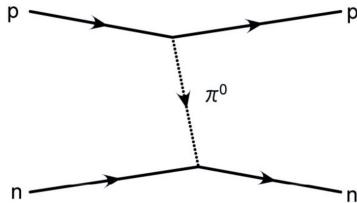
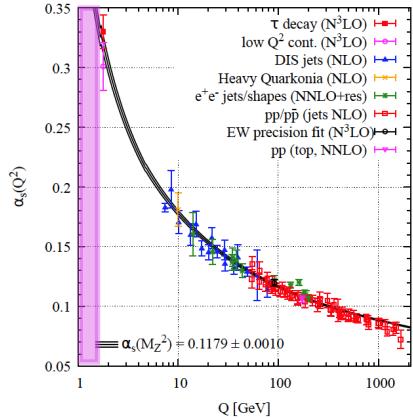


Recent results on strong interactions and hadron physics

Laura Fabbietti, Technische Universität München



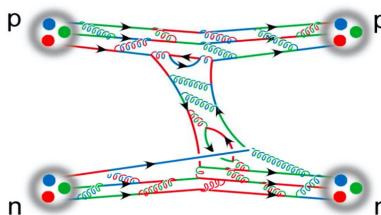
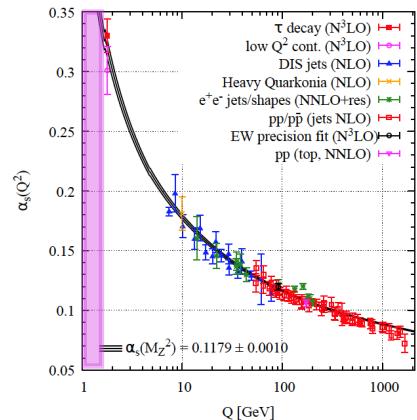
Residual strong interaction among hadrons



Non perturbative QCD $\rightarrow Q \sim 1$ GeV, $R \sim 1$ fm

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

Residual strong interaction among hadrons



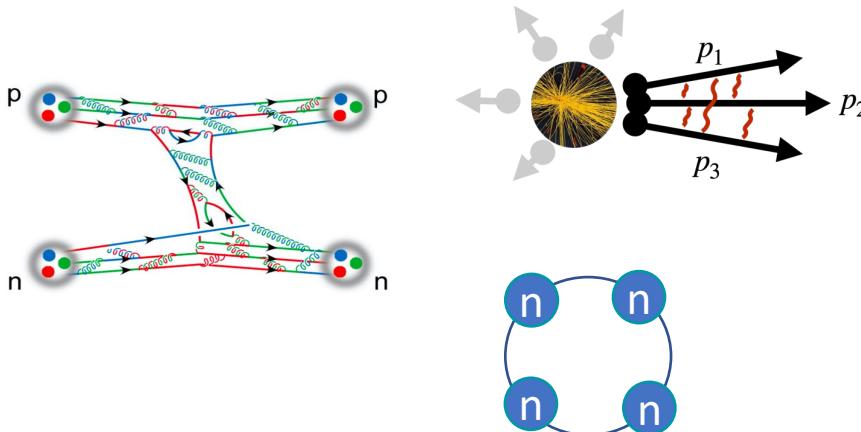
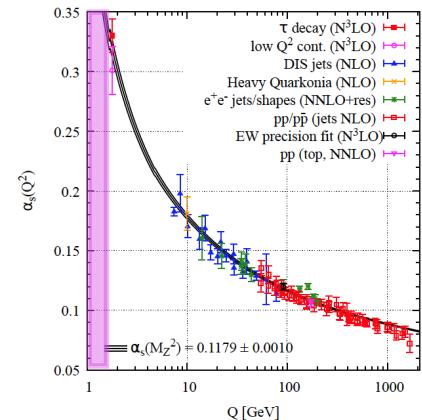
Non perturbative QCD $\rightarrow Q \sim 1$ GeV, $R \sim 1$ fm

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New results:

→ Understanding of the interaction starting from quark and gluons

Residual strong interaction among hadrons



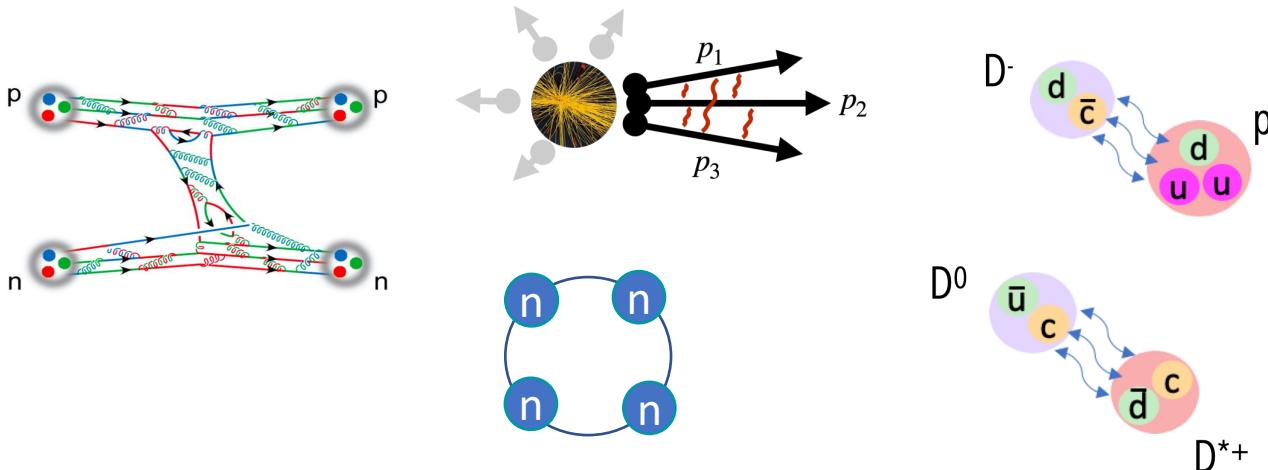
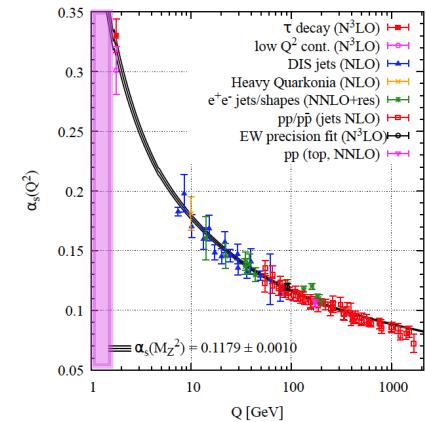
Non perturbative QCD $\rightarrow Q \sim 1$ GeV, $R \sim 1$ fm

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New results:

- Understanding of the interaction starting from quark and gluons
- New experimental methods to investigate three- and four-body systems

Residual strong interaction among hadrons



Non perturbative QCD $\rightarrow Q \sim 1$ GeV, $R \sim 1$ 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- and four-body systems
- First studies of the strong interaction for the charm sector

Hyperon appearance in neutron stars?

Dimensions

$R \sim 10 - 15$ km
 $M \sim 1.1 - 2.2 M_{\odot}$

Outer Crust

Ions, electron gas,
Neutrons

Inner Core

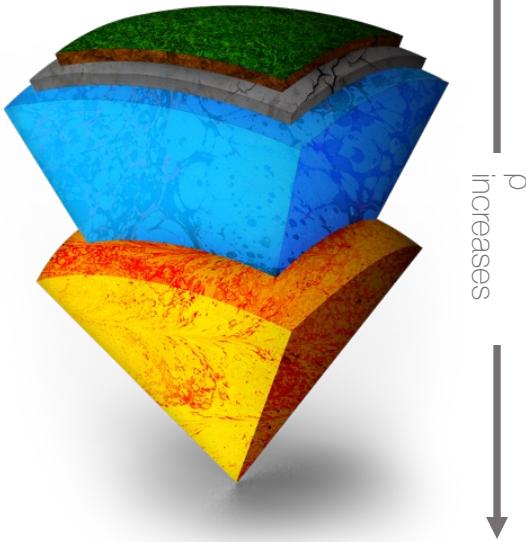
Neutrons?

Protons?

Hyperons?

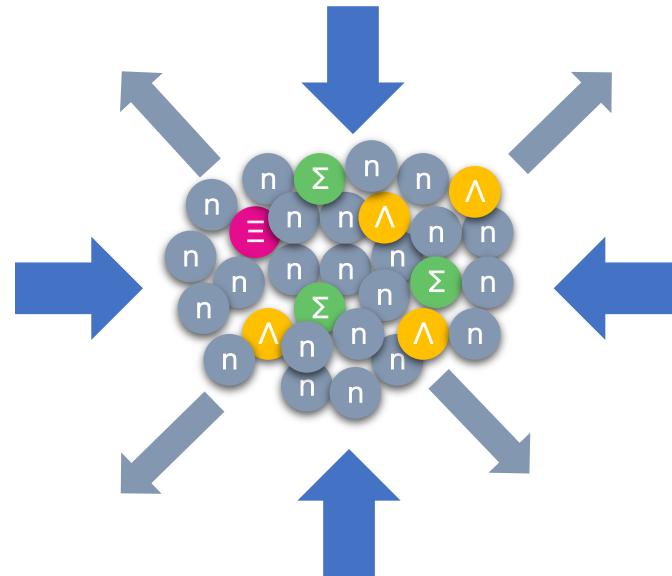
Kaon condensate?

Quark Matter?

