Thermal Charm production in Pb+Pb @ 40 TeV

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- Introduction
- Charm production in pQCD
- Charm production in QGP
- Charm production in Pb+Pb @ 40 TeV
- Summary

Why is understanding charm production important in Pb+Pb @ 40 TeV?

- Charmonium production: Braun-Munzinger, Thews, Greco ….

  - Yield depends quadratically on the charm quark number in statistical, kinetic, and coalescence models
  - Enhanced charm production could lead to possible charmonium enhancement instead of suppression so far observed at RHIC and LHC

- Charmed exotics production: Lee, Yasui, Liu & Ko, EPJC 54, 259 (2008); Cho et al., PRL 106, 212001 (2011); PRC 84, 064910 (2011)

  - Consideration of the color-spin interaction leads to possible stable charmed tetraquark meson $\mathrm{T_{cc}(ud\bar{c}\bar{c})}$ and pentaquark baryon $\Theta_{\mathrm{sc}}(\mathrm{uds\bar{c}})$
  - Enhanced charm production in Pb+Pb @ 40 TeV makes FCC a possible factory for studying charmed exotics

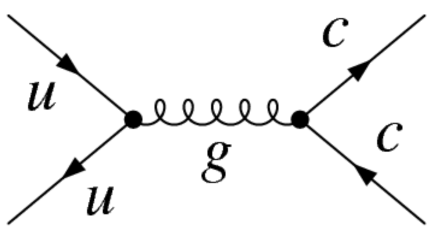
Four stages of charm production in HIC

- 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 @ 2.76 TeV
  - About 40 pairs in Pb+Pb @ 40 TeV
- 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), Zhang (08)
  - 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

