Hadronic effects on T_{cc} in relativistic heavy ion collisions
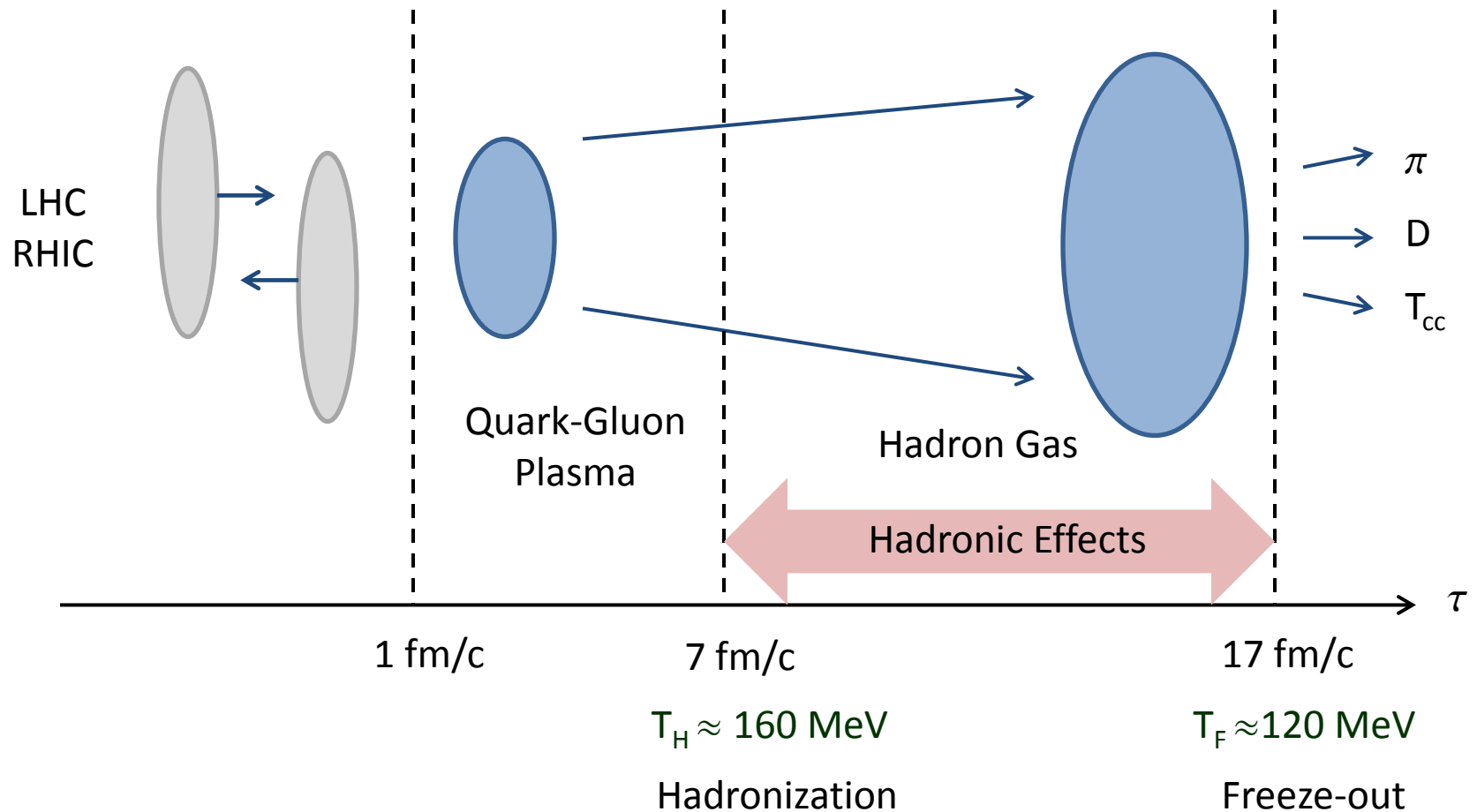
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arXiv: 1804.05336, JH, Sungtae Cho, Taesoo Song, and Su Houng Lee

