Studying two- and three-body hadron systems at the LHC

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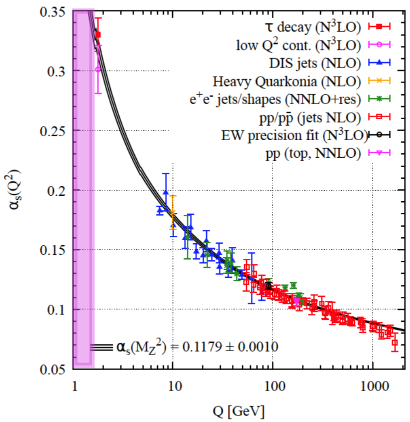
BMBF Forschungsschwerpunkt ALICE Experiment 202

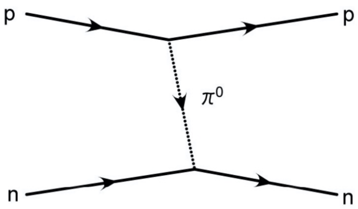
ALICE

SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

Residual strong interaction among hadrons

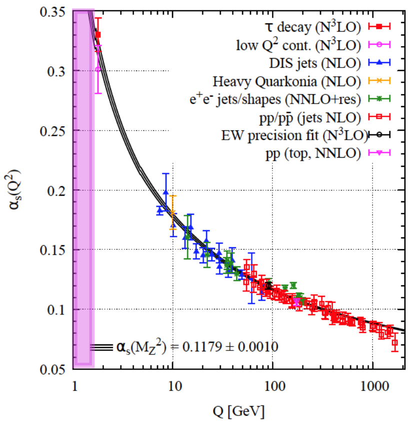


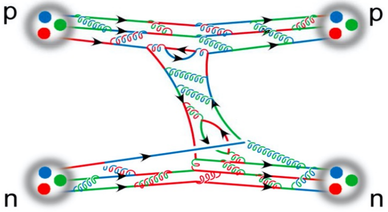


Non perturbative QCD → Q ~1 GeV, R ~ 1 fm

→ Effective theories with hadrons as degrees of freedom constrained to experimental data

Residual strong interaction among hadrons





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<u>New results:</u>

→ Understanding of the interaction starting from quark and gluons

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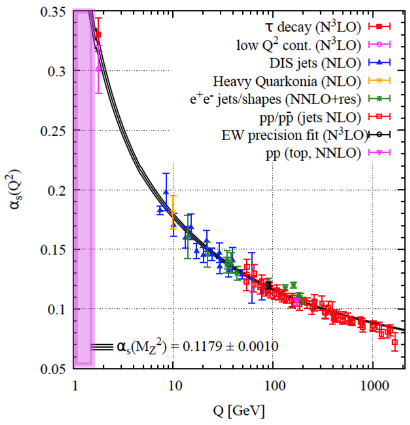

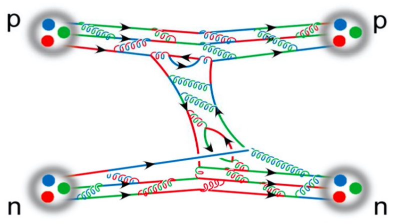

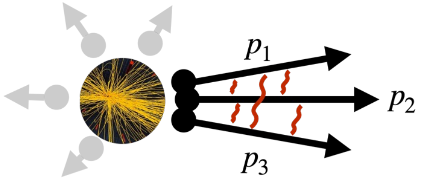

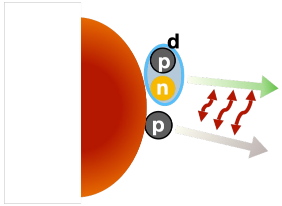

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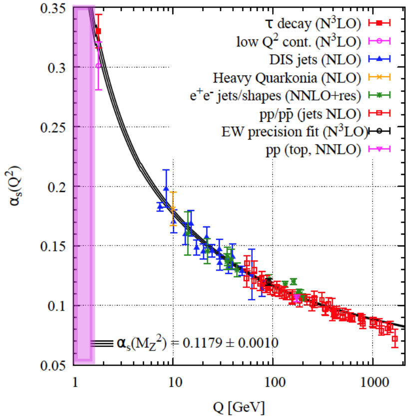
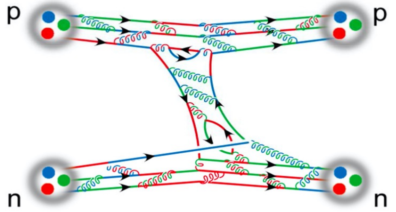
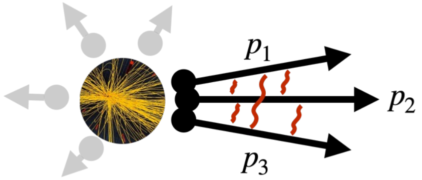
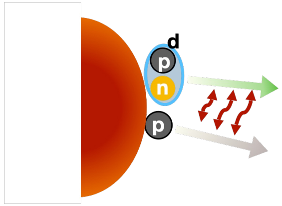
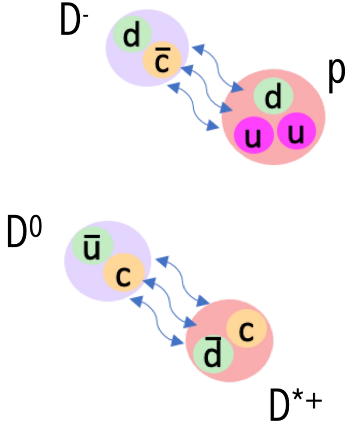










Non perturbative QCD → Q ~1 GeV, R ~ 1 fm

→ Effective theories with hadrons as degrees of freedom constrained to experimental data

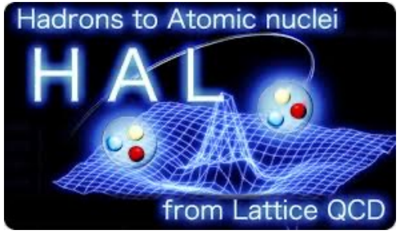
New results:

→ Understanding of the interaction starting from quark and gluons

→ New experimental methods to investigate three-body systems

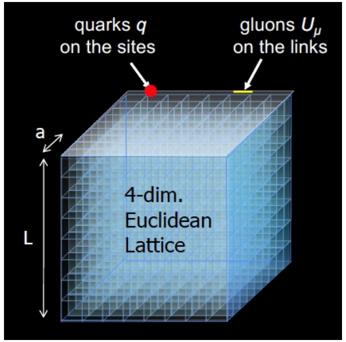
→ First studies of the strong interaction for the charm sector

Residual strong interaction from lattice



T. Hatsuda, K. Sasaki et al.

HAL QCD Coll. PLB 792 (2019)
HAL QCD Coll. NPA 998 (2020)
HAL QCD Coll. PRD 99 (2019)



$$a = 0.085 \text{ fm}$$
$$L = 8.1 \text{ fm}$$
$$m_\pi = 146 \text{ MeV}/c^2$$
$$m_{\mathrm{K}} = 525 \text{ MeV}/c^2$$

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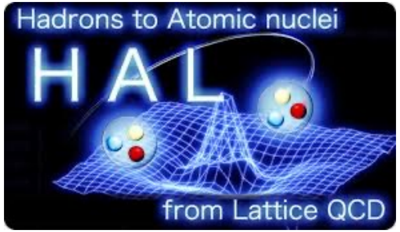

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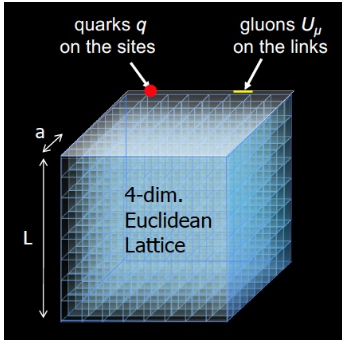

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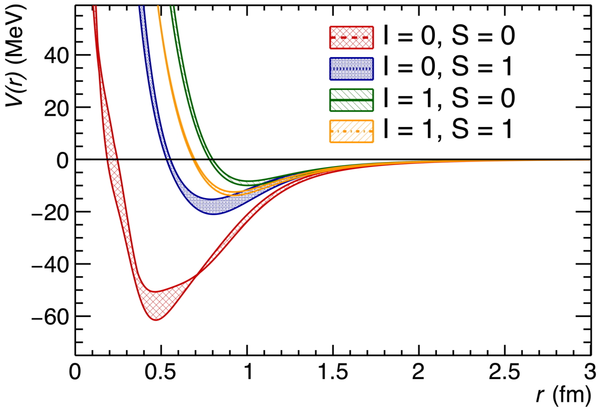
Local potentials for the nucleon-Ξ interactions



