Updated experimental insight into the $\bar{K}N$ interaction.

Otón Vázquez Doce (INFN Frascati)
QNP2022, Sept. 9th, 2022

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KbarN interaction

KbarN interaction: building block of non-perturbative regime of QCD

KN and KbarN strong interactions are very different
The presence of the strange quark has dramatic consequences

- Strong attractiveness in KbarN gives rise to bound states

Sub-threshold: **Λ(1405) is an "old object" not fitting in the standard 3-quark picture**

- Molecular state with two poles KbarN-Σπ
- Strong coupled channel dynamics

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Theoretical framework

Theoretical approaches:

- meson exchange
- phenomenological
- **chiral SU(3) dynamical**
- Lattice QCD

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Data is crucial to test (+feed) this approaches.

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- meson exchange
- phenomenological
- **chiral SU(3) dynamical**
- Lattice QCD

Data is crucial to test (+feed) this approaches.

Data fitting by chiral SU(3)

- Going to NLO (N^2LO?), s+p waves ⇒ more parameters to be fixed (by data)
- Adding **new data** helps to improve the model
- Adding **more precise data** helps to improve the model
- Adding **data at different energies** helps to improve the model

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Available experimental data

$\bar{K}N$ interaction

Lorentz-invariant formulation of chiral effective field theory (LO)

Ren, Epelbaum, Gegelia, Meißner, EPJC (2021)

Extension to higher energies (LO+NLO):

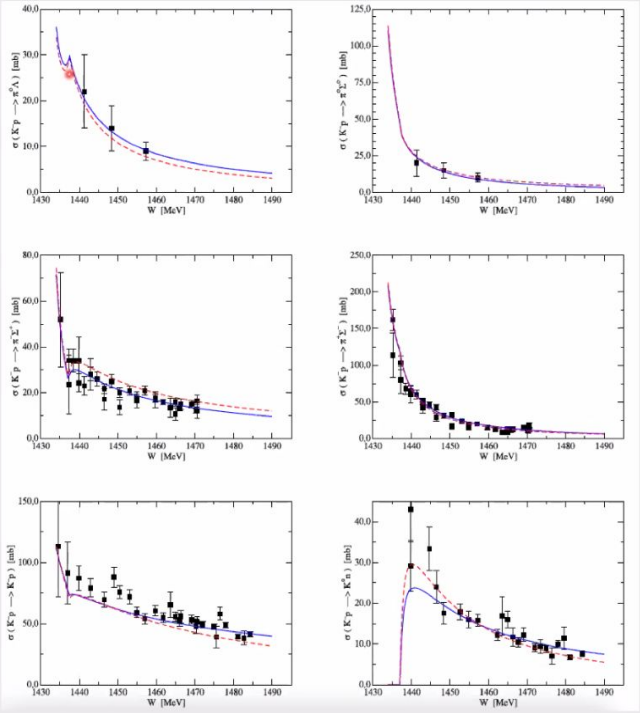
Feijoo, Magas, Ramos, PRC 2019

Bruns, Cieplý, NPA 2022

and higher partial waves:

Feijoo, Gazda, Magas, Ramos, Symmetry 2021

A. Ramos @ QNP2022



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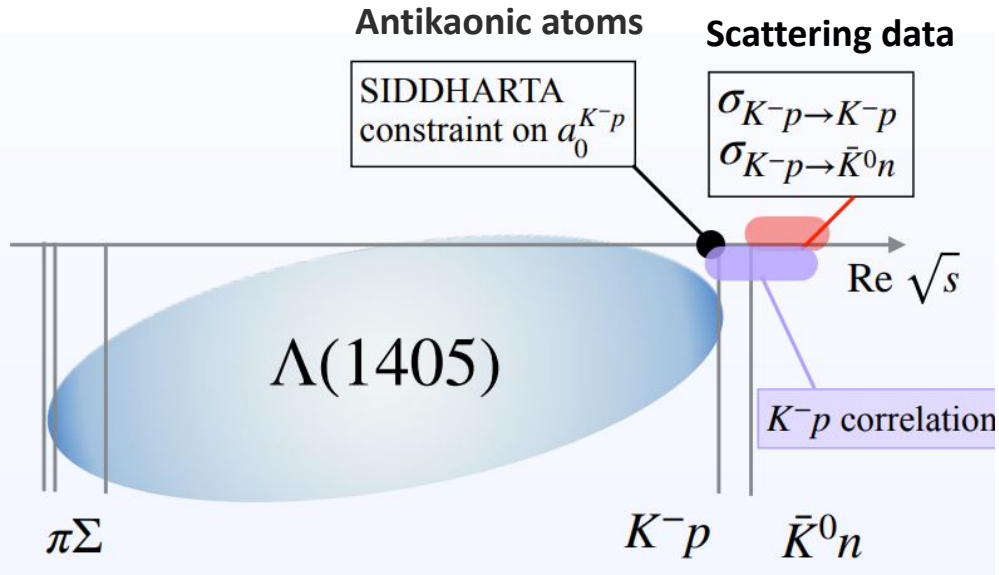

- B and Γ of kaonic nuclear states
- Single vs Multi-nucleonic absorption rates
- K-pp three body femtoscopy

Femtoscopy

Scattering amplitudes below threshold

Threshold branching ratios

Λ(1405) mass shape in different channels

image courtesy of Y. Kamiya

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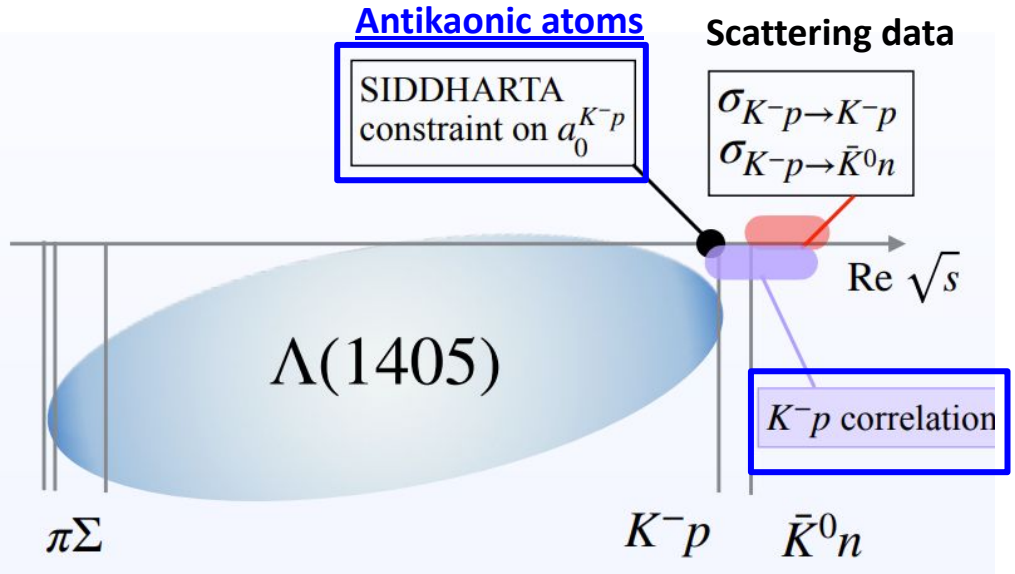
Available experimental data