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

LHC
RHIC

Quark-Gluon
Plasma

Hadron Gas

Hadronic Effects

π

D

T_{cc}

τ

1 fm/c

7 fm/c

17 fm/c

$T_H \approx 160$ MeV

$T_F \approx 120$ MeV

Hadronization

Freeze-out

- Absorption/production in the hadronic phase

Hydrodynamic evolution

- Hydrodynamics: $\quad \partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = \underbrace{(e+p)u^\mu u^\nu - p g^{\mu\nu}}_{\text{ideal}} + \underbrace{\pi^{\mu\nu}}_{\text{viscous: } \eta/s = 1/4\pi}$

- 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
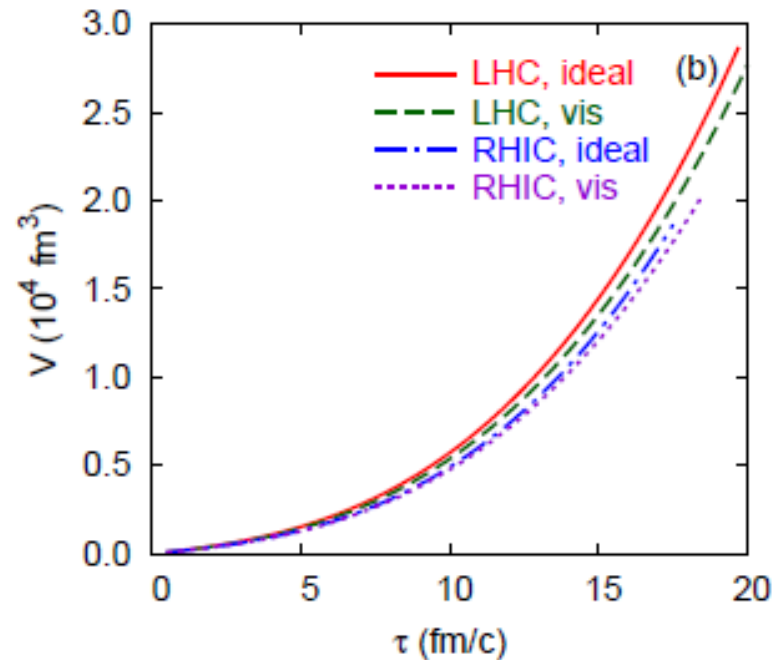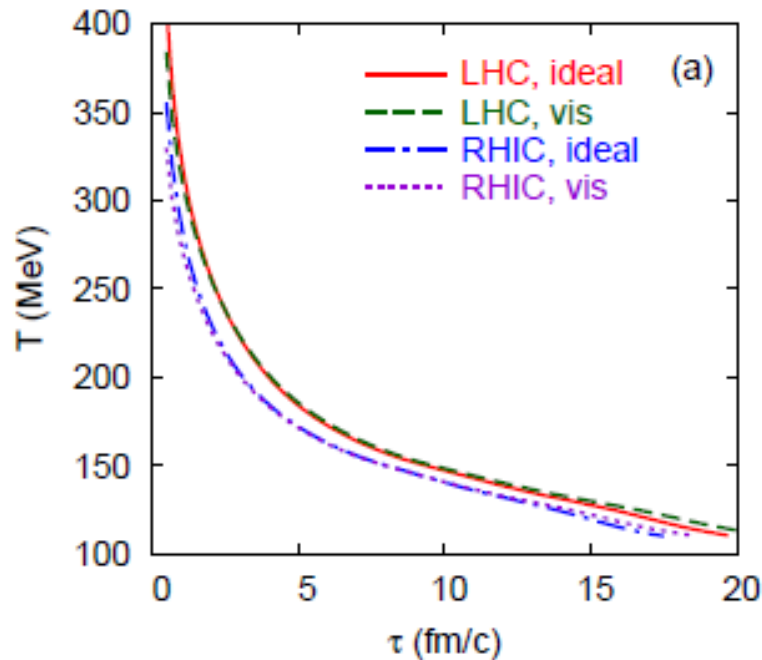
Phenomenological model

