山东大学
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Evolution of charm-meson ratios in an expanding hadron gas

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Based on arXiv:2209.04972

2022年第七届手征有效场论研讨会，2022/10/14-17, 东南大学

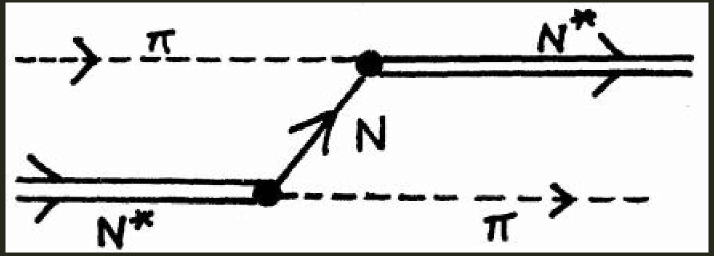
CONTENTS

t-channel singularity

- A t-channel scattering process: an unstable particle decays and one of its decay products is scattered.
- The singularity arises if the exchanged particle can be on-shell.

t-channel singularity

- First pointed out by Peierls in 1961 in π N* scattering



The exchanged N can be on-shell, which leads to a divergence in the cross section.

Peierls, PRL 6, 641-643 (1961)

t-channel singularity

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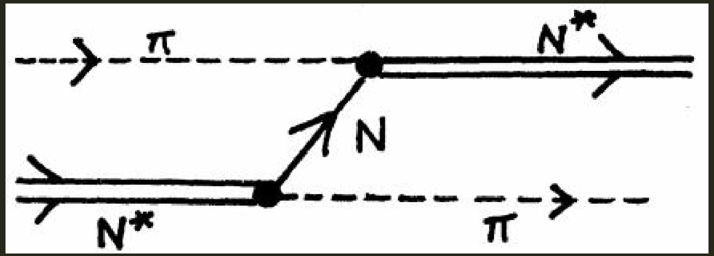


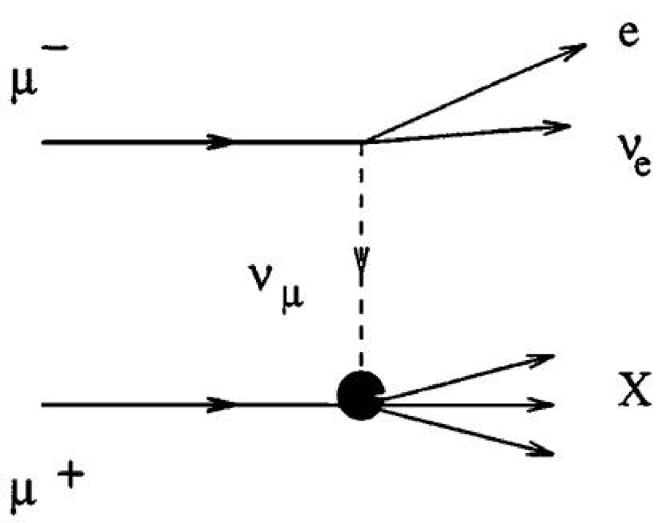
The exchanged N can be on-shell, which leads to a divergence in the cross section.

- Peierls suggested that reaction rate could be regularized by inserting width of N* into N propagator, but the large cross section is unphysical.

Peierls, PRL 6, 641-643 (1961)

t-channel singularity

- The t-channel singularities is unavoidable in reactions involving unstable particles.



Accounting for the finite sizes of the colliding beams results in the regularization of this singularity.

K. Melnikov and V.G. Serbo, PRL 76, 3263 (1996)

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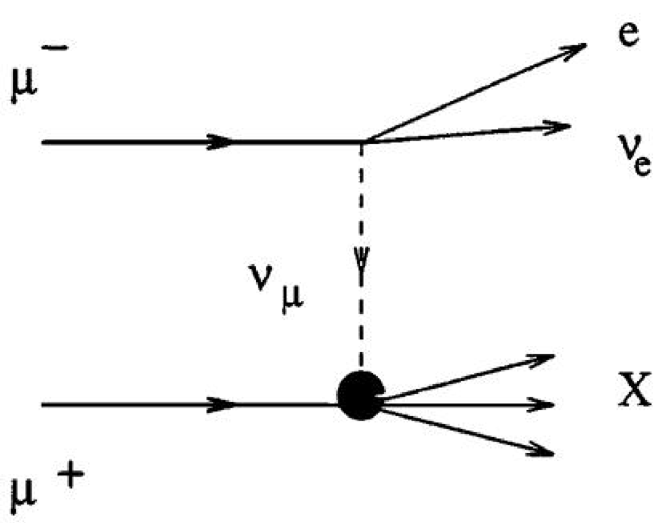

Accounting for the finite sizes of the colliding beams results in the regularization of this singularity.

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- Elastic scattering: $W^- e^- \to e^- W^-$ mediated by ν_e, *etc.*
  Inelastic scattering: $W^- \nu_e \to e^- Z$ mediated by vbar$_e$, *etc.*

t-channel singularity

- In a thermal medium, a t-channel singularity is regularized by the thermal width of the exchanged particle.

$$\frac{1}{t-M^2} \longrightarrow \frac{1}{t-M^2-\Pi}, \qquad \Pi \approx 2M\delta M - iM\Gamma$$

Grzadkowski, Iglicki, and Mr´owczy´nski ,
NPB 984, 115967 (2022)

t-channel singularity

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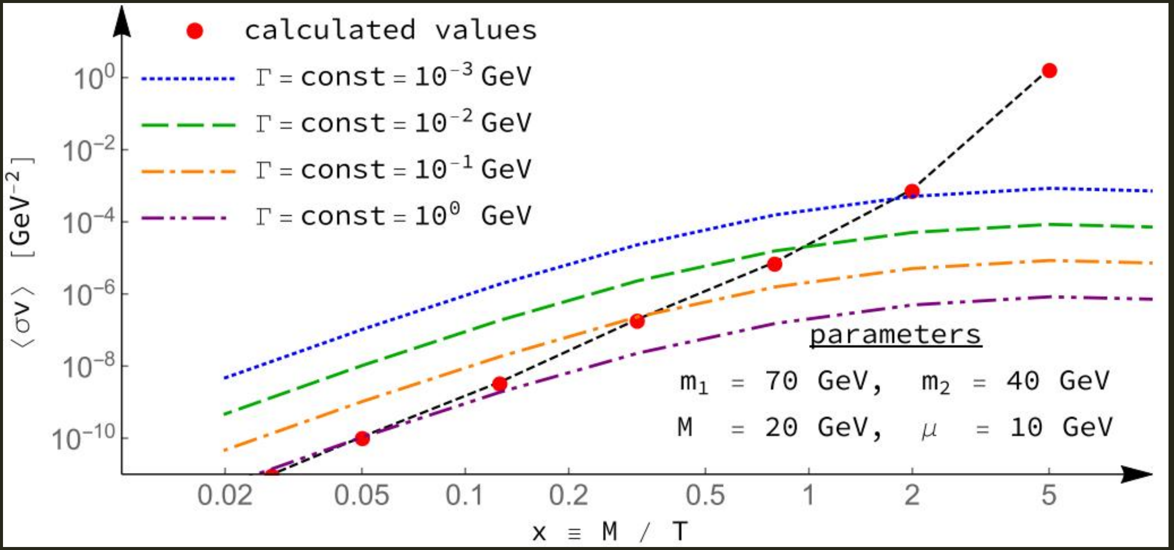
$$\frac{1}{t-M^2} \longrightarrow \frac{1}{t-M^2-\Pi}, \quad \Pi \approx 2M\delta M - iM\Gamma$$

