Theoretical status of antikaon-nucleon interactions


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Tokyo Metropolitan Univ.

2023, Jun. 26th

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Contents

$\Lambda(1405)$ and $\bar{K}N$ interactions

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
T. Hyodo, M. Niiyama, PPNP 120, 103868 (2021);
T. Hyodo, W. Weise, arXiv:2202.06181 [nucl-th] (Handbook of Nuclear Physics)

- Recent developments

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Talk by D. Mohler on 22nd June

K^-p femtoscopy

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL 124, 132501 (2020)

- Experimental data

ALICE collaboration, PRL 124, 092301 (2020); PLB 822, 136708 (2021);
EPJC 83, 340 (2023)

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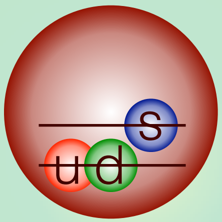
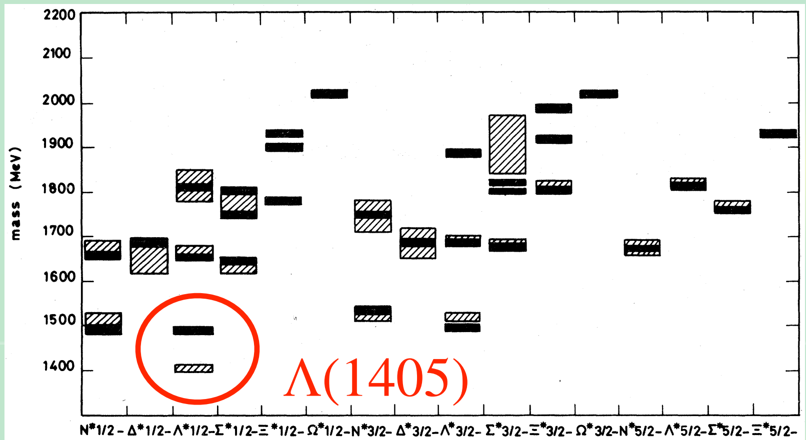
Summary

$\Lambda(1405)$ and $\bar{K}N$ scattering

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

N. Isgur and G. Karl, PRD 18, 4187 (1978)





: theory

: experiment

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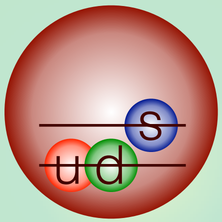
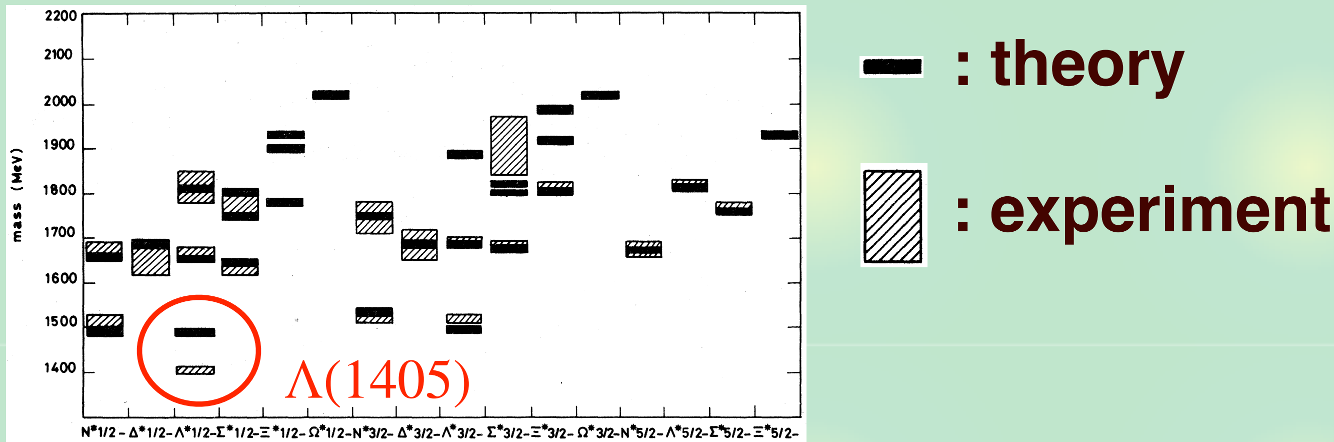
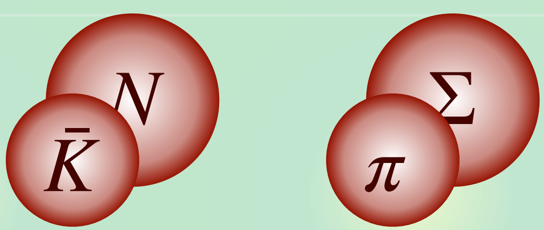
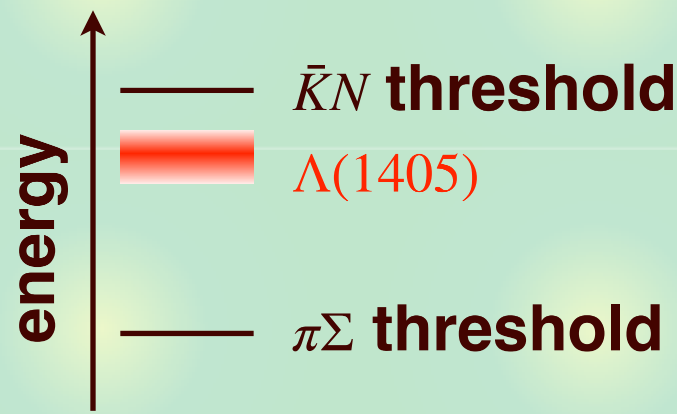