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

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

hadronize freeze-out | hydro | fitting

		$T_C = T_H$ (MeV)	T_F (MeV)	$\tau_C = \tau_H$ (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)

Statistical model

- Particle yields:

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

$$= \gamma_i N_i^0(\tau)$$

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

- Charm fugacity: from D, D*, D$_s$, D$_s^*$

$$N_c = \sum_{D_i = D, D^*, D_s, D_s^*} N_{D_i}(\tau) = \gamma_c \left[N_D^0(\tau) + N_{D^*}^0(\tau) + N_{D_s}^0(\tau) + N_{D_s^*}^0(\tau) \right]$$
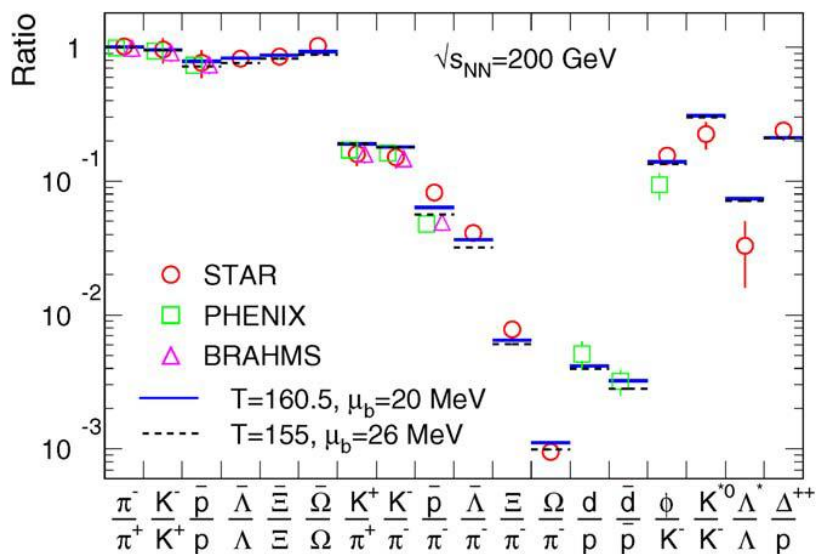
LHC	11	51
RHIC	4.1	22

at $\tau = \tau_H$

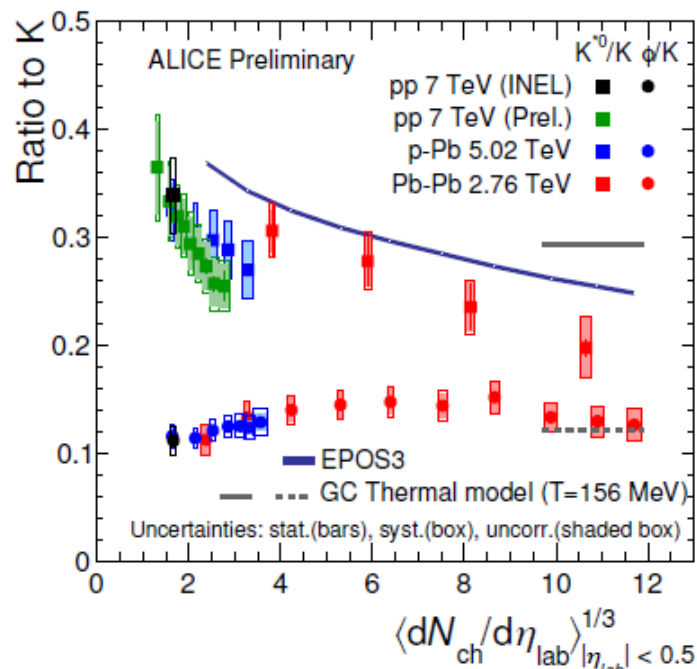ExHIC Collaboration (2017)

Hadronic effects

- Resonances with large widths:
  K* suppression

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

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

from J. Song's dissertation

T_{cc} absorption

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

- $T_{cc}(cc\bar{u}\bar{d} = DD^*)$

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

  $\underbrace{\qquad\qquad}_{\text{singlet}} \quad \underbrace{\qquad\qquad}_{\text{octet}}$

