Hadron-hadron interaction from heavy-ion results

Clusters & Hierarchies

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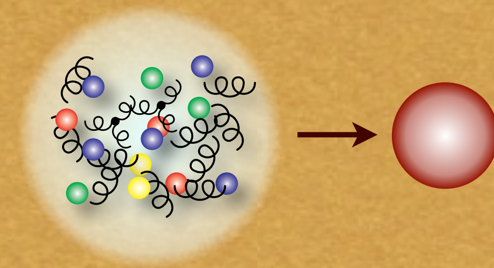
2021, Nov. 23rd

Contents

- **Introduction — T_{cc} and $X(3872)$**
- **Production yields (1-hadron detection)**

S. Cho *et al.*, ExHIC collaboration, PRL 106, 212001 (2011);
S. Cho *et al.*, ExHIC collaboration, PRC 84, 064910 (2011);
S. Cho *et al.*, ExHIC collaboration, PPNP 95, 279 (2017)



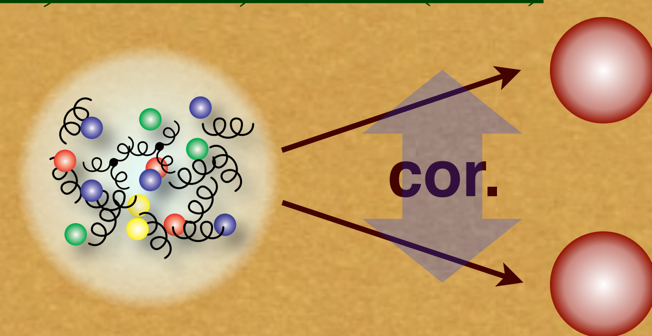
- **Correlation functions (2-hadron detection)**

  - $K^- p$ interactions

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

  - D meson sector

Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation



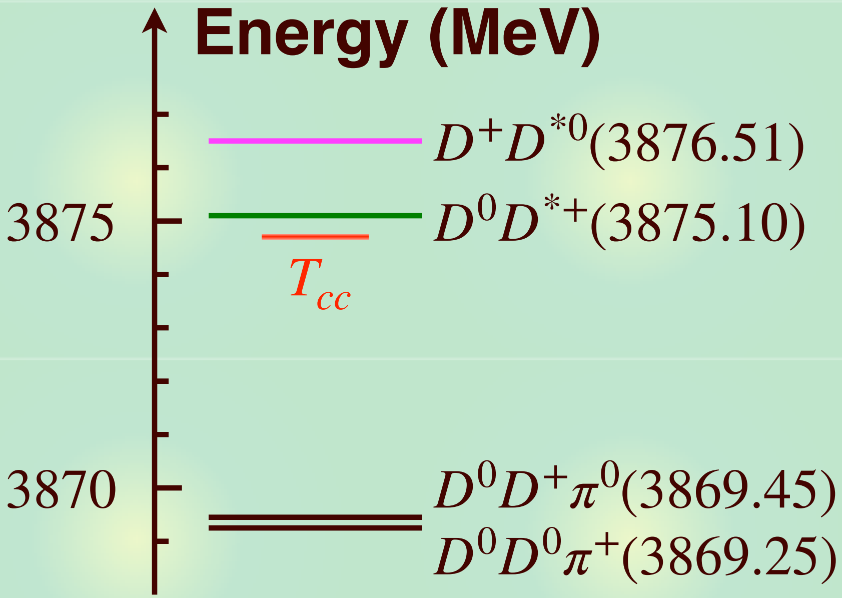
- **Summary**

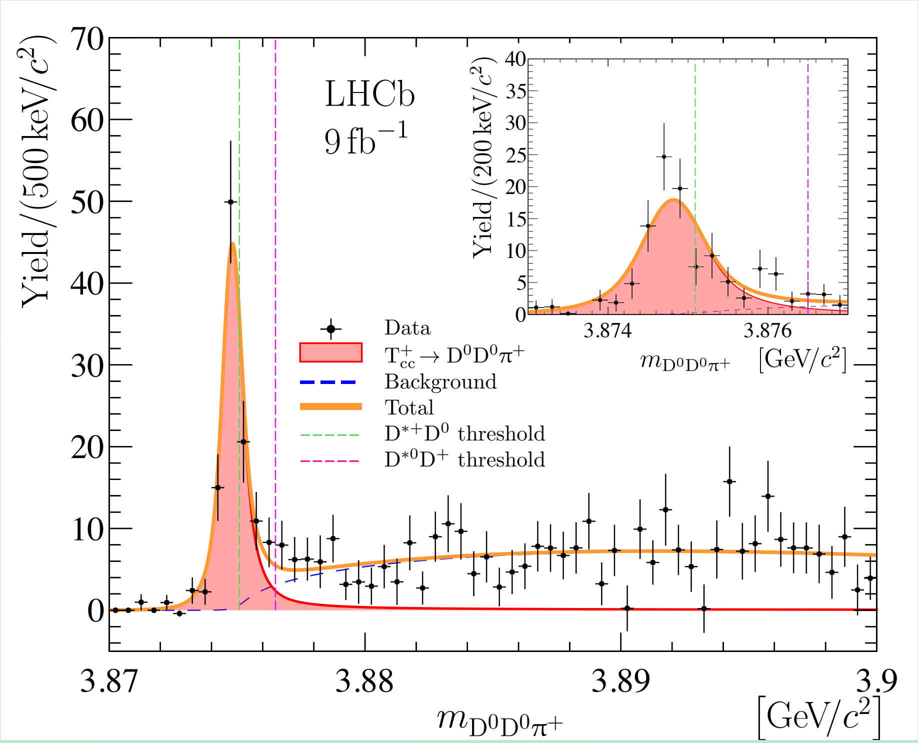
Observation of T_{cc}

T_{cc} observed in $D^0D^0\pi^+$ spectrum

LHCb collaboration, arXiv 2109.01038 [hep-ex], 2109.01056 [hep-ex]

- **Signal near DD^* threshold**
- **Charm $C = +2 : \sim cc\bar{u}\bar{d}$**
- **Level structure**



