Recent progress in the study of hadron interactions with femtoscopy





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Contents

- Introduction — Exotic hadrons
- Hadron interactions — Femtoscopy
- Applications
  - Coupled-channel K^-p interaction and $\Lambda(1405)$

    T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)
  - K^-p correlation functions

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

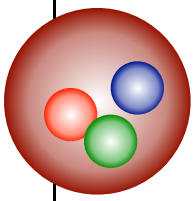
Observed hadrons (2022)

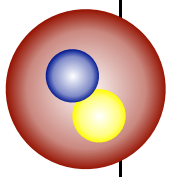
Particle Data Group (PDG) 2022 edition

http://pdg.lbl.gov/

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	Σ^+	$1/2^+$	****	Λ_c^+	$1/2^+$	****	Λ_b^0	$1/2^+$	***
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	****	Σ^0	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***	$\Lambda_b(5912)^0$	$1/2^-$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***	$\Lambda_b(5920)^0$	$3/2^-$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Lambda_c(2765)^+$		*	$\Lambda_b(6146)^0$	$3/2^+$	***
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1580)$	$3/2^-$	*	$\Lambda_c(2860)^+$	$3/2^+$	***	$\Lambda_b(6152)^0$	$5/2^+$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	***	$\Sigma(1620)$	$1/2^-$	*	$\Lambda_c(2880)^+$	$5/2^+$	***	Σ_b	$1/2^+$	***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1660)$	$1/2^+$	***	$\Lambda_c(2940)^+$	$3/2^-$	***	Σ_b^*	$3/2^+$	***
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1670)$	$3/2^-$	****	$\Sigma_c(2455)$	$1/2^+$	****	$\Sigma_b(6097)^+$		***
$N(1700)$	$3/2^-$	***	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1750)$	$1/2^-$	***	$\Sigma_c(2520)$	$3/2^+$	***	$\Sigma_b(6097)^-$		***
$N(1710)$	$1/2^+$	****	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1775)$	$5/2^-$	****	$\Sigma_c(2800)$		***	Ξ_b^-	$1/2^+$	***
$N(1720)$	$3/2^+$	****	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1780)$	$3/2^+$	*	Ξ_c^+	$1/2^+$	***	Ξ_b^0	$1/2^+$	***
$N(1860)$	$5/2^+$	**	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1880)$	$1/2^+$	**	Ξ_c^0	$1/2^+$	****	$\Xi_b'(5935)^-$	$1/2^+$	***
$N(1875)$	$3/2^-$	***	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1900)$	$1/2^-$	**	$\Xi_c'^+$	$1/2^+$	***	$\Xi_b(5945)^0$	$3/2^+$	***
$N(1880)$	$1/2^+$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1910)$	$3/2^-$	***	$\Xi_c'^0$	$1/2^+$	***	$\Xi_b(5955)^-$	$3/2^+$	***
$N(1895)$	$1/2^-$	****	$\Delta(2200)$	$7/2^-$	***	$\Sigma(1915)$	$5/2^+$	****	$\Xi_c(2645)$	$3/2^+$	***	$\Xi_b(6100)^-$	$3/2^-$	***
$N(1900)$	$3/2^+$	****	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1940)$	$3/2^+$	*	$\Xi_c(2790)$	$1/2^-$	***	$\Xi_b(6227)^-$		***
$N(1990)$	$7/2^+$	**	$\Delta(2350)$	$5/2^-$	*	$\Sigma(2010)$	$3/2^-$	*	$\Xi_c(2815)$	$3/2^-$	***	$\Xi_b(6227)^0$		***
$N(2000)$	$5/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(2030)$	$7/2^+$	****	$\Xi_c(2923)$		**	Ω_b^-	$1/2^+$	***
$N(2040)$	$3/2^+$	*	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2070)$	$5/2^+$	*	$\Xi_c(2930)$		**	$\Omega_b(6316)^-$		*
$N(2060)$	$5/2^-$	***	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2080)$	$3/2^+$	*	$\Xi_c(2970)$	$1/2^+$	***	$\Omega_b(6330)^-$		*
$N(2100)$	$1/2^+$	***	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2100)$	$7/2^-$	*	$\Xi_c(3055)$		***	$\Omega_b(6340)^-$		*
$N(2120)$	$3/2^-$	***	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2110)$	$1/2^-$	*	$\Xi_c(3080)$		***	$\Omega_b(6350)^-$		*
$N(2190)$	$7/2^-$	****				$\Sigma(2230)$	$3/2^+$	*	$\Xi_c(3123)$		*			
$N(2220)$	$9/2^+$	****	Λ	$1/2^+$	****	$\Sigma(2250)$		**	Ω_c^0	$1/2^+$	***	$P_c(4312)^+$		*
$N(2250)$	$9/2^-$	****	$\Lambda(1380)$	$1/2^-$	**	$\Sigma(2455)$		*	$\Omega_c(2770)^0$	$3/2^+$	***	$P_c(4380)^+$		*
$N(2300)$	$1/2^+$	**	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2620)$		*	$\Omega_c(3000)^0$		***	$P_c(4440)^+$		*
$N(2570)$	$5/2^-$	**	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(3000)$		*	$\Omega_c(3050)^0$		***	$P_c(4457)^+$		*
$N(2600)$	$11/2^-$	***	$\Lambda(1600)$	$1/2^+$	****	$\Sigma(3170)$		*	$\Omega_c(3065)^0$		***			
$N(2700)$	$13/2^+$	**	$\Lambda(1670)$	$1/2^-$	****				$\Omega_c(3090)^0$		***			
			$\Lambda(1690)$	$3/2^-$	****	Ξ^0	$1/2^+$	****	$\Omega_c(3120)^0$		***			
			$\Lambda(1710)$	$1/2^+$	*	Ξ^-	$1/2^+$	****						
			$\Lambda(1800)$	$1/2^-$	***	$\Xi(1530)$	$3/2^+$	****	Ξ_{cc}^+		*			
			$\Lambda(1810)$	$1/2^+$	***	$\Xi(1620)$		*	Ξ_{cc}^{++}		***			
			$\Lambda(1820)$	$5/2^+$	****	$\Xi(1690)$		***						
			$\Lambda(1830)$	$5/2^-$	****	$\Xi(1820)$	$3/2^-$	***						
			$\Lambda(1890)$	$3/2^+$	****	$\Xi(1950)$		***						
			$\Lambda(2000)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}$?	***						
			$\Lambda(2050)$	$3/2^-$	*	$\Xi(2120)$		*						
			$\Lambda(2070)$	$3/2^+$	*	$\Xi(2250)$		**						
			$\Lambda(2100)$	$7/2^-$	****	$\Xi(2370)$		**						
			$\Lambda(2110)$	$5/2^+$	***	$\Xi(2500)$		*						
			$\Lambda(2325)$	$3/2^-$	*									
			$\Lambda(2350)$	$9/2^+$	***	$\Omega(2250)^-$		***						
			$\Lambda(2585)$		*	$\Omega(2380)^-$		**						
						$\Omega(2470)^-$		**						