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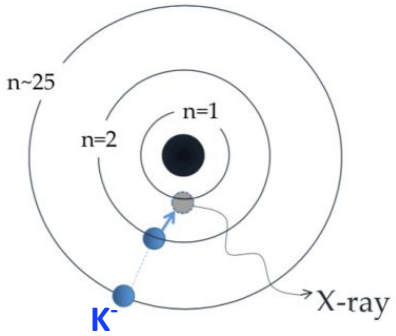
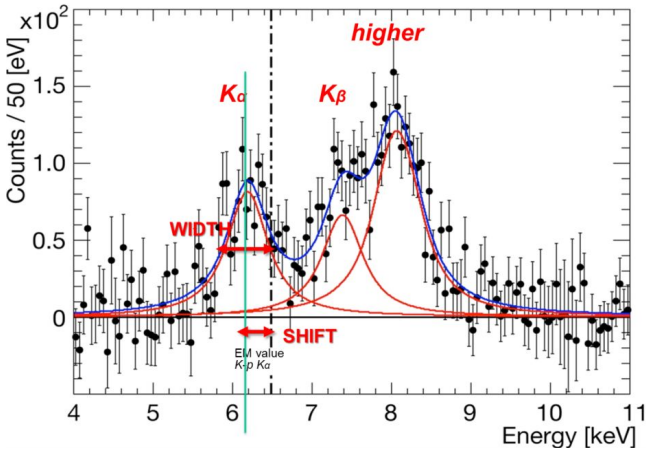
antikaonic hydrogen: SIDDHARTA



$2p \rightarrow 1s$
K_α transition

shift(ε), width(Γ) with respect to e.m. value caused by attractive/repulsive strong interaction and the presence of inelastic channels

Measurement of the **shift(ε) and width(Γ) induced by the strong interaction** in the lowest level atomic transition.



SIDDHARTA Coll., PLB 704 (2011) 113

$$\epsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV},$$

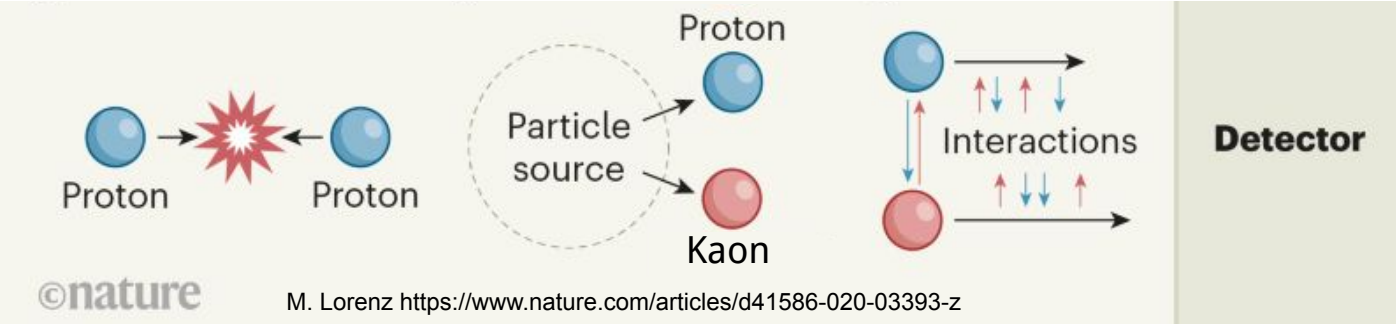
Translated via Desser-type Formula into a **K⁻p scattering length** that is an average of the KbarN scattering lengths for I=0 and I=1

$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_p\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_p\right)$$

$$a_{K^-p} = \frac{a_0(I=0) + a_1(I=1)}{2}$$

KbarN Femtoscopy with ALICE

Nucleus-Nucleus (pp, Pb-Pb) collisions at the LHC recorded by ALICE



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

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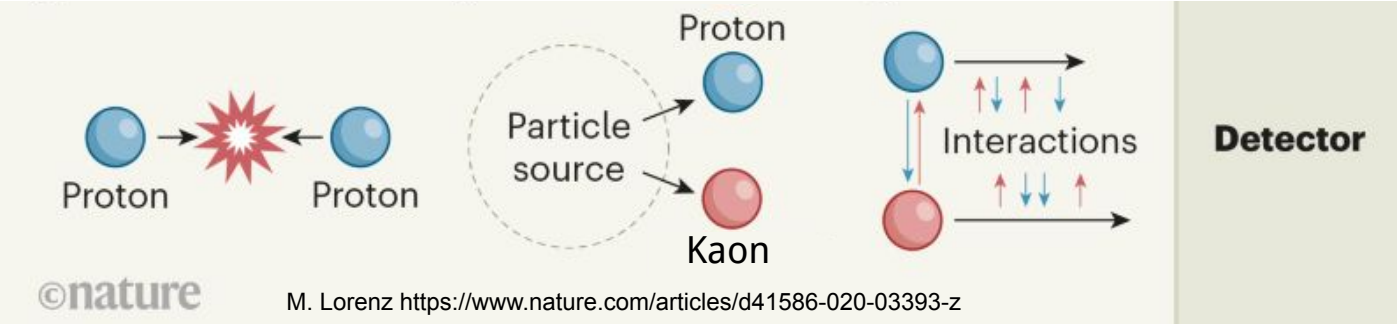

M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

Observable: **Correlation function of two final-state particles**

$$C(k^*) = \overbrace{\xi(k^*)\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}^{\text{experiment}}$$

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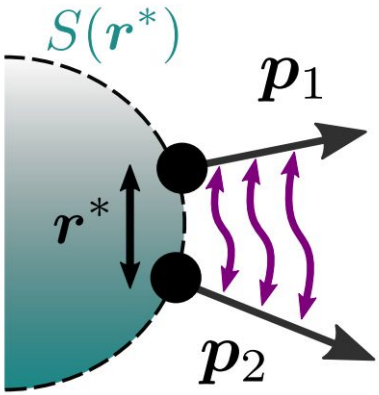
Femtoscopy: Theoretical correlation function

$$C(k^*) = \overbrace{\int \mathrm{d}^3\boldsymbol{r}^* \, \underbrace{S(\boldsymbol{r}^*)}_{\text{source}} \underbrace{|\psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2}_{\text{wave function}}}^{\text{theory}}$$

