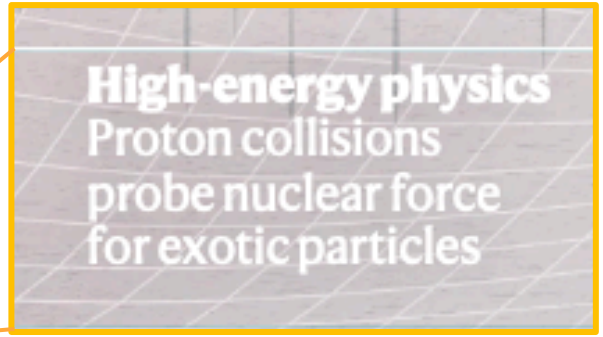
ALICE unveils strong interaction among stable and unstable hadrons

Laura Fabbietti
Technische Universität München

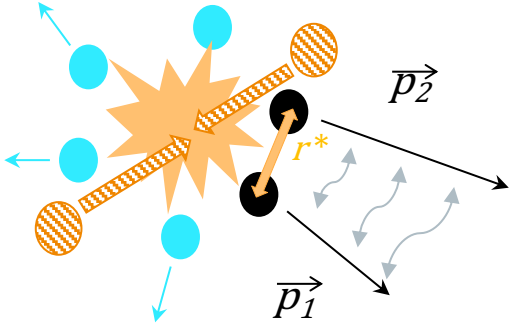
ALICE Coll. *Nature* **588**, 232–238 (2020)



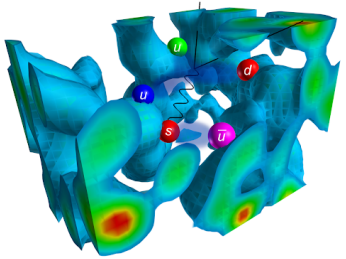
Overview

ALICE at the LHC

Effective strong interactions

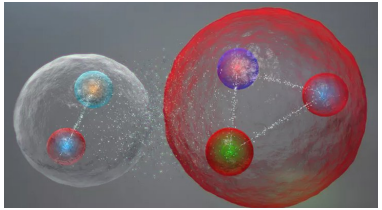


Test of first principle calculations

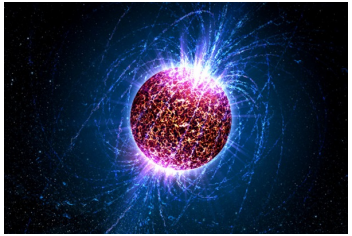


D. B. Leinweber/University of Adelaide

Search for new bound states

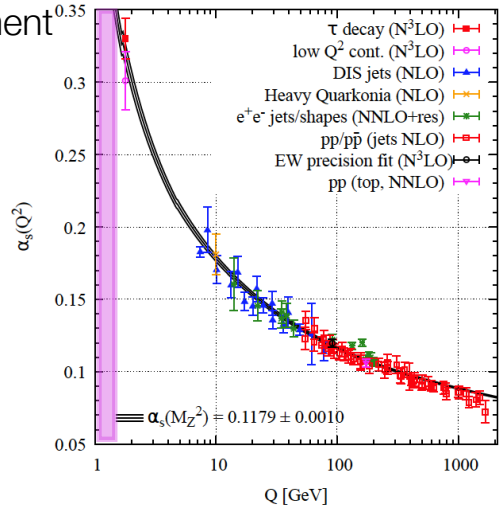


Equation of state of neutron stars



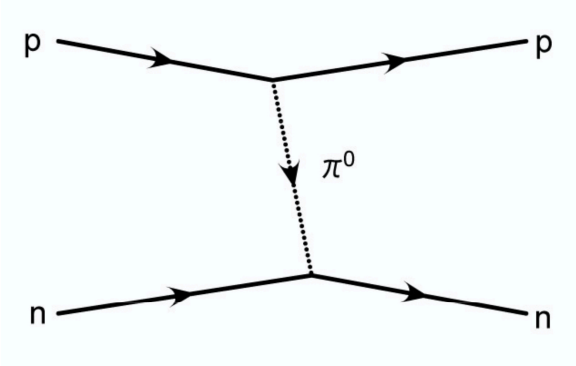
Residual strong interaction among hadrons

Confinement



PDG 2020

Asymptotic freedom



Running coupling constant defines the boundaries of Low energy QCD

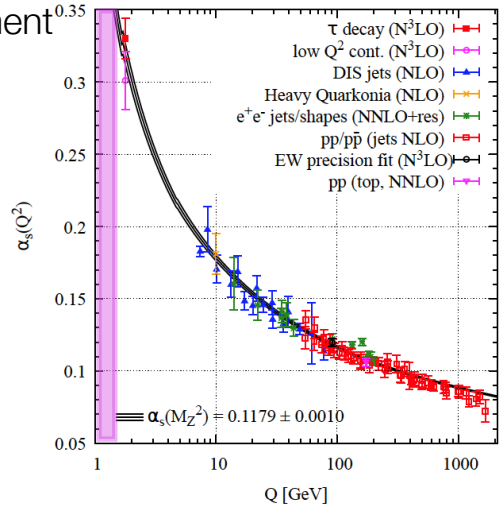
-> Q ~1 GeV, R ~ 1 fm

-> No perturbative methods are applicable

-> Effective theories with hadrons as degrees of freedom

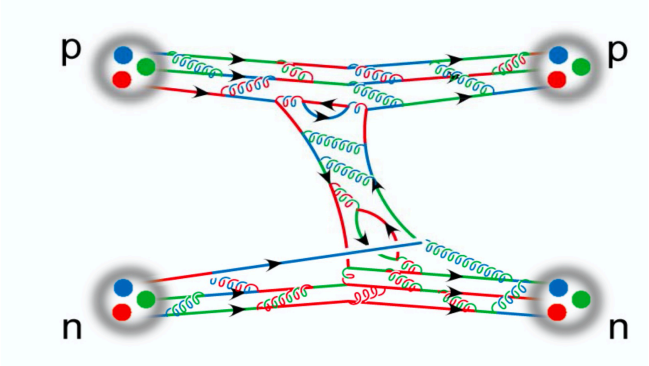
Residual strong interaction among hadrons

Confinement



PDG 2020

Asymptotic freedom



Running coupling constant defines the boundaries of Low energy QCD

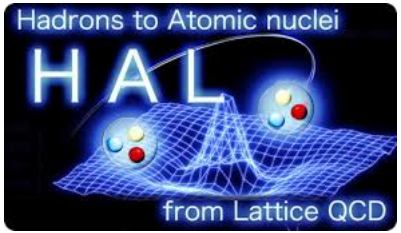
-> Q ~1 GeV, R ~ 1 fm

-> No perturbative methods are applicables

-> Effective theories with hadrons as degrees of freedom

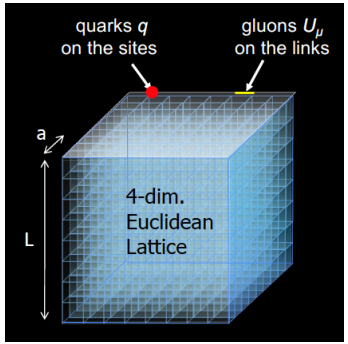
Next Step: Understanding of the interaction starting from quark and gluons

Strong interaction between (strange) hadrons



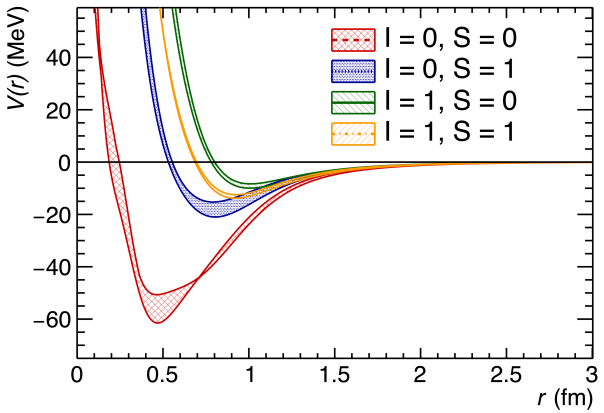
T. Hatsuda, K. Sasaki et al.

HAL QCD Coll., PLB 792 284-289 (2019)
HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737
HAL QCD Coll, Phys. Rev.D 99 (2019) 1, 014514



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

Local potentials for the Nucleon-Ξ interactions



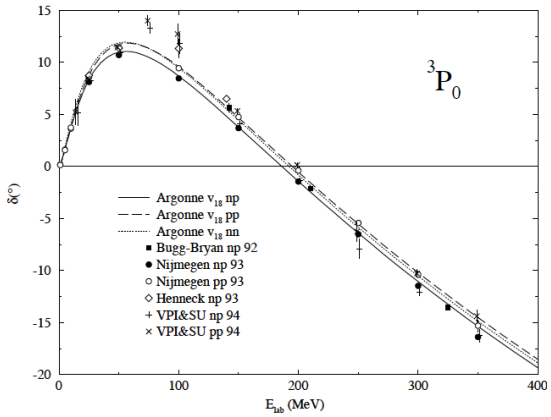
HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737

S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

Better S/N of LQCD

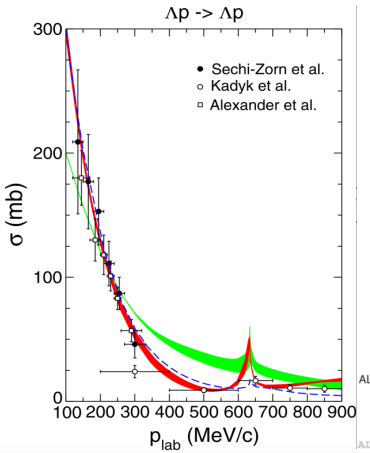
Strong interaction between (strange) hadrons

N–N → N–N



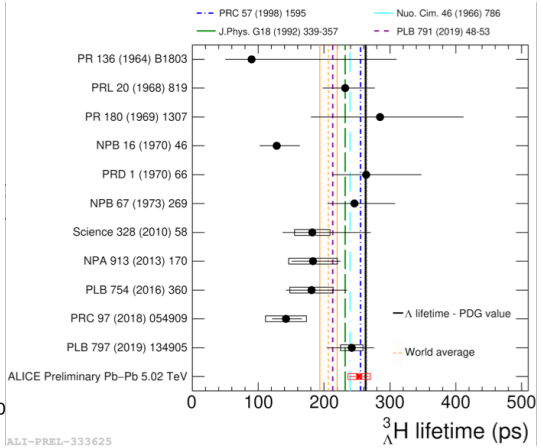
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

p–Λ → p–Λ

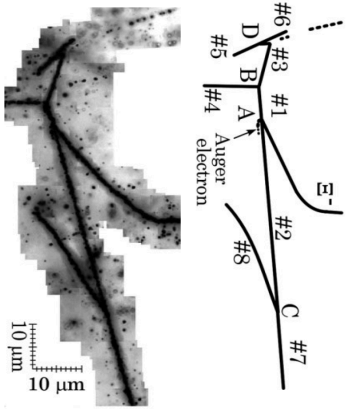


LO from H. Polinder, J.Haidenbauer, U. Meißner, NPA 779 (2006) 244 and NLO from J.Haidenbauer., N.Kaiser et al., NPA 915 (2013) 24.