~180 baryons





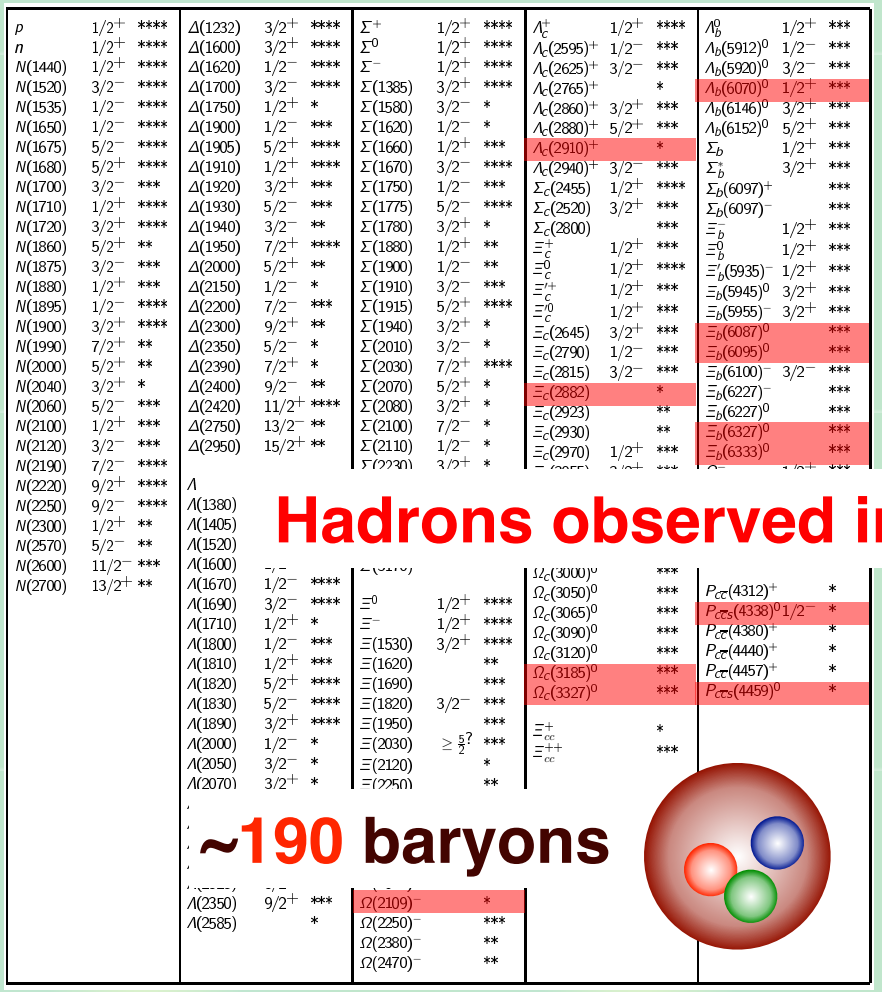
~220 mesons

All ~ 400 hadrons basically emerge as qqq or $q\bar{q}$

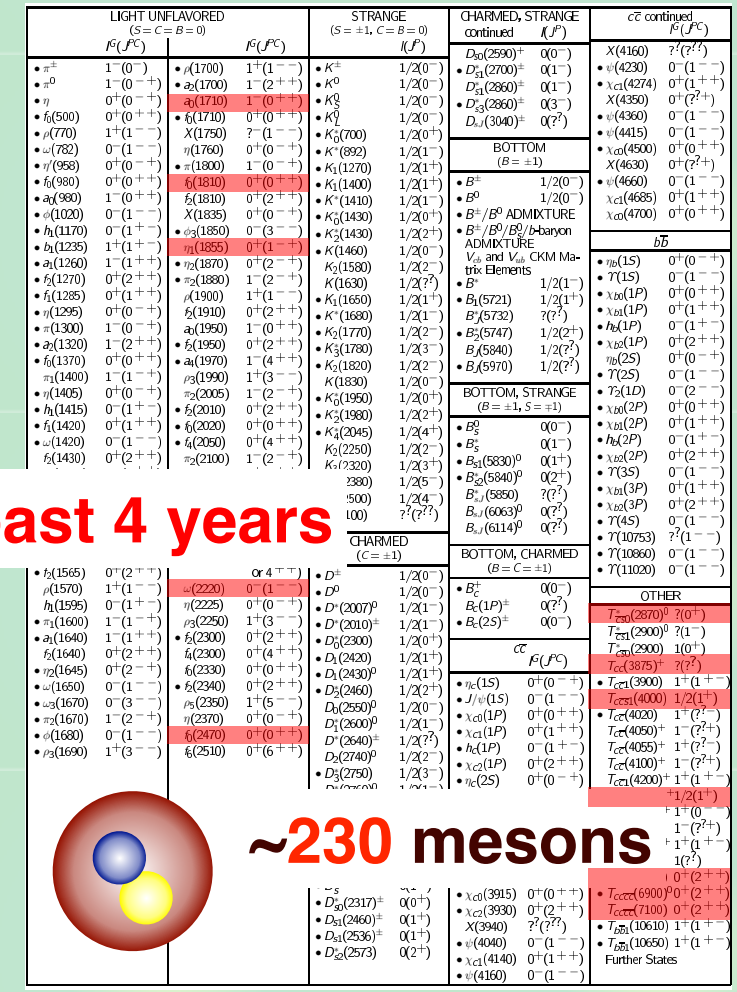
Observed hadrons (2026)

