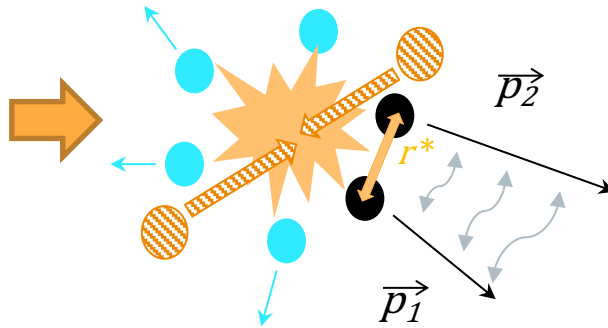


Measurements of hadron-hadron interactions with ALICE

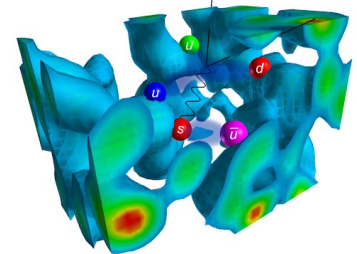
ALICE at the LHC



Effective strong interactions

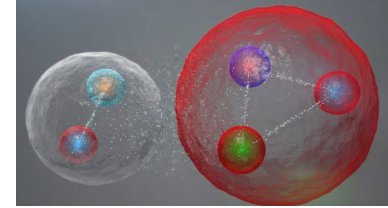


Test of first principle calculations

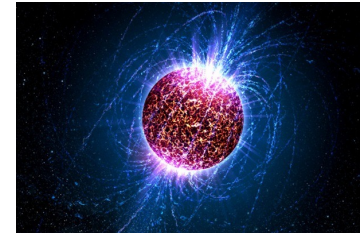


D. B. Leinweber/University of Adelaide

Search for new bound states

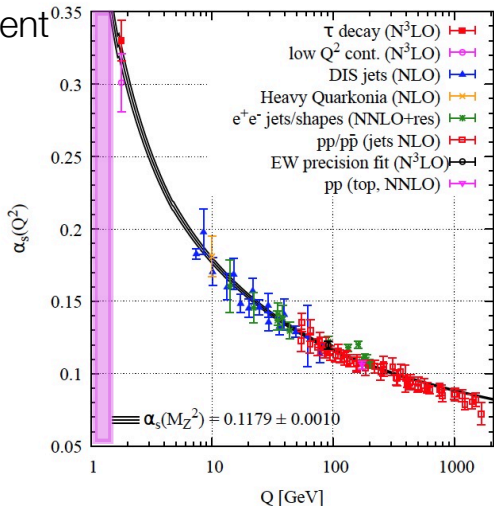


Equation of state of neutron stars



Residual strong interaction among hadrons

Confinement



PDG 2020

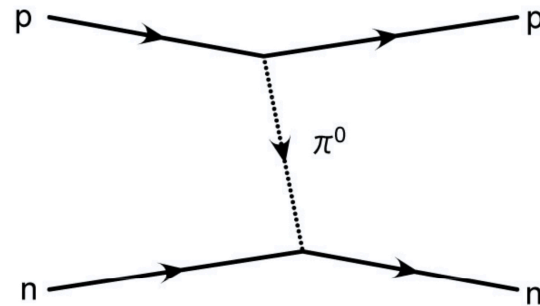
Asymptotic freedom

Running coupling constant defines the boundaries of Low energy QCD

-> $Q \sim 1 \text{ GeV}$, $R \sim 1 \text{ fm}$

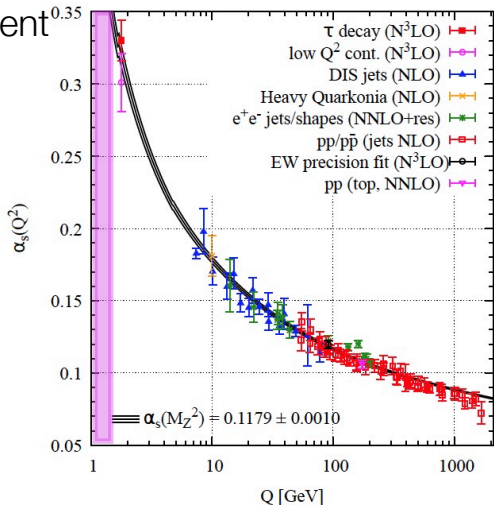
-> No perturbative methods are applicable

-> Effective theories with hadrons as degrees of freedom



Residual strong interaction among hadrons

Confinement



PDG 2020

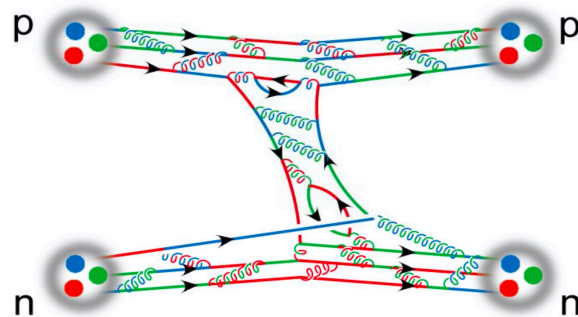
Asymptotic freedom

Running coupling constant defines the boundaries of Low energy QCD

-> $Q \sim 1 \text{ GeV}$, $R \sim 1 \text{ fm}$

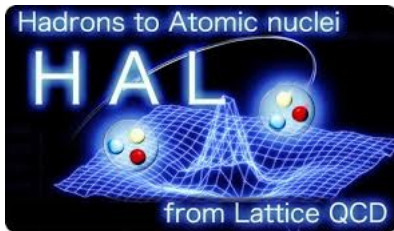
-> No perturbative methods are applicable

-> Effective theories with hadrons as degrees of freedom



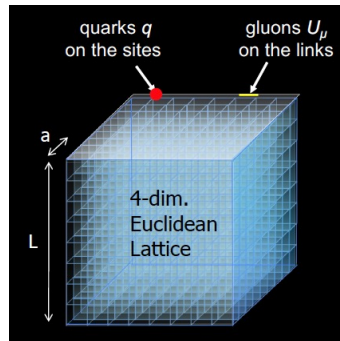
Next Step: Understanding of the interaction starting from quark and gluons

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



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

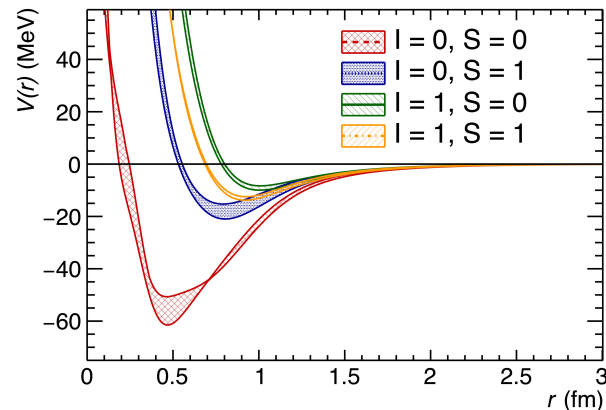
$$L = 8.1 \text{ fm}$$

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

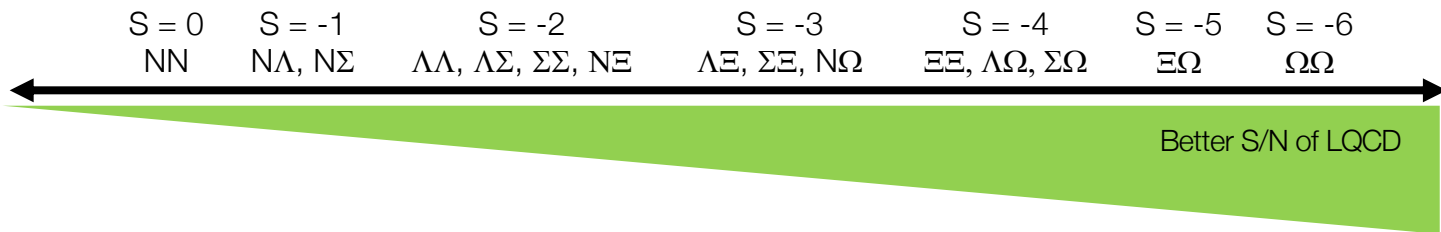
$$m_K = 525 \text{ MeV}/c^2$$



Local potentials for the Nucleon- Ξ interactions

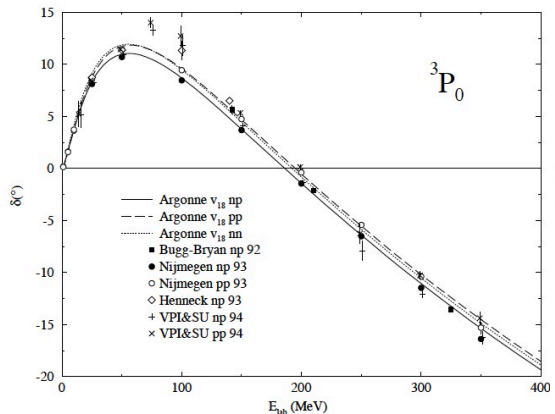


HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737



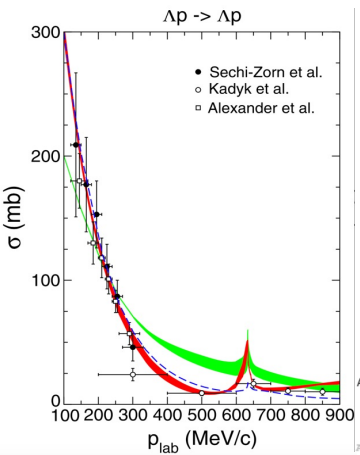
Strong interaction between (strange) hadrons

N-N → N-N



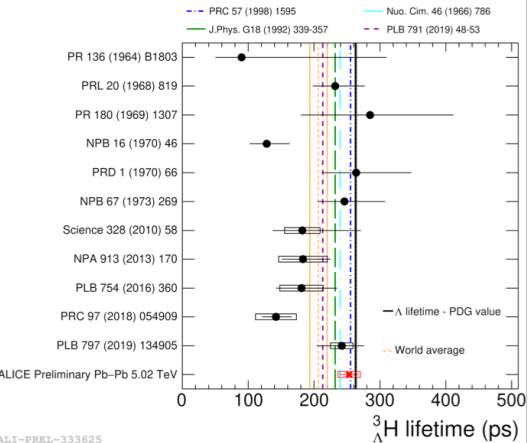
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

p-Λ → p-Λ

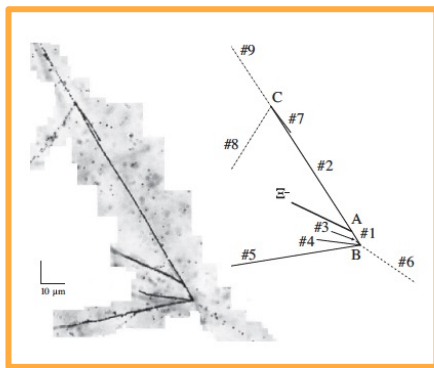


LO from H. Polinder, J.Haidenbauer, U. Meißner, NPA 779 (2006) 244 and NLO from J.Haidenbauer., N.Kaiser et al., NPA 915 (2013) 24.