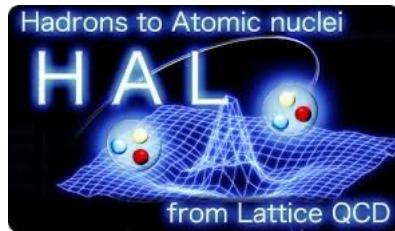


Neutron Stars: very dense, compact objects

- What are the constituents to consider?
- How do they interact?
- What is the equation of state?

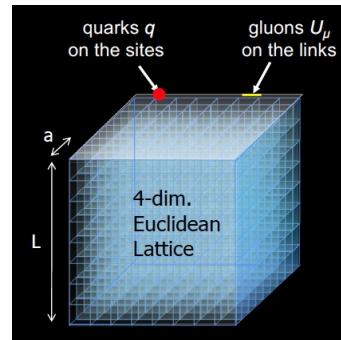


Residual strong interaction from lattice



T. Hatsuda, K. Sasaki et al.

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



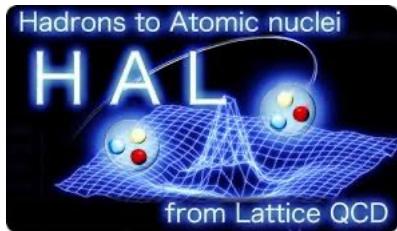
$$a = 0.085 \text{ fm}$$

$$L = 8.1 \text{ fm}$$

$$m_\pi = 146 \text{ MeV}/c^2$$

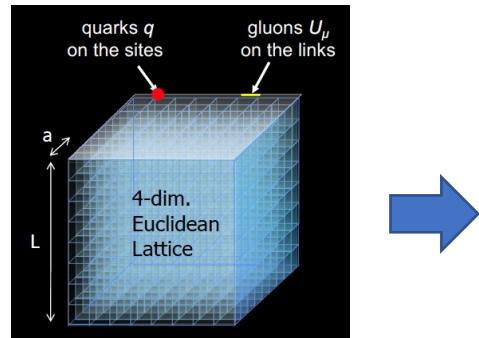
$$m_K = 525 \text{ MeV}/c^2$$

Residual strong interaction from lattice



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HAL QCD Coll. PLB 792 (2019)
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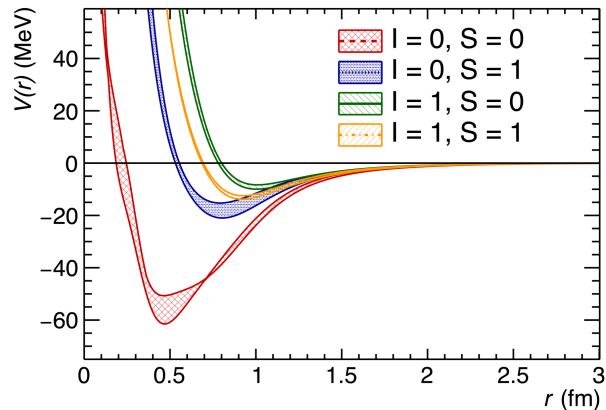
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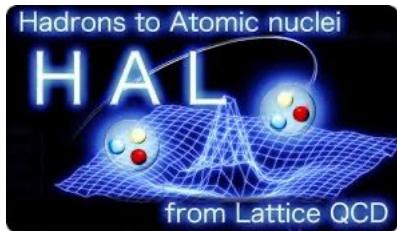
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Local potentials for the nucleon- Ξ interactions



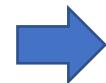
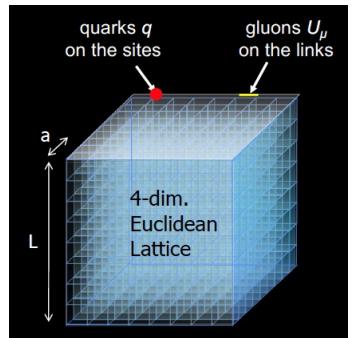
HAL QCD Coll. NPA 998 (2020)

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)

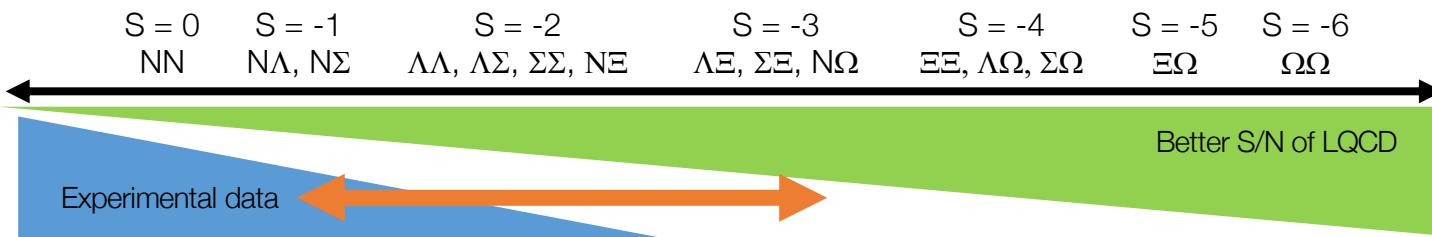


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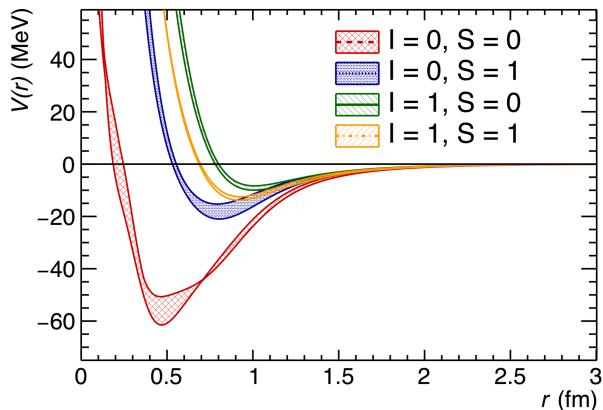
$$L = 8.1 \text{ fm}$$

$$m_\pi = 146 \text{ MeV}/c^2$$

$$m_K = 525 \text{ MeV}/c^2$$

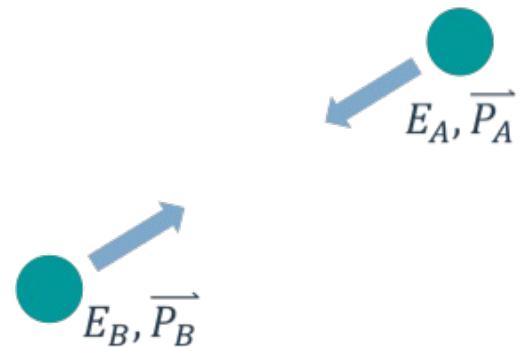


Local potentials for the nucleon- Ξ interactions

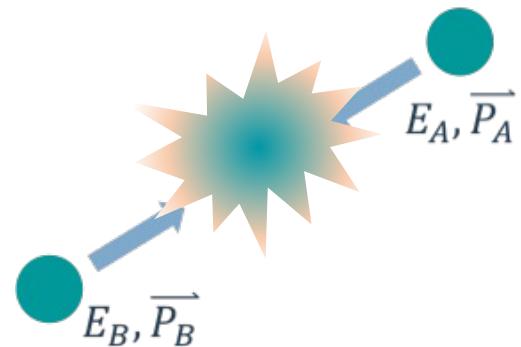


HAL QCD Coll. NPA 998 (2020)