Particle Data Group (PDG) 2026 edition

http://pdg.lbl.gov/



Hadrons observed in past 4 years



~190 baryons

~230 mesons

New states are continuously discovered

Exotic hadrons

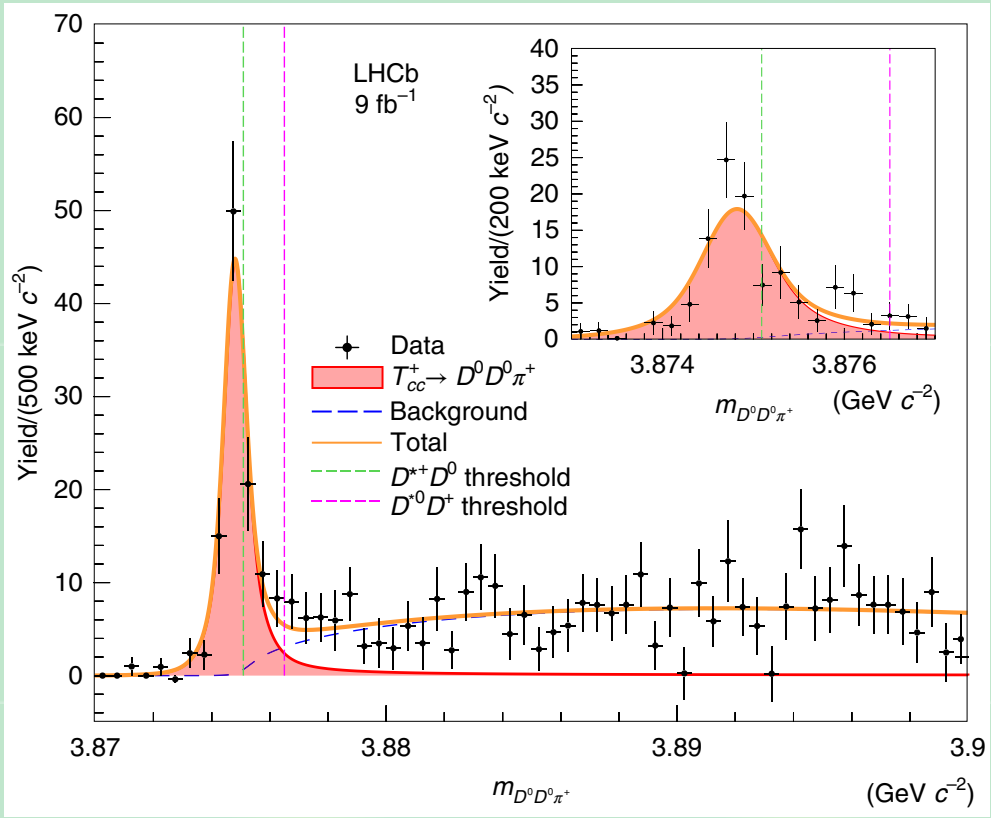
Observation of tetraquark T_{cc}

LHCb collaboration, Nature Phys. 18, 7, 751 (2022); Nature Commun. 13, 1, 3351 (2022)

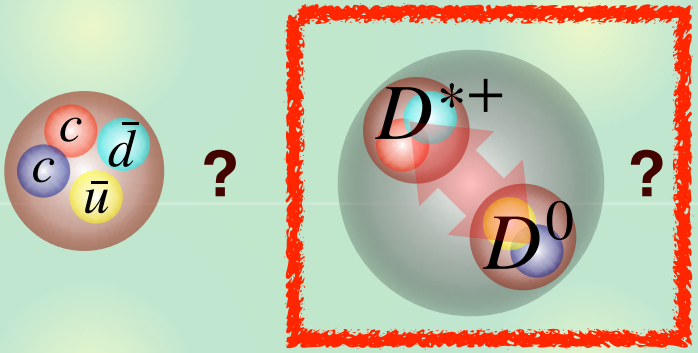
nature physics
LETTERS
https://doi.org/10.1038/s41567-022-01614-y
Check for updates
OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*



- Quark content $\sim cc\bar{u}\bar{d}$
- Internal structure?



Hadronic molecules <— hadron interactions

F. K. Guo, *et al.*, Rev. Mod. Phys. 90, 072501 (2018)

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  - K^-p correlation functions

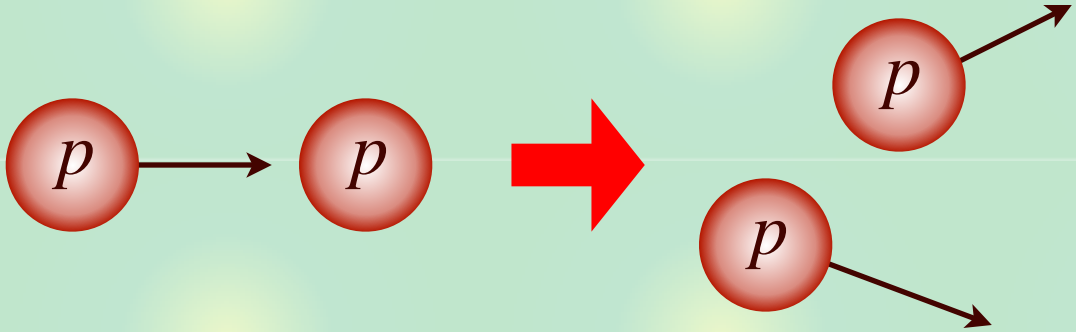
    Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)
- Summary