Hypertriton lifetime



Ξ hypernucleus



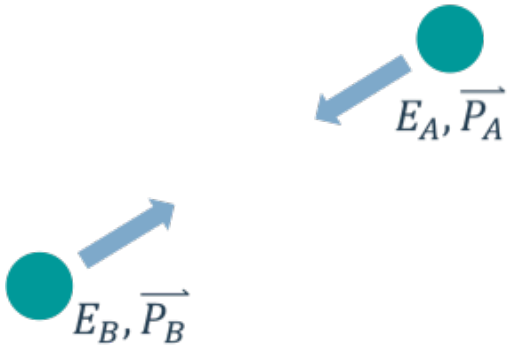
K. Nakazawa et al. PTEP 2015, 033D02

S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

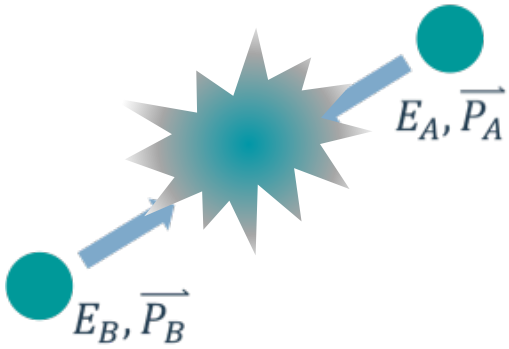
Better S/N of LQCD

Experimental data

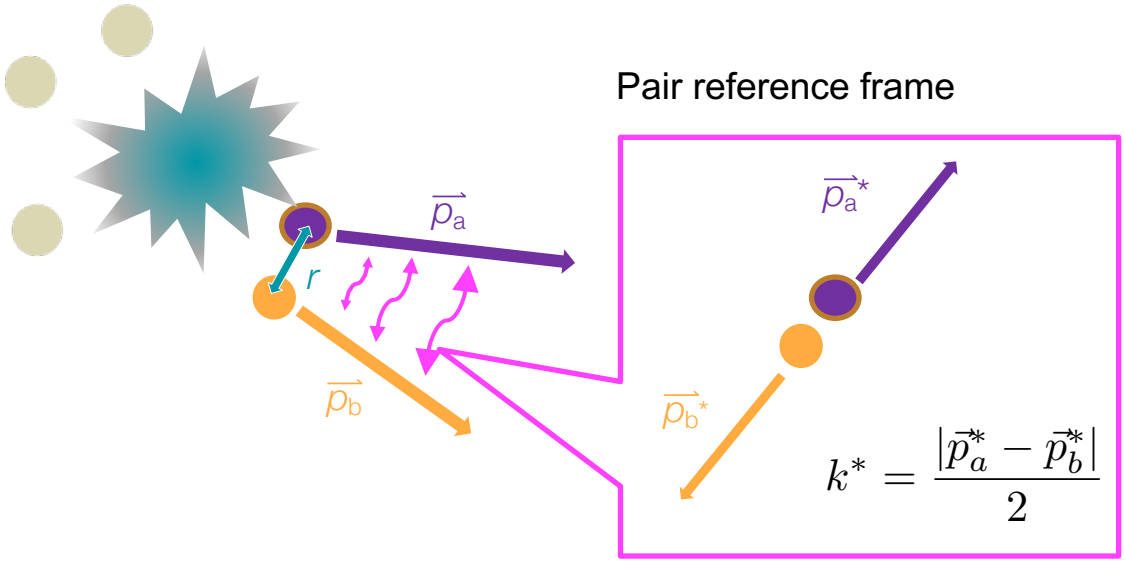
The femtoscopy method



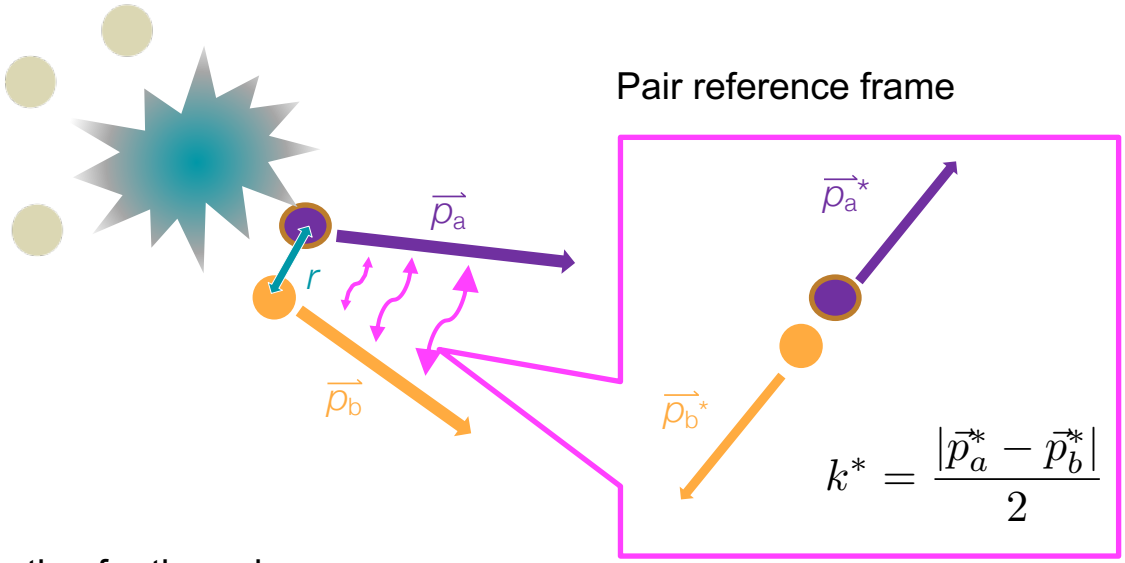
Nuclear collisions



Particle production and propagation



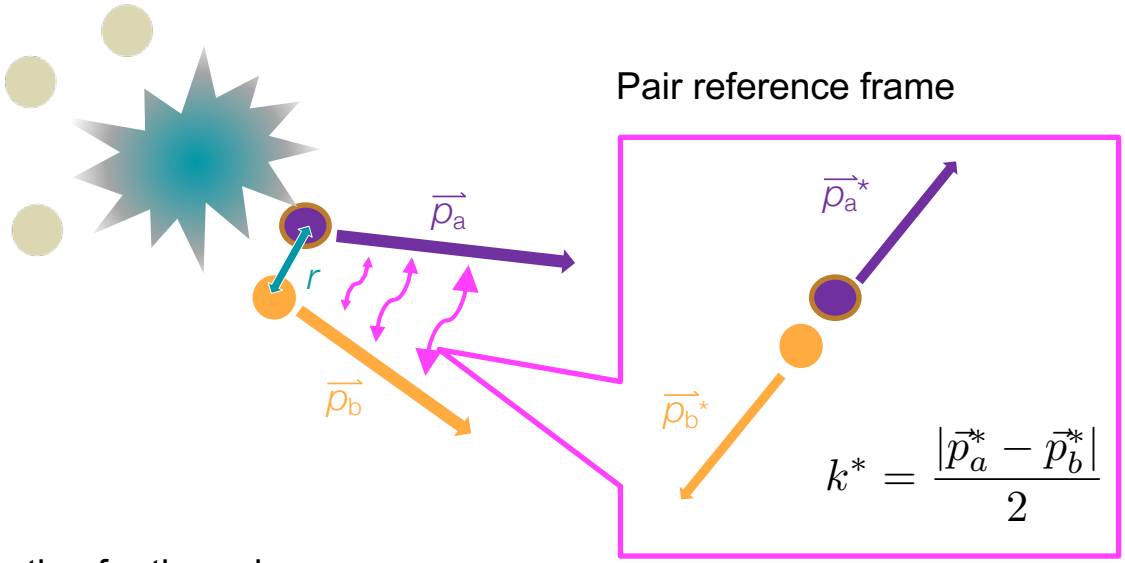
Particle production and propagation



Schrödinger Equation:

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

The femtoscopy technique



Schrödinger Equation:

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

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

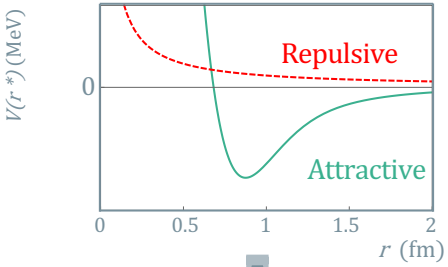
Emission source Two-particle wave function

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

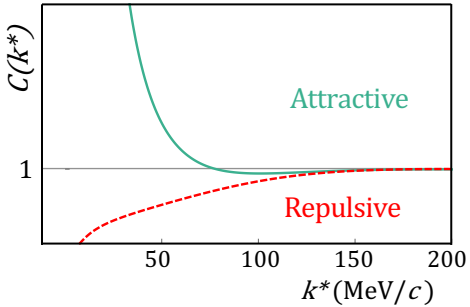
Example

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 $|\Psi(k^*, r\ \ )|$

**CATS (Correlation Analysis Tool using the Schödinger equation) D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

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

Emission source — Two-particle wave function

>1 if the interaction is attractive
= 1 if there is no interaction
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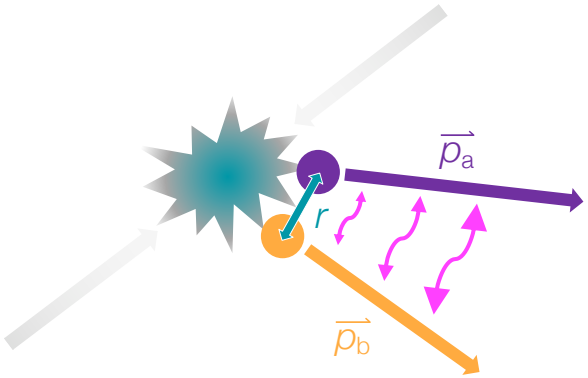
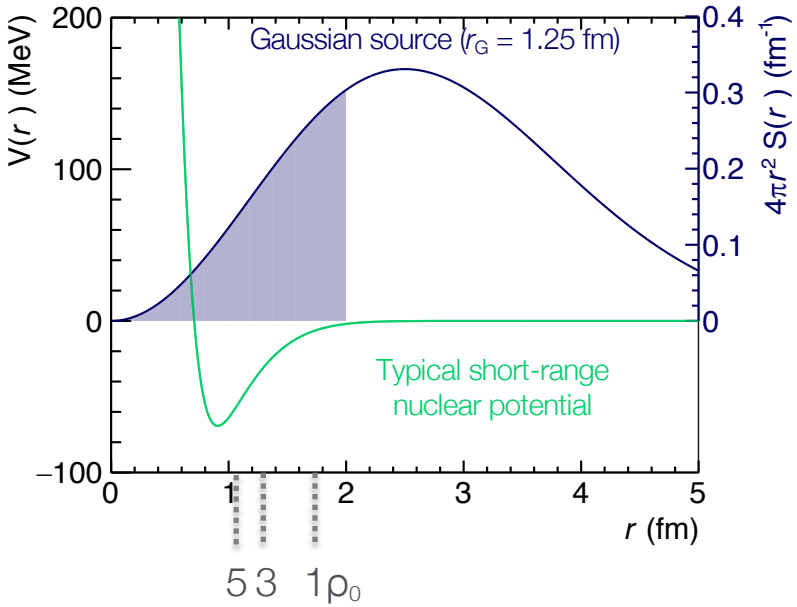
Femtoscopy with small sources