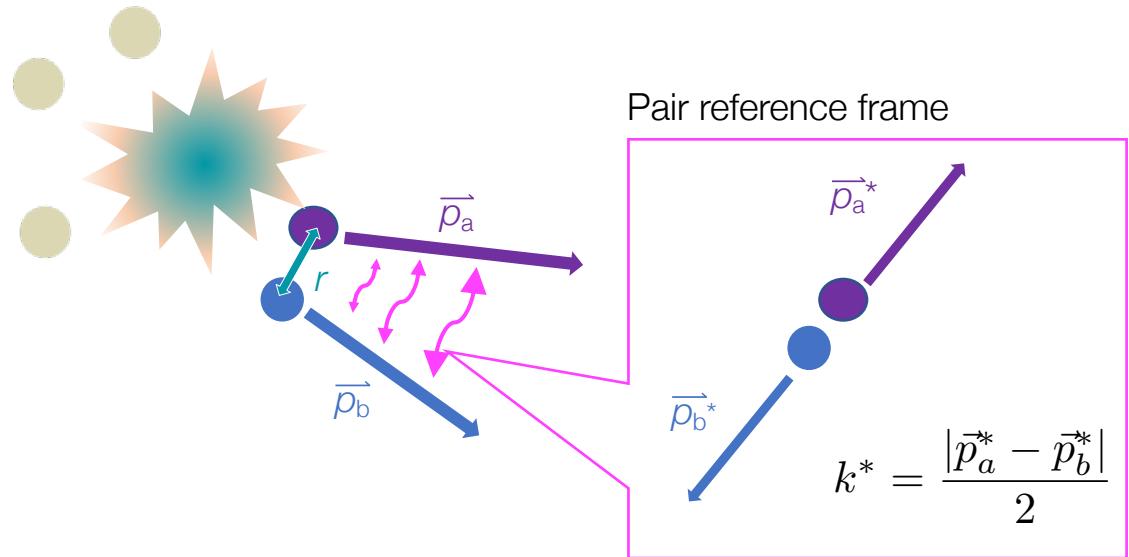
pp collisions at the LHC



pp collisions at the LHC



Particle production and propagation



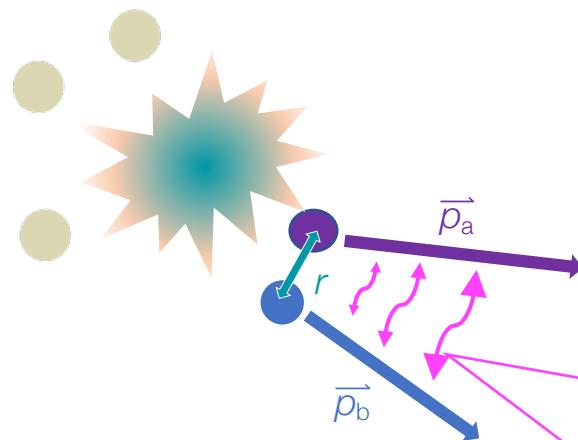
The Koonin-Pratt formalism

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

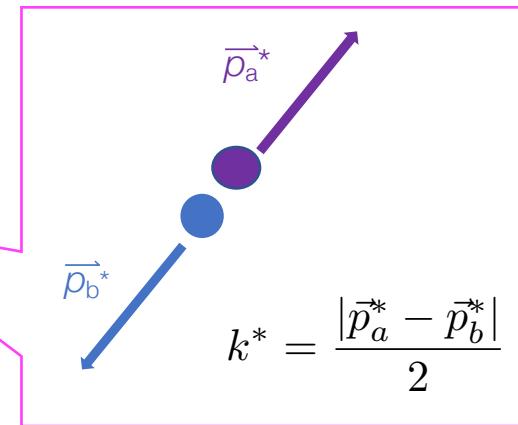
$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r) |\psi(\vec{k}^*, \vec{r})|^2 d^3r$$

Emission source

Two-particle wave function



Pair reference frame



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

Emission source

Two-particle wave function

Pair reference frame

$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2}$$

Schrödinger Equation:

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

Correlation function and potentials

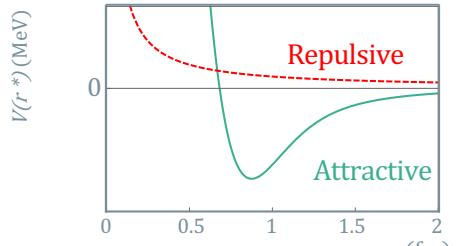
Source parametrisation



Gaussian source

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

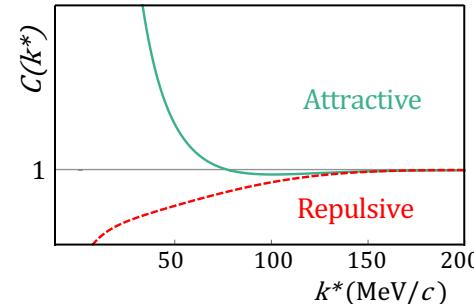
Interacting potential



Schrödinger \downarrow equation**

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

Correlation function



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

D. Mihaylov et al. EPJC 78 (2018)

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

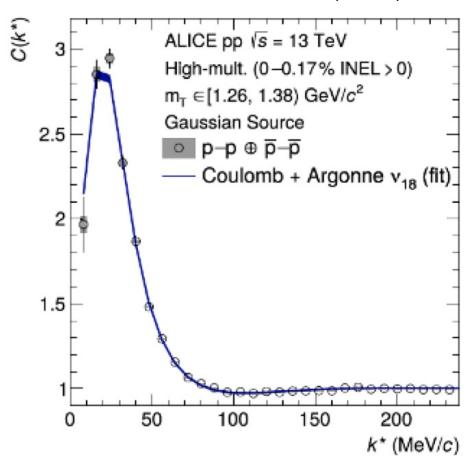
Emission source Two-particle wave function

$C(k^*) > 1$ if the interaction is attractive
 $= 1$ if there is no interaction
 < 1 if the interaction is repulsive

Source model



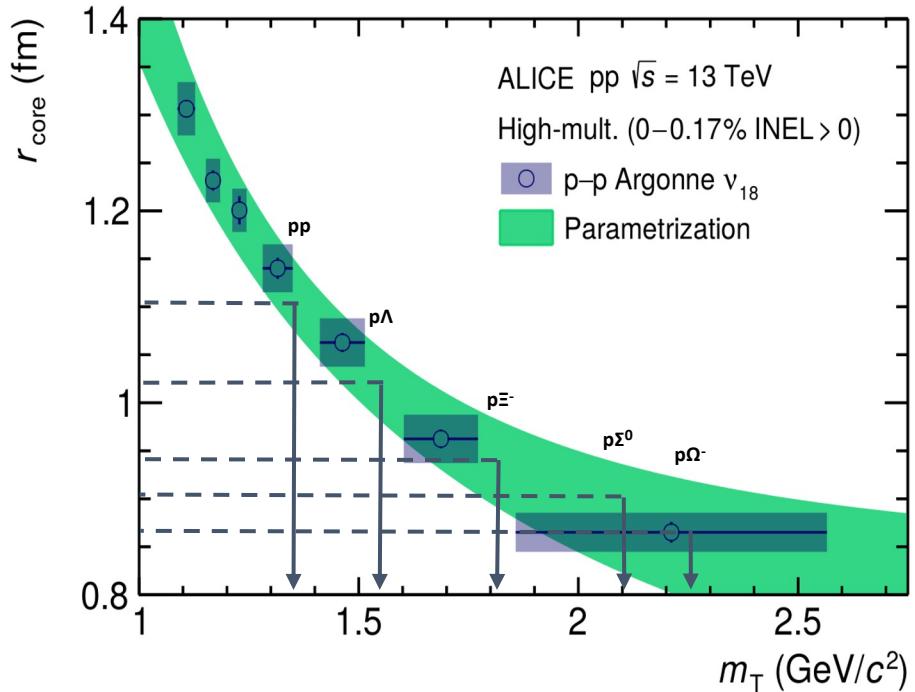
ALICE Coll., PLB, 811 (2020)



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

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

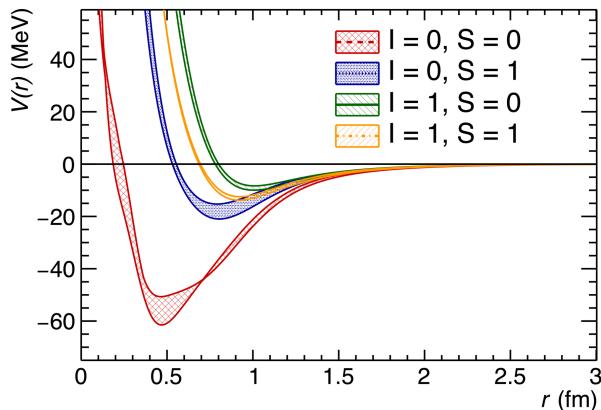
One universal source for all hadrons with strong resonance decays considered for each pair of interest



$|S|=2$ sector: $p\bar{\Xi}$ -interaction and first test of LQCD

Lattice QCD potentials from HAL
QCD collaboration available

Local potentials for the nucleon- Ξ
interactions



$$r_{\text{eff}} = 1.4, 0.85 \text{ fm}$$

$C(k^*) = \int S(r) |\psi(k^*, r)| d^3r$

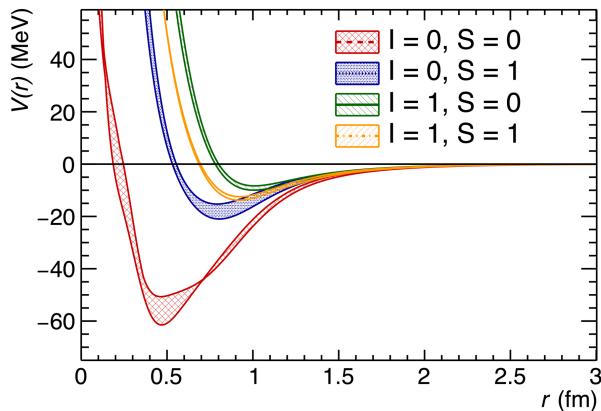
$$\hat{\mathcal{H}} \cdot \psi(k^*, r) = E \cdot \psi(k^*, r)$$

HAL QCD Coll. NPA 998 (2020)

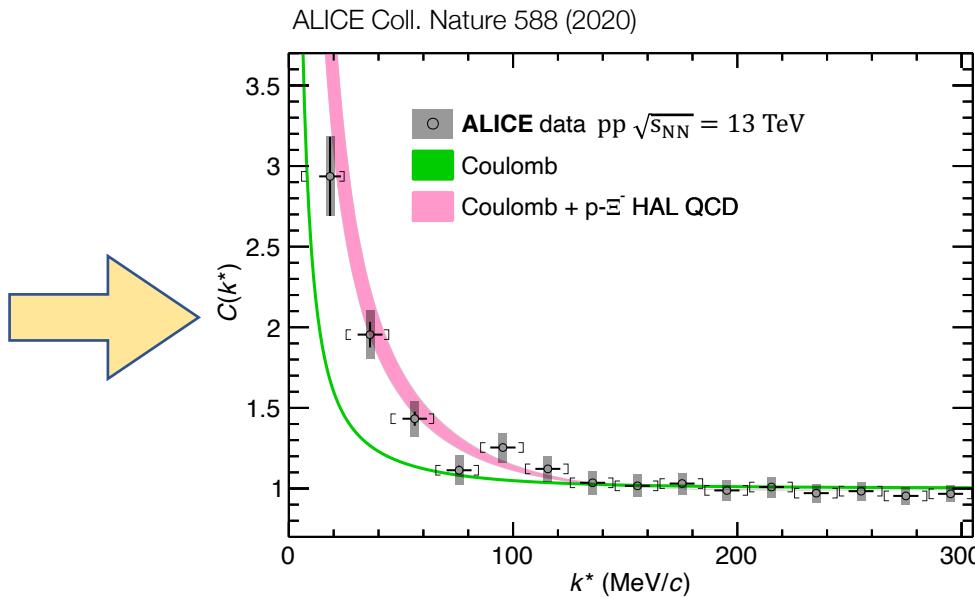
$|S|=2$ sector: $p\bar{\Xi}^-$ interaction and first test of LQCD

