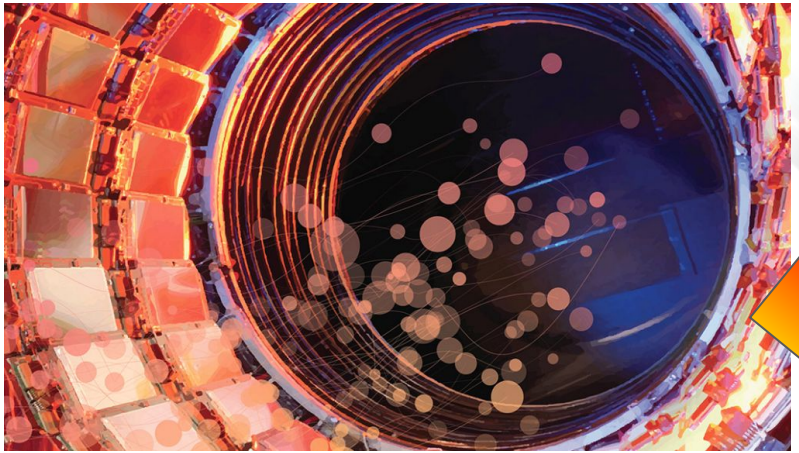
Study of the strong interaction among hadrons with correlations at the LHC

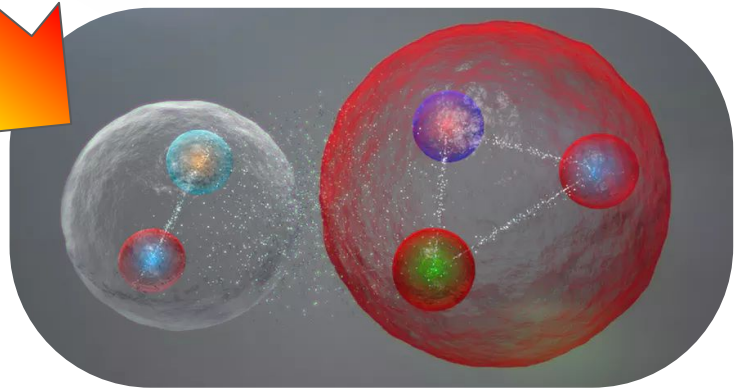
Otón Vázquez Doce (LNF -INFN)

Fundamental Physics at the Strangeness Frontier, Frascati (online)
26 February 2021

Outline



High-energy physics



Hadron physics
WITH STRANGENESS!

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LHC

Small collision systems:
- pp 13 TeV

⇒ **particles emitted from ~1fm source**

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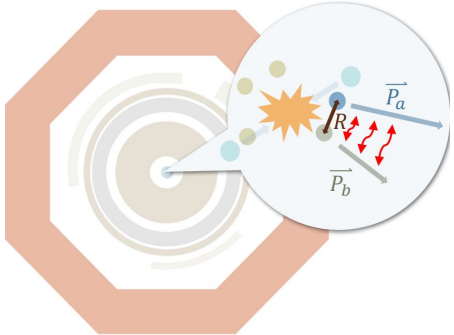

Central barrel tracking and PID

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

Allow to study up to S = -3, **p-Ω^-**

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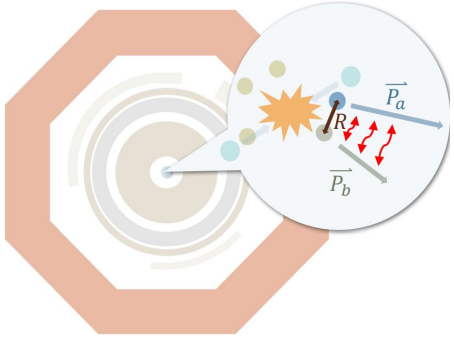

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- Λ→pπ
- Ξ→Λπ
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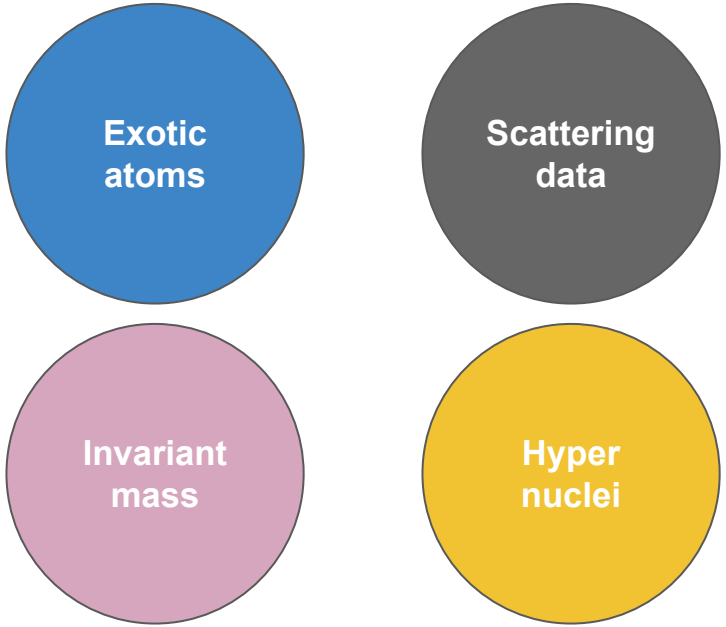
Experimental data for the study of hadron-hadron interactions with strangeness content