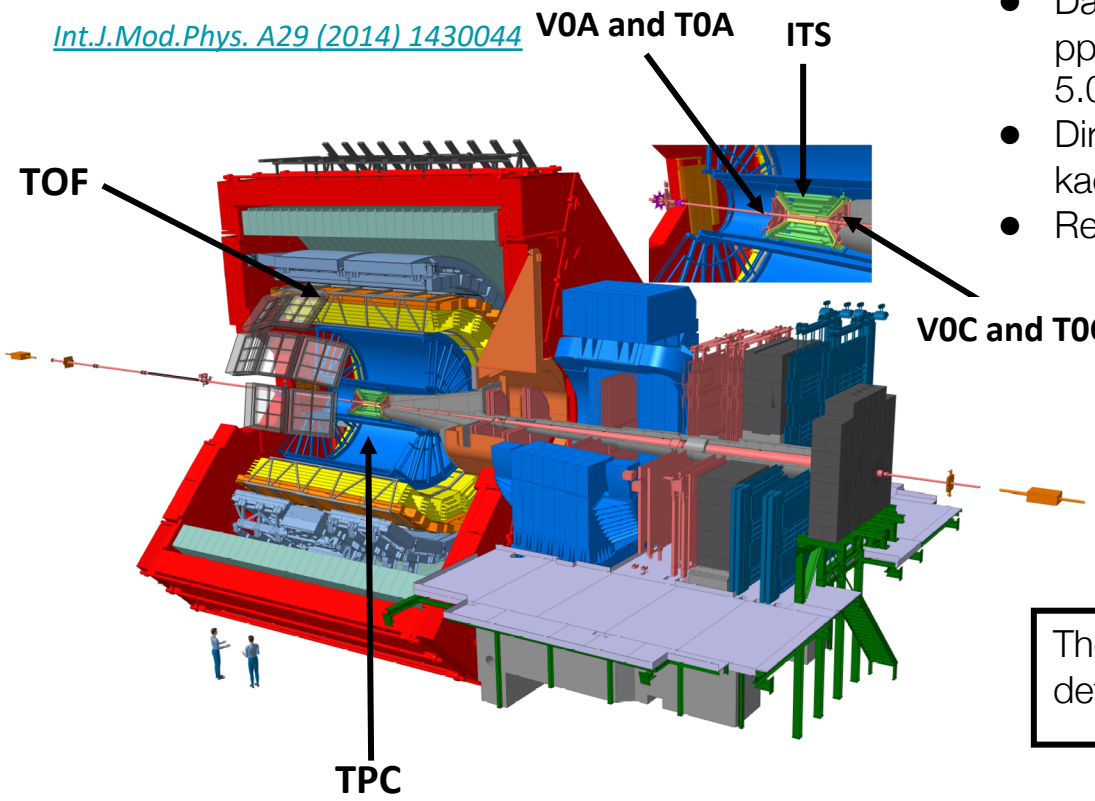
$$C(k^*) = \int S(r)\ \left|\psi(\vec{k}^*, \vec{r})\right|^2 \mathrm{d}^3 r = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Emission source — Two-particle wave function

Small particle-emitting source created in pp and p–Pb collisions at the LHC

- Essential ingredient for detailed studies of the strong interaction

ALICE data

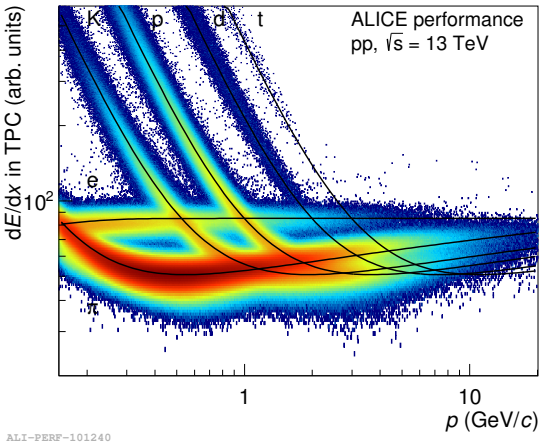


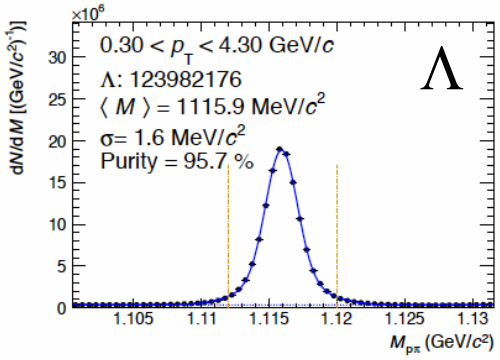
- Data set:
  pp 13 TeV (1000 M high multiplicity events), p-Pb 5.02 TeV (600 M minimum bias)
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:

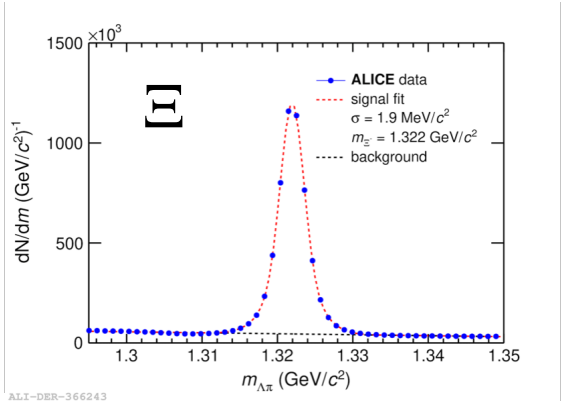
$$\Lambda \to p\pi^-$$
$$\boxed{\Xi^- \to \Lambda\pi^-}$$
$$\boxed{\Omega^- \to \Lambda K^-}$$
$$\Sigma^0 \to \Lambda\gamma$$

The very good PID capabilities of the detector result in very pure samples!

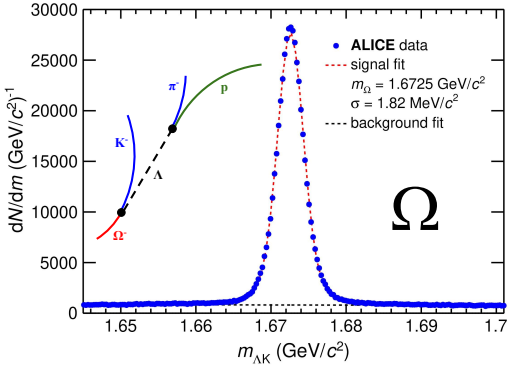
Hyperons @ ALICE in pp collisions

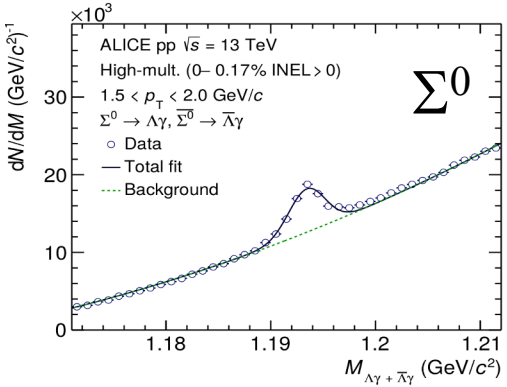




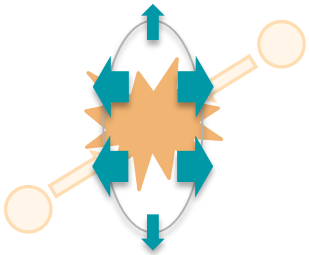


$$\Lambda \rightarrow p\pi^-$$
$$\Xi^- \rightarrow \Lambda\pi^-$$
$$\Omega^- \rightarrow \Lambda K^-$$
$$\Sigma^0 \rightarrow \Lambda\gamma$$





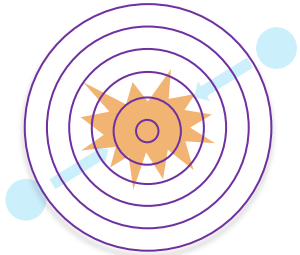
Collective effects and strong resonances



Anisotropic

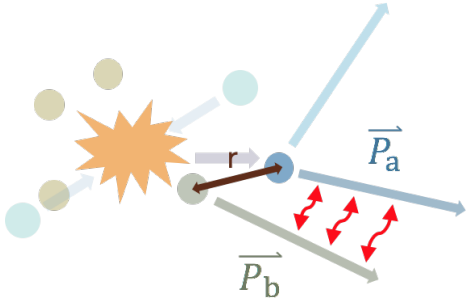
+

pressure gradients



Radial

Different effect on different masses



Resonances with cτ ~ r_0~ 1fm (Δ^{++},N*,Σ*)

Particle	Primordial fraction	Resonances <cτ>
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

U. Wiedemann U. Heinz (PRC56 R610, 1997)

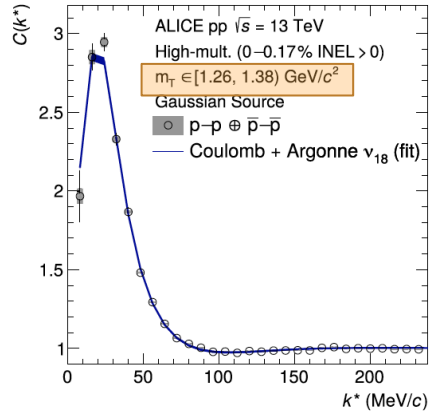
$$S(r) = G(r, r_{core}(m_T)) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right)$$

$\otimes$ Folded

$$E(r, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s}\exp(-\frac{r}{s})$$

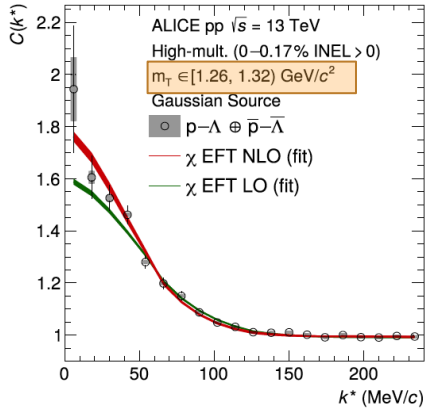
$$s = \beta\gamma\tau_{res} = \frac{p_{res}}{M_{res}}\tau_{res}$$

pp and pΛ correlations



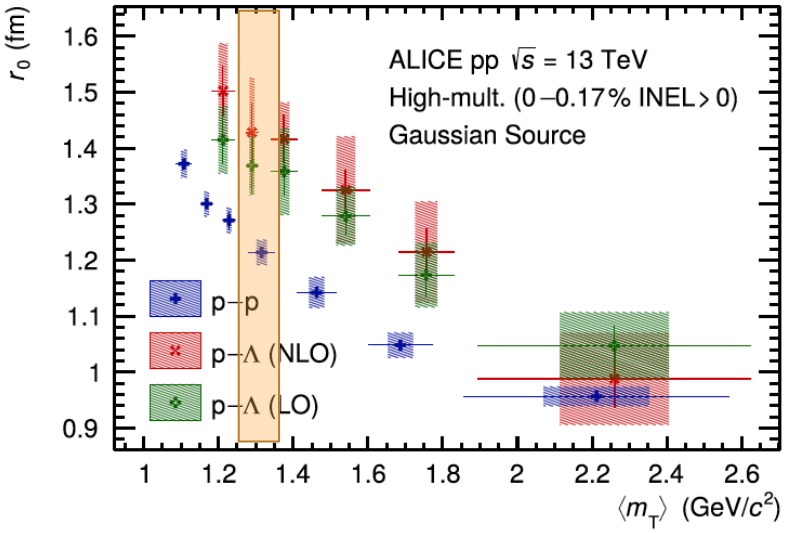
$$C(k^*) = \int \boxed{S(r)} \left|\psi(\vec{k}^*, \vec{r})\right|^2 d^3r$$

