Hadronic Effects on T_{cc} in Relativistic Heavy Ion Collisions

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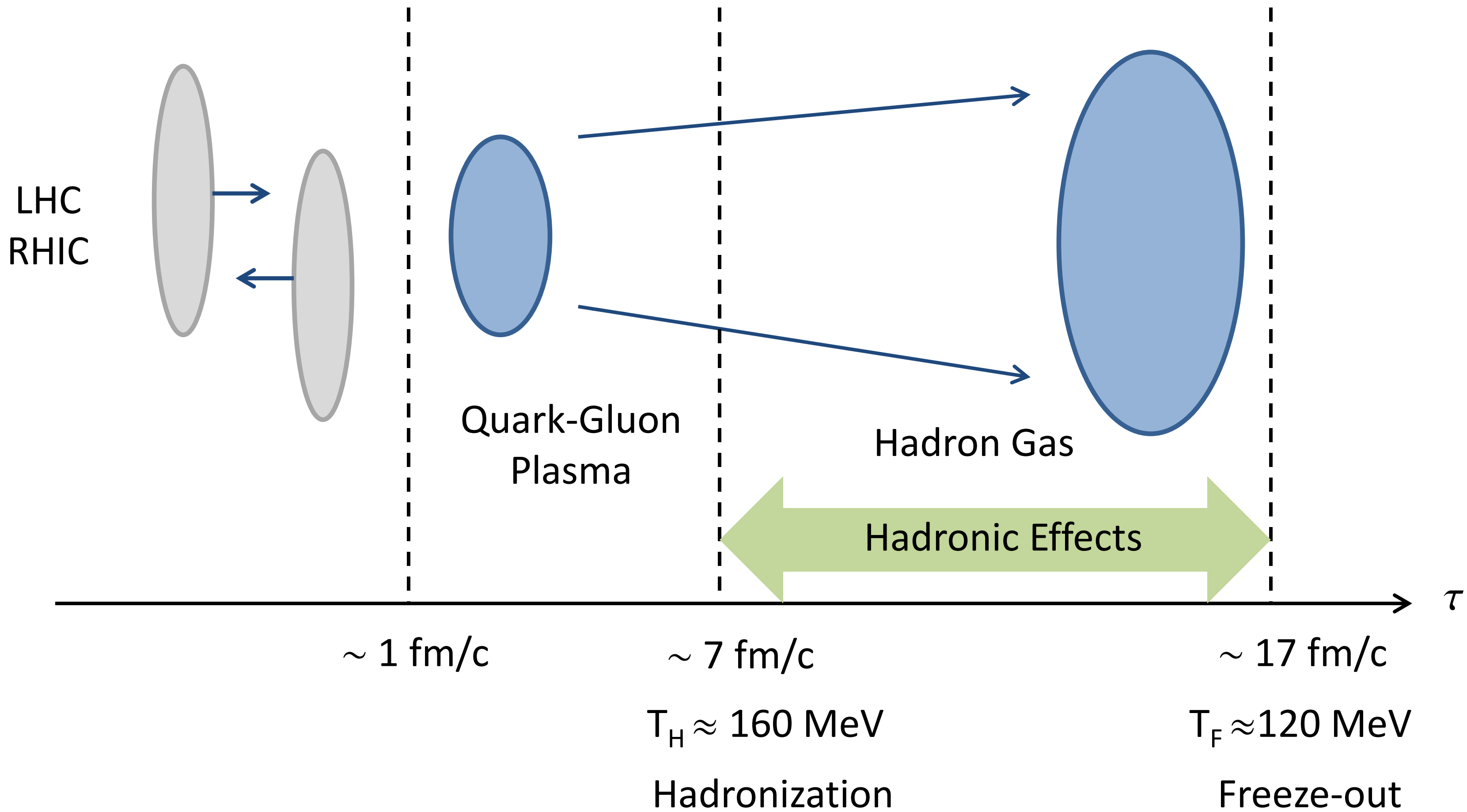
arXiv: 1804.05336, JH, Sungtae Cho, Taesoo Song, and Su Houng Lee

Outline

- Hadronic effects in relativistic heavy ion collisions
- Absorption of T_{cc} by pions
- Time evolution of T_{cc} abundance
- Measurements