Resonance in coupled-channel scattering

- Coupling to MB states





Detailed analysis of $\bar{K}N$-$\pi\Sigma$ scattering is necessary

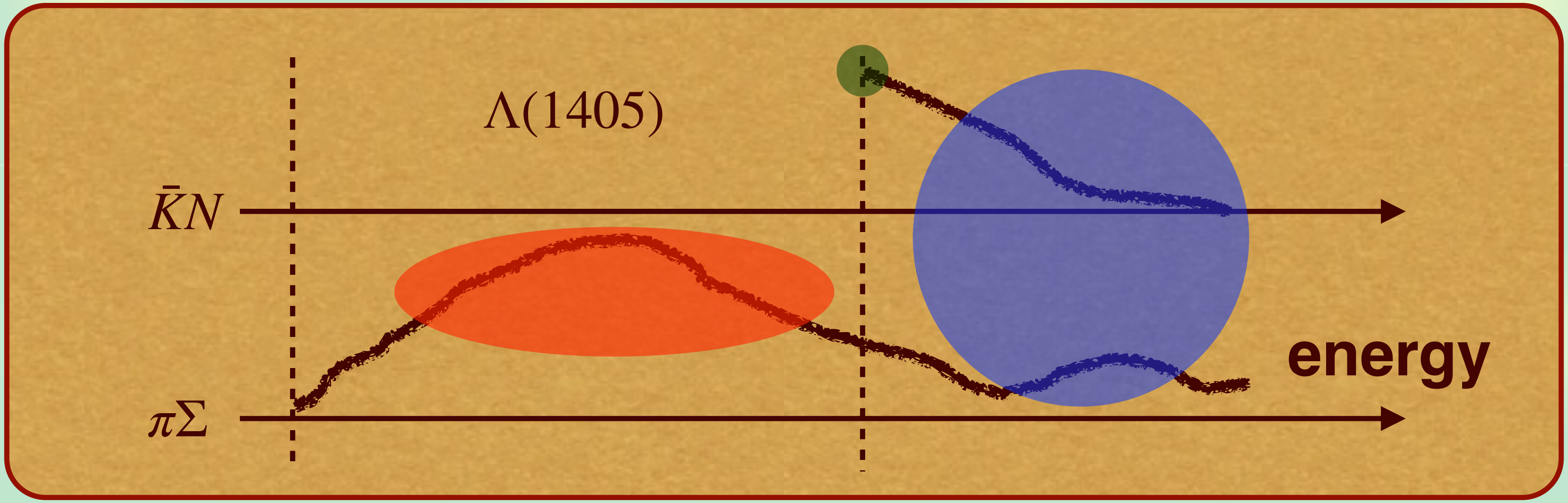
Strategy for $\bar{K}N$ interaction

Above the $\bar{K}N$ threshold : direct constraints

- K^-p **total cross sections** **(old data)**
- $\bar{K}N$ **threshold branching ratios (old data)**
- K^-p **scattering length (new data : SIDDHARTA)**

Below the $\bar{K}N$ threshold: indirect (reaction model needed)

- $\pi\Sigma$ **mass spectra** **(LEPS, CLAS, HADES, J-PARC, …)**



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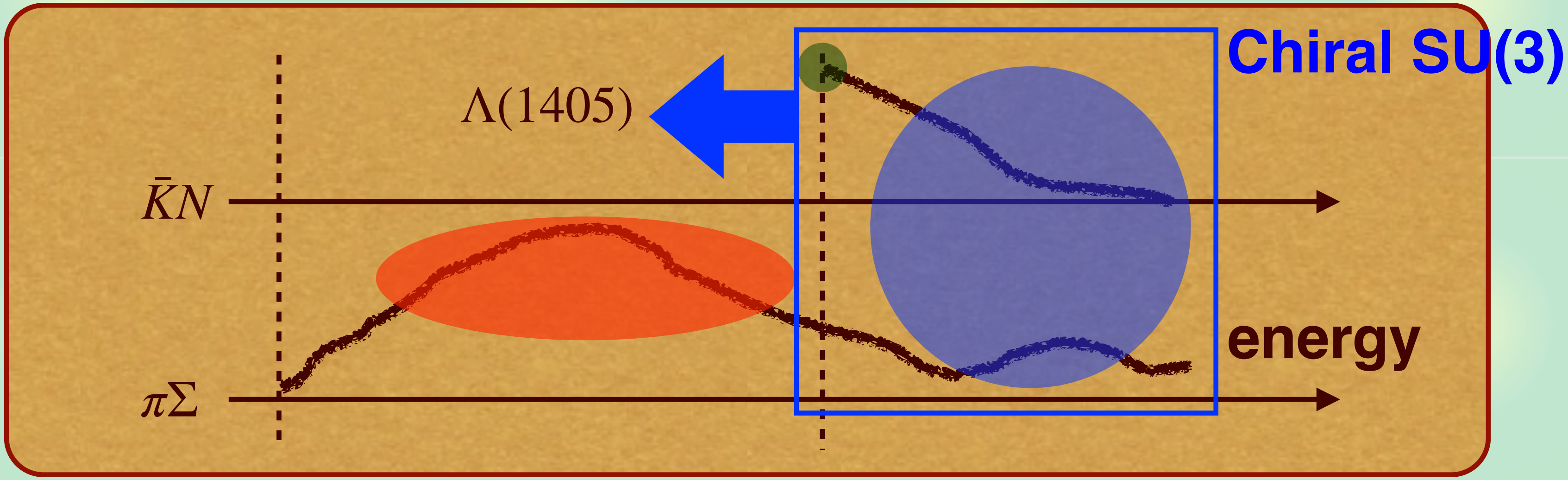


Best-fit results by chiral SU(3) dynamics

K at rest

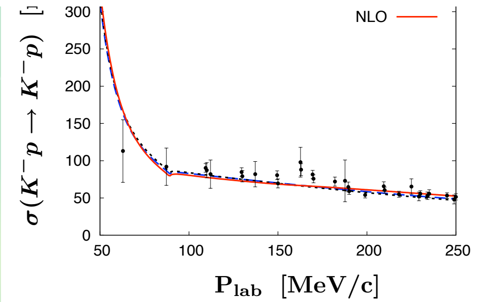
	TW	TWB	NLO	Experiment	
ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
χ^2/d.o.f	1.12	1.15	0.96		

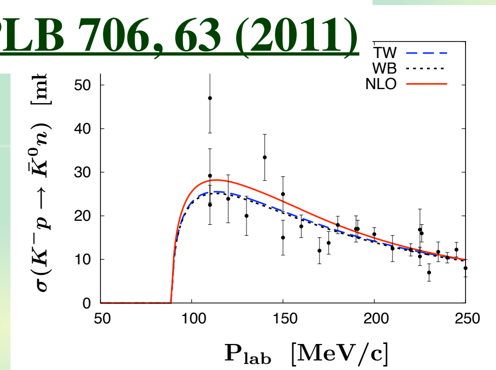
} **SIDDHARTA** (ΔE, Γ)