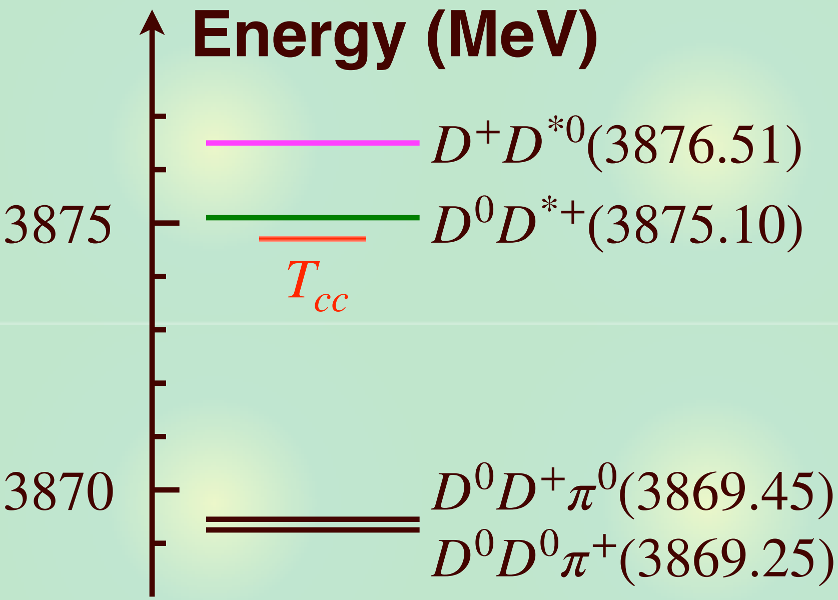


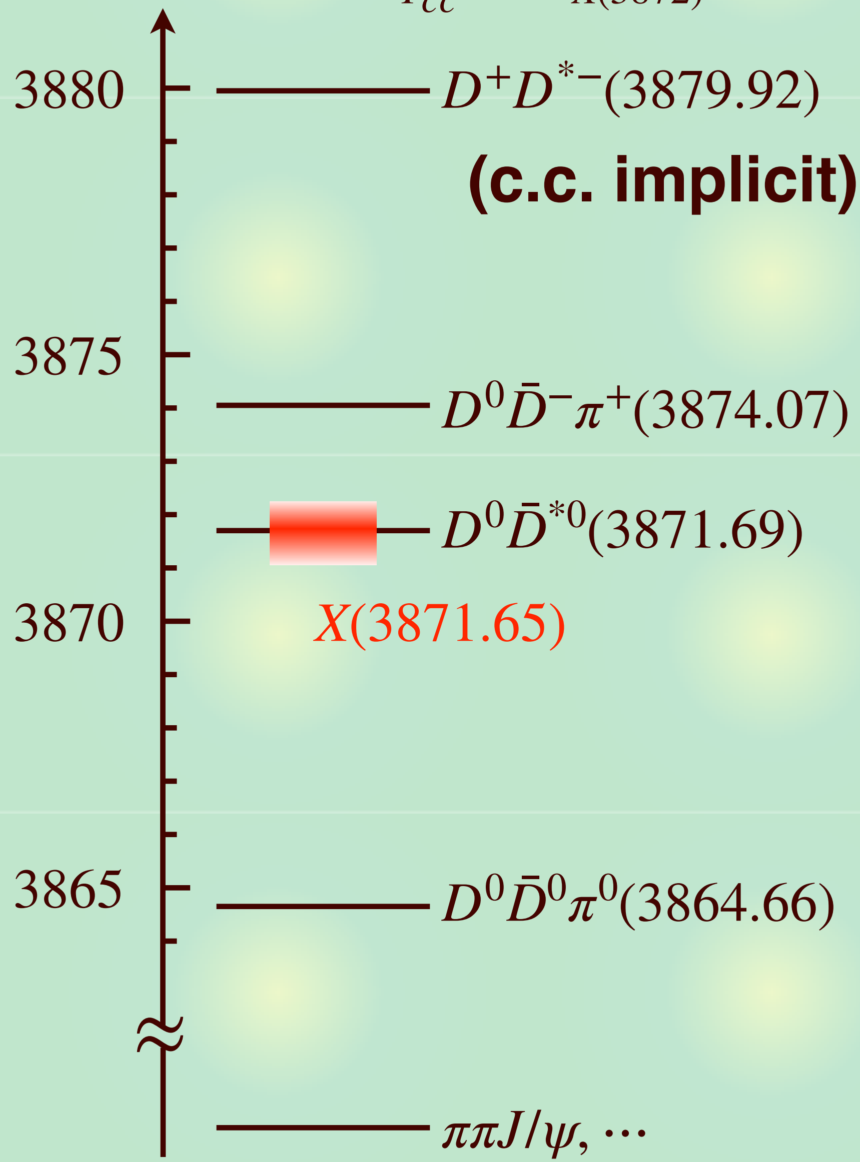
- **Very small (few MeV ~ keV) energy scale involved**

T_{cc} and $X(3872)$

$X(3872)$: another near-threshold state with $M_{T_{cc}} \sim M_{X(3872)}$

- Masses from PDG Live





- $T_{cc}/X(3872)$ near $DD^*/D\bar{D}^*$

  —> Molecule nature?

- $X(3872)$ has decay channels

ExHIC collaboration

Hadron production yields and internal structure

PRL **106,** 212001 (2011) PHYSICAL REVIEW LETTERS week ending 27 MAY 2011

Identifying Multiquark Hadrons from Heavy Ion Collisions

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1,2] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,3]

(ExHIC Collaboration)

PHYSICAL REVIEW C **84**, 064910 (2011)

Exotic hadrons in heavy ion collisions

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,9]
(ExHIC Collaboration)

Progress in Particle and Nuclear Physics 95 (2017) 279–322

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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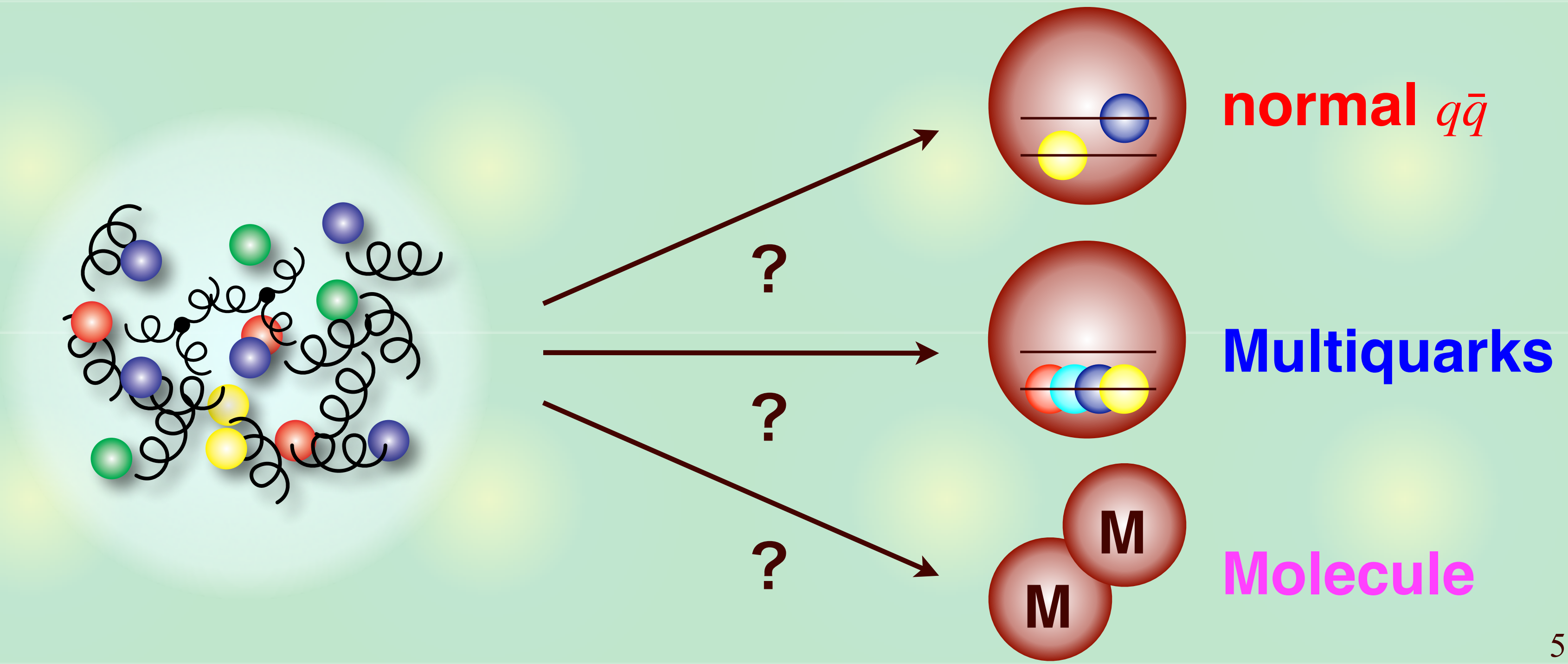
Review

Exotic hadrons from heavy ion collisions[☆]

Sungtae Cho[a], Tetsuo Hyodo[b], Daisuke Jido[c], Che Ming Ko[d], Su Houng Lee[e,*], Saori Maeda[f], Kenta Miyahara[g], Kenji Morita[b], Marina Nielsen[h], Akira Ohnishi[b], Takayasu Sekihara[i], Taesoo Song[j], Shigehiro Yasui[f], Koichi Yazaki[k] (ExHIC Collaboration)