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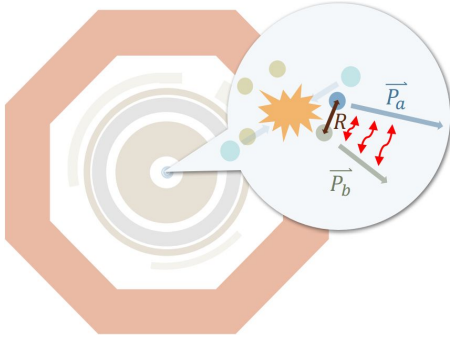

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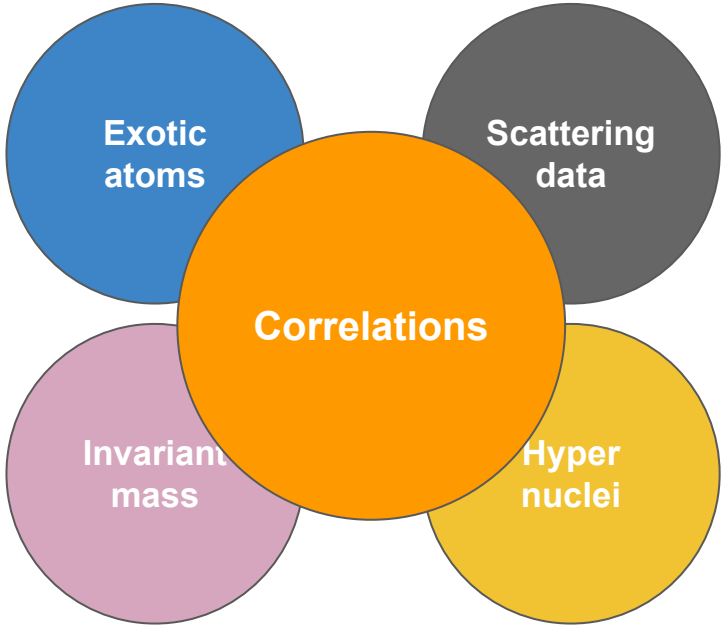

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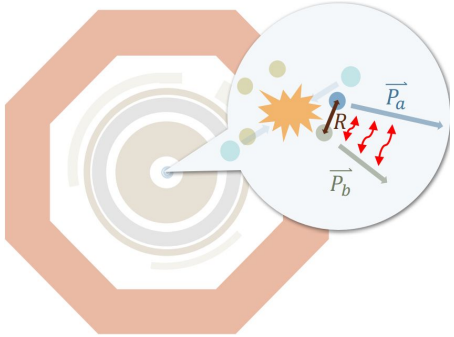

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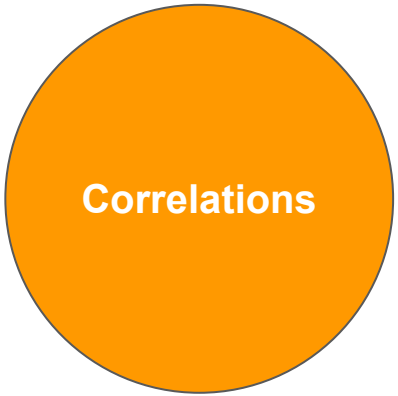


- **Precise data in the low momentum range**, in most cases not accessible with other approaches.
- **Test/constraint** ChET, meson exchange models, Lattice QCD, etc
- Consequences for, e.g., appearance of strange particles in neutron stars, existence of strange di-baryons