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: $gc \rightarrow gc \ (qc \rightarrow qc)$

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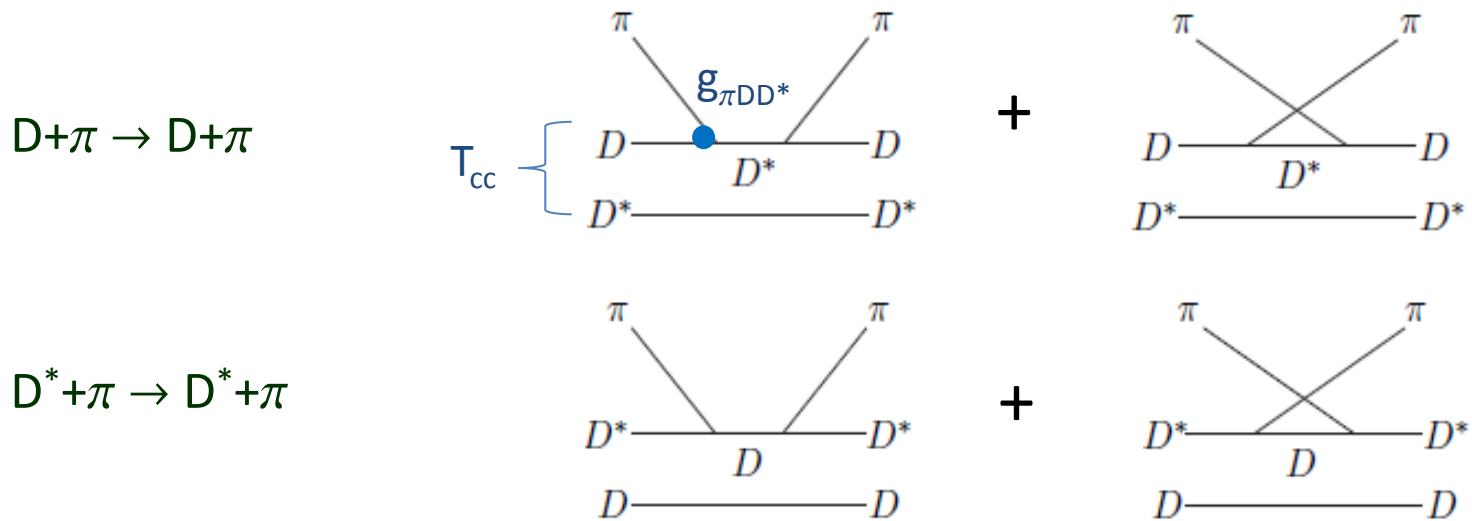$$= \sigma_{QF}.$$

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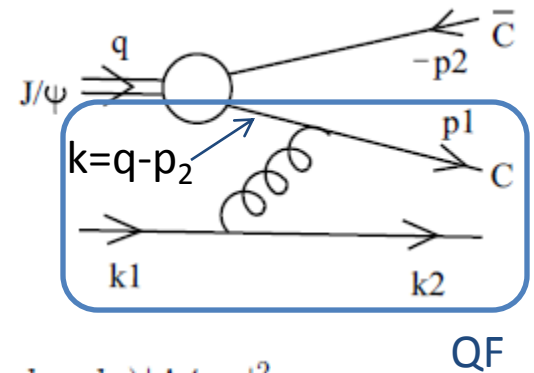
T. Song, W. Park, S. H. Lee (2010)