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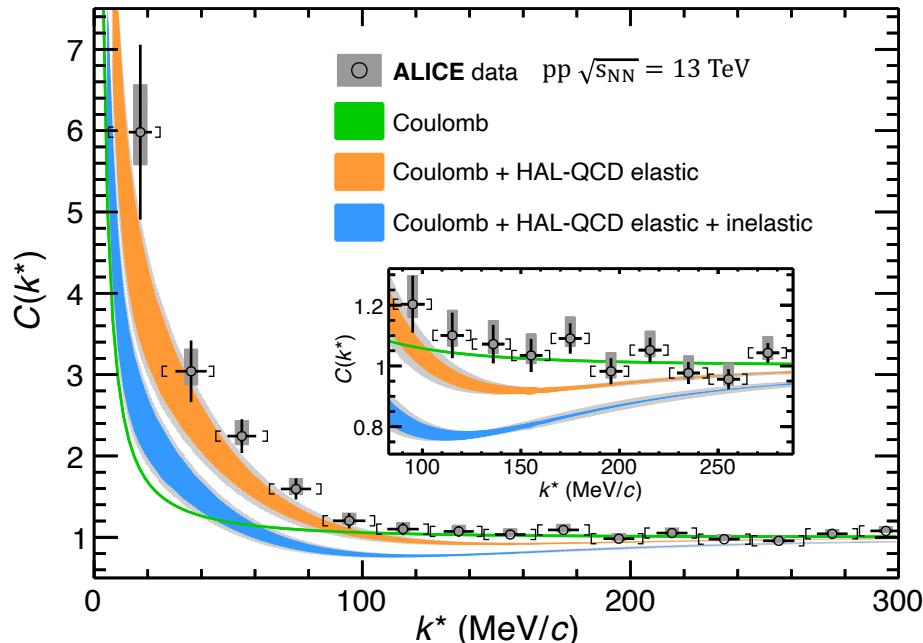
HAL QCD Coll. NPA 998 (2020)



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

$p-\Omega^-$ correlation function in pp at 13 TeV

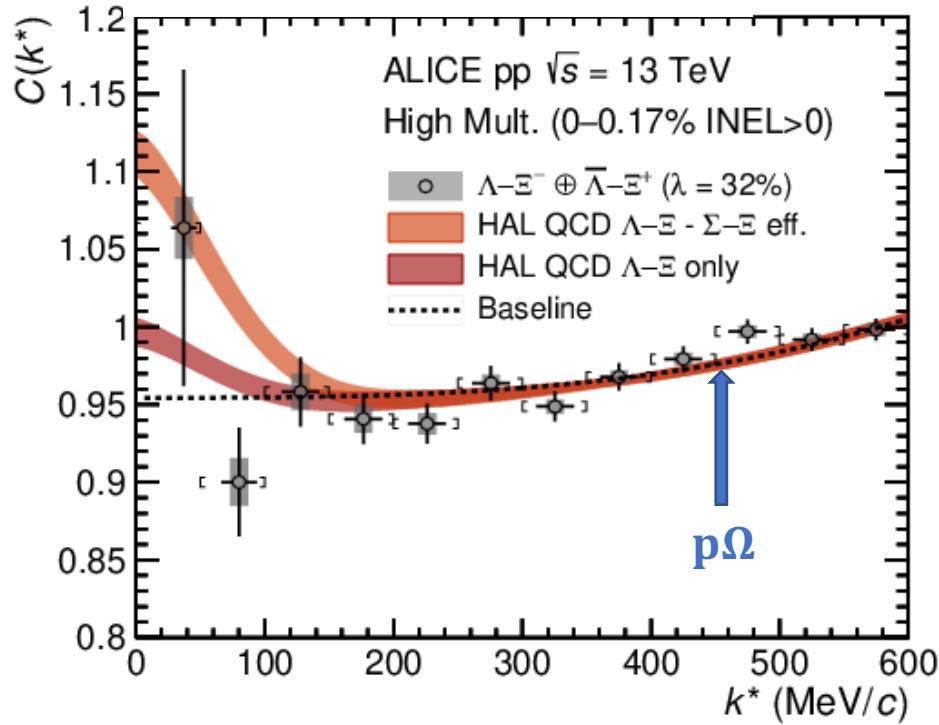
ALICE Coll. Nature 588, 232–238 (2020)



- 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

$|S| = 3: \Lambda\bar{\Xi}^-$ interaction – with femtoscopy

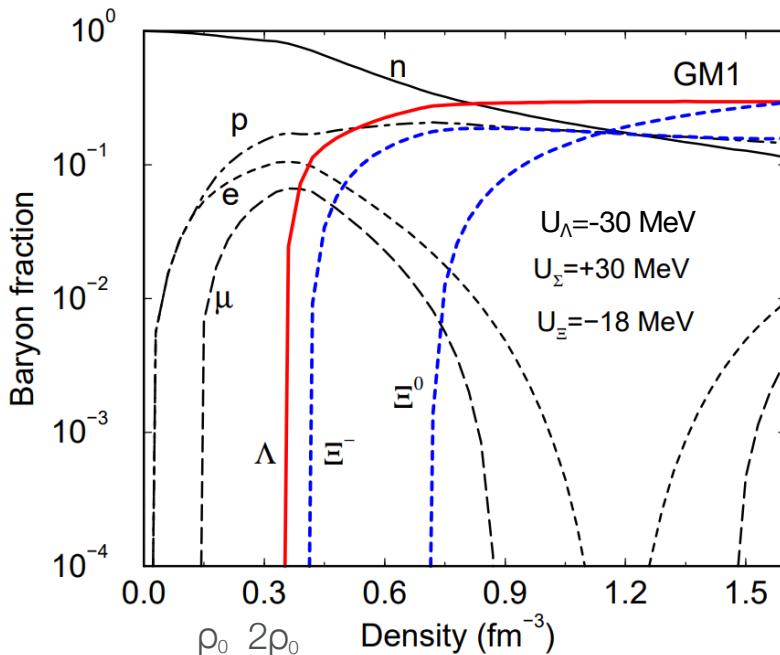
ALICE Coll., arXiv:2204.10258



- Unknown contribution from coupled channels in Lattice QCD calculations
→ Coupling $\Lambda\bar{\Xi}^- - \Sigma\bar{\Xi}$ sizable in HAL QCD calculation
- → No sensitivity yet (“No coupling” 0.64 no vs. „Coupling“ 1.43 $n\sigma$)
- No $N\Omega$ cusp visible
→ Hint to negligible $N\Omega\bar{\Lambda}\Xi$ coupling

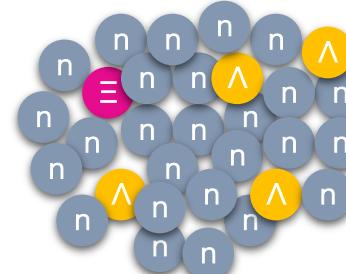
Hyperon appearance in neutron stars?

U = single particle potential



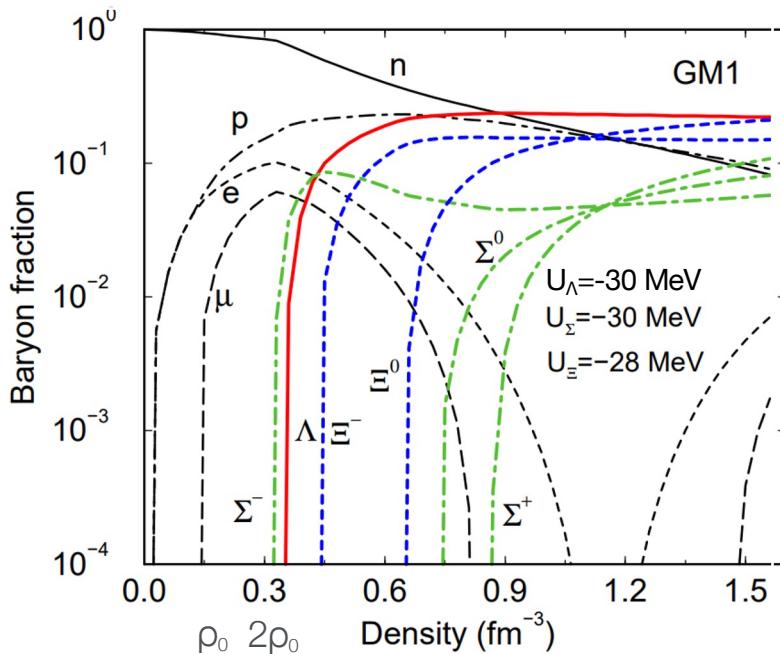
J. Schaffner-Bielich et al NPA 835 (2010)