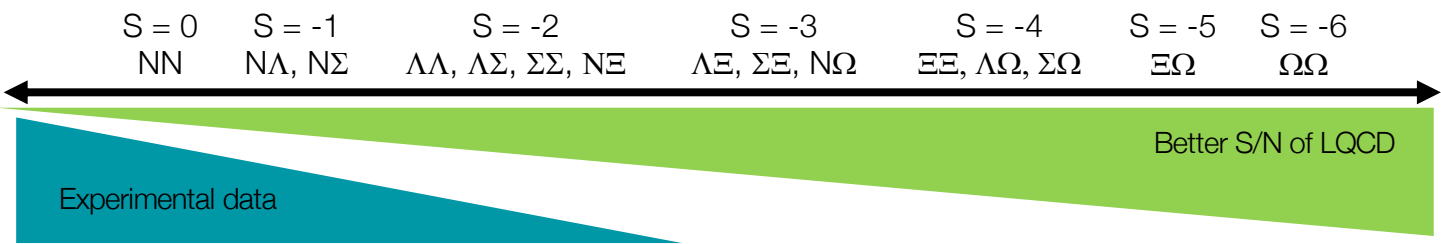
Hypertriton lifetime



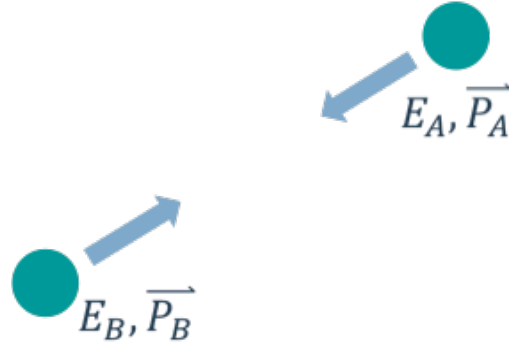
≡ hypernucleus



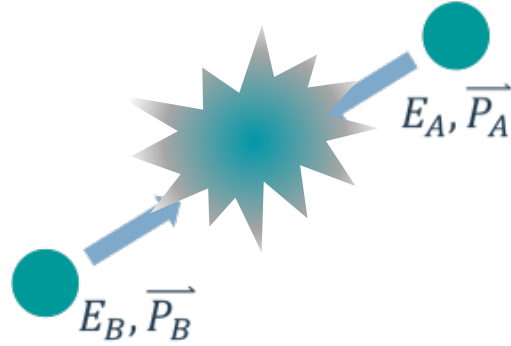
J-PARC E07 Coll. PRL 126, 062501 (2021)



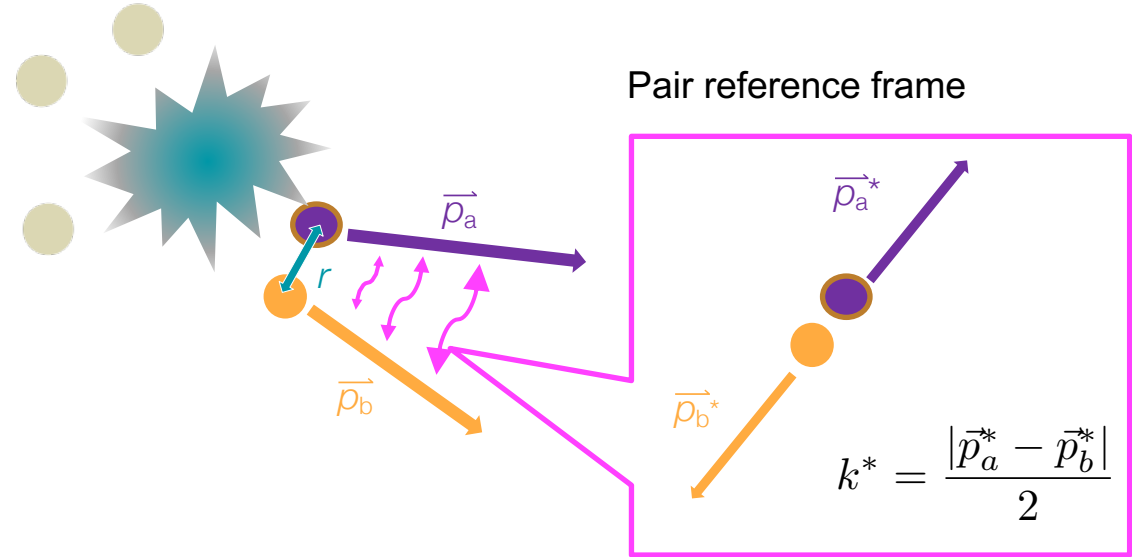
The femtoscopy technique



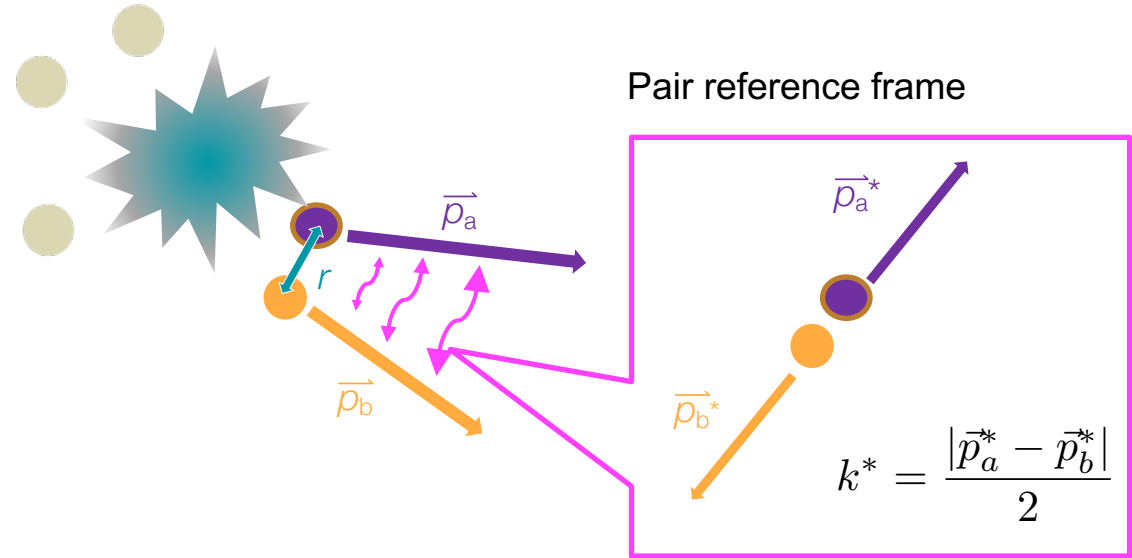
Nuclear collisions



Particle production and propagation



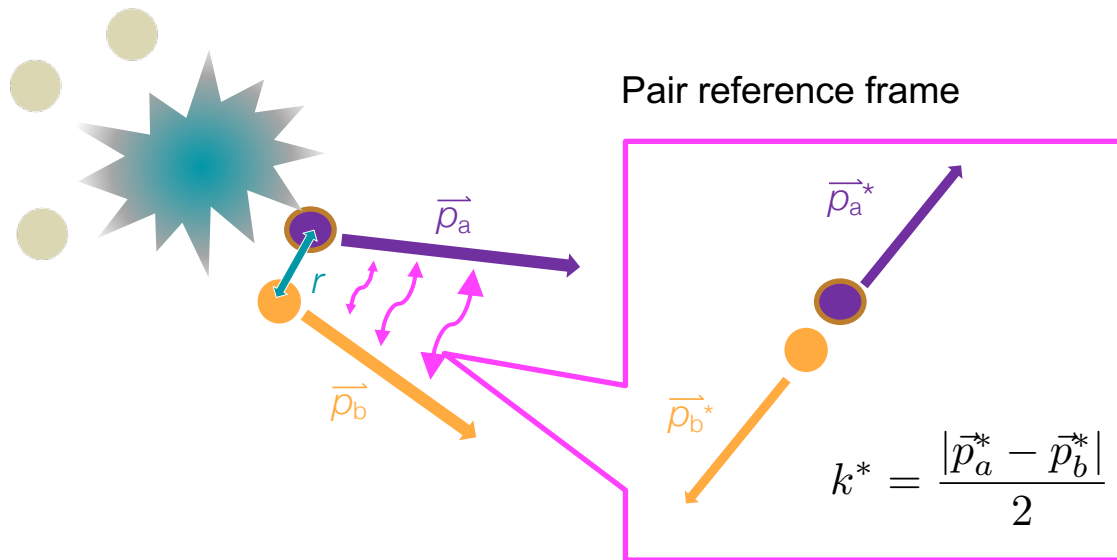
Particle production and propagation



Schrödinger Equation:

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

The femtoscopy technique



Schrödinger Equation:

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

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

Emission source Two-particle wave function

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

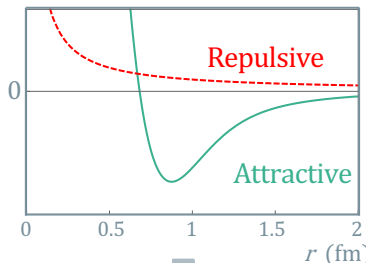
Example

Source parametrisation

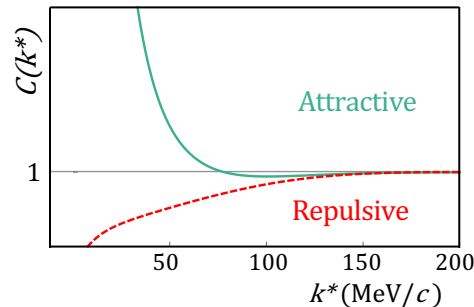


$V(r^*)$ (MeV)

Interacting potential



Correlation function



Gaussian source

Schrödinger equation**

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

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

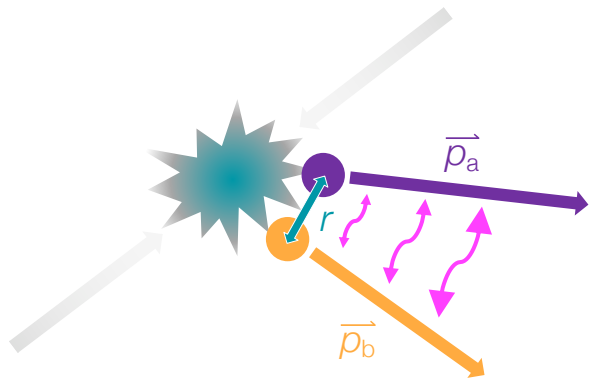
****CATS** (Correlation Analysis Tool using the Schödinger equation) D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

