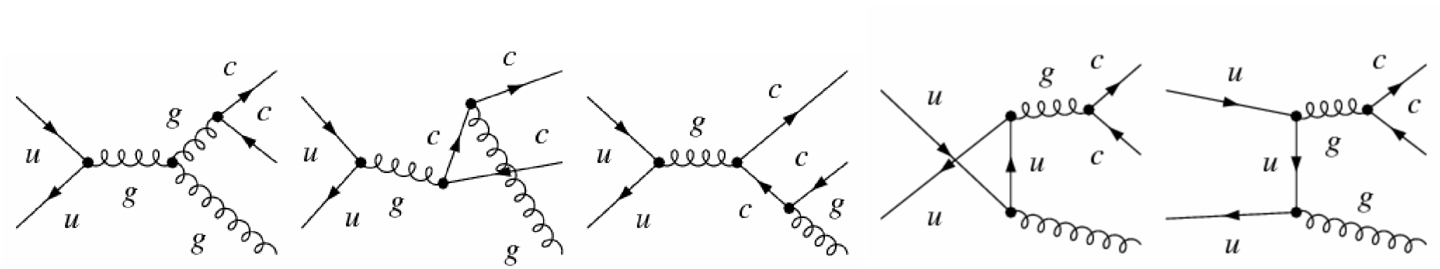


2) $gg \rightarrow c\bar{c}$



Next-Leading-order diagrams for charm production

1) $q\bar{q} \rightarrow c\bar{c}g$



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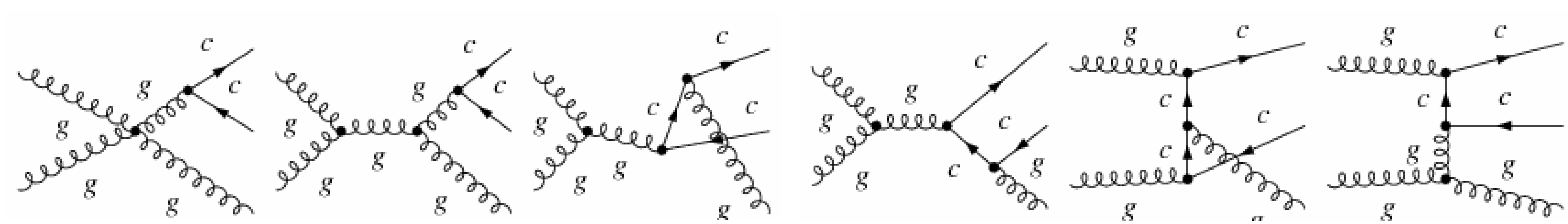
2) $gg \rightarrow c\bar{c}g$



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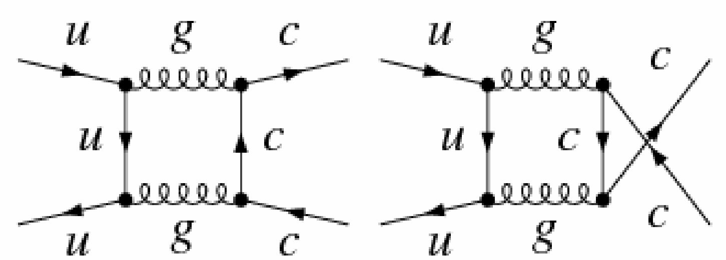
Virtual corrections to leading-order diagrams

1) $q\bar{q} \rightarrow c\bar{c}$



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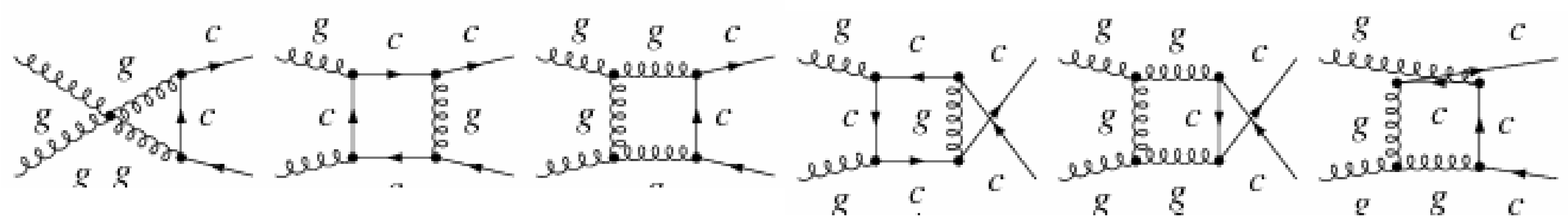
2) $gg \rightarrow c\bar{c}$