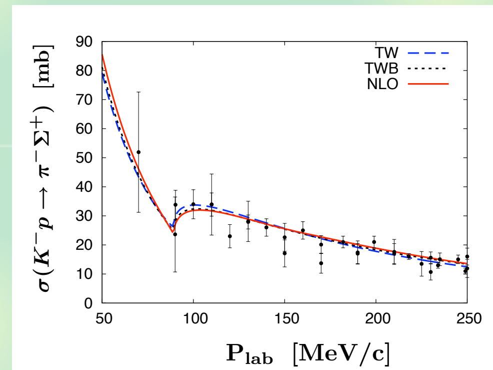
} **Branching ratios** (γ, R_n, R_c)

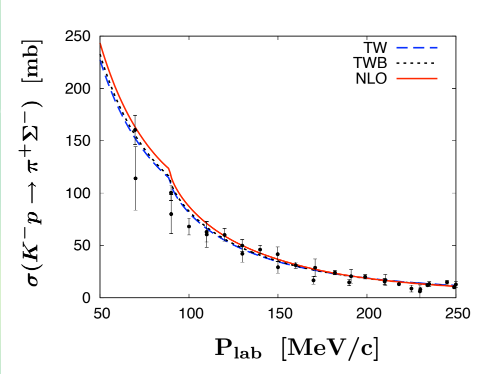
Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

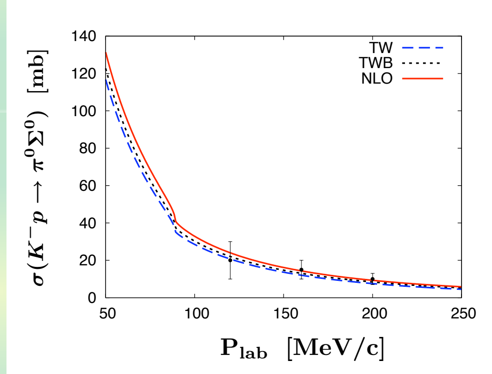
K^-p cross sections

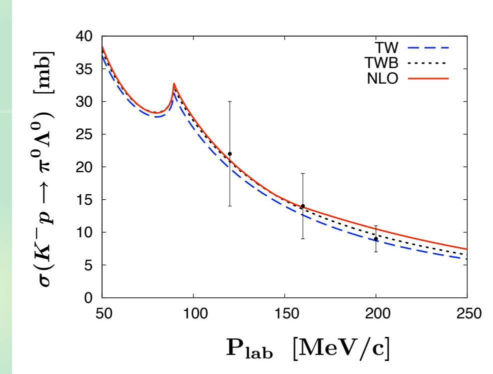












Accurate description of all existing data (χ^2/d.o.f ~ 1)

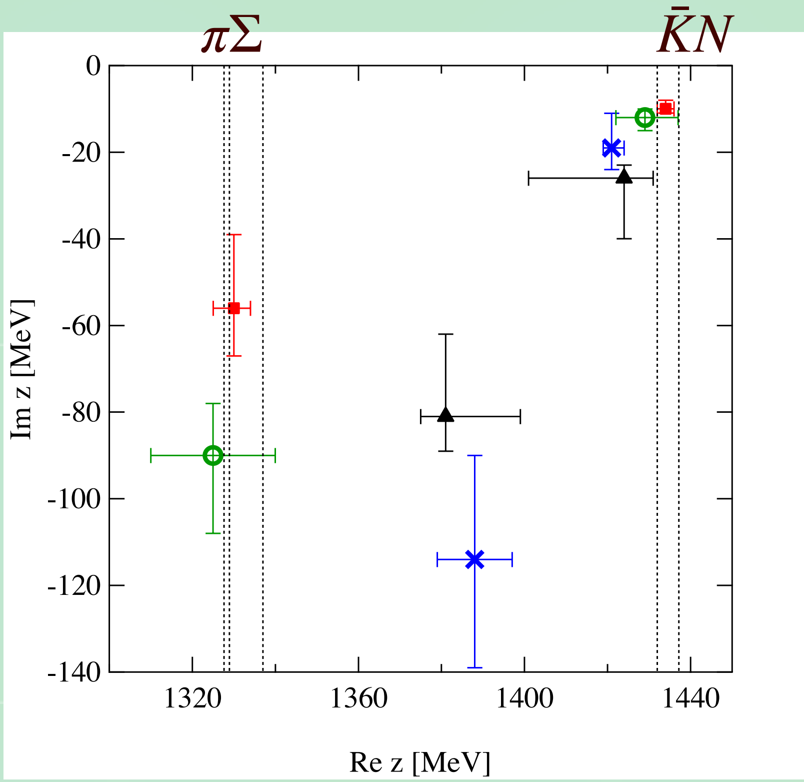
PDG has changed

2020 update of PDG

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012); ▲

Z.H. Guo, J.A. Oller, PRC 87, 035202 (2013); ×

M. Mai, U.G. Meißner, EPJA 51, 30 (2015) ■ ○



T. Hyodo, M. Niiyama, PPNP 120, 103868 (2021)

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- **Particle Listing section:**

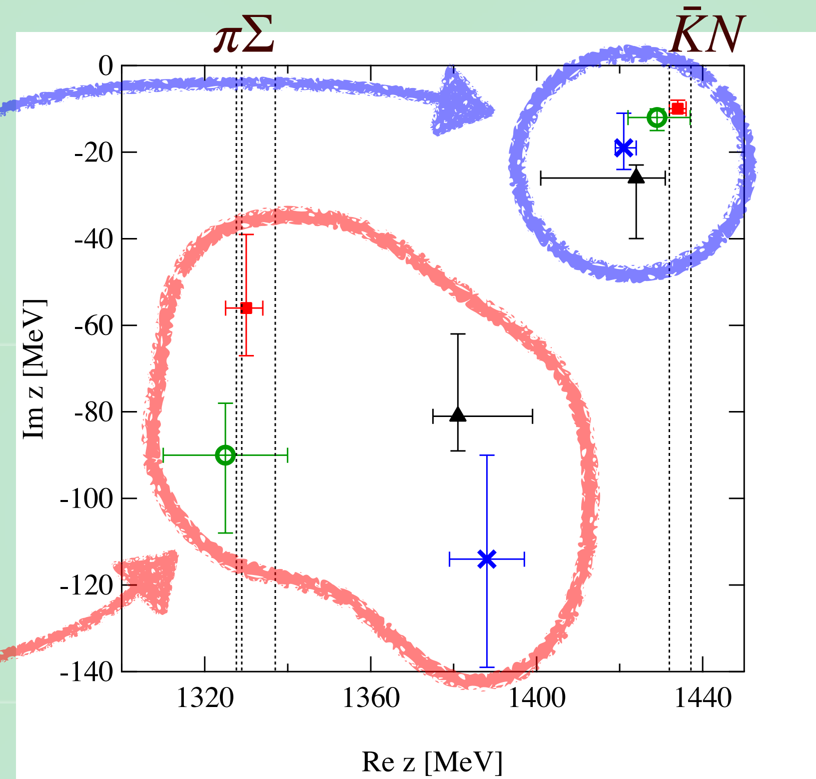
Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\boxed{\Lambda(1405)\ 1/2^-}$ $I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\boxed{\Lambda(1380)\ 1/2^-}$ $J^P = \frac{1}{2}^-$ Status: ∗∗

new!