Hadronic effects
in relativistic heavy ion collisions

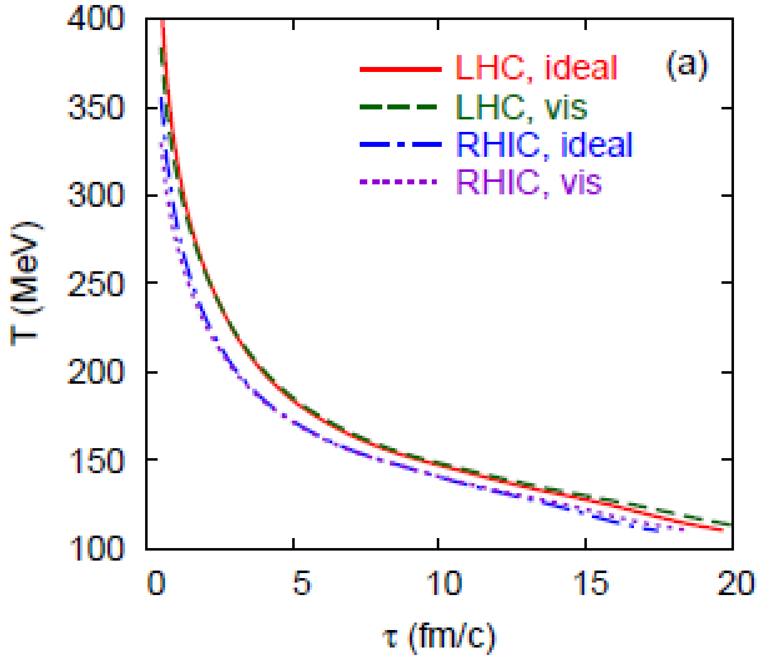
Relativistic heavy ion collisions

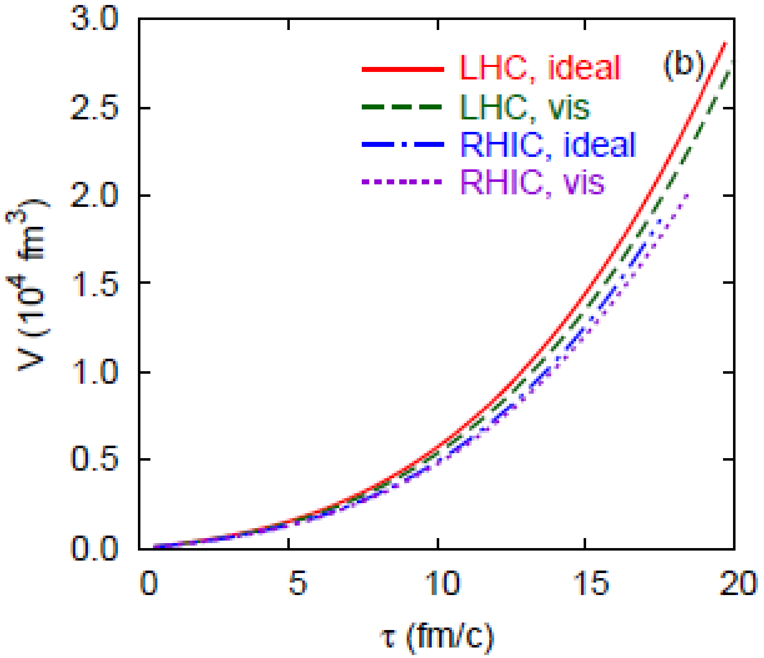


- Absorption/production in the hadronic phase

Hydrodynamic evolution

- Hydrodynamics: $\partial_\mu T^{\mu\nu}=0$, $T^{\mu\nu} = \underbrace{(e+p)u^\mu u^\nu - pg^{\mu\nu}}_{\text{ideal}} + \underbrace{\pi^{\mu\nu}}_{\text{viscous: } \eta/s=1/4\pi}$
- Lattice equation of state
- Pb+Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV at LHC
  Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV at RHIC





Phenomenological model

$$V(\tau) = \pi\left[R + v(\tau - \tau_C) + \frac{a}{2}(\tau - \tau_C)^2\right]^2 c\tau$$