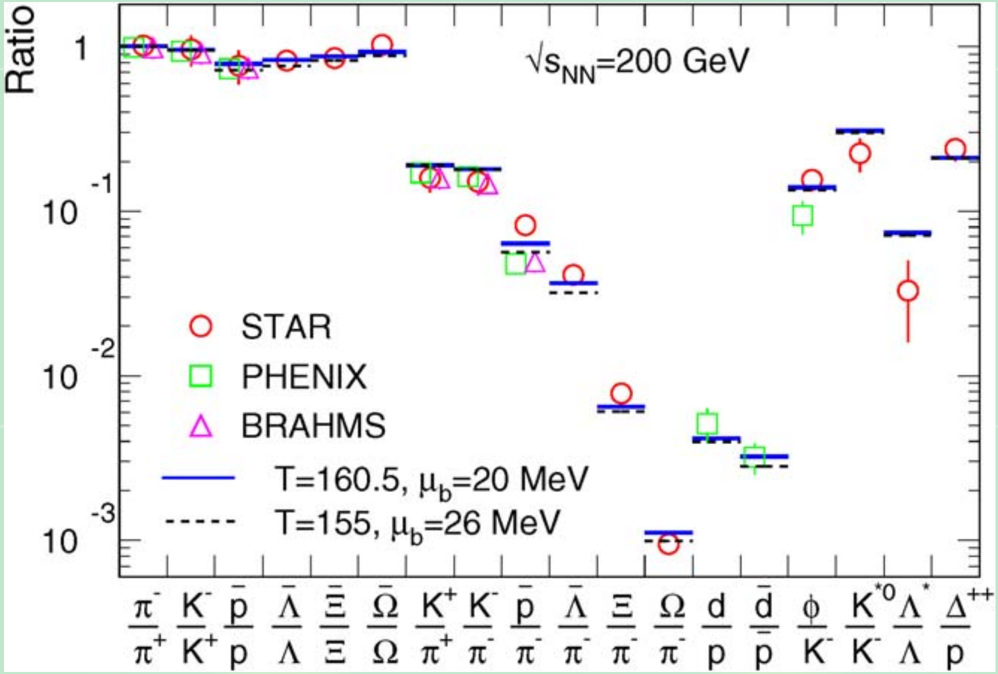
Statistical model

Statistical production yield for hadron h

A. Andronic, P. Braun-Munzinger, J. Stachel, NPA 772, 167 (2006)

$$N_h^{\rm stat} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_h^{-1} e^{E_h/T_H} \pm 1}$$

- Fugacity γ_h : chemical equilibrium for u, d, s, tuned for c, b



- works well for normal hadrons

Coalescence model

Coalescence (overlap of constituents and hadron w.f.)

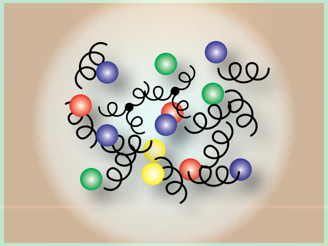
V. Greco, C. M. Ko, P. Levai, PRL 90, 202302 (2003)

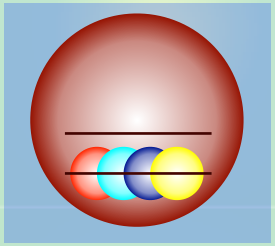
$$N_h^{\mathrm{coal}} = g_h \int \prod_{i=1}^{n} \left[\frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{d^3 p_i}{E_i} f(x_i, p_i) \right] f^W(x_1, \cdots, x_n; p_1, \cdots, p_n)$$

- Model parameters <— statistical yields of normal hadrons

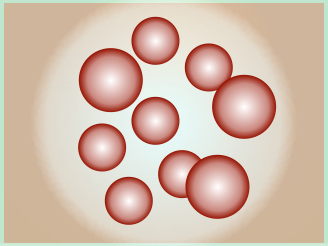
Prediction for exotic hadrons

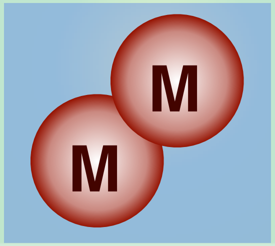
- Multiquarks by quark coalescence





- Hadronic molecule by hadron coalescence





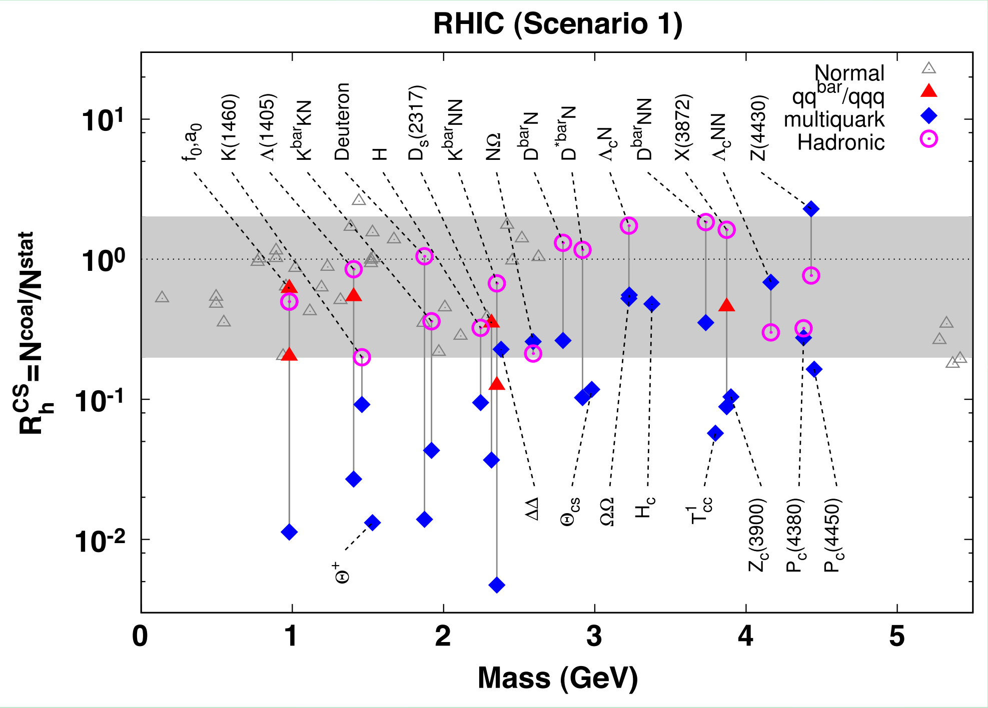
Yield estimation

Coalescence-statistical ratio

S. Cho *et al.*, ExHIC collaboration, PPNP 95, 279 (2017)

$$R_h^{CS} = \frac{N_h^{coal}}{N_h^{stat}}$$

- **Multiquarks** suppressed
- **Molecules** enhanced



Yields (Pb-Pb @ 5.02 TeV)

$$N_N = 32$$

$N_{T_{cc}}^{stat} = 4.4 \times 10^{-3}$ $\quad N_{T_{cc}}^{cc\bar{u}\bar{d}} = (1.8 - 2.1) \times 10^{-4}$

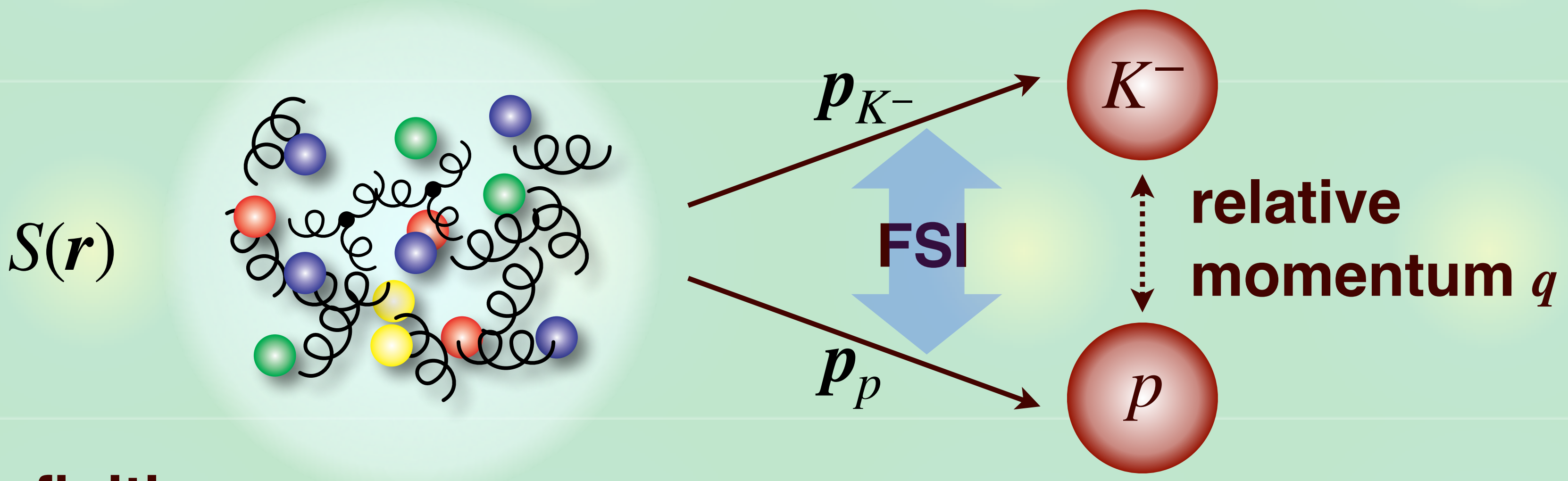
$N_{X(3872)}^{stat} = 2.8 \times 10^{-3}$ $\quad N_{X(3872)}^{c\bar{c}q\bar{q}} = (1.8 - 2.1) \times 10^{-4}$ $\quad N_{X(3872)}^{molecule} = (4.5) \times 10^{-3}$