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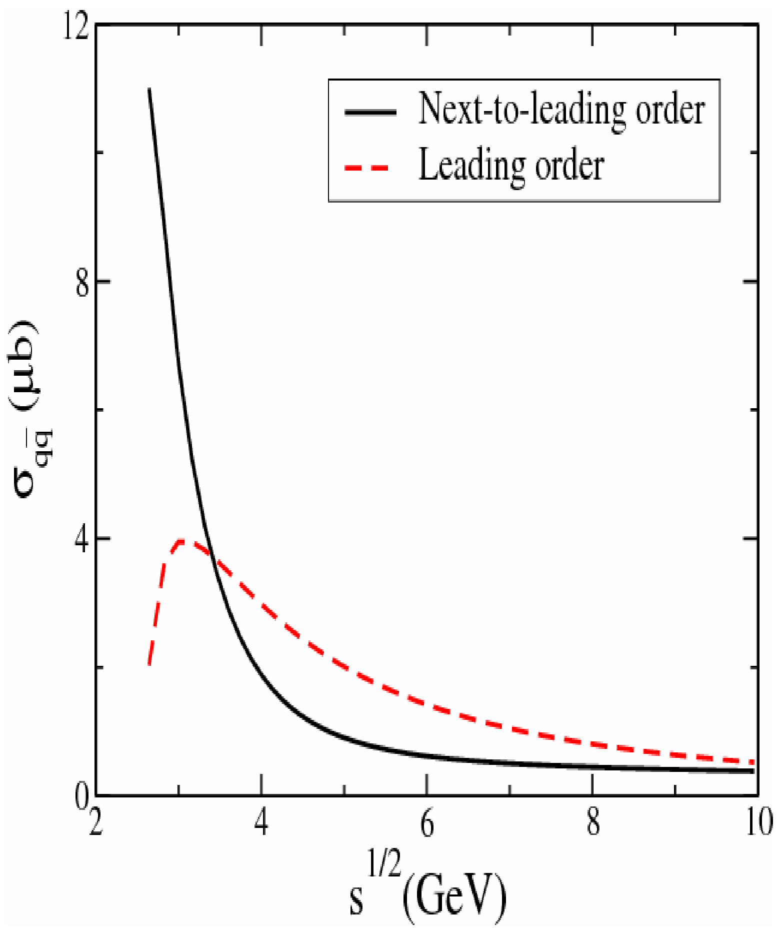
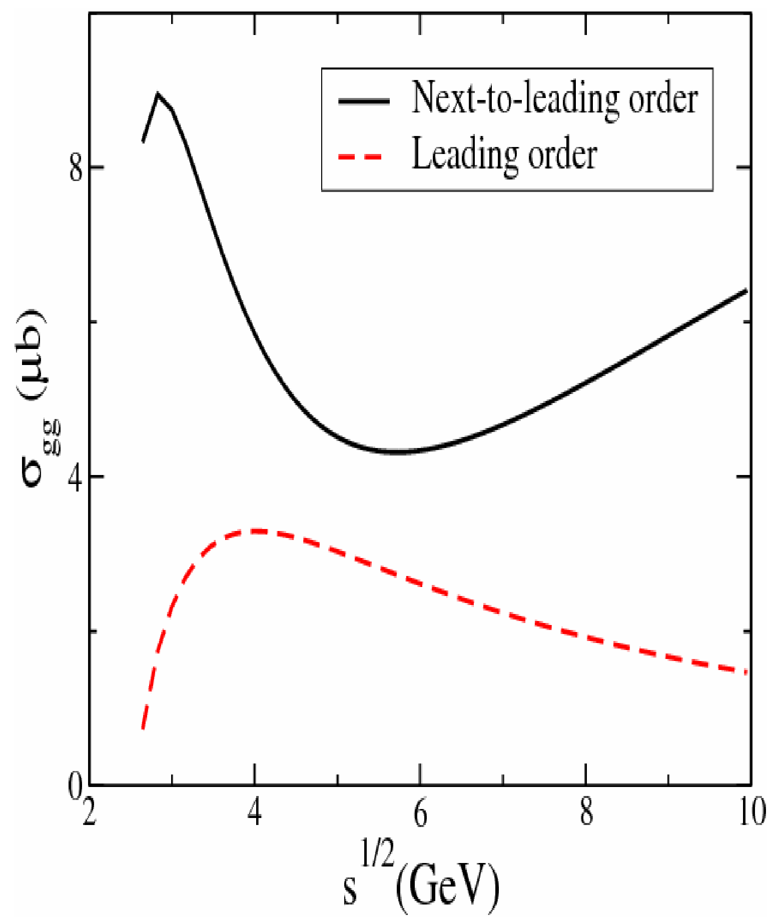
Charm quark production cross sections

P. Nason, S. Dawson & R.K. Ellis, NPB 303, 607 (1988)





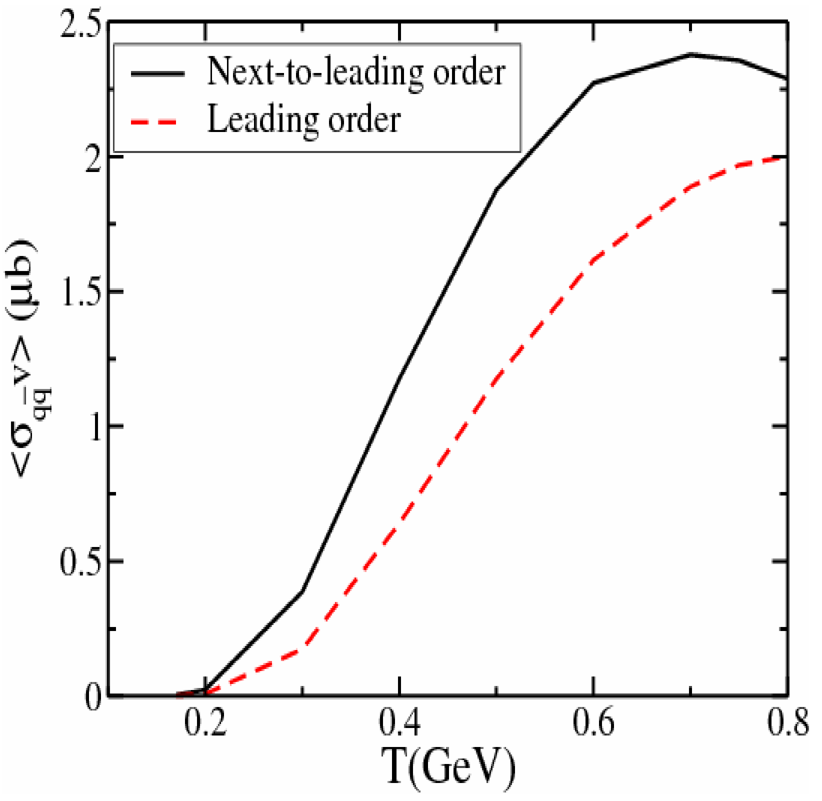
Next-to-leading order generally gives a larger cross section than the leading order except in qqbar annihilation at high energies.