$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{\alpha} \qquad \text{for } \tau > \tau_H$$

		hadronize	freeze-out	hydro		fitting			
		T_C=T_H (MeV)	T_F (MeV)	τ_C=τ_H (fm/c)	τ_F (fm/c)	R (fm)	v (c)	a (c^2/fm)	α
LHC	Ideal	156	115	8.1	18.3	12.1	0.70	0.022	0.95
	viscous	156	115	8.3	19.5	11.9	0.67	0.020	0.93
RHIC	Ideal	162	119	6.1	15.1	9.9	0.59	0.030	0.85
	viscous	162	119	6.1	15.7	9.8	0.58	0.024	0.79

ExHIC Collaboration (2017)

hadronic phase ~ 10 fm/c

Statistical model

- Particle yields: $$N_i^{eq}(\tau) = g_i \gamma_i V(\tau) \int \frac{d^3p}{(2\pi)^3} \exp\left[-\sqrt{p^2 + m_i^2}/T(\tau)\right]$$ $$= \gamma_i N_i^0(\tau)$$

- Spin-isospin degeneracy: g = (2S+1)(2I+1)

- Charm fugacity: from D, D^*, D_s, D_s^*

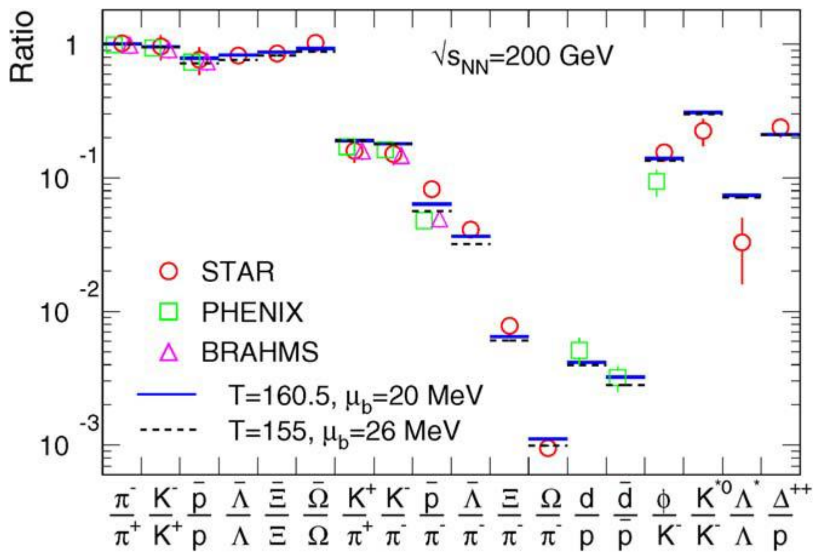
$$\underbrace{N_c}_{} = \sum_{D_i = D, D^*, D_s, D_s^*} N_{D_i}(\tau) = \underbrace{\gamma_c}_{}\left[N_D^0(\tau) + N_{D^*}^0(\tau) + N_{D_s}^0(\tau) + N_{D_s^*}^0(\tau)\right]$$

	N_c	γ_c	
LHC	11	51	at $\tau = \tau_H$
RHIC	4.1	22	

ExHIC Collaboration (2017)