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

Emission source Two-particle wave function

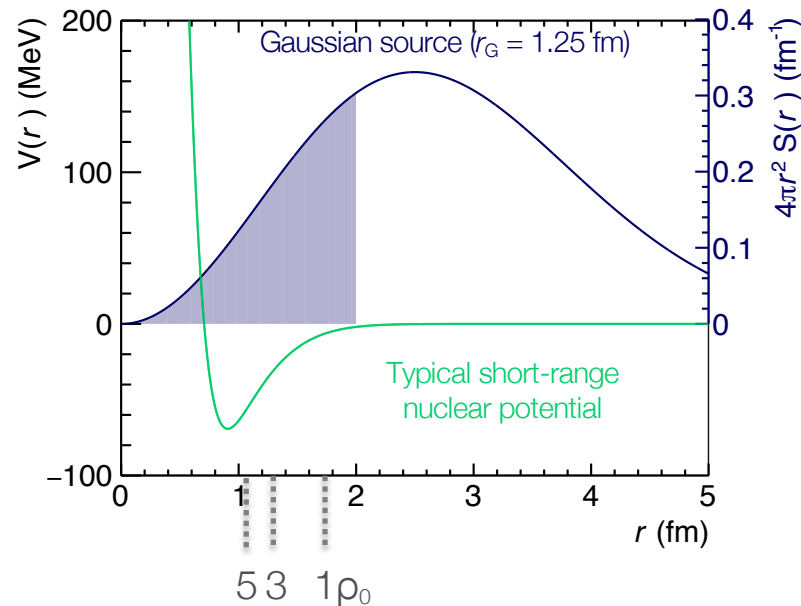
>1 if the interaction is attractive
= 1 if there is no interaction
<1 if the interaction is repulsive

Femtoscscopy with small sources



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

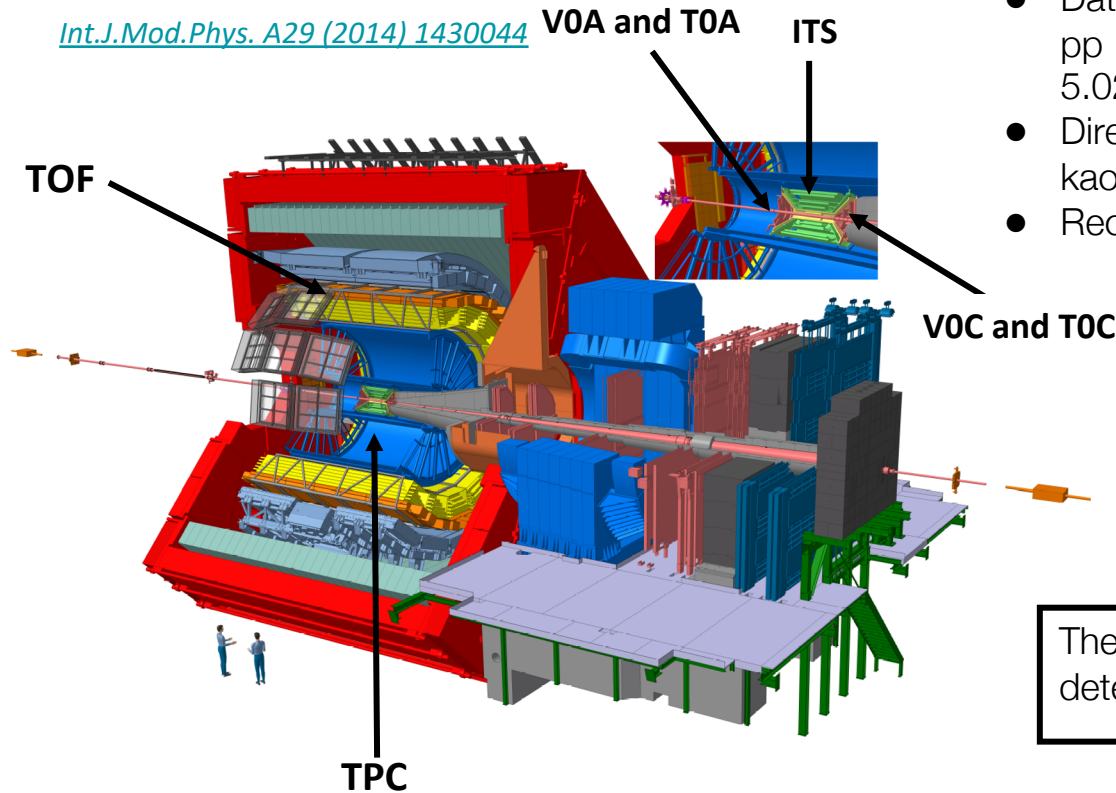
Emission source Two-particle wave function



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

- Essential ingredient for detailed studies of the strong interaction

[Int.J.Mod.Phys. A29 \(2014\) 1430044](#)



- 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:

$$\Lambda \rightarrow p\pi^-$$

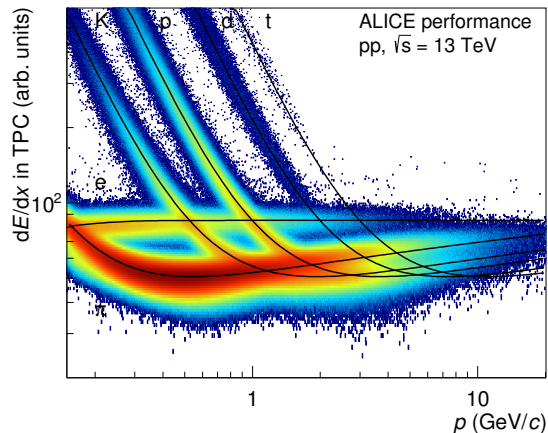
$$\Xi^- \rightarrow \Lambda\pi^-$$

$$\Omega^- \rightarrow \Lambda K^-$$

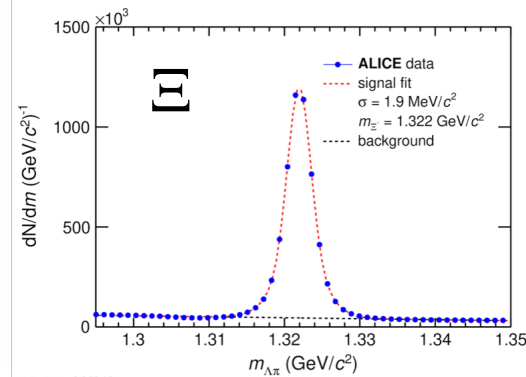
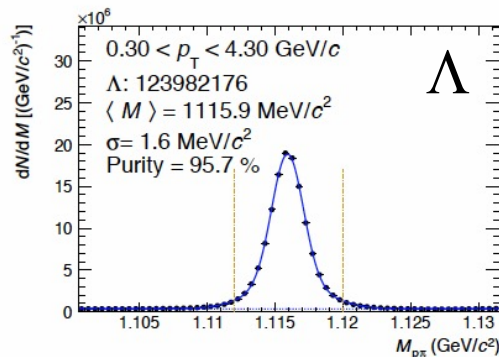
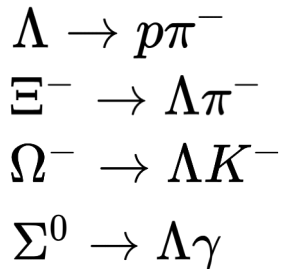
$$\Sigma^0 \rightarrow \Lambda\gamma$$

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

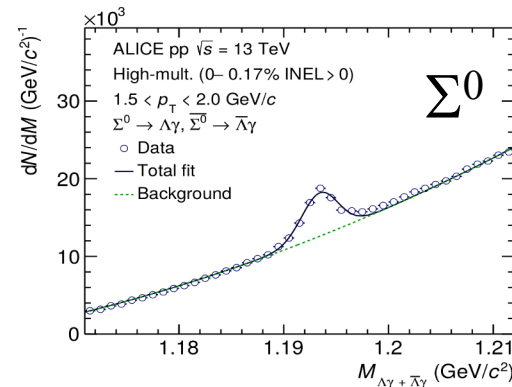
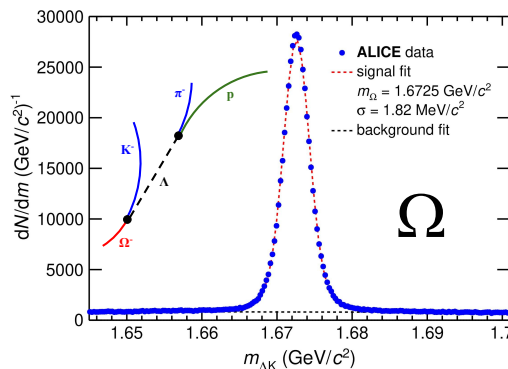
Hyperons @ ALICE in pp collisions



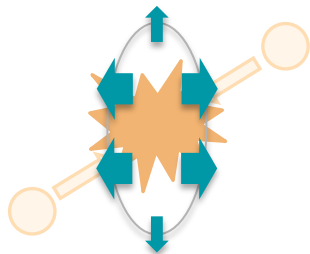
ALI-PERF-101240



ALI-DER-366243

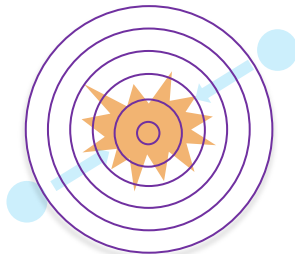


Collective effects and strong resonances



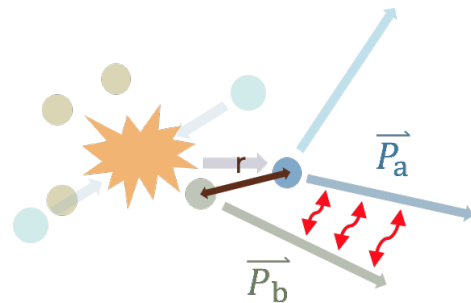
Anisotropic

+
pressure gradients



Radial

Different effect on different masses



Resonances with $c\tau \sim r_0 \sim 1\text{fm}$ ($\Delta^{++}, N^*, \Sigma^*$)

Particle	Primordial fraction	Resonances $\langle c\tau \rangle$
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

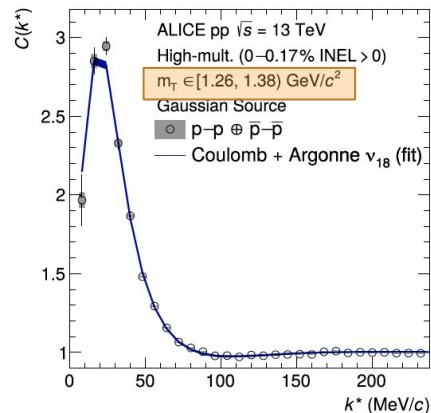
U. Wiedemann U. Heinz (PRC56 R610, 1997)