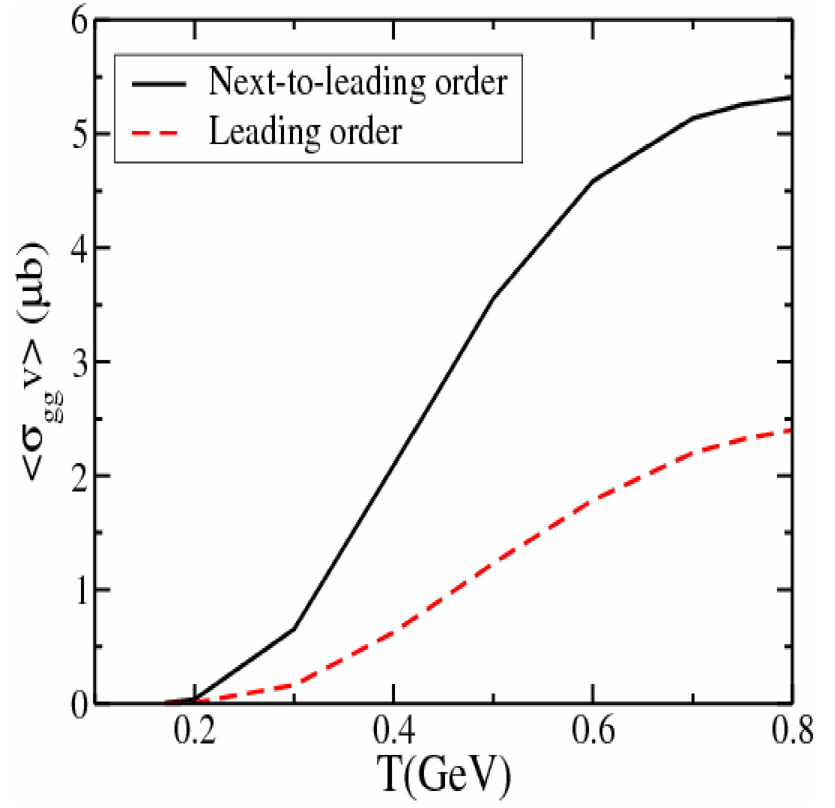
Thermal averaged charm production cross sections

$$\langle \sigma_{ab\to cd} v\rangle = \frac{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b)\sigma_{ab\to cd} v}{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b)}$$

Thermal masses

$$m_q = \frac{gT}{\sqrt{6}}, \quad m_g = \frac{gT}{\sqrt{2}}$$

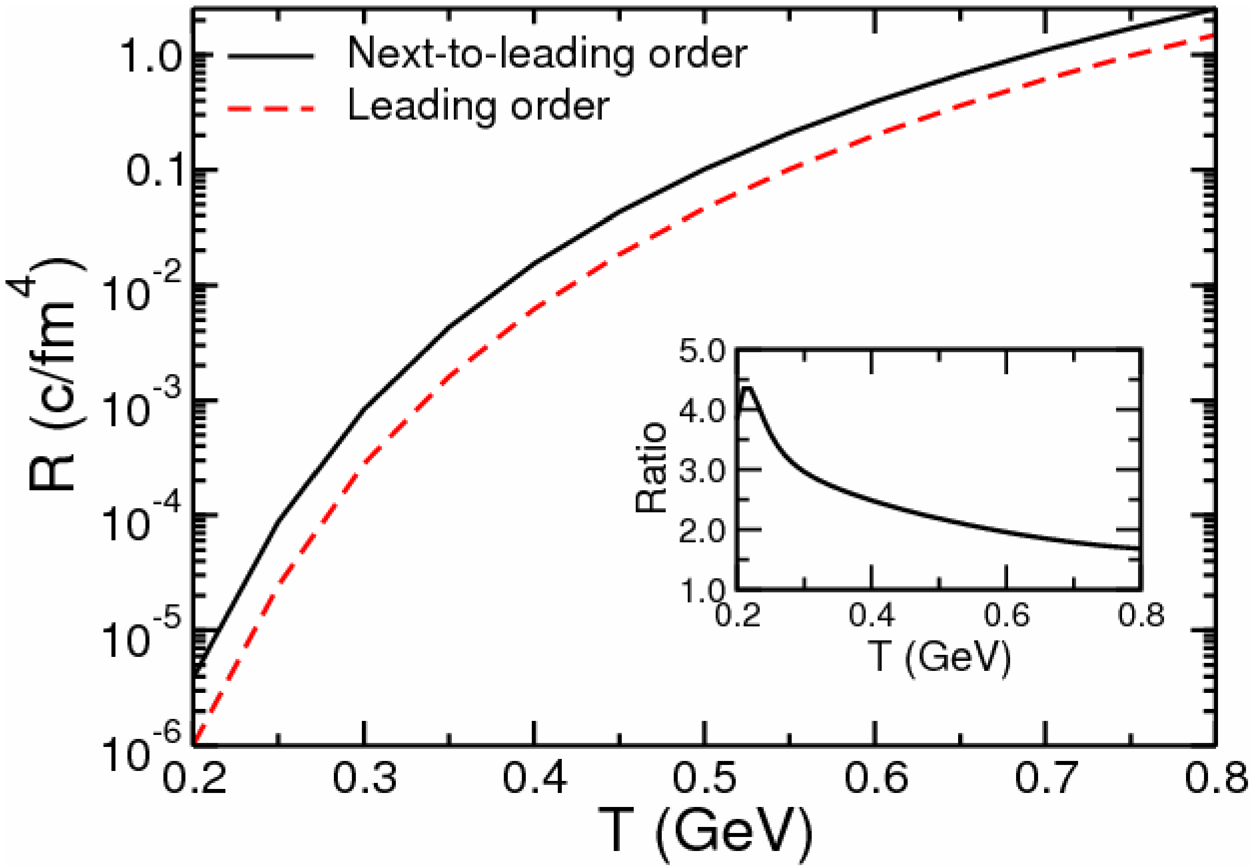




Thermal averaged cross sections are larger in next-to-leading order, particularly in the gg channel. Slightly smaller if using massless partons.

Charm production rate

$$R = \left[\left\langle \sigma_{q\bar{q}\to c\bar{c}} v \right\rangle + \left\langle \sigma_{q\bar{q}\to c\bar{c}g} v \right\rangle\right] n_q^{eq} n_{\bar{q}}^{eq} + \frac{1}{2}\left[\left\langle \sigma_{gg\to c\bar{c}} v \right\rangle + \left\langle \sigma_{gg\to c\bar{c}g} v \right\rangle\right] (n_g^{eq})^2$$



Production rate increases exponentially with temperature

Rate equation for charm production from QGP

$$\frac{1}{V}\frac{dN_{c\bar{c}}}{d\tau} \approx [\left(\left\langle \sigma_{q\bar{q}\to c\bar{c}} v\right\rangle + \left\langle \sigma_{q\bar{q}\to c\bar{c}g} v\right\rangle\right) n_q^{eq} n_{\bar{q}}^{eq}$$
$$+\frac{1}{2}\left(\left\langle \sigma_{gg\to c\bar{c}} v\right\rangle + \left\langle \sigma_{gg\to c\bar{c}g} v\right\rangle\right)(n_g^{eq})^2]\left[1-\left(\frac{n_{c\bar{c}}}{n_{c\bar{c}}^{eq}}\right)^2\right]$$