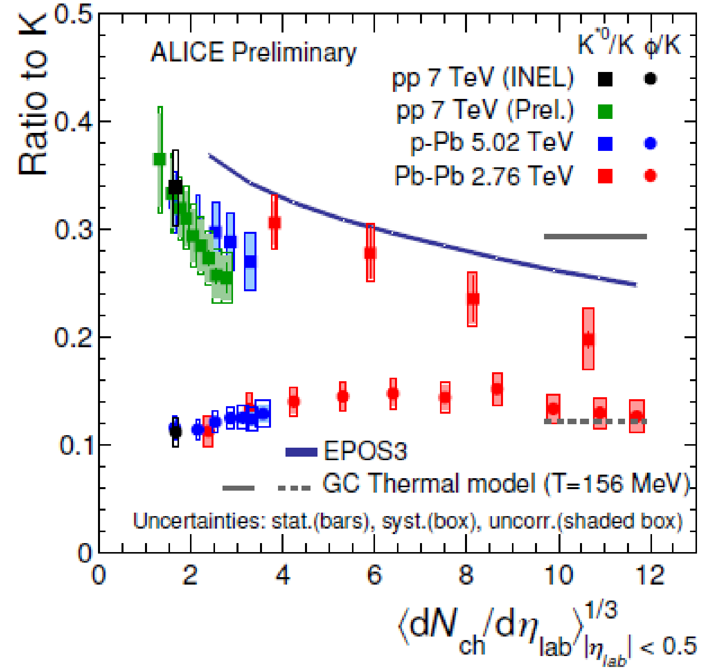
Hadronic effects

- Resonances with large widths:
  K^* suppression



A. Andronic, P. Braun-Munzinger, J. Stachel (2006)

- Particle yield ratios:
  K^*/K, ϕ/K depending on system size



from J. Song's dissertation

T_{cc} absorption

Doubly charmed tetraquark $T_{cc}(1^+)$

- $\mathrm{T_{cc}(cc\bar{u}\bar{d} = DD^*)}$
- The only possible flavor exotic particle
- Consitituent quark model: stronger attraction in the compact configuration than two separate mesons

in $c\bar{q}$ color states: $$\mathrm{T_{cc}} = \underbrace{\frac{1}{\sqrt{3}}(\mathrm{D_1 D_1^*})}_{\text{singlet}} - \underbrace{\sqrt{\frac{2}{3}}(\mathrm{D_8 D_8^*})}_{\text{octet}}$$

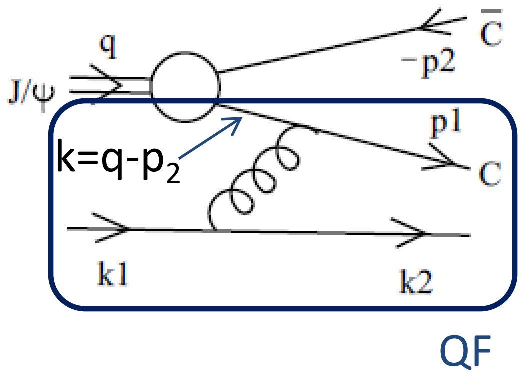
Quasifree approximation

- J/ψ dissociation by parton: $g + J/\psi \rightarrow c + \bar{c}$ L. Grandchamp, R. Rapp (2001)

- For a loosely bound charmonium state:
  break-up by inelastic parton scattering, $g(q,\bar{q}) + J/\psi \rightarrow g(q,\bar{q}) + c + \bar{c}$

- Quasifree approximation using LO QCD: $g(q) + c \rightarrow g(q) + c$

$$\sigma_{\mathrm{diss}} = \frac{1}{2E_q 2E_{k_1} v_{qk_1} g_q g_{k_1}} \int \frac{d^3 p_2}{(2\pi)^3 2E_{p_2}} \frac{d^3 p_1}{(2\pi)^3 2E_{p_1}} \frac{d^3 k_2}{(2\pi)^3 2E_{k_2}} \times (2\pi)^4 \delta^4(p_1 + p_2 + k_2 - q - k_1) |M|^2$$
$$\approx \frac{1}{2E_k 2E_{k_1} v_{kk_1} g_k g_{k_1}} \int \frac{d^3 p_1}{(2\pi)^3 2E_{p_1}} \frac{d^3 k_2}{(2\pi)^3 2E_{k_2}} \times (2\pi)^4 \delta^4(p_1 + k_2 - k - k_1) |M_{QF}|^2$$
$$= \sigma_{QF}$$



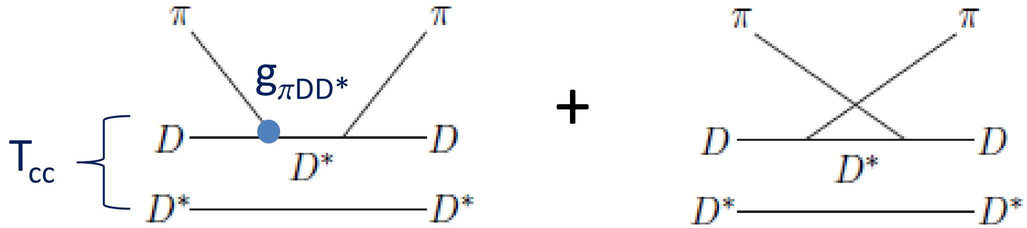
- NLO calculations seem to agree on the order of magnitude