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



pΛ Correlation: χEFT LO and NLO $\psi(\vec{k}^*, \vec{r})$ are used

Physics Lett. B, 811, 135849



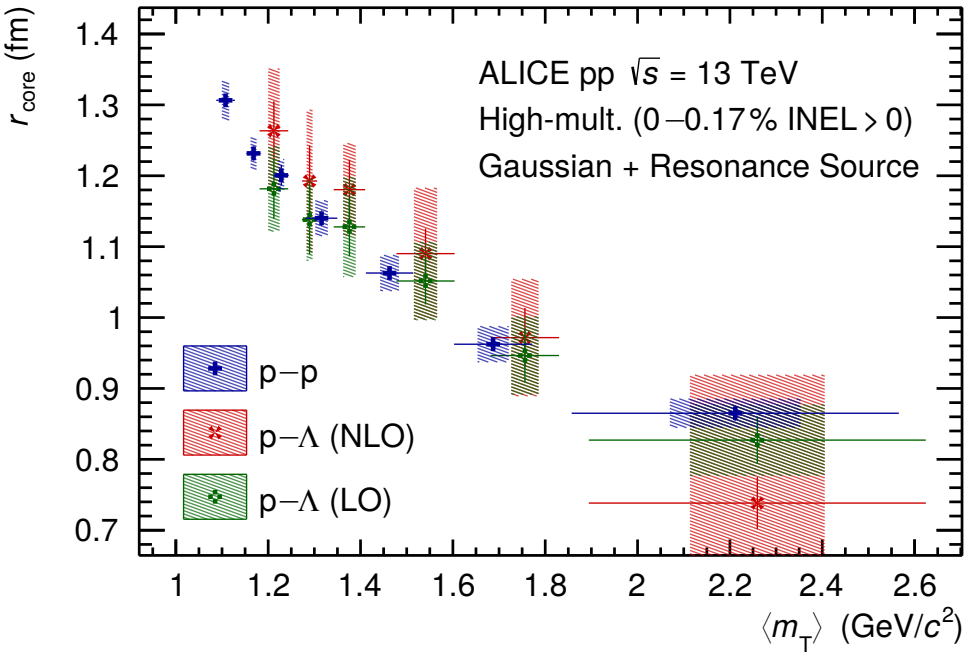
$$m_T = \sqrt{k_T^2 + m^2} \qquad k_T = \frac{1}{2}|p_{T,1} + p_{T,2}|$$

A fit with a Gaussian profile for the source delivers different source dimensions r_0 for pp and pΛ pairs.

CATS: D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

A Gaussian source with resonances

Physics Lett. B, 811, 135849

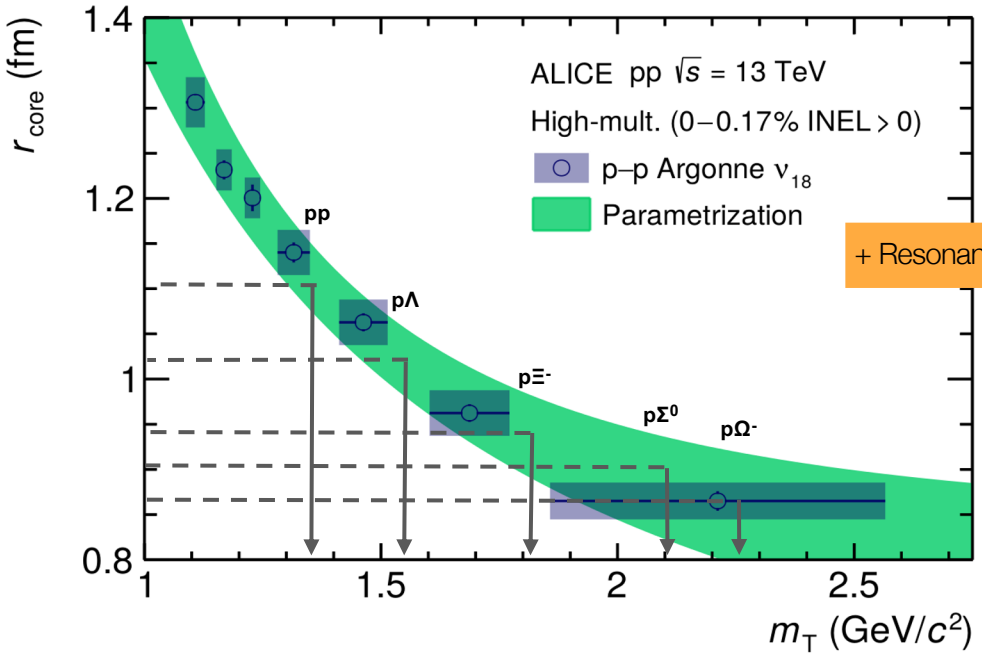


- Radii measured from the p-p and p-Λ correlation function
  - Input: production fraction/life-times (Statistical Hadronization Model*) and angular distributions (EPOS event generator**)
- Observation of a common m_T scaling of the core radius
  - Hypothesis of a universal emission source of baryons

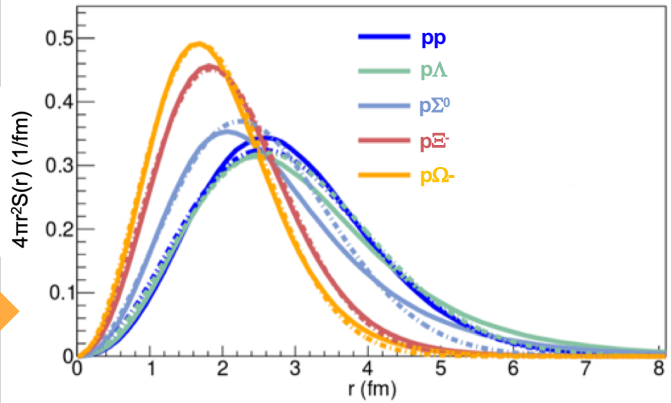
* F. Becattini and G. Passaleva Eur.Phys.J.C 23 (2002) 551-583
**T. Pierog et al.m PRC 92 (2015) 3, 034906

A Gaussian source with resonances

Physics Lett. B, 811, 135849

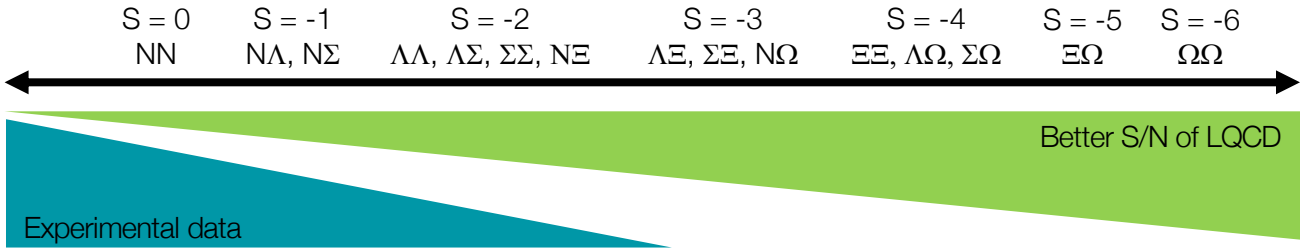


+ Resonances

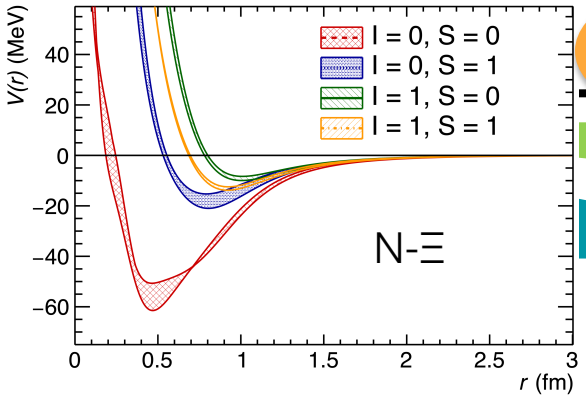


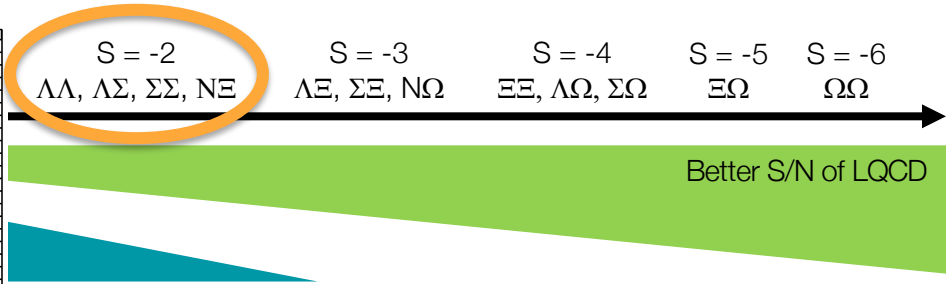
Pair	r_{Core} [fm]	r_{Eff} [fm]
p-p	1.1	1.2
p-Λ	1.0	1.3
p-Σ^0	0.87	1.02
p-Ξ^-	0.93	1.02
p-Ω^-	0.86	0.95

QCD p-Ξ^- and p-Ω^- lattice potentials



QCD p-Ξ⁻ and p-Ω⁻ lattice potentials

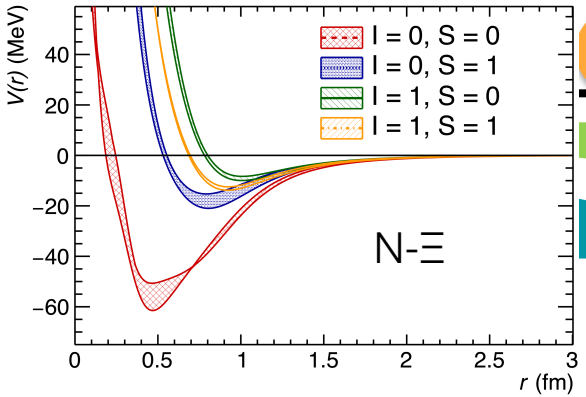


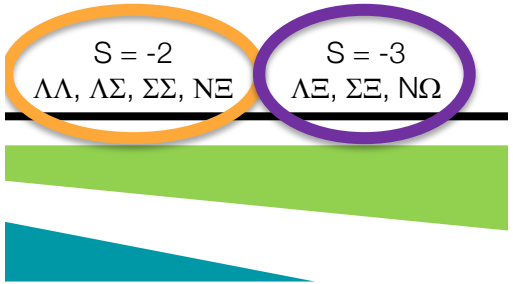


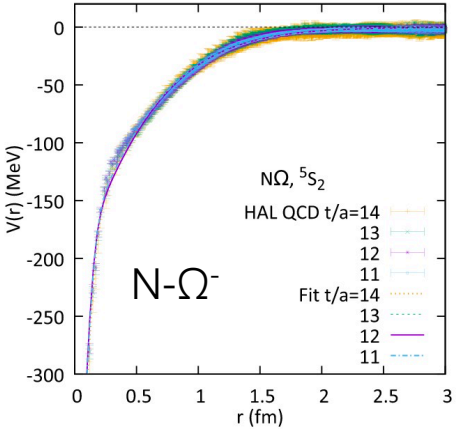
- Interaction of p–Ξ⁻ pairs in four Isospin (I = 0,1) and Spin (S=0,1) states

HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737

QCD p-Ξ⁻ and p-Ω⁻ lattice potentials



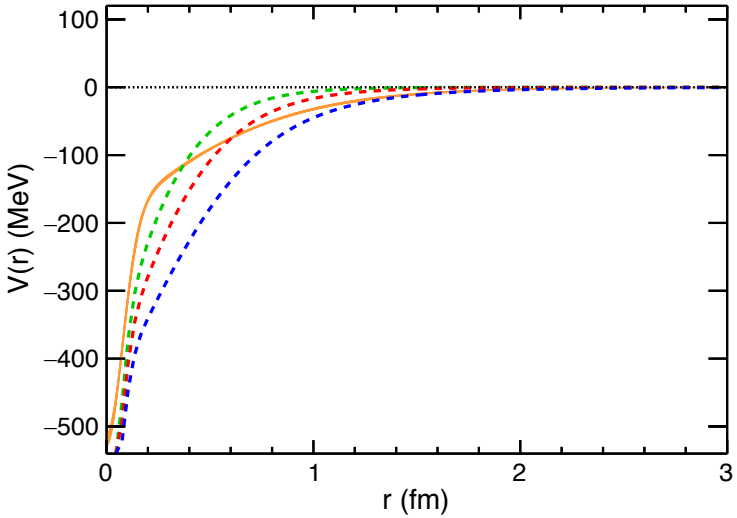




- Interaction of p–Ξ⁻ pairs in four isospin (I = 0,1) and spin (S=0,1) states
- Interaction of p–Ω⁻ pairs in $^3S_1$ or $^5S_2$ (S=1, 2) states
  - Inelastic channels (e.g. pΩ⁻ →ΛΞ⁻) in $^3S_1$ not yet calculated on the lattice
  - Attraction in $^5S_2$ results in the prediction of a bound state (B.E. = 1.54 MeV)

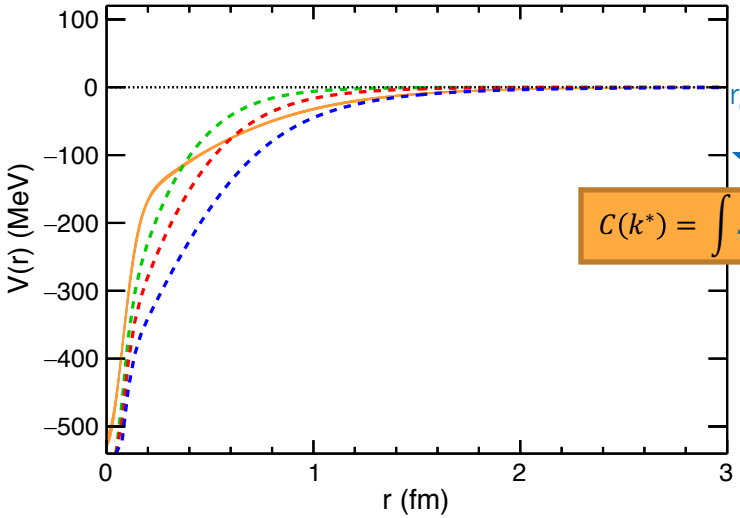
HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737
HAL QCD Coll., Phys. Rev. C 101, 015201

Correlation functions and bound states



K. Morita et al., Phys. Rev. C 101, 015201 (2020)

Correlation functions and bound states



r_{eff}= 0.95 fm

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

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

K. Morita et al., Phys. Rev. C 101, 015201 (2020)

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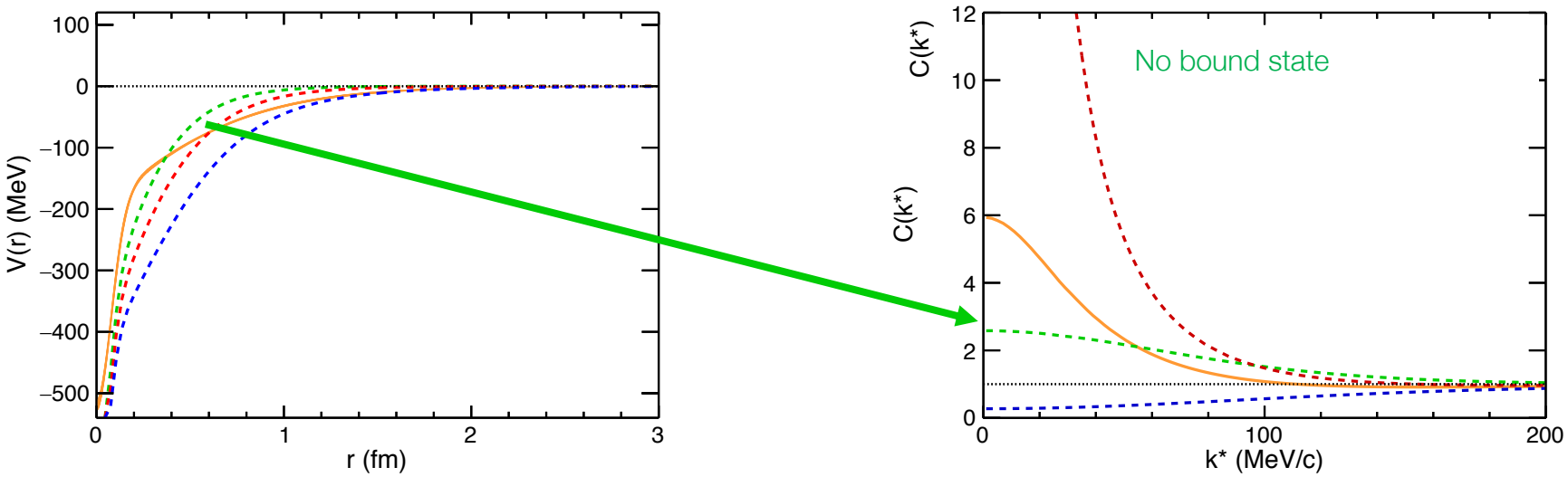

K. Morita et al., Phys. Rev. C 101, 015201 (2020)

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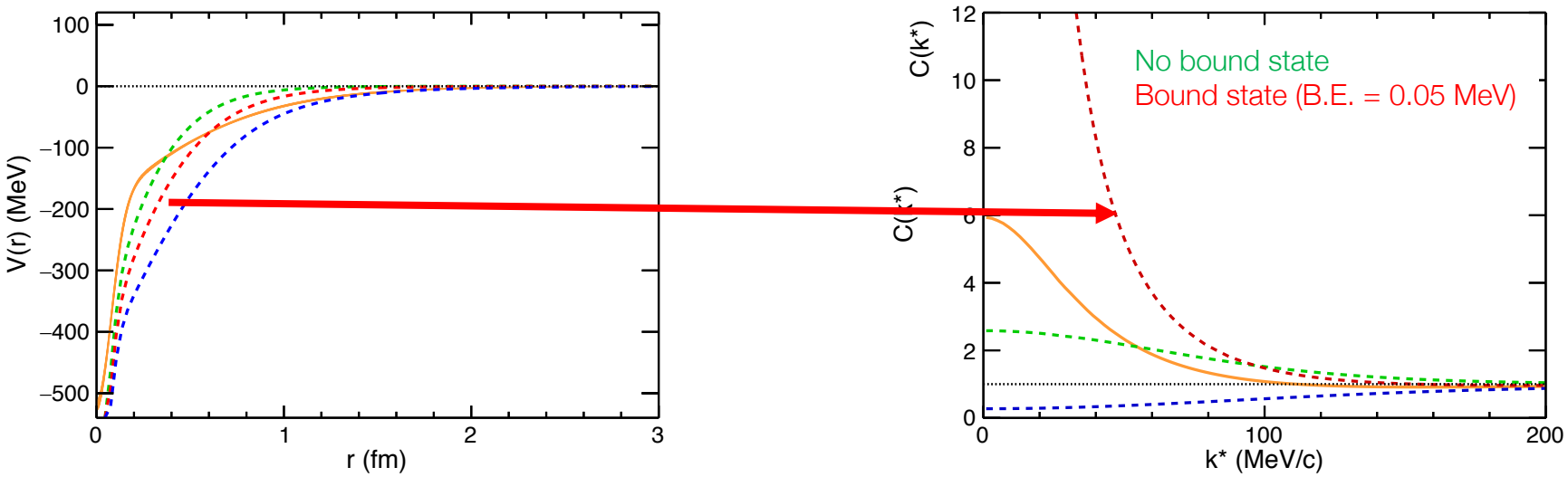