QGP fire-cylinder dynamics at LHC

- Longitudinally boost invariant and transversely accelerated → volume

$$V(\tau) = \pi\left[R_0 + \frac{a}{2}(\tau - \tau_0)^2\right]^2 \tau$$

- For Pb+Pb @ 5.5 ATeV, R_0~ 1.2 $A^{1/3}$ ~ 7 fm
- Expecting the QGP formation time τ_0 to be less than ~ 0.5 fm/c at RHIC, we take $\tau_0 = 0.2$ fm/c
- Taking transverse acceleration a=0.1 c^2/fm, similar to that at RHIC

Initial temperature of QGP formed in HIC

- Color glass condenstate: T. Lappi, PLB 643, 11 (2006)

  - At LHC, energy density at $\tau = 0.07\ \text{fm/c}$: ε ~ 700 GeV/fm^3

  - Assuming ε decreases with time as $1/\tau$ → ε_0 ~ 245 GeV/fm^3 at $\tau_0 = 0.2\ \text{fm/c}$

  - Using ε ~ (T/160)^4 GeV/fm^3 → T_0 ~ 633 MeV at LHC

  - At RHIC, ε ~ 130 GeV/fm^3 at $\tau = 0.1\ \text{fm/c}$ → T_0 ~ 361 MeV at $\tau_0 = 0.5\ \text{fm/c}$

  - Uncertainty is , however, large due to Q_S^4 dependence

- HIJING (Gyulassy and Wang) or AMPT: Lin et al., PRC 72, 064901 (2005)

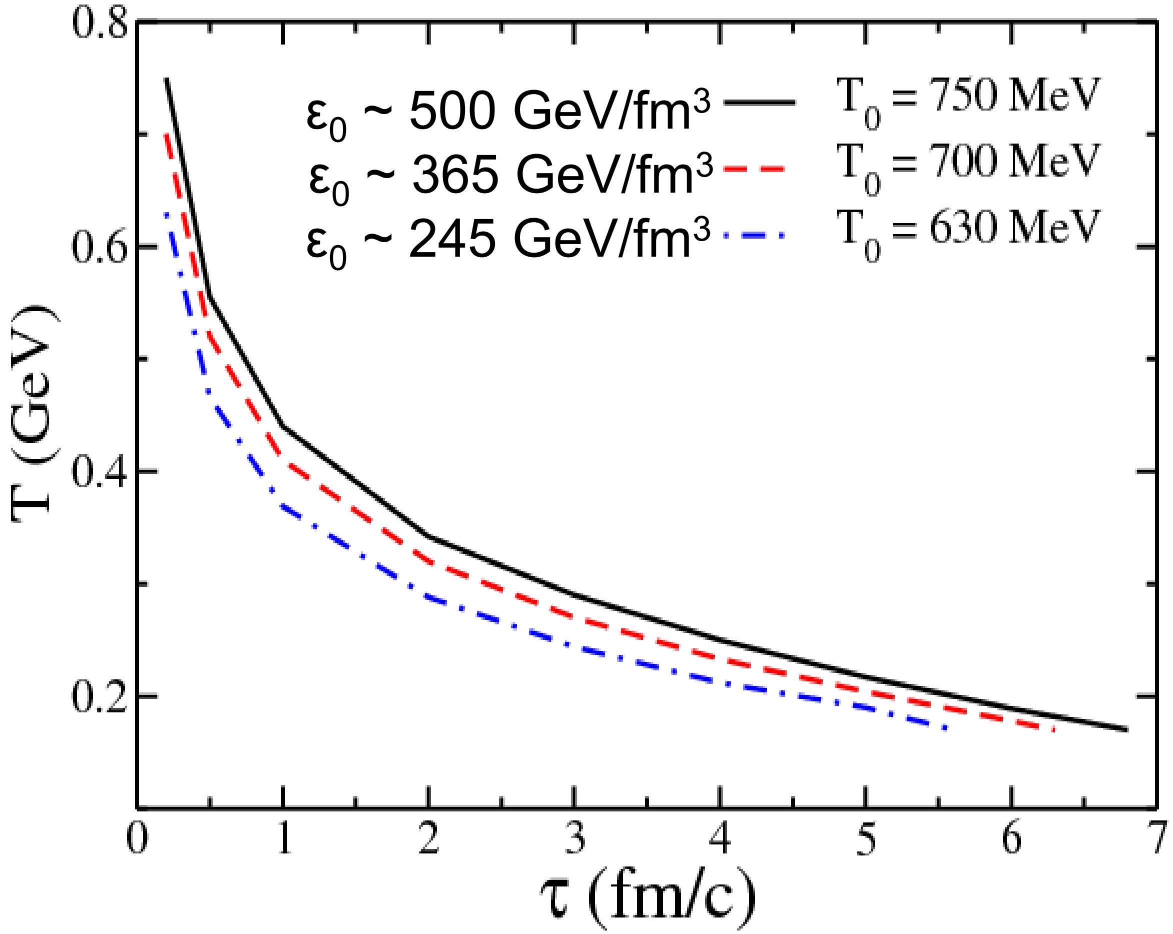
  - Initial transverse energy dE_T/dy~3000 GeV at LHC

$$\varepsilon_0 \approx \frac{dE_T/dy}{\pi R_0^2 \tau_0} \approx \frac{3000}{3\times 4.7^2 \times 0.2} \approx 226\ \text{GeV/fm}^3 \to T_0 \approx 620\ \text{MeV}$$

  - At RHIC, dE_T/dy ~ 1000 GeV → ε_0 ~ 33 GeV/fm^3 → T_0 ~ 383 MeV at $\tau_0 = 0.5\ \text{fm/c}$