T. Song, S. H. Lee (2005), T. Song, W. Park, S. H. Lee (2010)

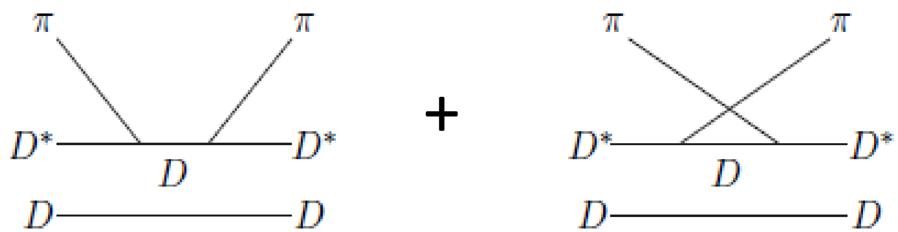
T_{cc}+ π classical elastic scattering

- T_{cc} absorption/production by pions: $T_{cc} + \pi \leftrightarrow D + D^* + \pi$
- Quasifree approximation: $\sigma_{T_{cc}\pi}{}^{tot} = \sigma_{D\pi}{}^{tot} + \sigma_{D^*\pi}{}^{tot}$ (no interference)

$D+\pi \rightarrow D+\pi$



$D^*+\pi \rightarrow D^*+\pi$

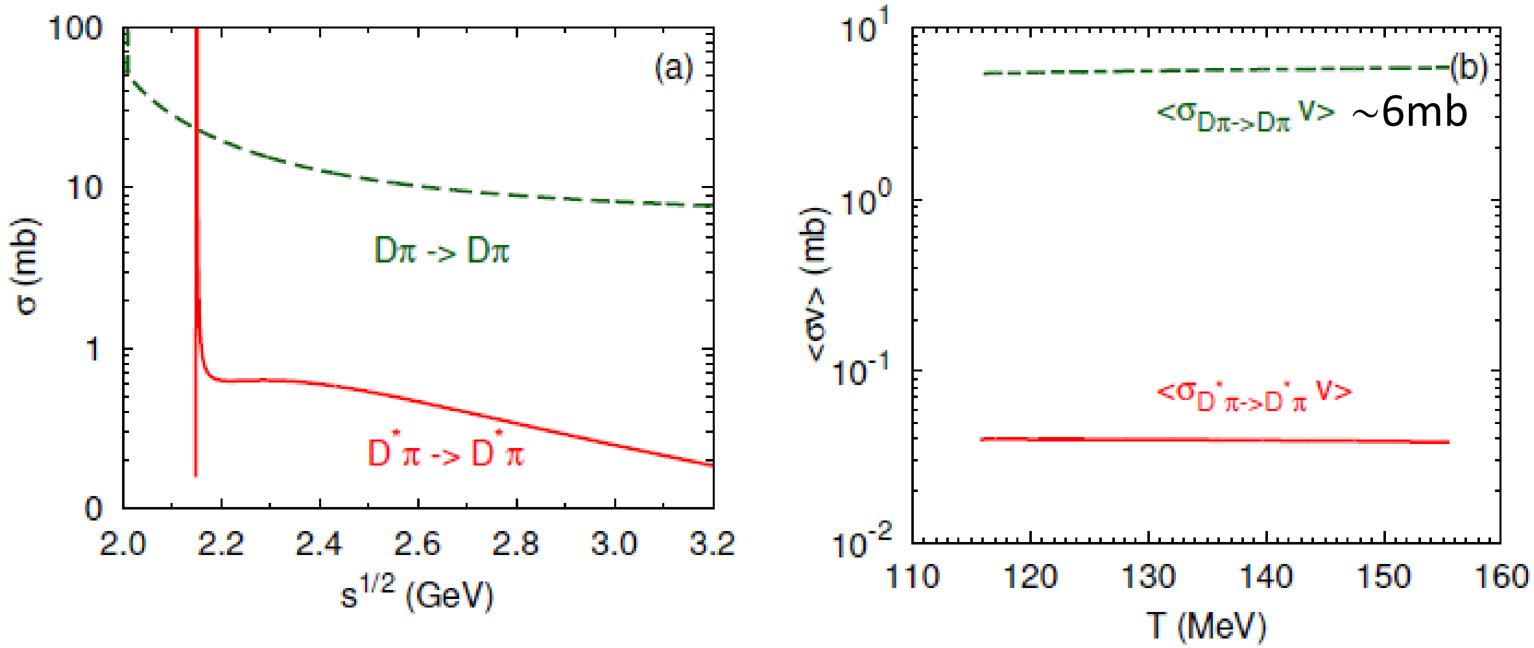


- Effective Lagrangian: $\mathrm{L}_{\pi DD^*} = i g_{\pi DD^*} D^{*\mu} \tau \bullet \left(\bar{D} \partial_\mu \pi - \partial_\mu \bar{D} \pi \right) + \mathrm{h.c.}$
- Decay width: $\Gamma_{D^* \rightarrow D\pi} = \dfrac{g_{\pi DD^*}^2 p_{cm}^3}{2\pi m_{D^*}^2}$ = 83.4 keV