Lisa, Pratt, Wiedemann,Solz, Ann. Rev. Nucl. Part. Sci. 55 (2005) 357



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source wave function

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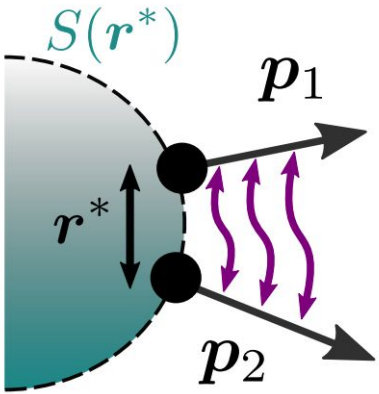
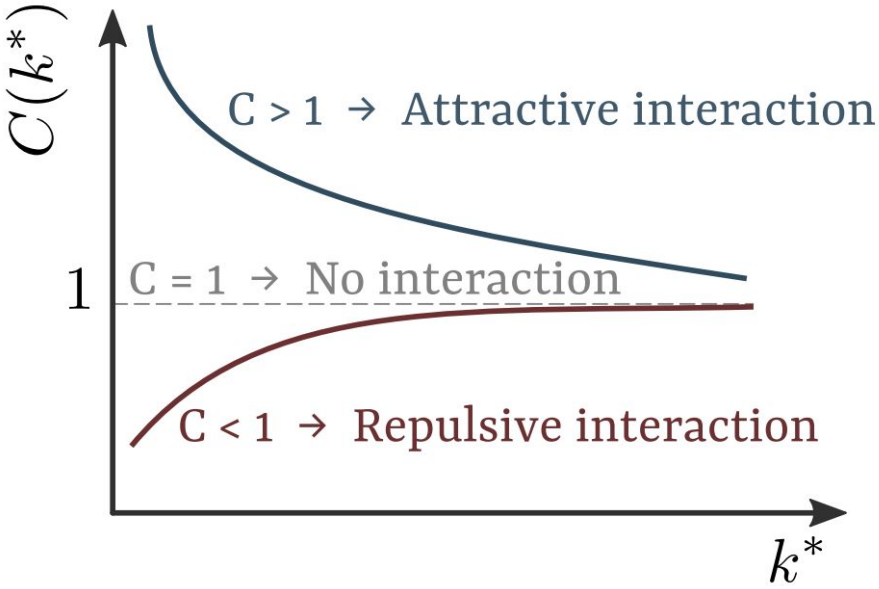
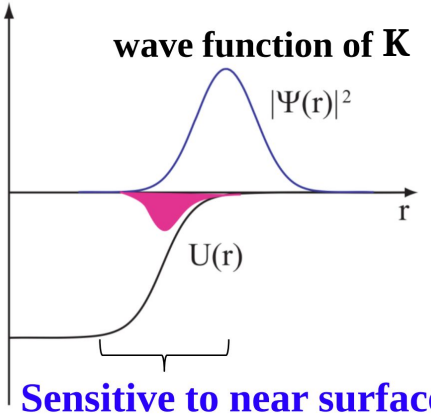




KbarN at threshold and low momentum

SIDDHARTA: antiKaonic Hydrogen



Sensitive to near surface potential shape

* for antikaonic hydrogen the K- p distance is ~100 times the Bohr radius

The overlap of the kaon wavefunction with the nucleon delivers insight into the effects of the strong interaction, competing with Coulomb effects

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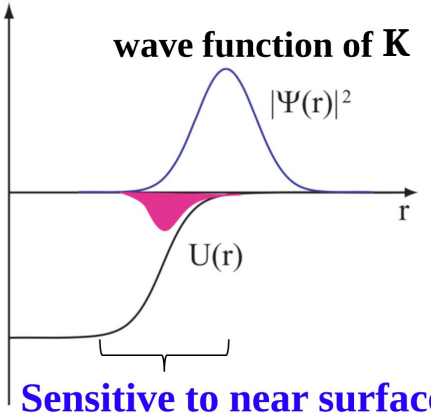

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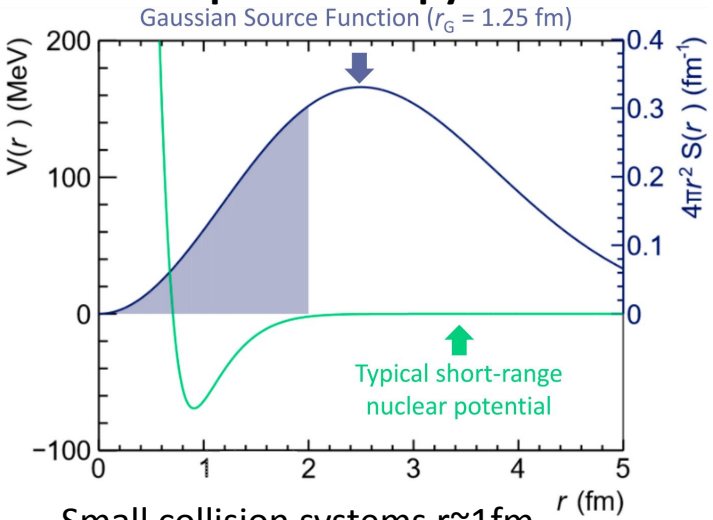
ALICE: K^-p femtoscopy



Small collision systems r~1fm

⇒ effect of the interaction is enhanced

$$C(k^*) = \int S(r^*) \left|\Psi(k^*, \vec{r^*})\right|^2 d^3r^*$$

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KbarN at threshold and low momentum

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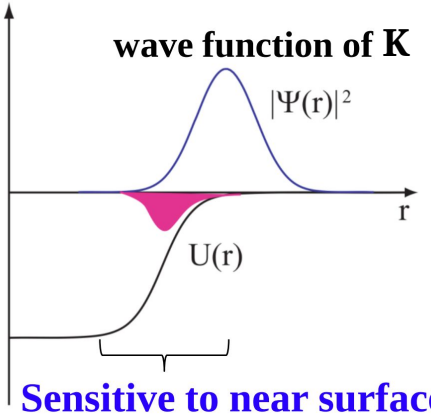

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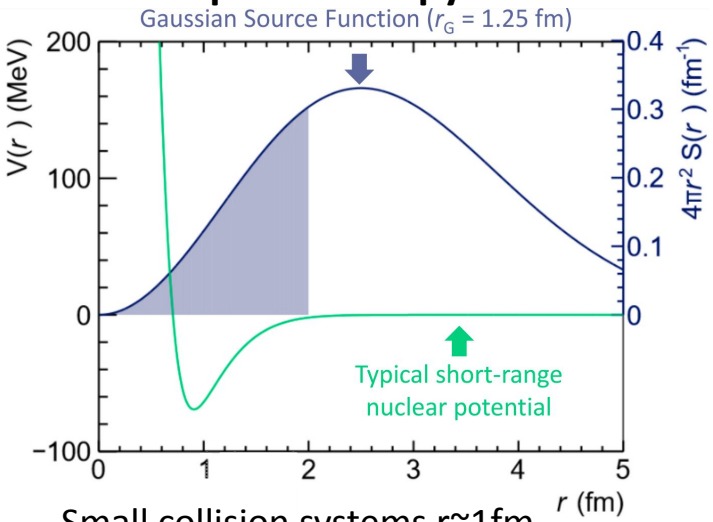

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⇒ effect of the interaction is enhanced

$$C(k^*) = \int S(r^*) \left|\Psi(k^*, \vec{r^*})\right|^2 d^3r^*$$

Deliver different observables ⇐⇒ scattering lengths can be obtained from both
(via approximations: Deser-type and Lednický–Lyuboshitz formulae)

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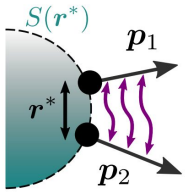
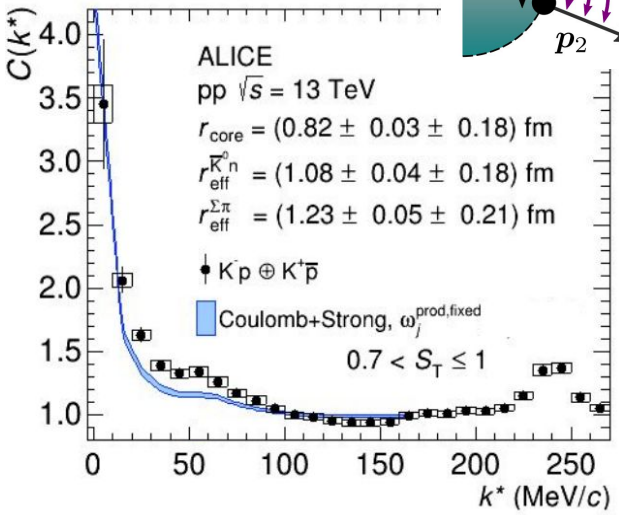
K⁻p Femtoscopy with ALICE in pp collisions