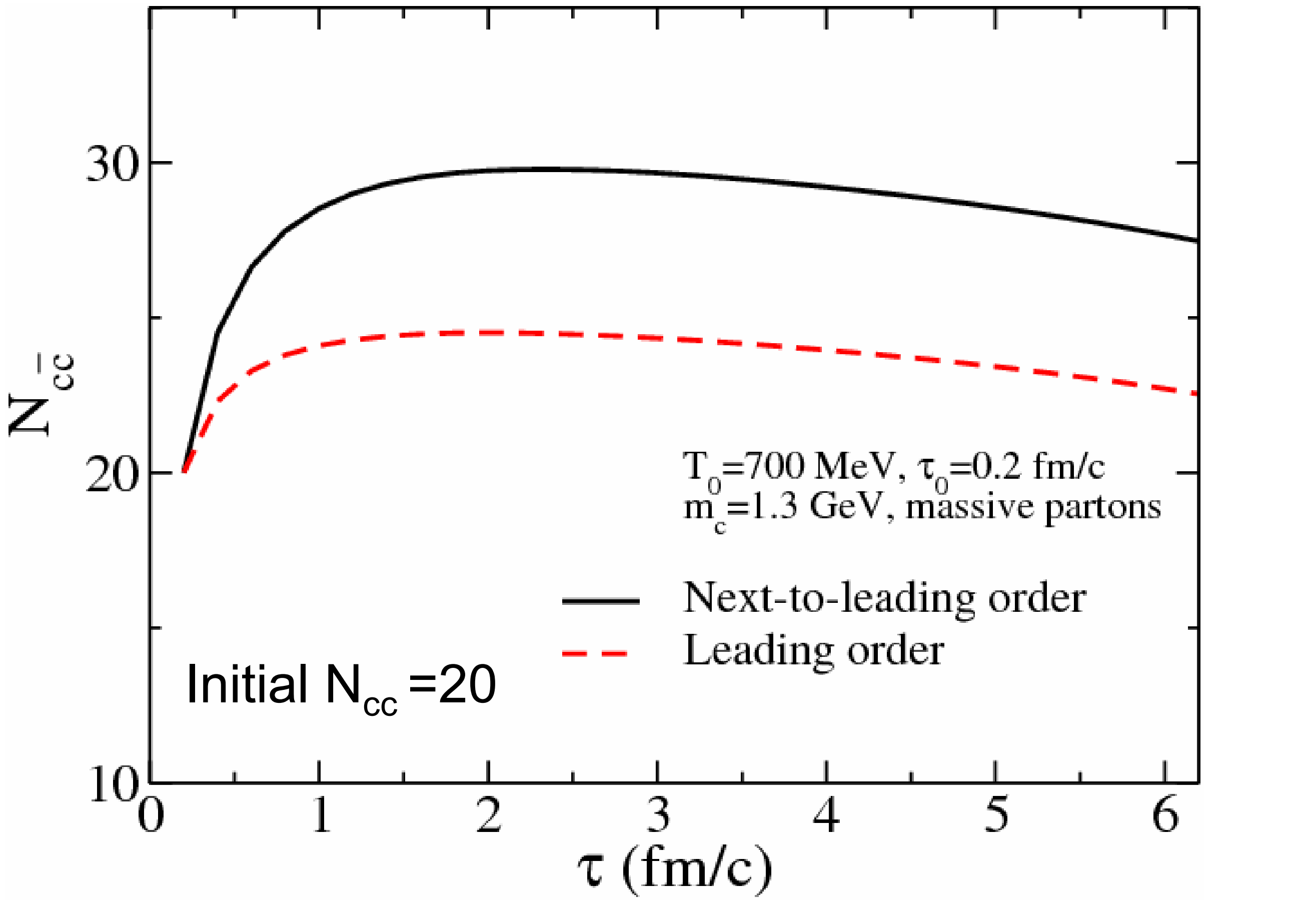
Temperature evolution at LHC

Entropy conservation →



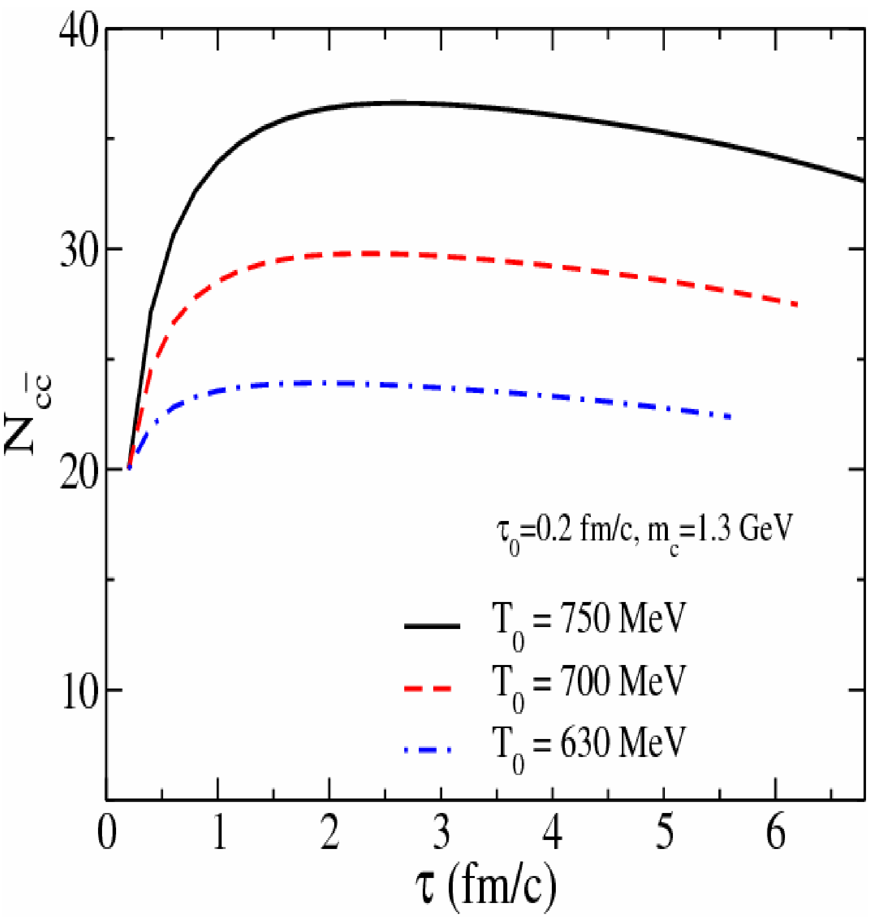
High temperature only exists briefly during early stage of QGP