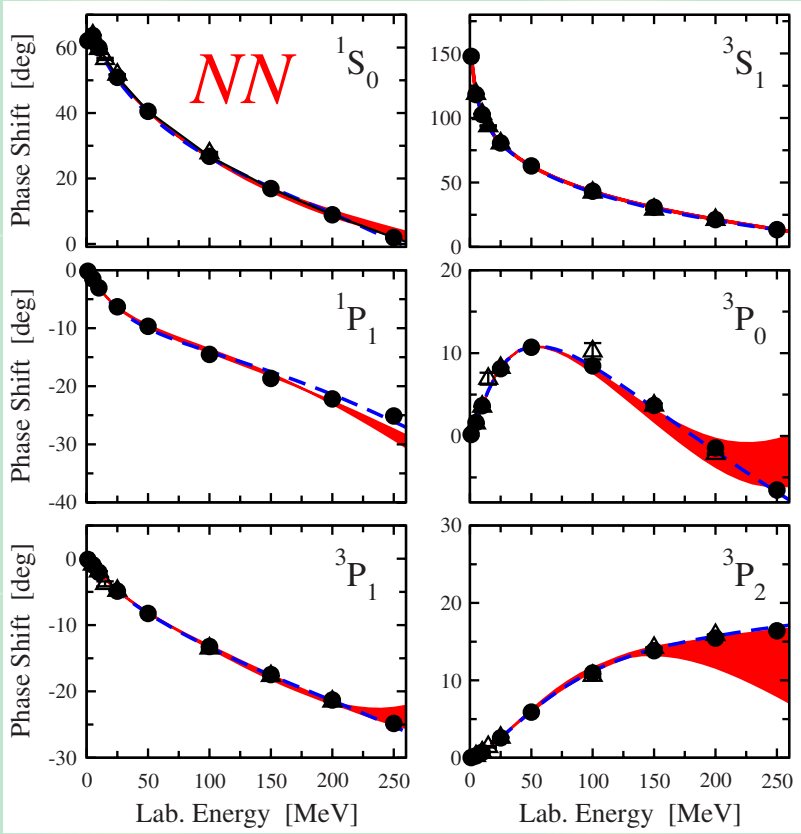
Study of hadron interactions

Traditional methods: scattering experiments

- differential cross sections -> phase shift

E. Epelbaum, H.W. Hammer, U.-G Meißner RMP 81, 1773 (2009)





Problems

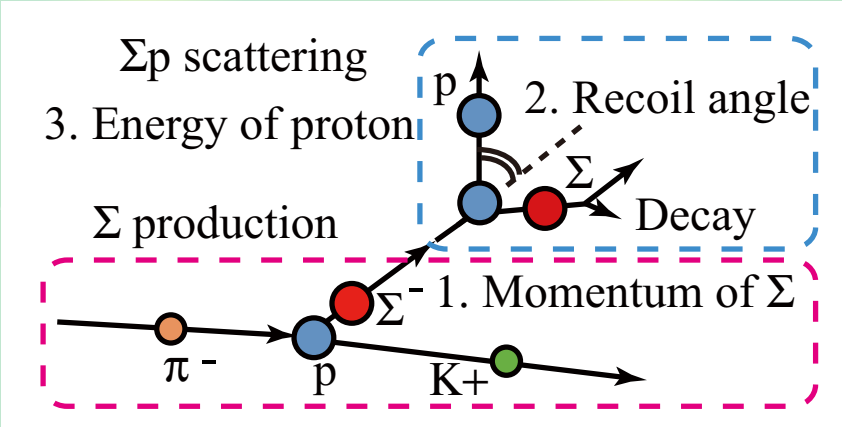
- Stable beam/target particles
- Limited channels: $pp, \pi^{\pm}p, K^{\pm}p, \cdots$
- Heavy (c, b) hadrons: impossible
- Limited statistics (low-energy region)

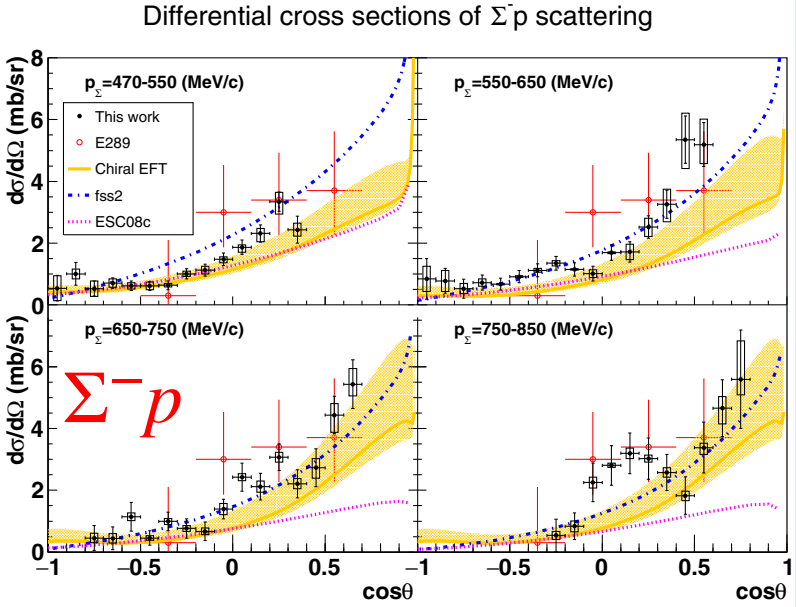
New developments

$\Sigma^- p$ scattering (J-PARC E40)

K. Miwa, *et al.*, J-PARC E40, PRC 104, 045204 (2021); PRL 128, 072501 (2022)

- high intencity π beam

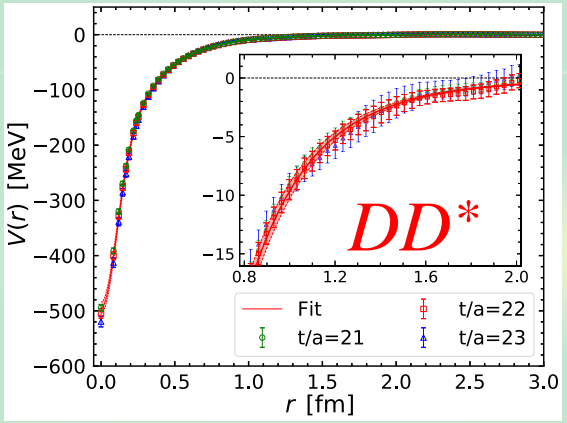




Lattice QCD (HAL QCD)