ALICE coll. arXiv: 2205.15176



Strong interaction: Kyoto model
K. Miyahara, T. Hyodo, W. Weise, Phys. Rev. C98, 2, (2018) 025201

Small systems: pp collisions r~1fm

⇒ Provides a **quantitative test of coupled channels in the theory**

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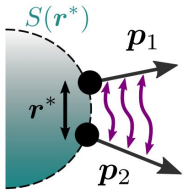

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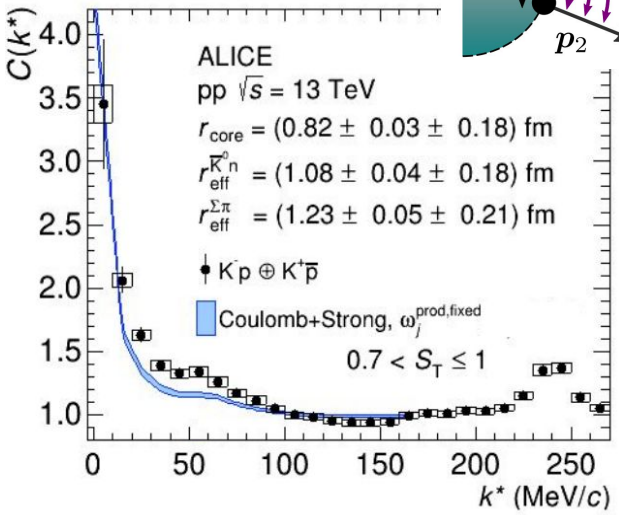

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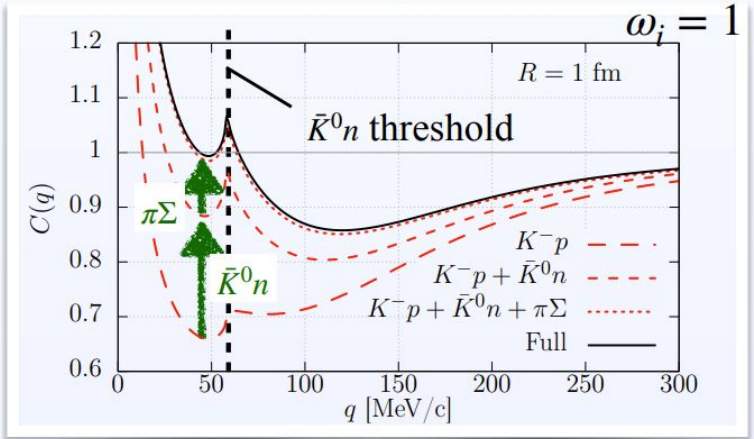
Effects of coupled channels enhanced by small source

- less important for large sources of HIC



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

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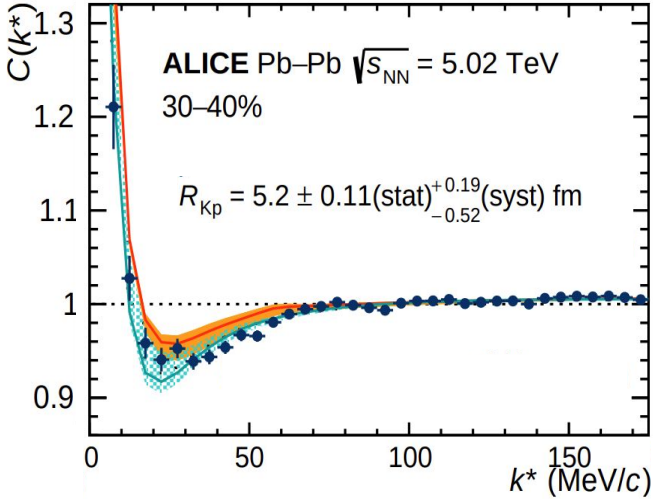
K^-p Femtoscopy with ALICE in Pb-Pb collisions

ALICE Coll., PLB 822 (2021) 136708



<u>Large systems (HIC):</u> Pb-Pb collisions, up to r~9fm

Strength of coupled channels significantly reduced

- **Kyoto model**
- **Fit to the scattering parameters** R. Lednický Phys. Atom. Nucl. 67 (2004) 72

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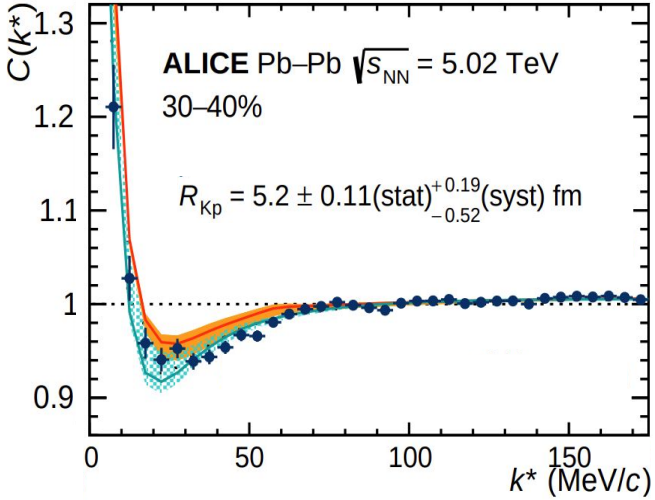
K⁻p Femtoscopy with ALICE in Pb-Pb collisions

ALICE Coll., PLB 822 (2021) 136708



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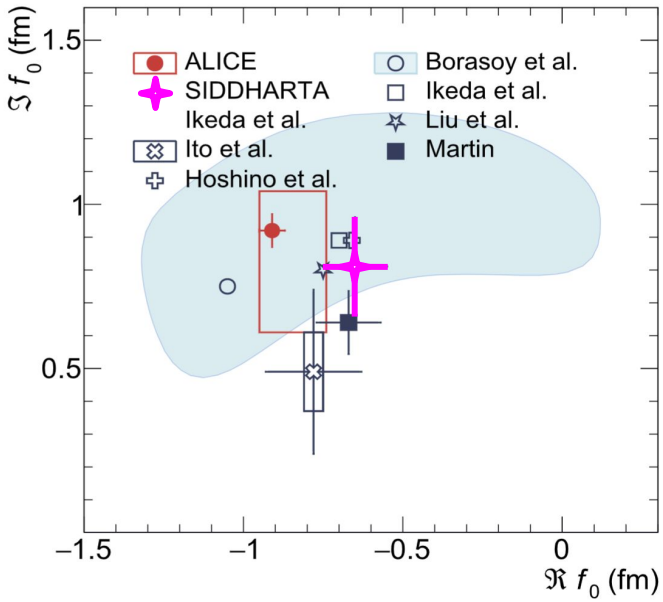

⇒ Antikaonic-hydrogen and K-p femtoscopy scattering parameters compatible

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Upcoming: Accessing KbarN I=1 interaction