Outline

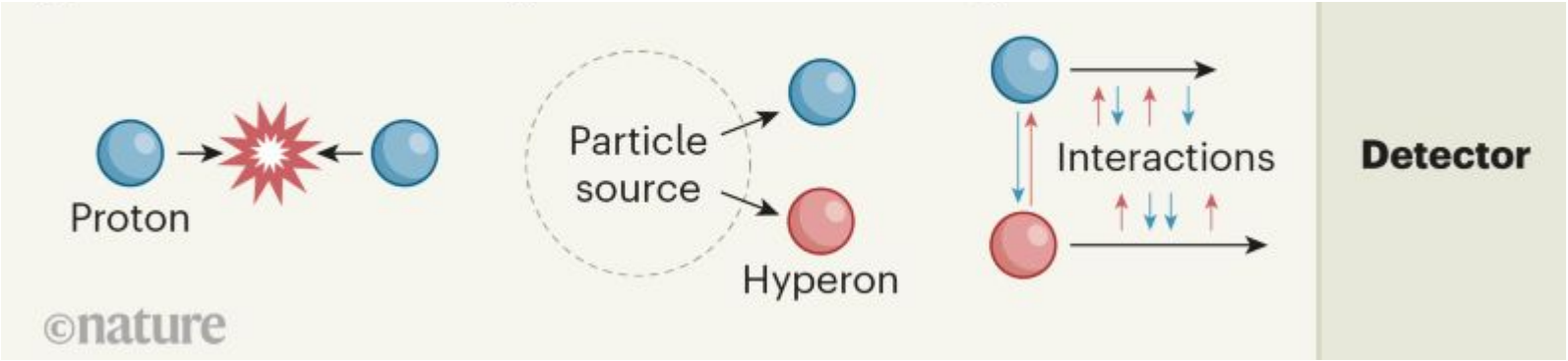
Correlation method

- Femtoscopy-like studies
- Detailed knowledge of the source of particles

Experimental results:

- K^--p
- p-Ω^-

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



https://www.nature.com/articles/d41586-020-03393-z

Femtoscopy (HBT) analyses in **Heavy Ions Collisions**:

- Study pairs of particles with “known” interaction
- Centered in **study the dimensions of the source** (2-5 fm)

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

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

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

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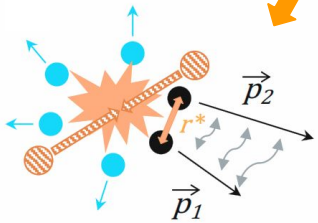

Emission source $S(r^*)$

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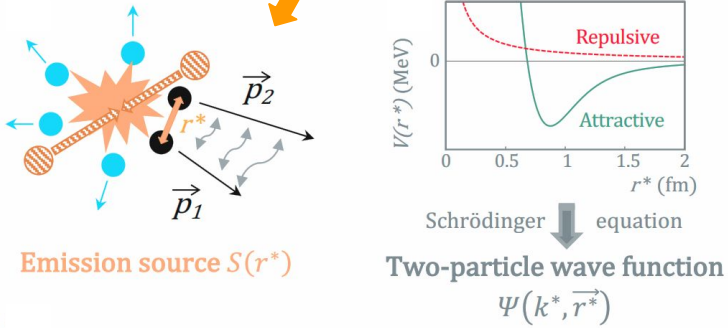

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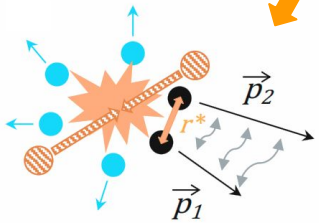

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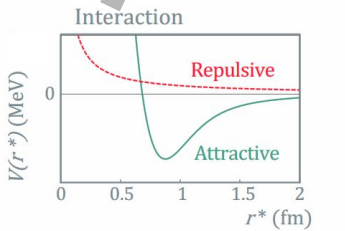
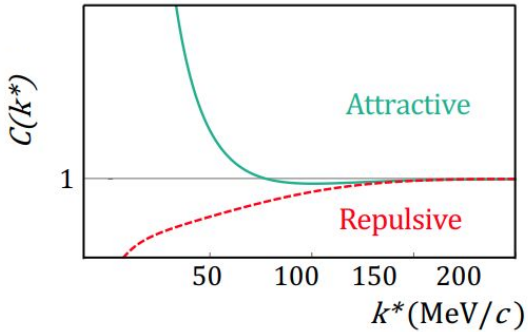


Schrödinger equation

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



CATS: Schrödinger equation solver

D.L.Mihaylov et al. Eur. Phys. J. C78 no. 5, 394, (2018)

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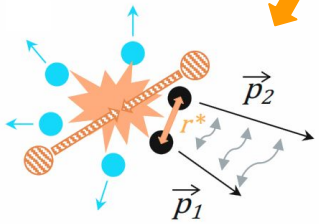

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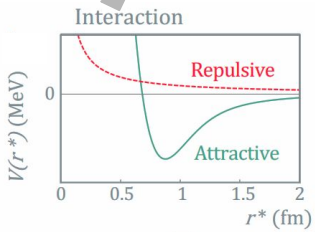

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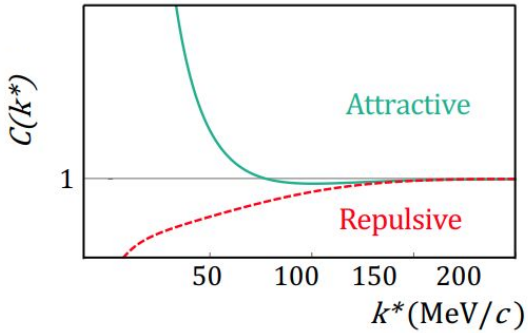

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Normalization, resolution effects, residual correlations.