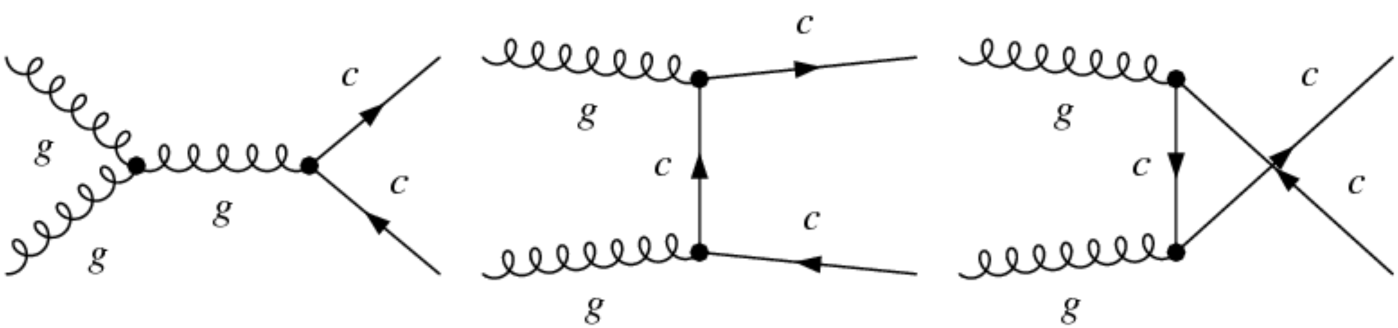
Charm production in pQCD

- Leading-order diagrams for charm production

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

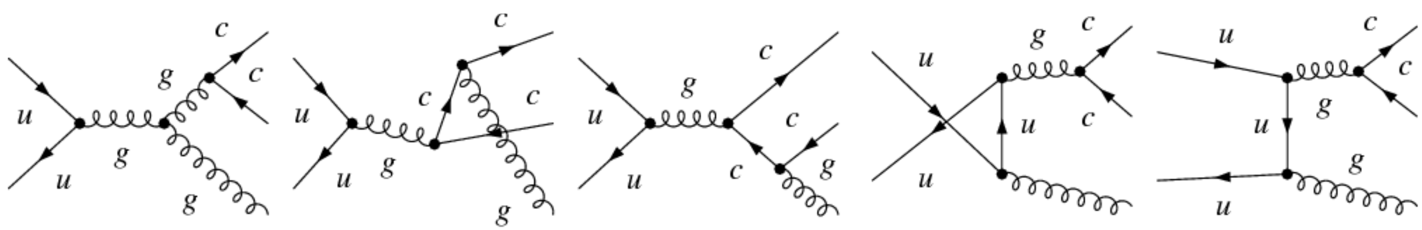


2) $gg \rightarrow c\bar{c}$



- Next-Leading-order diagrams for charm production

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



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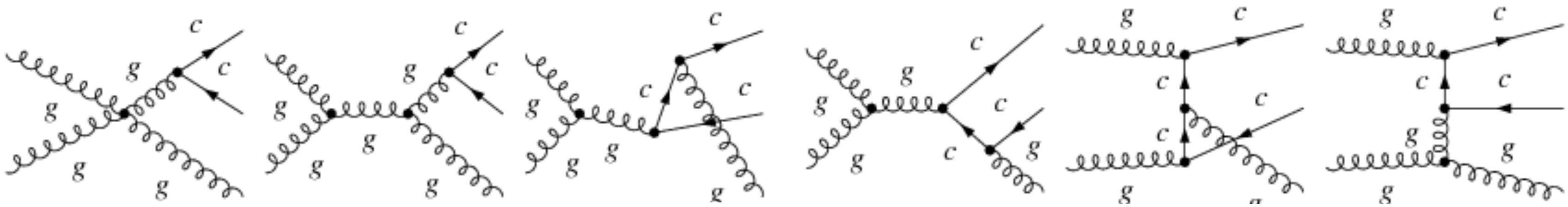
2) $gg \rightarrow c\bar{c}g$



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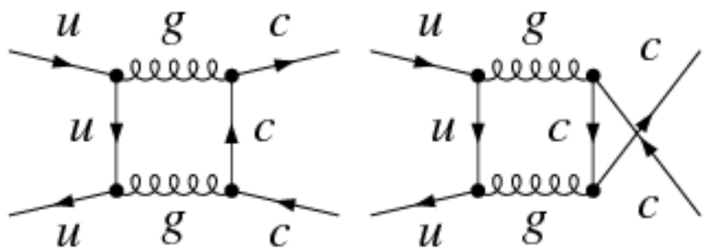
- Virtual corrections to leading-order diagrams

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



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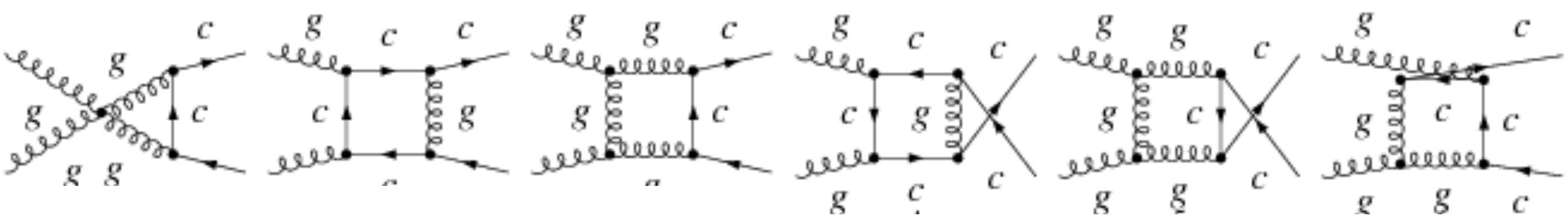
2) $gg \rightarrow c\bar{c}$



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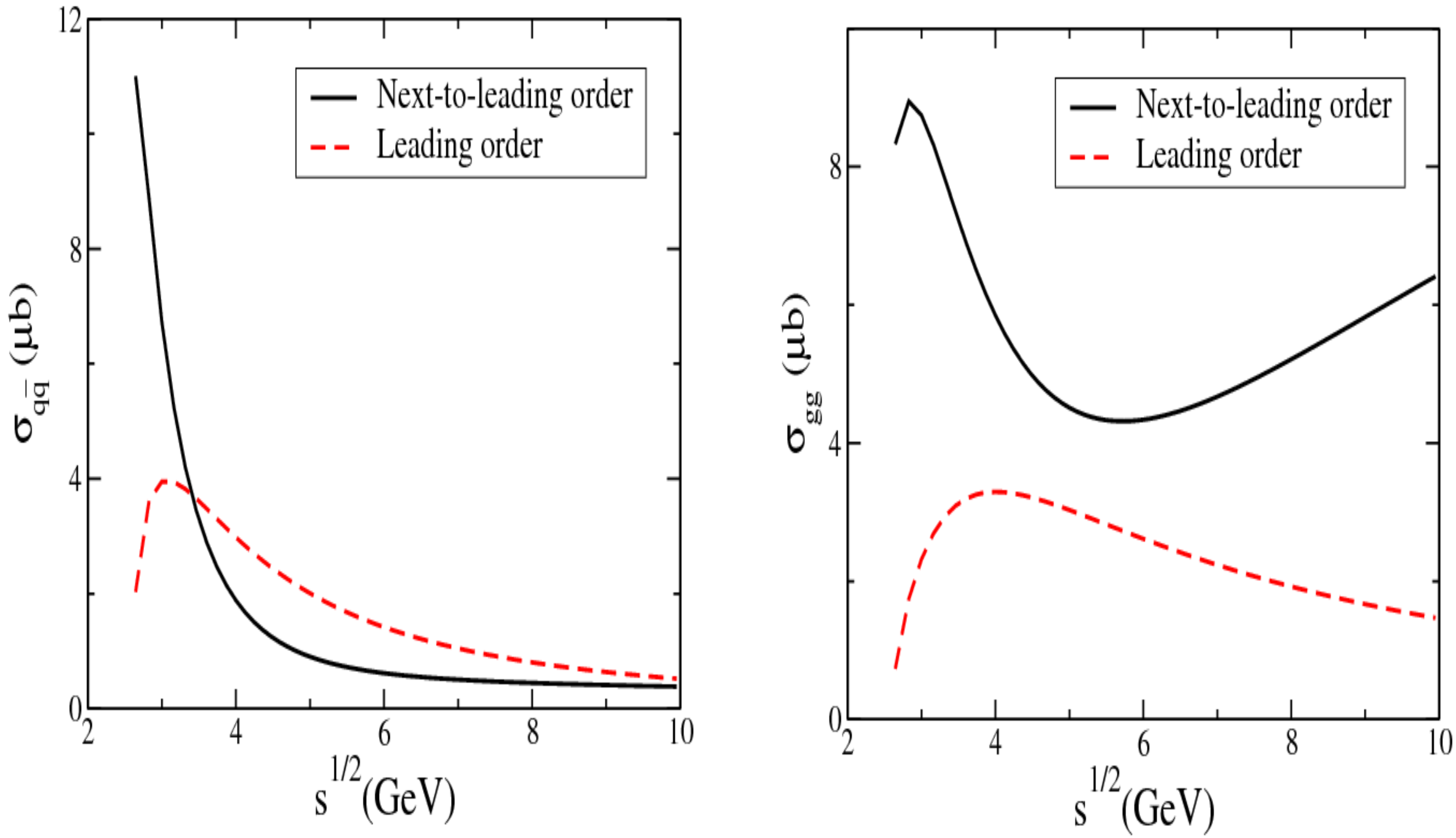
Charm quark production cross sections

