ALICE measurements of p-Ξ^- and p-Ω^- interactions and constraints on lattice QCD

Otón Vázquez Doce (TUM)
for the ALICE Collaboration

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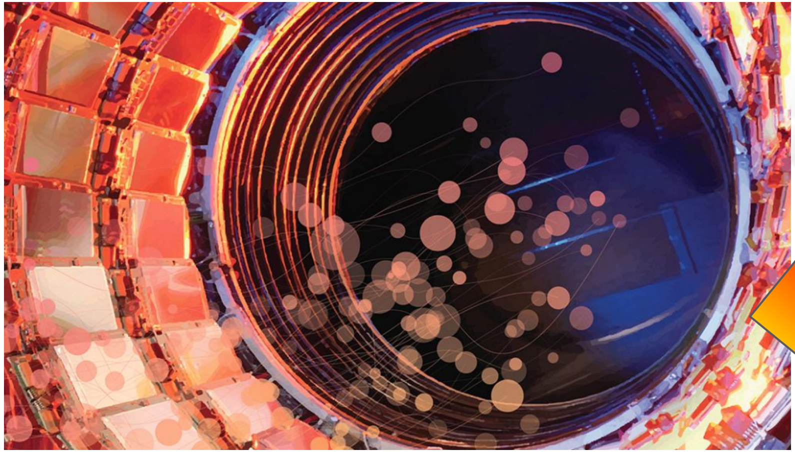
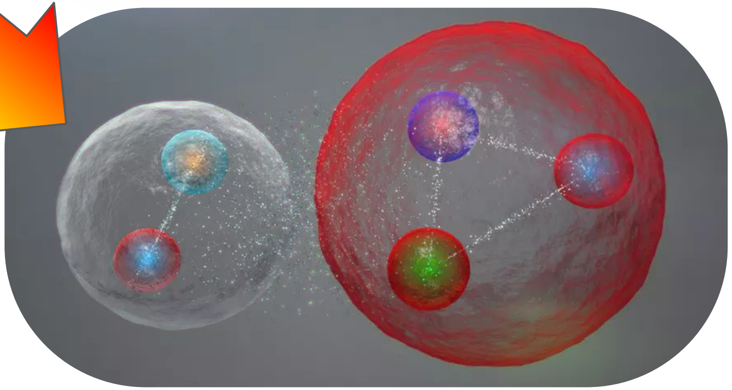
29 July 2020

Outline



High-energy physics

Hadron physics



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LHC

Small collision systems:
- pp 13 TeV
- p-Pb 5.02 TeV

⇒ **particle sources below 1 fm**

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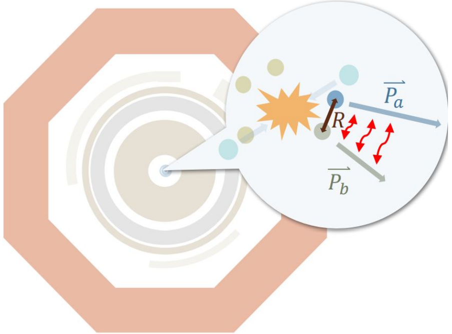

Central barrel tracking and PID:
- Inner Tracking System
- Time Projection Chamber
- Time Of Flight

Reconstruction of hyperons:
- $\Lambda \to p\pi$
- $\Xi \to \Lambda\pi$
- $\Omega \to \Lambda K$

Study of **p-Ξ^-, p-Ω^- pairs**

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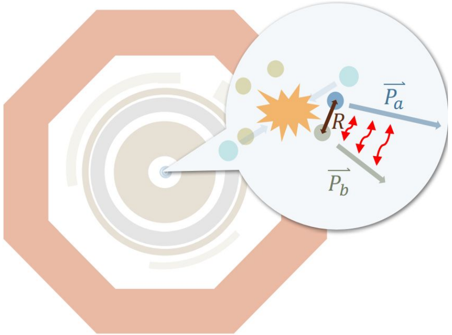

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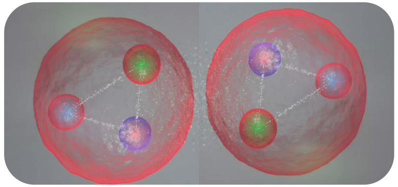
Hadron physics

Interaction of baryons with **strange content:**
- First principle calculations: **Recent developments by lattice QCD** at the physical point
- Models are constrained by data with limited precision, in contrast with N-N interactions

Correlation studies with ALICE:
- **Precise data** in the low momentum range, **not accessible with other approaches.**
- Consequences for: appearance of hyperons in neutron stars, existence of strange di-baryons.

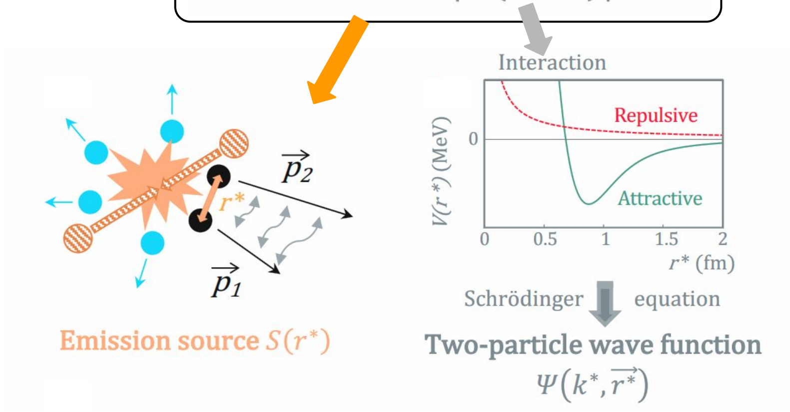


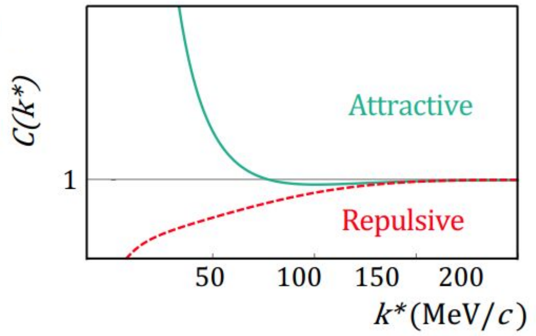
Recent publications: arXiv:2004.08018 [nucl-ex]
arXiv:2005.11495 [nucl-ex]

Two-particle correlations as a tool for studying h-h interactions

Based on the correlation function $C(k^*) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$, with $k^* = |\vec{p}_2^* - \vec{p}_1^*|/2$ and $p_1^* = -p_2^*$

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





CATS: Schrödinger equation solver
D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394

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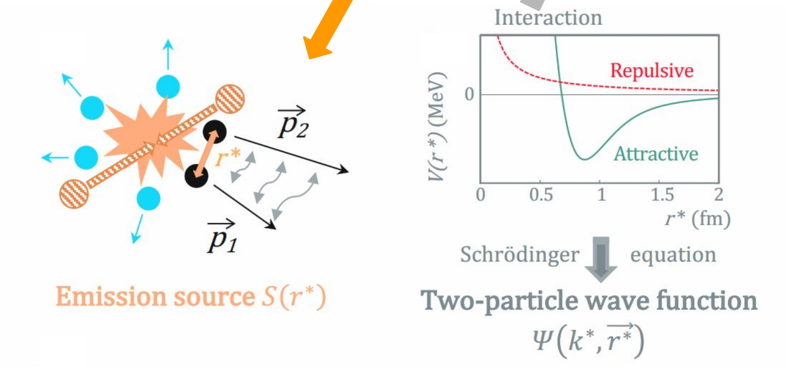

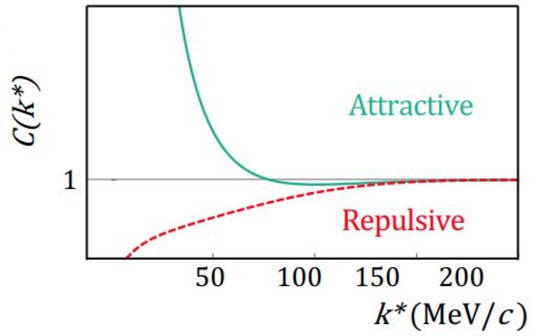

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Experimentally obtained: $C(k^*) = \xi(k^*) \otimes \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$

Normalization, resolution effects, residual correlations.

