Particle Production and freeze-out Q1: flavor dependent freeze-out

First principle calculation & fluctuation measurements
(PRL 111 (2013) 202302 & *Phys.Rev.C* 99 (2019) 3, 034912



Experimental evidence from yields and strangeness enhancement *Phys.Lett.B* 814 (2021) 136098 & *Phys.Lett.B* 834 (2022) 137473



Particle Production and freeze-out Q2: flavor dependent chiral symmetry restoration

Experimental evidence (UH thesis – Myers)

Lattice QCD calculation (JHEP 06 (2017) 034)

X→A(A)K[±], 0.0-100.0 %, 1.0<p_<20.0 GeV/c 57774.1 1.6 1.8223 ± 0.00081 Mean octet (spin 1/2) 0.0187 ± 0.00237 Width S_{2} S=0Sigma 0.0051 ± 0.00000 Mean Vs. <dN,/dn> chi2/hdf 0.5915 1.457847.2 Yield Bi 1.2N(-)N(+) $m(T)/m_{+}(T_{0})$ E[®](1820) pp@13 T E^{*}(1820) pPb@5.02 Te E[®](1820) PbPb@5.02 Te E^{*}(1820) PDG Mean E"(1820) PDG Mea 1814 int Mass IGeWich X→Λ(Λ)K[#], 0.0-100.0 %, 1.0<p_<20.0 GeV/c 1812 36836.6 1.8226 + 0.001131.2Width 0.0236 ± 0.00325 $\Lambda(-)$ $\Xi(-)$ 0.0051 + 0.00000Sigma 10^{2} <dN_103 $\Xi(+)$ $\square \Lambda(+)$ chi2/ndf 0.6554 Vield Bi 35962 0.20.8 0.40.6 0.20.40.8 0.6 T/T_c Width Vs. <dN,,/dn> - Ξ^{*}(1820) pp@13 TeV 2²(1820) oPb@5.02 TeV decuplet (spin 3/2) S = -1T'(1820) P5P5 95.02 TeV <u>s=0</u> 2"(1820) PDG width E^{*}(1820) PDG width e $\mathbf{L4}$ X→Λ(Λ)K[∓], 30.0-50.0 % , 1.0<*p*_<20.0 GeV/*c* 1.2 $\Delta (-)$ Integra 419564.7 °40000 $\Delta(+)$ 1.8168 +- 0.00220 Mean Width 0.0367 +- 0.00558 Sigma 0.0044 +- 0.00000 0.9736 chi2/nd 408533.4 <dN.../dn> $\mathbf{12}$ -10000 Ξ (-) $\alpha - \alpha$ $\Xi^{*}(+)$ -20000 1.7 1.85 1.75 1.8 2.05 1.95 1.9 東 Invariant Mass [GeV/c2] 0.20.40.6 0.8 0.8 0 0.20.4 0.6 T/T_{e}

Particle Production and freeze-out Q3: lack of multi-quark states in strange sector

Experimental evidence in charm sector





State	$\frac{Mass}{(MeV/c^2)}$	Width (MeV/c ²)	S-wave threshold (MeV/c^2)	Coupled Channels
X(3872) [226]	3872.0 ± 0.2	1.19±0.21	${D^{*0}}{D^0}(-0.04), \ {D^{*+}}{D^-}(-8.11)$	$\pi^+\pi^-\mathrm{J}/\psi,\ \pi^+\pi^-\pi^0\mathrm{J}/\psi$
X(3940) [226]	3942 ±9	37	D*D* (-75 ±9)	D*D
X(4140) [226]	4147.0 ± 4.5	83 ±21	$D_s \overline{D}_s^* (-66^{+4.9}_{-3.2})$	$\phi J/\psi$
X(4274) [226]	4273.0 ± 8.3	56 ±11	$D_s \overline{D}_s^* (-49.1^{+19.1}_{-9.1})$	$\phi J/\psi$
Z _b (10610) [226]	$10607.0\pm\!2.0$	18.4 ± 2.4	BB*(4±3.2)	$\pi^{\pm} \Upsilon(nS) \ \pi^{\pm} h_b(nP)$
$Z_b^{\pm}(10650)$ [226]	10652.2 ± 1.5	11.5 ± 2.2	B*B*(+2.9)	$\pi^{\pm} \Upsilon(nS) \ \pi^{\pm} h_b(nP)$
$P_c^+(4312)$ [83]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$		$\Sigma_c D(-9.7)$	pJ/ψ
$P_c^+(4440)$ [83]	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c \bar{D}^*(-21.8)$	$pJ/\psi, \Sigma_c D \Sigma_c^* D$
$P_c^+(4457)$ [83]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c \bar{D}^*(-4.8)$	$pJ/\psi, \Sigma_c D \Sigma_c^* D$
T _{cc} ⁺ [57]	3874.827	0.410	$D^{*+}\bar{D}^{0}(-0.273),$ $D^{*0}\bar{D}^{+}(-1.523)$	$\mathrm{D}^{0}\mathrm{D}^{0}\pi^{+}$

Table 5: Selection of candidates for hadronic molecules with a mass close to a hadron-hadron mass threshold [57,83,226].

Particle Production and freeze-out Q4: large small system vs small large system

 Λ_{c}^{+}/D^{0}

0.9

0.8

0.7

0.6

0.5

0.3

0.2

0.

0

ALI-PUB-500979



ALI-PREL-503055

Common thermal production in heavy ions?





0.2

10²

10

 10^{3}

 $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

extr.

40

 $\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}$ ALI-DER-507238

30

p-Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

20

10

CR vs. thermal production

Particle Production and freeze-out Q5: 'thermalization' from entanglement initial entropy production = final particle production



Bose condensate measurement



ep collisions: (H1 data at different x-values)