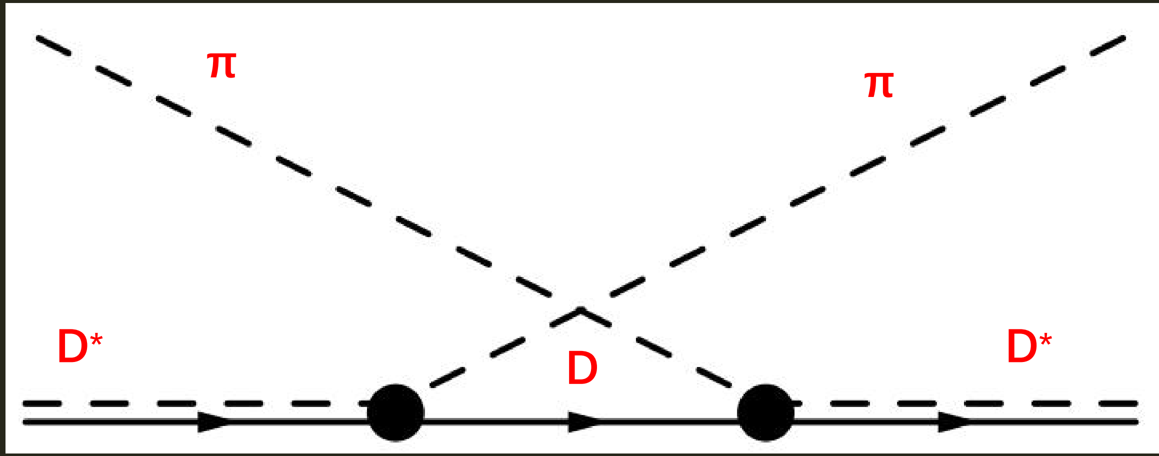


Thermally averaged cross section quickly increases with $x \equiv M/T$.

Grzadkowski, Iglicki, and Mr´owczy´nski , NPB 984, 115967 (2022)

t-channel singularity

- $\pi D^* \to \pi D^*$ scattering has t-channel singularity because exchanged D can be on-shell.
- In hadron gas, the divergences are regularized by thermal width of D.



t-channel singularity region: $2M_*^2 - M^2 + 2m^2 < s < (M_*^2 - m^2)^2/M^2,$

M*: mass of D*

M: mass of D

m: mass of π

Motivation

- Does t-channel singularities in charm-meson reactions have any observable consequences?

  One possibility is that t-channel singularities could modify the charm-meson abundances produced in a high-energy collision through the interactions with hadron gas (mainly pions after kinetic freezeout).

Motivation

- Does t-channel singularities in charm-meson reactions have any observable consequences?

  One possibility is that t-channel singularities could modify the charm-meson abundances produced in a high-energy collision through the interactions with hadron gas (mainly pions after kinetic freezeout).

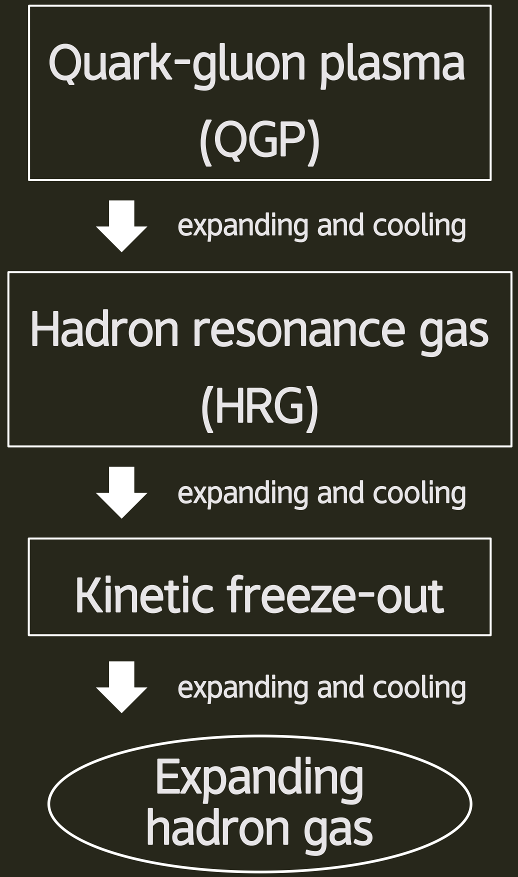
- The observed numbers N_0 and N_+ of D^0 and D^+ can be predicted in terms of the numbers $(N_a)_0$ and $(N_{*a})_0$ before D^* decays and the branching fraction B_{+0} = 68% for $D^{*+} \to D^0\pi^+$:

$$N_0 = (N_0)_0 + (N_{*0})_0 + B_{+0}\,(N_{*+})_0\,,$$
$$N_+ = (N_+)_0 + 0 + (1 - B_{+0})\,(N_{*+})_0\,,$$

We will show that the charm-meson abundances are modified by t-channel singularities.