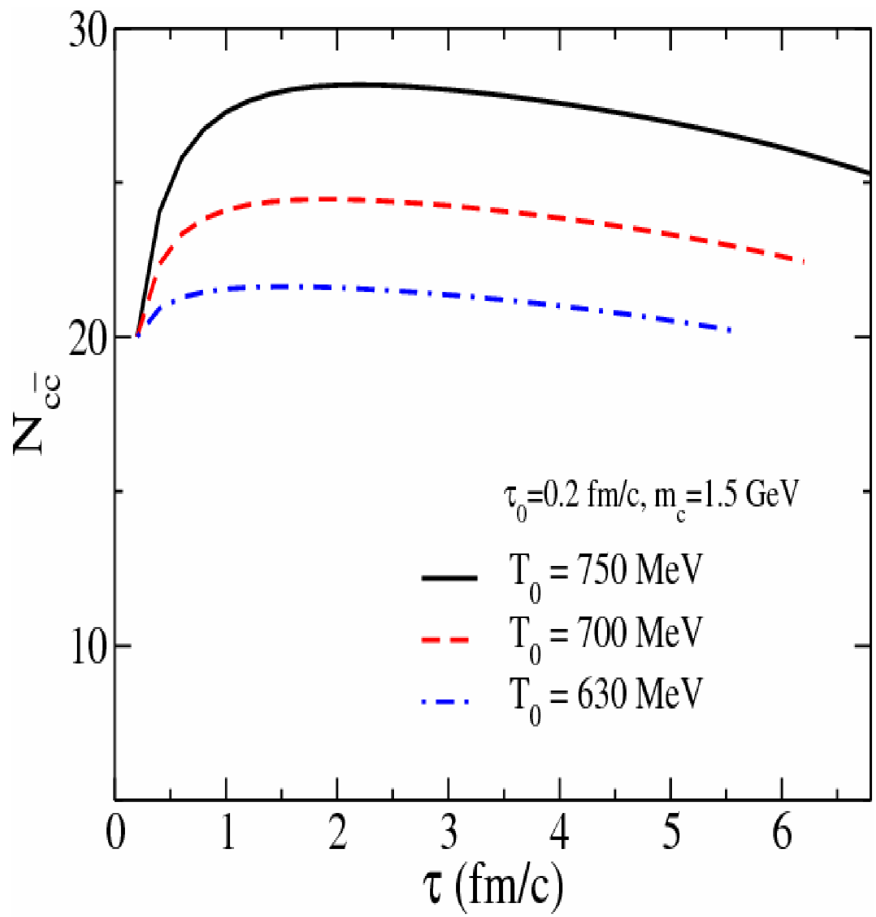
Time evolution of charm quark pair at LHC



- Charm production in next-to-leading order is more than a factor of two larger than in the leading order
- Results using massless gluons are slightly larger

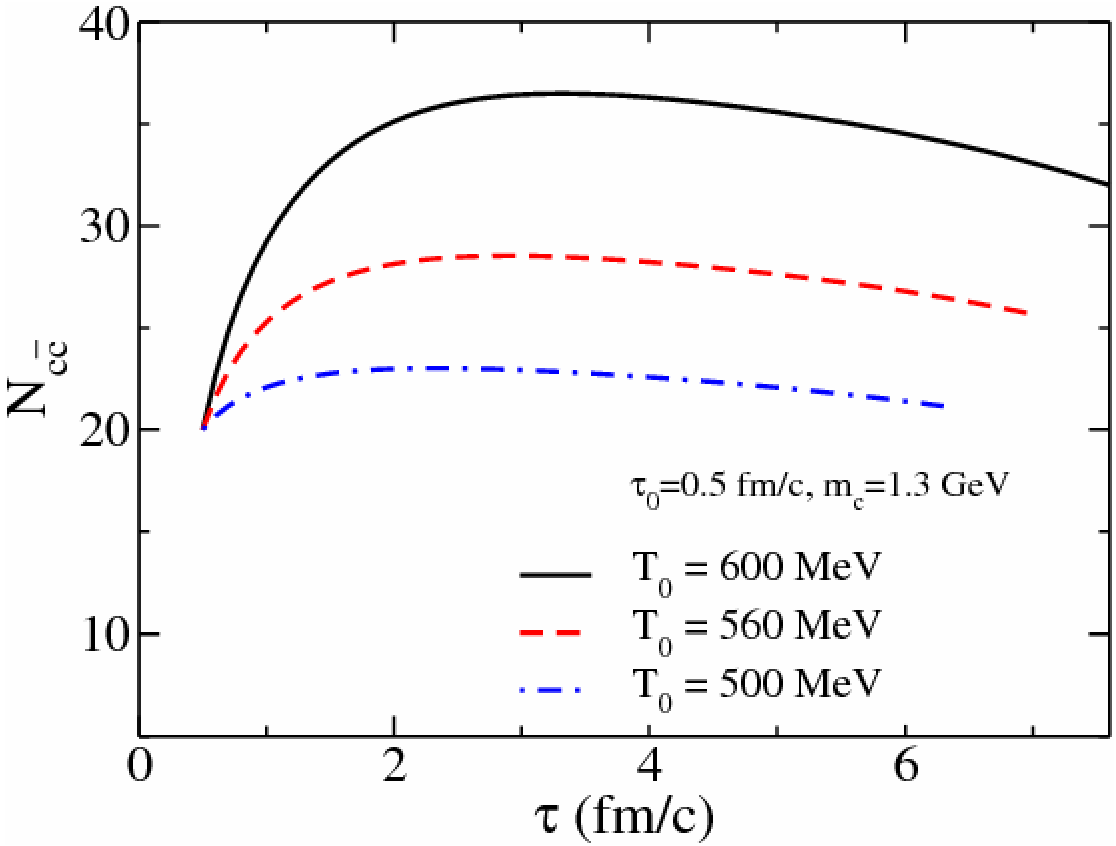
Initial temperature and charm quark mass dependence of thermal charm production





Increases with initial temperature but decreases with charm quark mass.