Full isospin dependence needs K^-d interaction measurements:

$$a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$$

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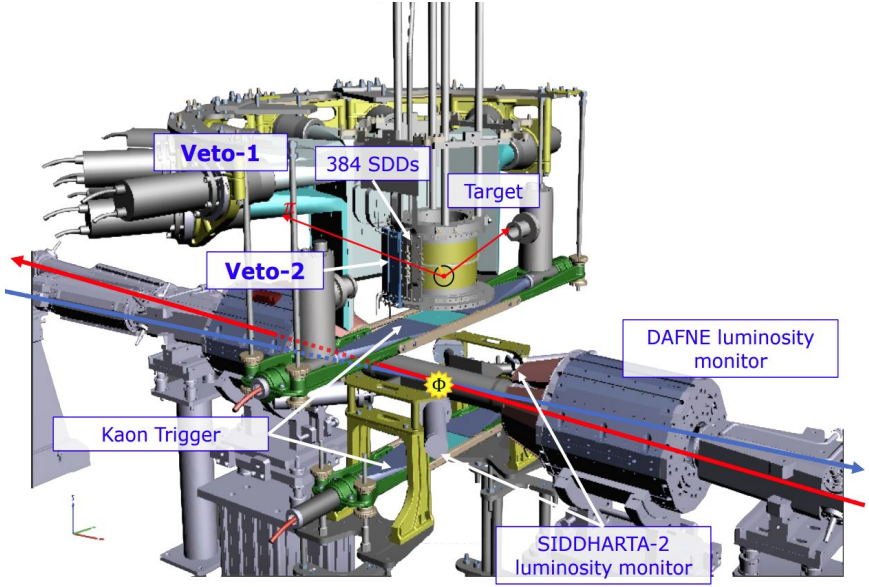
SIDDHARTA-2 with new experimental setup

→measurement of **antikaonic deuterium**

→very challenging! low yield of signal

→Complete upgrade of SIDDHARTA setup



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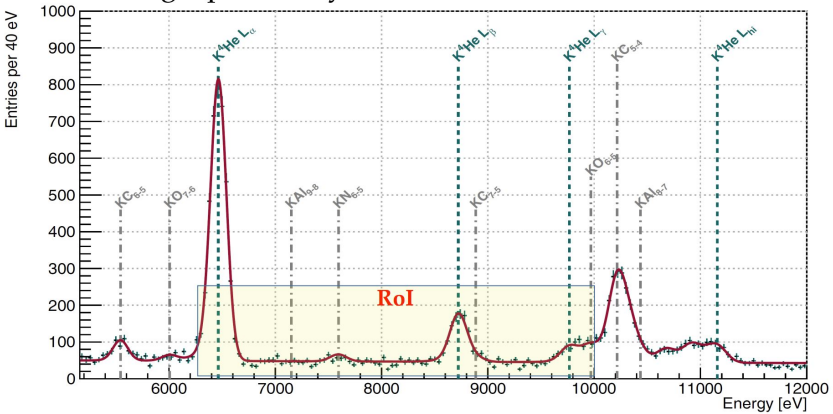
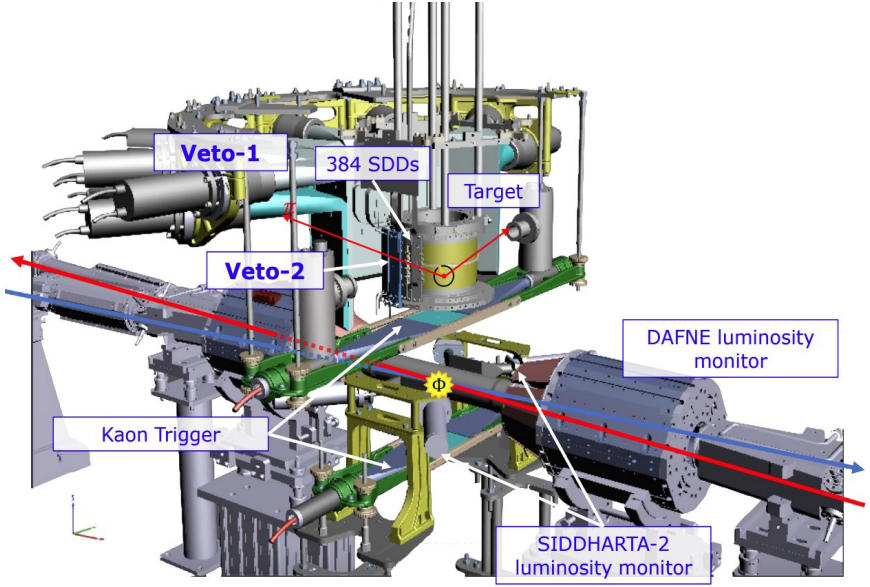
Beam tuning April – May 2022, He measurement



➢ *Deuterium measurement started begin of June 2022 at DAΦNE*



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Accessing KbarN I=1 interaction with ALICE

Access to I=1 KbarN interaction via femtoscopy

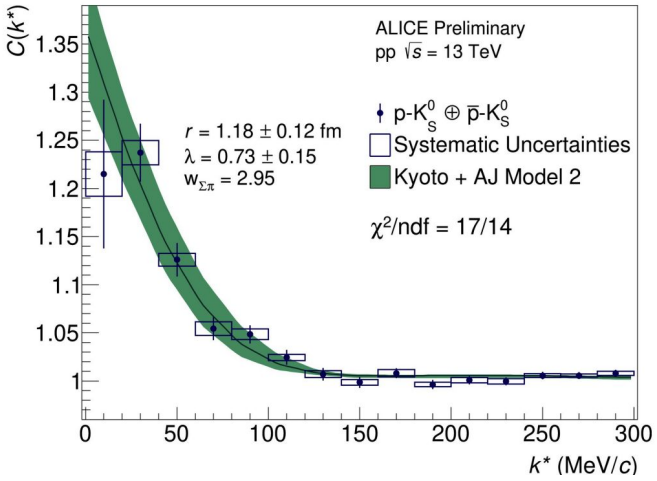
$$C_{K^0_S p} = [C_{\bar{K}^0 p} + C_{K^0 p}]/2$$

- $K^0_S p$ correlation

$$|K^0_S p\rangle = [|\bar{K}^0 p\rangle - |K^0 p\rangle]/\sqrt{2}$$

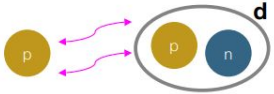
$\bar{K}N, I = 1$ $\quad$ $KN, I = 0, 1$

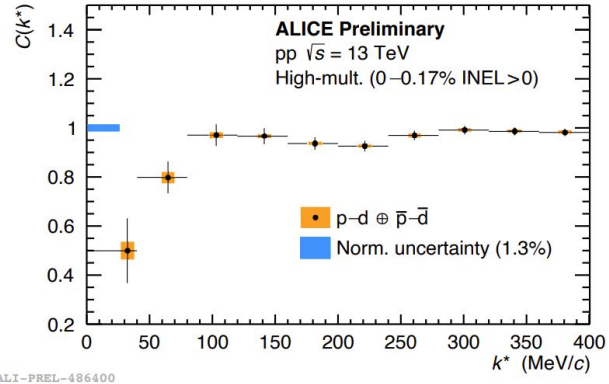
- $I = 1$ component only
- Well determined with scat. exp.