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



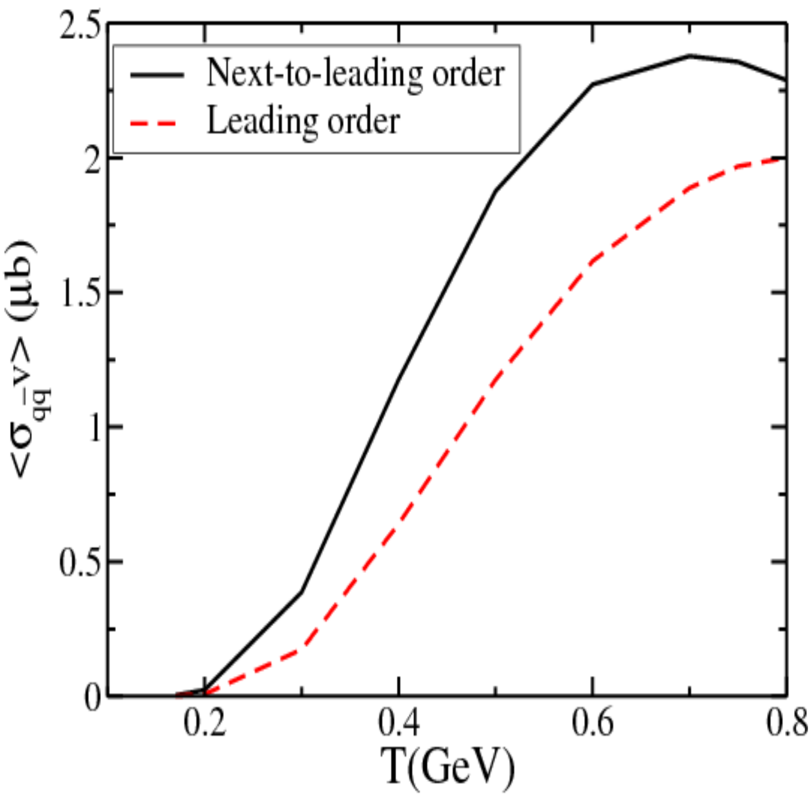
Next-to-leading order generally gives a larger cross section than the leading order except in qqbar annihilation at high energies.