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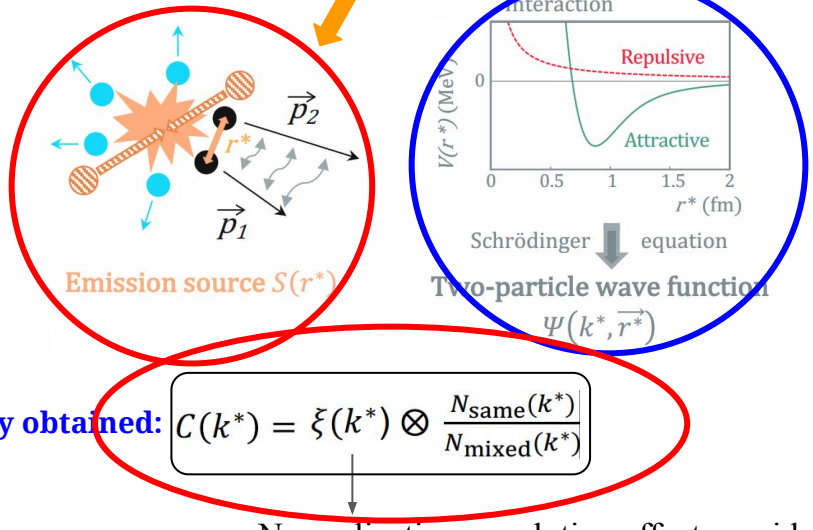

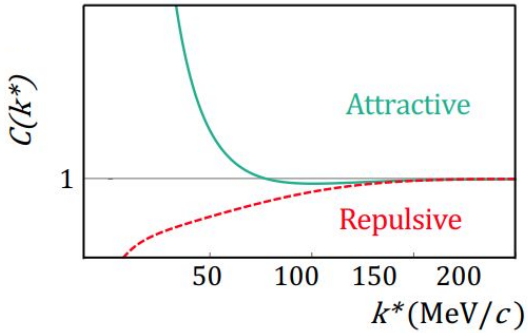

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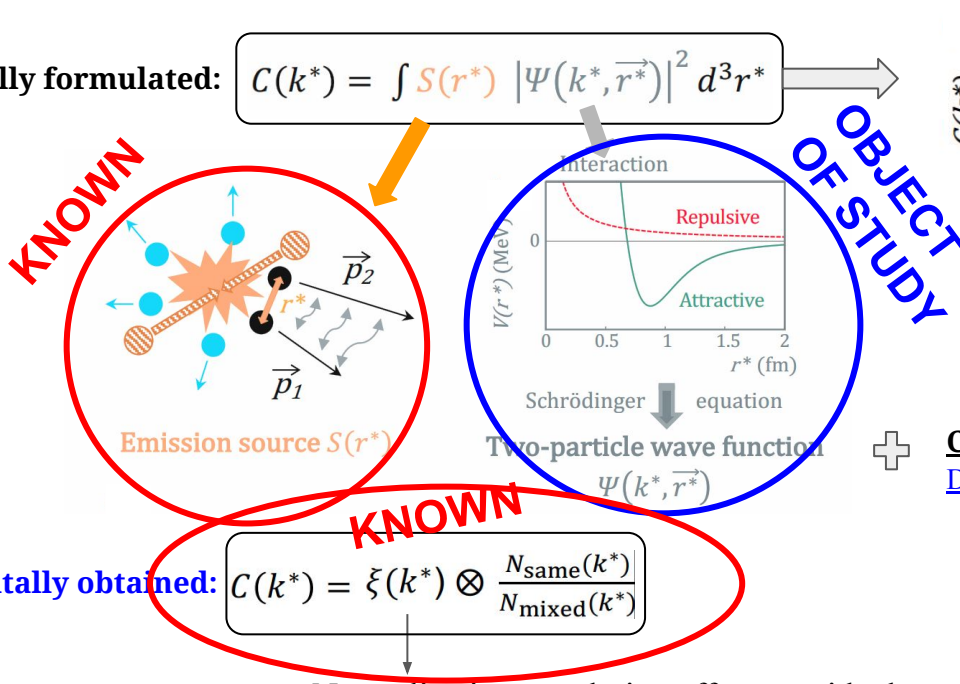

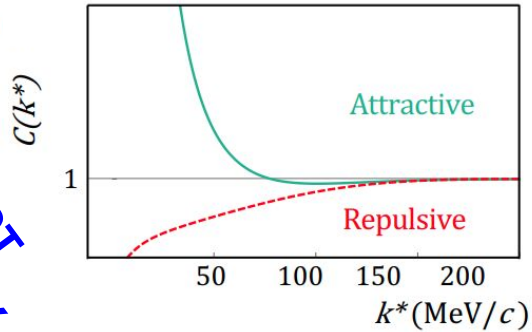

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Setting the source

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

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

- p-p strong interaction described by AV18 potential R. B. Wiringa et al., Phys. Rev. C51 (1995) 38
- p-Λ interaction described by ChEFT at LO H. Polinder et al., Nucl. Phys. A779, 27 (2006) 244, NLO Y. Ikeda et al., Phys. Lett. B706 (2011) 63