Charm production at LHC for tau_0=0.5 fm/c

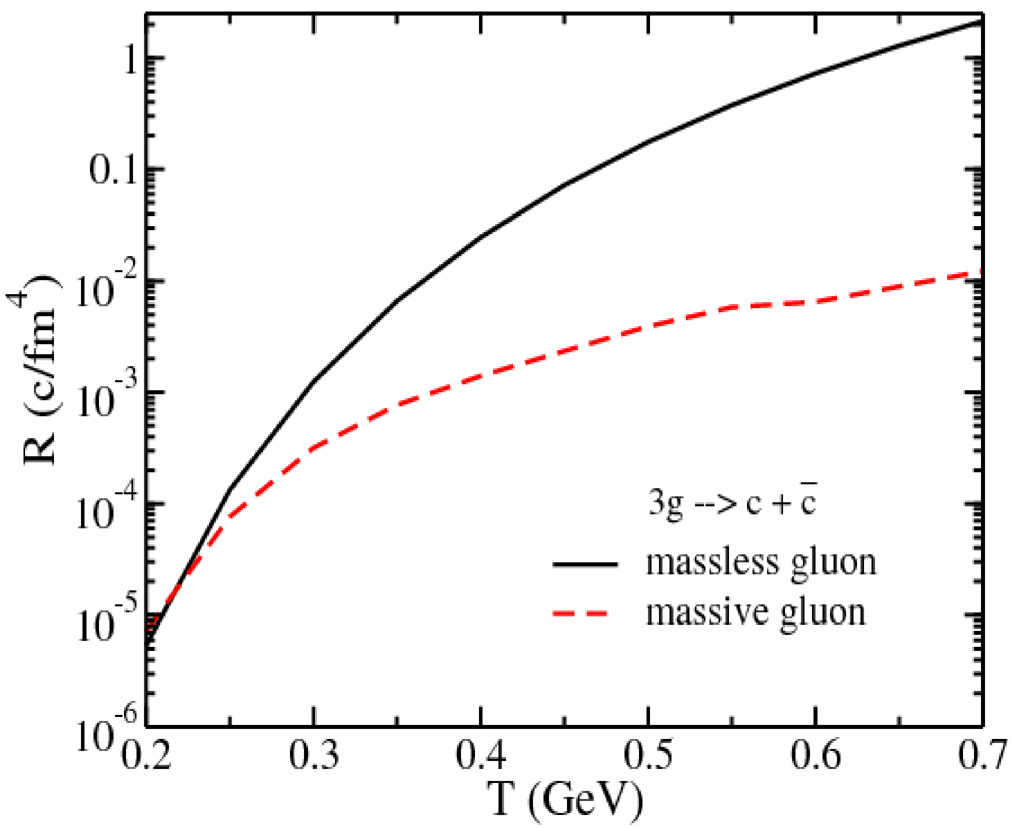


Similar results as $\tau_0 = 0.2$ fm/c, although initial temperature is lower

Charm production from three-gluon interaction ggg→cc

Determine rate for $ggg \rightarrow c\bar{c}$ from $c\bar{c} \rightarrow ggg$ via detailed balance

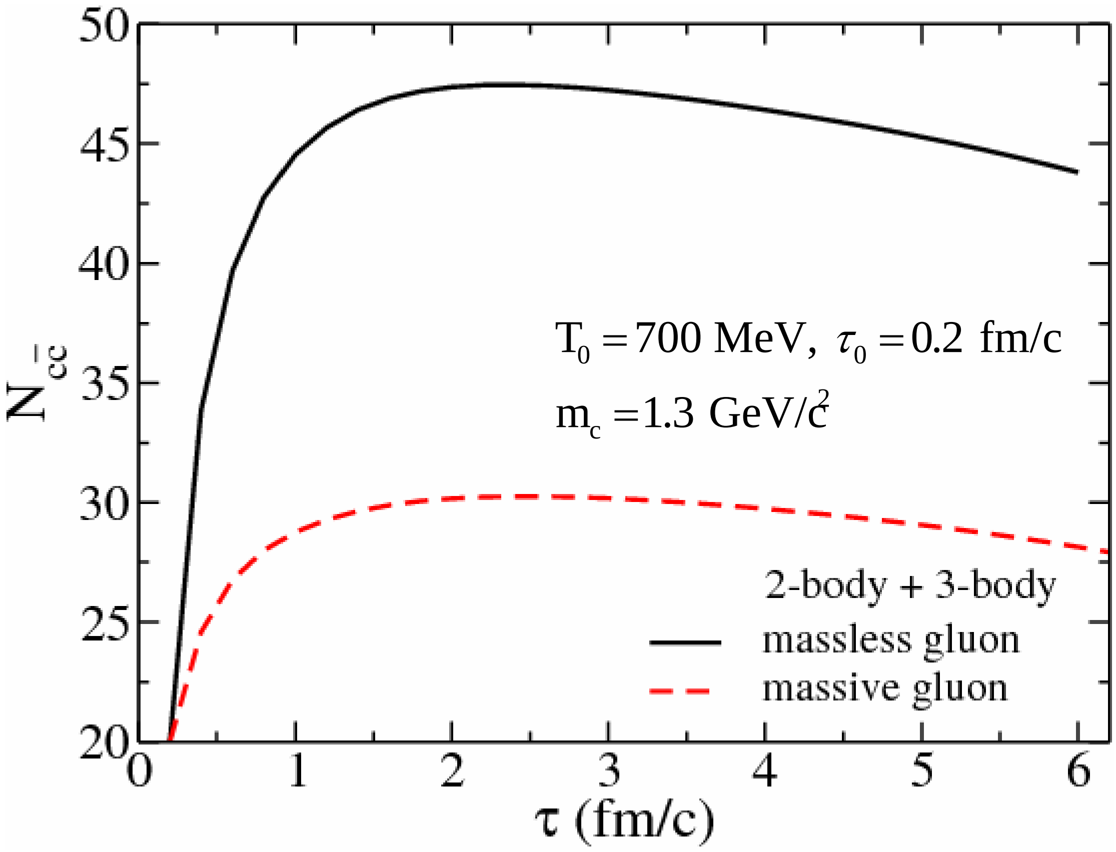
$$R \propto \frac{1}{3}\int \prod_{i=1}^{5} d^3p_i f_i(p_i) \left|M_{ggg\rightarrow c\bar{c}}\right|^2 \delta^{(4)}(p_1+p_2+p_3-p_4-p_5) \propto \left\langle \sigma_{c\bar{c}\rightarrow ggg} v \right\rangle n_c^{eq} n_{\bar{c}}^{eq}$$