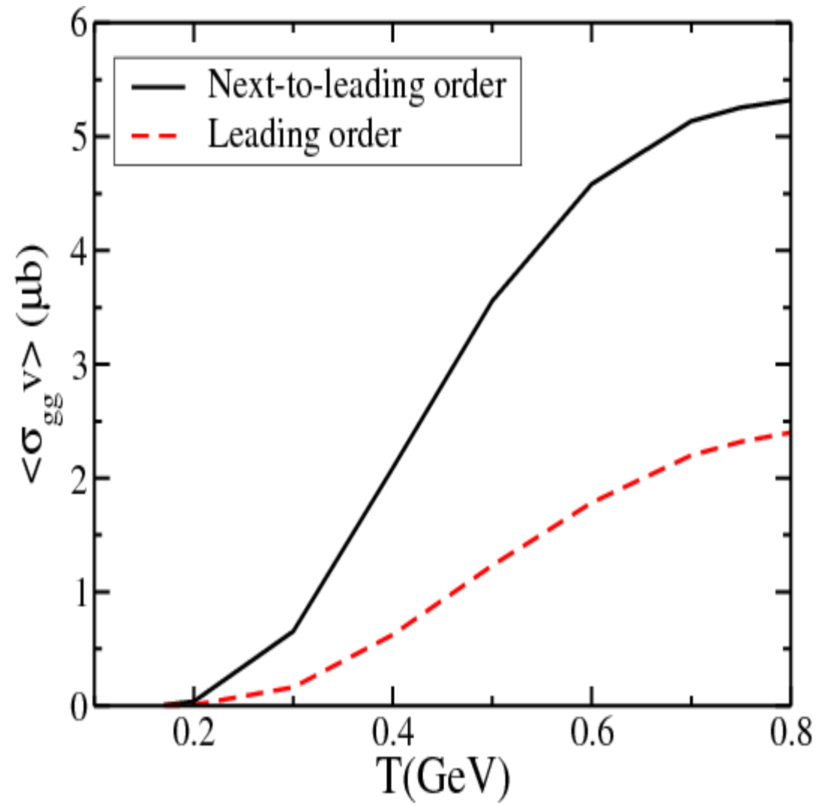
Thermal averaged charm production cross sections

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

Thermal masses

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



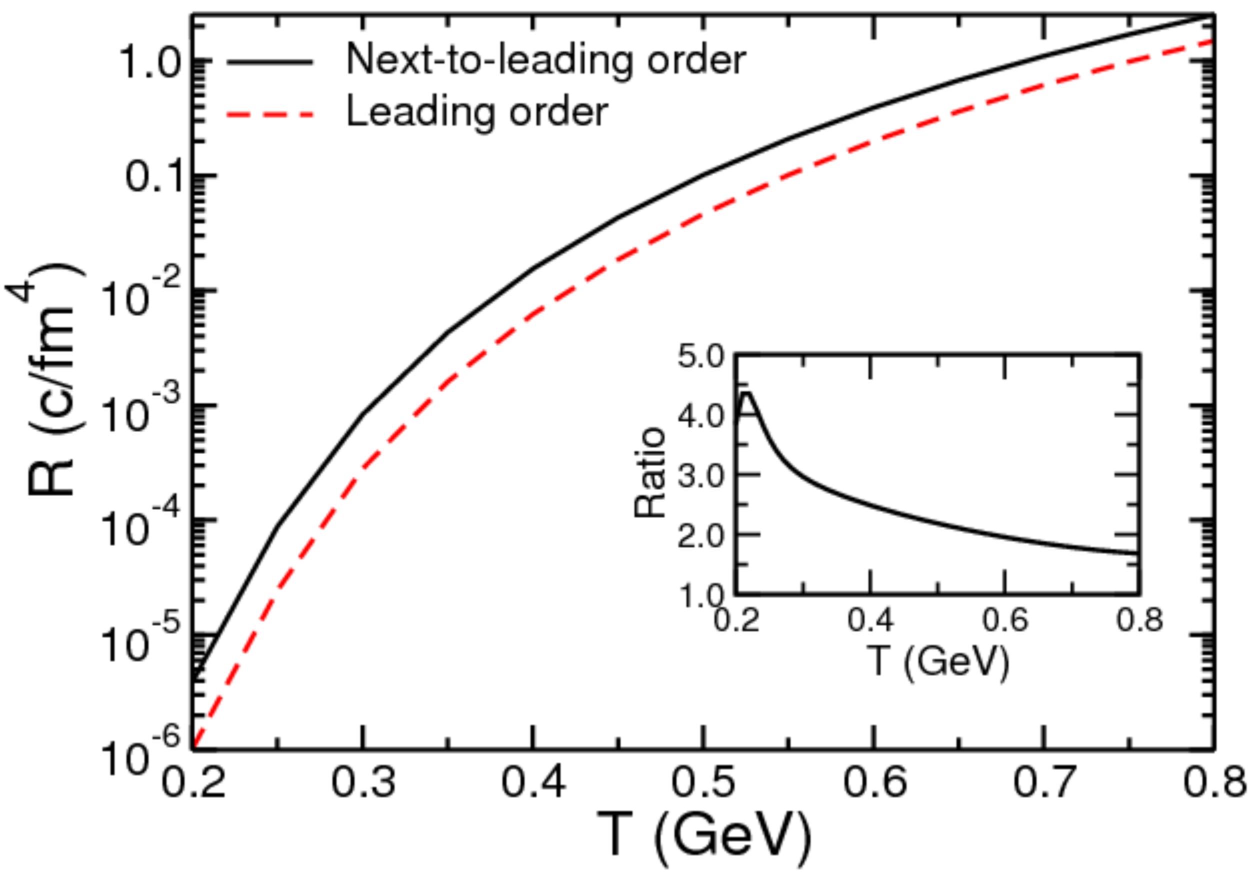


Thermal averaged cross sections are larger in next-to-leading order, particularly in the gg channel. Slightly smaller if using massless partons.