On the horizon: **K⁻d femtoscopy**

Femtoscopy with deuterons (K^+d, pd) by ALICE in small systems and by STAR in HIC H. Zbroszczyk @ HYP2022





Kaonic nuclei

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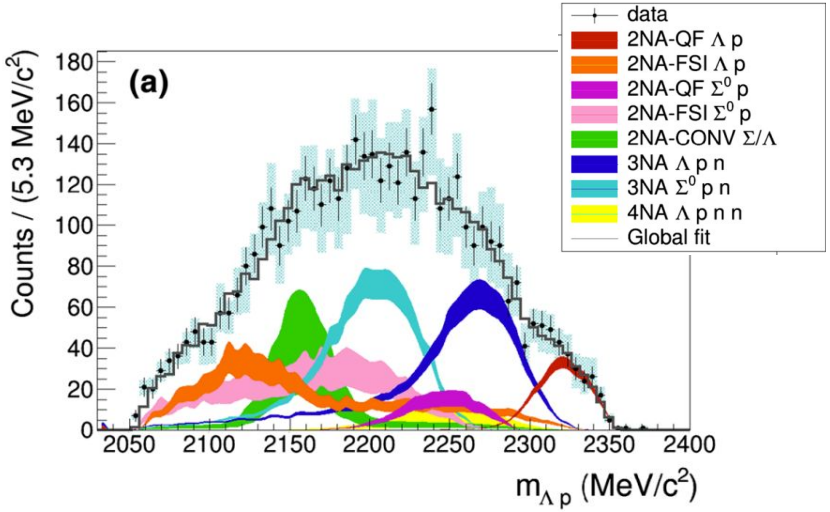
AMADEUS: K^- absorption in ^4He and ^{12}C



invariant mass

$K^- + A \rightarrow Yp + A'$

Multi-nucleon absorption processes dominate

AMADEUS Coll. PLB 758 (2016) 134
AMADEUS Coll. PLB 782 (2018) 339
AMADEUS Coll. FBS 62 (2021) 7.

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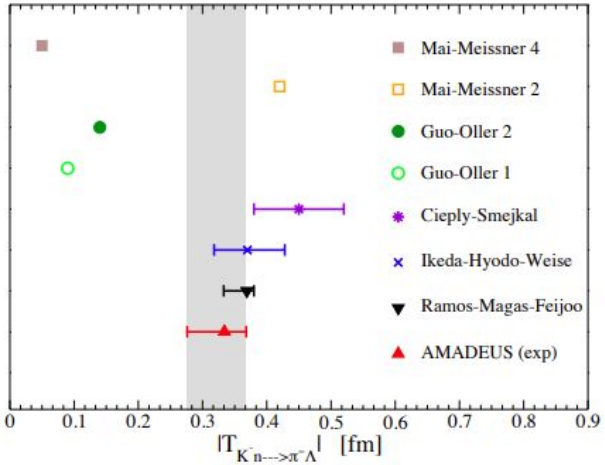
AMADEUS: K^- absorption in ^{4}He and ^{12}C

Below threshold (-33 MeV)

$K^-n \rightarrow \Lambda\pi^-$ amplitude, non resonant I=1

$$|A_{K^-n\to\Lambda\pi^-}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\ \mathrm{fm}.$$

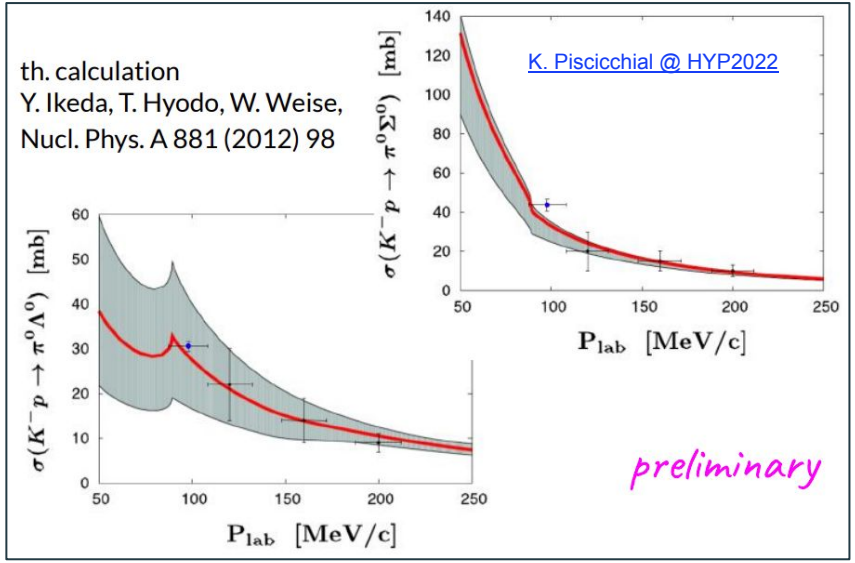
AMADEUS Coll., PLB 782 (2018) 339-345]



Avobe threshold

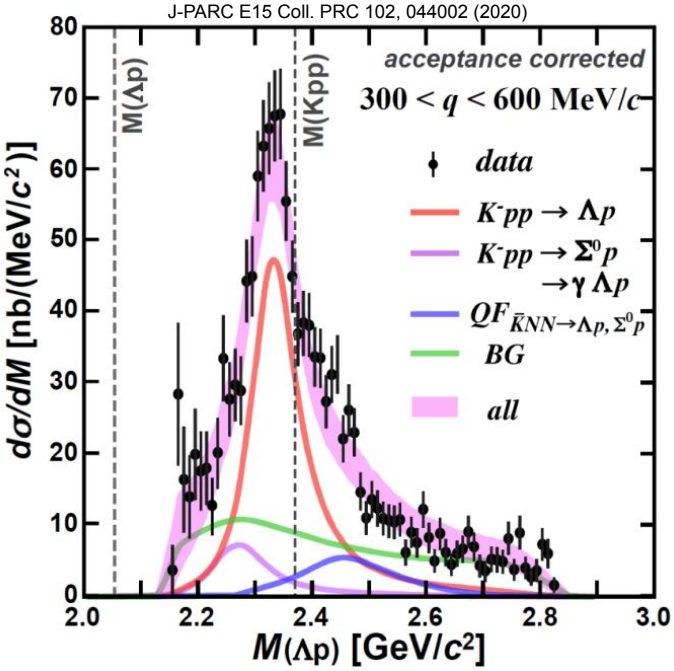
$K^-p \rightarrow \Lambda\pi^0$, $\Sigma^0\pi^0$ cross sections (preliminary)