- Hyperon might appear in neutron stars since it is energetically favourable
- But the resulting equation of state might be too soft to explain heavy neutron stars



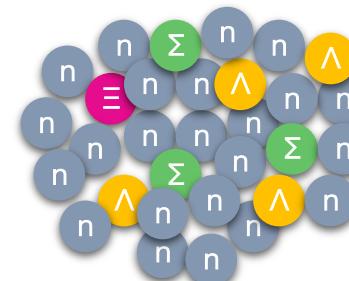
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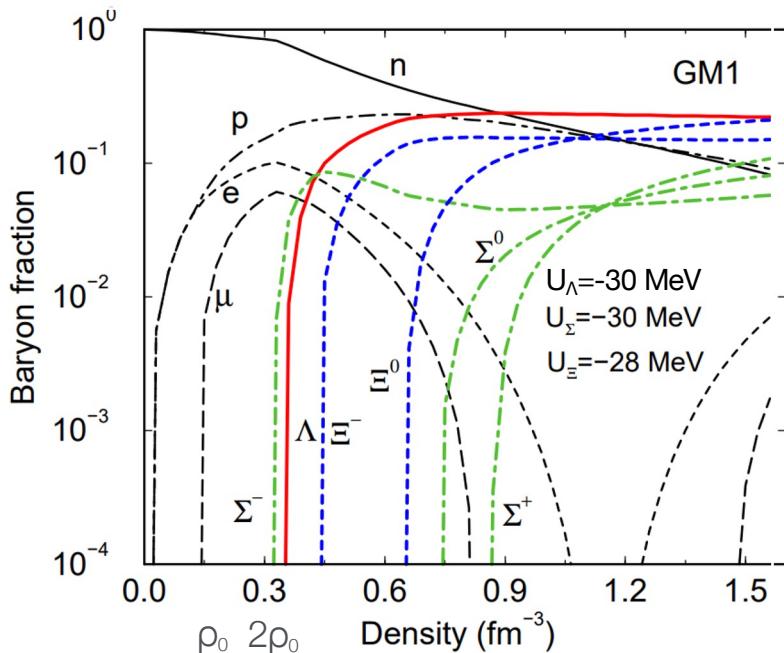
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- Different hyperon-nucleon interactions lead to different equation of states



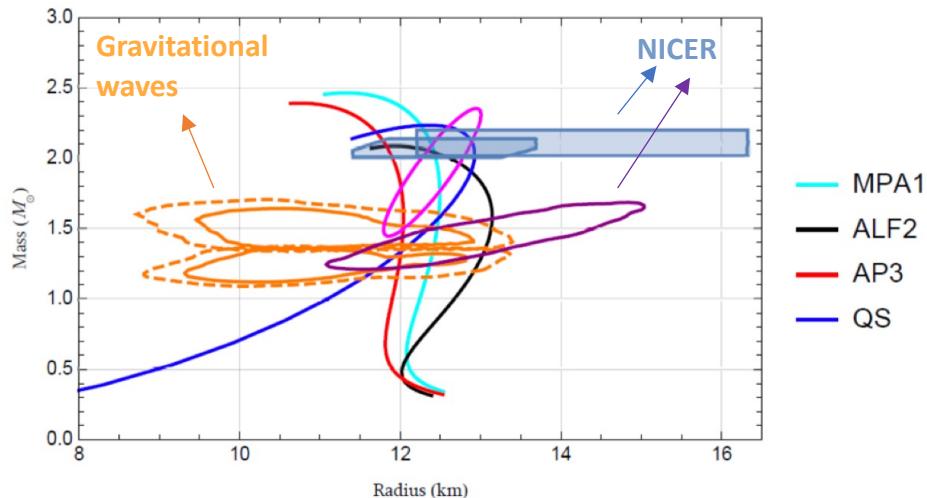
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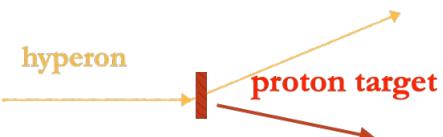
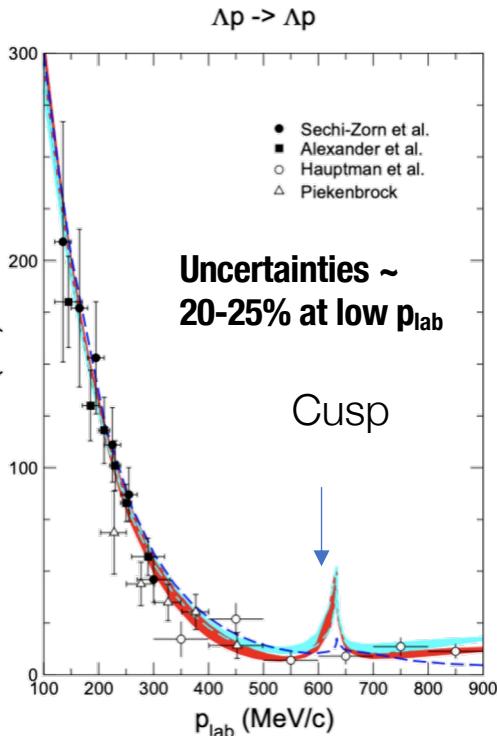
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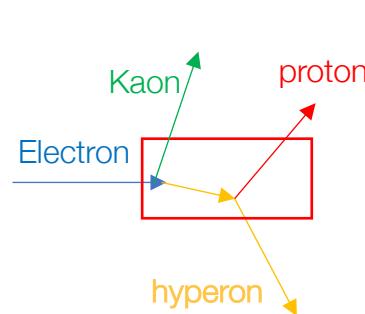
$|S|=1: \Lambda p$ Interaction in scattering data

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

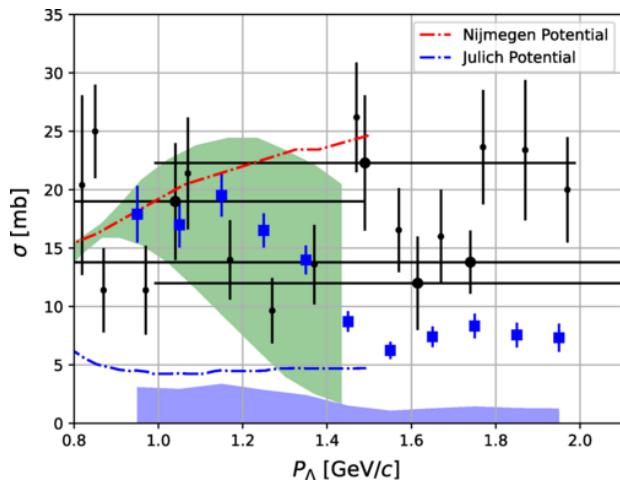


$p\Lambda$ scattering data from 80ies

- Low-statistics scattering at low momentum
- $\Sigma N - \Lambda N$ coupling is experimentally not seen



CLAS Coll. PRL 127 (2021)



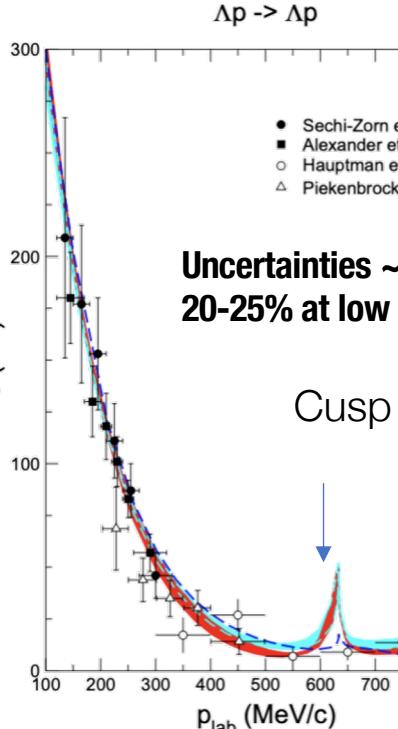
$p\Lambda$ scattering in CLAS (2021)

- Improved statistics at large momenta

$|S|=1$: Λp Interaction and ΣN coupling

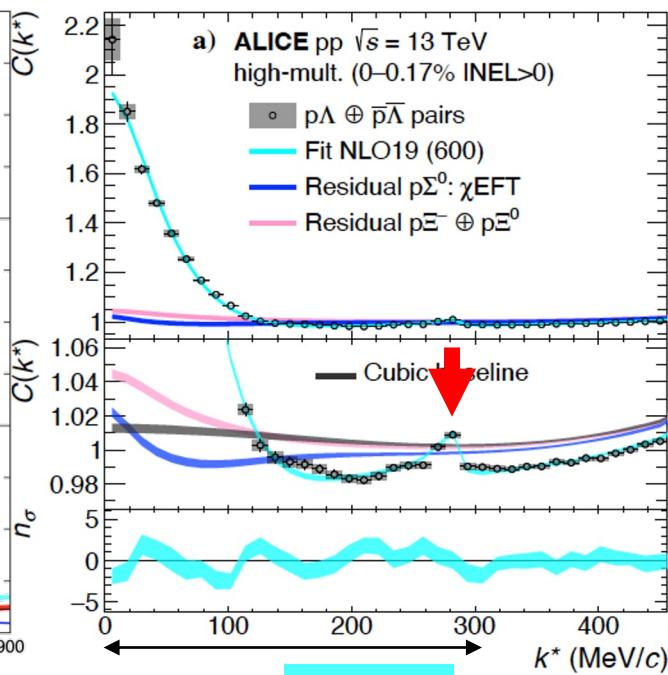
$\Lambda p \rightarrow \Lambda p$

NLO13: J.Haidenbauer et al. *NPA* 915 (2013)
 NLO19: J.Haidenbauer et al. *EPJA* 56 (2020)