Gluon density ~ 0.5/fm^3 at T_C and much larger initially

- Negligible rate for massive gluons as the threshold becomes larger than the charm pair mass
- With massless gluons, the rate is comparable to that of two-body processes

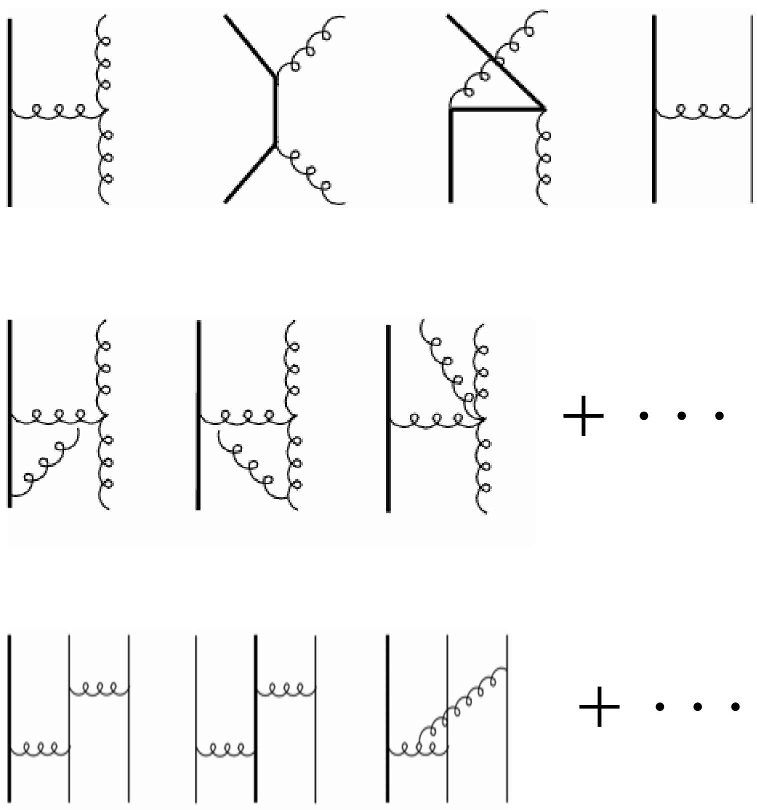
Time evolution of charm quark pairs at LHC including both two- and three-body interactions

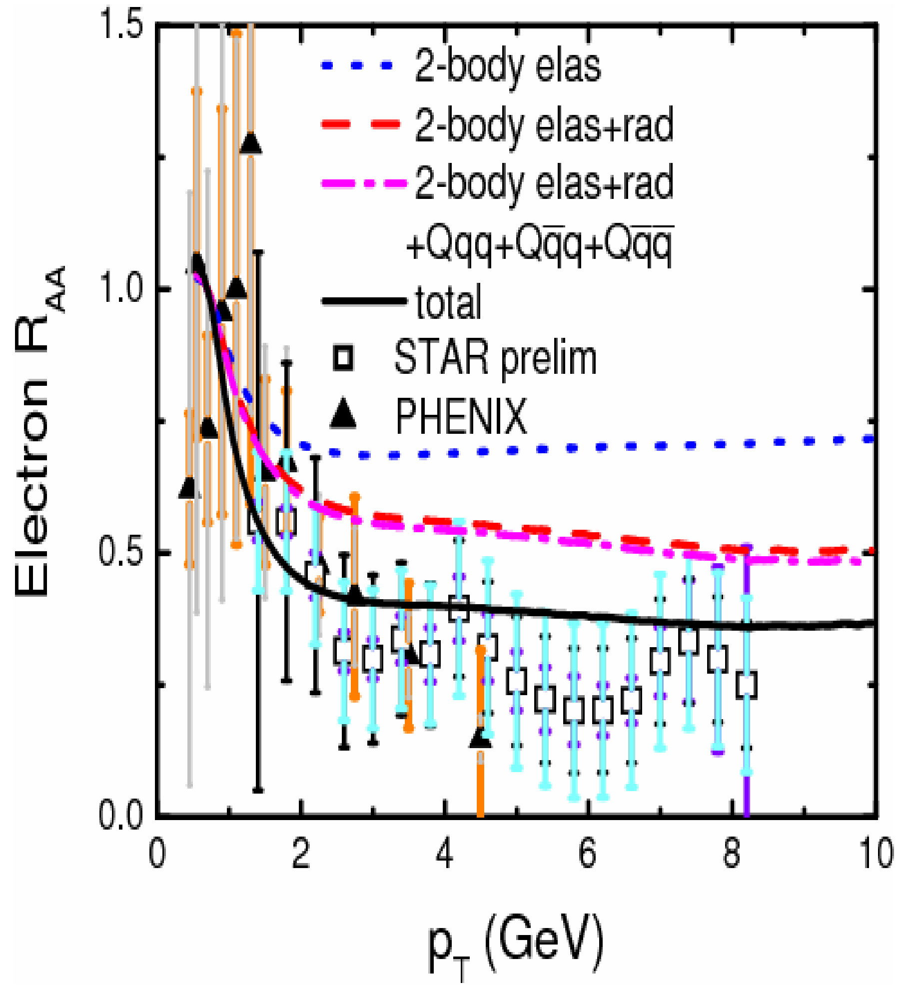


Significant thermal production of charms from QGP of massless gluons

Nuclear modification factor for electrons from heavy meson decays

W. Liu & CMK, NPA 783, 233 (07); nucl-th/0603004





Reasonable agreement with data from Au+Au @ 200A GeV after including heavy quark three-body scattering.

Summary

- Thermal charm production rate increases ~ exponentially with the temperature of QGP.
- Next-to-leading order enhances thermal production rate by more than a factor of 2.
- Charm production from three-gluon interactions is important if gluons are massless.
- Thermal charm production could be important at LHC.
- Understanding thermal charm quark production is important for understanding charmonium production in HIC.
- LHC provides the possibility to search for charmed exotics such as charmed tetraquark mesons and pentaquark baryons.