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

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

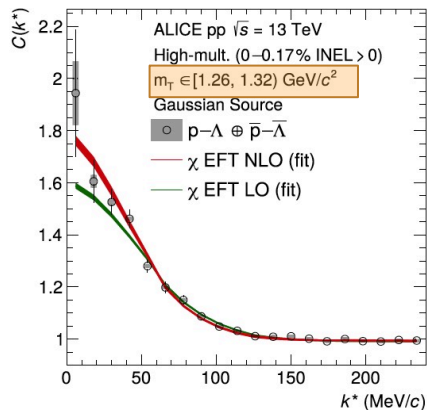
$$s = \beta\gamma\tau_{res} = \frac{p_{res}}{M_{res}} \tau_{res}$$

pp and p Λ correlations

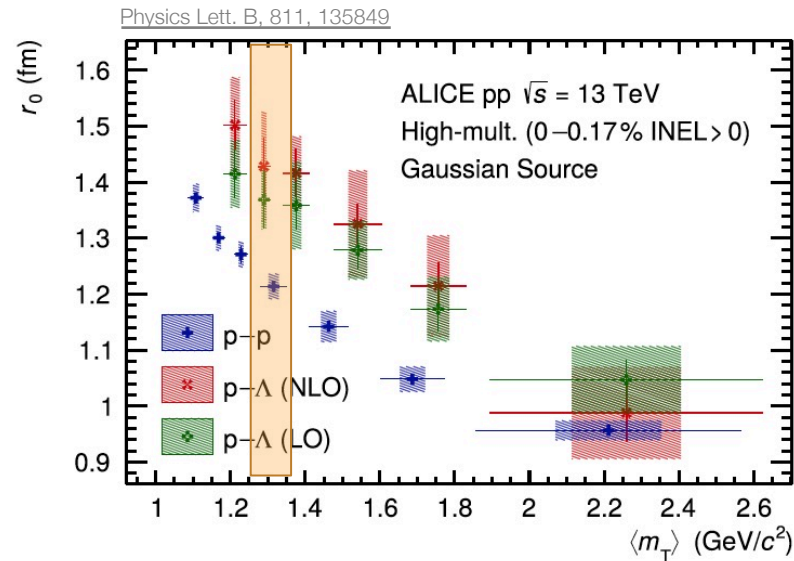


$$c(k^*) = \int \boxed{S(r)} |\psi(\vec{k}^*, \vec{r})|^2 d^3r$$

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



p Λ Correlation:
 χ EFT LO and NLO
 $\psi(\vec{k}^*, \vec{r})$ are used



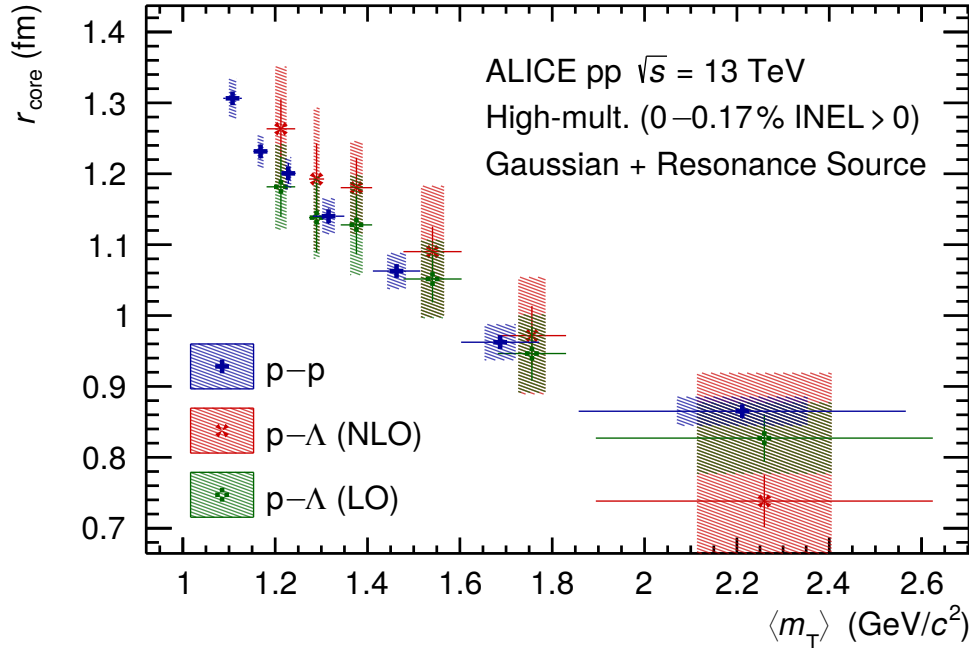
$$m_T = \sqrt{k_T^2 + m^2}$$

$$k_T = \frac{1}{2} |p_{T,1} + p_{T,2}|$$

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

A Gaussian source with resonances

Physics Lett. B, 811, 135849



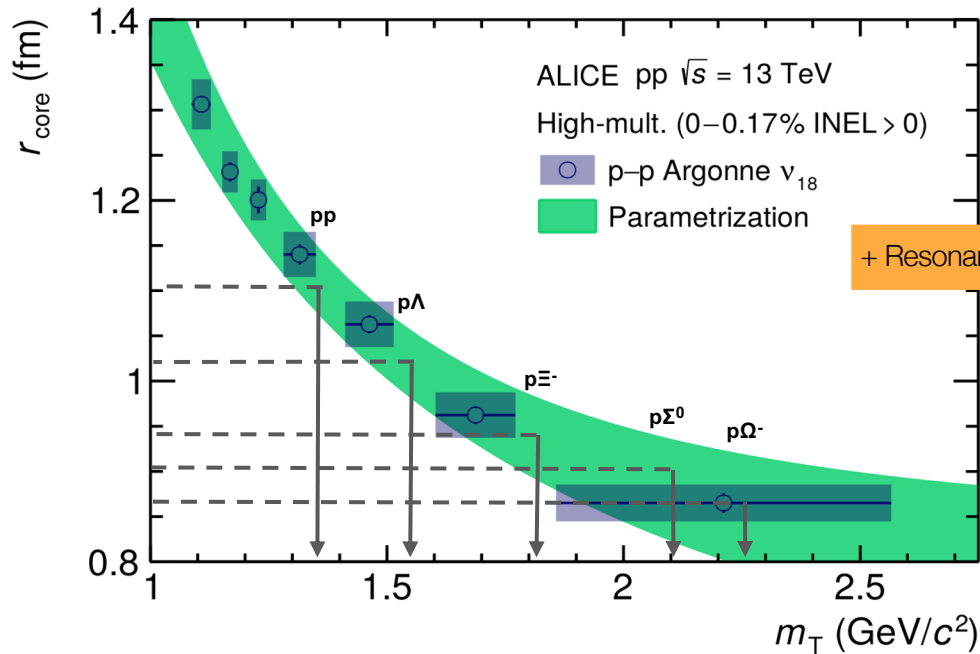
- Radii measured from the p-p and p- Λ correlation function
 - Input: production fraction/life-times (Statistical Hadronization Model*) and angular distributions (EPOS event generator**)
- Observation of a common m_T scaling of the core radius
 - Hypothesis of a universal emission source of baryons

* F. Becattini and G. Passaleva Eur.Phys.J.C 23 (2002) 551-583

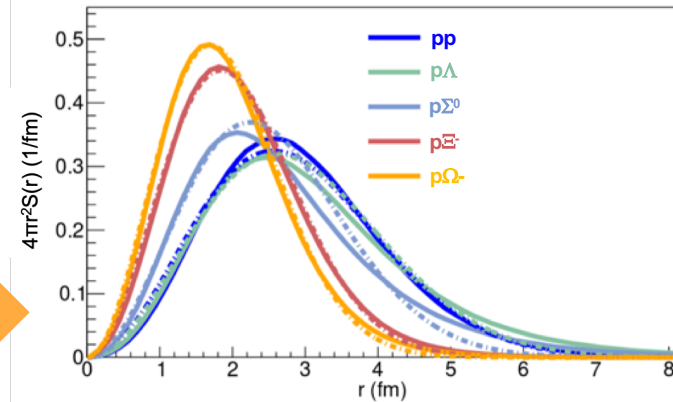
**T. Pierog et al. PRC 92 (2015) 3, 034906

A Gaussian source with resonances

Physics Lett. B, 811, 135849

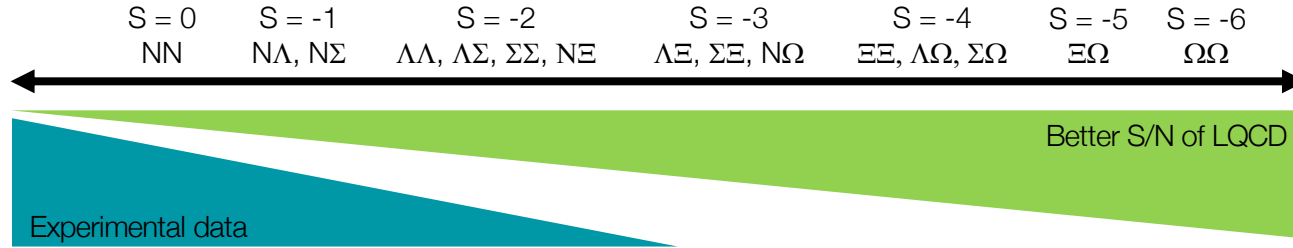


+ Resonances

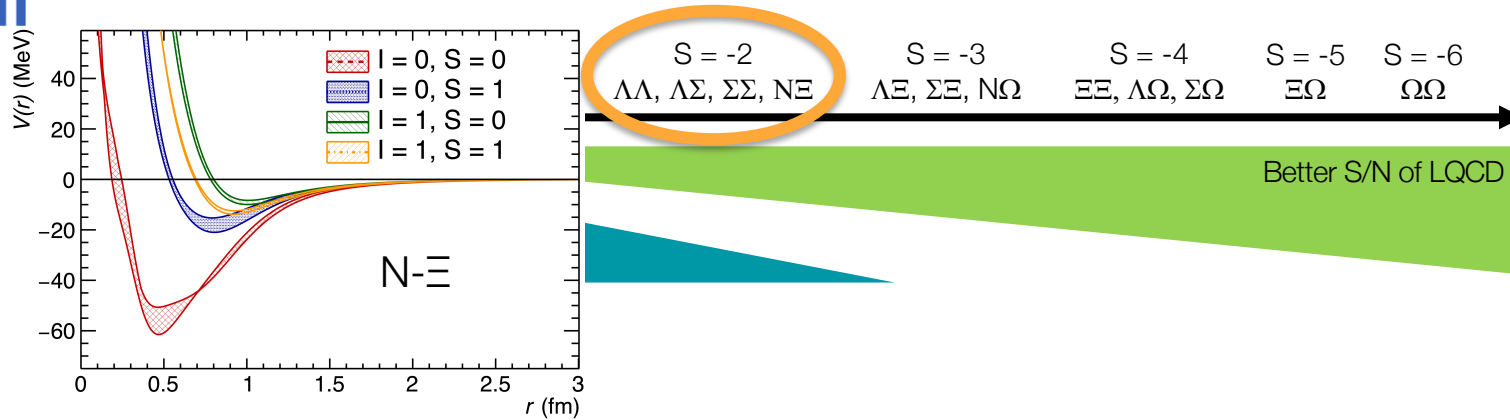


Pair	r_{Core} [fm]	r_{Eff} [fm]
p–p	1.1	1.2
p– Λ	1.0	1.3
p– Σ^0	0.87	1.02
p– Ξ^-	0.93	1.02
p– Ω^-	0.86	0.95