T. Hyodo, M. Niiyama, PPNP 120, 103868 (2021)

- "$\Lambda(1405)$" is no longer at 1405 MeV but ~ 1420 MeV.

- Lower pole : two-star resonance $\Lambda(1380)$

Construction of $\bar{K}N$ potentials

Local $\bar{K}N$ potential is useful for various applications

meson-baryon amplitude
(chiral SU(3) EFT)

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

Kyoto $\bar{K}N$ potential
(single-channel, complex)

K. Miyahara. T. Hyodo,
PRC 93, 015201 (2016)

Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential
(coupled-channel, real)

K. Miyahara, T. Hyodo, W. Weise,
PRC 98, 025201 (2018)

Kaonic nuclei

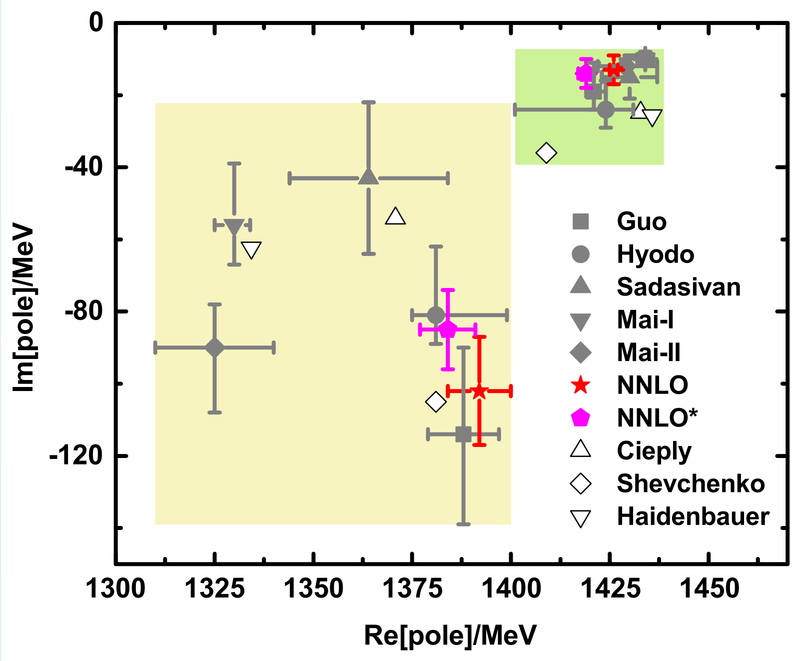
Kaonic deuterium

$K^{-}p$ correlation function

NNLO analysis

New analysis at NNLO! (KN and πN included)

J.-X. Lu, L.S. Geng, M. Doering, M. Mai, PRL 130, 071902 (2023)



	Pole positions (MeV)
$\Lambda(1380)$	$1392 \pm 8 - i(102 \pm 15)$
$\Lambda(1405)$	$1425 \pm 1 - i(13 \pm 4)$

Two poles are confirmed at NNLO

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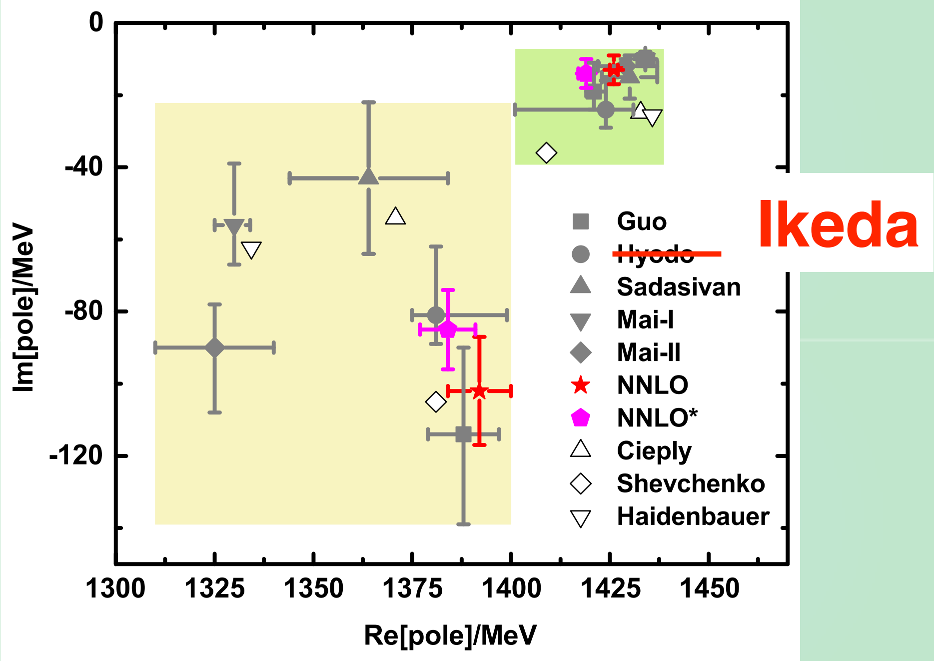