If T_{cc} is a DD^* molecule, yield would be $\sim 10^{-3}$

J. Hong, S. Cho T. Song, S.H. Lee, PRC 98, 014913 (2018)

Correlation function and hadron interaction

High-energy collision: chaotic source $S(\boldsymbol{r})$ of hadron emission



- Definition

$$C(\boldsymbol{q}) = \frac{N_{K^-p}(\boldsymbol{p}_{K^-}, \boldsymbol{p}_p)}{N_{K^-}(\boldsymbol{p}_{K^-})N_p(\boldsymbol{p}_p)}$$ **(= 1 in the absence of FSI/QS)**

- Theory (Koonin-Pratt formula)

$$C(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\; S(\boldsymbol{r})\,|\,\Psi^{(-)}_{\boldsymbol{q}}(\boldsymbol{r})\,|^2$$

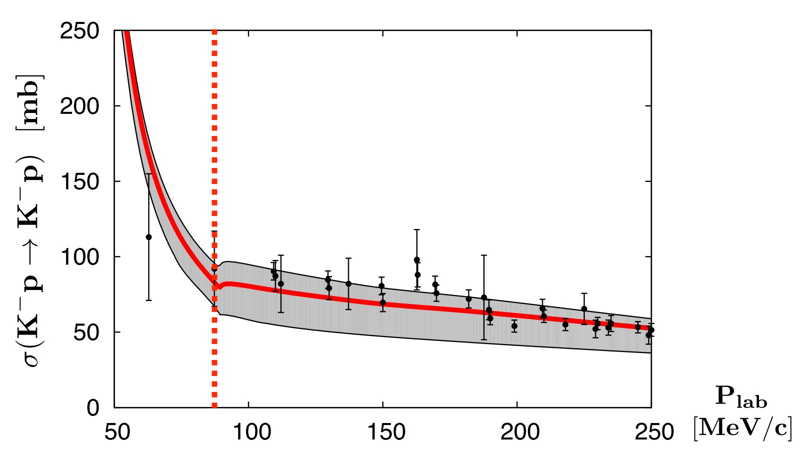
Source function <—> two-body wave function (FSI)

ALICE collaboration, Nature 588, 232 (2020); …

Experimental data of K^-p correlation

K^-p total cross sections

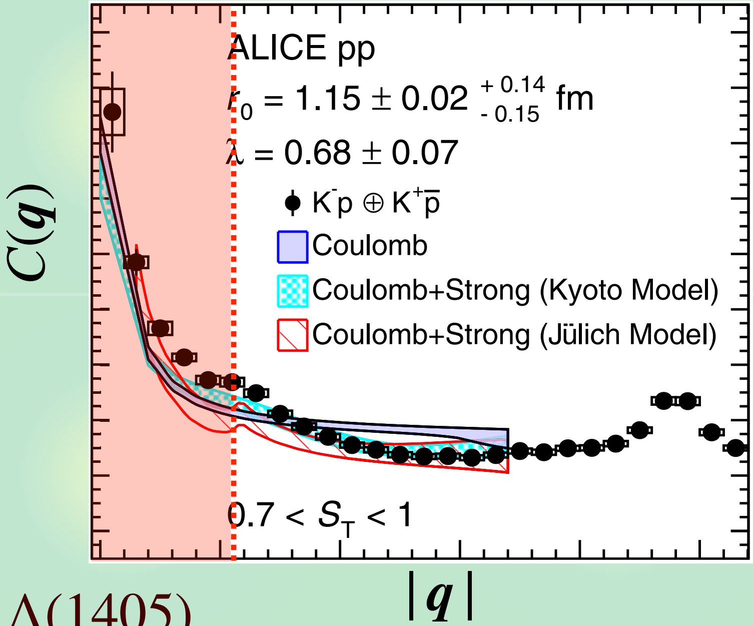
Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)



- Old bubble chamber data
- Resolution is not good
- Threshold cusp is not visible

K^-p correlation function

ALICE collaboration, PRL 124, 092301 (2020)



- Excellent **precision** ($\bar{K}^0 n$ cusp)
- Low-energy data **below** $\bar{K}^0 n$

—> Important constraint on $\bar{K}N$ and $\Lambda(1405)$

Coupled-channel correlation function

Schrödinger equation (s-wave)

$$\begin{pmatrix} -\frac{\nabla^2}{2\mu_1} + V_{11}(r) + V_C(r) & V_{12}(r) & \cdots \\ V_{21}(r) & -\frac{\nabla^2}{2\mu_2} + V_{22}(r) + \Delta_2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} = E \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix}$$

Coulomb threshold energy difference

Coupled-channel formulation

R. Lednicky, V.V. Lyuboshitz, V.L.Lyuboshitz, Phys. Atom. Nucl. 61, 2050 (1997);
J. Haidenbauer, NPA 981, 1 (2019)

$$C_{K^-p}(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S_{K^-p}(\boldsymbol{r})\, |\, \Psi^{(-)}_{K^-p,\boldsymbol{q}}(\boldsymbol{r})\,|^2 + \sum_{i \neq K^-p} \omega_i \int d^3\boldsymbol{r}\, S_i(\boldsymbol{r})\, |\, \Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})\,|^2$$

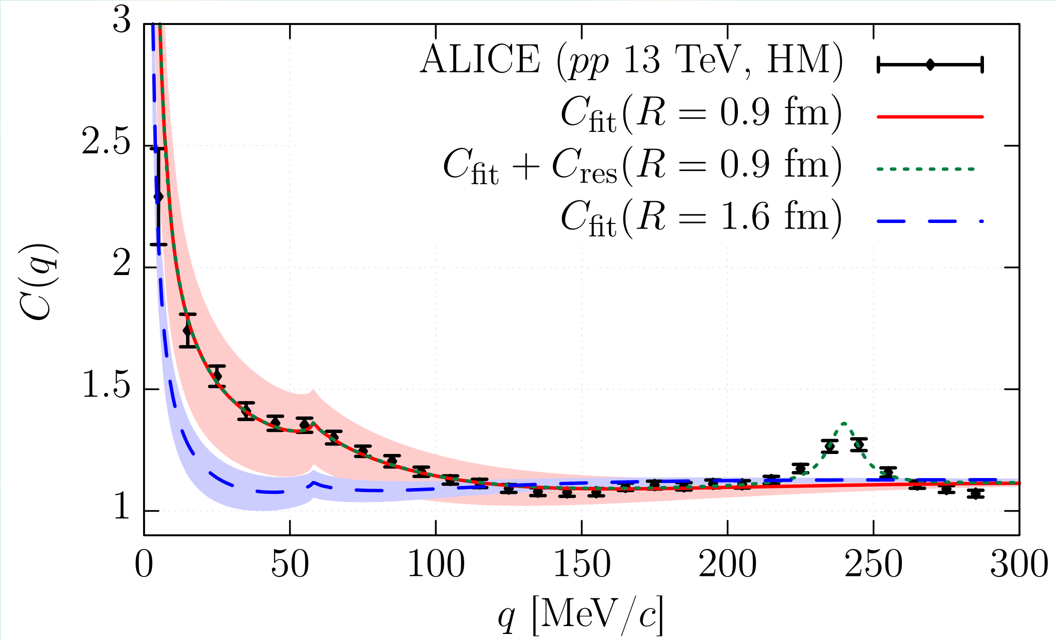
- Transition from $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$
- ω_i : weight of source channel i relative to K^-p