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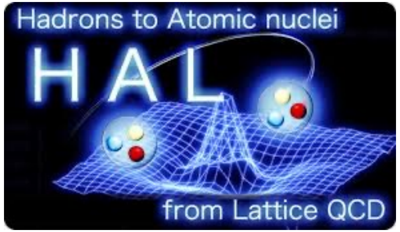

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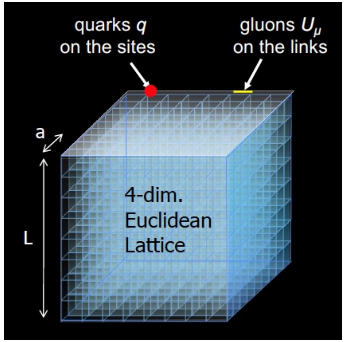

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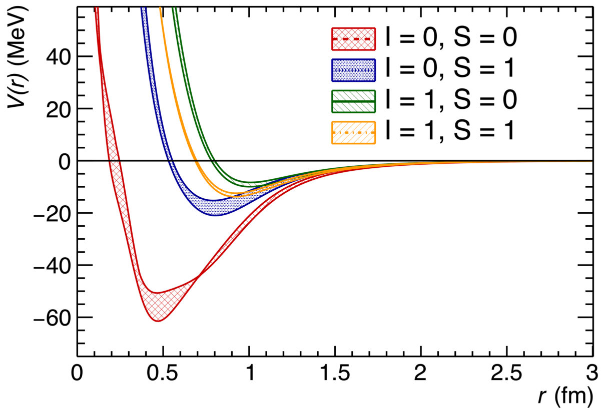

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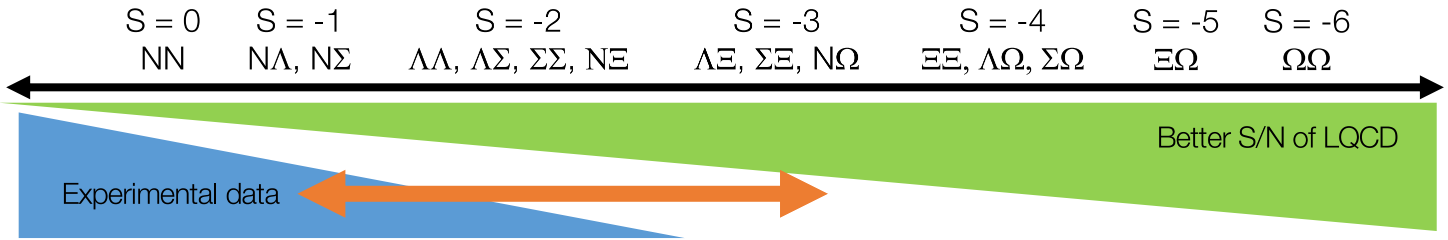
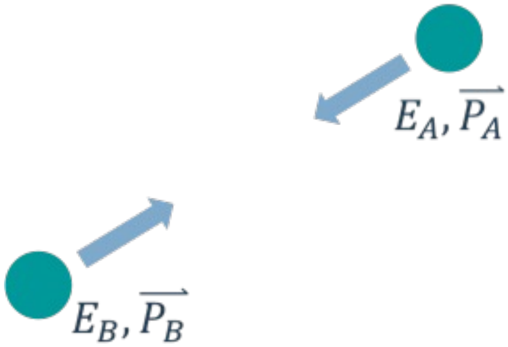


pp collisions at the LHC



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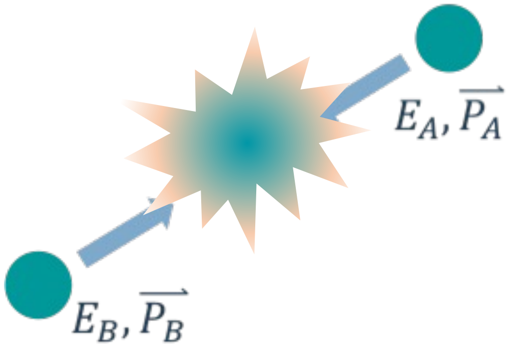
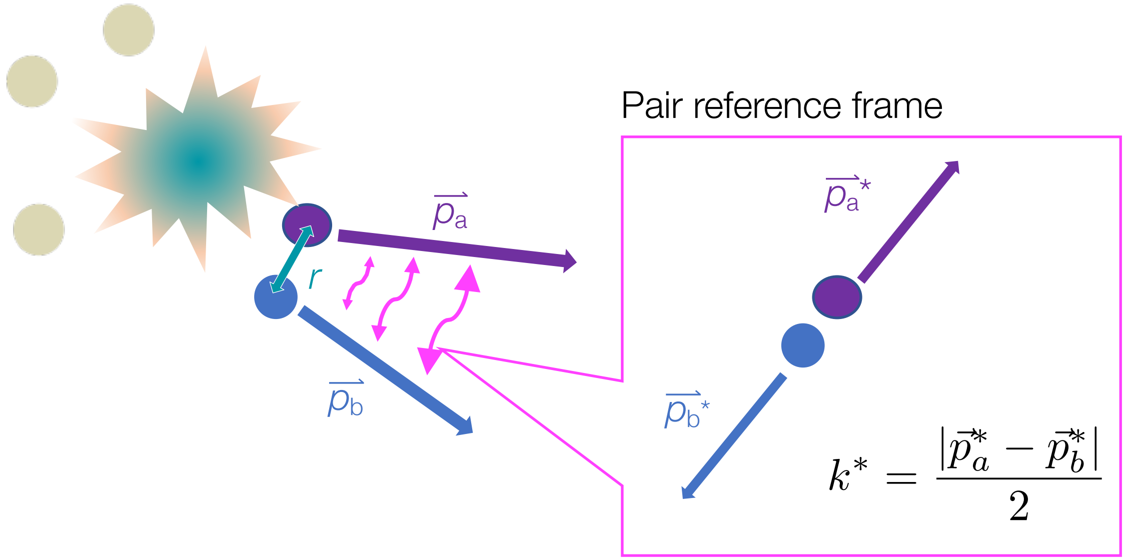
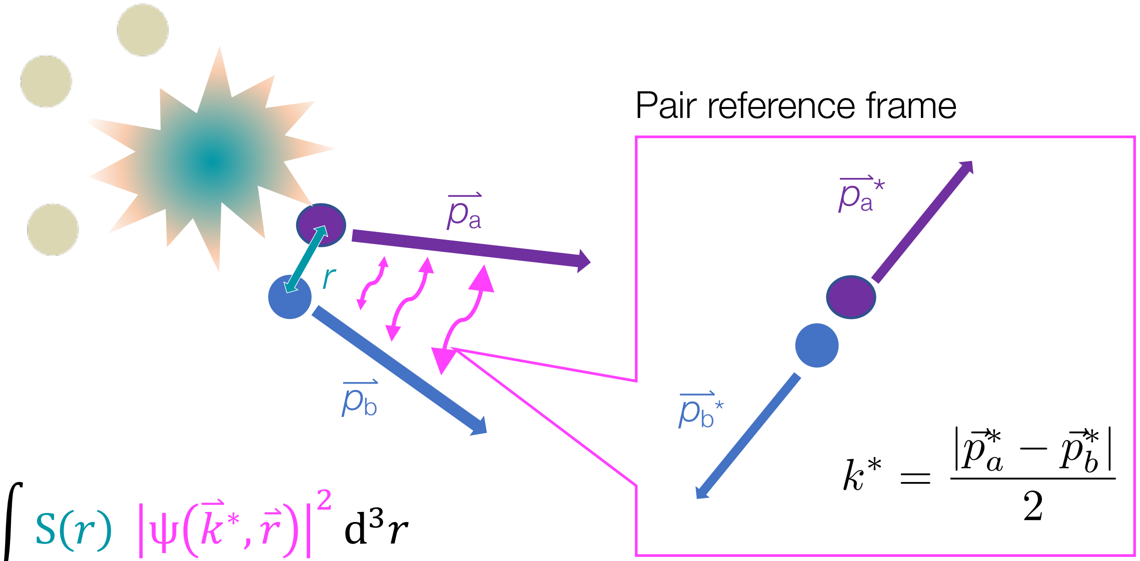