Y. Liu, *et al.*, HAL QCD, PRL 131, 161901 (2023)

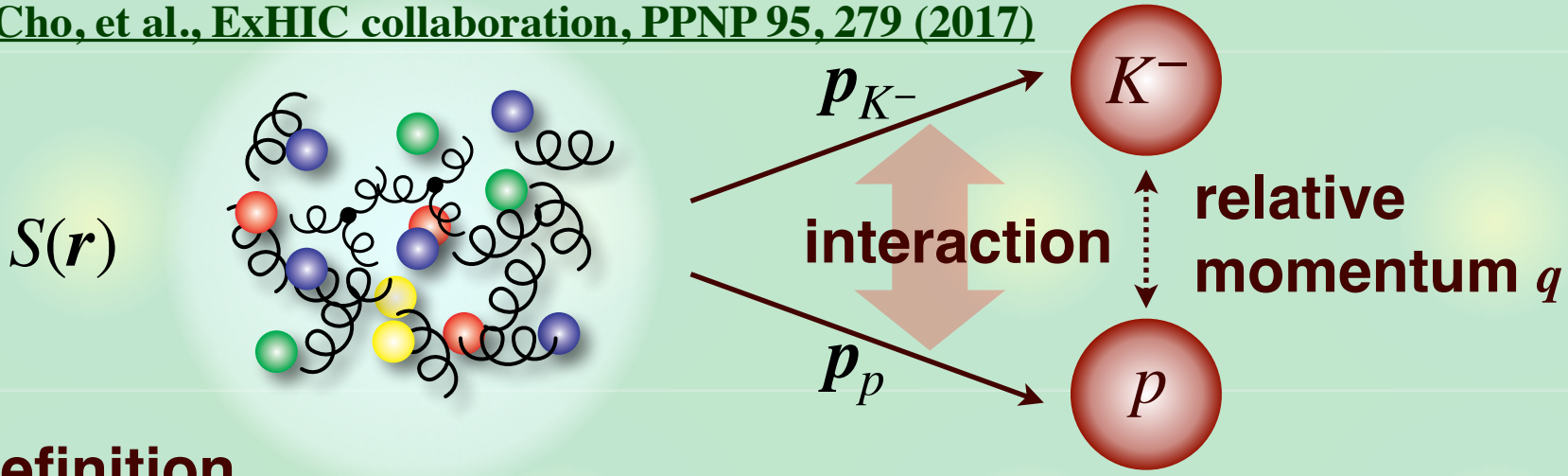
- First principle QCD calculation
- Hadron-hadron potential for T_{cc}



Femtoscopy : Correlation function

High-energy collision: chaotic source $S(r)$ of hadron emission

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



- Definition

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

- Theory (Koonin-Pratt formula)

S.E. Koonin, PLB 70, 43 (1977); S. Pratt, PRD 33, 1314 (1986)

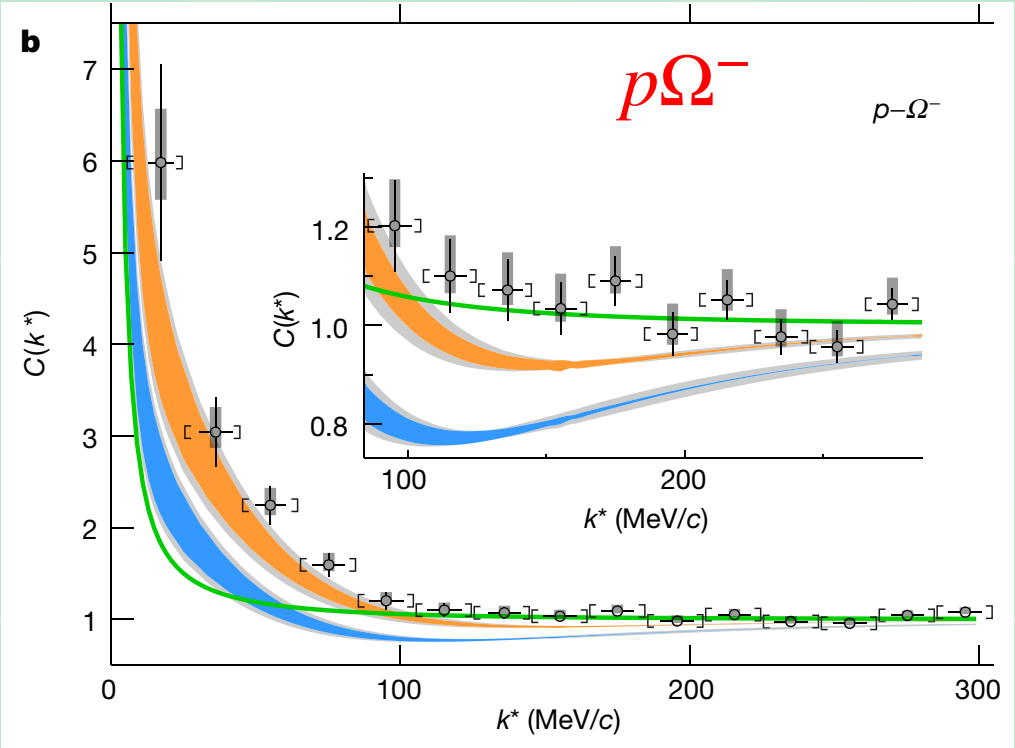
$$C(q) \simeq \int d^3r\, S(r)\, |\Psi_q^{(-)}(r)|^2$$