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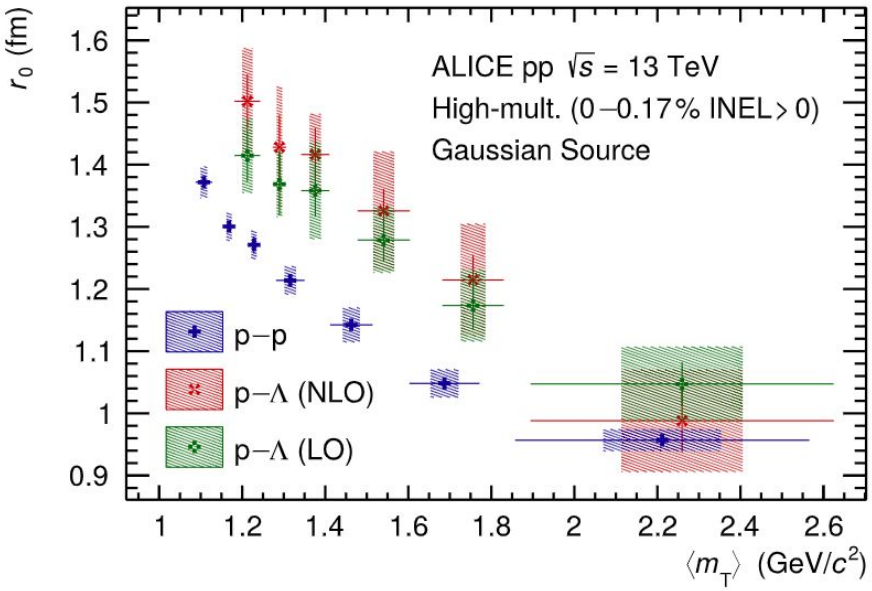

"Search for a common baryon source in high-multiplicity pp collisions at the LHC", ALICE Coll., Phys. Lett. B811, 10, 135849 (2020)

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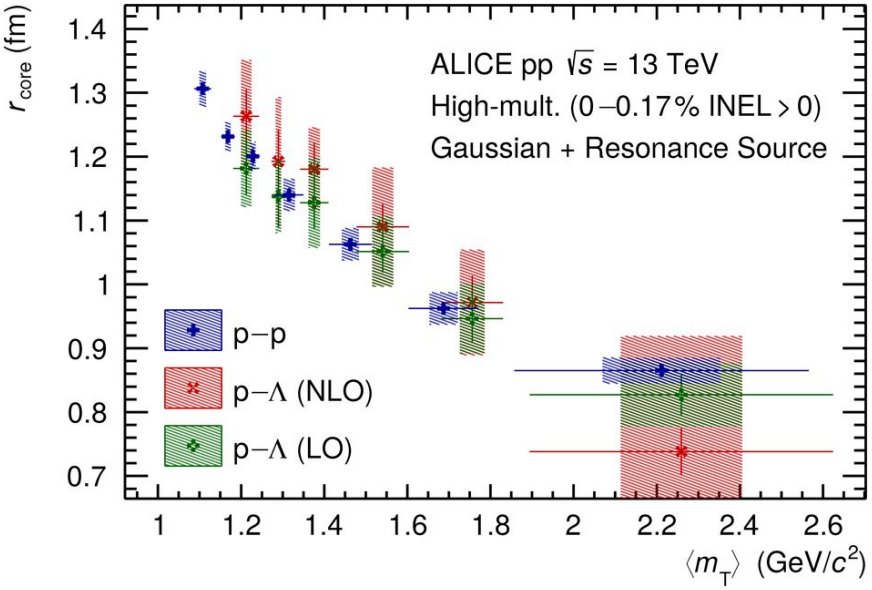
  - Decomposition in gaussian "core" source convoluted with non-gaussian tails due to resonances