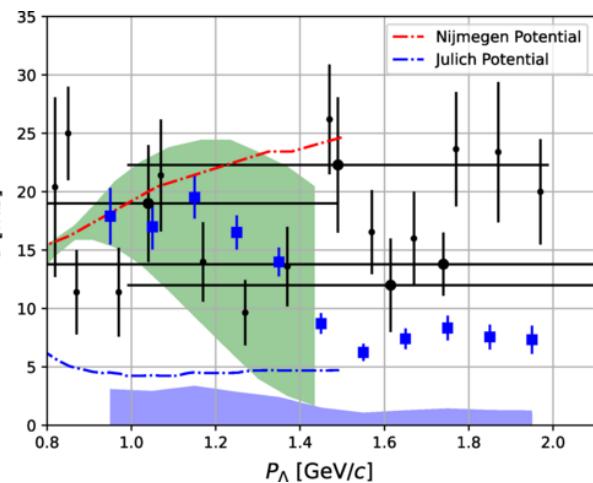


$\rho\Lambda$ Correlation function measured by ALICE
 → ΣN - ΛN cusp visible for the first time
 → 30 times more precise at low momentum
 → Challenges NLO19

ALICE Coll. arXiv:2104.04427, accepted by PLB

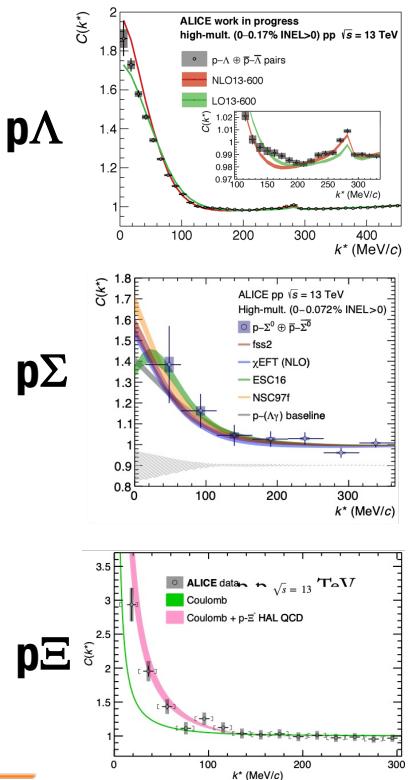


CLAS Coll. PRL 127 (2021)

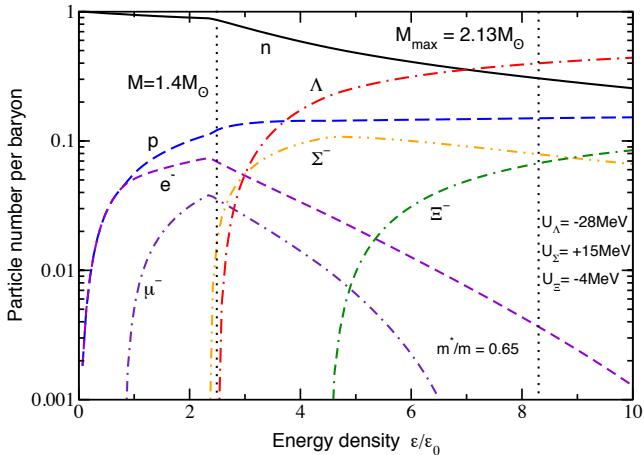


An example of equation of state for neutron stars

Correlation = two-body interaction

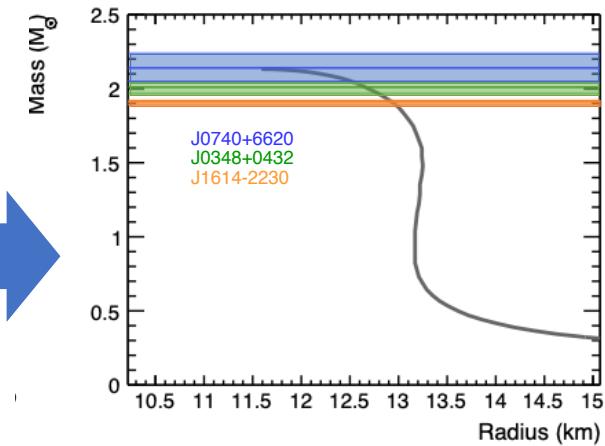


Single particle potentials = Equation of state



Courtesy J. Schaffner-Bielich 2020

Mass-Radius diagram for hyperon stars



LF et al. Ann.Rev.Nucl.Part.Sci. 71 (2021)

What about the strong interaction three- and four-body strong interactions?

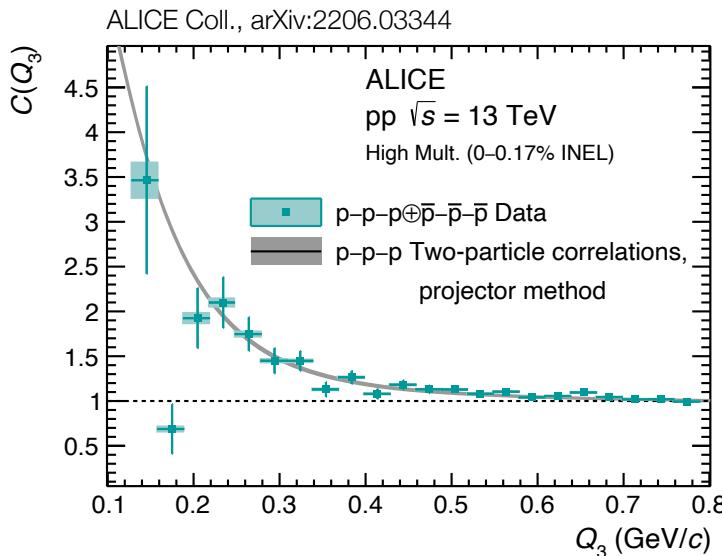
p-p-p and p-p- Λ Correlation functions

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

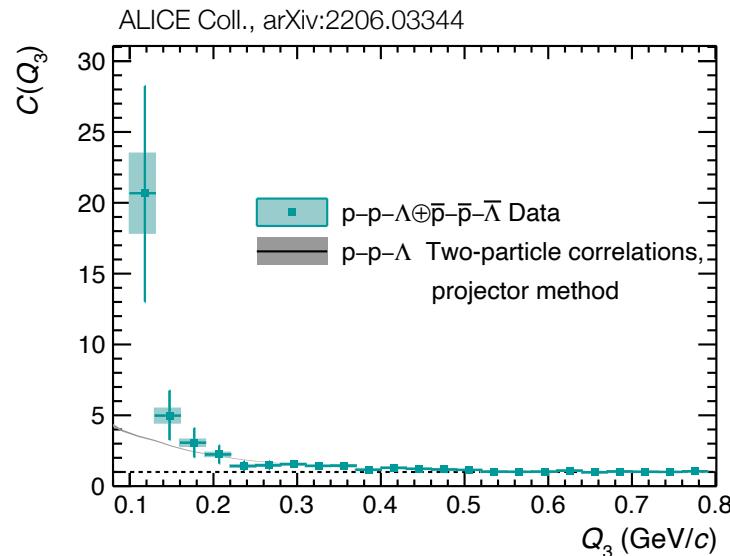
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

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

p-p-p correlation function

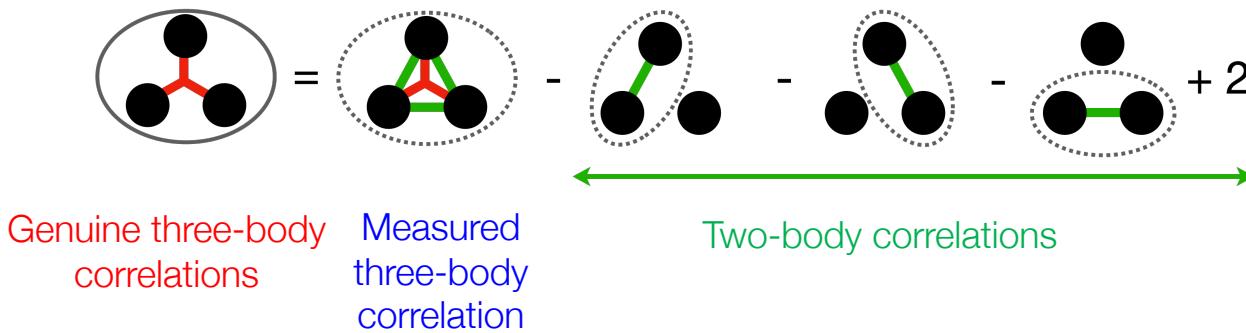


p-p- Λ correlation function



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:

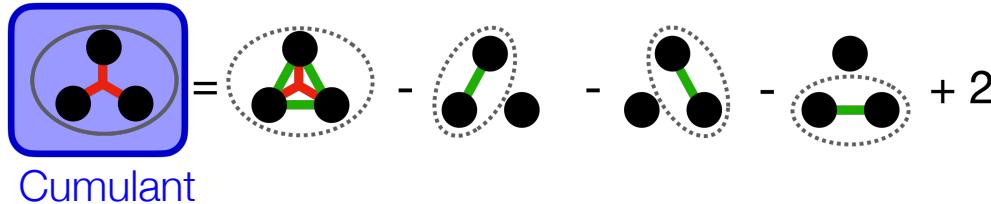
$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