K. Morita et al., Phys. Rev. C 101, 015201 (2020)

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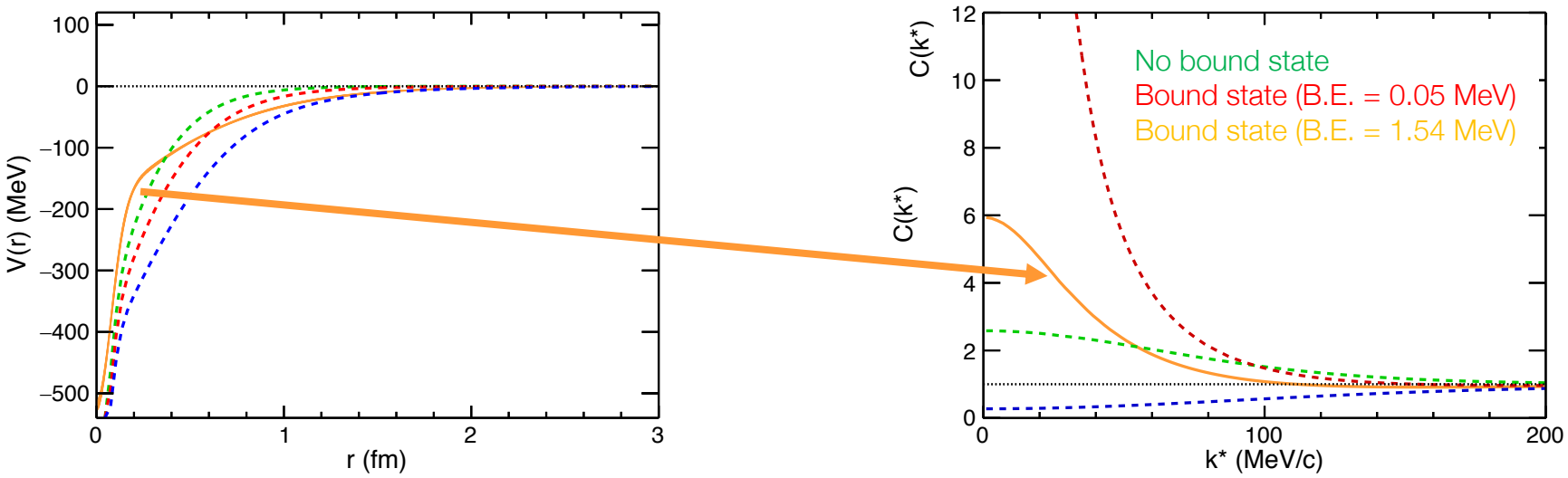
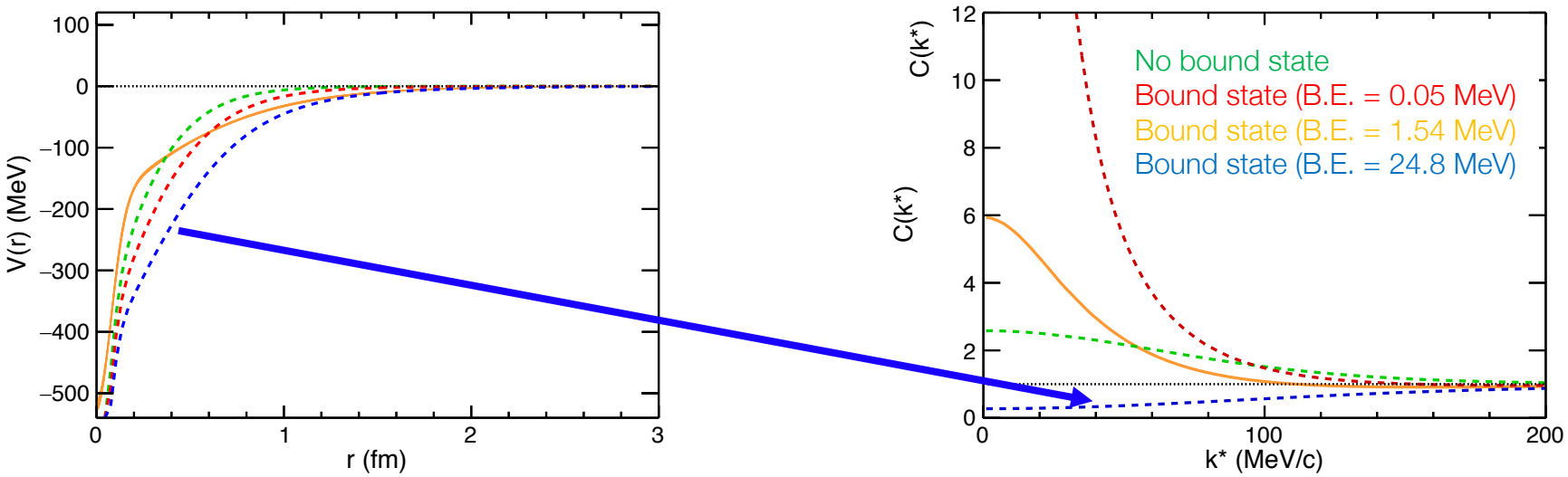


K. Morita et al., Phys. Rev. C 101, 015201 (2020)

Correlation functions and bound states

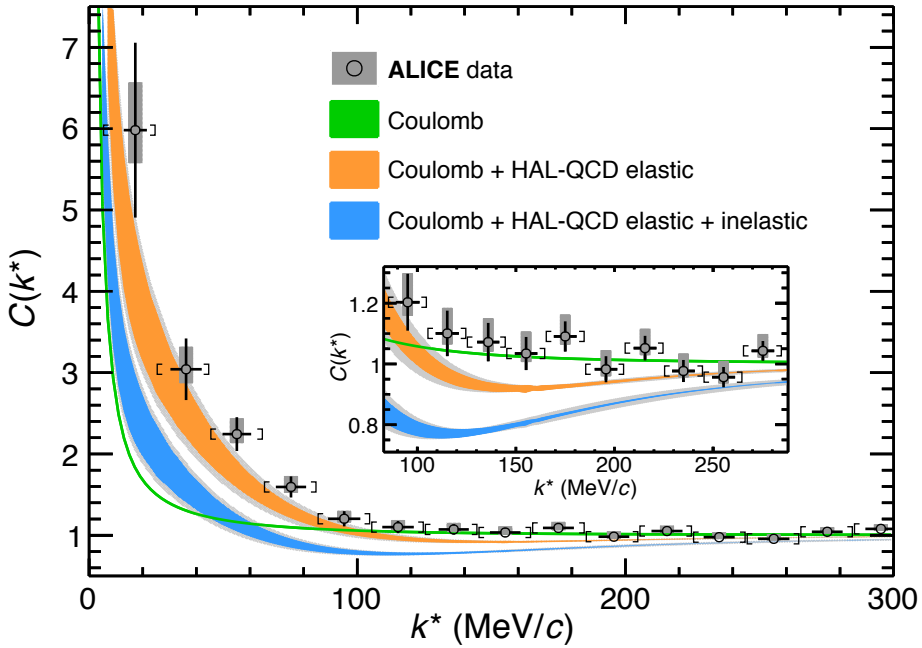


K. Morita et al., Phys. Rev. C 101, 015201 (2020)

- Predicted correlation function sensitive to changes of the B.E.
- Femtoscopy in pp collisions at the LHC sensitive to small differences among the interaction potentials

p–Ω⁻ correlation function in pp at 13 TeV

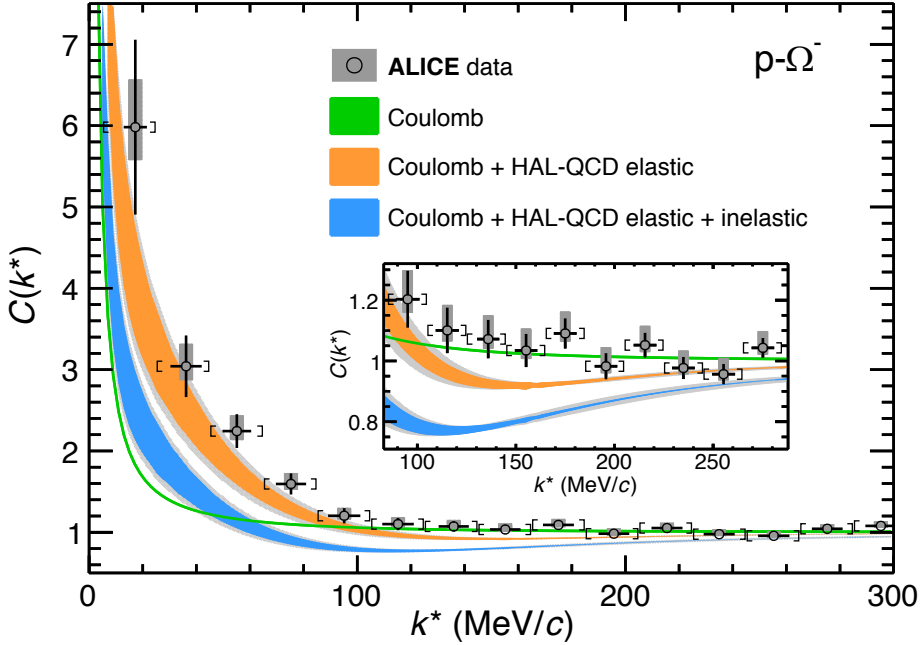
ALICE Coll. *Nature* **588**, 232–238 (2020)

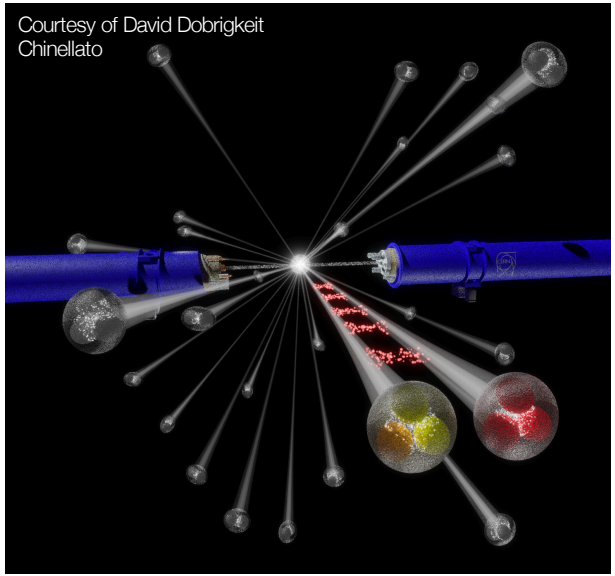


- Enhancement above Coulomb
  → Observation of the strong interaction
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  - Inelastic channels dominated by absorption
  - Neglecting inelastic channels
- Data more precise than lattice calculations
- So far, no indication of a bound state

p–Ω⁻ correlation function in pp at 13 TeV

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





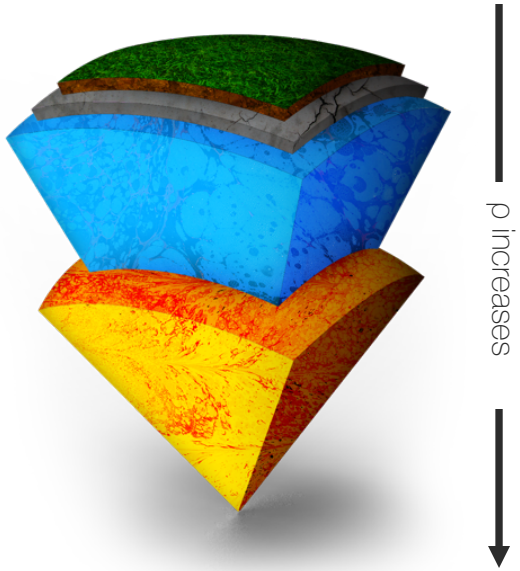
Excursion to neutron stars

Hyperon appearance in neutron stars?

Dimensions:
R ~ 10 – 15 km
M ~ 1.2 – 2.2 $M_\odot$

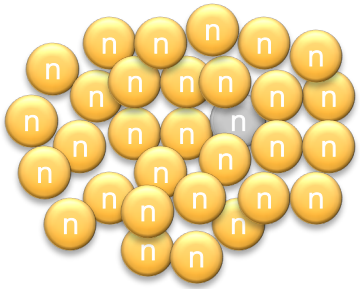
Outer crust:
Ions, electron gas, neutrons

Inner core:
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark matter?



Neutron stars: very dense, compact objects

- How does the equation of state of neutron star look like?
  - What are the constituents to consider?
  - How do they interact?