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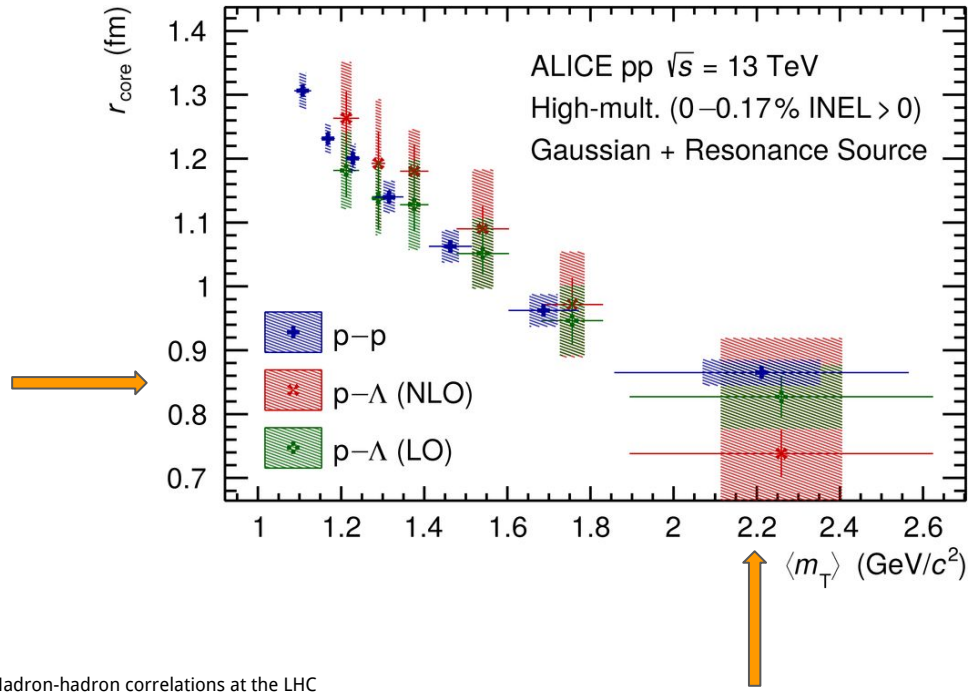

The source is **determined given the pair <m_T>:**

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

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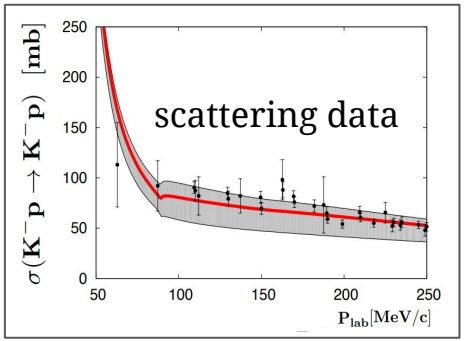
- K^-p features a strong attraction
  - appearance of the $\Lambda(1405)$ below threshold
  - $\Lambda(1405)$: antiKN-$\Sigma\pi$ molecular state
- K^-p scattering data and kaonic hydrogen data used to constrain the amplitude below threshold

Experiments:

$\Lambda(1405) \rightarrow \Sigma\pi$

Kaonic atoms



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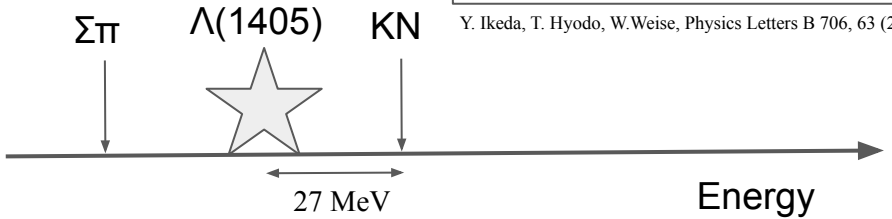

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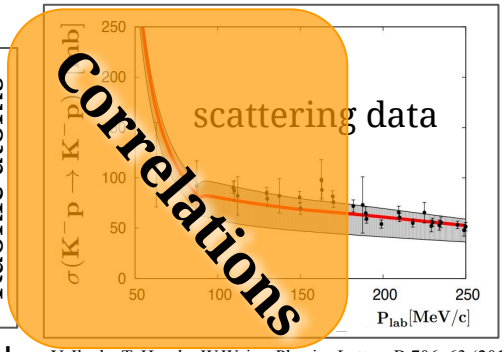

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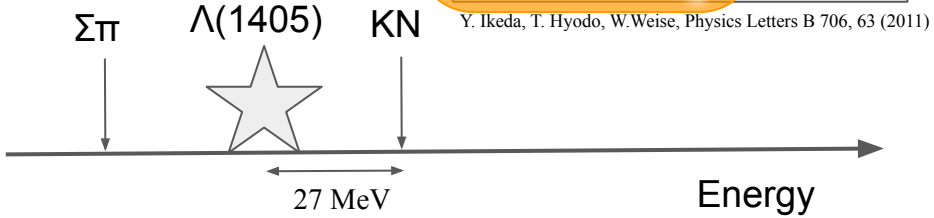
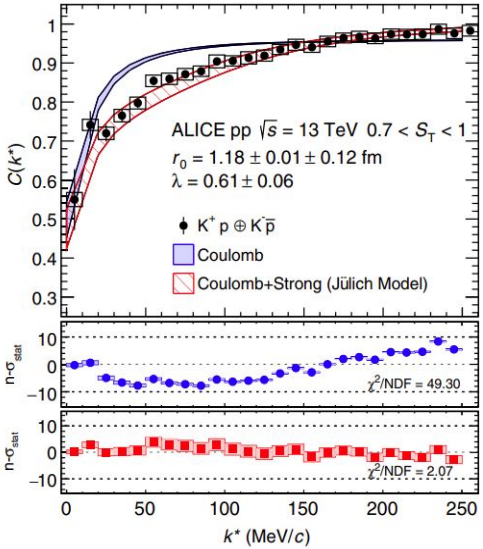