Correlation from chiral SU(3) dynamics

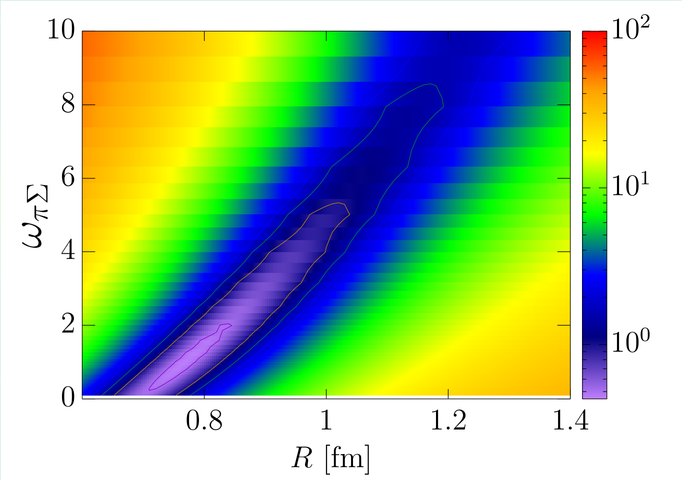
Wave function $\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})$: coupled-channel $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

K. Miyahara, T. Hyodo, W. Weise, PRC98, 025201 (2018)

- **Source function $S(r)$: Gaussian, $R \sim 1$ fm in K^+p data**
- **Source weight $\omega_{\pi\Sigma} \sim 2$ by simple statistical model estimate**



reduced χ^2



Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

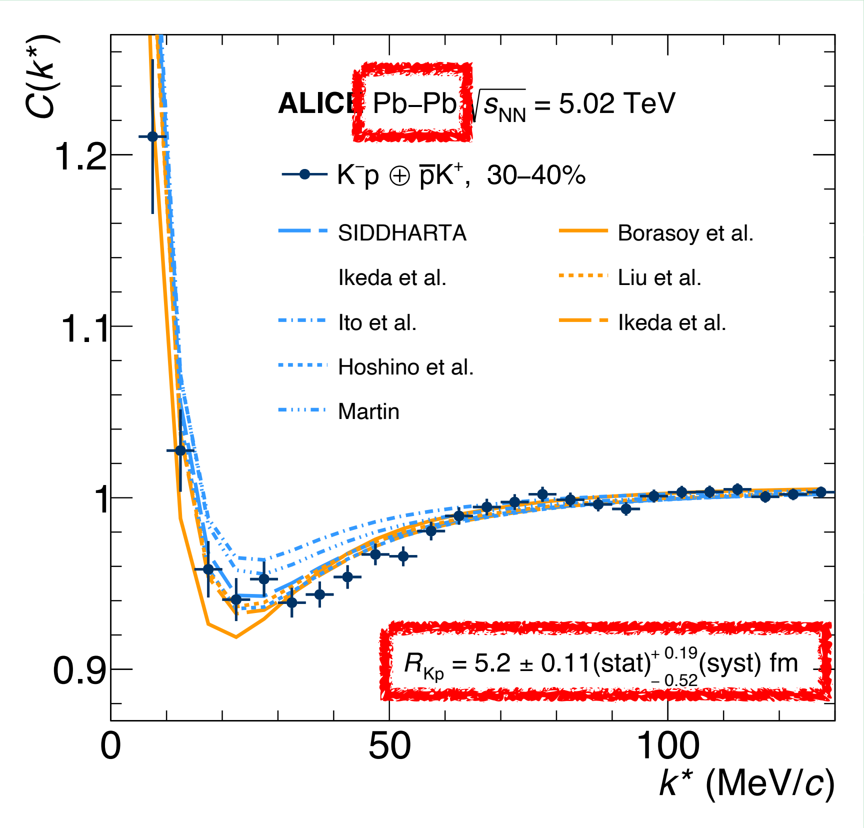
Correlation function by ALICE is well reproduced

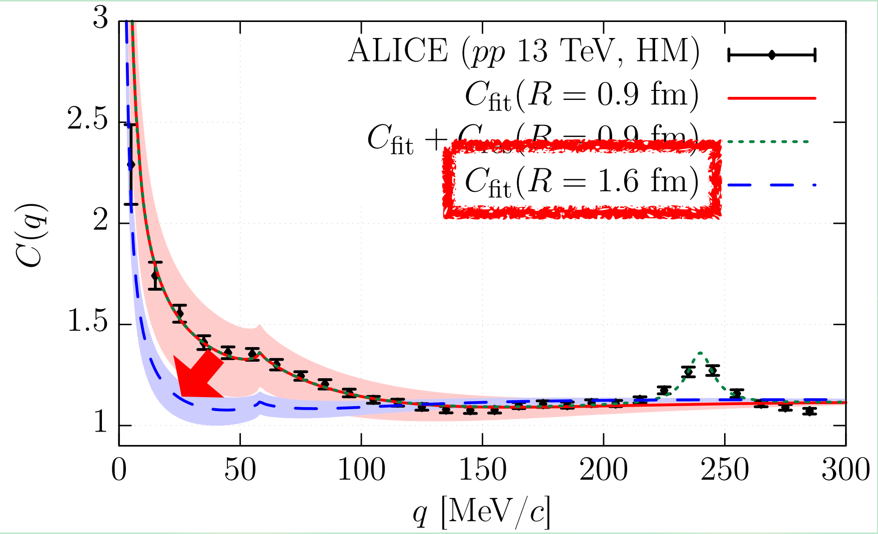
Source size dependence

New data of Pb-Pb collisions at 5.02 TeV

ALICE collaboration, PLB 822, 136708 (2021)

- Scattering length $a_{K^-p} = -0.91 + 0.92i$ fm

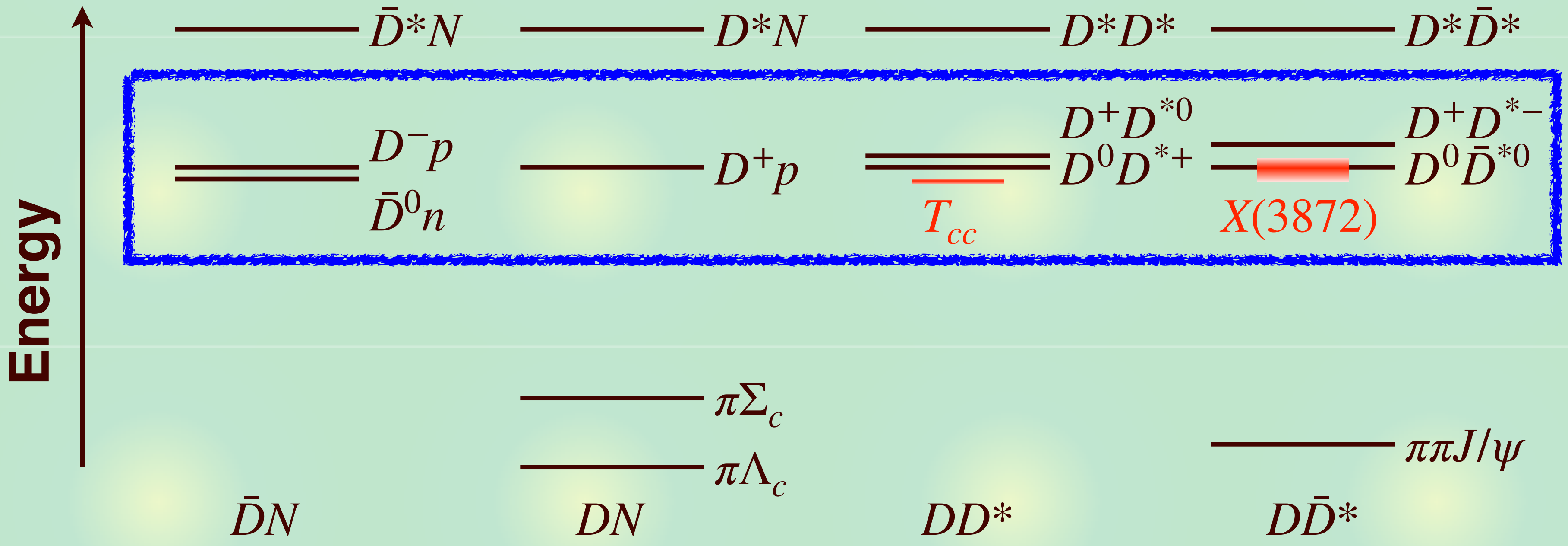




Correlation is suppressed at larger R, as predicted

Strategy

Schematic threshold structures in D meson sector



One-range gaussian potentials

$$V(r) = V_0 \exp\{-m^2 r^2\}$$

- V_0 <— **Scattering length in theoretical models** ($\bar{D}N, DN$)
- V_0 <— **Binding energies of** $T_{cc}, X(3872)$ ($DD^*, D\bar{D}^*$)