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

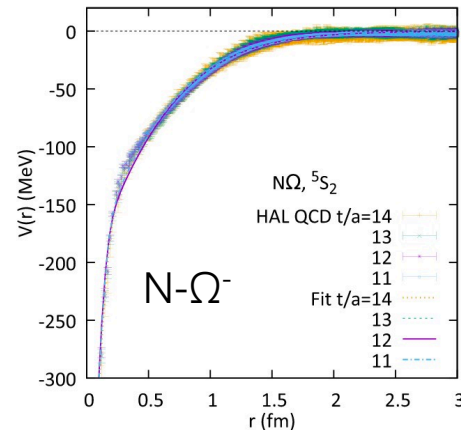
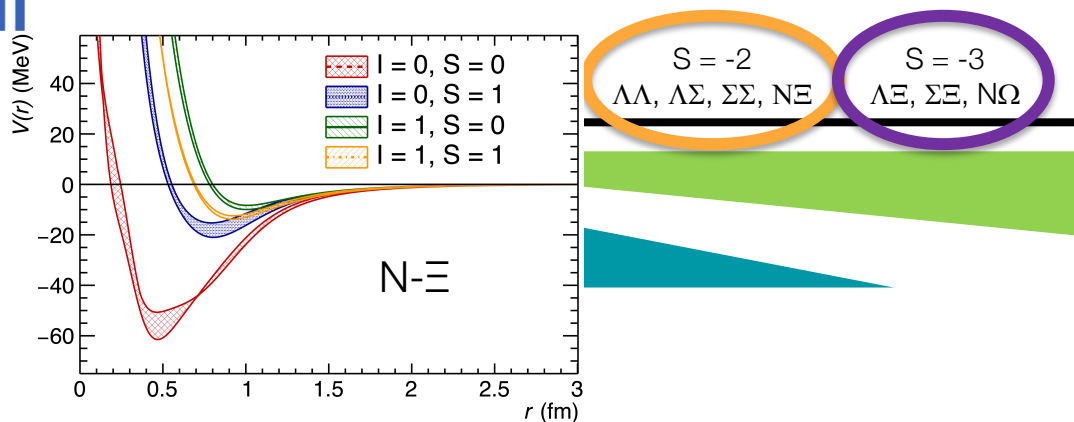


QCD $p\Xi^-$ and $p\Omega^-$ lattice potentials



- Interaction of $p\Xi^-$ pairs in four Isospin ($I = 0, 1$) and Spin ($S=0, 1$) states

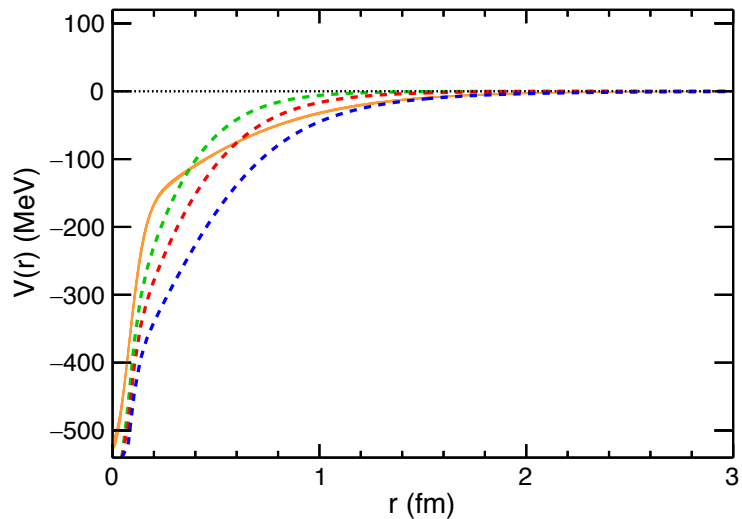
QCD $p-\Xi^-$ and $p-\Omega^-$ lattice potentials



- Interaction of $p-\Xi^-$ pairs in four isospin ($I=0,1$) and spin ($S=0,1$) states
- Interaction of $p-\Omega^-$ pairs in 3S_1 or 5S_2 ($S=1, 2$) states
 - Inelastic channels (e.g. $p\Omega^- \rightarrow \Lambda\Xi^-$) 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)

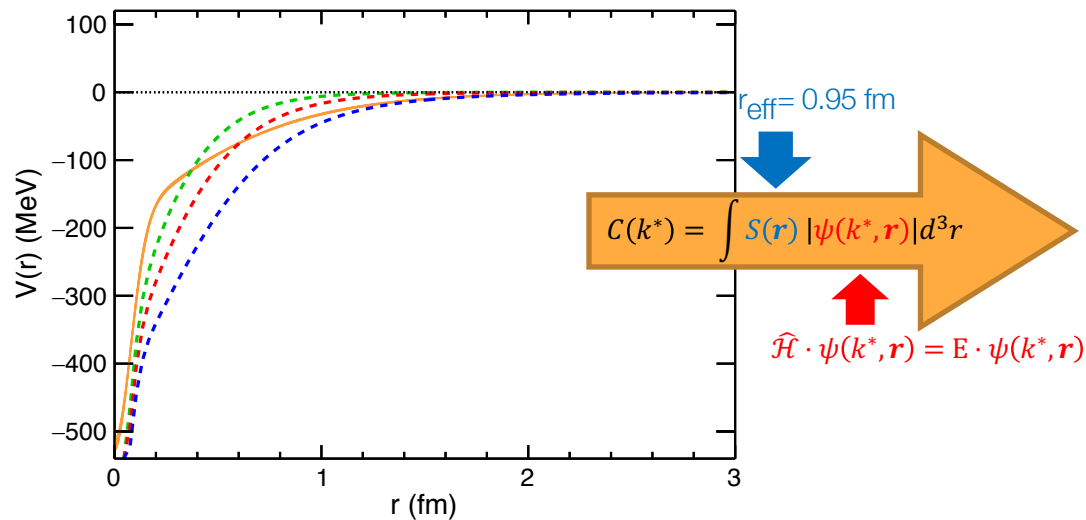
HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737
 HAL QCD Coll., Phys. Rev. C 101, 015201

Correlation functions and bound states



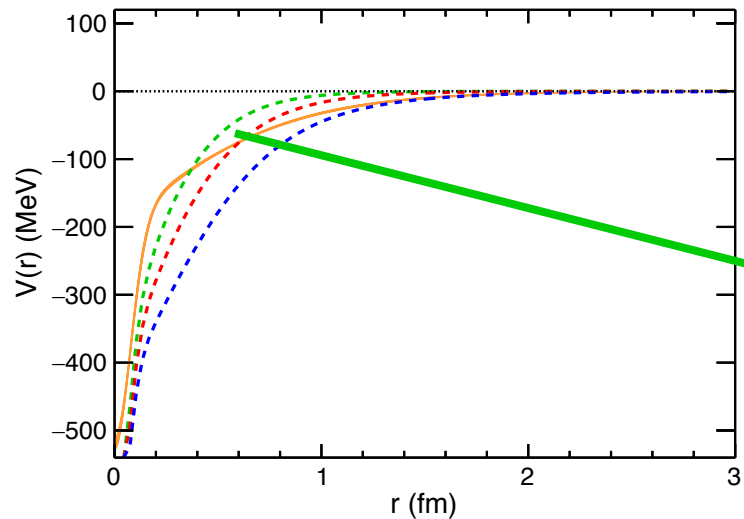
K. Morita et al., Phys. Rev. C 101, 015201 (2020)

Correlation functions and bound states

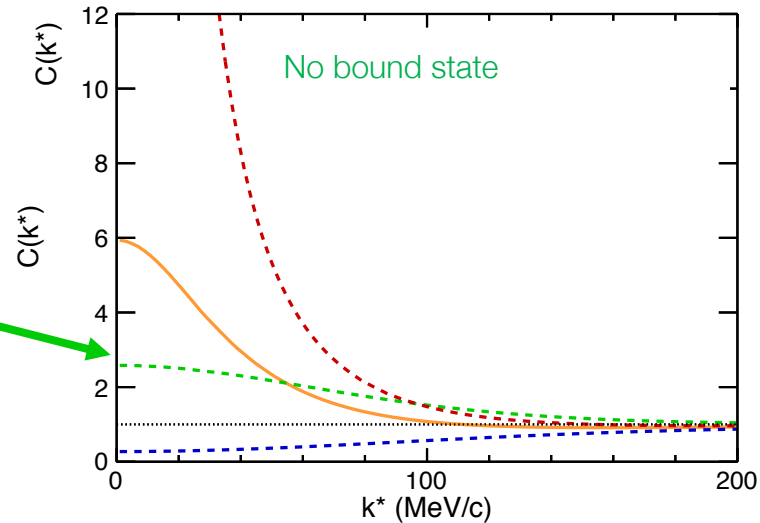


K. Morita et al., Phys. Rev. C 101, 015201 (2020)

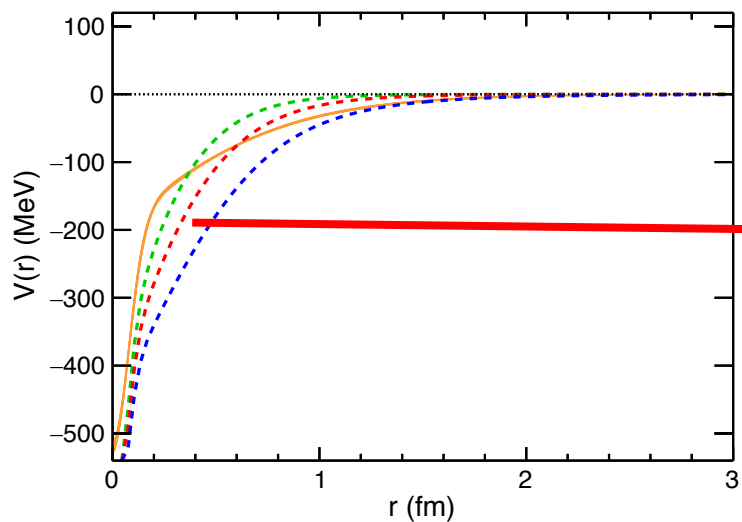
Correlation functions and bound states



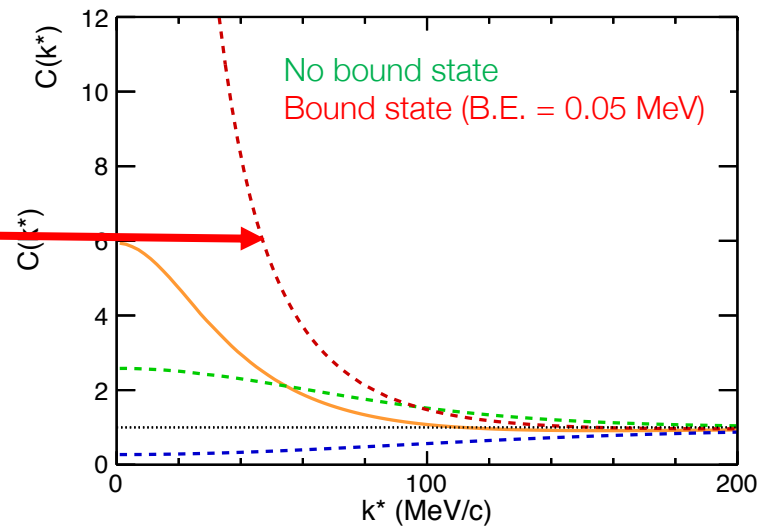
K. Morita et al., Phys. Rev. C 101, 015201 (2020)