Charm production rate

Zhang, Liu & Ko, PRC 77, 024901 (2008)

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

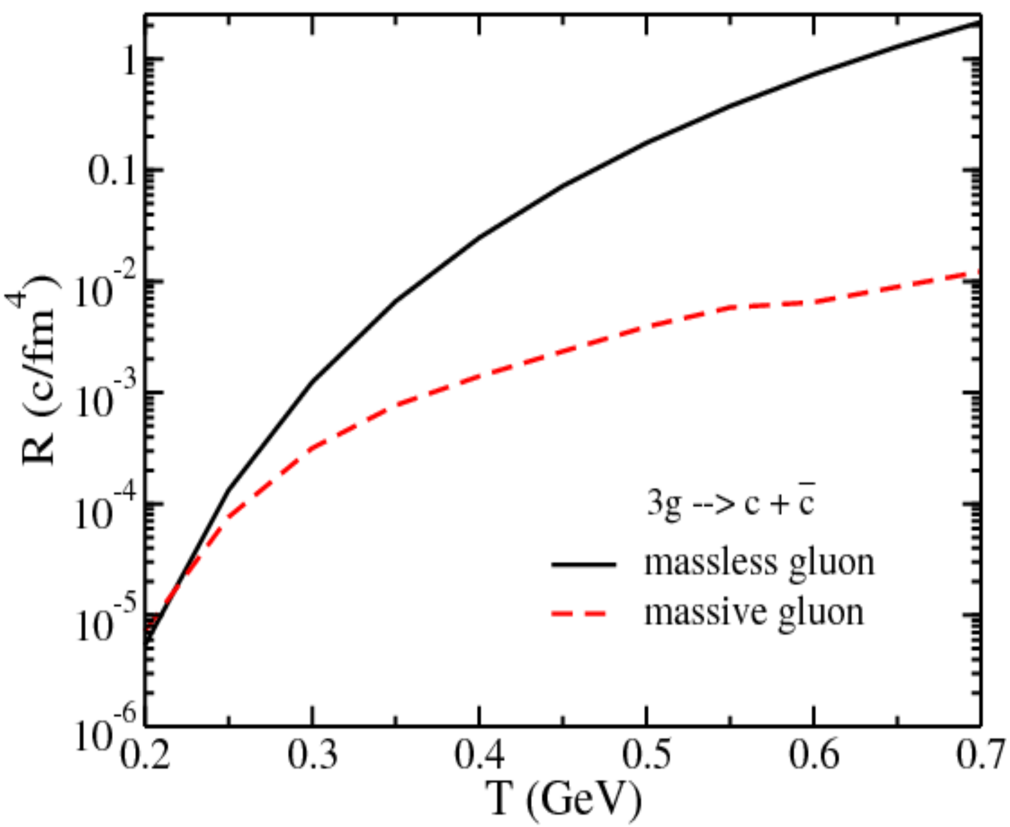


Production rate increases exponentially with temperature

Charm production from three-gluon interaction $ggg \rightarrow cc$

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

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



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

Charm production in Pb+Pb @ 40 TeV

- Fire cylinder evolution: Bjorken's boost invariant expansion, with local density proportional to the thickness function $T_{AB}(\mathbf{x}_T)$, and entropy conservation

$$s(\mathbf{x_T},\tau) = \frac{\tau_0}{\tau} s(\mathbf{x_T},\tau_0), \quad s(\mathbf{x_T},\tau) = s(\mathbf{0},\tau)\frac{T_{AB}(\mathbf{x}_T)}{T_{AB}(\mathbf{0})}$$

- Equation of state: Non-interacting massless parton for QGP and massive hadrons for hadronic matter with a bag constant such that phase transition temperature T_c = 165 MeV