Projector method

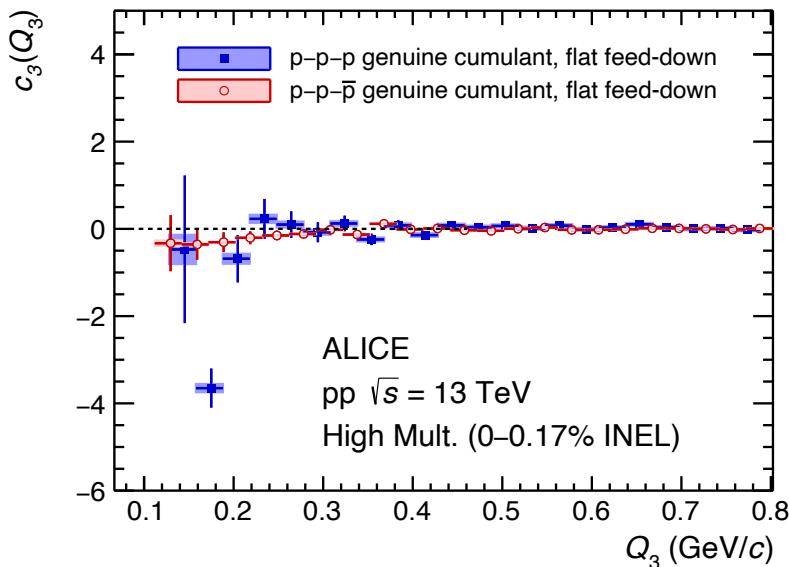
Event mixing method

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

p-p-p Cumulants



ALICE Coll., arXiv:2206.03344



Statistical significance

$\rightarrow n_\sigma = 6.7$ for $Q_3 < 0.4$ GeV/c

Conclusion

\rightarrow Genuine three-body effect in the p-p-p system

Possible interpretations

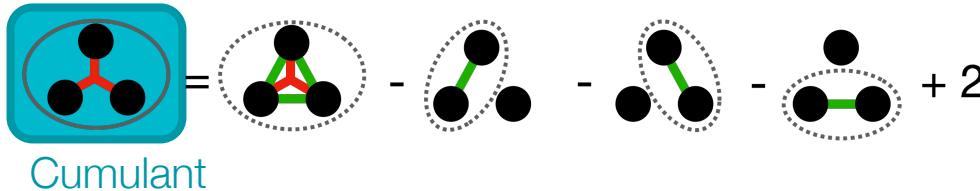
\rightarrow Pauli blocking at the three-particle level

\rightarrow Long range Coulomb interaction effects

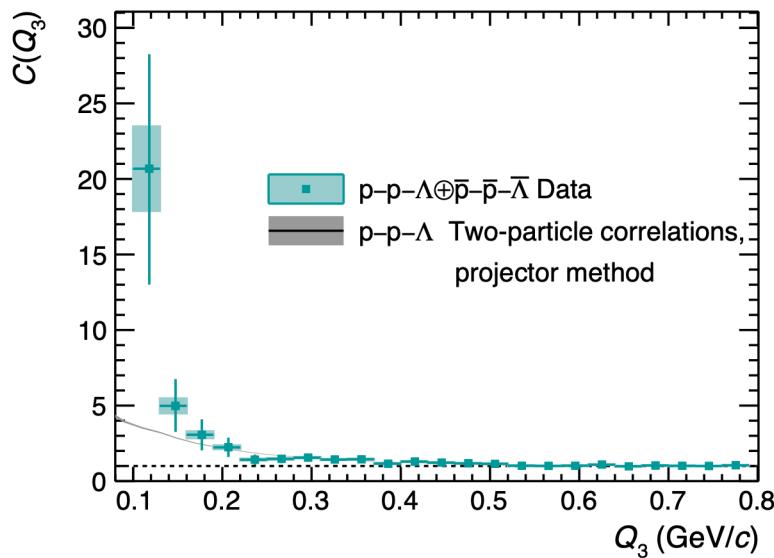
\rightarrow Three-body strong interaction

Test with mixed-charge particles, cumulant negligible

p-p- Λ Cumulants



ALICE Coll., arXiv:2206.03344



Statistical significance

→ $n_\sigma = 0.8$ for $Q_3 < 0.4$ GeV/c

Conclusion

→ No significant deviation from the null hypothesis

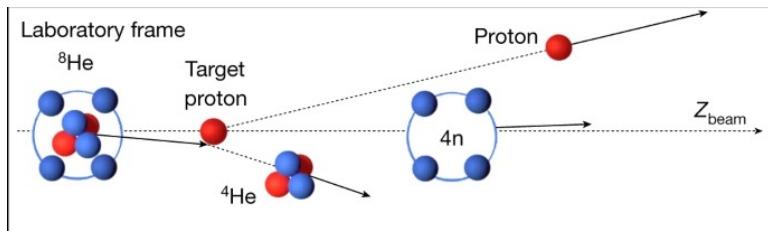
A factor 500 in statistics from the Run 3 data taking

→ Non-zero cumulant can be directly linked to the three-body strong interaction

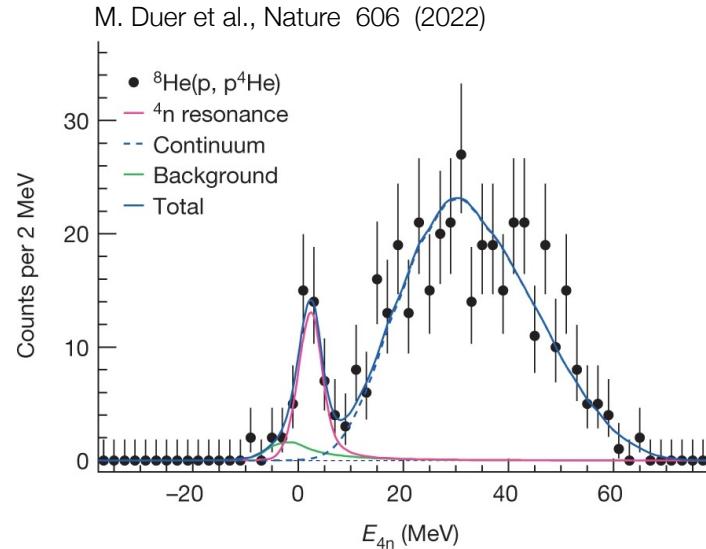
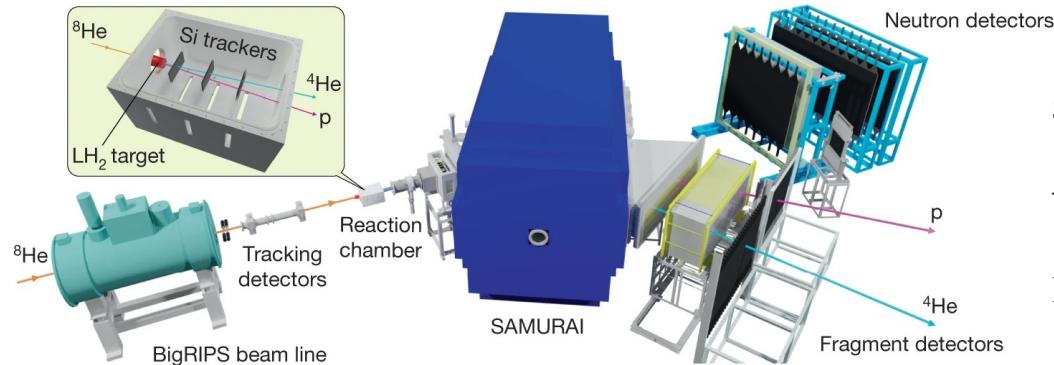
→ Important measurement for neutron stars

Moving to 4 nucleons

Quasi-free knockout of α core to produce a recoil-free 4 neutron system in the cm of ${}^8\text{He}$



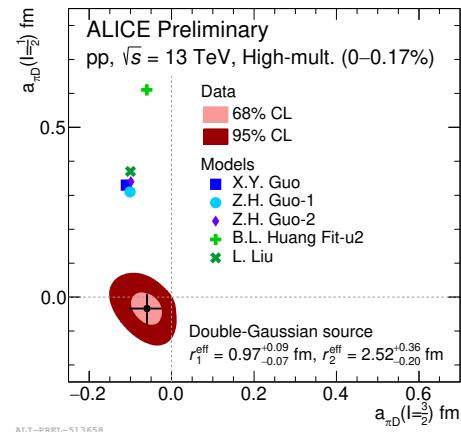
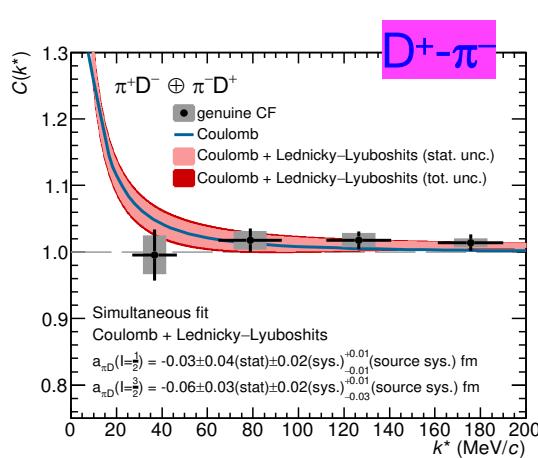
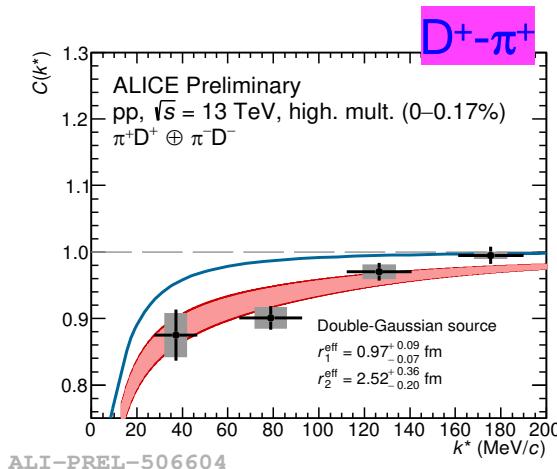
The SAMURAI set-up