- NLO calculations seem to agree on the order of magnitude

T$_{cc}$ + π reaction

- T$_{cc}$ absorption/production by pions: T$_{cc}$+π $\leftrightarrow$ D+D*+π
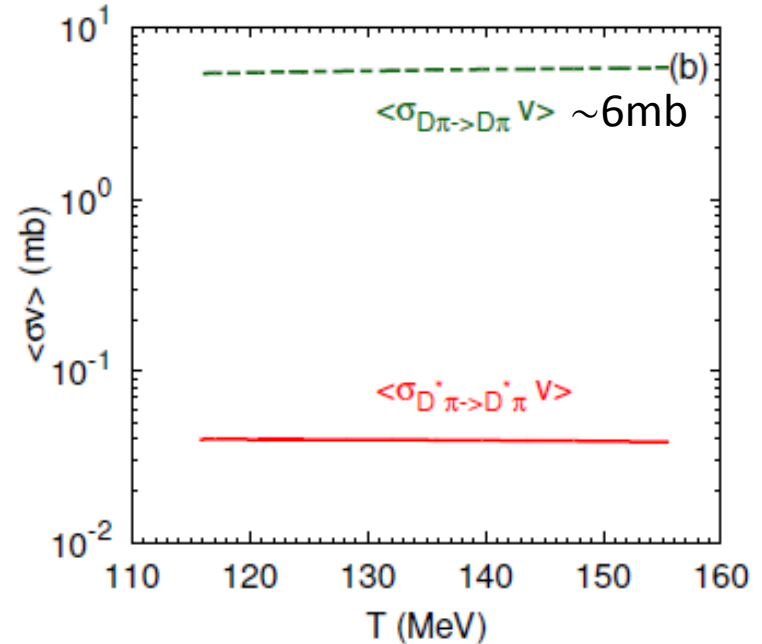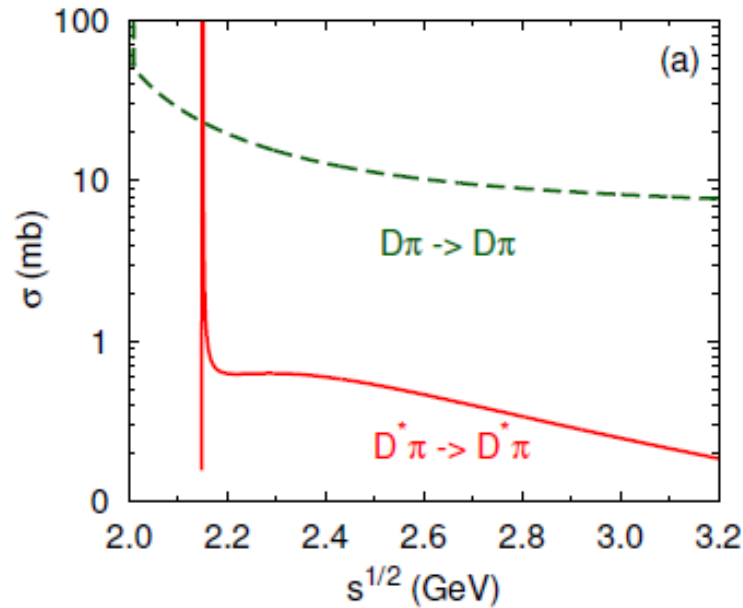
- Quasifree approximation:

D+π $\rightarrow$ D+π

D*+π $\rightarrow$ D*+π

- Effective Lagrangian: $\quad \mathcal{L}_{\pi DD^*} = ig_{\pi DD^*} D^{*\mu} \boldsymbol{\tau} \cdot (\bar{D}\partial_\mu \boldsymbol{\pi} - \partial_\mu \bar{D}\boldsymbol{\pi}) + \text{h.c.}$

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

- Decay width: $\quad \Gamma_{D^* \rightarrow D\pi} = \dfrac{g^2_{\pi DD^*} p^3_{cm}}{2\pi m^2_{D^*}}$ = 83.4 keV

T$_{cc}$ absorption cross section

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

- Spin-isospin averaged cross section: $\sigma = \dfrac{1}{64\pi^2 g_1 g_2 s}\dfrac{|\boldsymbol{p}_f|}{|\boldsymbol{p}_i|}\displaystyle\int d\Omega \sum_{S,I} |\mathcal{M}|^2 F^4$