Setting the source

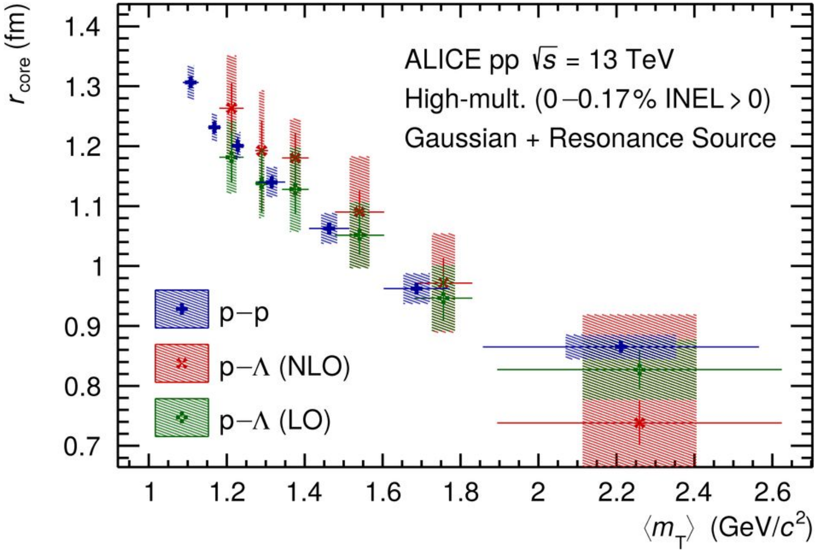
A. Mathis, “07.Heavy Ions”, 31-July, 8:48

“Search for a common baryon source in high-multiplicity pp collisions at the LHC”, ALICE Coll., arXiv:2004.08018 [nucl-ex] (submitted to PLB)

Ansatz: similar source for all baryon-baryon pairs in small collision systems

Source characteristics **determined via femtoscopic analysis of p-p correlations**

- **Transverse mass <m_T> dependence** due **to collective effects**
- Effect of strong short-lived resonances computed for all hadrons



The p-Ξ^-, p-Ω^- sources **determined given the pair <m_T>:**

p-Ξ^-: <m_T> = 1.9 GeV/c ⇒ r_{core} = 0.92 ± 0.05 fm

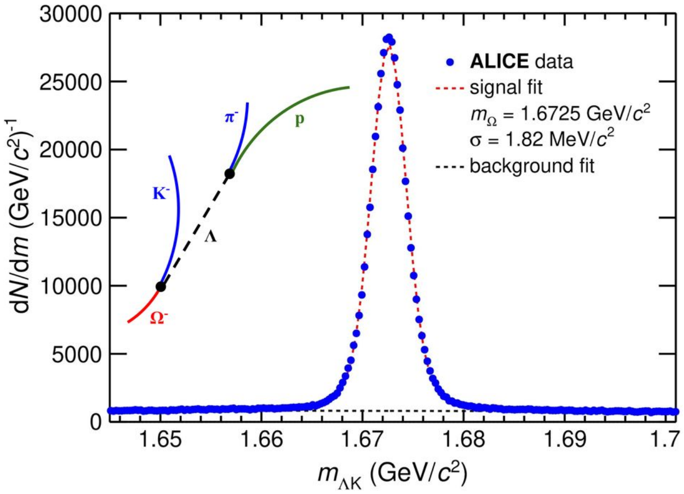
p-Ω^-: <m_T> = 2.2 GeV/c ⇒ r_{core} = 0.86 ± 0.06 fm

Detecting hyperons with ALICE

Enhanced production of strange hadrons in high multiplicity (HM) pp collisions ALICE Coll. Nature Physics 13, 535 (2017)

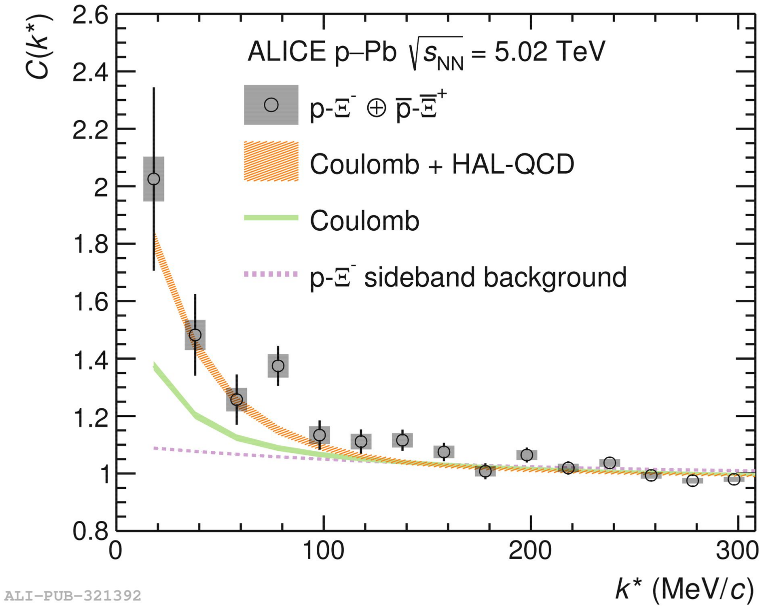
Weak decay reconstruction in HM pp collisions:

- Purity of Ξ selection 92%, Ω selection 95%
- p-Ξ^- pairs: 5.$\cdot 10^6$ ($37\cdot 10^3$ pairs for k* < 200 MeV/c)
- p-Ω^- pairs: $0.6\cdot 10^6$ ($4\cdot 10^3$ pairs for k* < 200 MeV/c)



p-Ξ^- in p-Pb at 5.02 TeV

"First Observation of an Attractive Interaction between a Proton and a Cascade Baryon", ALICE Coll., Phys. Rev. Lett. 123, (2019) 112002



$r_0 = 1.427 \pm 0.007 \text{ (stat.) } ^{+0.001}_{-0.014} \text{ (syst.) fm}$ (-20%, resonances)

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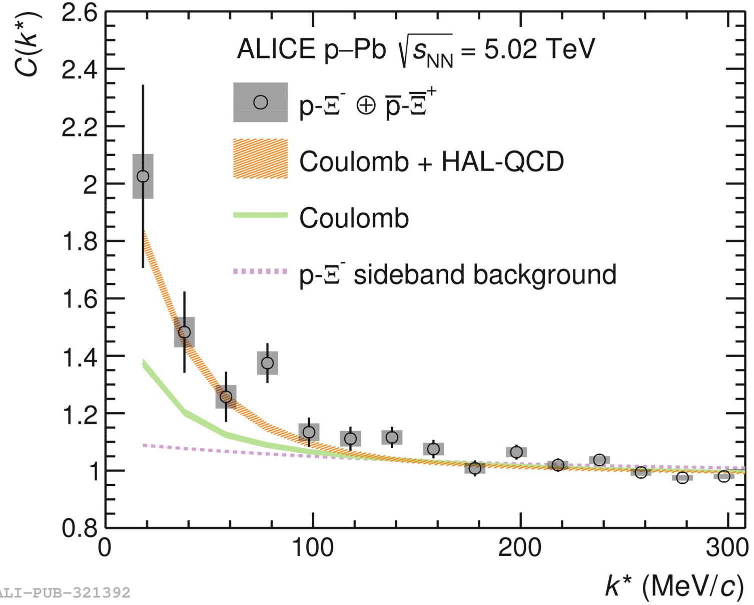

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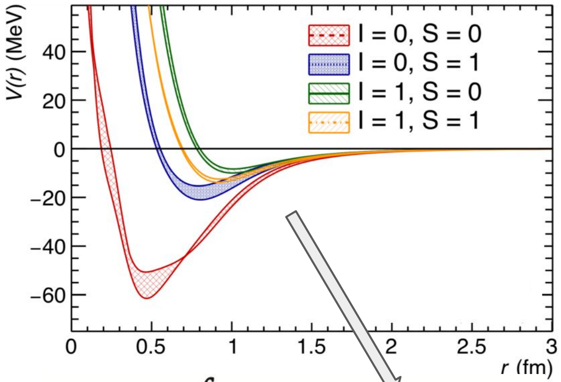
p-Ξ- potential from lattice QCD



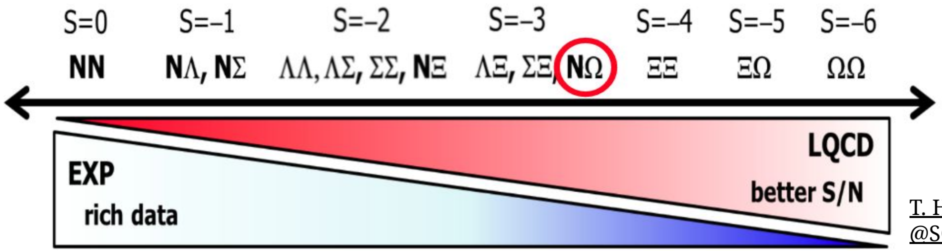
K. Sasaki et al. (HAL QCD), Nucl. Phys. A330, 998 (2020)

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

Lattice QCD:
U_{Ξ^-} single particle potential **slightly repulsive (6 MeV) in pure neutron matter (NS)**

Repulsive interaction ⇒ Ξ pushed to high densities
⇒ **stiffer EoS**, higher masses

Lattice QCD with S=-3



T. Hatsuda
@SQM19Bari

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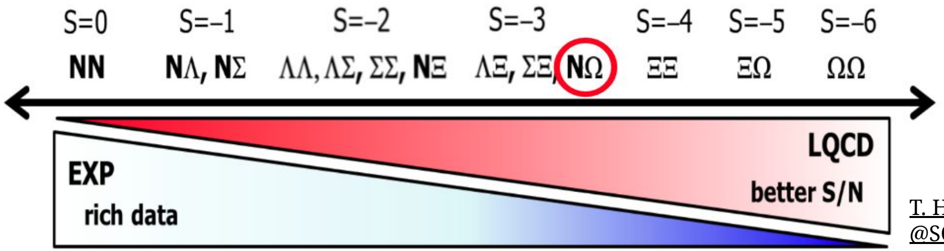

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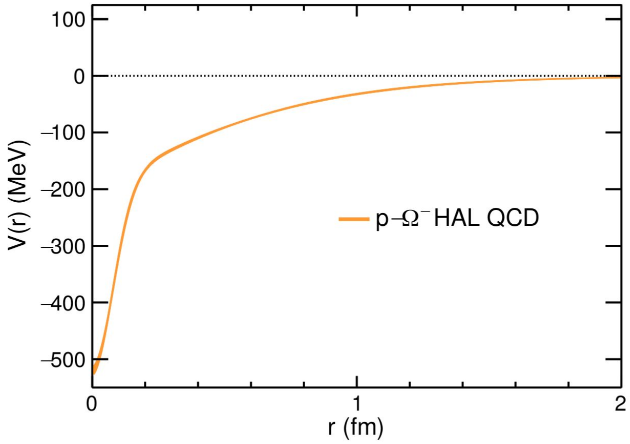
- **HAL QCD p-Ω^- potential** with physical quark masses
  - m_π = 146 MeV/c^2, m_K = 525 MeV/c^2
- Predicts the formation of a **p-Ω^- di-baryon**.