$\vec{p}_a$
r
$\vec{p}_b$
Pair reference frame
$\vec{p}_a^{\,*}$
$\vec{p}_b^{\,*}$
$k^* = \frac{|\vec{p}_a^{\,*} - \vec{p}_b^{\,*}|}{2}$

The Koonin-Pratt formalism

S. E. Koonin et al. PLB 70 (1977)



$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r)\ \left|\psi(\vec{k}^*, \vec{r})\right|^2 d^3r$$

Emission source

Two-particle wave function

The Koonin-Pratt formalism

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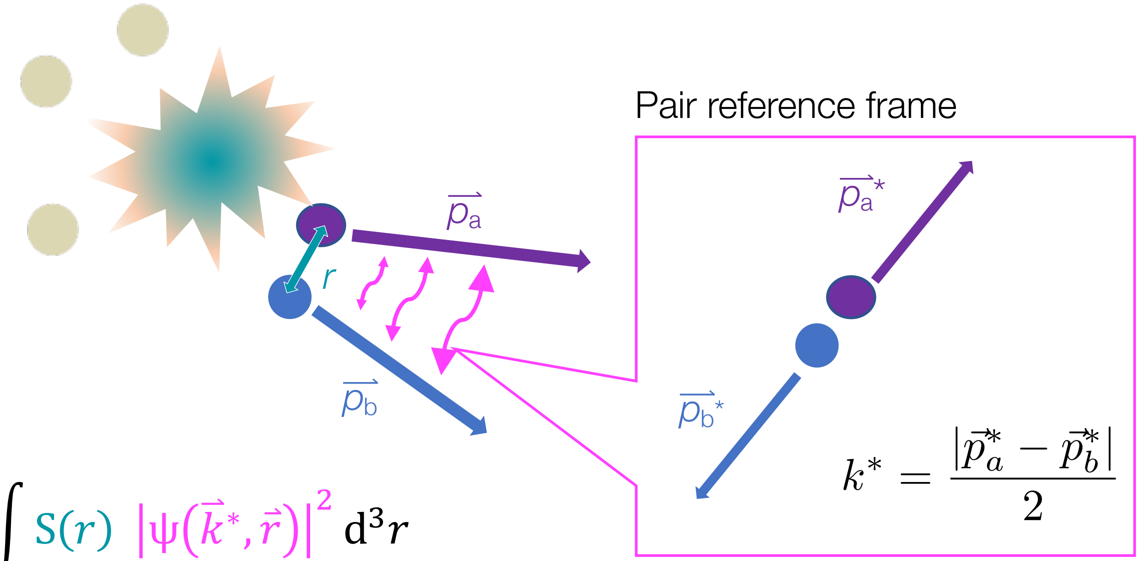

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Emission source

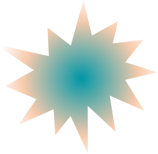
Two-particle wave function

Schrödinger Equation:

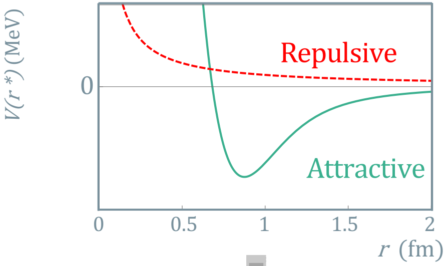
V(r) → $\left|\psi(\vec{k}^*, \vec{r})\right|^2$ relative wave function for the pair

Correlation function and potentials

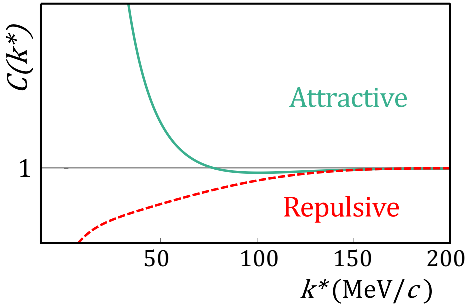
Source parametrisation



Interacting potential



Correlation function



Gaussian source

$$S(r) = (4\pi r_0^2)^{-3/2} \cdot exp\left(-\frac{r^2}{4r_0^2}\right)$$

Schrödinger equation**

Two-particle wave function$|\Psi(\mathrm{k}^*, \mathrm{r})|$

**CATS (Correlation Analysis Tool using the Schödinger equation)

D. Mihaylov et al. EPJC 78 (2018)

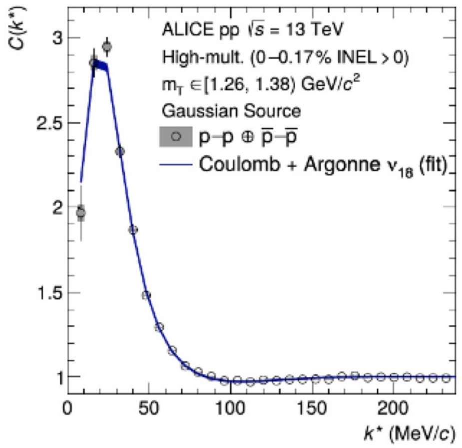
$$\mathrm{C}(k^*) = \int S(r)\ \left|\psi(\vec{k}^*, \vec{r})\right|^2 \mathrm{d}^3 r$$

Emission source — Two-particle wave function

>1 if the interaction is attractive
= 1 if there is no interaction
<1 if the interaction is repulsive

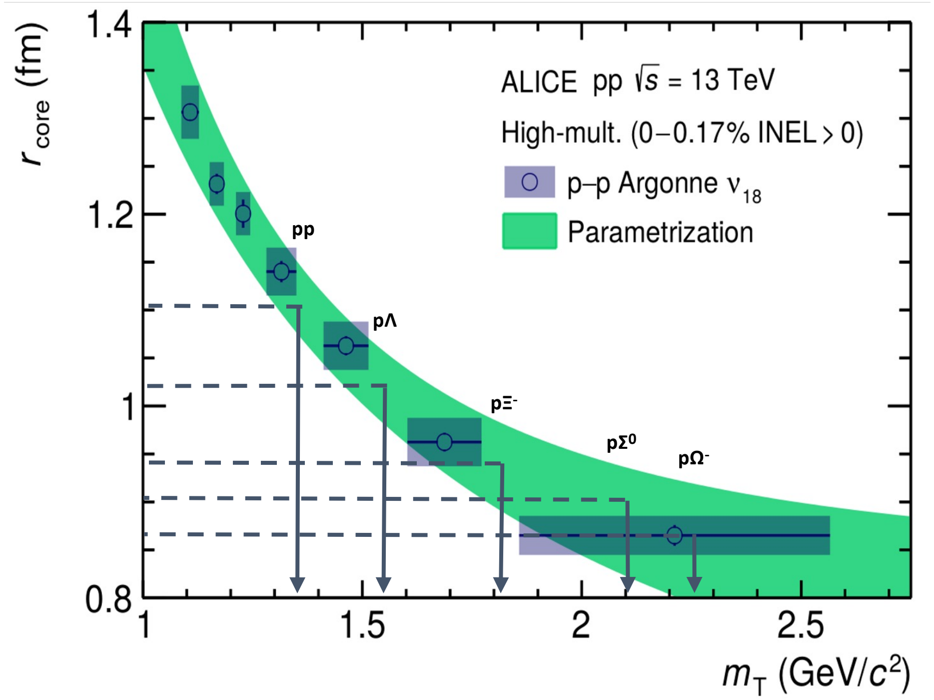
Source model

ALICE Coll., PLB, 811 (2020)