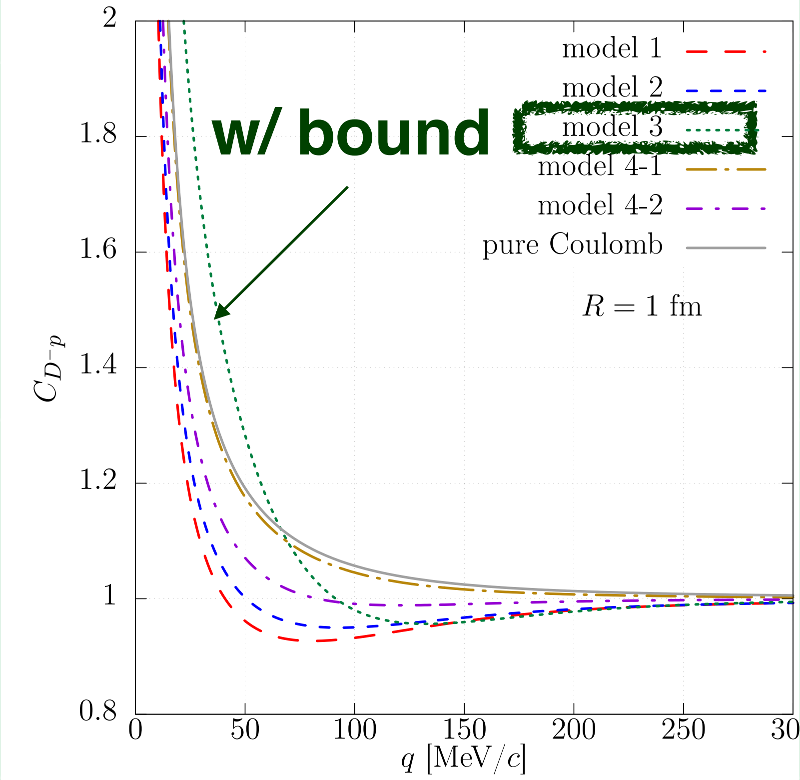
Exotic DN sector

$D^{-}p$ correlation functions ($\bar{c}duud$, exotic)

- Coupled with $\bar{D}^0 n$
- No decay channels below
- Theoretical models

[1] J. Hofmann, M.F.M. Lutz, NPA763, 90 (2005);
[2] J. Haidenbauer *et al.*, EPJA33, 107 (2007);
[3] Y. Yamaguchi *et al.*, PRD84, 014032 (2011);
[4] C. Fontoura *et al.*, PRD87, 025206 (2013)

- Gaussian potentials with $a_0(I = 0,1)$



- Model 3 with a **bound state** : dip structure
- To be compared with experiments in future

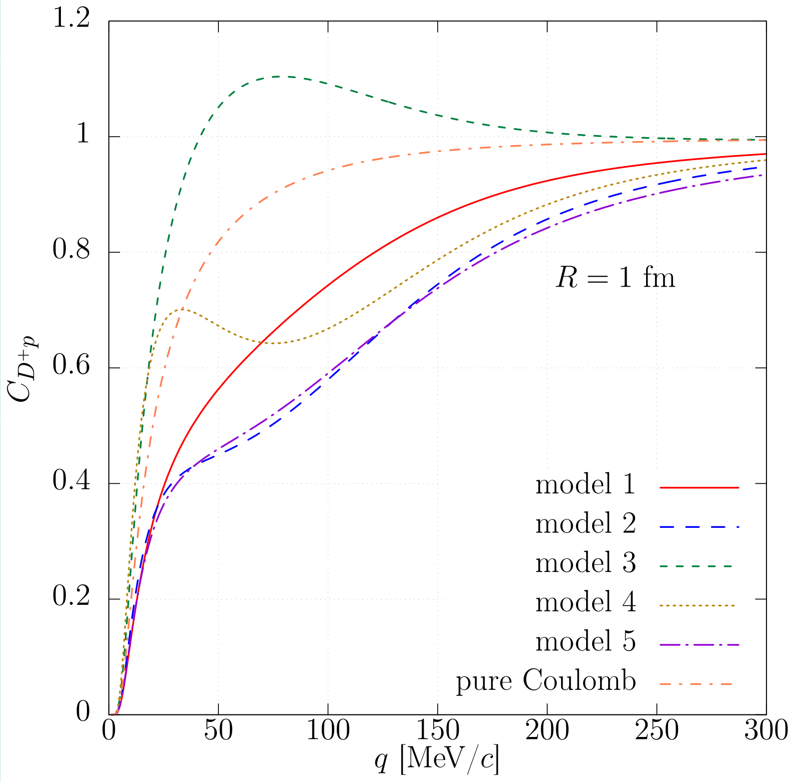
Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation

Non-exotic $\bar{D}N$ sector

D^+p correlation functions ($c\bar{d}uud$, non-exotic)

- No isospin partner in DN
- With decay channels ($\pi\Lambda_c$, $\pi\Sigma_c$)
- Theoretical models

[1] J. Hofmann, M.F.M. Lutz, NPA763, 90 (2005);
[2] T. Mizutani, A. Ramos, PRC74, 065201 (2006);
[3] C. Garcia-Recio *et al.*, PRD79, 054004 (2009);
[4] J. Haidenbauer *et al.*, EPJA47, 18 (2011);
[5] U. Raha *et al.*, PRC98, 034002 (2018)



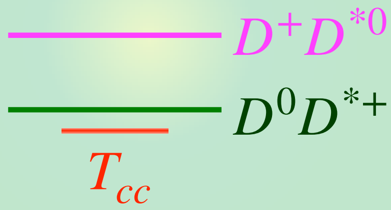
- Effective single-channel potential
  <— $a_0(I=1)$

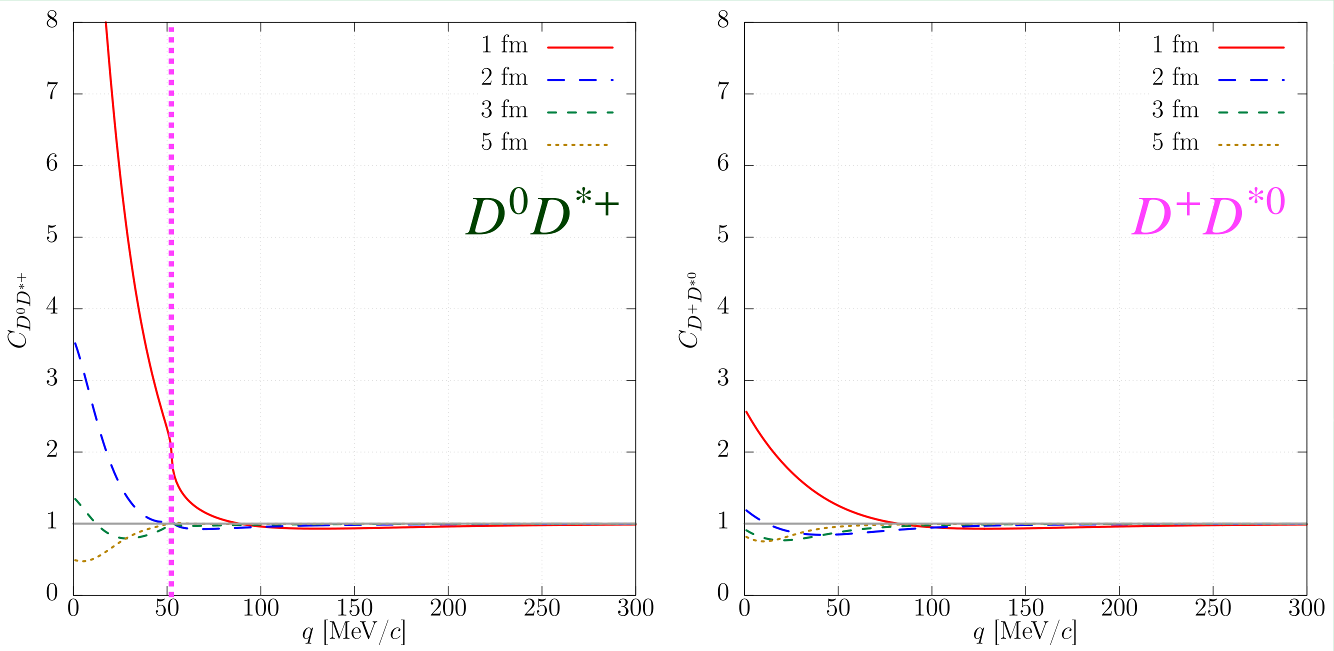
- Sizable dependence on the scattering length

Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation

$DD^* \sim T_{cc}$ sector

D^0D^{*+} and D^+D^{*0} correlation functions ($cc\bar{u}\bar{d}$, exotic)



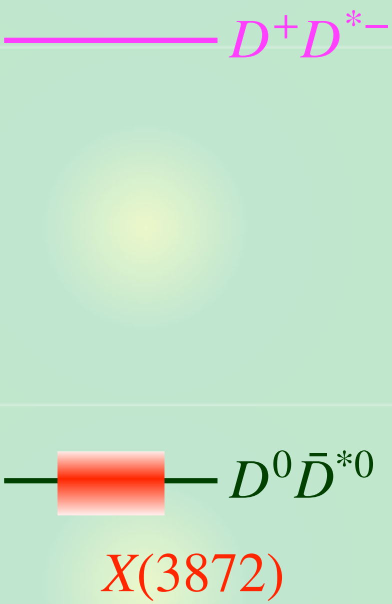


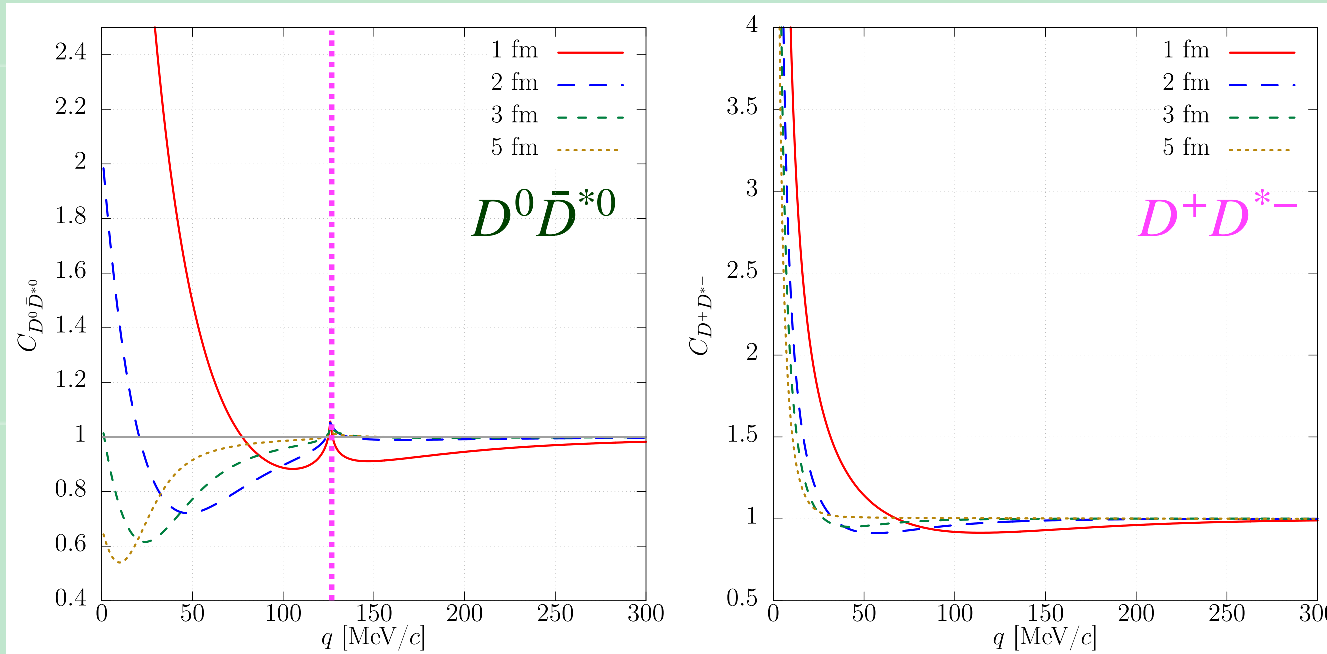
- Bound state feature (source size dep.) in both channels
- Strong signal in D^0D^{*+}, weaker one in D^+D^{*0}
- D^+D^{*0} cusp in D^0D^{*+} ($q \sim 52$ MeV) is not very prominent

Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation

$D\bar{D}^* \sim X(3872)$ sector

$D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$ correlation functions ($c\bar{c}q\bar{q}$)





- Bound state feature in $D^0\bar{D}^{*0}$ correlation
- Sizable D^+D^{*-} cusp in $D^0\bar{D}^{*0}$ ($q \sim 126$ MeV)
- D^+D^{*-} correlation : Coulomb attraction dominance

Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation

Summary

- **Hadron production yields <— internal structure**

S. Cho *et al.*, ExHIC collaboration, PRL 106, 212001 (2011);
S. Cho *et al.*, ExHIC collaboration, PRC 84, 064910 (2011);
S. Cho *et al.*, ExHIC collaboration, PPNP 95, 279 (2017)

- **$K^{-}p$ correlation in pp collisions**
  - **well described by chiral SU(3) dynamics**

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

- **$D^{-}p$ and $D^{+}p$ correlations**
  - **sizable scattering length dependence**
- **$D^{0}D^{*+}$ and $D^{0}\bar{D}^{*0}$ correlations**
  - **(quasi-)bound nature of T_{cc} and $X(3872)$**

Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation

ExHIC parameters

Table 3.1
Statistical and coalescence model parameters for Scenario 1 and 2 at RHIC (200 GeV), LHC (2.76 TeV) and LHC (5.02 TeV), and those given in Refs. [14,15]. Quark masses are taken to be $m_q = 350$ MeV, $m_s = 500$ MeV, $m_c = 1500$ MeV and $m_b = 4700$ MeV. In Refs. [14,15], light quark masses were taken to be $m_q = 300$ MeV.