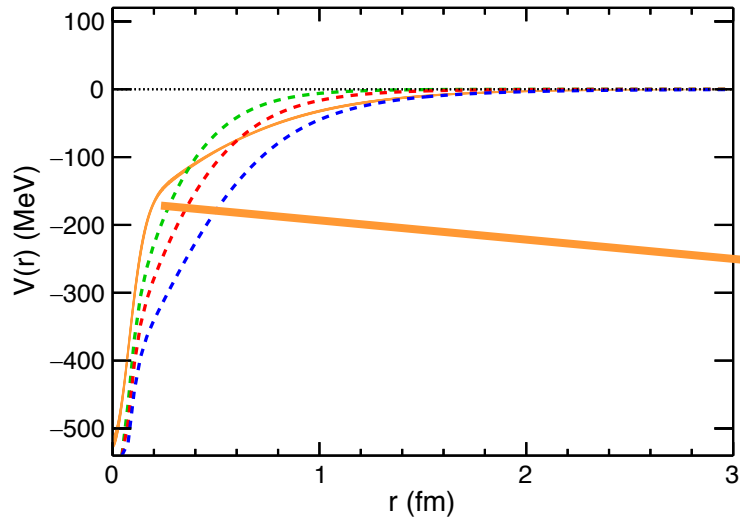
Correlation functions and bound states



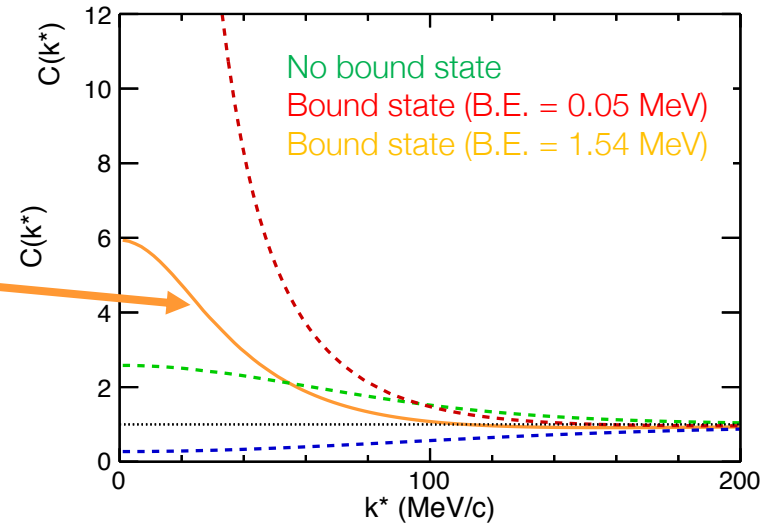
K. Morita et al., Phys. Rev. C 101, 015201 (2020)



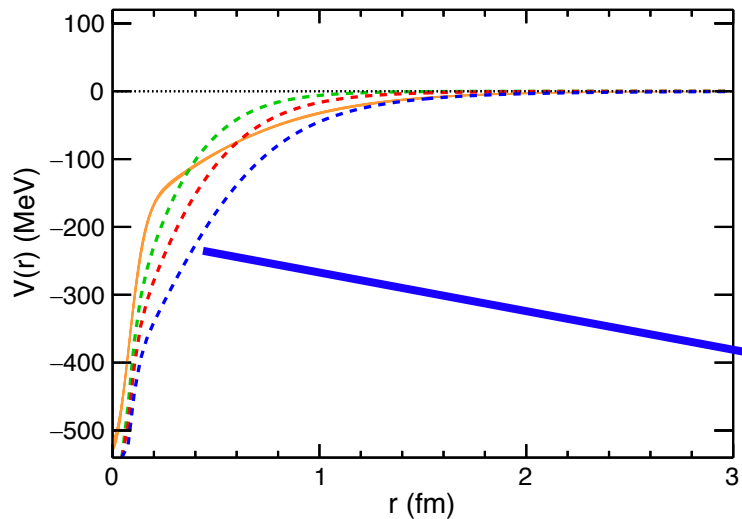
Correlation functions and bound states



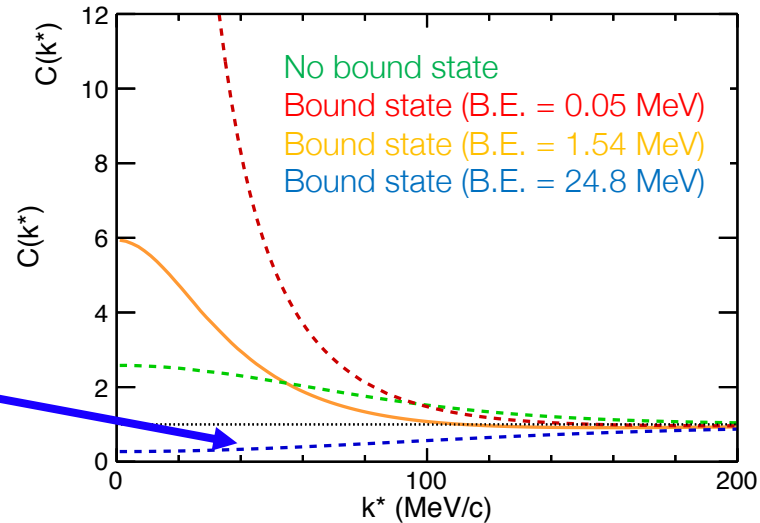
K. Morita et al., Phys. Rev. C 101, 015201 (2020)



Correlation functions and bound states



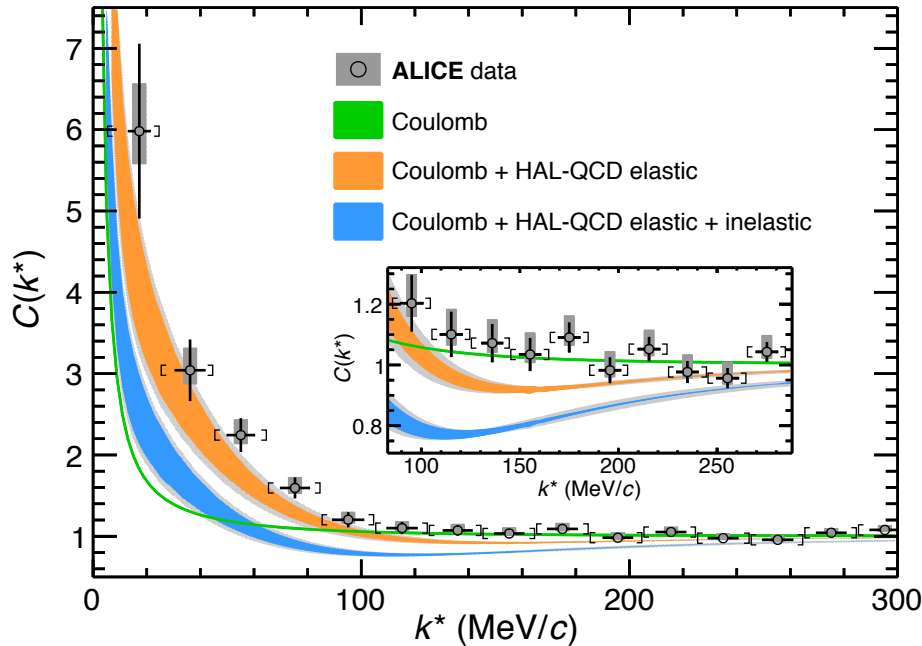
K. Morita et al., Phys. Rev. C 101, 015201 (2020)



- 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

-> Poster Georgios Mantzaridis

Excursion to neutron stars

Hyperon appearance in neutron stars?

Dimensions:

$R \sim 10 - 15 \text{ km}$

$M \sim 1.2 - 2.2 M_{\odot}$

Outer crust:

Ions, electron gas,
neutrons

Inner core:

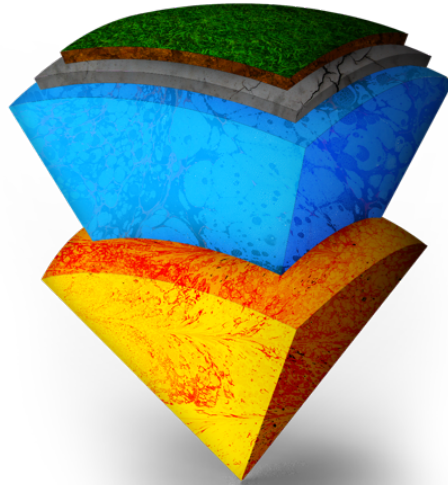
Neutrons?

Protons?

Hyperons?

Kaon condensate?

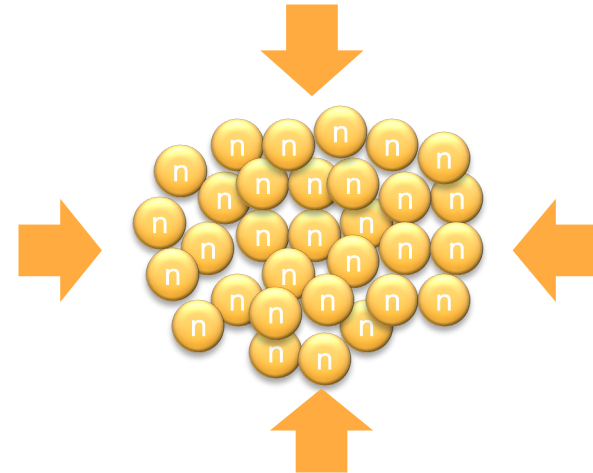
Quark matter?



p increases

Neutron stars: very dense, compact objects

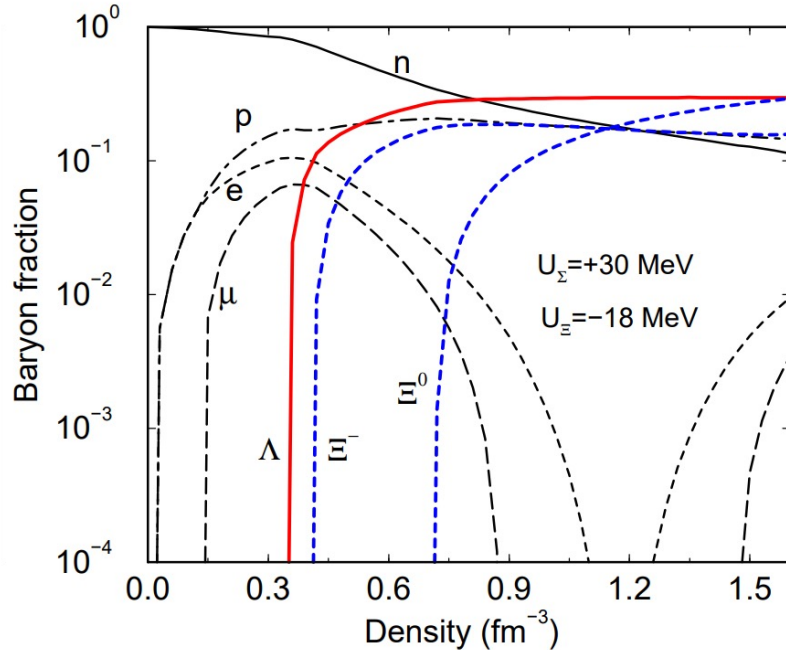
- How does the equation of state of neutron star look like?
 - What are the constituents to consider?
 - How do they interact?



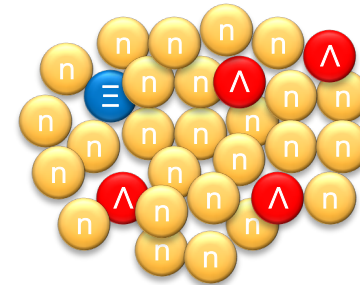
Hyperon appearance in neutron stars?