Charm-mesons in heavy-ion collision

- Heavy-ion collisions proceed through several stages:

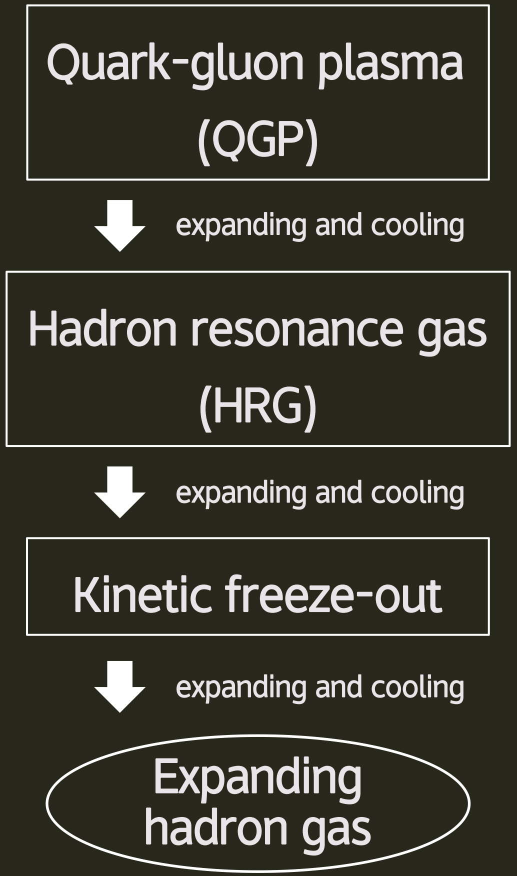


The formation and thermalization of the QGP

The deconfined quarks and gluons hadronize into HRG

Particles stop interacting, momentum distributions frozen

Charm-mesons in heavy-ion collision



Charm quarks are primarily created in the hard collisions of the heavy ions.

Hadronization:

Statistical Hadronization Model (SHM)

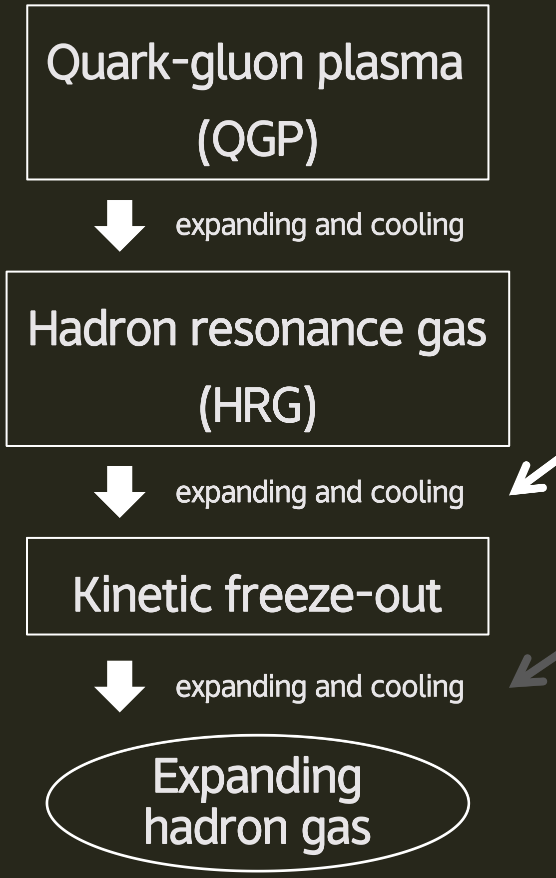
SHMc (SHM for charm)

Multiplicities before D* decays predicted by SHMc：

$$(dN_0/dy)_0 = 2.12, \qquad (dN_+/dy)_0 = 2.03,$$
$$(dN_{*0}/dy)_0 = 2.59, \qquad (dN_{*+}/dy)_0 = 2.52.$$

A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 772, 167-199 (2006);
A. Andronic, *etc.*, JHEP 07, 035 (2021).

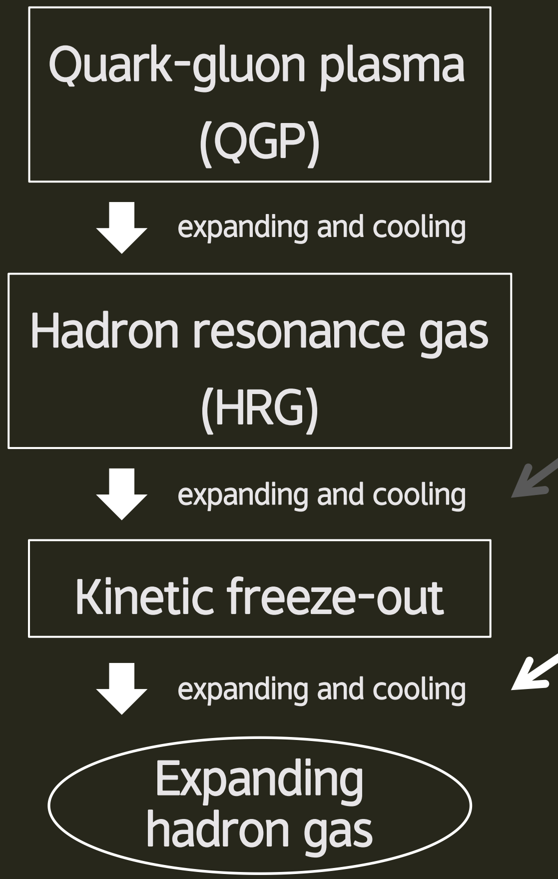
Charm-mesons in heavy-ion collision



The t-channel singularities in charm meson reactions could have significant effects

- either during the expansion and cooling of the HRG between hadronization and kinetic freezeout (requires a full treatment of the HRG)
- or during the expansion of the hadron gas after kinetic freezeout (thermal widths are determined primarily by the pion number density).

Charm-mesons in heavy-ion collision



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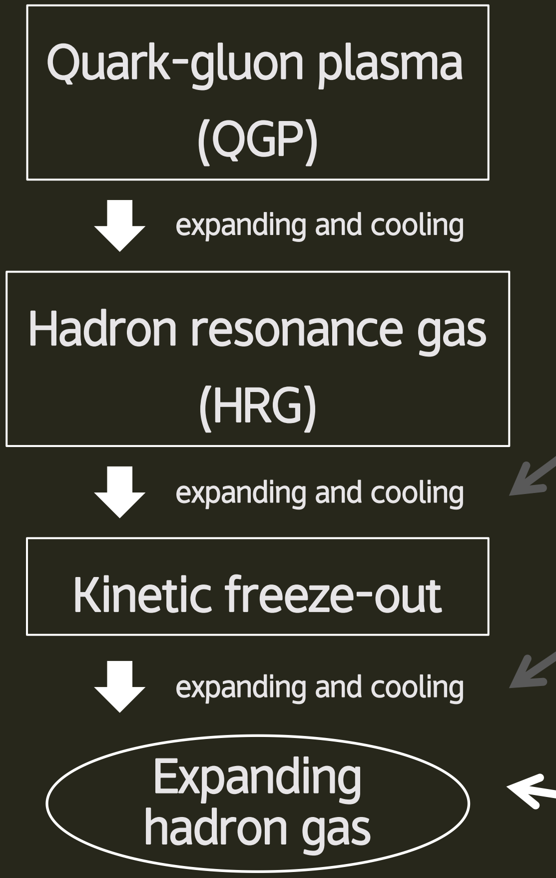