	HAL QCD: pΩ^- binding energy
Strong interaction	1.5 MeV
Strong + Coulomb	2.5 MeV

T. Iritani et al., PLB792 (2019) 284.



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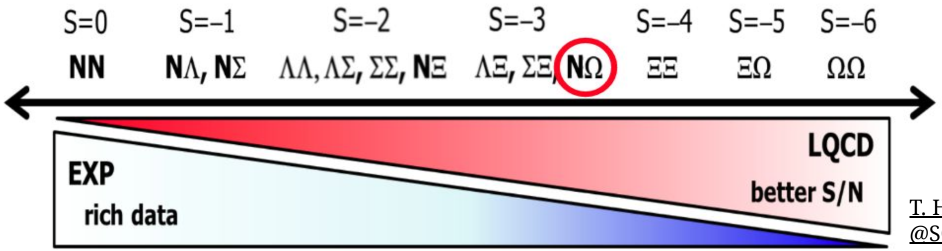

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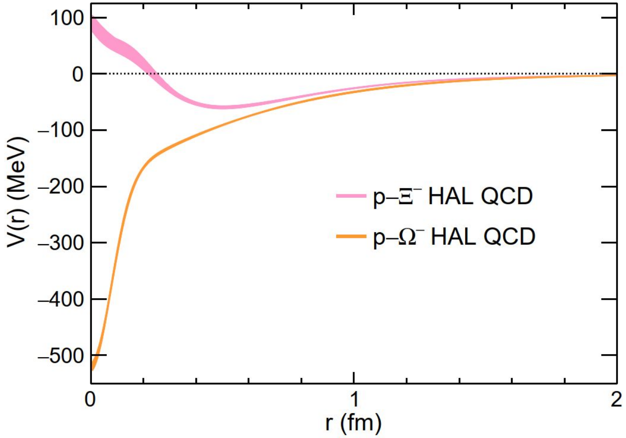
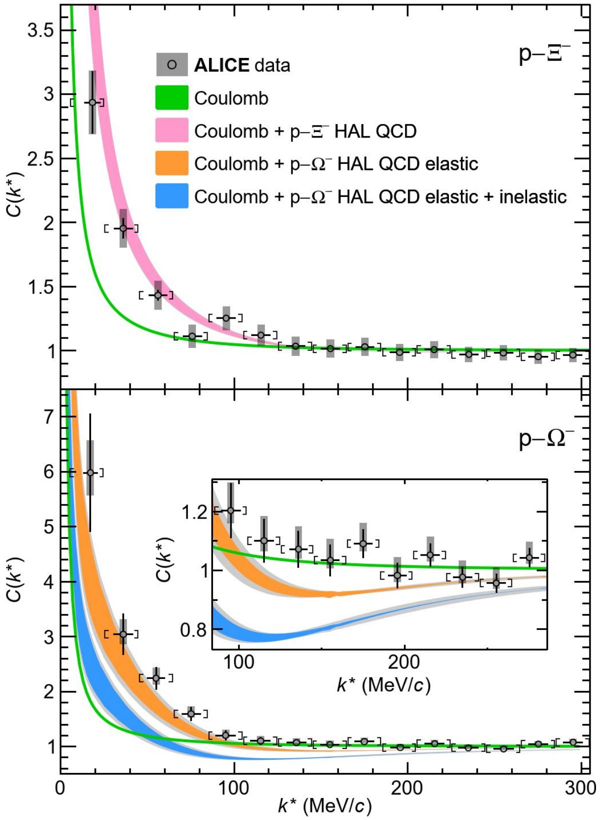


- Substantial differences for r < 1fm
- p-Ω^- attractive interaction at all distances

p-Ξ^- and p-Ω^- in pp at 13 TeV

"*A new laboratory to study hadron–hadron interactions*", ALICE Coll., arXiv:2005.11495 [nucl-ex] (submitted to Nature)



- Evidence of **attractive** strong **interaction** for both p-Ξ^- and p-Ω^- systems
- Data show a **p-Ω^- correlation function enhanced** with respect to p-Ξ^-
- Precise p-Ω^- ALICE data provide first **constraint** for lattice QCD calculations:
  - Inelastic channels not accounted for quantitatively within the lattice.
  - The data do not follow the depletion in the correlation function expected due to the p-Ω^- bound state
- The method can be extended:
  - Search for bound state: study of systems with slightly larger sources
  - Inelastic channels: measurements of Λ-Ξ^- and Σ^0-Ξ^- correlations

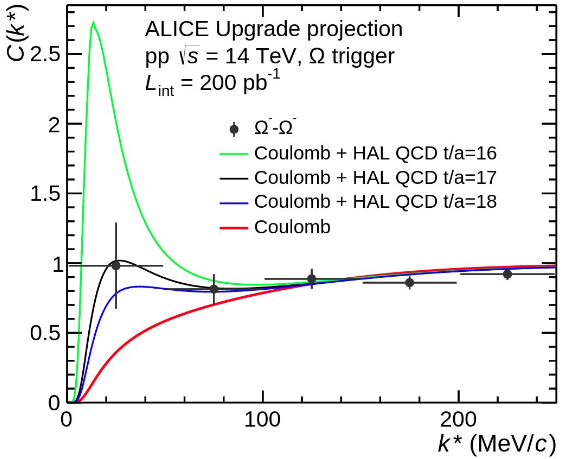
p-Ξ^-: $r = 1.02 \pm 0.05$ fm
p-Ω^-: $r = 0.95 \pm 0.06$ fm

Outlook

- The LHC provides precise testing of the hadron-hadron interaction at distances lower than 1 fm. Correlation data complements/substitutes other approaches.

- First principle calculations of interactions involving hyperons can be tested. Necessary to compute reliable Equations of State and study the existence of strange di-baryons.

- Run 3 and 4 data will provide the possibility of carrying out new and differential studies and investigate 3-body interactions.



ALICE-PUBLIC-2020-005,
https://cds.cern.ch/record/2724925

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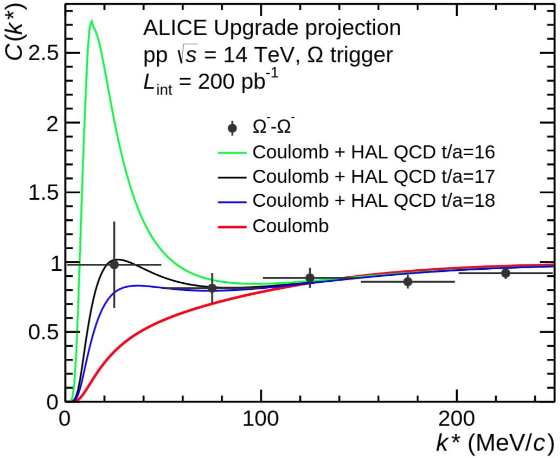
THANK YOU



ALICE-PUBLIC-2020-005,
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Backup

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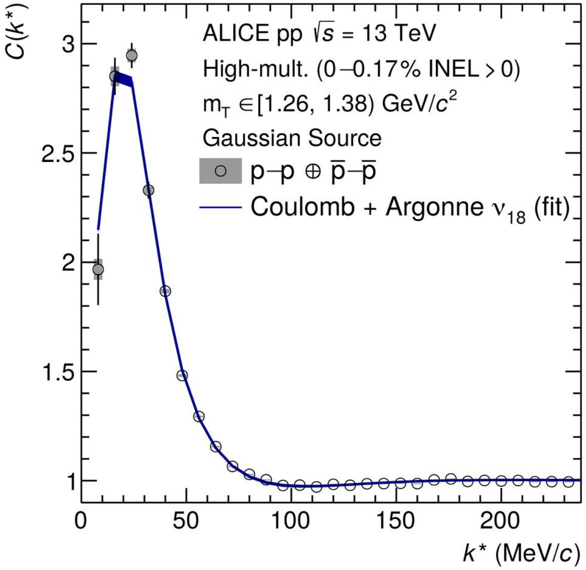