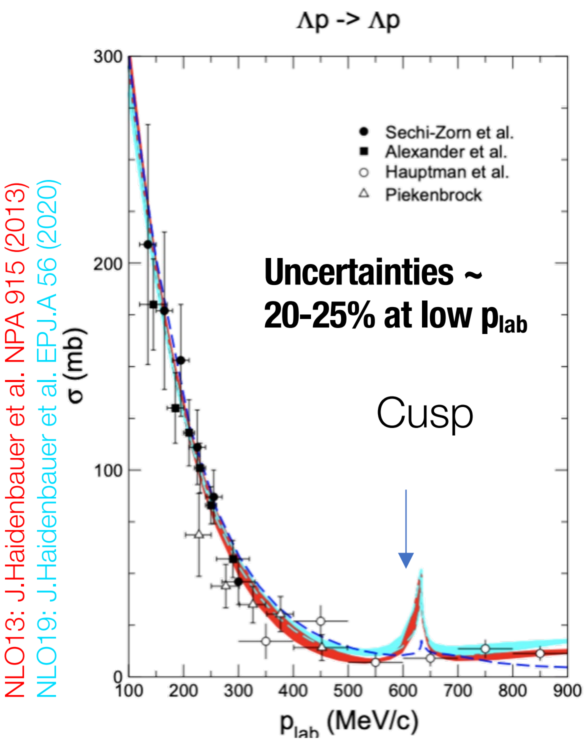
$$C(k^*) = \int S(r)\, \left|\psi(\vec{k}^*, \vec{r})\right|^2 d^3r$$

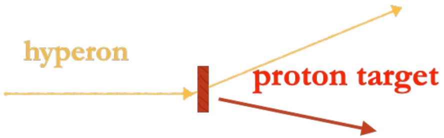
pp Correlation: AV18 + Coulomb potentials used to calculate $\psi(\vec{k}^*, \vec{r})$

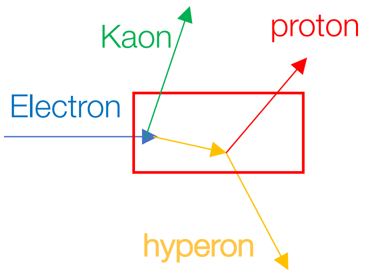


One universal source for all hadrons with strong resonance decays considered for each pair of interest

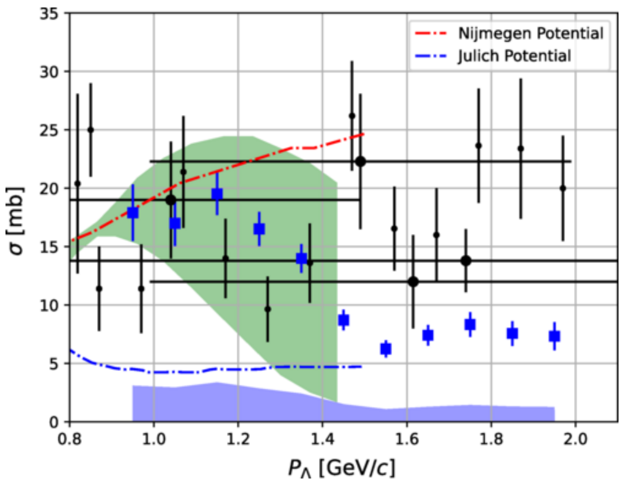
|S|=1: Λp Interaction in scattering data







CLAS Coll. PRL 127 (2021)

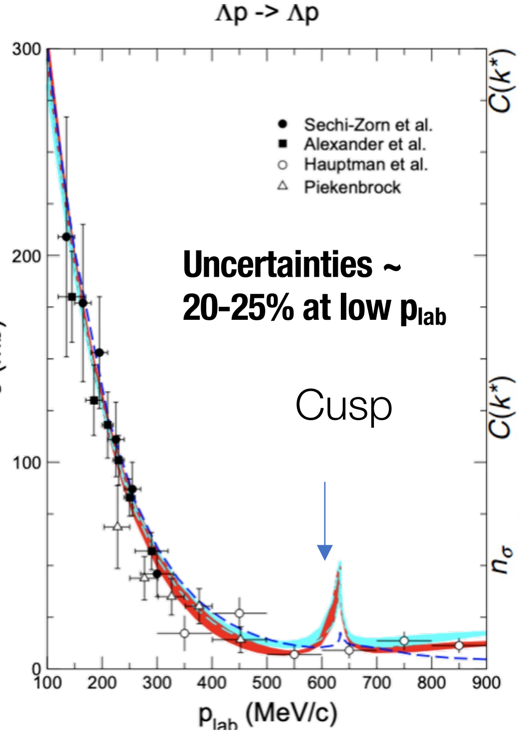


pΛ scattering data from 80ies
→ Low-statistics scattering at low momentum
→ ΣN-ΛN coupling is experimentally not seen

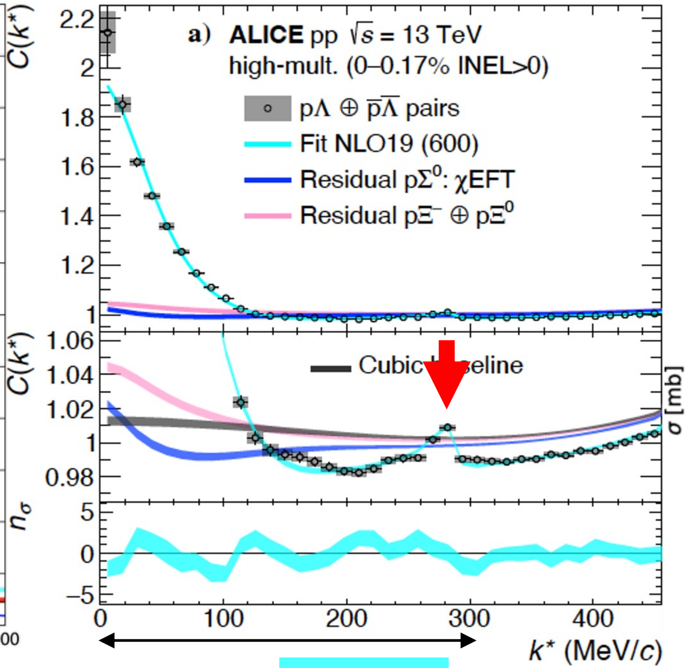
pΛ scattering in CLAS (2021)
→ Improved statistics at large momenta

|S|=1: Λp Interaction and ΣN coupling

NLO13: J.Haidenbauer et al. NPA 915 (2013)
NLO19: J.Haidenbauer et al. EPJ.A 56 (2020)



ALICE PLB 833 (2022) 137272



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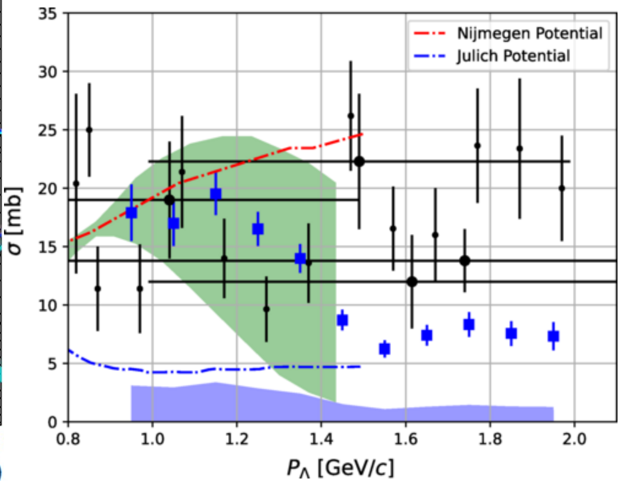


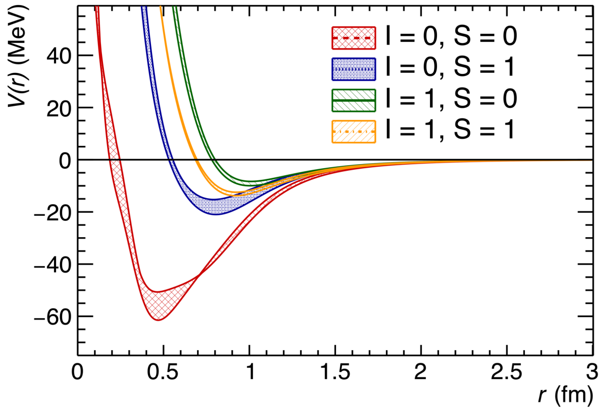
n_σ = 3.9

pΛ Correlation function measured by ALICE
→ ΣN-ΛN cusp visible for the first time
→ 30 times more precise at low momentum
→ Challenges NLO19