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$\Lambda(1380)$	$1392 \pm 8 - i(102 \pm 15)$
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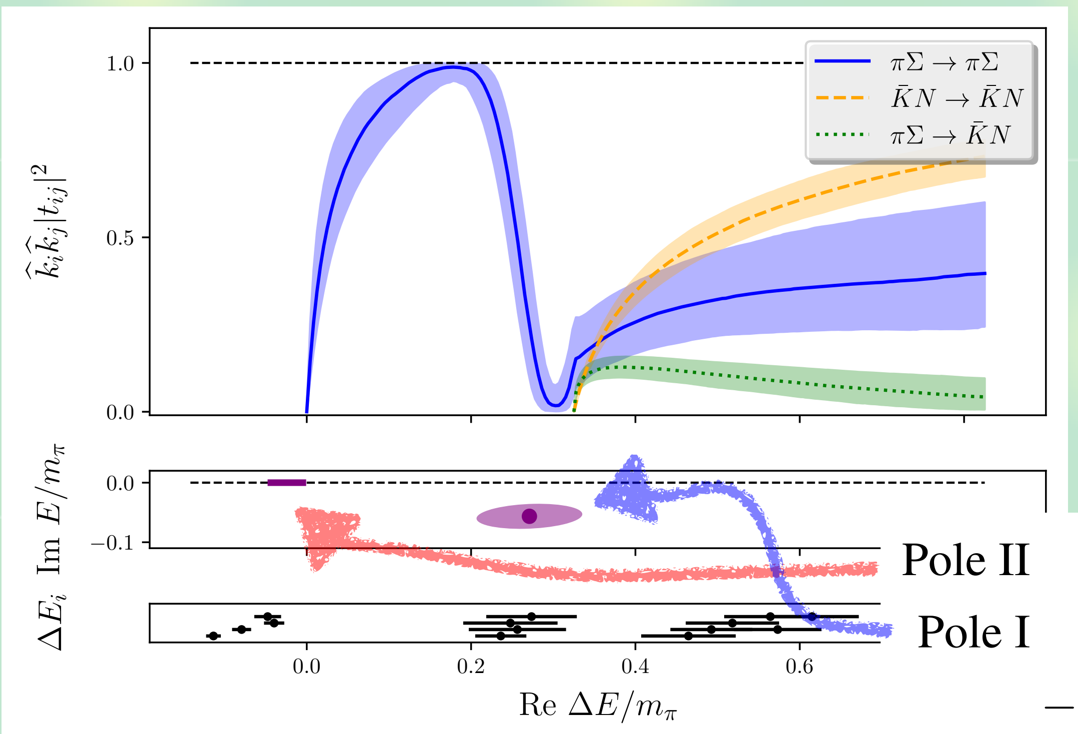
Two poles are confirmed at NNLO

Coupled-channel scattering by lattice QCD

Lattice calculation of $\bar{K}N$-$\pi\Sigma$ scattering

Talk by D. Mohler on 22nd June

a [fm]	$T \times L^3$	m_π [MeV]	m_K [MeV]	$m_\pi L$	N_{cnfg}
0.0633(4)(6)	128×64^3	200	480	4.3	2000



Pole II	$1395(9)_{\mathrm{stat}}(2)_{\mathrm{model}}(16)_{\mathrm{a}}$ MeV
Pole I	$1456(14)_{\mathrm{stat}}(2)_{\mathrm{model}}(16)_{\mathrm{a}}$ MeV
	$-\,i \times 11.7(4.3)_{\mathrm{stat}}(4)_{\mathrm{model}}(0.1)_{\mathrm{a}}$ MeV

Two poles are found on the lattice

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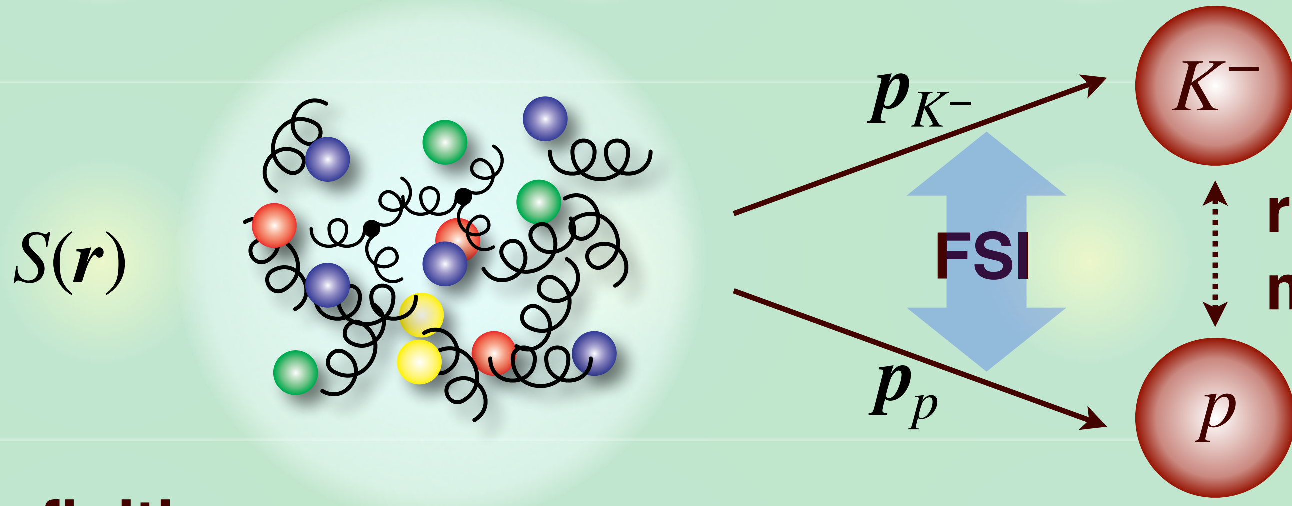
Correlation function and hadron interaction