- Form factor: $F = \dfrac{\Lambda^2}{\Lambda^2 + \boldsymbol{q}^2}$

- Thermal effects: $\langle \sigma_{ab \to cd} v_{ab} \rangle(\tau) = \dfrac{\int d^3 \boldsymbol{p}_a d^3 \boldsymbol{p}_b\, f_a(\boldsymbol{p}_a) f_b(\boldsymbol{p}_b)\, \sigma_{ab \to cd} v_{ab}}{\int d^3 \boldsymbol{p}_a d^3 \boldsymbol{p}_b\, f_a(\boldsymbol{p}_a) f_b(\boldsymbol{p}_b)}$

Evolution of T$_{cc}$ multiplicity

Rate equation

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

$$2E_{T_{cc}} 2E_{\pi^i} v_{T_{cc}\pi^i} g_{T_{cc}} g_\pi \, \sigma_{T_{cc}+\pi \to D+D^*+\pi}$$

$$\frac{dN_{T_{cc}}}{V d\tau} = - \int \frac{d^3 \boldsymbol{p}_D}{(2\pi)^3 2E_D} \frac{d^3 \boldsymbol{p}_{D^*}}{(2\pi)^3 2E_{D^*}} \frac{d^3 \boldsymbol{p}_{\pi^f}}{(2\pi)^3 2E_{\pi^f}} \frac{d^3 \boldsymbol{p}_{T_{cc}}}{(2\pi)^3 2E_{T_{cc}}} \frac{d^3 \boldsymbol{p}_{\pi^i}}{(2\pi)^3 2E_{\pi^i}}$$

$$\times f(\boldsymbol{p}_{T_{cc}}) f(\boldsymbol{p}_{\pi^i}) (2\pi)^4 \delta^{(4)}(p_D + p_{D^*} + p_{\pi^f} - p_{T_{cc}} - p_{\pi^i}) |\mathcal{M}_{T_{cc}+\pi \to D+D^*+\pi}|^2$$

$$\frac{dN_{T_{cc}}}{V d\tau} = - \langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle n_{T_{cc}} n_\pi$$

- Production: $D + D^* + \pi \to T_{cc} + \pi$ $\qquad f(\boldsymbol{p}_D) f(\boldsymbol{p}_{D^*}) f(\boldsymbol{p}_{\pi^f}) = f(\boldsymbol{p}_{T_{cc}}) f(\boldsymbol{p}_{\pi^i})$

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

Evolution of T_{cc} abundance

- Rate equation:

$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau)\, n_\pi(\tau) \left[-N_{T_{cc}}(\tau) + N_{T_{cc}}^{eq}(\tau) \frac{N_D(\tau)\, N_{D^*}(\tau)}{N_D^{eq}(\tau)\, N_{D^*}^{eq}(\tau)} \right]$$
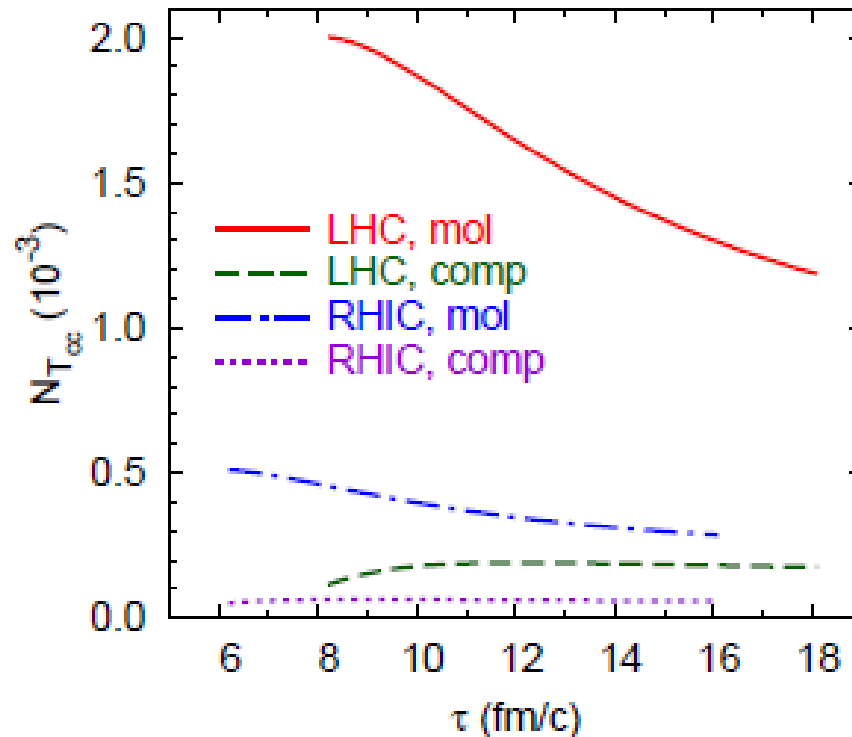
$$\langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau) = c_1 \langle \sigma_{D\pi \to D\pi} v_{T_{cc}\pi} \rangle(\tau) + c_1 \langle \sigma_{D^*\pi \to D^*\pi} v_{T_{cc}\pi} \rangle(\tau)$$