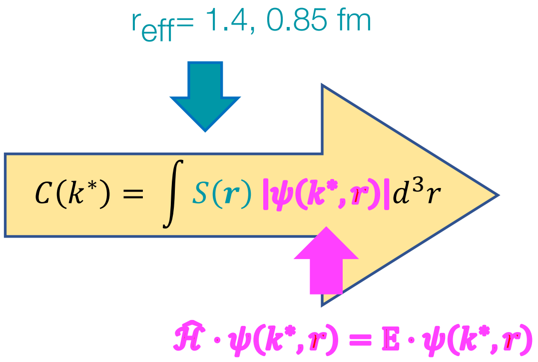
|S|=2 sector: pΞ^- interaction and first test of LQCD

Lattice QCD potentials from HAL QCD collaboration available

Local potentials for the nucleon-Ξ interactions



HAL QCD Coll. NPA 998 (2020)



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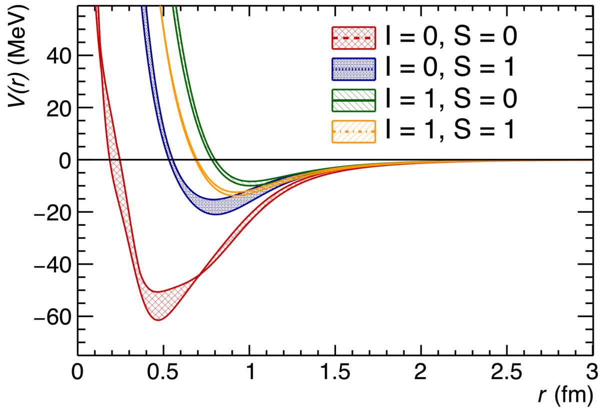
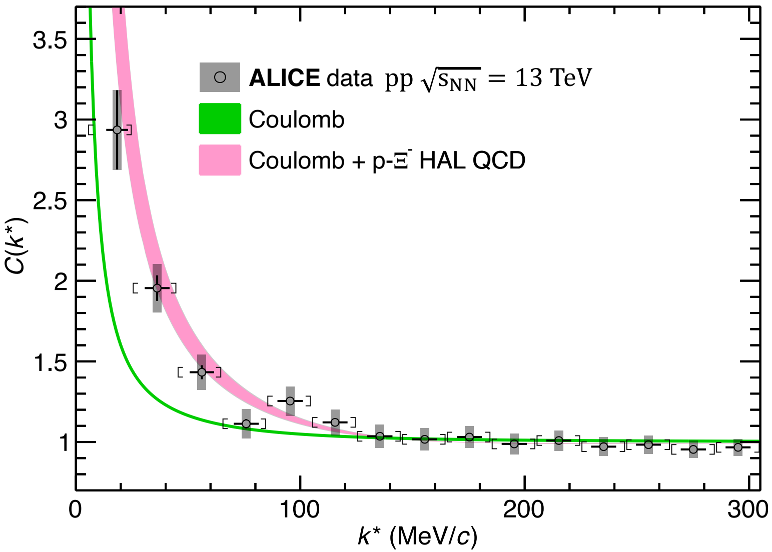


HAL QCD Coll. NPA 998 (2020)

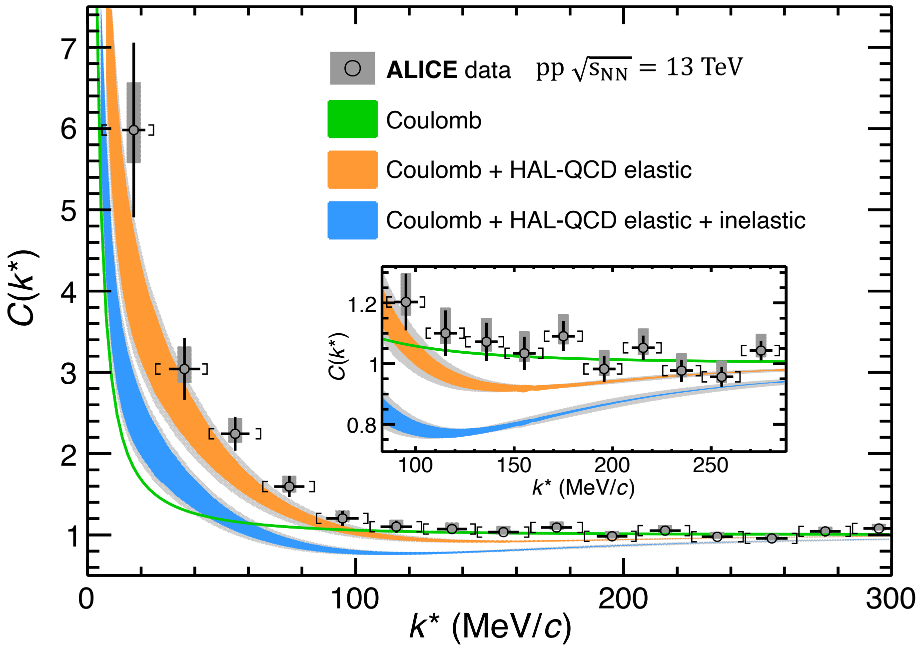
ALICE Coll. Nature 588 (2020)



Observation of a strong **attractive interaction** beyond Coulomb in agreement with lattice predictions

p–Ω⁻ correlation function in pp at 13 TeV

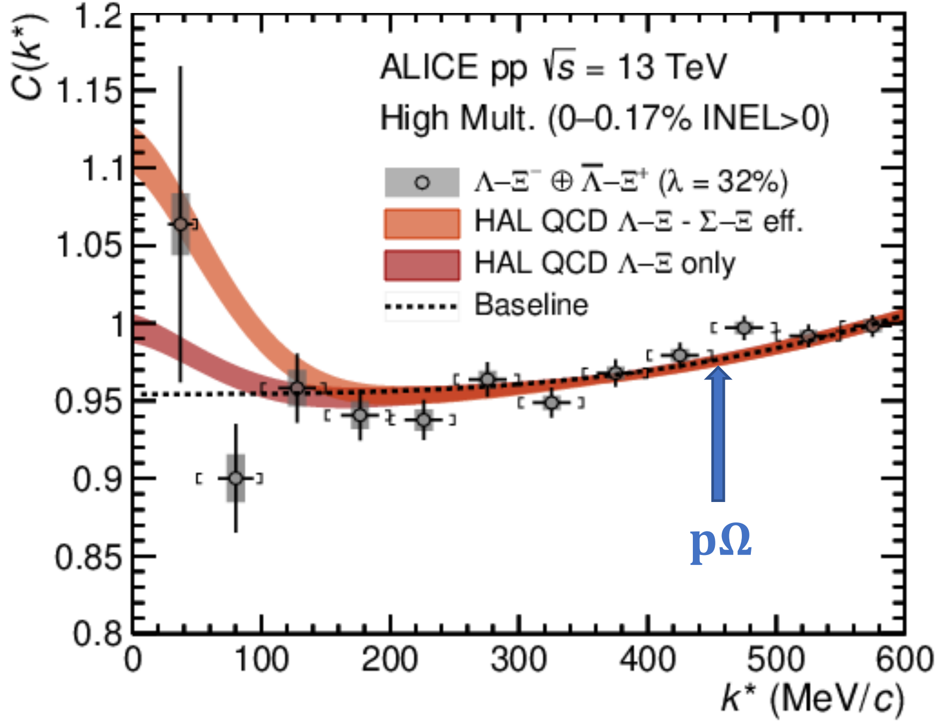
ALICE Coll. Nature 588, 232–238 (2020)



- Enhancement above Coulomb
  → Observation of the strong interaction
- Attraction in $^5S_2$ results in the prediction of a bound state (B.E. = 1.54 MeV)
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  - Inelastic channels dominated by absorption
  - Neglecting inelastic channels
- Data more precise than lattice calculations
- So far, no indication of a bound state

|S| = 3: Λ-Ξ⁻ interaction – with femtoscopy

ALICE Coll., arXiv:2204.10258, accepted by PLB



- Unknown contribution from coupled channels in Lattice QCD calculations
  → Coupling ΛΞ–ΣΞ sizable in HAL QCD calculation
  → No sensitivity yet ("No coupling" 0.64 nσ vs. „Coupling" 1.43 nσ)
- No NΩ cusp visible
  → Hint to negligible NΩ-ΛΞ coupling