	RHIC		LHC (2.76 TeV)		LHC (5.02 TeV)		RHIC	LHC (5 TeV)
	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Refs [14,15]	
T_H (MeV)	162		156				175	
V_H (fm^3)	2100		5380				1908	5152
μ_B (MeV)	24		0				20	0
μ_s (MeV)	10		0				10	0
γ_c	22		39		50		6.40	15.8
γ_b	4.0×10^7		8.6×10^8		1.4×10^9		2.2×10^6	3.3×10^7
T_C (MeV)	162	166	156	166	156	166	175	
V_C (fm^3)	2100	1791	5380	3533	5380	3533	1000	2700
ω (MeV)	590	608	564	609	564	609	550	
ω_s (MeV)	431	462	426	502	426	502	519	
ω_c (MeV)	222	244	219	278	220	279	385	
ω_b (MeV)	183	202	181	232	182	234	338	
$N_u = N_d$	320	302	700	593	700	593	245	662
$N_s = N_{\bar{s}}$	183	176	386	347	386	347	150	405
$N_c = N_{\bar{c}}$	4.1		11		14		3	20
$N_b = N_{\bar{b}}$	0.03		0.44		0.71		0.02	0.8
T_F (MeV)	119		115				125	
V_F (fm^3)	20355		50646				11322	30569
N_K	67.5		134				142[a]	363[a]
$N_{\bar{K}}$	59.6		134				127[a]	363[a]
N_N	20		32				62[a]	150[a]
N_Δ	18		28				–	–
N_Λ	3.8		6.5				–	–
N_Ξ	2.6		4.4				4.7	13
N_Ω	0.37		0.62				0.81	2.3
$N_D = N_{\bar{D}}$	1.5		4.0		5.2		1.0	6.9
$N_{D^*} = N_{\bar{D}^*}$	2.0		5.4		6.9		1.5	10
$N_{D_1} = N_{\bar{D}_1}$	0.20		0.49		0.63		0.19	1.3
$N_B = N_{\bar{B}}$	8.1×10^{-3}		0.12		0.20		5.3×10^{-3}	0.21
$N_{B^*} = N_{\bar{B}^*}$	1.9×10^{-2}		0.27		0.45		1.2×10^{-2}	0.49
N_{Λ_c}	0.17		0.36		0.46		–	–
N_{Σ_c}	0.2		0.41		0.52		–	–
$N_{\Sigma_c^*}$	0.28		0.56		0.71		–	–
N_{Ξ_c}	0.11		0.25		0.32		0.10	0.65

[a] Values contain feed down contributions.

S. Cho *et al.*, ExHIC collaboration, PPNP 95, 279 (2017)

T_{cc} and $X(3872)$ yields

Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
RHIC						
T_{cc}^1	–	5.0×10^{-5}	–	5.3×10^{-5}	–	8.9×10^{-4}
LHC (2.76 TeV)						
T_{cc}^1	–	1.1×10^{-4}	–	1.3×10^{-4}	–	2.7×10^{-3}
LHC (5.02 TeV)						
T_{cc}^1	–	1.8×10^{-4}	–	2.1×10^{-4}	–	4.4×10^{-3}

Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
RHIC						
$D_s(2317)$	2.3×10^{-2}	2.4×10^{-3}	2.3×10^{-2}	2.5×10^{-3}	6.5×10^{-3}	6.6×10^{-2}
$X(3872)$	5.4×10^{-4}	5.0×10^{-5}	5.6×10^{-4}	5.3×10^{-5}	9.1×10^{-4}	5.7×10^{-4}
LHC (2.76 TeV)						
$D_s(2317)$	5.2×10^{-2}	4.3×10^{-3}	5.0×10^{-2}	4.5×10^{-3}	1.4×10^{-2}	1.5×10^{-1}
$X(3872)$	1.6×10^{-3}	1.1×10^{-4}	1.7×10^{-3}	1.3×10^{-4}	2.7×10^{-3}	1.7×10^{-3}
LHC (5.02 TeV)						
$D_s(2317)$	6.5×10^{-2}	5.4×10^{-3}	6.4×10^{-2}	5.7×10^{-3}	1.8×10^{-2}	1.9×10^{-1}
$X(3872)$	2.5×10^{-3}	1.8×10^{-4}	2.7×10^{-3}	2.1×10^{-4}	4.5×10^{-3}	2.8×10^{-3}

S. Cho *et al.*, ExHIC collaboration, PPNP 95, 279 (2017)

Boundary conditions

Asymptotic ($r \to \infty$) wave function

$$\begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} \propto \begin{pmatrix} \# e^{-iqr} + \# e^{iqr} \\ \# e^{-iq_2 r} + \# e^{iq_2 r} \\ \vdots \end{pmatrix}$$

incoming + outgoing

- Usual scattering: normalize incoming flux of beam

$$\begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} \propto \begin{pmatrix} e^{-iqr} + c_1^{(+)} e^{iqr} \\ + c_2^{(+)} e^{iq_2 r} \\ \vdots \end{pmatrix}$$

coefficient ~ S-matrix

$$c_i^{(+)} \propto s_{1i}(q)$$

- Correlation function: normalize outgoing flux

$$\psi^{(-)} = \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} \propto \begin{pmatrix} c_1^{(-)} e^{-iqr} + e^{iqr} \\ c_2^{(-)} e^{-iq_2 r} \\ \vdots \end{pmatrix}$$

$$c_i^{(-)} \propto s_{1i}^{\dagger}(q)$$

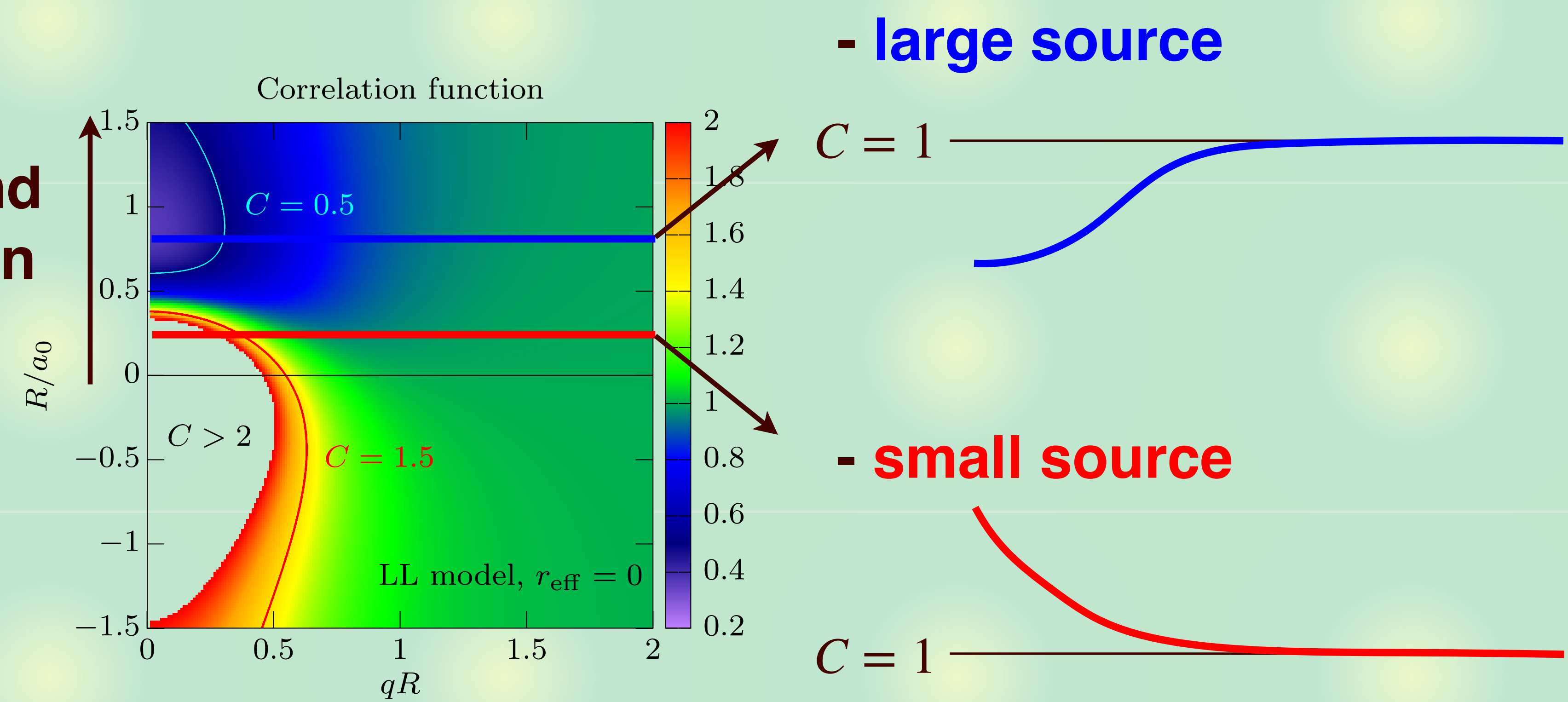
—> $\psi^{(-)}$ should be calculated with full coupled channels.

Bound state in correlation function

Y. Kamiya, K. Sasaki, T. Fukui, T. Hyodo, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda, arXiv 2108.09644 [hep-ph]

Lednicky-Lyuboshitz model with $r_e = 0$

Bound region



Bound state —> small size enhancement & large size dip