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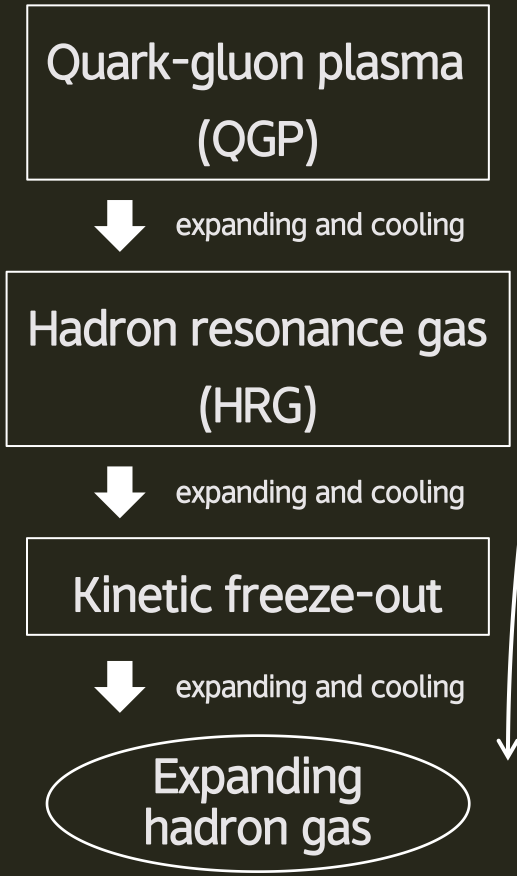
- either during the expansion and cooling of the HRG between hadronization and kinetic freezeout (requires a full treatment of the HRG)
- or during the expansion of the hadron gas after kinetic freezeout (thermal widths are determined primarily by the pion number density).

We study the effects of t-channel singularities in charm meson reactions in the expansion of the hadron gas after kinetic freeze-out.

Expanding hadron gas



Expanding hadron gas is mainly PIONS!

Volume V(τ) for $\tau > \tau_F$: $$V(\tau) = \pi\left[R_F + v_F(\tau - \tau_F)\right]^2 c\tau,$$

$$\tau_F = 21.5\ \mathrm{fm}/c,\ R_F = 24.0\ \mathrm{fm},\ \text{and}\ v_F = 1.00\ c$$

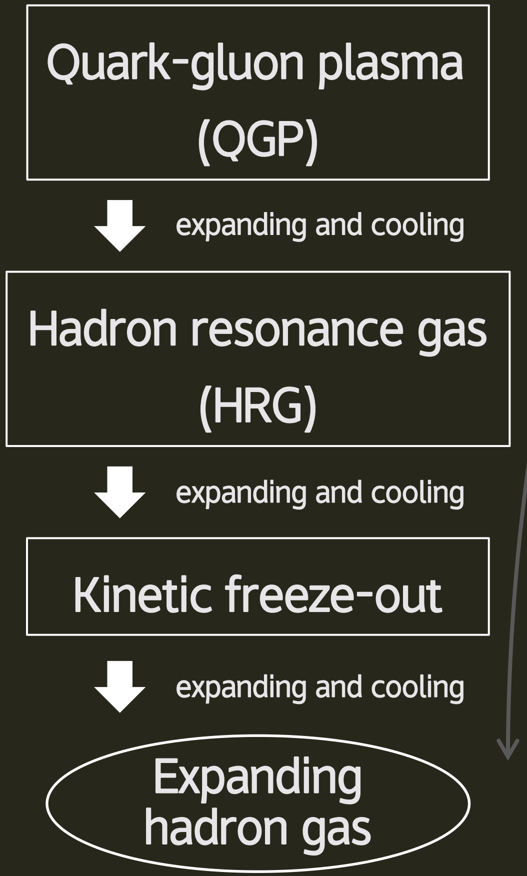
Number density for pions as system expanding:

$$\mathfrak{n}_\pi(\tau) = [V(\tau_F)/V(\tau)]\mathfrak{n}_\pi(\tau_F).$$

J.D. Bjorken, PRD 27, 140-151 (1983));
J. Hong, *etc.*, PRC 98, 014913 (2018);
L.M. Abreu, PRD 103, 036013 (2021).

1 The beginning of a story

Expanding hadron gas



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Volume $V(\tau)$ for $\tau > \tau_F$: $V(\tau) = \pi\left[R_F + v_F(\tau - \tau_F)\right]^2 c\tau,$

$\tau_F = 21.5$ fm/c, $R_F = 24.0$ fm, and $v_F = 1.00\ c$

Number density for pions as system expanding:

$$\mathfrak{n}_\pi(\tau) = \left[V(\tau_F)/V(\tau)\right]\mathfrak{n}_\pi(\tau_F).$$

We can estimate the charm-meson number densities at times τ before D^* decays (initial parameters):

$$\mathfrak{n}_{D^{(*)}}(\tau) = \left[(dN_{D^{(*)}}/dy)/(dN_\pi/dy)\right]_0 \mathfrak{n}_\pi(\tau).$$

$dN_\pi/dy = 769 \pm 34.$

J.D. Bjorken, PRD 27, 140-151 (1983));
J. Hong, *etc.*, PRC 98, 014913 (2018);
L.M. Abreu, PRD 103, 036013 (2021).
S. Acharya et al. [ALICE], PRC 101, 044907 (2020)

2 Thermal mass shifts and widths

Pion momentum distribution

- We consider a pion gas in which the momentum distribution of the pions is a Bose-Einstein distribution with temperature T.

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Pion momentum distribution

- We consider a pion gas in which the momentum distribution of the pions is a Bose-Einstein distribution with temperature T.

In thermal equilibrium at temperature T, the number density:

$$\mathfrak{n}_\pi^{(\mathrm{eq})} = \int \frac{d^3q}{(2\pi)^3} \frac{1}{e^{\beta\omega_q} - 1}.$$

where $\beta = 1/T$.