K-p correlations in pp collisions

"Scattering Studies with Low-Energy Kaon-Proton Femtoscopy in Proton-Proton Collisions at the LHC", ALICE Coll. Phys. Rev. Lett. 124 (2020) 092301



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

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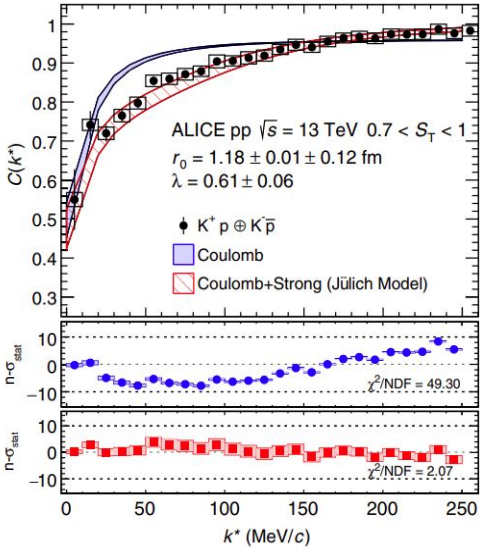

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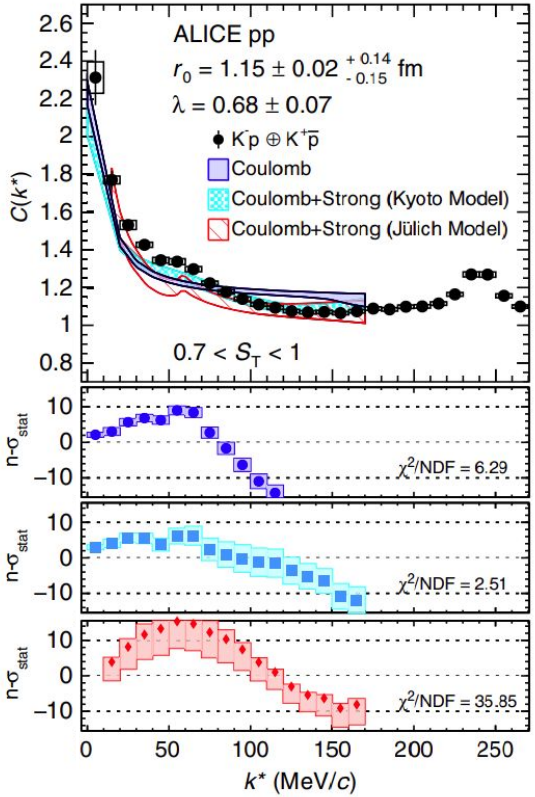

Coulomb potential only

Coulomb + Chiral Kyoto model

Phys. Rev. C93 no. 1, 015201 (2016)

Coulomb + Jülich meson exchange model

Nucl. Phys. A 981 (2019)

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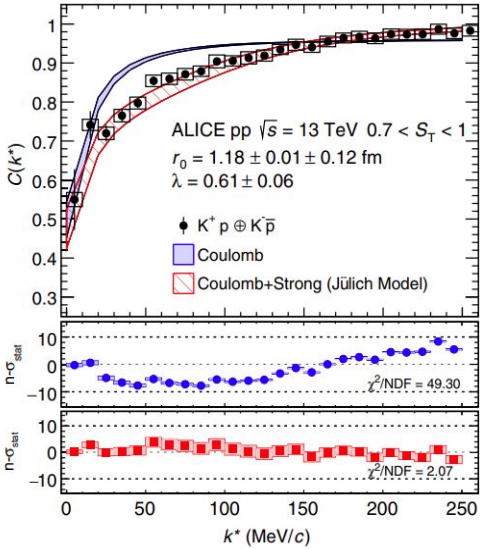