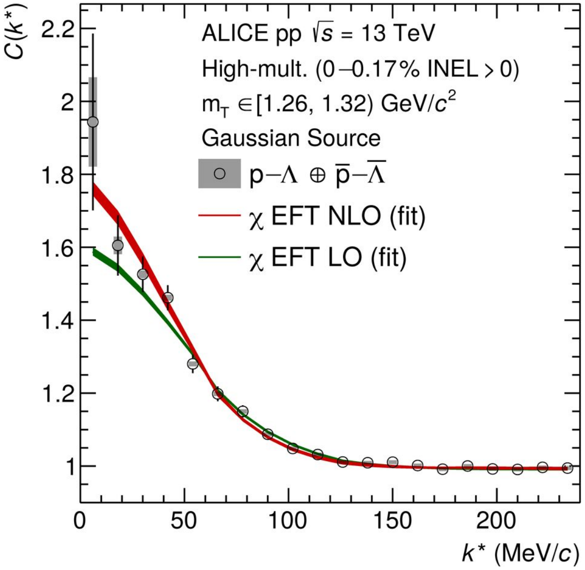

“Search for a common baryon source in high-multiplicity pp collisions at the LHC”, ALICE Coll., [arXiv:2004.08018 [nucl-ex]](arXiv:2004.08018) (submitted to PLB)

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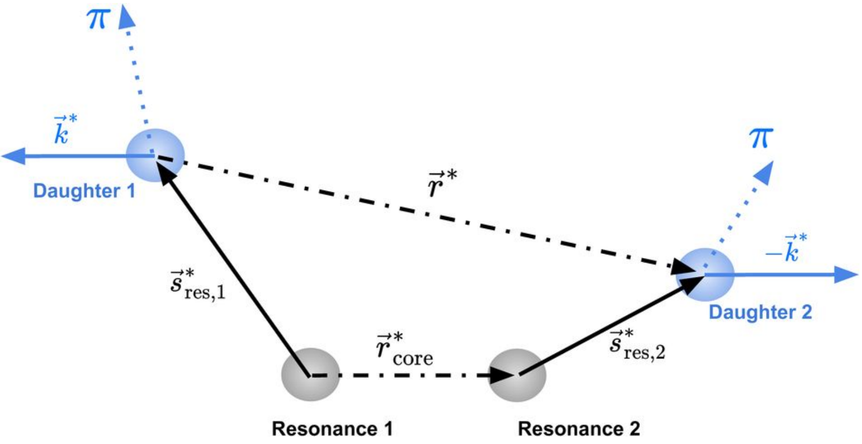
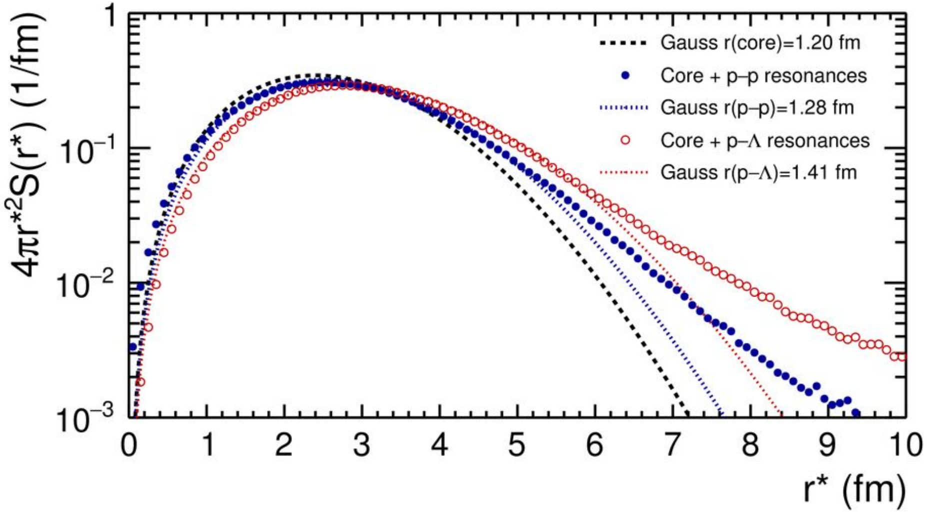
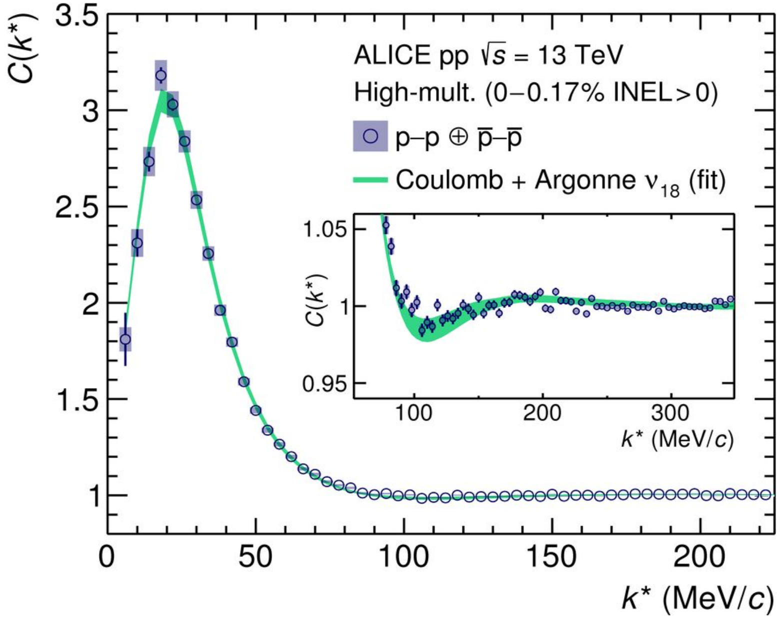
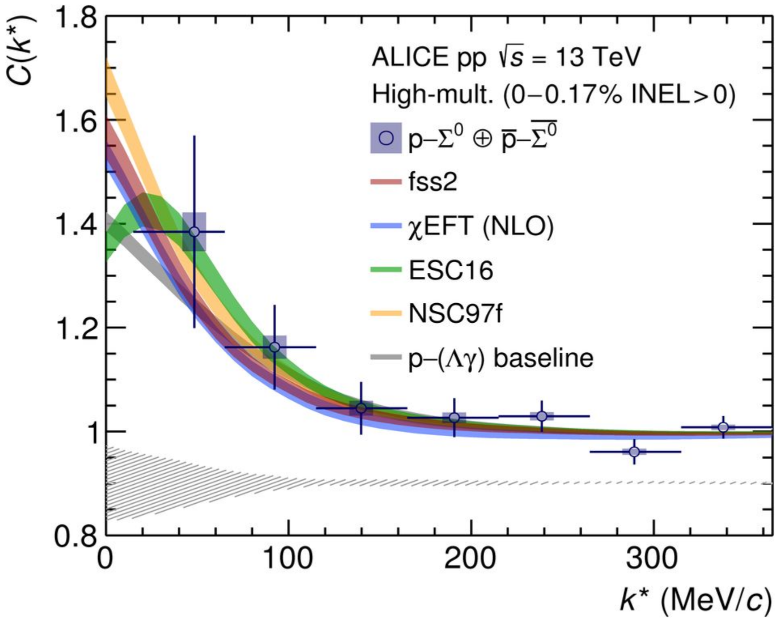


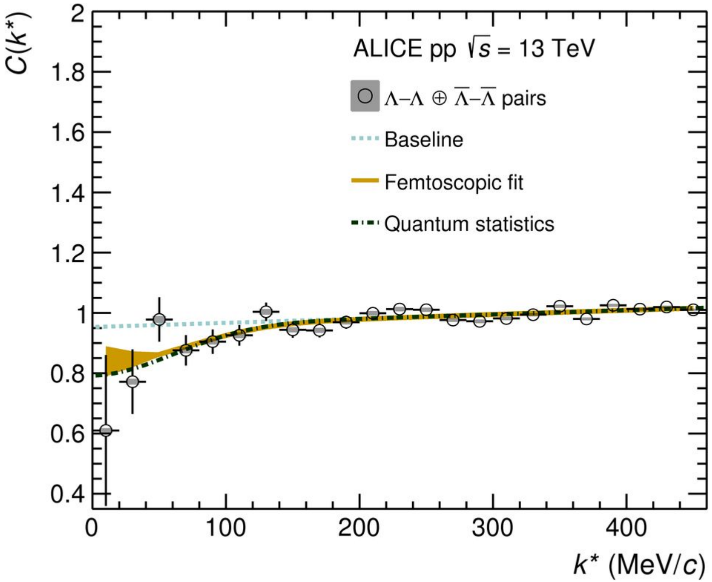


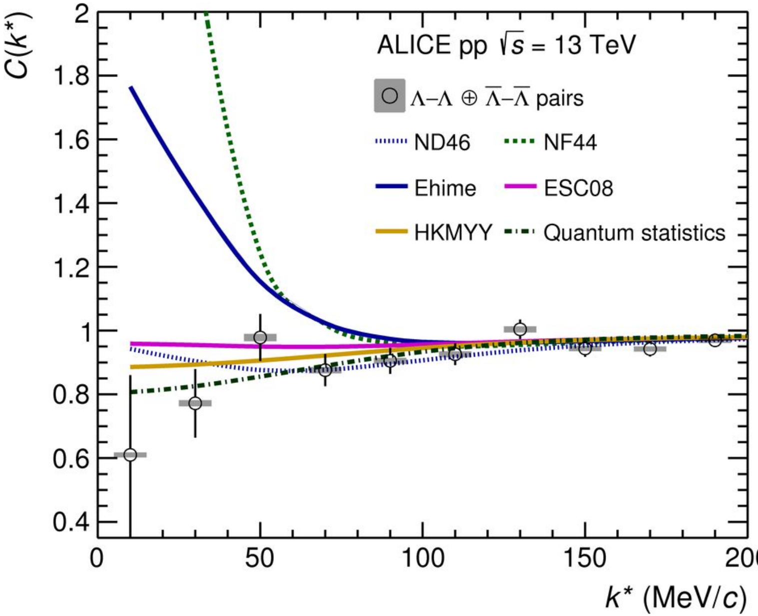
"Investigation of the p-Σ^0 interaction via femtoscopy in pp collisions", ALICE collaboration, [Phys. Lett. B805 (2020) 135419]