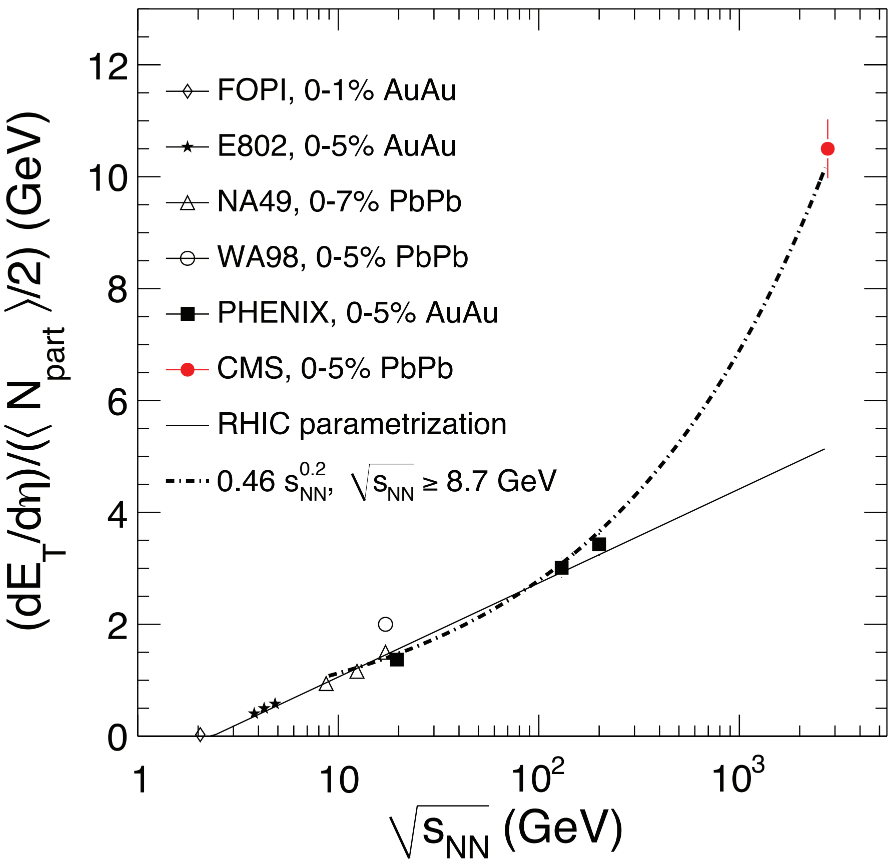
- Initial charm quark number: About 43 pairs from PYTHIA, corresponding to 0.026 pairs per p+p collision or

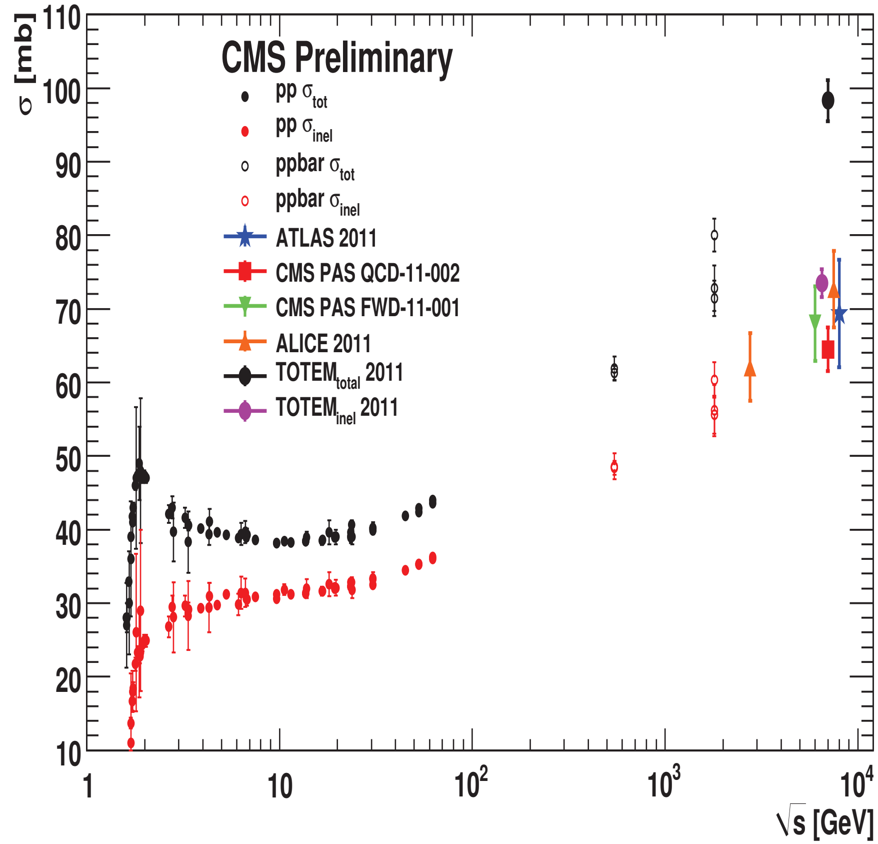
$$\frac{d\sigma_{pp}^{c\bar{c}}}{dy}(\sqrt{s} = 40 \text{ TeV}) = 1.4 \text{ mb}$$

compared to

$$\frac{d\sigma_{pp}^{c\bar{c}}}{dy}(\sqrt{s} = 2.76 \text{ TeV}) = 0.62 \text{ mb}$$