Pion momentum distribution for isothermally expanding pion gas:

$$\mathfrak{f}_\pi(\omega_q) = \frac{\mathfrak{n}_\pi}{\mathfrak{n}_\pi^{(\mathrm{eq})}} \frac{1}{e^{\beta\omega_q} - 1}.$$

Integral of a function weighted by the pion momentum distribution:

$$\int \frac{d^3q}{(2\pi)^3} \mathfrak{f}_\pi(\omega_q)\, F(\boldsymbol{q}) = \mathfrak{n}_\pi \left\langle F(\boldsymbol{q}) \right\rangle.$$

Pion mass shift and thermal width

- The pion mass shift and thermal width after kinetic freeze-out can be calculated using χEFT at LO:

$$\delta m_\pi = (m_\pi / 2 f_\pi^2)\, \mathfrak{n}_\pi \left\langle 1/\omega_q \right\rangle ,$$

The pion thermal width is 0 at this order.

D(*) mass shift and thermal width

- The charm-meson mass shift and thermal width can be calculated using HHχEFT at LO:

$$\delta M = (3g_\pi^2/2f_\pi^2)\, \mathfrak{n}_\pi\, \Delta \langle 1/\omega_q \rangle , \quad \delta M_* = -\delta M/3,$$

$$\Gamma_a = 3\, \mathfrak{f}_\pi(\Delta) \sum_c \Gamma_{*c,a},$$

$$\Gamma_{*a} = [1 + \mathfrak{f}_\pi(\Delta)] \sum \Gamma_{*a,c} + \Gamma_{*a,\gamma},$$

with $\mathfrak{f}_\pi(\Delta) = 0.414 \frac{\mathfrak{n}_\pi}{\mathfrak{n}_\pi^{(eq)}}$

where decay rates in the vacuum:

$$\Gamma_{*+,+} = \frac{g_\pi^2}{12\pi\, f_\pi^2} \left[(M_{*+} - M_+)^2 - m_{\pi 0}^2 \right]^{3/2},$$

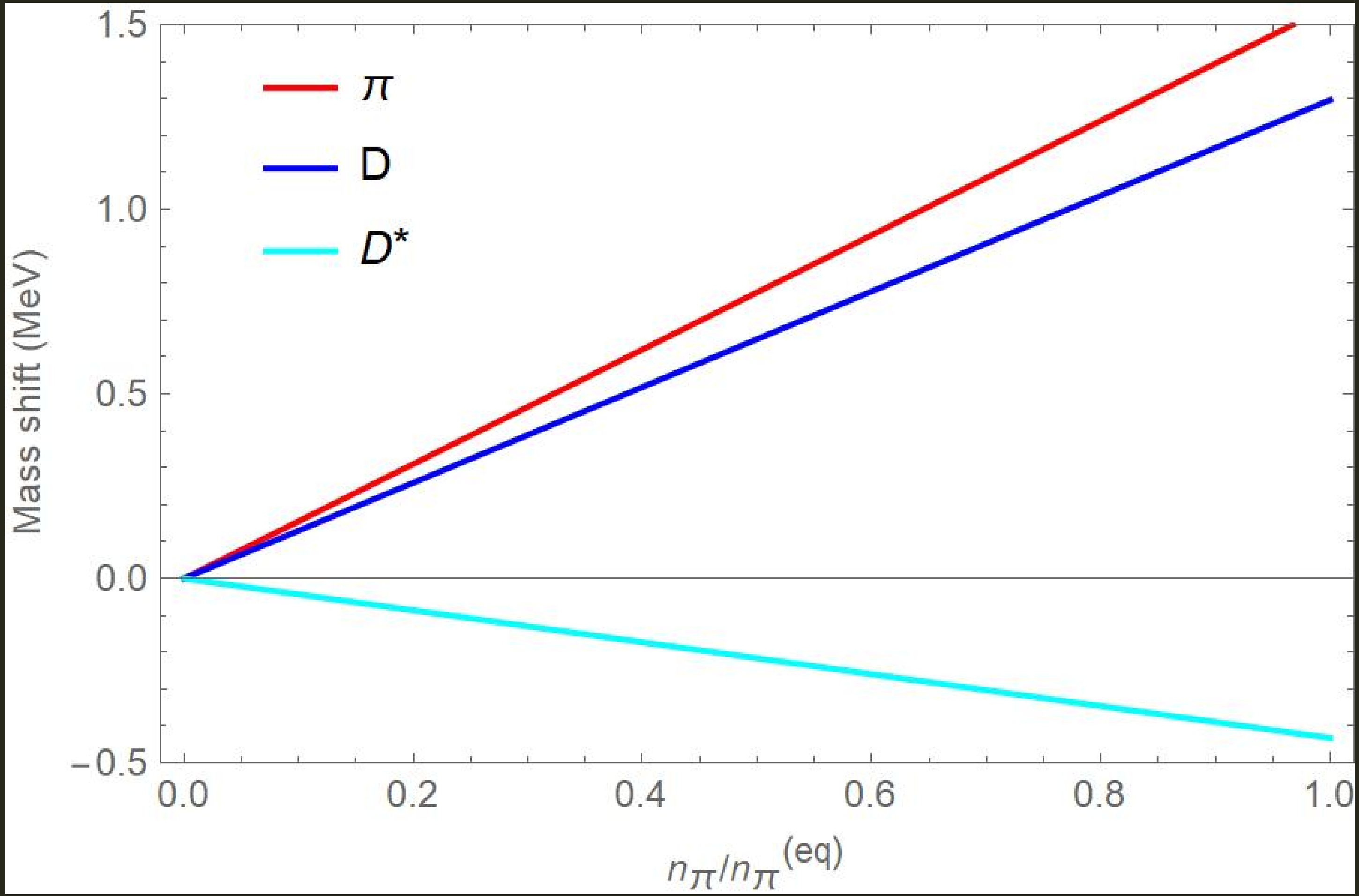
$$\Gamma_{*+,0} = \frac{g_\pi^2}{6\pi\, f_\pi^2} \left[(M_{*+} - M_0)^2 - m_{\pi +}^2 \right]^{3/2},$$

$$\Gamma_{*0,0} = \frac{g_\pi^2}{12\pi\, f_\pi^2} \left[(M_{*0} - M_0)^2 - m_{\pi 0}^2 \right]^{3/2},$$