Neutron stars: very dense, compact objects

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

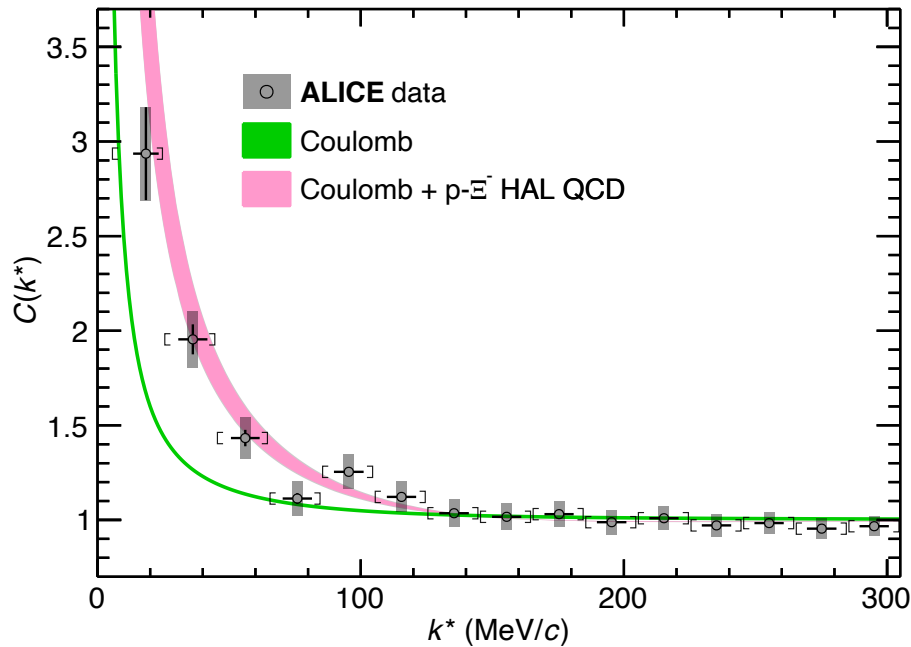


J. Schaffner-Bielich, Nucl. Phys. A 835 (2010) 279



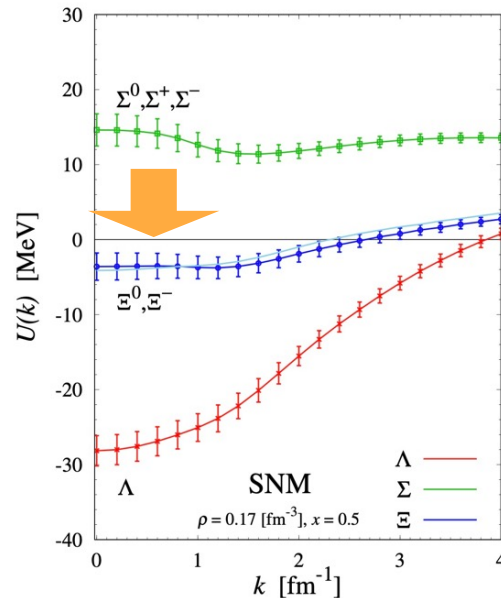
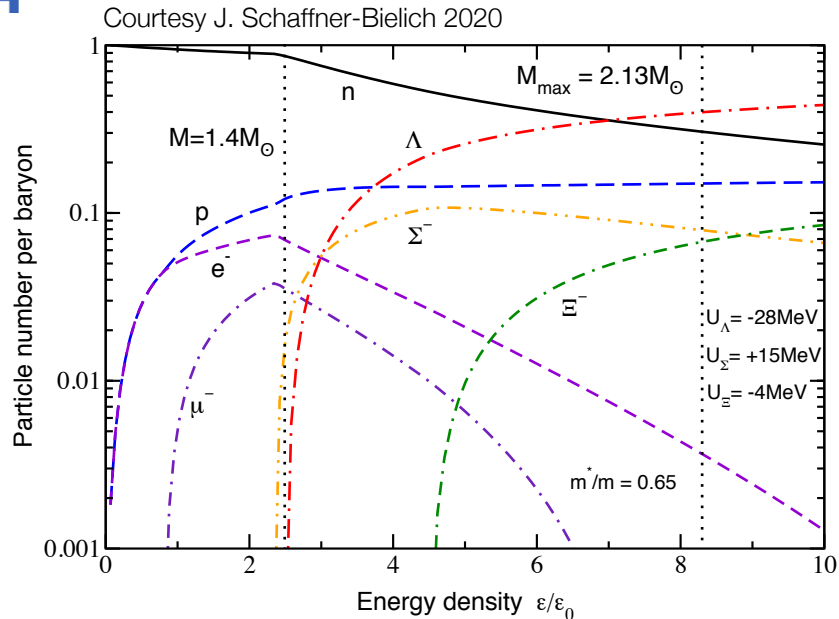
p- Ξ^- correlation function in pp at 13 TeV

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

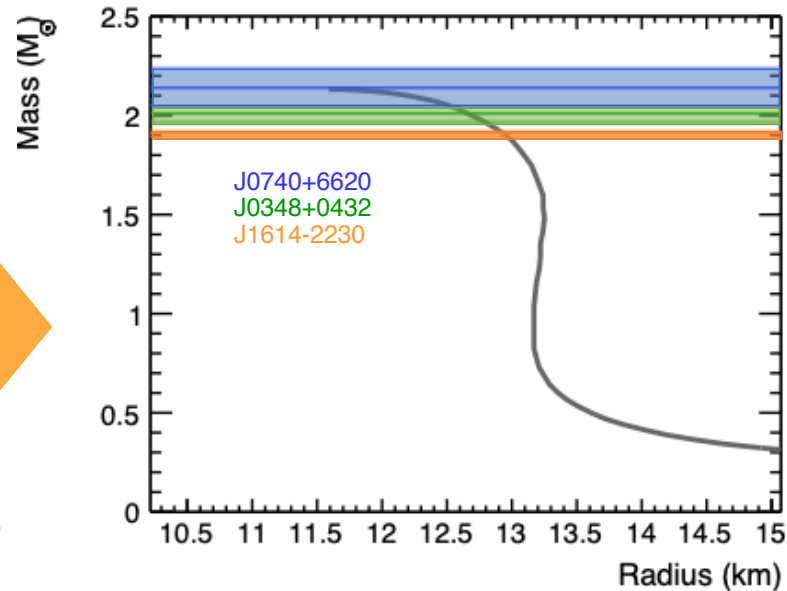
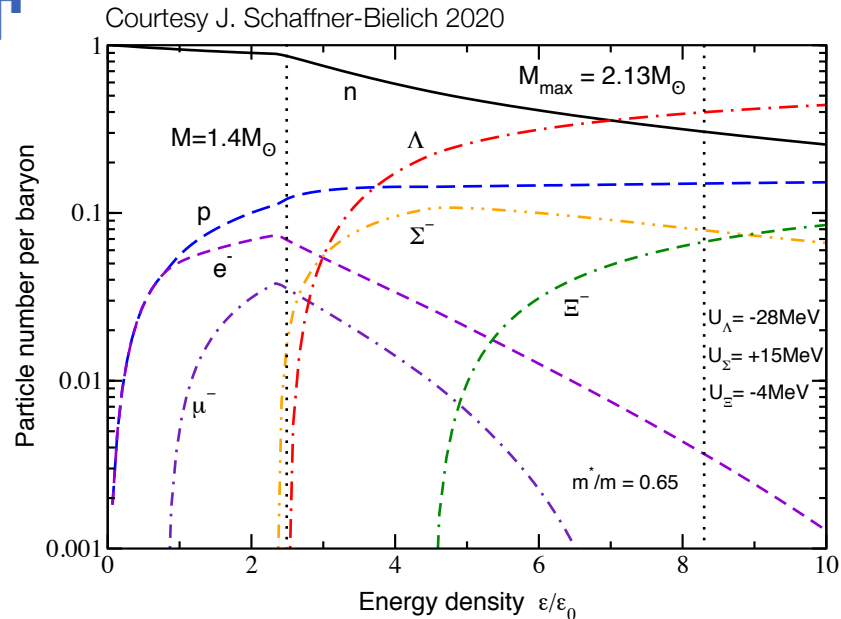
Single particle potentials from lattice QCD



Attractive $p\Xi^-$ 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)