- Transverse energy





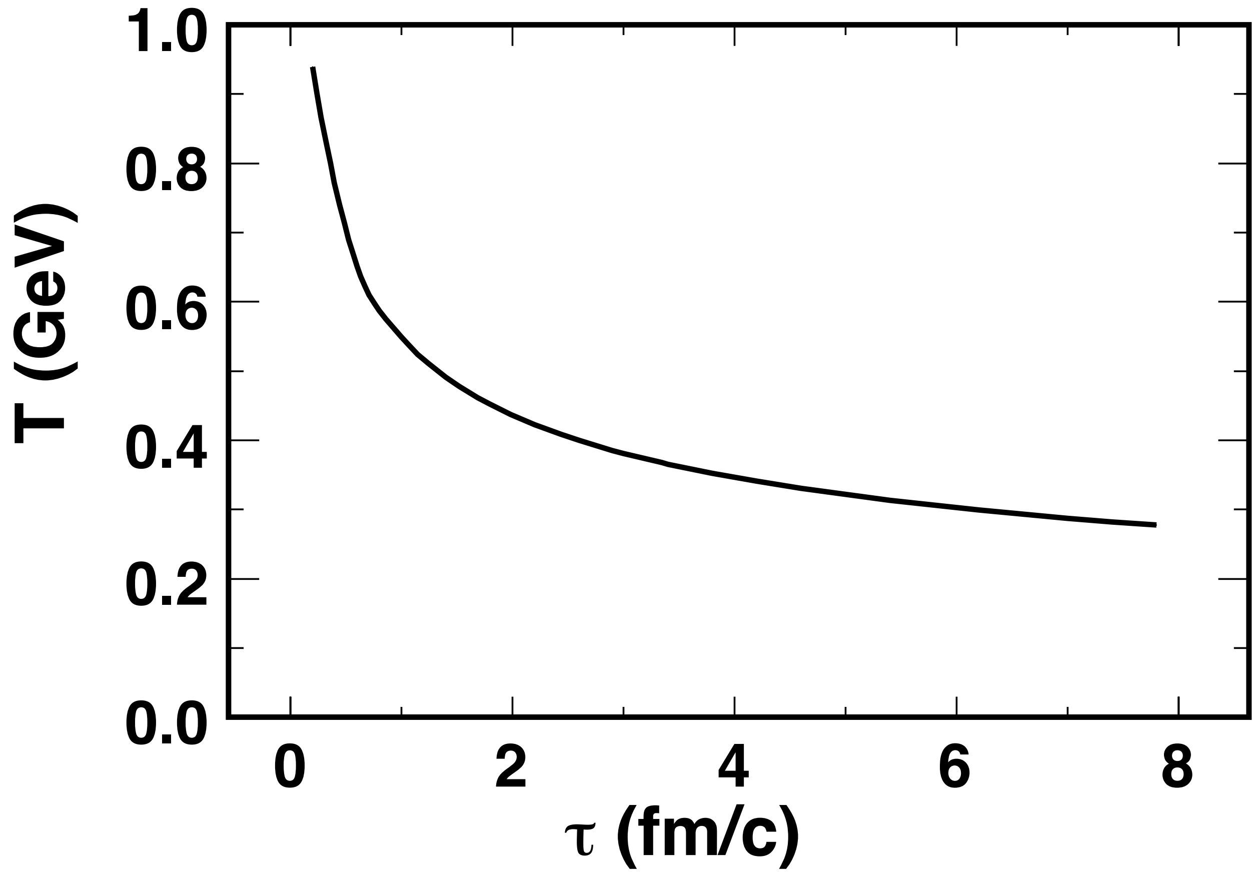
$$\frac{dE_T/d\eta}{0.5 N_{\text{part}}} = 0.46 \left(\frac{\sqrt{s_{\text{NN}}}}{1\ \text{GeV}} \right)^{0.4} \text{GeV} \qquad \sigma_{pp}^{\text{in}} = 8.20 \ln \frac{\sqrt{s}}{1.436\ \text{GeV}}\ \text{mb}$$

$$\rightarrow N_{\text{part}}(40\ \text{TeV}) \approx 408 \rightarrow \frac{dE_T}{d\eta}(40\ \text{TeV}) \approx 6,500\ \text{GeV}$$

- Temperature at center ($\mathbf{x}_T = 0$) of firecyclinder at $\tau_f = 5$ fm/c