(*) *N. Ishii et al.. EPJ Web of Conferences 175, 05013 (2018)*

p-p-p and p-p-Λ Correlation functions

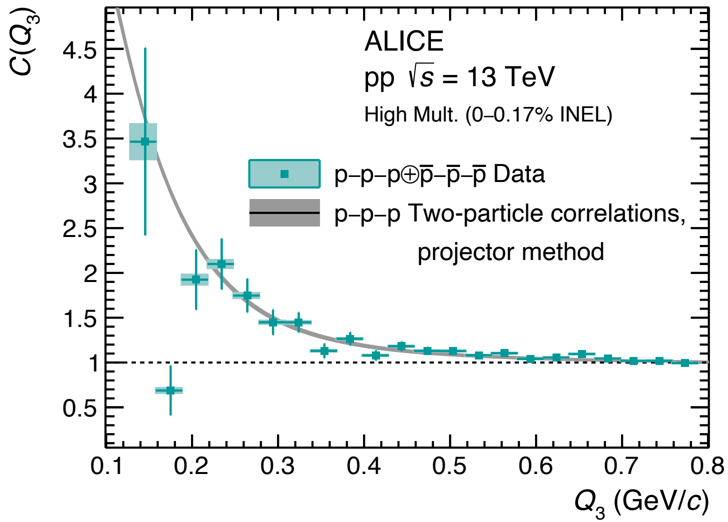
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2) \cdot P(\mathbf{p}_3)} = \mathcal{N} \cdot \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

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

$$q_{ij}^\mu = \left(p_i - p_j\right)^\mu - \frac{\left(p_i - p_j\right) \cdot P_{ij}}{P_{ij}^2} P_{ij}^\mu \qquad P_{ij} \equiv p_i + p_j$$

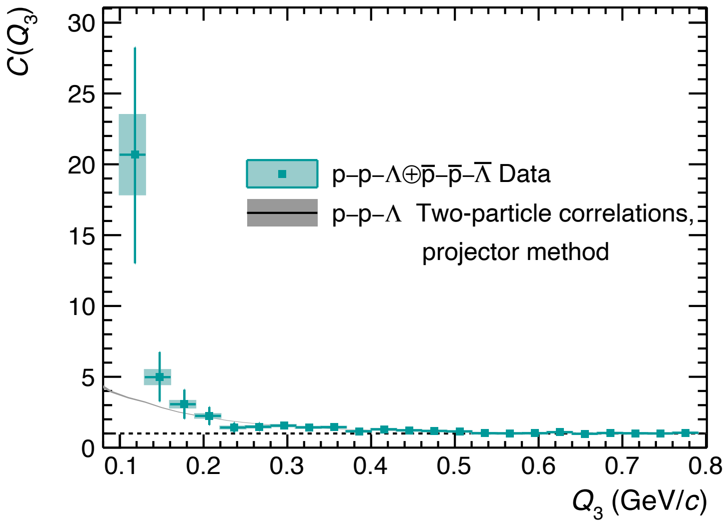
p-p-p correlation function

ALICE Coll., arXiv:2206.03344, accepted by EPJA



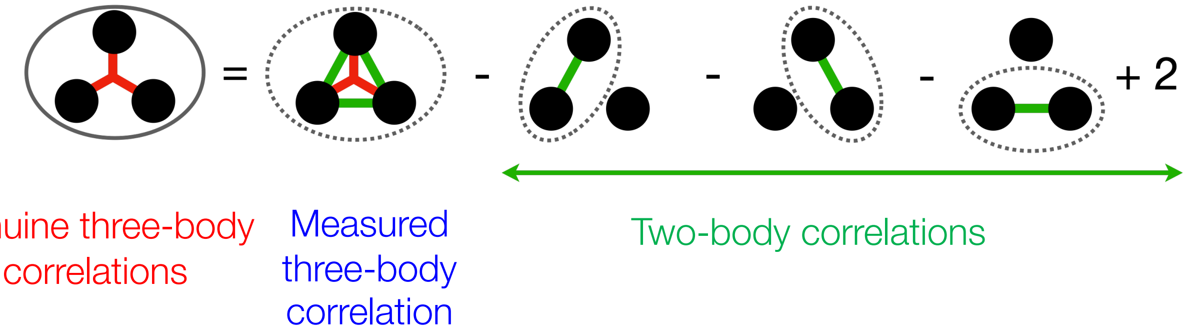
p-p-Λ correlation function

ALICE Coll., arXiv:2206.03344, accepted by EPJA



Cumulants

Genuine three-particle correlations isolated using the Kubo's cumulant expansion method:
R. Kubo, J. Phys. Soc. Jpn. 177 (1962)



In terms of correlation functions:

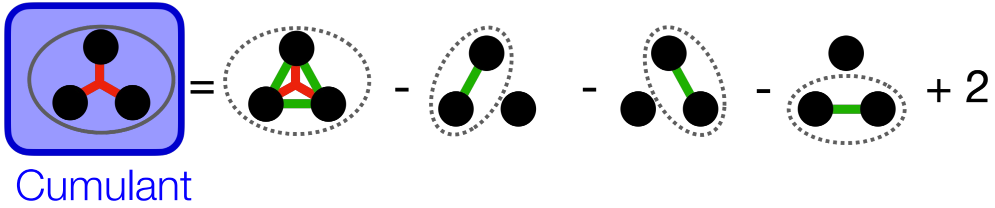
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

Projector method

Event mixing method

R. Del Grande et al. EPJC 82 (2022) 244

p-p-p Cumulants



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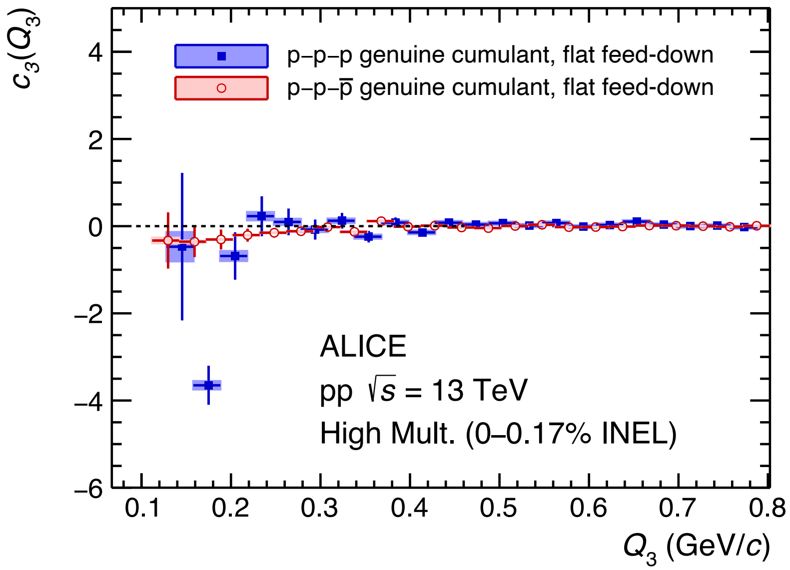


Statistical significance

→ n_σ = 6.7 for Q_3 < 0.4 GeV/c

Conclusion

→ Genuine three-body effect in the p-p-p system

Possible interpretations

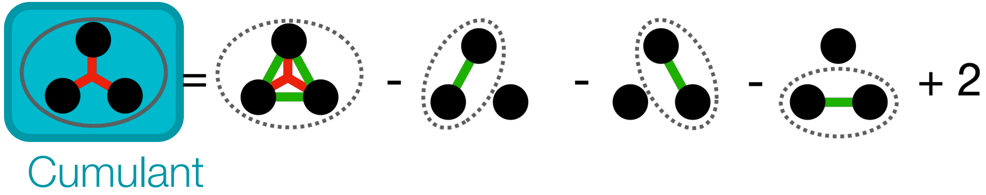
→ Pauli blocking at the three-particle level