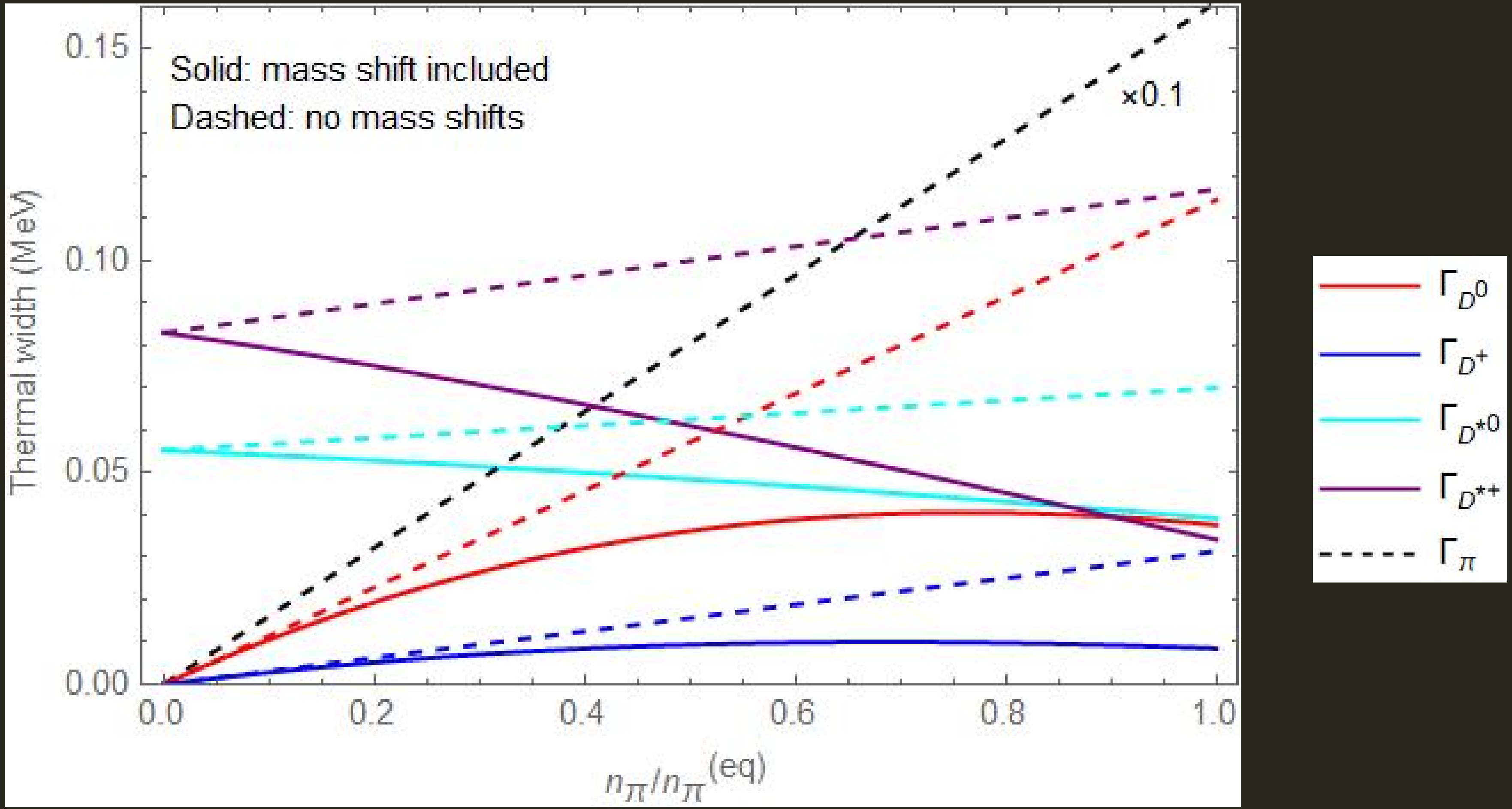
$$\Gamma_{*0,+} = 0.$$

$\Gamma_{*a,\gamma}$ is the radiative decay rate

D(*) mass shift and thermal width



D(*) mass shift and thermal width



3 Reaction rates

π $D^{(*)}$ reaction rates in pion gas

The reaction rates of π **$D^{(*)}$** near the kinetic freezeout temperature would have large effects on the charm-meson abundances:

- spin transitions between D and D*,
- isospin transitions between $D^{(*)0}$ and $D^{(*)+}$.

π $D^{(*)}$ reaction rates in pion gas

- $D^a \pi \to D^{*b}$: increase D* density, but decrease D density.

$$\langle v\sigma_{\pi D^+ \to D^{*+}} \rangle = \left[\mathfrak{f}_\pi(\Delta)/\mathfrak{n}_\pi\right] \Gamma_{D^{*+} \to D^+ \pi},$$

$$\langle v\sigma_{\pi D^0 \to D^{*+}} \rangle = \left[\mathfrak{f}_\pi(\Delta)/\mathfrak{n}_\pi\right] \Gamma_{D^{*+} \to D^0 \pi},$$

$$\langle v\sigma_{\pi D^0 \to D^{*0}} \rangle = \left[\mathfrak{f}_\pi(\Delta)/\mathfrak{n}_\pi\right] \Gamma_{D^{*0} \to D^0 \pi},$$

$$\langle v\sigma_{\pi D^+ \to D^{*0}} \rangle = 0.$$

π D(*) reaction rates in pion gas

- $\pi D^{*a} \leftrightarrow \pi D^{b}$: increase/decrease D* density, but decrease/increase D density.

$$\langle v\sigma_{\pi*0,\pi0}\rangle = \langle v\sigma_{\pi*+,\pi+}\rangle = 0.2446\, g_\pi^4\, m_\pi^2/f_\pi^4,$$
$$\langle v\sigma_{\pi*0,\pi+}\rangle = \langle v\sigma_{\pi*+,\pi0}\rangle = 0.0056\, g_\pi^4\, m_\pi^2/f_\pi^4,$$
$$\langle v\sigma_{\pi0,\pi*0}\rangle = \langle v\sigma_{\pi+,\pi*+}\rangle = 0.2181\, g_\pi^4\, m_\pi^2/f_\pi^4,$$
$$\langle v\sigma_{\pi0,\pi*+}\rangle = \langle v\sigma_{\pi+,\pi*0}\rangle = 0.0049\, g_\pi^4\, m_\pi^2/f_\pi^4.$$

π D(*) reaction rates in pion gas

- $\pi D^a \rightarrow \pi D^b$: change the D^0 and D^+ densities

$$\langle v\sigma_{\pi D^0\to\pi D^0}\rangle = (0.5004 + 0.1900\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\left(\frac{\Gamma^2_{D^{*0}\to D^0\pi}}{\Gamma_{*0}} + \frac{\Gamma^2_{D^{*+}\to D^0\pi}}{\Gamma_{*+}}\right),$$

$$\langle v\sigma_{\pi D^0\to\pi D^+}\rangle = (1.0007 + 0.3336\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\frac{\Gamma_{D^{*+}\to D^0\pi}\,\Gamma_{D^{*+}\to D^+\pi}}{\Gamma_{*+}},$$

s-resonance

$$\langle v\sigma_{\pi D^+\to\pi D^0}\rangle = (1.0007 + 0.3336\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\frac{\Gamma_{D^{*+}\to D^0\pi}\,\Gamma_{D^{*+}\to D^+\pi}}{\Gamma_{*+}},$$

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The resonance term is about three orders of magnitude smaller than the nonresonant term for $n_\pi < n^{(eq)}_\pi$.