Z. Lin, C. M. Ko (2000)
Particle Data Group (2016)

T_{cc} absorption cross section

at $\sqrt{s_0}$, $m_{D^*} \approx m_D + m_\pi$



- Spin-isospin averaged cross section: $$\sigma = \frac{1}{64\pi^2 g_1 g_2 s}\frac{|p_f|}{|p_i|}\int d\Omega \sum_{S,I}|M|^2 F^4$$
- Form factor: $$F = \frac{\Lambda^2}{\Lambda^2 + q^2}$$
- Thermal effects: $$\langle \sigma_{ab\to cd} v_{ab} \rangle(\tau) = \frac{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b) \sigma_{ab\to cd} v_{ab}}{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b)}$$

Evolution of T_{cc} multiplicity

Rate equation

- Absorption: $T_{cc}+\pi \rightarrow D+D^{*}+\pi$

$$\frac{dN_{T_{cc}}}{Vd\tau}=-\boxed{\int\frac{d^3p_D}{(2\pi)^3 2E_D}\frac{d^3p_{D^*}}{(2\pi)^3 2E_{D^*}}\frac{d^3p_{\pi^f}}{(2\pi)^3 2E_{\pi^f}}}\overbrace{\frac{d^3p_{T_{cc}}}{(2\pi)^3 2E_{T_{cc}}}\frac{d^3p_{\pi^i}}{(2\pi)^3 2E_{\pi^i}}}^{2E_{T_{cc}}2E_{\pi^i}v_{T_{cc}\pi^i}g_{T_{cc}}g_{\pi}\sigma_{T_{cc}\pi\rightarrow DD^*\pi}}$$

$$\times f(p_{T_{cc}})f(p_{\pi^i})\boxed{(2\pi)^4\delta^4\left(p_D+p_{D^*}+p_{\pi^f}-p_{T_{cc}}-p_{\pi^i}\right)\left|M_{T_{cc}\pi\rightarrow DD^*\pi}\right|^2}$$

$$\frac{dN_{T_{cc}}}{Vd\tau}=-\underbrace{\langle\sigma_{T_{cc}\pi\rightarrow DD^*\pi}v_{T_{cc}\pi}\rangle}_{\text{absorption rate}}n_{\pi}n_{T_{cc}}$$

- Production: $D+D^{*}+\pi \rightarrow T_{cc}+\pi$, $\quad f(p_D)f(p_{D^*})f\left(p_{\pi^f}\right)=f(p_{T_{cc}})f\left(p_{\pi^i}\right)$

$$\frac{dN_{T_{cc}}}{Vd\tau}=\langle\sigma_{T_{cc}\pi\rightarrow DD^*\pi}v_{T_{cc}\pi}\rangle n_{\pi}n_{T_{cc}}^{eq}\frac{n_D n_{D^*}}{n_D^{eq}n_{D^*}^{eq}}$$

Evolution of T_{cc} abundance

- Rate equation: $$\frac{dN_{T_{cc}}(\tau)}{Vd\tau} = \langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau) n_\pi(\tau) \left[-N_{T_{cc}}(\tau) + N^{eq}_{T_{cc}}(\tau) \frac{N_D(\tau) N_{D^*}(\tau)}{N^{eq}_D(\tau) N^{eq}_{D^*}(\tau)} \right]$$

$$\langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau) = c_1 \langle \sigma_{D\pi \to D\pi} v_{T_{cc}\pi} \rangle(\tau) + c_1 \langle \sigma_{D^*\pi \to D^*\pi} v_{T_{cc}\pi} \rangle(\tau)$$

- Absorption rate: $\langle \sigma \upsilon \rangle n_\pi \sim$ (6mb)(0.1fm^{-3}) $\sim$ 0.06 c/fm

  Lifetime of hadronic phase $\sim$ 10 fm/c

  Hadronic effects on T_{cc}: Exp[- $\langle \sigma \upsilon \rangle n_\pi \tau$] $\sim$ 45% reduction