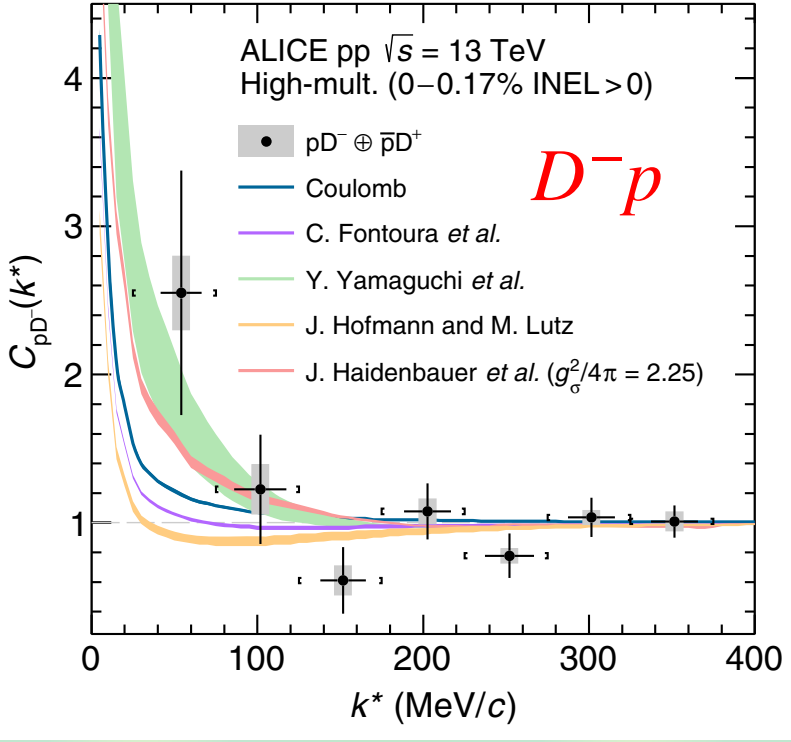
Source function $S(r)$ <—> wave function $\Psi_q^{(-)}(r)$ (interaction)

Experimental data in charm sector

Correlation functions observed by ALICE@LHC

ALICE collaboration, Nature 588, 232 (2020);
ALICE collaboration, PRD 106, 052010 (2022)





$\Omega^- \sim sss$: **strangeness** $S = -3$, $D^- \sim \bar{c}d$: **charm** $C = -1$

Almost impossible in scattering experiments

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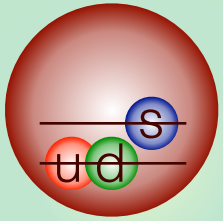
  - Femtoscopy for K^-p correlation functions

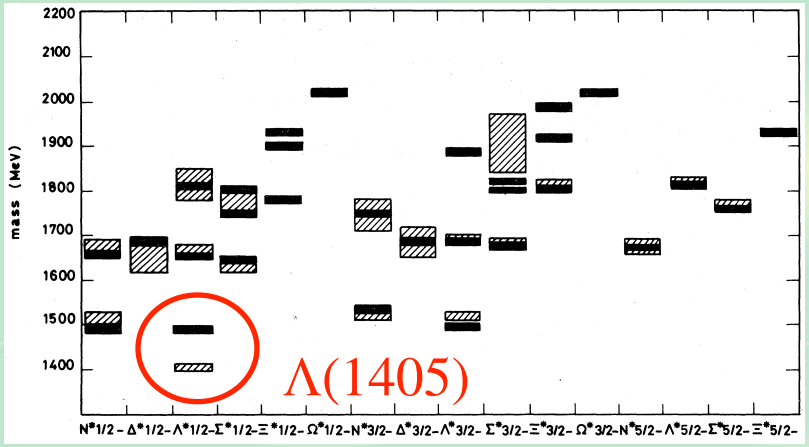
    Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)
- Summary

$\Lambda(1405)$ and K^-p scattering

$\Lambda(1405)$ does not fit in standard picture —> exotic candidate

N. Isgur and G. Karl, PRD18, 4187 (1978)



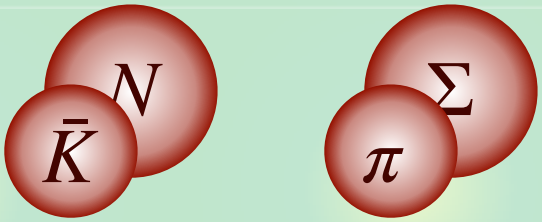


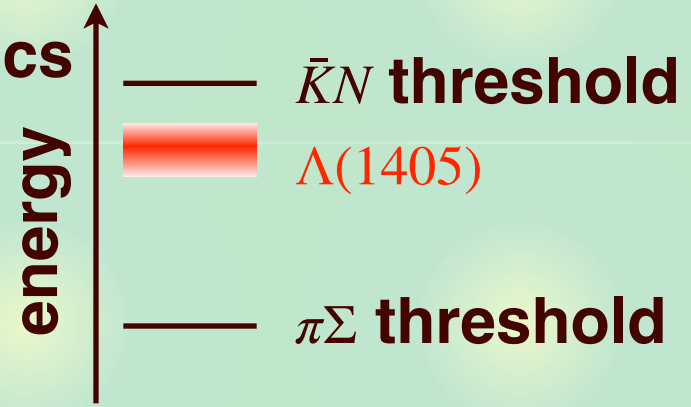
: theory

: experiment

Resonance in coupled-channel scattering

- Coupling to MB: chiral SU(3) dynamics





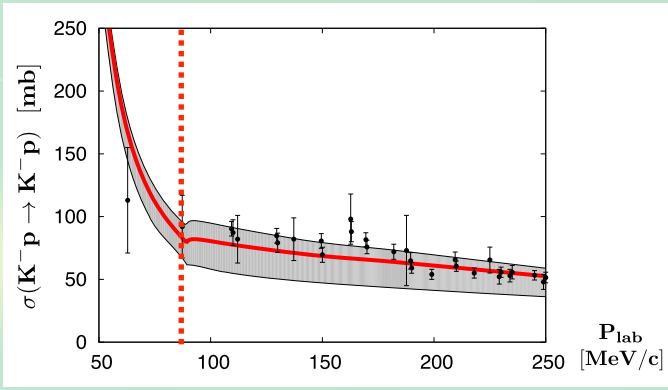
T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)