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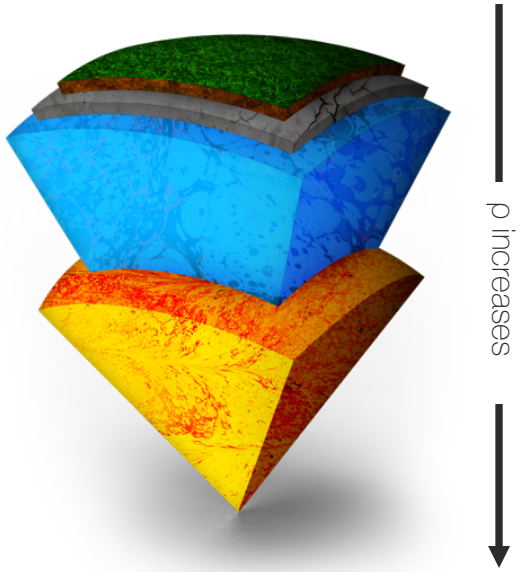

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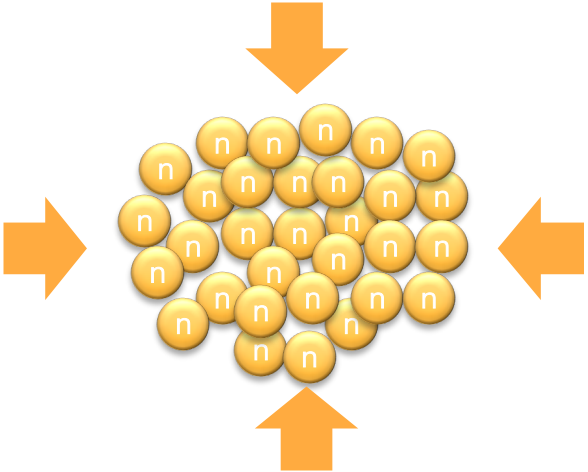
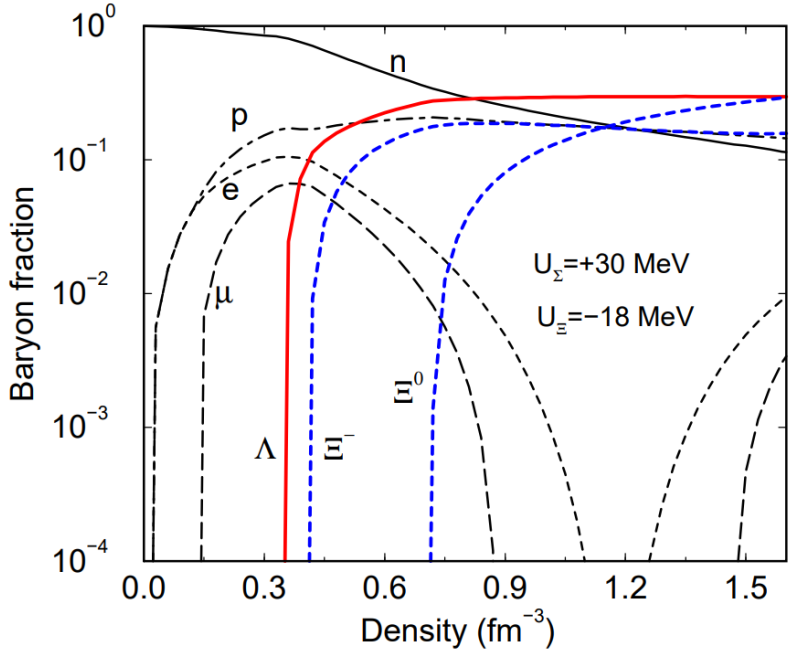


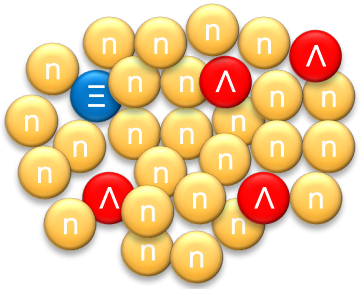
Hyperon appearance in neutron stars?



J. Schaffner-Bielich, Nucl. Phys. A 835 (2010) 279

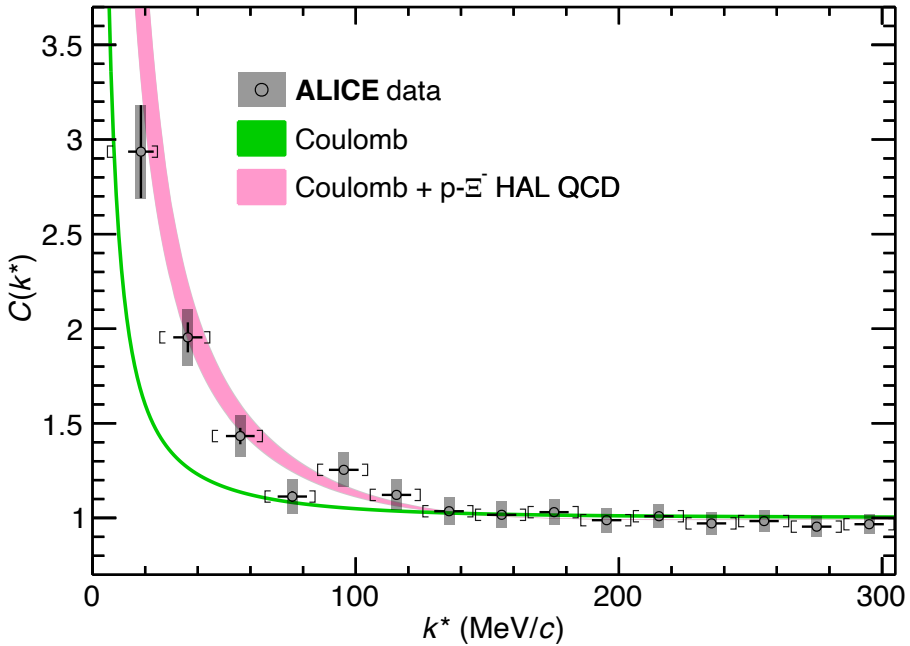
Neutron stars: very dense, compact objects

- With increasing baryonic densities **hyperon** production becomes energetically favorable
- Exact composition strongly depends on constituent interactions and couplings!



p–Ξ⁻ correlation function in pp at 13 TeV

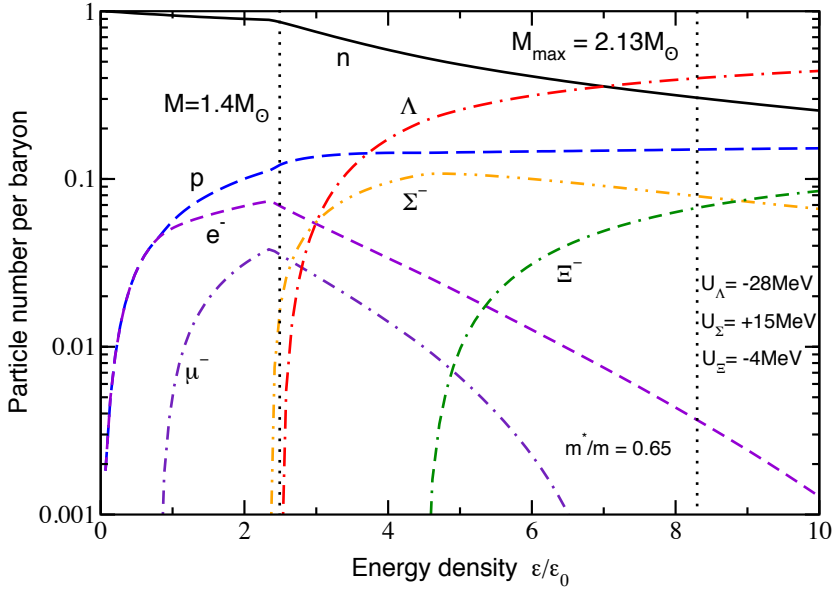
ALICE Coll. *Nature* **588**, 232–238 (2020)

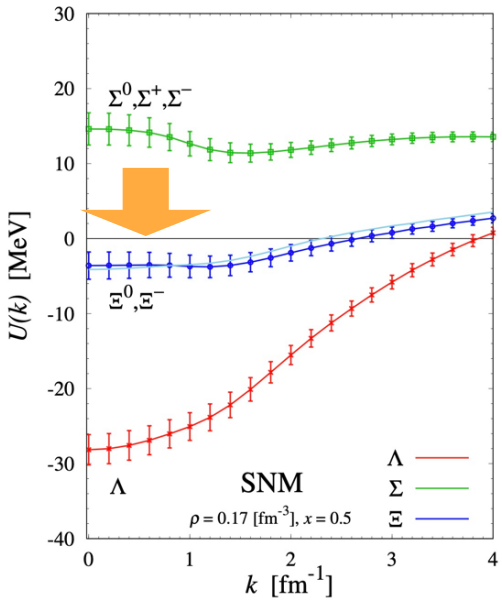


- Enhancement above Coulomb
  → Observation of the strong interaction
- Measurement in different collision system retains excellent agreement with lattice predictions (HAL-QCD)
  - Continuation of the study in the p-Pb system Phys. Rev. Lett. 123, 112002

Single particle potentials from lattice QCD

Courtesy J. Schaffner-Bielich 2020



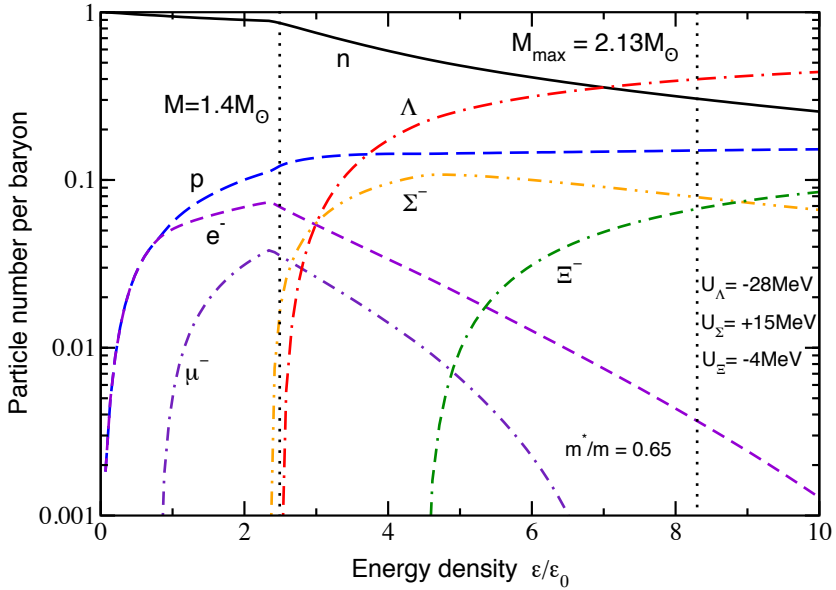


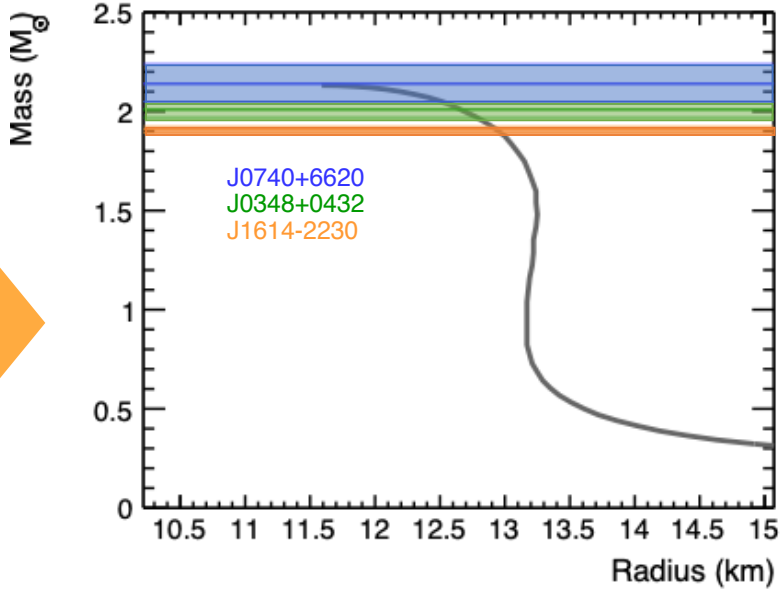
Attractive pΞ^- interaction lead to slightly attractive single particle potential in symmetric nuclear matter (SNM) and slight repulsion in neutron rich matter. Ξ^- appears at larger densities in NS