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)**

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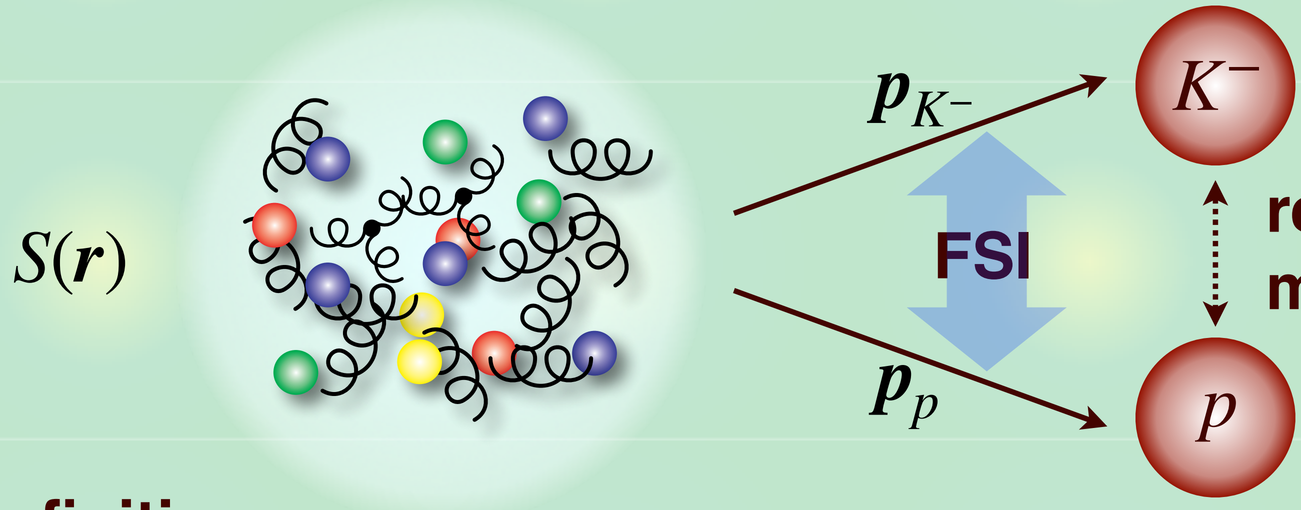

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- Theory (Koonin-Pratt formula)

S.E. Koonin PLB 70, 43 (1977); S. Pratt, PRD 33, 1314 (2986)

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

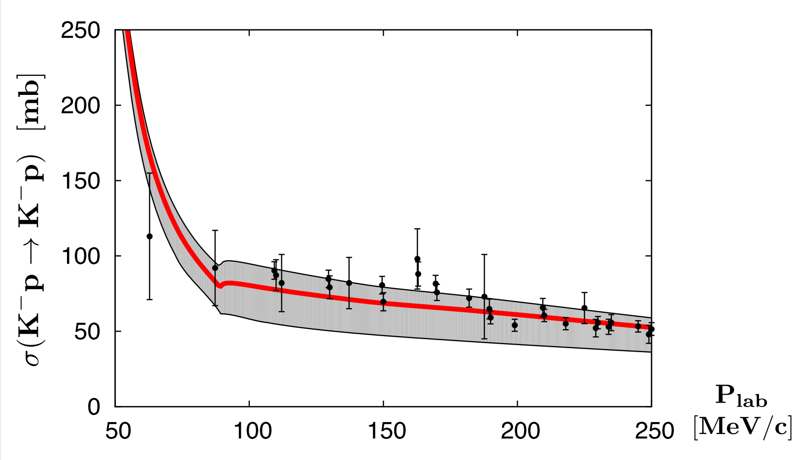
Source function $S(\boldsymbol{r})$ <—> wave function $\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})$ (FSI)

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



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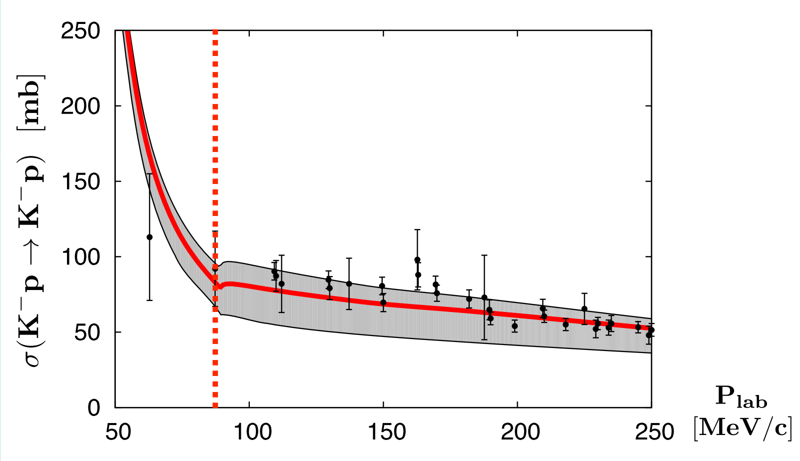
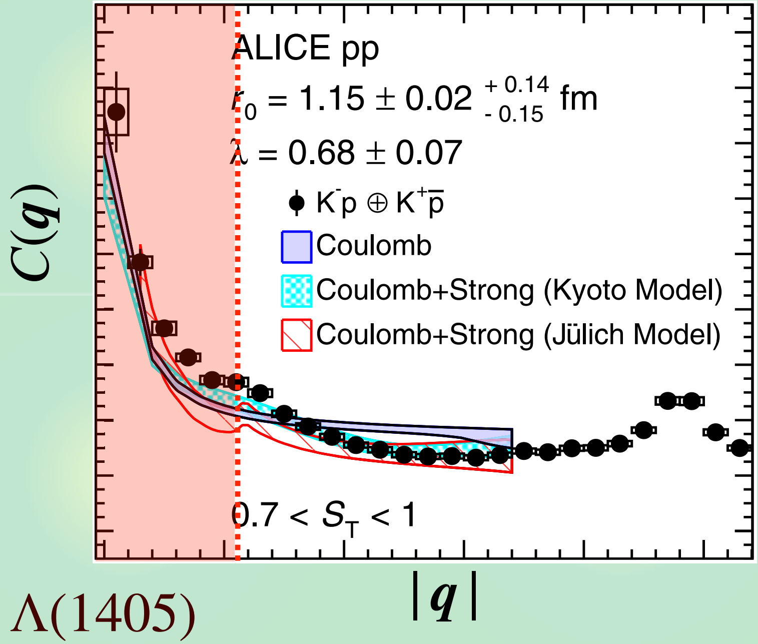


$K^- p$ correlation function

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 effects

Schrödinger equation (s-wave)

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

Coulomb threshold energy difference

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Coulomb threshold energy difference

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

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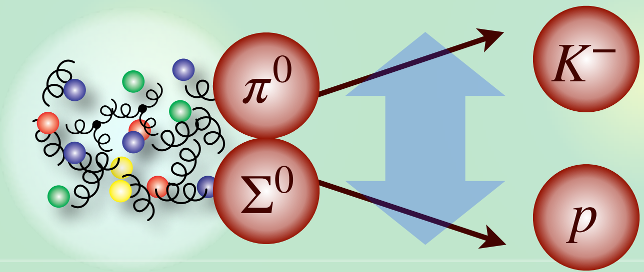
incoming + outgoing

- Transition from $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$ is in $\psi_i(r)$ with $i \neq K^-p$