Scattering experiments and femtoscopy

K^-p scattering data

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

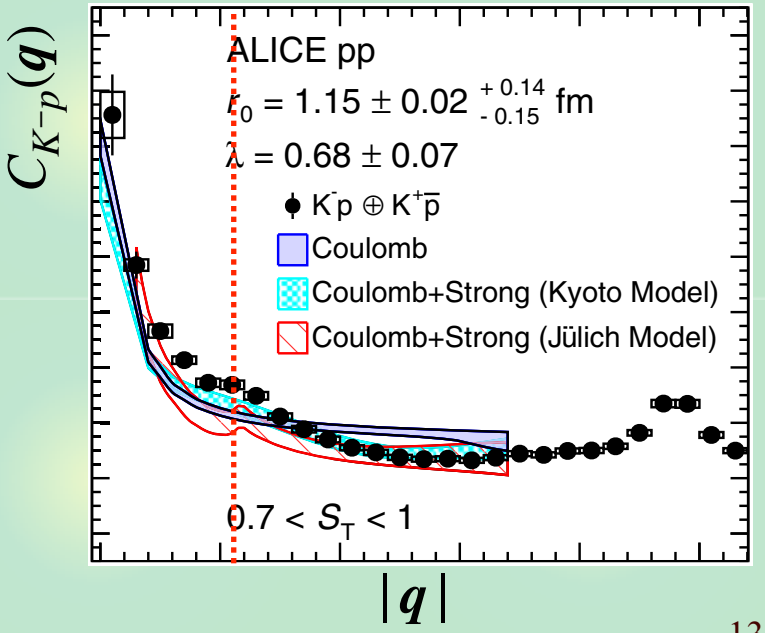
- Old bubble chamber experiments
- Limited statistics (low-energy)



Femtoscopy: correlation function

ALICE collaboration, PRL 124, 092301 (2020)

- Excellent precision ($\bar{K}^0n$ cusp)
- Data below $\bar{K}^0n$ threshold



Important constraints on $\Lambda(1405)$

Coupled-channel effects

Coupled-channel Schrödinger equation (s-wave)

$$\begin{pmatrix} \frac{-1}{2\mu_1}\frac{d^2}{dr^2} + V_{11}(r) + V_C(r) & V_{12}(r) & \cdots \\ V_{21}(r) & \frac{-1}{2\mu_2}\frac{d^2}{dr^2} + V_{22}(r) + \Delta_2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} = E \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix}$$

Coulomb — threshold energy difference

Coupled-channel Koonin-Pratt formula

R. Lednicky, V.V. Lyuboshitz, V.L. Lyuboshitz, Phys. Atom. Nucl. 61, 2950 (1998);
J. Haidenbauer, NPA 981, 1 (2019);
Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

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

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

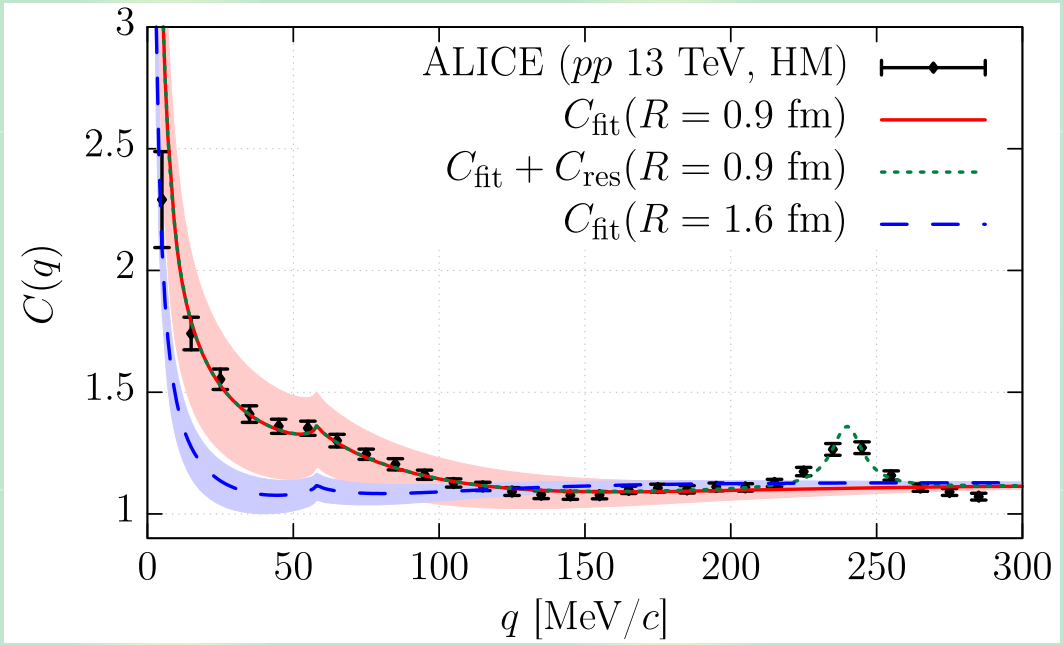
Correlation from chiral SU(3) dynamics

Wave function $\Psi^{(-)}_{i,q}(r)$: Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

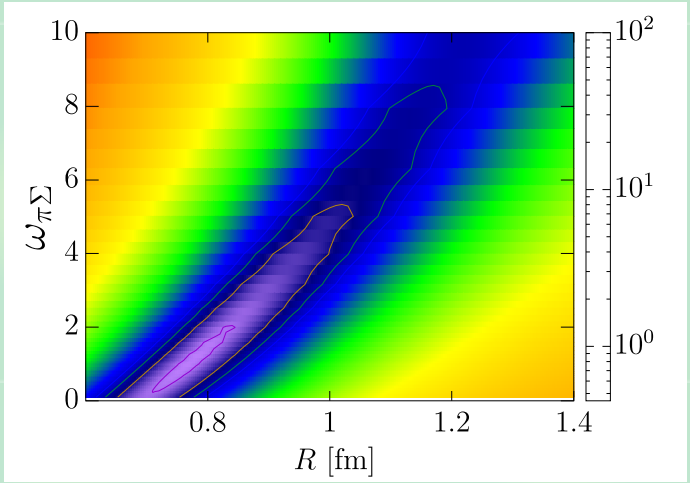
K. Miyahara, T. Hyodo, W. Weise, PRC98, 025201 (2018)

- Source function $S(r)$: gaussian, $R \sim 1$ fm from 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 is well reproduced by chiral SU(3) potential