“Study of the Λ-Λ interaction with femtoscopy correlations in pp and p-Pb collisions at the LHC”
ALICE collaboration, Phys. Lett. B 797 (2019) 134822





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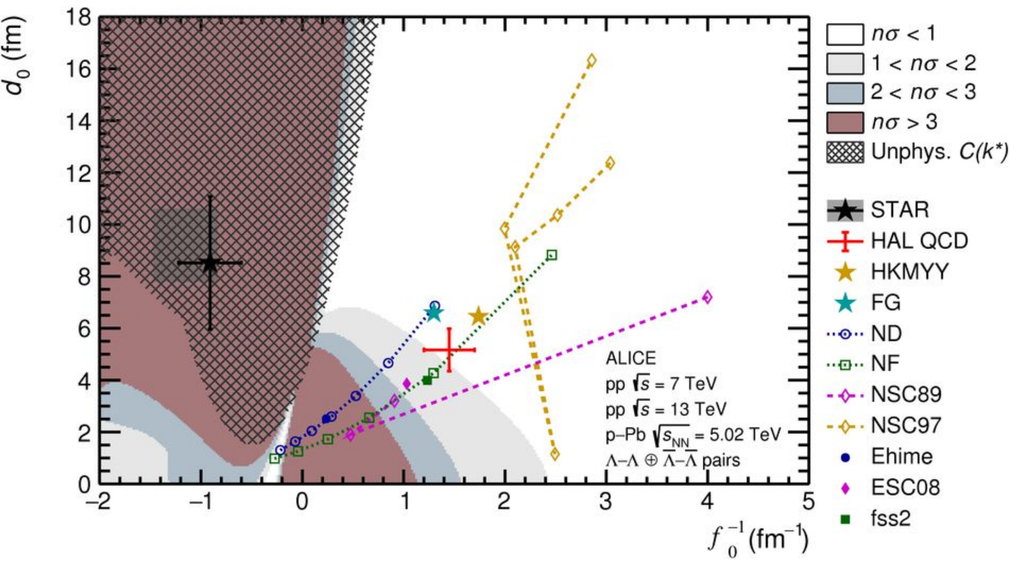
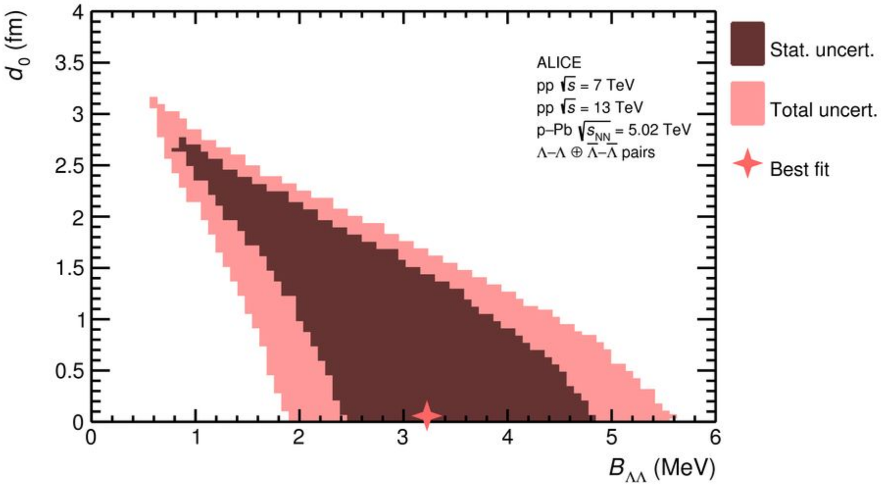
ALICE collaboration, [Phys. Lett. B 797 (2019) 134822]





H-Dibaryon binding energy upper limit

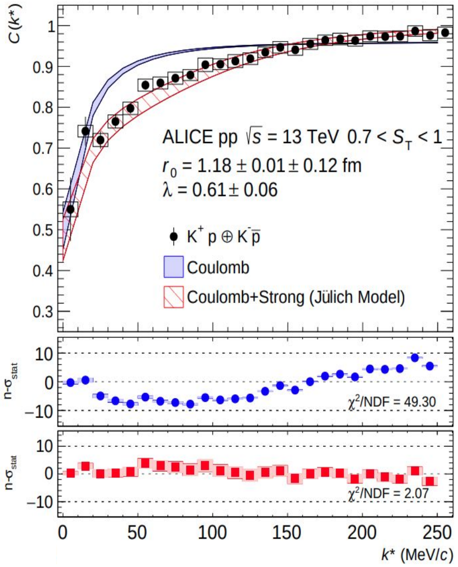
$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2} \cdot \left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)$$

S. Gonbgyo et al., PRL 120(2018) 212001
P. Naidon and S. Endo, Rept. Prog. Phys. 80 (2017) 056001

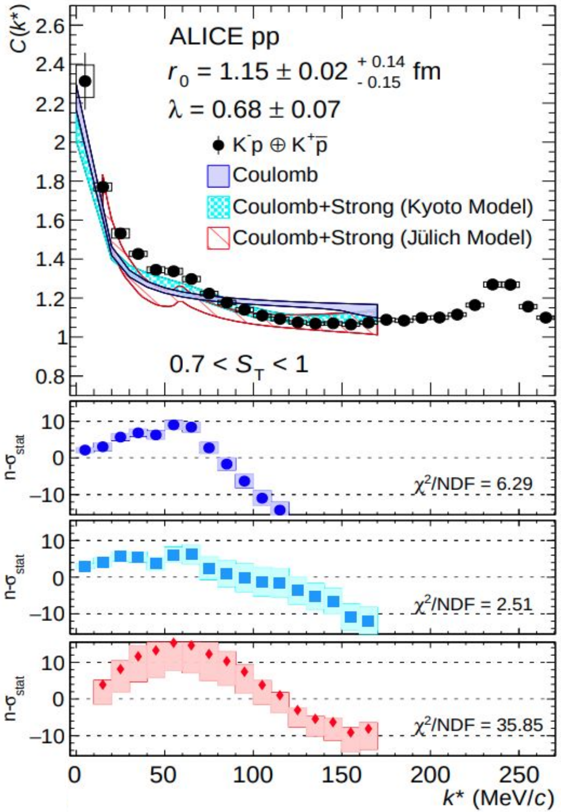
Test agreement between data-Lednicky model (number of sigmas)

Small source size limits the prediction power of the Lednicky model

“Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC”
ALICE collaboration, [Phys. Rev. Lett. 124 (2020) 092301]



Jülich meson exchange model
Eur.Phys.J. A47 (2011) 18

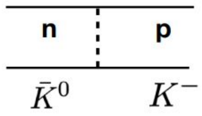


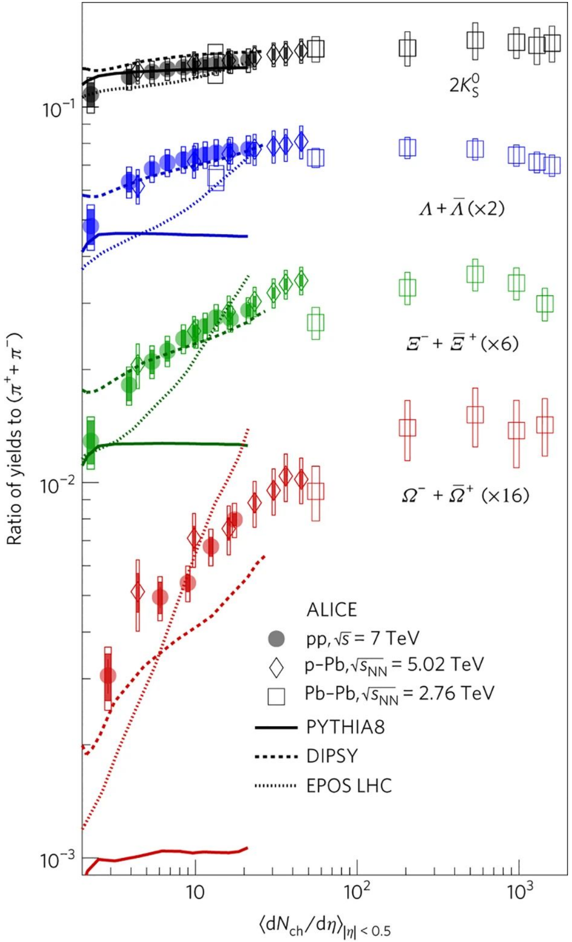
Kyoto Model: Phys. Rev. C93 no. 1, (2016) 015201
Jülich Model: Nucl. Phys. A981 (2019)

Bump close to the K^0n threshold (58 MeV/c in CM frame): First experimental evidence of the opening of the K^0n isospin breaking channel