Inoue, T. Strange nuclear physics from QCD on lattice. AIP Conference Proceedings 2130, 020002 (2019)

Equation of state for neutron stars

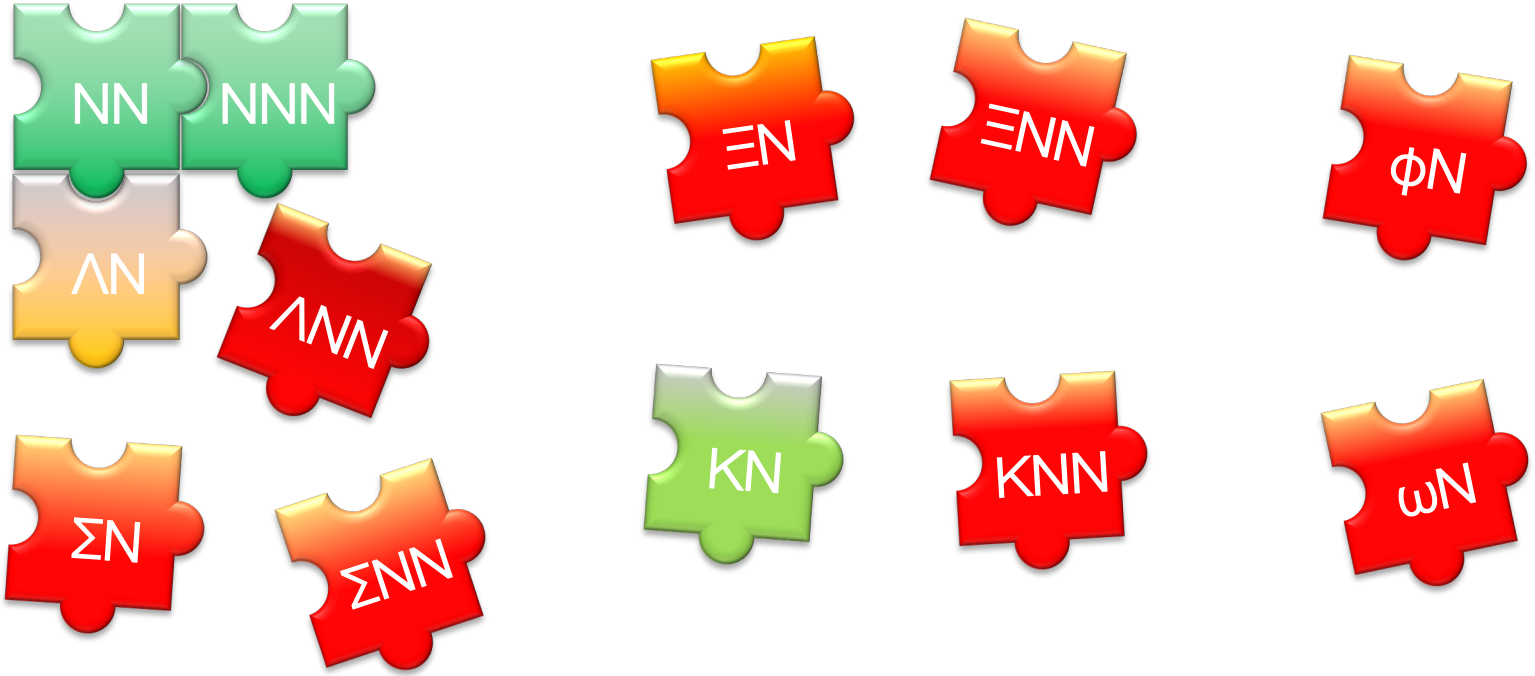
Courtesy J. Schaffner-Bielich 2020



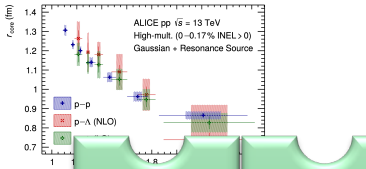


The resulting equation of state for neutron star is stiffer and the observation of 2 solar masses is matched.
This is not the end of the story…

The Hyperon Puzzle

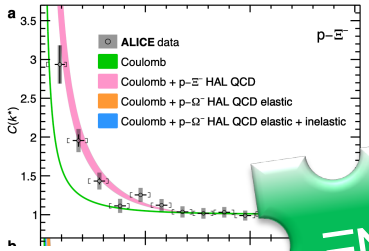


Harvest of LHC Run 1 & 2



NN

NNN

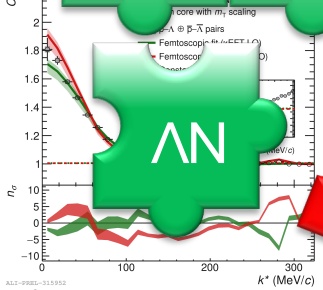


ΞN

ΞNN

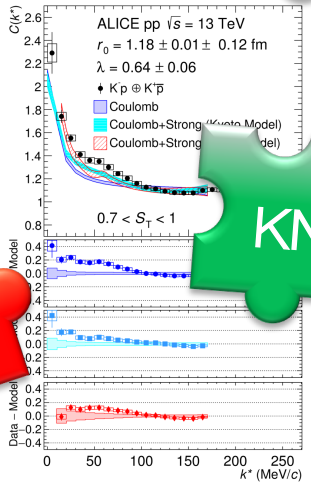
ΦN

ωN



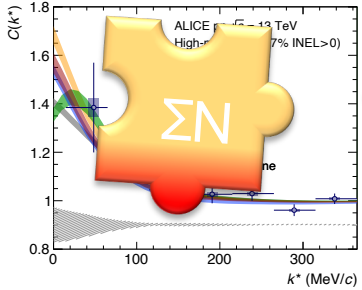
ΛN

ΛNN



KN

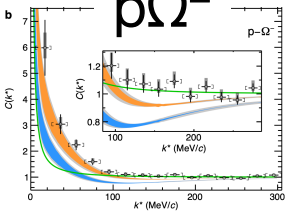
KNN



ΣN

ΣNN

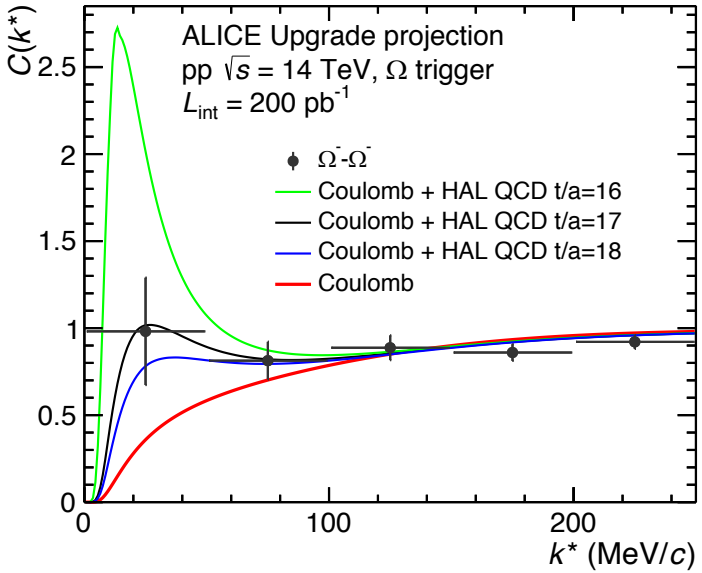
pΩ⁻

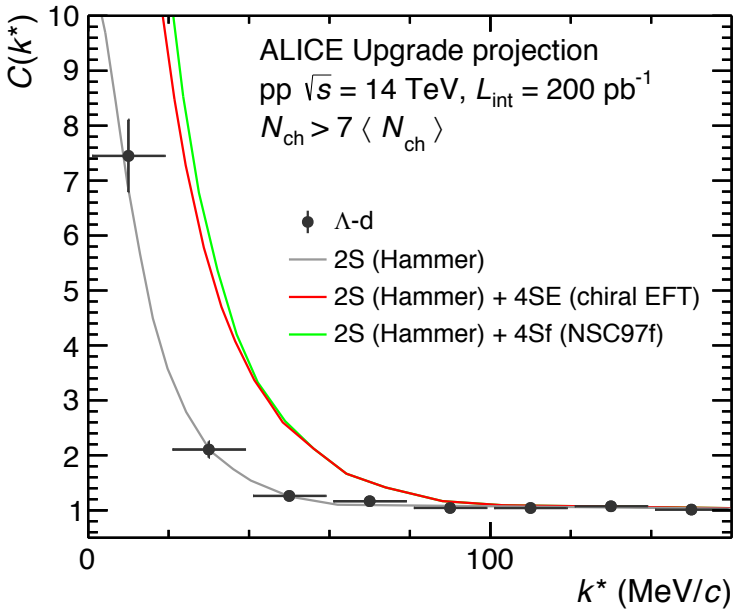


PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232–238

Outlook

The shown studies can be extended to more hadron pairs
Projection for the Run 3 data taking:



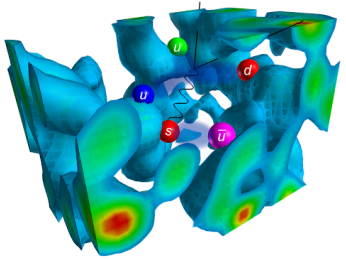


CERN-LHCC-2020-018 ; LHCC-G-179
Future high-energy pp programme with ALICE

Summary

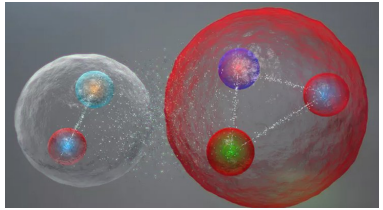
- Femtoscopy technique can be used to provide unprecedented constraints on hadron-hadron interactions
- We have tested lattice calculations
- We can study bound states
- We provide important constraints to the equation of state of neutron stars
- More precision studies within reach with the large data samples collected in Run 3 & 4
    - Direct measurements of three-body interactions for the first time
    - And then we move to charmed hadrons...

Test of first principles calculations

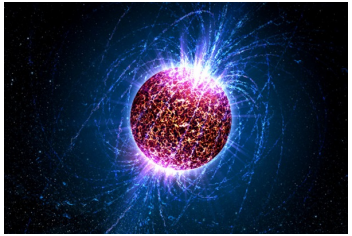


D. B. Leinweber/University of Adelaide

Search for new bound states



Equation of state of neutron stars



Stay tuned for much more to come…