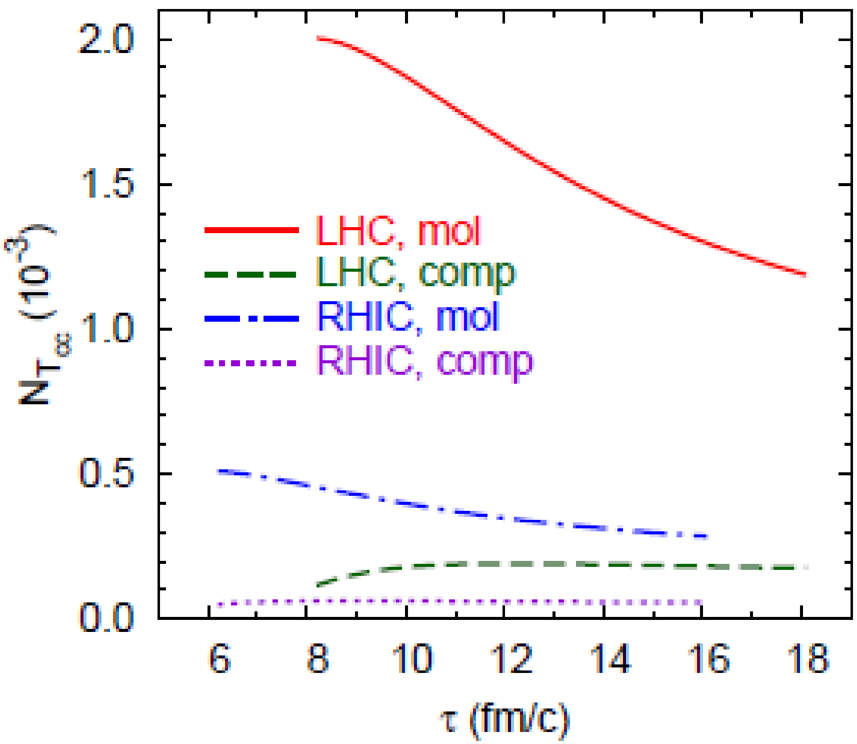
- Time evolution of T_{cc} multiplicity with τ dependence of V(τ), T(τ)

- Initial $N_{Tcc}(\tau_H)$ depends on its structure
- (1) Molecular configuration (c_1=1): $N_{Tcc} \sim 10^{-3}$

  (2) Compact multiquark (c_1=1/3): $N_{Tcc} \sim 10^{-4}$

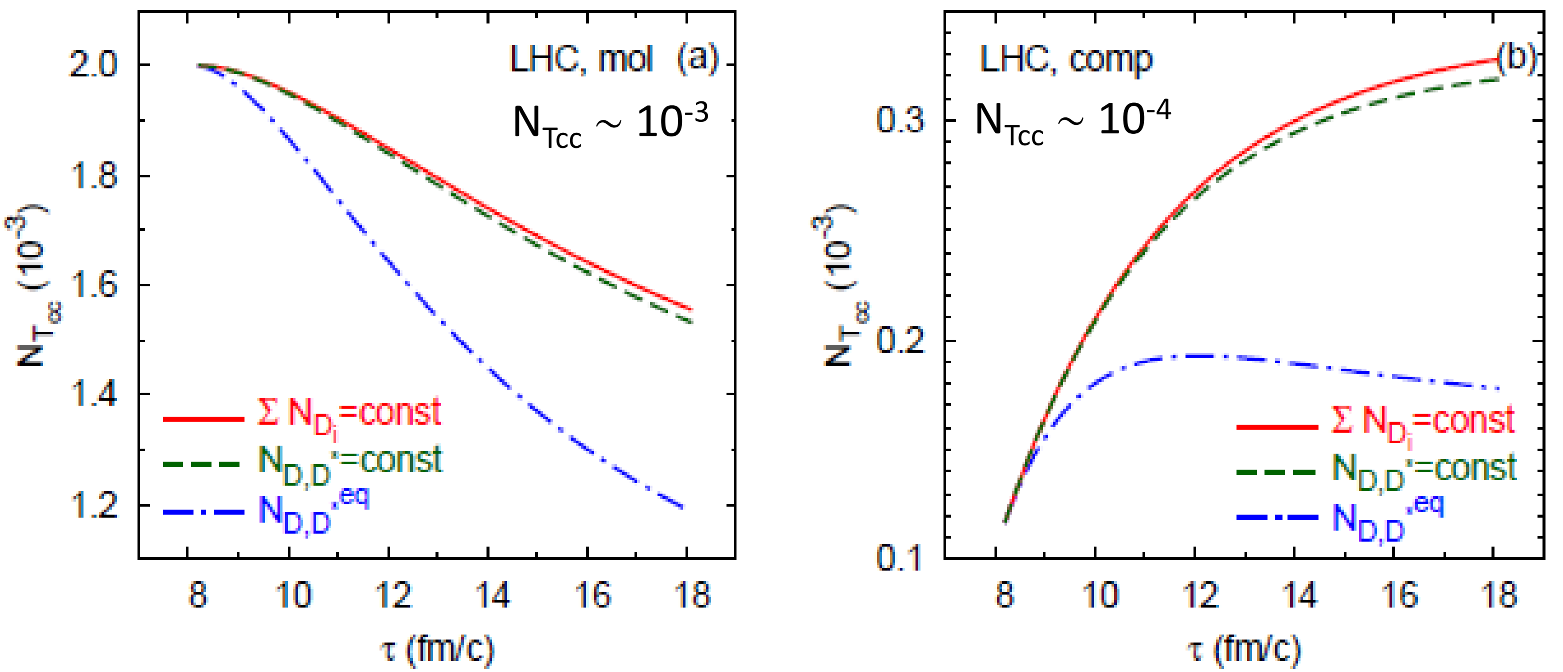
$$T_{cc} = \boxed{\frac{1}{\sqrt{3}}}(D_1 D_1^*) - \sqrt{\frac{2}{3}}(D_8 D_8^*)$$