Coupled channel effect

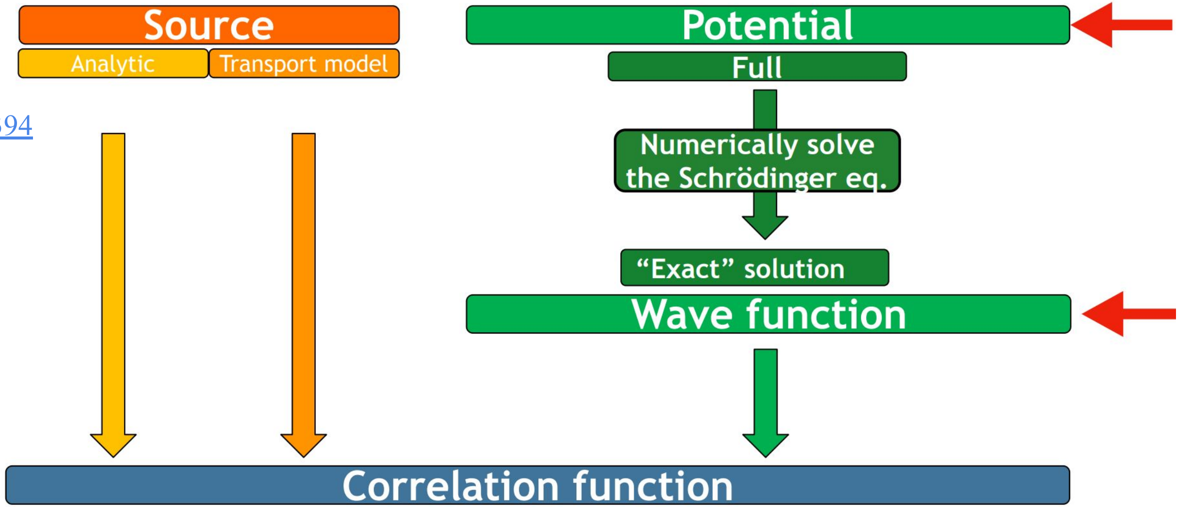
$$M(K^- p) + 5\,\mathrm{MeV} = M(n\bar{K}^0)$$





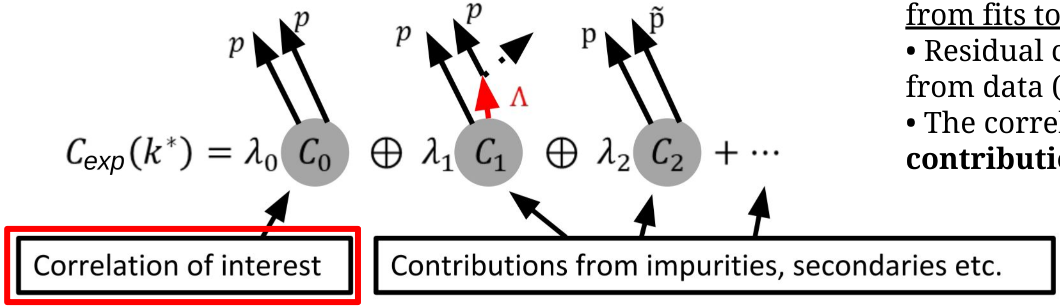
Enhanced production of multi-strange hadrons in high multiplicity pp collisions
[ALICE Coll. Nature Physics volume 13, 535 (2017)]

CATS: Correlation Analysis Tool Using the Schrödinger Equation
D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394



Provides a exact solution computing the correlation function from the model given a local potential or wave function form.

Theory



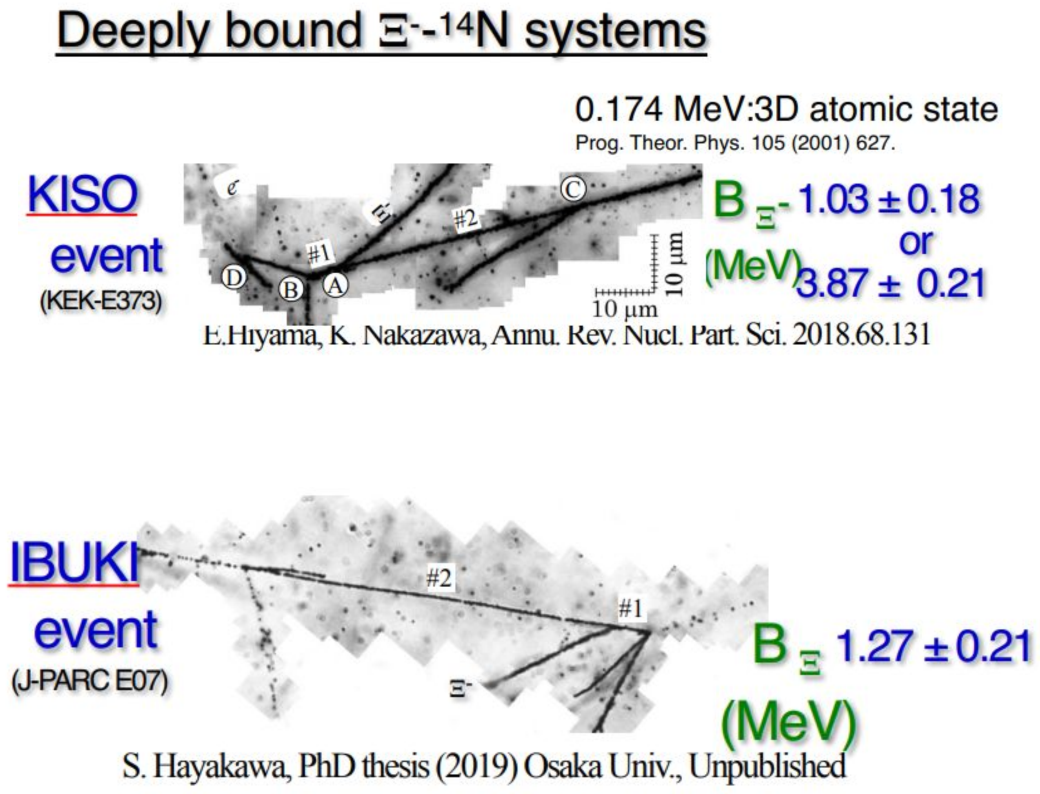
- Contributions from weak decays and impurities determined from fits to experimental data
- Residual correlations are modelled (weak decays) or obtained from data (impurities)
- The correlation function is corrected for **residual contributions** and finite **resolution effects**

Experiment

Contributions from residual correlations and impurities

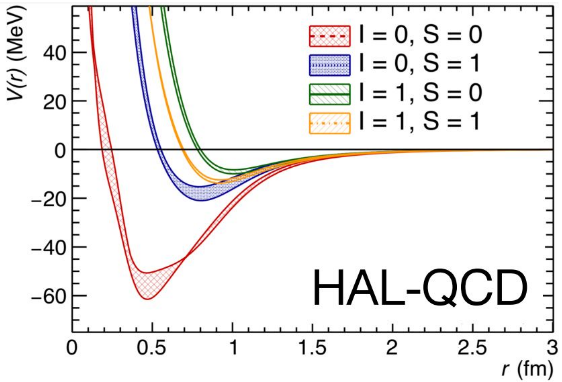
		$p–\Xi^-$			
Pair	λ [%]	Pair	λ [%]	Pair	λ [%]
$p–\Xi^-$	58.3	$p_{\Lambda}–\Xi^-_{\Omega}$	0.08	$\tilde{p}–\Xi^-_{\Xi^0(1530)}$	0.09
$p–\Xi^-_{\Xi^-(1530)}$	6.5	$p_{\Sigma^+}–\Xi^-$	1.1	$\tilde{p}–\Xi^-_{\Omega}$	0.00
$p–\Xi^-_{\Xi^0(1530)}$	12.9	$p_{\Sigma^+}–\Xi^-_{\Xi^-(1530)}$	0.12	$p–\tilde{\Xi}^-$	7.3
$p–\Xi^-_{\Omega}$	0.6	$p_{\Sigma^+}–\Xi^-_{\Xi^0(1530)}$	0.24	$p_{\Lambda}–\tilde{\Xi}^-$	1.0
$p_{\Lambda}–\Xi^-$	8.4	$p_{\Sigma^+}–\Xi^-_{\Omega}$	0.01	$p_{\Sigma^+}–\tilde{\Xi}^-$	0.14
$p_{\Lambda}–\Xi^-_{\Xi^-(1530)}$	0.93	$\tilde{p}–\Xi^-$	0.39	$\tilde{p}–\tilde{\Xi}^-$	0.05
$p_{\Lambda}–\Xi^-_{\Xi^0(1530)}$	1.87	$\tilde{p}–\Xi^-_{\Xi^-(1530)}$	0.04		

Pair	λ [%]
$p–\Omega^-$	79.0
$p_{\Lambda}–\Omega^-$	9.9
$p_{\Sigma^+}–\Omega^-$	5.1
$\tilde{p}–\Omega^-$	0.9
$p–\tilde{\Omega}^-$	4.2
$p_{\Lambda}–\tilde{\Omega}^-$	0.6
$p_{\Sigma^+}–\tilde{\Omega}^-$	0.3
$\tilde{p}–\tilde{\Omega}^-$	0.1