Coupled-channel correlation function

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)

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

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

- **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

Coupled-channel correlation function

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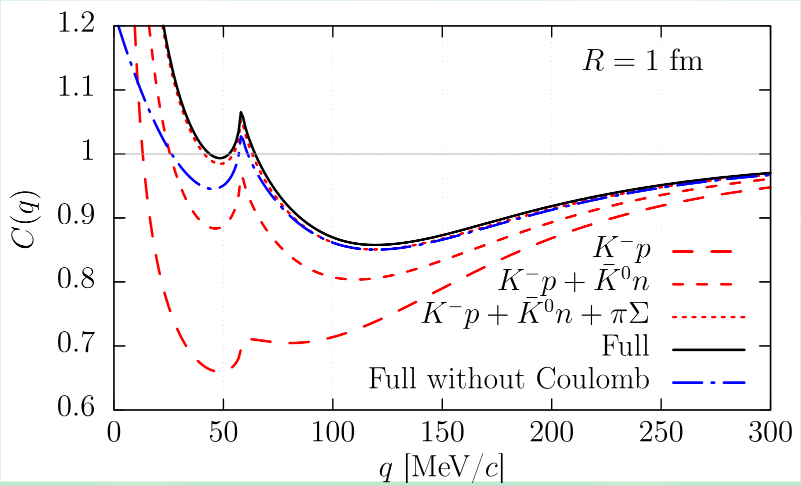
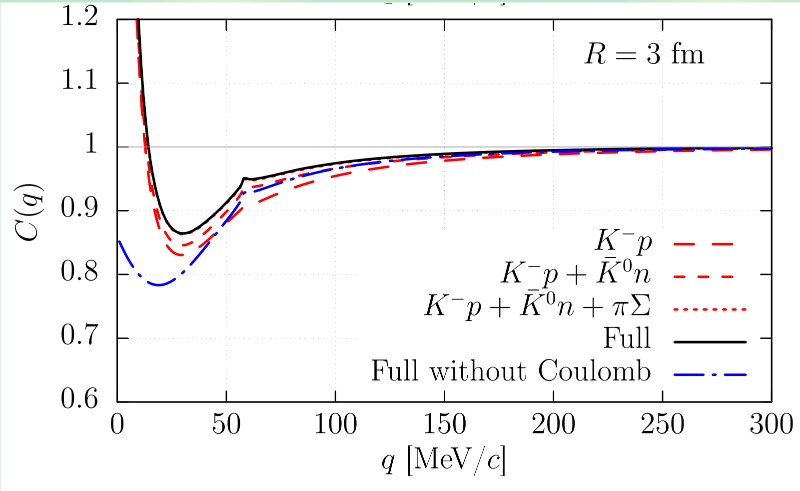
- **Transition** from $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$
- ω_i : weight of source channel i relative to $K^- p$





Coupled-channel effect is enhanced for small sources

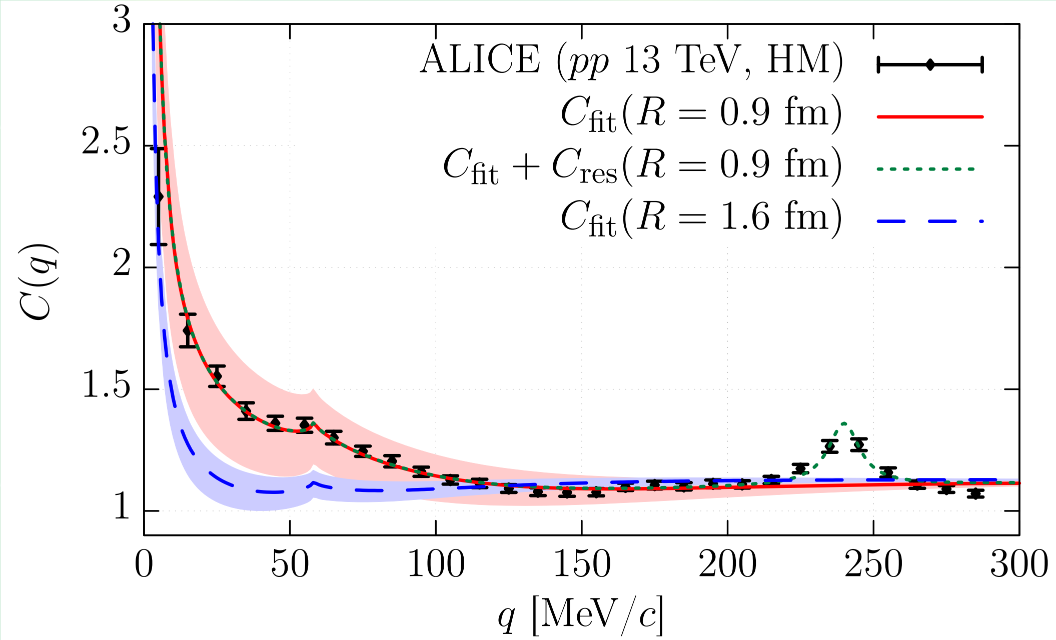
Correlation from chiral SU(3) dynamics

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

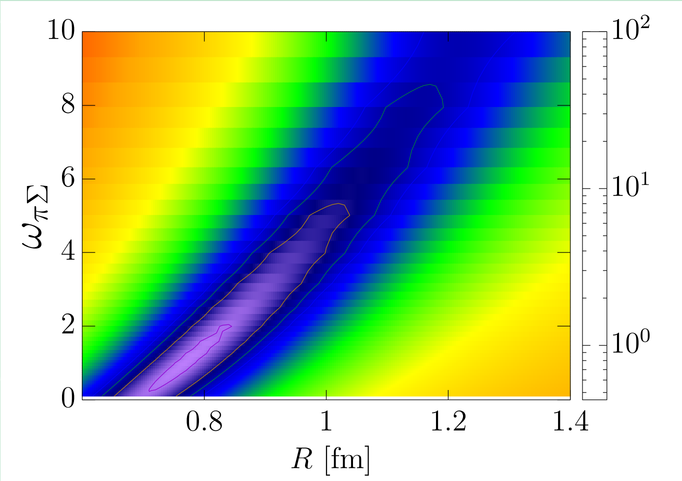
K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018)

- 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, PRL 124, 132501 (2020)