$$\langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau) = c_1 \langle \sigma_{D\pi \to D\pi} v_{T_{cc}\pi} \rangle(\tau) + c_1 \langle \sigma_{D^*\pi \to D^*\pi} v_{T_{cc}\pi} \rangle(\tau)$$



- Hadronic effects ~ 42%
- N_{Tcc} depends on its initial number at QGP

- D, D* in non-equilibrium: larger N_{Tcc}
  (1) D, D* = const
  (2) time dependent fugacity $$\sum_{D_i = D, D^*, D_s, D_s^*} N_{D_i}(\tau) = \gamma_c(\tau)\left[N_D^0(\tau) + N_{D^*}^0(\tau) + N_{D_s}^0(\tau) + N_{D_s^*}^0(\tau)\right]$$



- N_{Tcc}(mol) ≥ 5 N_{Tcc}(comp)

Measurements

Possible final states

- T_{cc} can be reconstructed by measuring possible final states
- (1) $m_{T_{cc}} \geq m_D + m_{D^*}$

$$T_{cc} \rightarrow D^0 + D^{*+} \qquad \text{or} \qquad \underbrace{D^+ + D^{*0}}_{\text{not easy to detect directly}} \qquad \text{or} \qquad \boxed{D^+ + D^+ + \pi^-}$$

$$D^0 \rightarrow K^- + \pi^+ \qquad D^{*+} \rightarrow D^0 + \pi^+$$

(2) $m_D + m_{D^*} \geq m_{T_{cc}} \geq m_D + m_D + m_\pi$

$$T_{cc} \rightarrow \boxed{D^0 + \overbrace{D^0 + \pi^+}^{\text{virtual } D^{*+}}}$$

(3) $m_{T_{cc}} \leq m_D + m_D + m_\pi$

$$T_{cc} \rightarrow D^0 + K^- + \pi^+ + \pi^+ \qquad \text{or} \qquad D^+ + K^- + \overbrace{\pi^+ + \pi^+ + \pi^-}^{\text{virtual } D^+}$$

Summary

- Time evolution of T_{cc} abundance by solving the rate equation
- Absorption by pions: hadronic effects $\sim 42\%$
- T_{cc} multiplicity depends strongly on initial yields of QGP phase
- N_{Tcc}(mol) $\sim 10^{-3} \gg N_{Tcc}$(comp) $\sim 10^{-4}$
- N_{Tcc} measurement is useful to obtain its structure information
- $D^+ + D^+ + \pi^-$ and $D^0 + D^0 + \pi^+$ seem to be the most probable cases to reconstruct T_{cc}

Thank you for your attention!