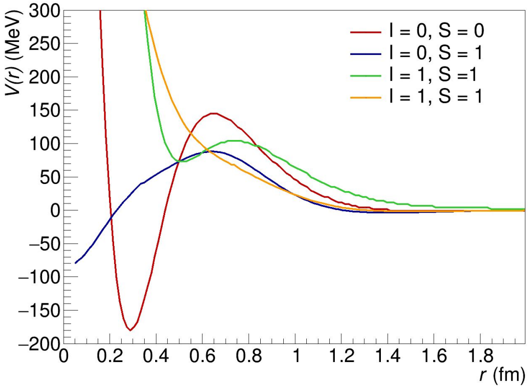


Implies an attractive interaction

Models of the p-Ξ- potential



K. Sasaki et al. (HAL QCD), Nucl. Phys. A330, 998 (2020)



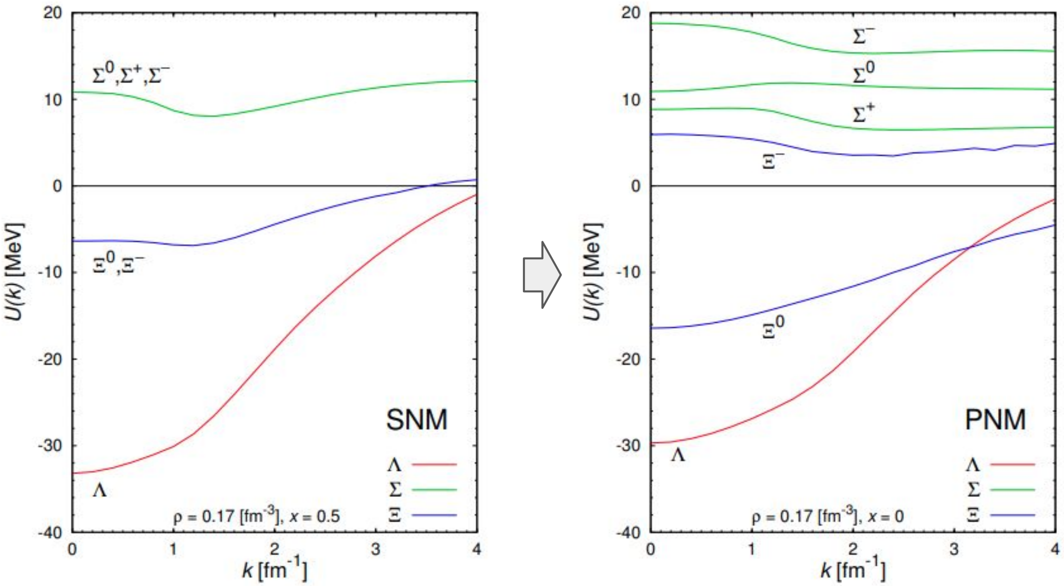
ESC16L Meson exchange model

M. M. Nagels et al., Phys. Rev. C 99, 044003 (2019)

In medium: Many body interaction,
average Ξ^- Single particle potential (U_{Ξ^-})

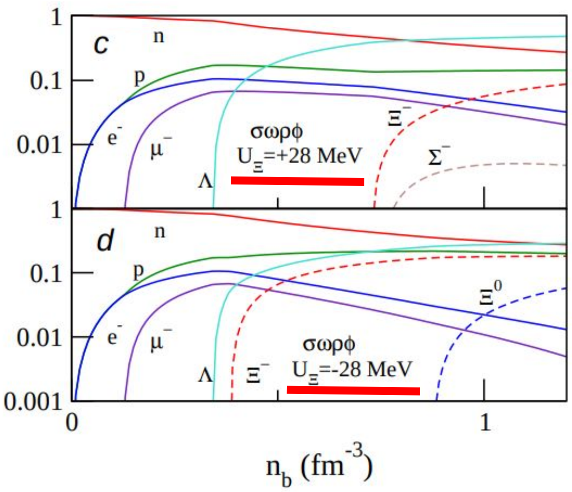
<u>Lattice QCD:</u>
U_{Ξ^-} moves from slightly attractive in symmetric nuclear matter to **slightly repulsive U_{Ξ^-}~6 MeV in pure neutron matter (NS)**

HAL QCD Coll., PoS INPC2016 (2016) 277

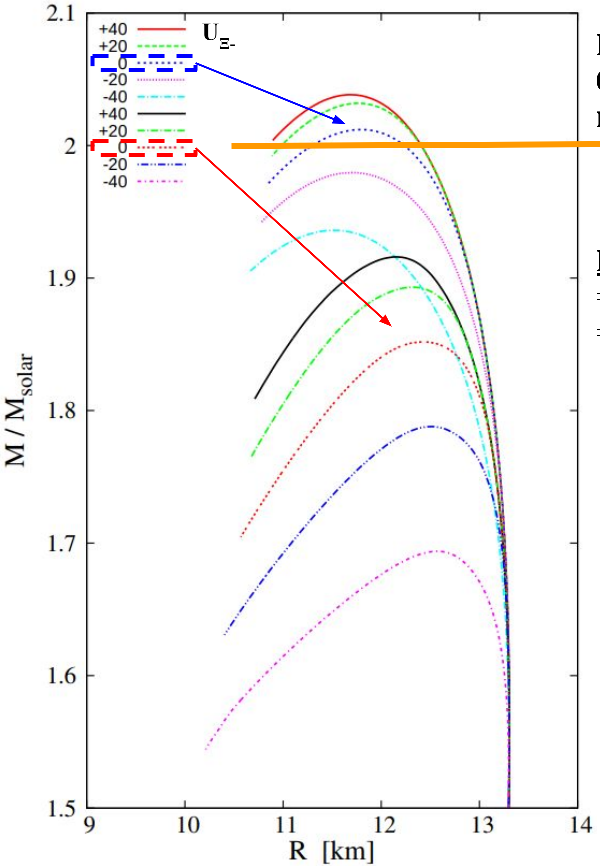


- RMF models: Equation Of State (EoS) of neutron-rich matter with hyperon content

→ use single particle potential at saturation densities as input



Weissenborn et al., Nucl. Phys. A881 (2012) 62-77



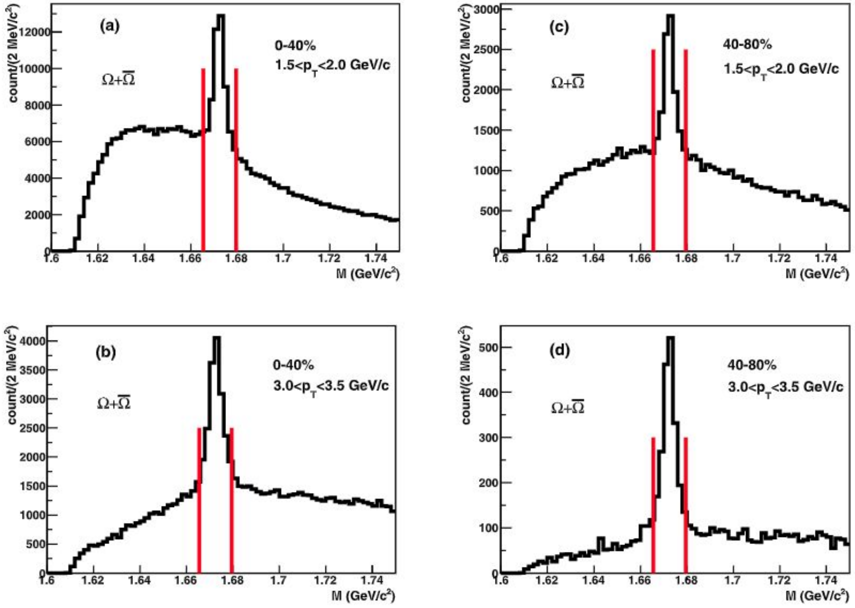
Experimental constraint: Observation of ~2 solar masses NS

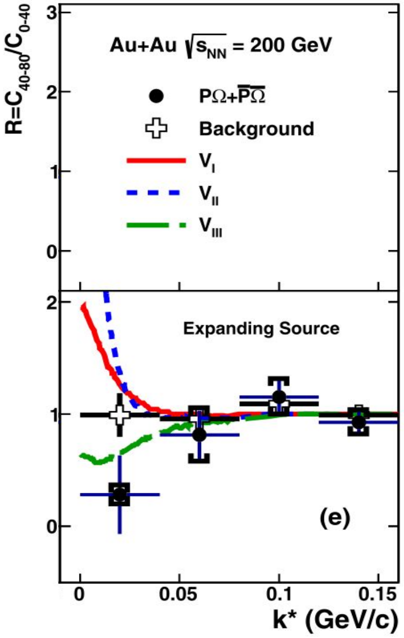
Repulsive interaction:
⇒ Ξ pushed to high densities
⇒ **stiffer EoS**, higher masses

The Proton-Ω correlation function in Au+Au collisions at \sqrt{s_{NN}} =200 GeV
STAR Collaboration. Phys.Lett.B 790 (2019) 490-497

Table 2
Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65





Lattice calculations with heavy quark masses, m_π = 875 MeV/c^2, m_K = 916 MeV/c^2
F. Etminan et al.(HAL QCD Collaboration), Nucl. Phys. A928,89(2014)

Fitted by an attractive Gaussian core + an attractive tail, vary range parameter at long distance (b_5)
K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

$$V(r) = b_1 e^{-b_2 r^2} + b_3(1 - e^{-b_4 r^2})(e^{-b_5 r}/r)^2$$

- V_{II}: best fit to Lattice calculations
- V_I / V_{III}: weaker / stronger attraction