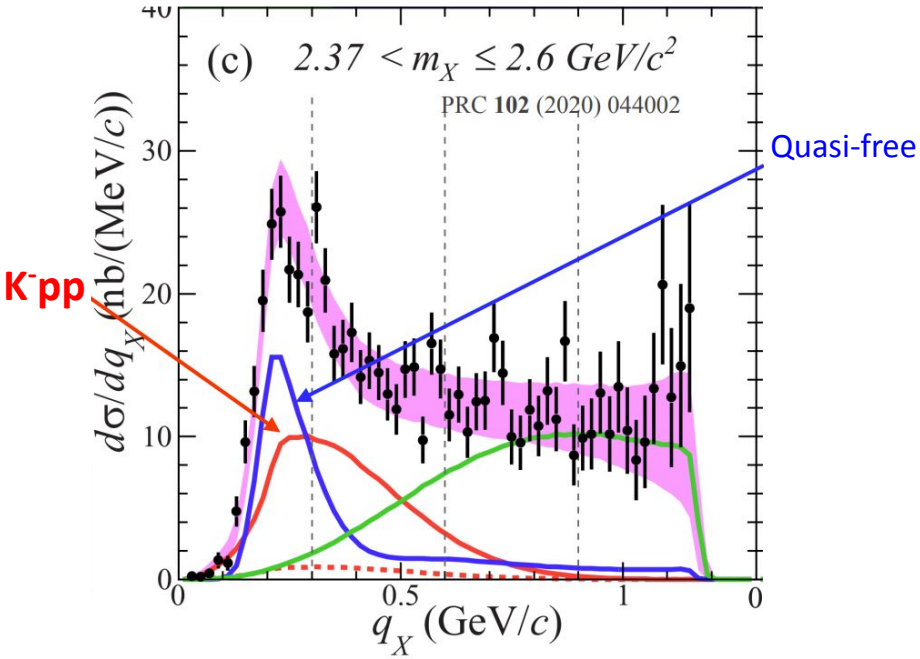
- $\sigma_{K^-p\to\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)\ \mathrm{mb}$
- $\sigma_{K^-p\to\Lambda\pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)\ \mathrm{mb}\,,$



J-PARC E15

In-flight ^{3}**He(K$^-$,n)Λp** reaction @ 1.0 GeV/c





$$B_K = 42 \pm 3(\text{stat.})^{+3}_{-4}(\text{syst.})\ \text{MeV}$$
$$\Gamma_K = 100 \pm 7(\text{stat.})^{+19}_{-9}(\text{syst.})\ \text{MeV}$$

3-Body femtoscopy by ALICE

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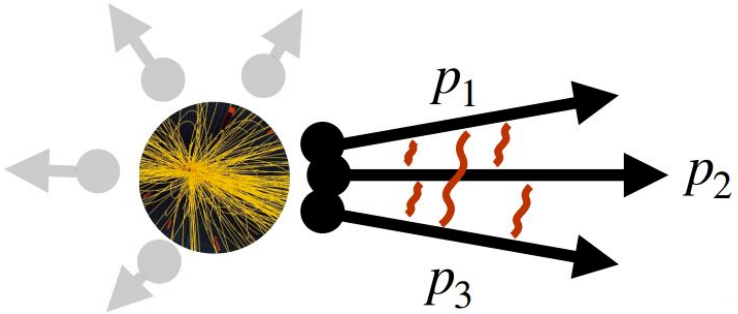
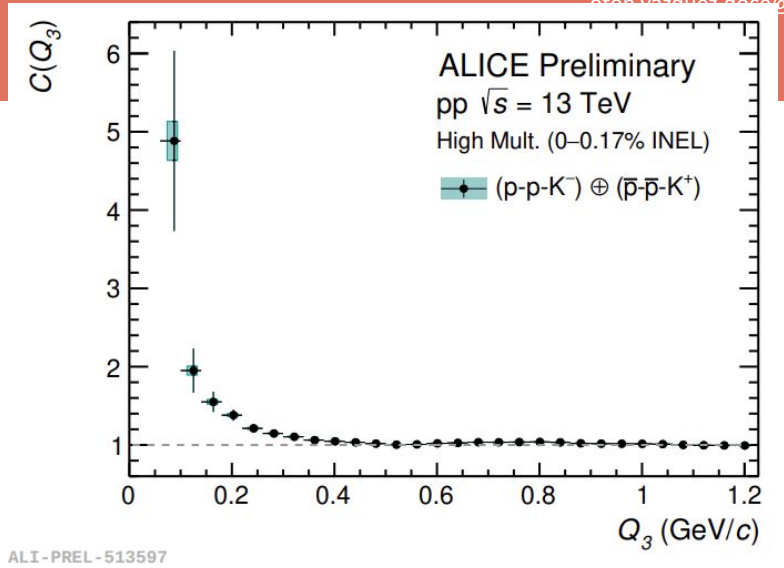


R. Del Grande @ QNP2022

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$



3-Body femtoscopy by ALICE

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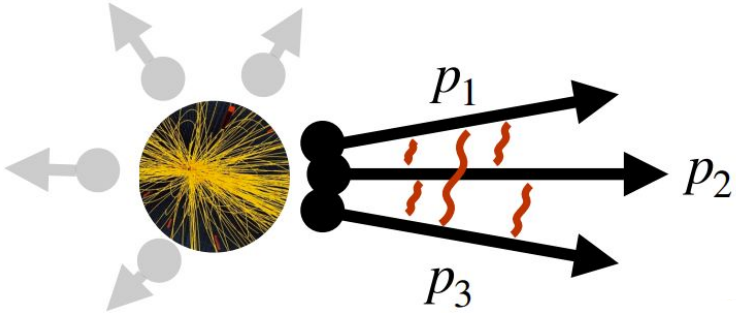
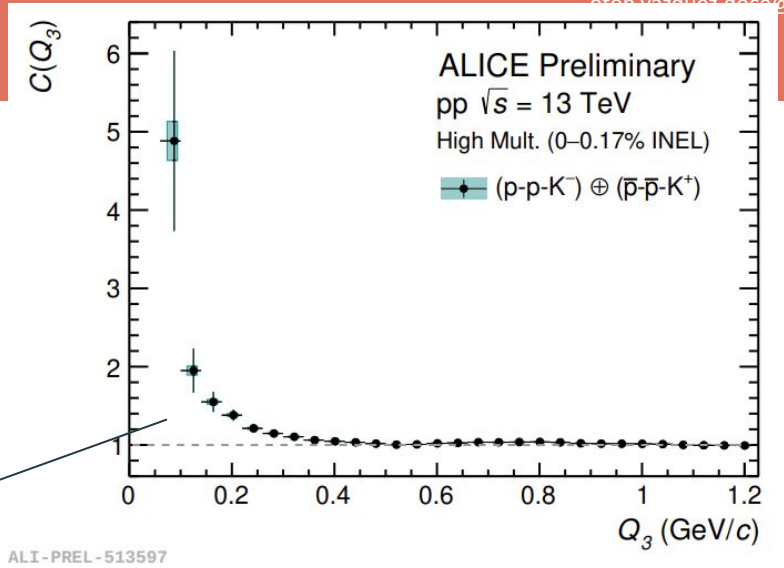


R. Del Grande @ QNP2022

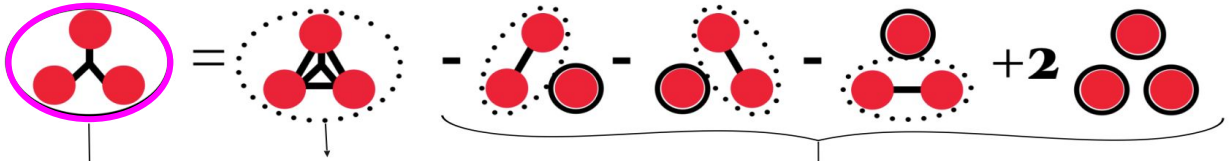
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$



Isolation of the **three-body effects** in the correlation function:

$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

2-body correlations experimentally determined



Genuine three-body correlations (cumulant)