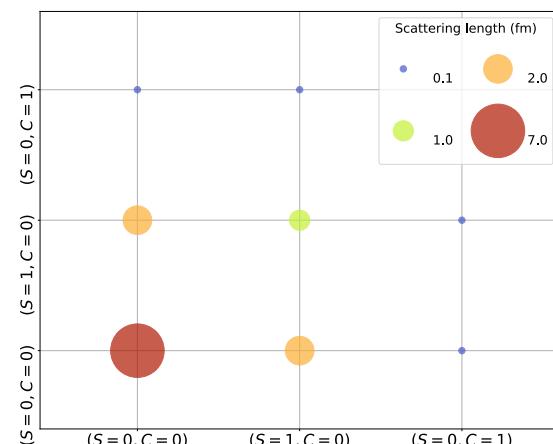
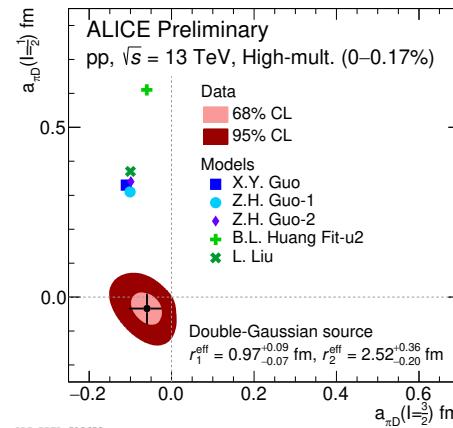
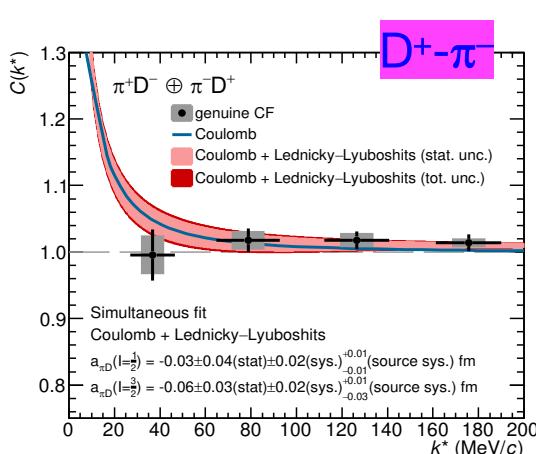
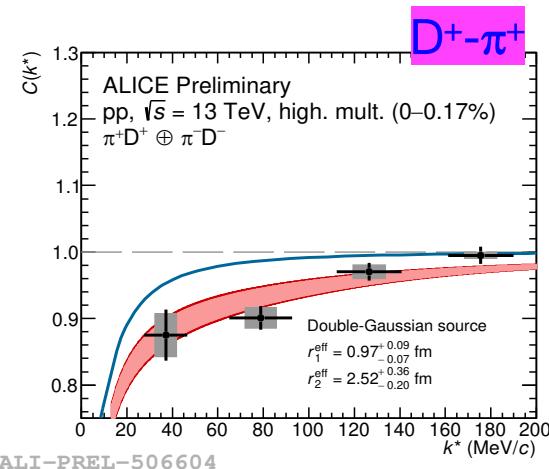
Searched for 60 years and theory disagrees
Is it a resonance or a scattering / continuum feature?

$$E_R = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.}) \text{ MeV},$$

$$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.}) \text{ MeV}.$$



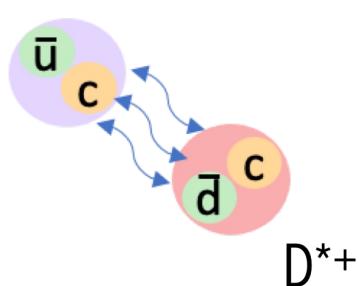
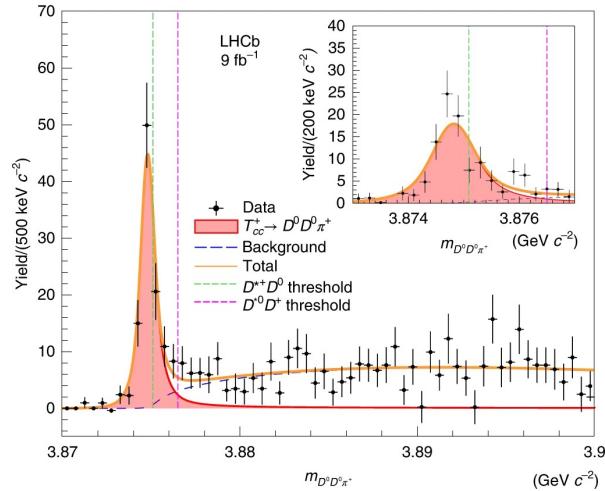
Simultaneous fits of D- π and D-K correlations allow to determine the $l= \frac{1}{2}$ and $l= \frac{3}{2}$ scattering parameters. For $l=1/2$ the results agree with theoretical predictions



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

D^{*}D correlation and link to molecular states

LHCb Coll. Nature Phys. (2022)

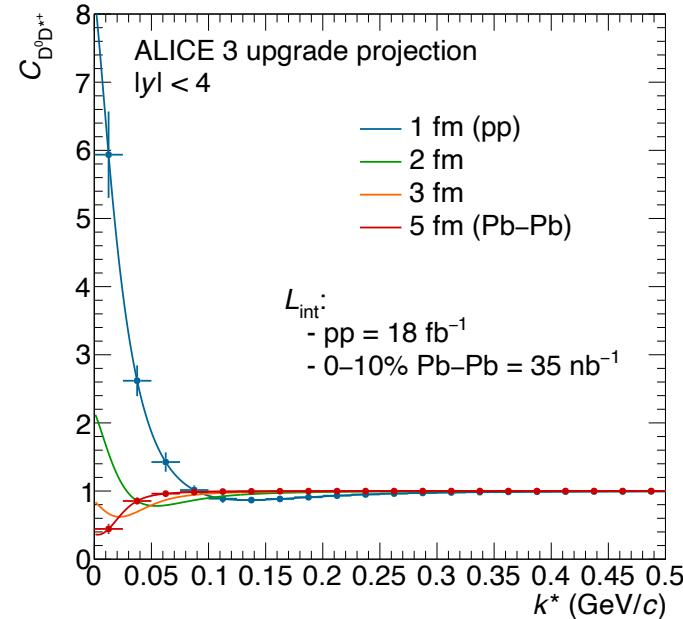


T_{cc}^+ ($J^P = 1^+, I = 0$): molecular state LHCb coll. Nature Comm. 13 3351 (2022)

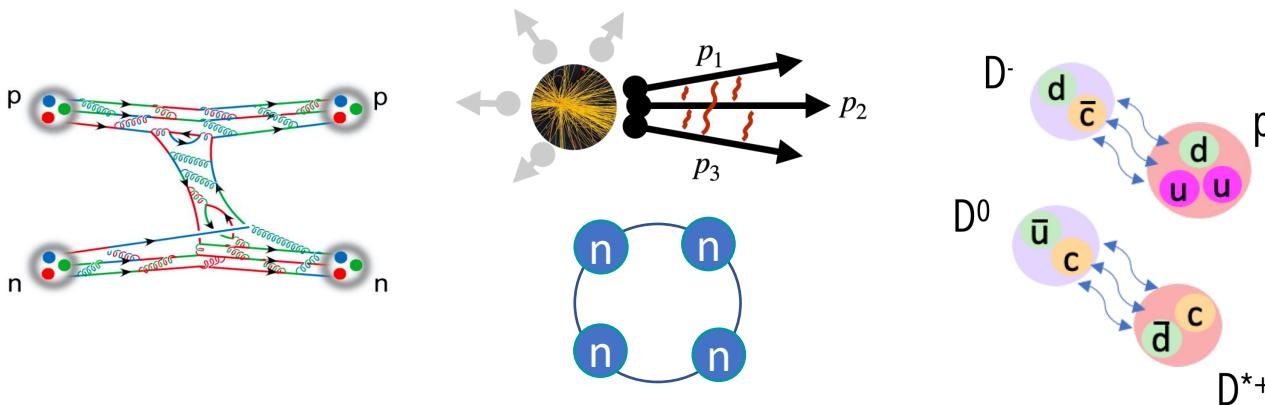
The scattering length of the $D^{*+}D^0$ pair should experience an inversion of sign at threshold

This translates into an inversion of the correlation function from pp to Pb-Pb collisions at the LHC Y. Kamiya et al. arXiv:2203.13814

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



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
- Tetraneutron correlated system measured for the first time at low energies
- First measurements of the residual strong interaction in the charm sector
- Implications for the study of molecular states containing charm quarks

Stay tuned for much more to come...