→ Long range Coulomb interaction effects

→ Three-body strong interaction

Test with mixed-charge particles, cumulant negligible

p-p-Λ Cumulants



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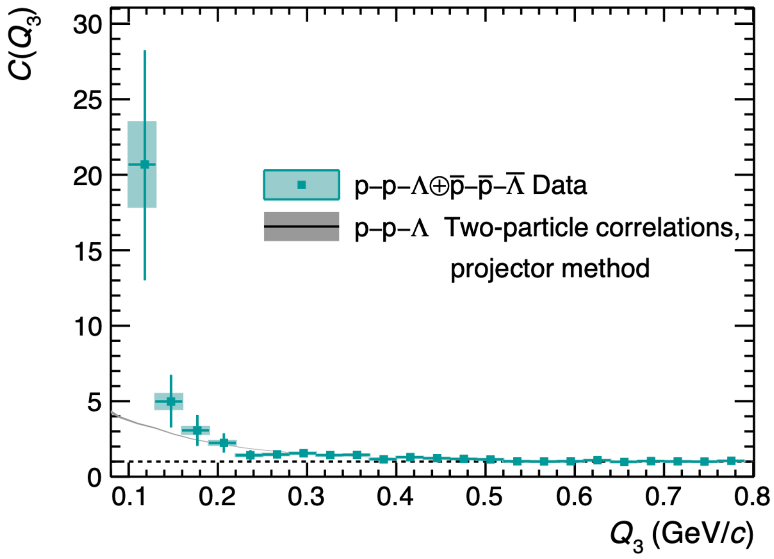


Statistical significance
→ n_σ = 0.8 for Q_3 < 0.4 GeV/c

Conclusion
→ No significant deviation from the null hypothesis

A factor 500 in statistics from the Run 3 data taking

→ Non-zero cumulant can be directly linked to the three-body strong interaction
→ Important measurement for neutron stars

Scattering parameters for pd and kd

kd scattering parameters from:

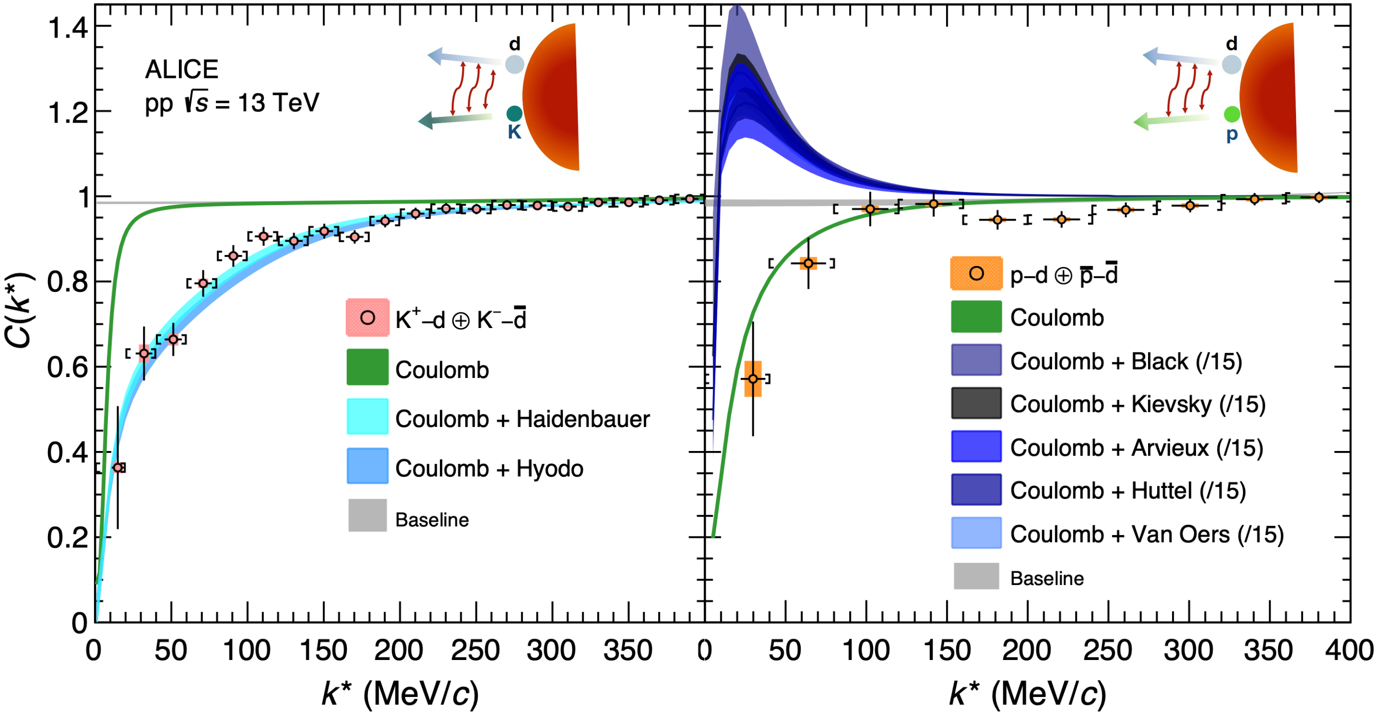
- From Haidenbauer: [a = - 0.470 fm, r= - 1.75fm] based on potential describing K+-d low-energy cross sections T. Takaki Phys. Rev. C 81, 055204 (2010),
- From Hyodo [a = - 0.540 fm, r= 0.0 fm] Starting from Chiral model KN scattering lengths : K. Aoki and D. Jido, PTEP 2019, 013D01 (2019)

Pd scattering parameters from: experiments and calculations listed in the table below

System	Spin averaged		S = 1/2		S = 3/2		References
	f_0(fm)	r_0(fm)	f_0(fm)	r_0(fm)	f_0(fm)	r_0(fm)	
pd			$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$	Van Oers et al. [15]
			$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.40}_{-0.10}$	$2.63^{+0.01}_{-0.02}$	Arvieux et al. [16]
			-4.0	—	-11.1	—	Huttel et al. [17]
			-0.024	—	-13.7	—	Kievsky et al. [18]
			$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—	Black et al. [19]
K^+d	-0.470	1.75					J.Haidenbaur et al.
	-0.540	0.0					T. Hyodo et al.

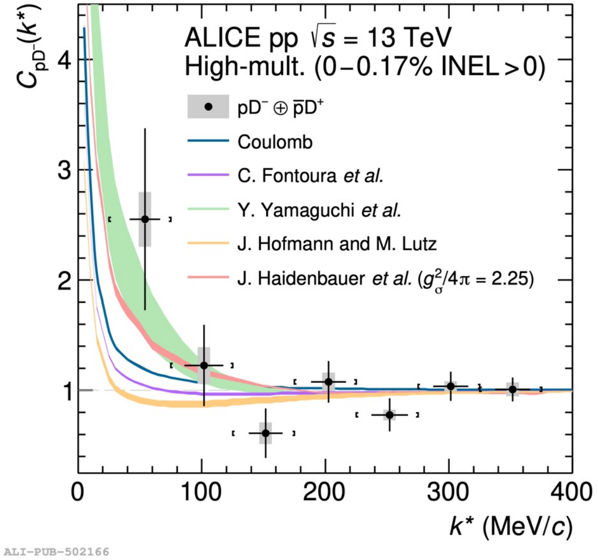
Comparison of model and data

- Source size:
  - $r_{\text{eff}}^{\text{K}^+\text{d}} = 1.41^{+0.03}_{-0.06}$ fm
  - $r_{\text{eff}}^{\text{pd}} = 1.08^{+0.06}_{-0.06}$ fm
- Remarks:
  - Kd data are well reproduced
  - for pd the Lednicky formula does not work!