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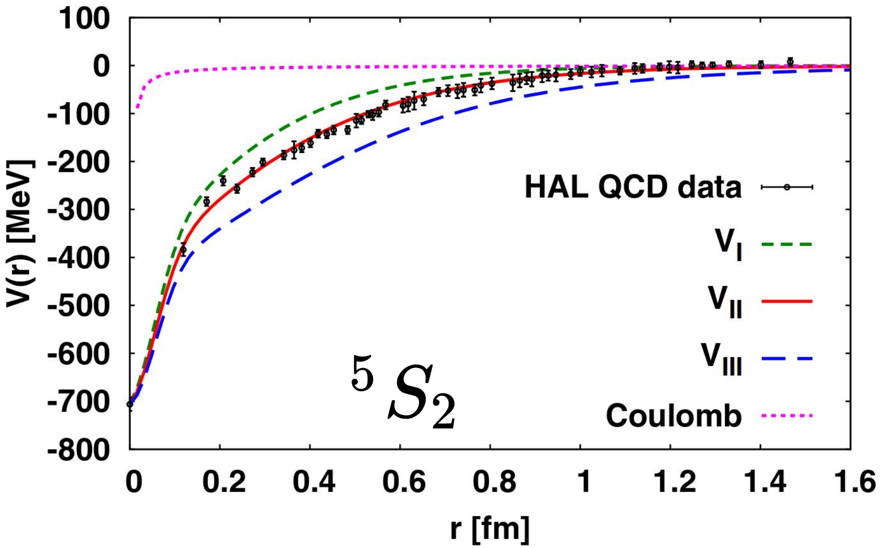

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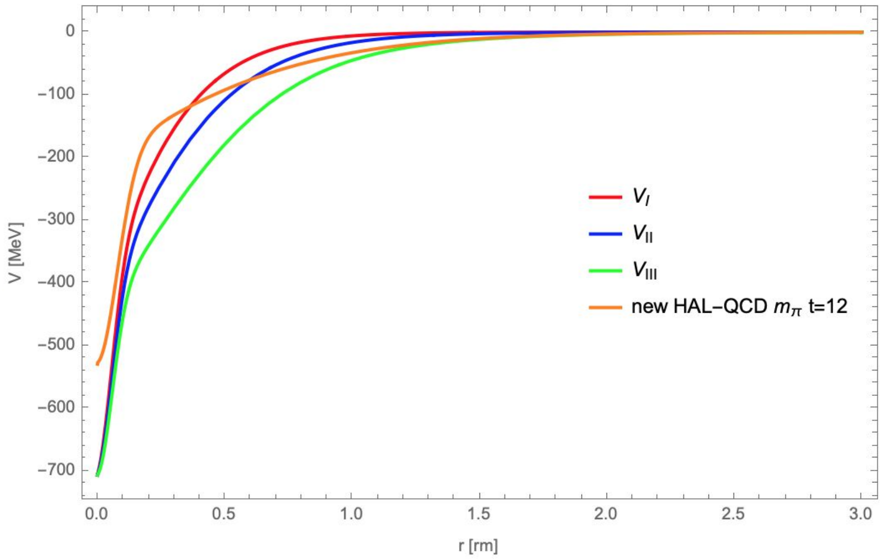


Models of the p-Ω- interaction

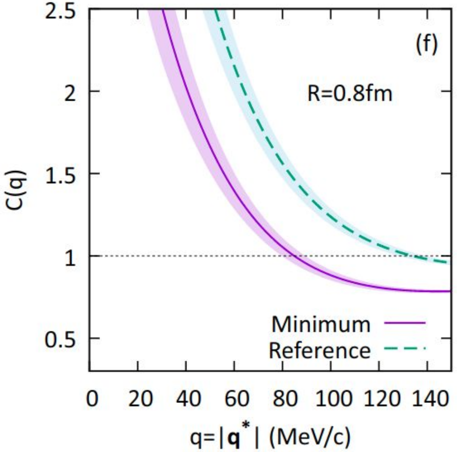
-> Calculations provide the potential shape for the $^5S_2$ channel (weight ⅝).

-> Currently, no model for the other channel in S-wave interaction, $^3S_1$ (weight ⅜). Requires coupled channel treatment.

Assume two different (~extreme) scenarios:

1.- Complete absorption for distances $r < r_0$.
r_0 chosen from the condition $|V(^5S_2)| < |V(\text{Coulomb})|$ for $r > r_0$

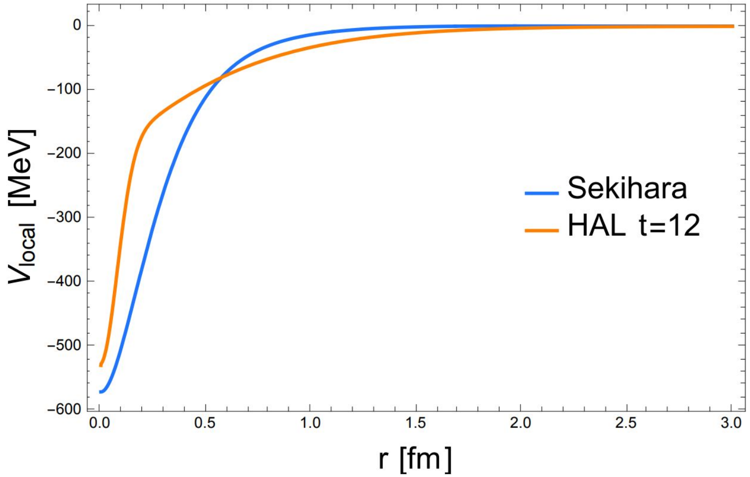
2.- Complete elastic with a similar attraction as $^5S_2$
Kenji Morita et al., Phys. Rev. C101, 015201 (2020)



Models of the p-Ω^- interaction

- Lattice **HAL-QCD** potential with physical quark masses ($^5S_2$ channel) T. Iritani et al., Phys. Lett. B792 (2019) 284.
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2

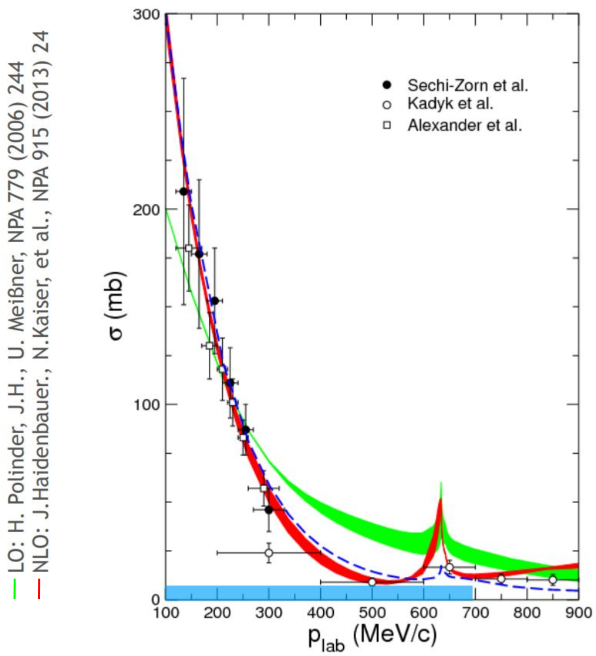
- **Sekihara**: Meson-exchange model ($^5S_2$ channel) T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)
  - Short range attractive interaction fitted to previous HAL-QCD scattering parameters



Model	pΩ^- binding energy (strong interaction only)
HAL-QCD	1.54 MeV
Sekihara	0.1 MeV

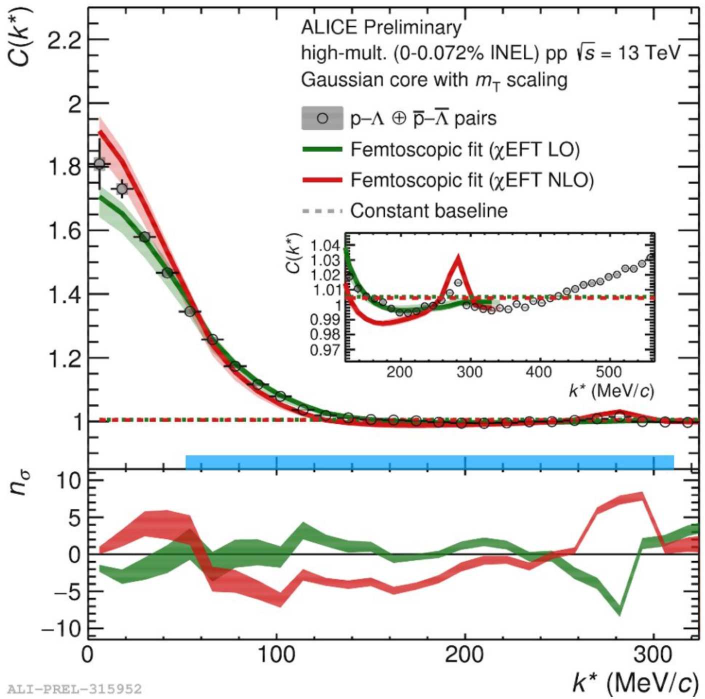
+1 MeV with Coulomb

→ Models provide so far only $^5S_2$ channel (weight ⅝)



Previous scattering data
No experimental evidence of the cusp due to ΣN/ΛN coupling, responsible for the appearance of a repulsive short range component in the Λp interaction

Λp correlations in pp@13TeV by ALICE



- Extension of the kinematic range and **improved precision.**
- **Clear experimental evidence** of the cusp
- LO and NLO calculations within xEFT fail to reproduce the data