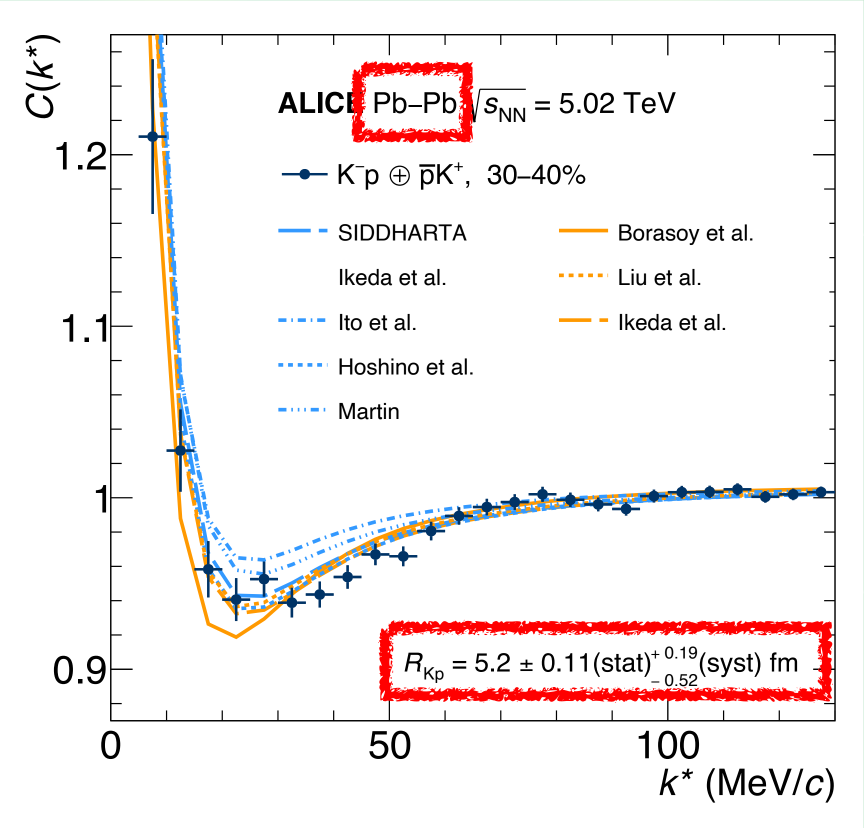
Correlation function by ALICE is well reproduced

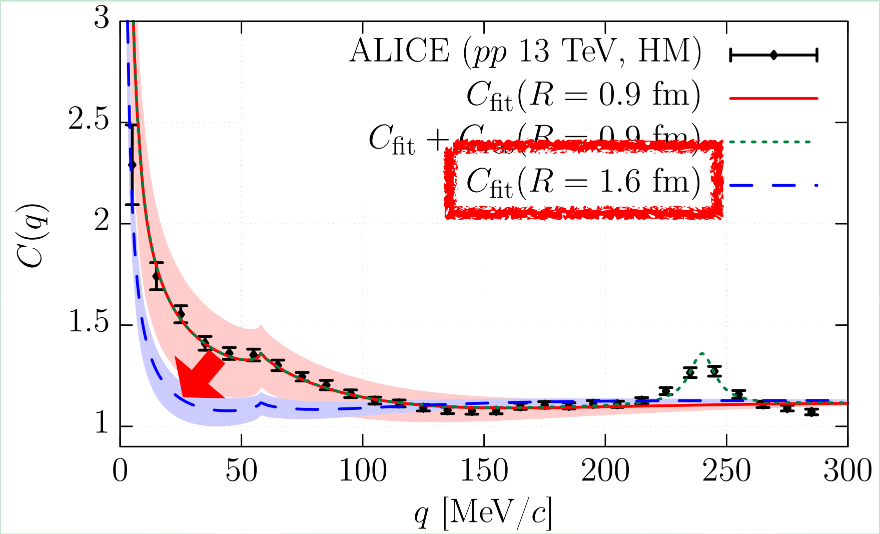
Source size dependence

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





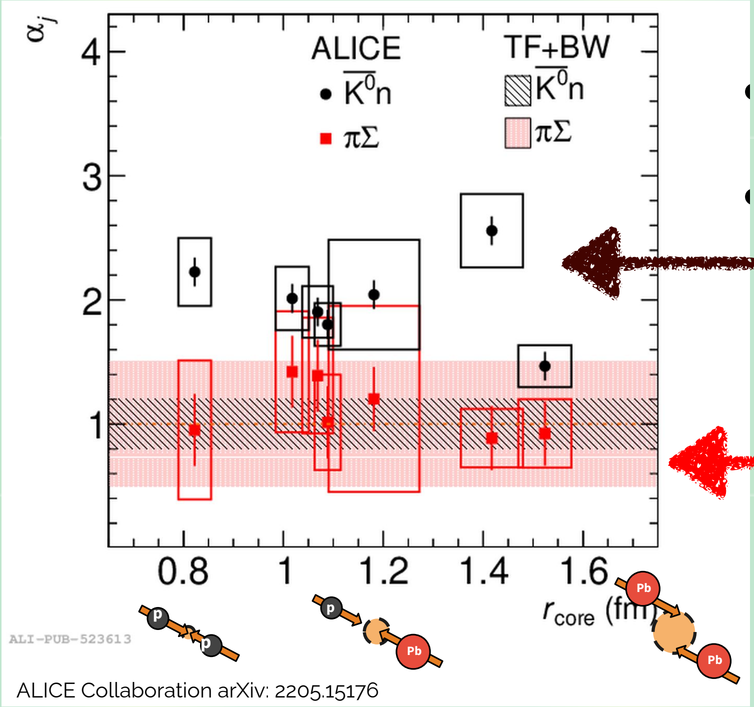
Correlation is suppressed at larger R, as predicted

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)

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



enhancement needed to explain data

Expected weight ω_i by Thermal Fist + Blast Wave

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

Summary

- K^-p **scattering and kaonic hydrogen are well described by NLO chiral SU(3) dynamics.**

  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012)

  - NNLO, scattering on the lattice, …

  J.-X. Lu, L.S. Geng, M. Doering, M. Mai, PRL 130, 071902 (2023);
  Talk by D. Mohler on 22nd June

- **Global structures of** K^-p **correlation functions are reproduced by Kyoto** $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ **potential.**

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

  - Source size dependence

  ALICE collaboration, PRL 124, 092301 (2020); PLB 822, 136708 (2021);
  EPJC 83, 340 (2023)