π D(*) reaction rates in pion gas

- $\pi D^{*a} \to \pi D^{*b}$: change the D*0 and D*+ densities

$$\langle v\sigma_{\pi D^{*0}\to\pi D^{*0}}\rangle = (0.5004 + 0.4739\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\frac{\Gamma^2_{D^{*0}\to D^0\pi}}{\Gamma_0},$$

$$\langle v\sigma_{\pi D^{*0}\to\pi D^{*+}}\rangle = (1.0007 + 0.3086\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\frac{\Gamma_{D^{*0}\to D^0\pi}\,\Gamma_{D^{*+}\to D^0\pi}}{\Gamma_0},$$

$$\langle v\sigma_{\pi D^{*+}\to\pi D^{*0}}\rangle = (1.0007 + 0.3086\, g_\pi^4)\frac{m_\pi^2}{f_\pi^4} + \frac{\mathfrak{f}_\pi(\Delta)}{\mathfrak{n}_\pi}\frac{\Gamma_{D^{*0}\to D^0\pi}\,\Gamma_{D^{*+}\to D^0\pi}}{\Gamma_0},$$

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t-singularity

The t-channel singularity term is larger than the nonsingular term when $n_\pi < 10^{-3}\, n^{(eq)}_\pi$.

4 Evolution of charm-meson abundance

Evolution equations

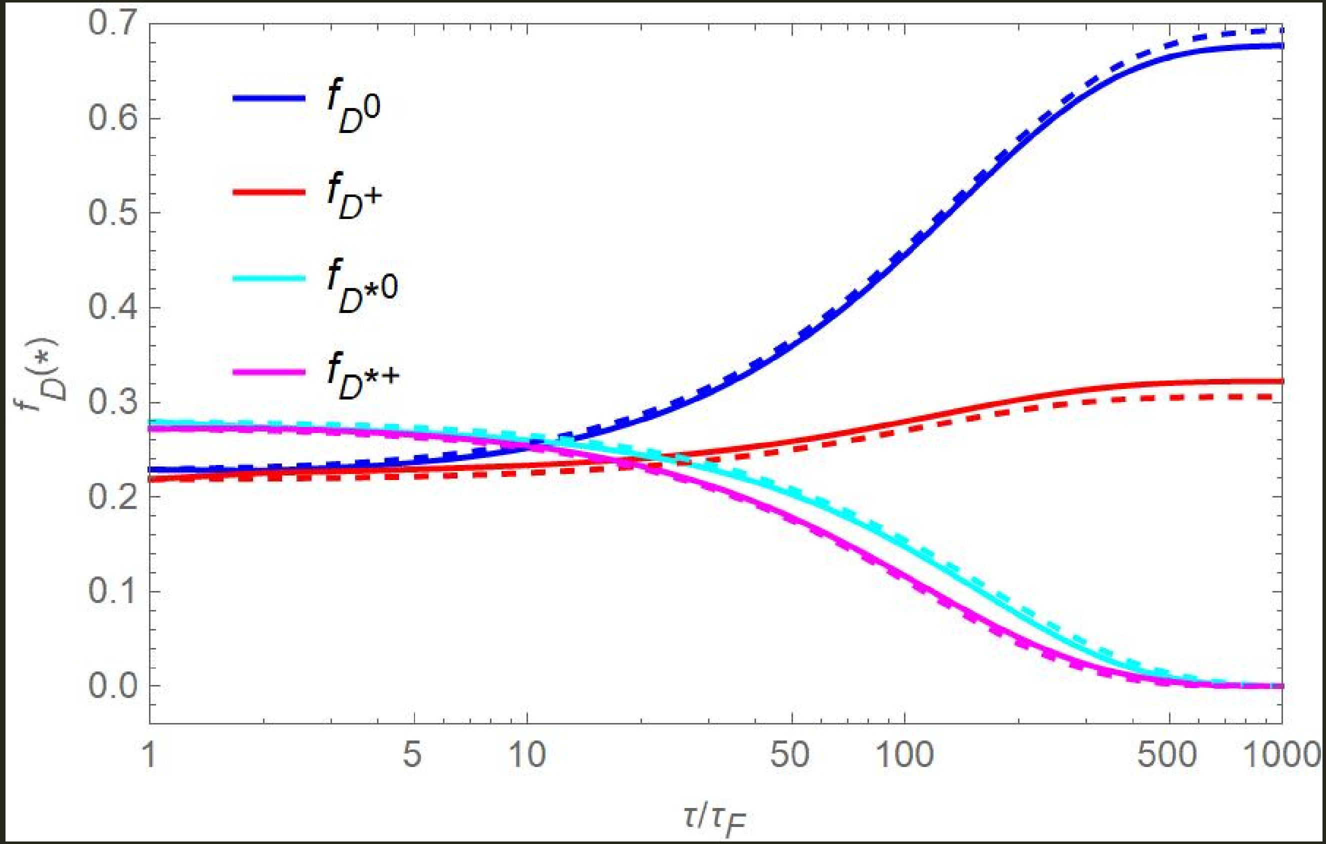
$$\mathfrak{n}_\pi \frac{d}{d\tau}\left(\frac{\mathfrak{n}_{D^a}}{\mathfrak{n}_\pi}\right) = [1+\mathfrak{f}_\pi(\Delta)]\sum_b \Gamma_{*b,a}\,\mathfrak{n}_{D^{*b}} + \Gamma_{*a,\gamma}\,\mathfrak{n}_{D^{*a}} - 3\sum_b \langle v\sigma_{\pi a,*b}\rangle\;\mathfrak{n}_{D^a}\,\mathfrak{n}_\pi$$
$$+3\sum_{b\neq a}\langle v\sigma_{\pi b,\pi a}\rangle\;(\mathfrak{n}_{D^b}-\mathfrak{n}_{D^a})\mathfrak{n}_\pi + 3\sum_b\left(\langle v\sigma_{\pi *b,\pi a}\rangle\;\mathfrak{n}_{D^{*b}} - \langle v\sigma_{\pi a,\pi *b}\rangle\,\mathfrak{n}_{D^a}\right)\mathfrak{n}_\pi + \ldots,$$

$$\mathfrak{n}_\pi \frac{d}{d\tau}\left(\frac{\mathfrak{n}_{D^{*a}}}{\mathfrak{n}_\pi}\right) = 3\sum_b \langle v\sigma_{\pi b\to *a}\rangle\,\mathfrak{n}_{D^b}\,\mathfrak{n}_\pi - \left([1+\mathfrak{f}_\pi(\Delta)]\sum_b \Gamma_{*a,b} + \Gamma_{*a,\gamma}\right)\mathfrak{n}_{D^{*a}}$$
$$+3\sum_b\left(\langle v\sigma_{\pi b,\pi *a}\rangle\;\mathfrak{n}_{D^b} - \langle v\sigma_{\pi *a,\pi b}\rangle\,\mathfrak{n}_{D^{*a}}\right)\mathfrak{n}_\pi + 3\sum_{b\neq a}\langle v\sigma_{\pi *b,\pi *a}\rangle\;(\mathfrak{n}_{D^{*b}}-\mathfrak{n}_{D^{*a}})\mathfrak{n}_\pi + \ldots.$$