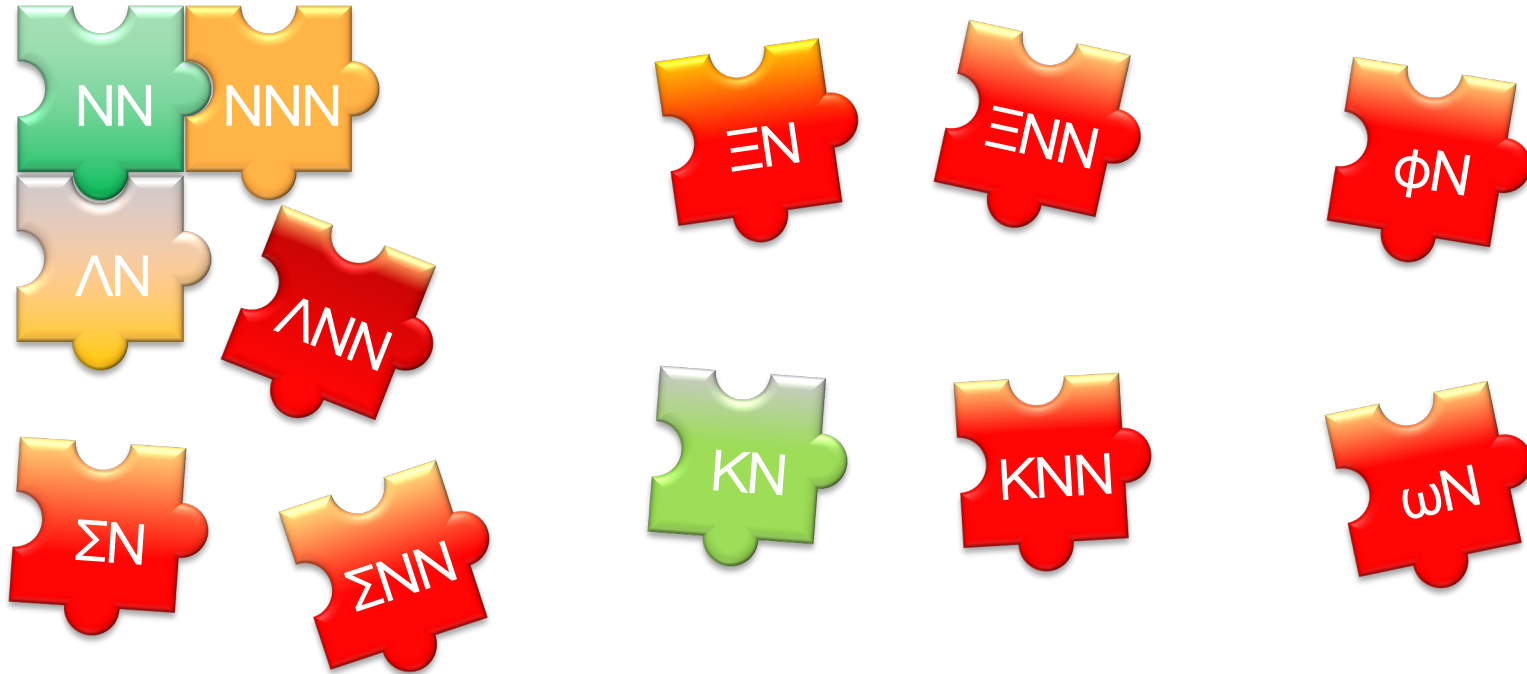
Equation of state for neutron stars



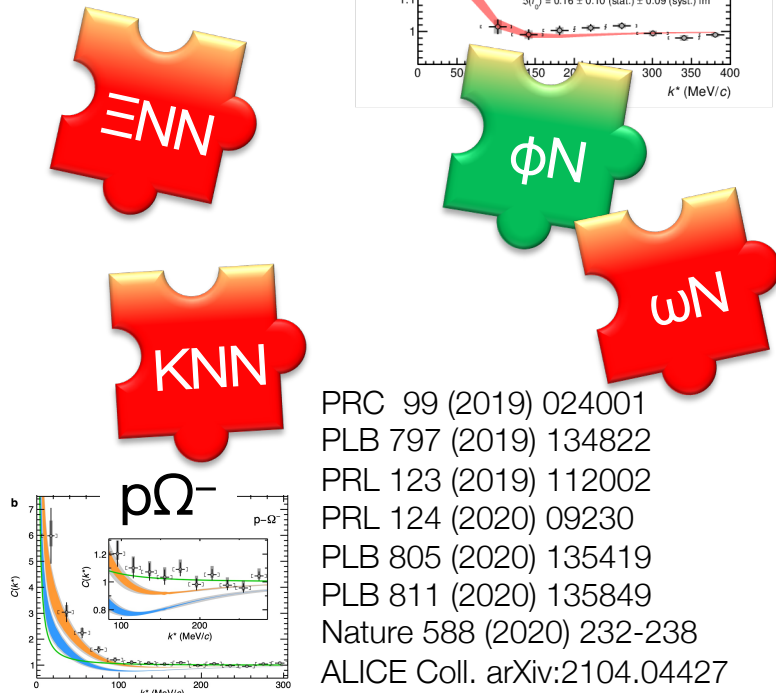
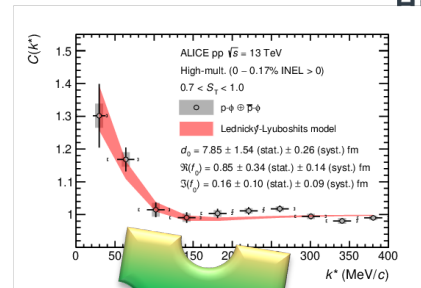
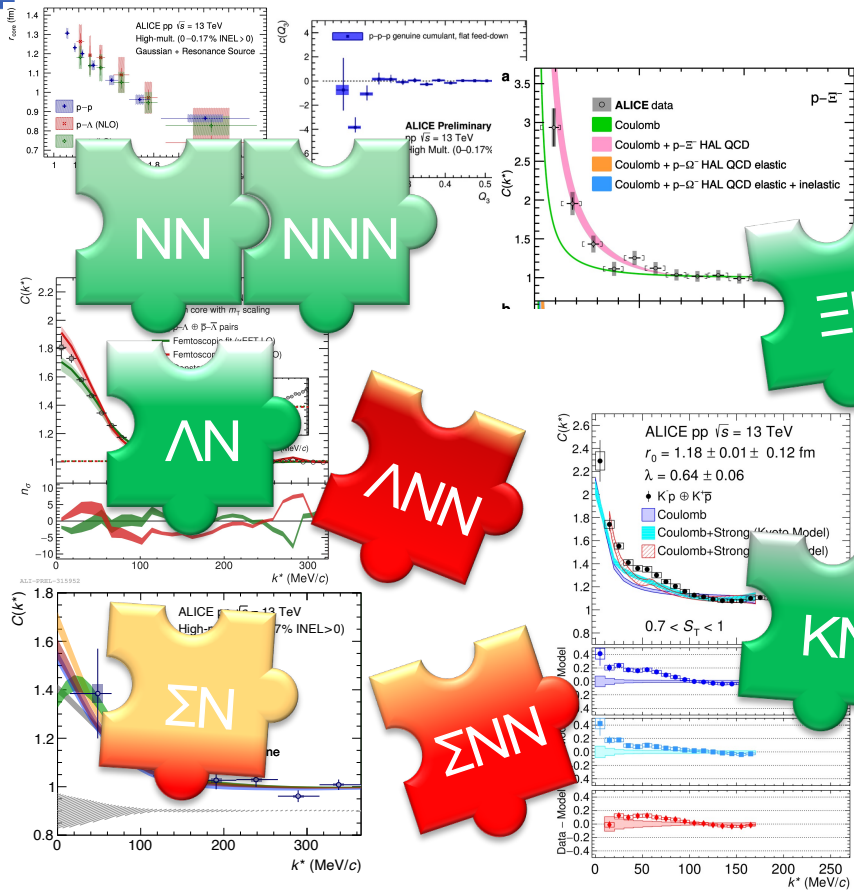
The resulting equation of state for neutron star is stiffer and the observation of 2 solar masses is matched.

This is not the end of the story...

The Hyperon Puzzle



Harvest of LHC Run 1 & 2

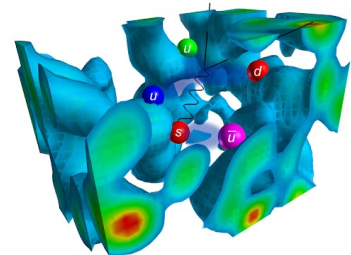


PRC 99 (2019) 024001
 PLB 797 (2019) 134822
 PRL 123 (2019) 112002
 PRL 124 (2020) 09230
 PLB 805 (2020) 135419
 PLB 811 (2020) 135849
 Nature 588 (2020) 232-238
 ALICE Coll. arXiv:2104.04427
 ALICE Coll. arXiv:2105.05578
 ALICE Coll. arXiv:2105.05190

Summary

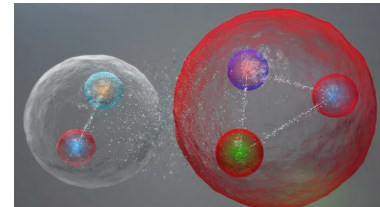
- Femtoscopy technique can be used to provide unprecedented constraints on hadron-hadron interactions
- We have tested lattice calculations
- We can study bound states
- We provide important constraints to the equation of state of neutron stars
- More precision studies within reach with the large data samples collected in Run 3 & 4
 - Direct measurements of three-body interactions for the first time **-> Poster Raffaele Del Grande**
 - 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

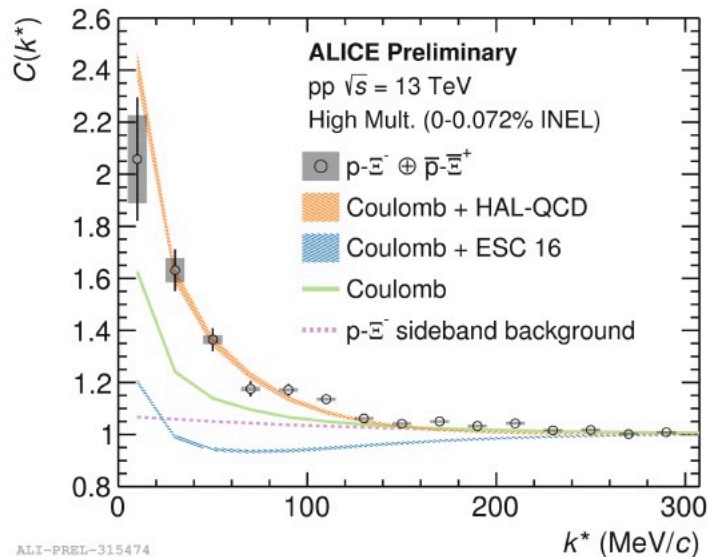
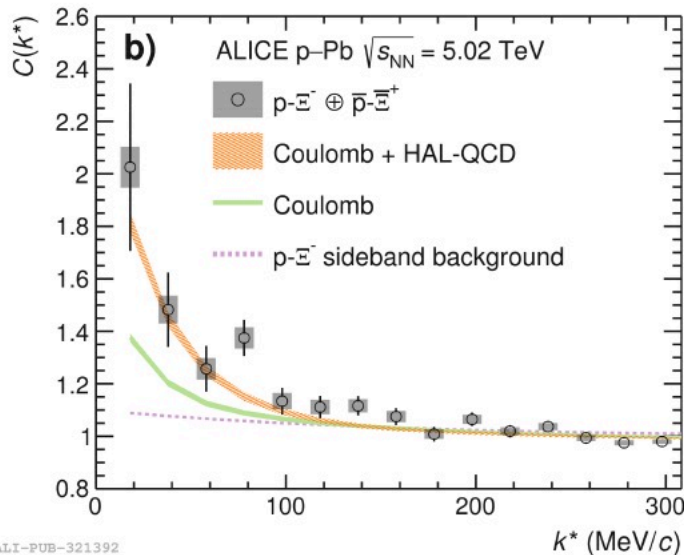


Stay tuned for much more to come...

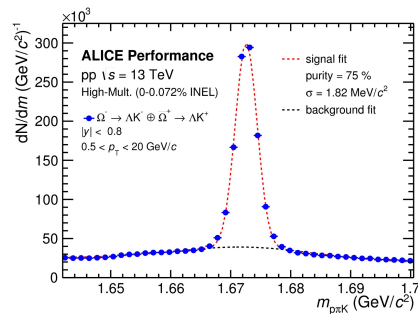
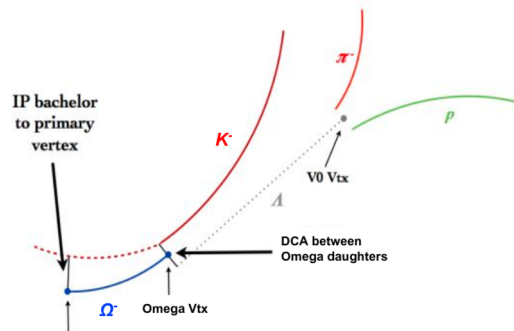


p Ξ^- Comparisons to ESC08

Phys.Rev.Lett. 123 (2019) 11, 112002

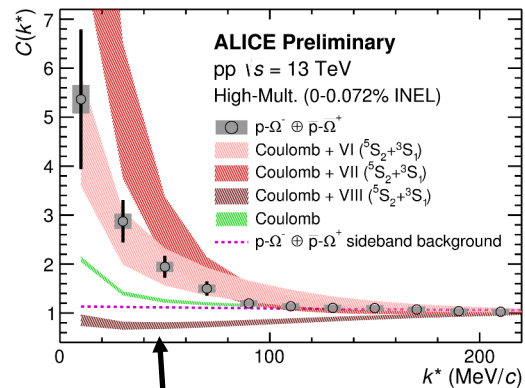


$p \Omega^-$: the ALICE Measurement

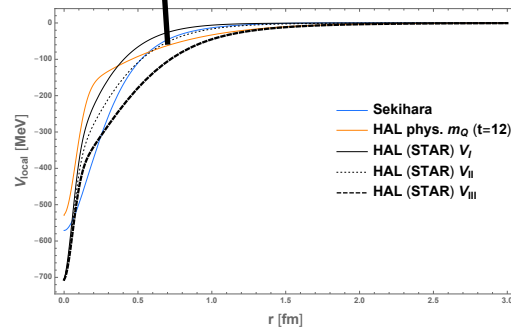


ALI-PREL-315635

Correlation Function



ALI-PREL-325870



VIII excluded

B.E. = 26.9 MeV