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

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

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

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

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

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

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

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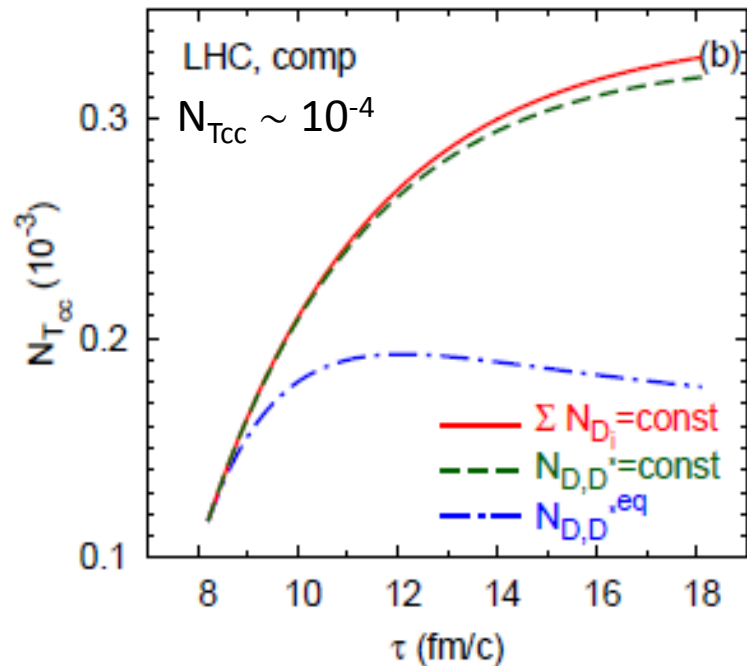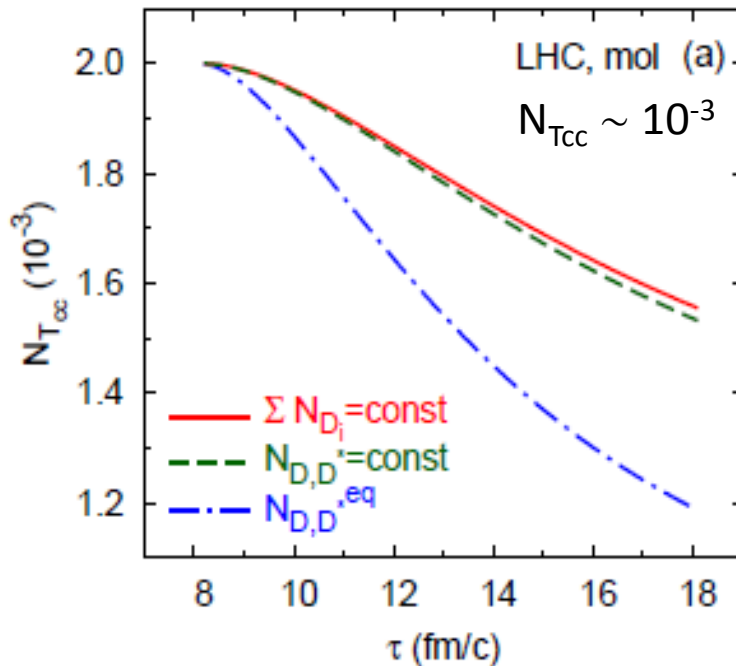