Note: $$\mathfrak{n}_\pi \frac{d}{d\tau}\left(\frac{\mathfrak{n}_{D^0}+\mathfrak{n}_{D^+}+\mathfrak{n}_{D^{*0}}+\mathfrak{n}_{D^{*+}}}{\mathfrak{n}_\pi}\right) = 0$$

Evolution of the charm-meson fractions

- charm-meson fractions $f_{D^{(*)}} = \mathfrak{n}_{D^{(*)}}/(\mathfrak{n}_{D^0} + \mathfrak{n}_{D^+} + \mathfrak{n}_{D^{*0}} + \mathfrak{n}_{D^{*+}})$ (sum is 1)



solid: solving complete evolution equations

dashed: solving evolution equations with only D* decay terms

Analytical solution to evolution equations

- At times τ large enough, the only terms in evolution equations that survive are 1-body terms: decay terms and t-channel singularities.

Analytical solution to evolution function

- At times τ large enough, the only terms in evoluation function that survive are 1-body terms: decay terms and t-channel singularities.
- If we only keep the 1-body terms with the vacuum values of $\Gamma_{*a,b}$, the evolution equations can be solved analytically.

$$\frac{d}{d\tau}R(\tau) = \begin{pmatrix} 0 & 0 & \Gamma_{*0} & B_{+0}\Gamma_{*+} \\ 0 & 0 & 0 & (1-B_{+0})\Gamma_{*+} \\ 0 & 0 & -(\Gamma_{*0}+\gamma) & \gamma \\ 0 & 0 & \gamma & -(\Gamma_{*+}+\gamma) \end{pmatrix} R(\tau), \; R(\tau) = \begin{pmatrix} n_{D^0}/n_\pi \\ n_{D^+}/n_\pi \\ n_{D^{*0}}/n_\pi \\ n_{D^{*+}}/n_\pi \end{pmatrix}$$

$$\frac{1}{\gamma} = \frac{1}{B_{00}\Gamma_{*0}} + \frac{1}{B_{+0}\Gamma_{*+}}$$

B_{00}: fraction of $D^{*0} \to D^0\pi^0$; B_{+0}: fraction of $D^{*+} \to D^0\pi^+$

Analytical solution to evolution function

- The resulting predictions for the numbers of D^0 and D^+ are

$$N_0 = (N_0)_0 + \left(1 - \frac{(1-B_{+0})\Gamma_{*+}\,\gamma}{\Gamma_{*+}\Gamma_{*0} + (\Gamma_{*+}+\Gamma_{*0})\,\gamma}\right)(N_{*0})_0 + \left(B_{+0} + \frac{(1-B_{+0})\Gamma_{*0}\,\gamma}{\Gamma_{*+}\Gamma_{*0} + (\Gamma_{*+}+\Gamma_{*0})\,\gamma}\right)(N_{*+})_0\,,$$

$$N_+ = (N_+)_0 + \frac{(1-B_{+0})\Gamma_{*+}\,\gamma}{\Gamma_{*+}\Gamma_{*0} + (\Gamma_{*+}+\Gamma_{*0})\,\gamma}(N_{*0})_0 + \left(1 - B_{+0} - \frac{(1-B_{+0})\Gamma_{*0}\,\gamma}{\Gamma_{*+}\Gamma_{*0} + (\Gamma_{*+}+\Gamma_{*0})\,\gamma}\right)(N_{*+})_0\,,$$

in comparison with the naive predictions

$$N_0 = (N_0)_0 + (N_{*0})_0 + B_{+0}\,(N_{*+})_0\,,$$
$$N_+ = (N_+)_0 + 0 + (1-B_{+0})\,(N_{*+})_0\,,$$

Numerical comparison

- initial: SHMc prediction before D* decays
- numerical: solve the complete evolution equations
- naive: consider D* decays only
- analytical: consider 1-body terms (D* decays + t-channel singularity)

	initial	numerical	naive	analytic
N_0/N_+	1.044	2.100	2.256 ± 0.014	2.177 ± 0.016

Errors are from B_{00}, B_{+0}, Γ_{*0}, Γ_{*0+}.

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	initial	numerical	naive	analytic
N_0/N_+	1.044	2.100	2.256 ± 0.014	2.177 ± 0.016

$$\left(\frac{N_0}{N_+}\right)_{\text{naive}} - \left(\frac{N_0}{N_+}\right)_{\text{analytic}} = 0.079 \pm 0.006$$

This difference (with or without t-channel singularity) differs from 0 by about 13 standard deviations.

Errors are from B_{00}, B_{+0}, Γ_{*0}, Γ_{*0+}.

Summary

- The evolution of charm-meson abundances after the kinetic freeze-out of an expanding hadron gas produced by a central heavy-ion collision is studied.
- We have shown that the t-channel singularities in charm-meson reactions can have observable consequences in charm-meson ratio.

Outlook

- The charm-meson reactions $\pi D^* \leftrightarrow \pi\pi D$ have a pion t-channel singularity from the decay $D^* \to D\pi$ followed by the scattering $\pi\pi \to \pi\pi$.
  Preliminary results indicate that pion t-channel singularities are more important than D-meson t-channel singularities.

- The t-channel singularities have been completely overlooked in studies of the charm mesons in a thermal hadronic medium.

- It might be worthwhile to look for other aspects of the thermal physics of charm mesons in which the effects of t-channel singularities are significant, for example the production of the exotic heavy hadrons like X(3872) and $T_{cc}(3875)$.

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THANK YOU

Evolution of charm-meson ratios

in an expanding hadron gas

汇报人：蒋军

2022年第七届手征有效场论研讨会，2022/10/14-17, 东南大学