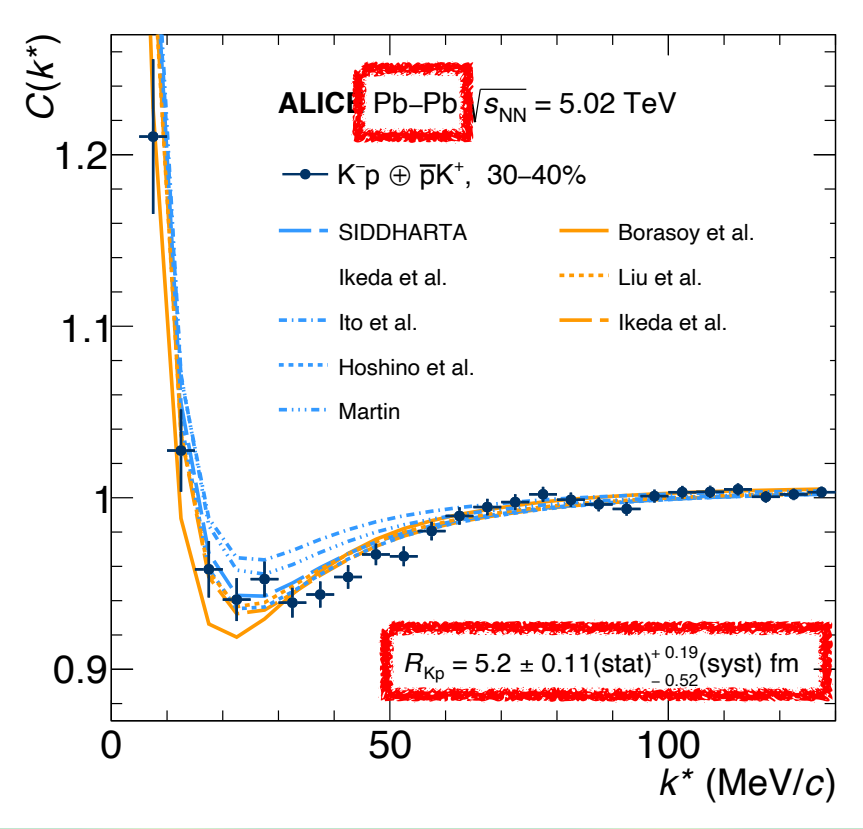
Applications: K^-p correlations for $\Lambda(1405)$

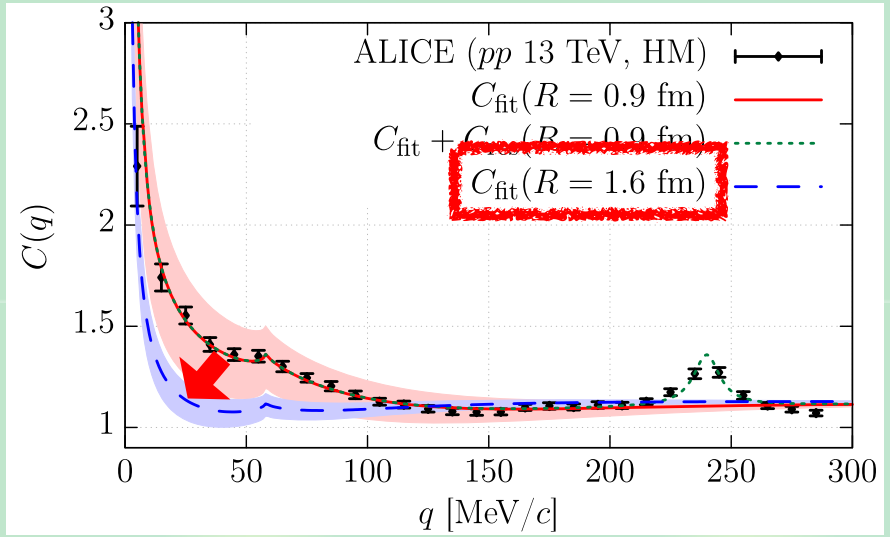
Large source case

New data with Pb-Pb collisions at 5.02 TeV

ALICE collaboration, PLB 822, 136708 (2021)

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





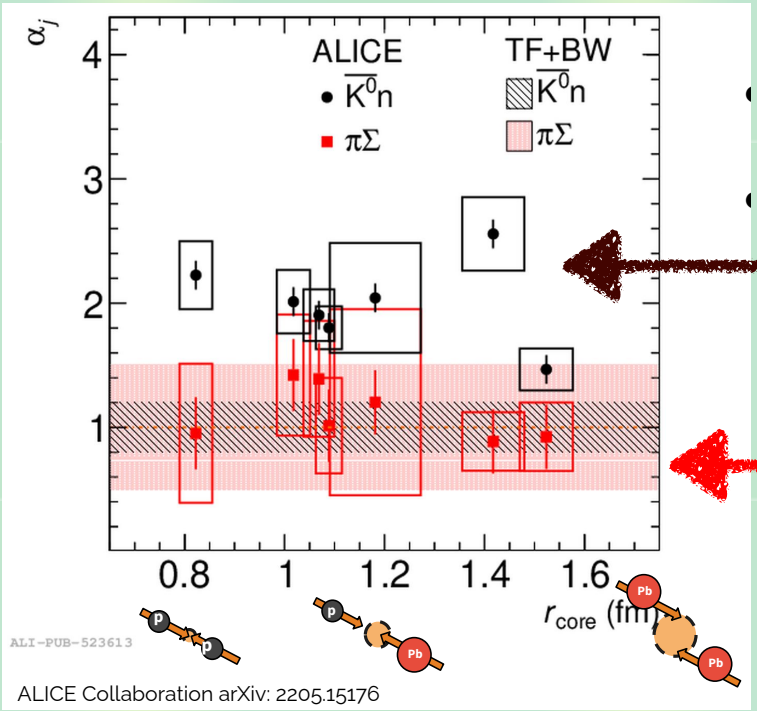
Correlation is suppressed at larger R, as predicted

Systematic study of source size dependence

Correlations in pp, p-Pb, Pb-Pb by Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

ALICE collaboration, EPJC 83, 340 (2023)

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



ALICE Collaboration arXiv: 2205.15176

ω_i: expected weight by Thermal Fist + Blast Wave

enhancement needed to explain data

expected weight is OK

More strength is needed in the $\bar{K}^0n$ channel

Summary

- Hadron interactions —> hadronic molecules
- Femtoscopy: novel method to study hadron interactions
- Coupled-channel K^-p interaction and $\Lambda(1405)$
  - Prototype of hadronic molecule

  T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)
- Femtoscopy for K^-p correlation functions
  - Precise test for $\Lambda(1405)$ and K^-p interactions

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