- Hadronic effects $\sim 42\%$
- N_{Tcc} depends on its initial number at QGP

- D, D* in non-eqilibrium: larger N_{Tcc}
  (1) D, D* = const
  (2) time dependent fugacity

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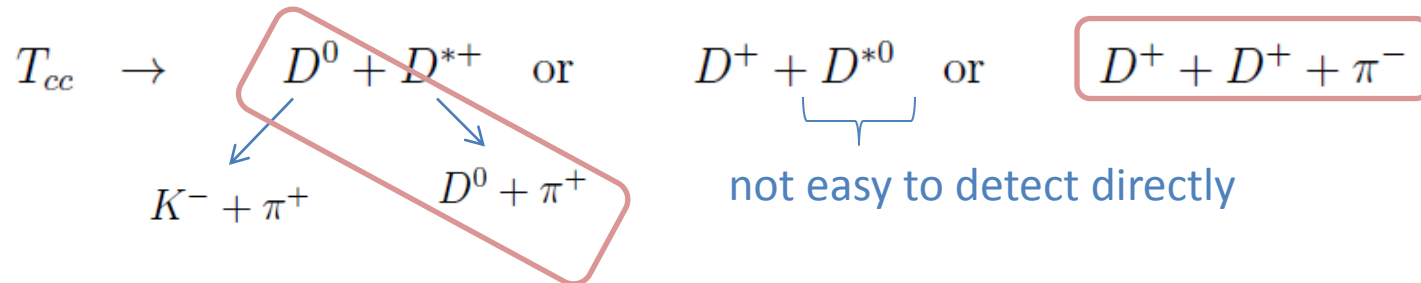

LHC, mol (a) $N_{Tcc} \sim 10^{-3}$

LHC, comp $N_{Tcc} \sim 10^{-4}$ (b)
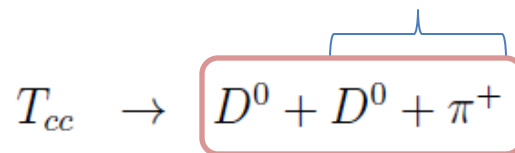
- $N_{Tcc}(mol) \geq 5\, N_{Tcc}(comp)$

Measurements

Possible final states

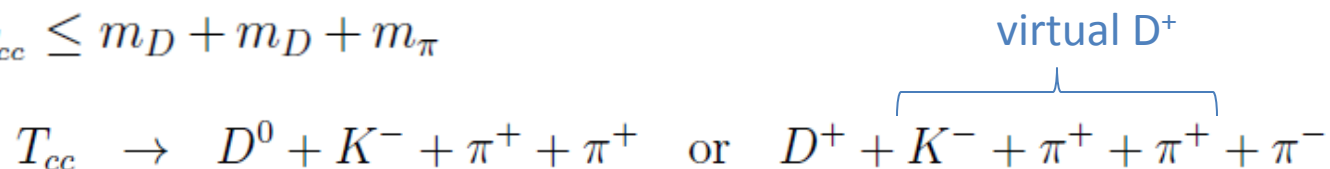- T_{cc} can be reconstructed by measuring possible final states

- (1) $m_{T_{cc}} \geq m_D + m_{D^*}$

$$T_{cc} \rightarrow \quad D^0 + D^{*+} \quad \text{or} \quad D^+ + D^{*0} \quad \text{or} \quad D^+ + D^+ + \pi^-$$

$$K^- + \pi^+ \qquad D^0 + \pi^+$$

not easy to detect directly

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

$$T_{cc} \rightarrow \quad D^0 + D^0 + \pi^+$$

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

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

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

- $N_{Tcc}(\text{mol}) \sim 10^{-3} \; \gg \; N_{Tcc}(\text{comp}) \sim 10^{-4}$

- 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!