Measured triplets

Lower-order correlations

R. Kubo, J. Phys. Soc. Jpn. 17, 1100 (1962)

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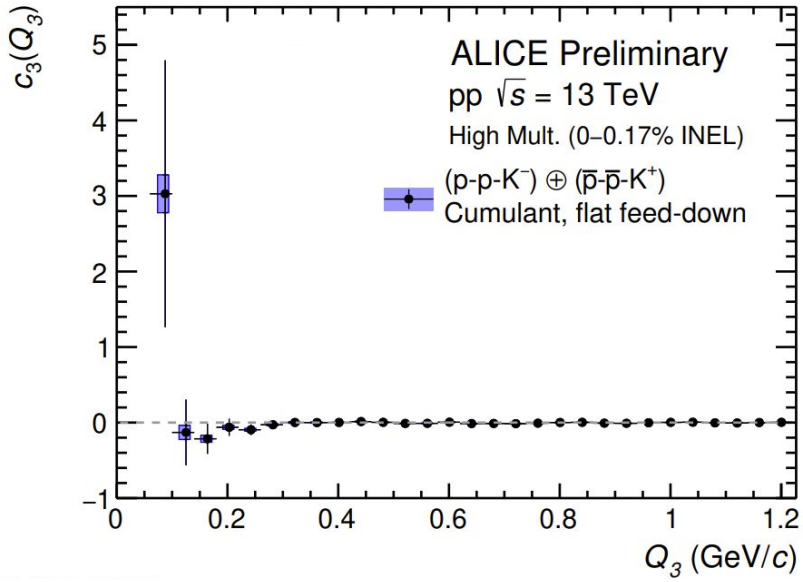
ppK$^-$ cumulant



⇒ **ppK$^-$ cumulant** is **compatible with zero.**

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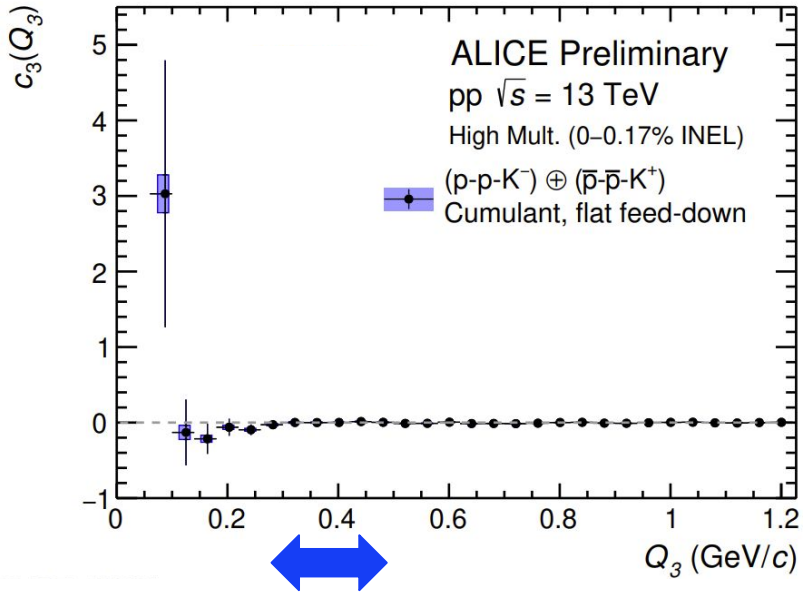
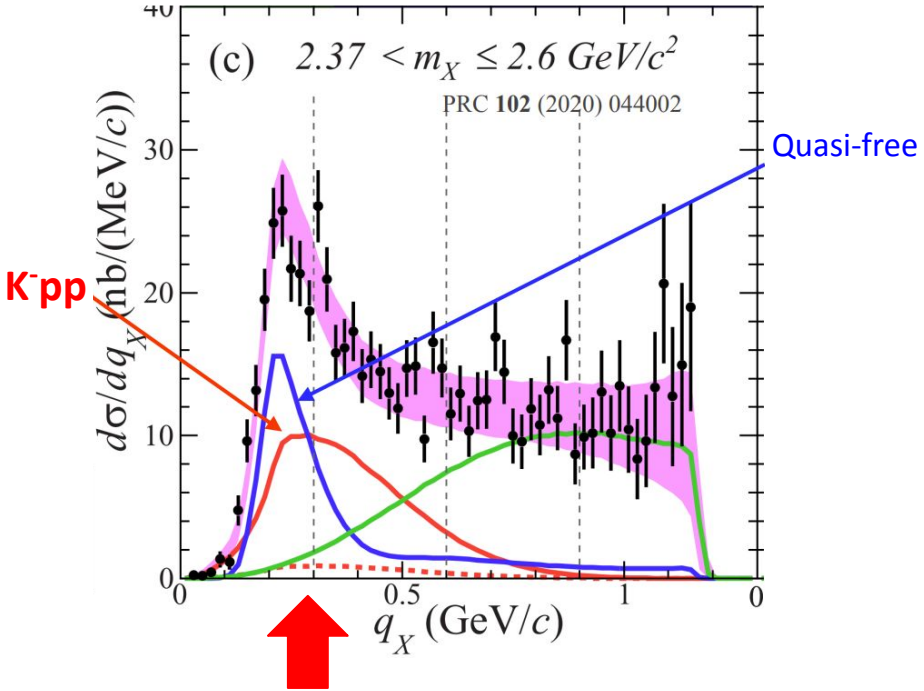
ppK⁻ cumulant





⇒ **ppK⁻ cumulant** is **compatible with zero.**

⇒ Suggest that **three-body effects** are **not relevant for the description of the K⁻pp system**

In p-p-p correlations significant 3-body effect (pauli blocking? FSI?)
⇒ relevant for the description of the K-NNN system?

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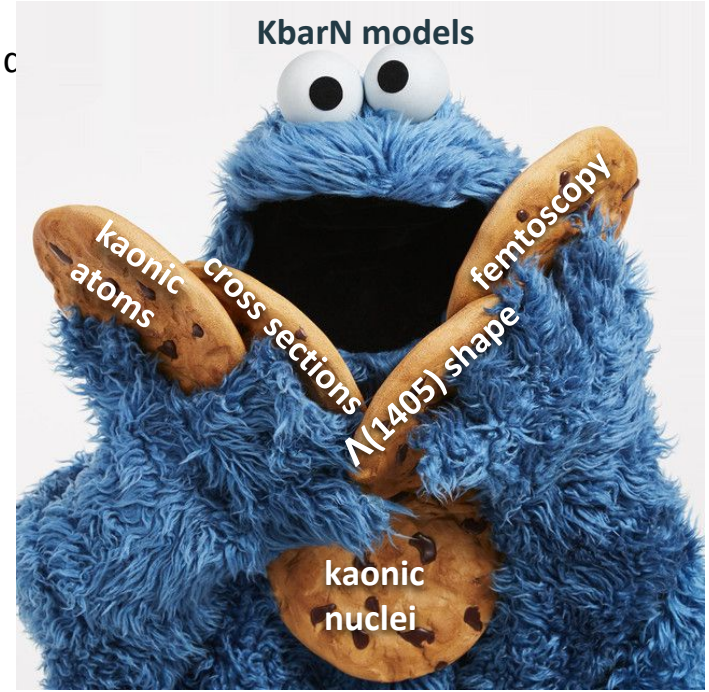
Outlook

We are collecting new data (e.g. ALICE run 3 with x500 stats and improved tracking, SIDDHARTA-2 running)
In the near future:
- new experimental apparatus
- new facilities

In the KbarN field a boost similar to the precise measurement of antikaonic hydrogen is expected

…still on the search for a <u>description of the KbarN interaction</u> that can accommodate all the data from above to below threshold



you really need to eat ALL the cookies!