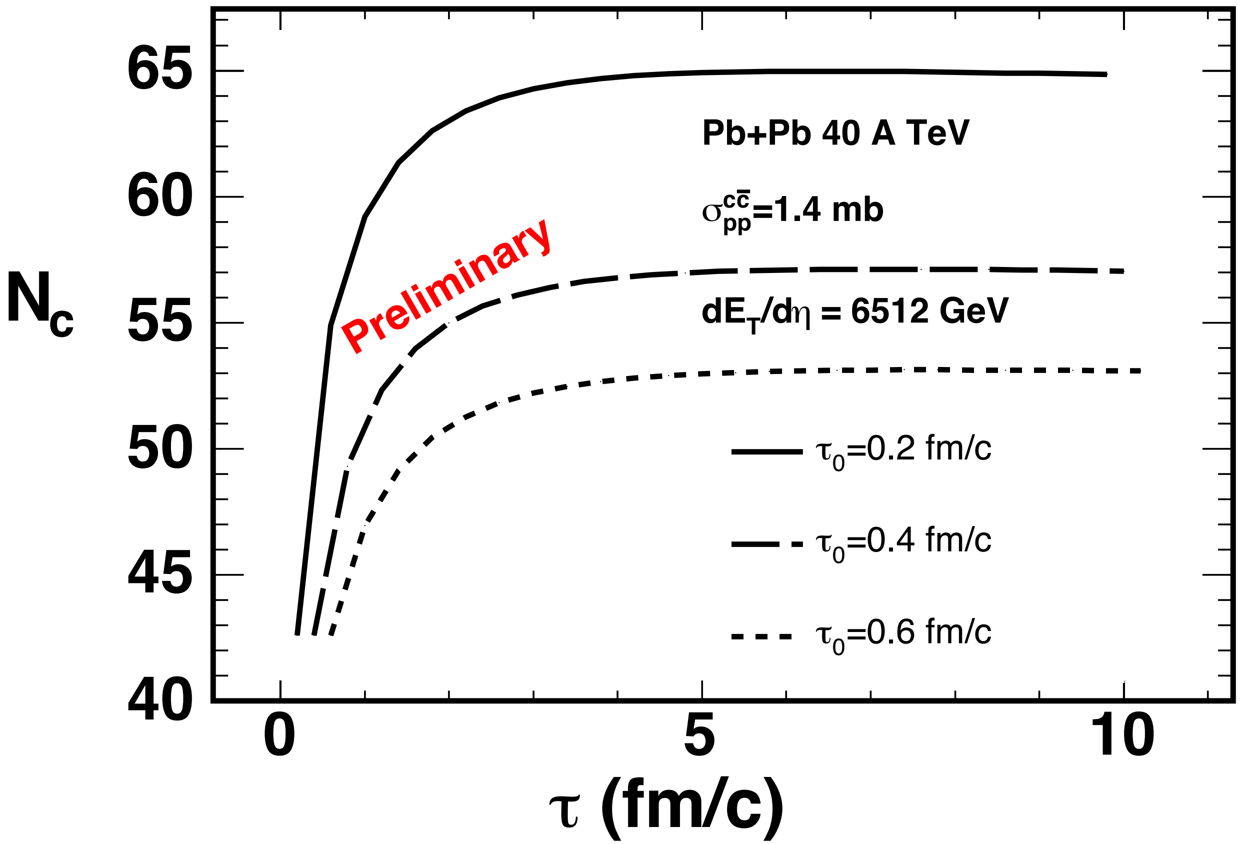
$$\int d\mathbf{x}_T \epsilon(s(\mathbf{x}_T, \tau_f)) = \frac{1}{\tau_f} \frac{dE_T}{d\eta} \rightarrow T(\mathbf{x}_T = \mathbf{0}, \tau_f) \approx 350 \text{ MeV}$$

- Time evolution of temperature at center: determined from entropy conservation through EOS



- Time evolution of charm quark number (not including $ggg \rightarrow c\bar{c}$)

$$\partial_\tau(\tau n_c) = \tau R \left[1 - \left(\frac{n_c}{n_c^{\mathrm{eq}}}\right)^2\right], \quad n_c^{\mathrm{eq}} = \frac{3Tm_c^2}{\pi^2} K_2(m_c/T)$$



- Enhancement: ~ 50% for QGP thermalization time τ_0=0.2 fm/c, ~ 35% for τ_0=0.4 fm/c, ~ 20% at τ_0=0.6 fm/c

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 may be enhanced by 50% in Pb+Pb @ 40 TeV, from 43 pairs to 65 pairs.

- Understanding thermal charm quark production is important for understanding charmonium production in HIC.

- Pb+Pb @ 40 TeV provides the possibility to search for charmed exotics such as charmed tetraquark mesons and pentaquark baryons.