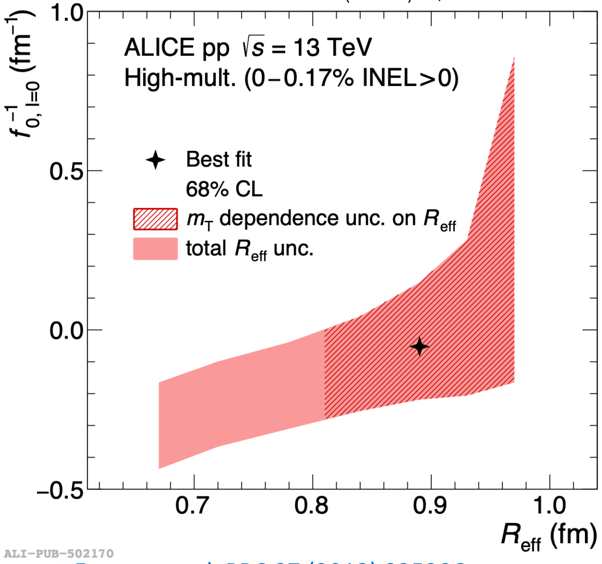


First measurement of D-p residual strong interaction

Small compared to other interactions (scattering lengths light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
Many models predict repulsive interaction
Possible bound state formation (Yamaguchi et al)



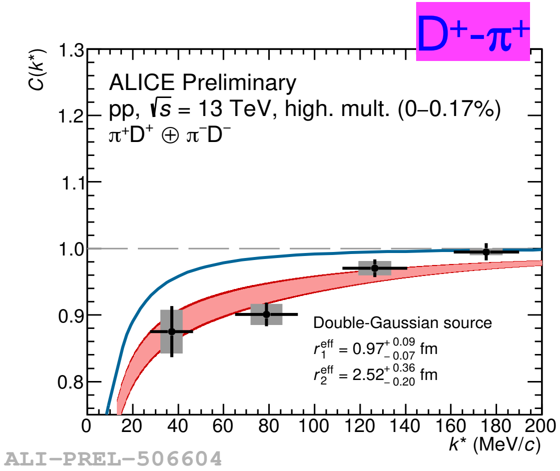
ALICE Coll. PRD 106 (2022) 5, 052010

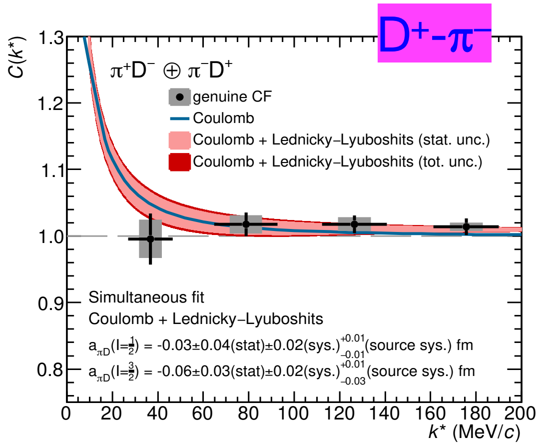


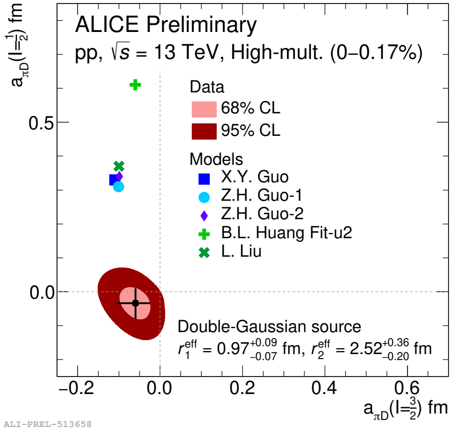
- Interval of scattering length for isospin I=0 at 68% CL indicates either attractive interaction with or without the formation of a bound state

J. Haidenbauer et al, EPJA 33 (2007) 107—117
J. Hofmann and M. Lutz, NPA 763 (2005) 90—139
Fontura et al, PRC 87 (2013) 025206
Yamaguchi et al, PRD 84 (2011) 014032

First measurement of D-K and D-π residual strong interaction



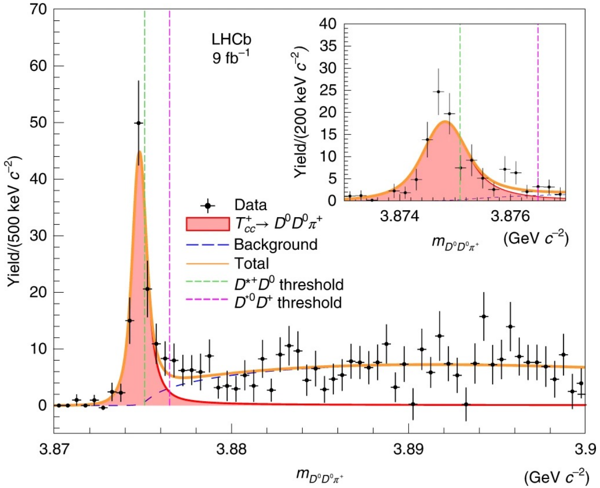


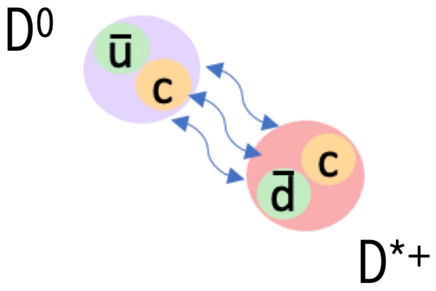


Simultenous fits of D-π and D-K correlations allow to determine the I= ½ and I= 3/2 scattering parameters. For I=1/2 the results agree with theoretical predictions

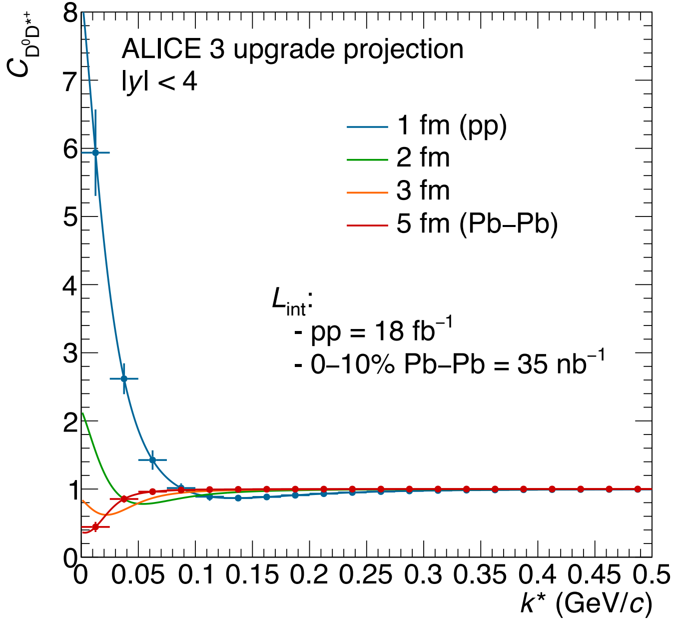
D*D correlation and link to molecular states

LHCb Coll. Nature Phys. (2022)





ALICE3 LoI https://cds.cern.ch/record/2803563

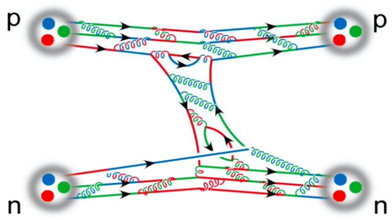


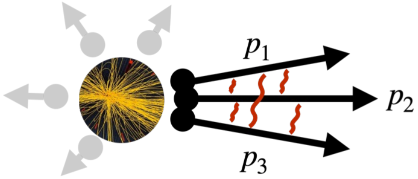
T_{cc}^{+} (J^P= 1+, I= 0): molecular state LHCb coll. Nature Comm. 13 3351 (2022)

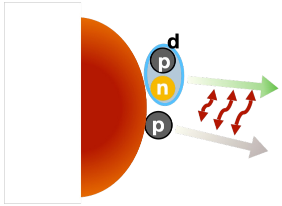
The scattering length of the $D^{*+}D^0$ pair should experience an inversion of sign at threshold

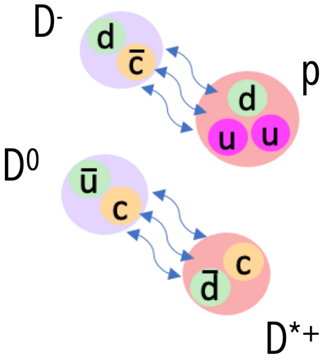
This translates into an inversion of the correlation function from pp to Pb-Pb collisions at the LHC Y. Kamiya and A. Ohnishi EPJA 58 (2022) 7,131

Summary









- Several two-body residual strong interaction have been measured with good precision and first test of lattice have been made possible
- The implication of the new findings on hyperon-nucleon interactions for the physics of neutron star could be important
- Three-body interactions can be investigated at the LHC
- First measurements of the residual strong interaction in the charm sector
- Implications for the study of molecular states containing charm quarks