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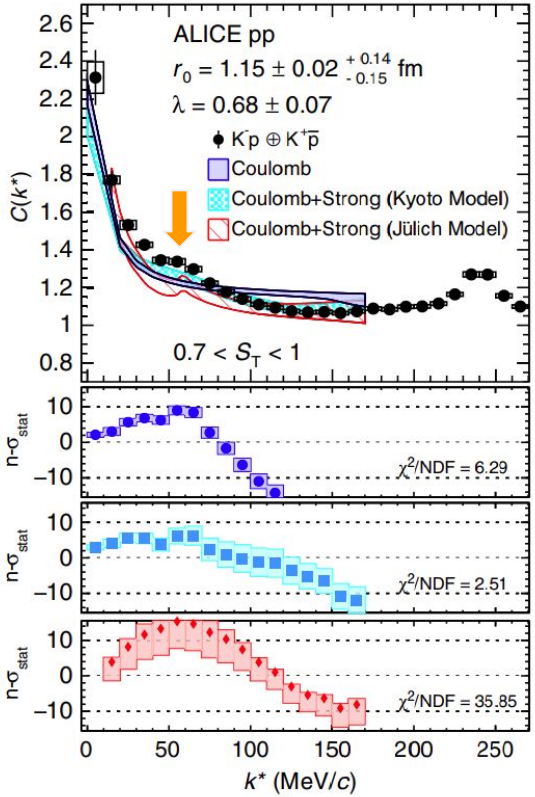
Jülich meson exchange model: Eur. Phys. J. A47, 18 (2011)



Coulomb potential only

Coulomb + Chiral Kyoto model

Phys. Rev. C93 no. 1, 015201 (2016)

Coulomb + Jülich meson exchange model

Nucl. Phys. A 981 (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

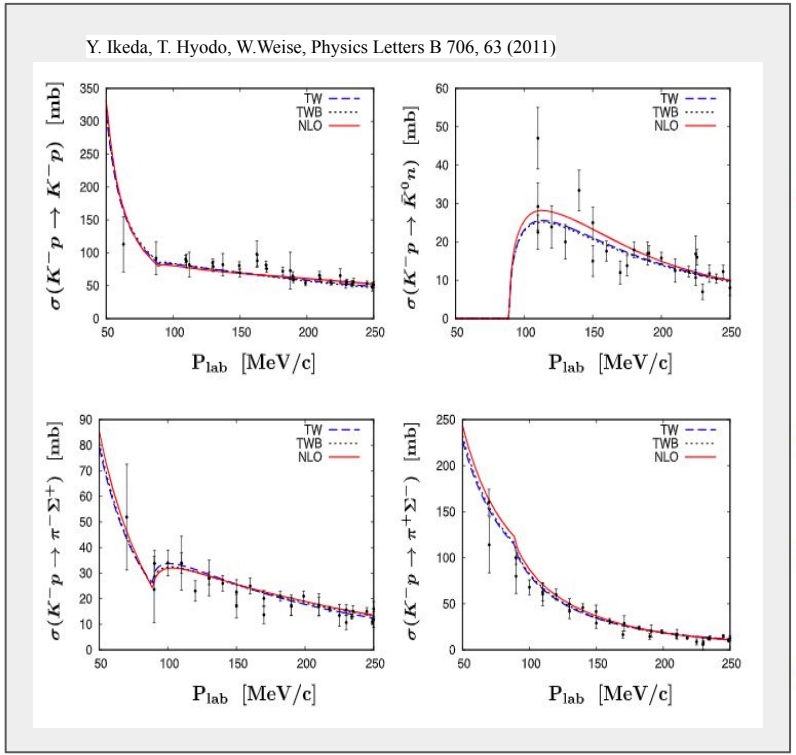
Coupled channel effect

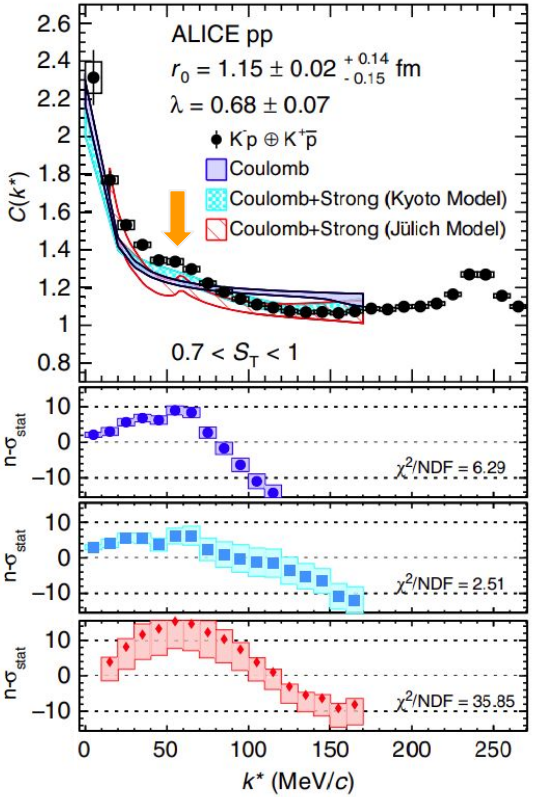
$$M(K^-p) + 5\,\mathrm{MeV} = M(n\bar{K}^0)$$

n	p
$\bar{K}^0$	K^-

K-p correlations in pp collisions

"Scattering Studies with Low-Energy Kaon-Proton Femtoscopy in Proton-Proton Collisions at the LHC", ALICE Coll. Phys. Rev. Lett. 124 (2020) 092301





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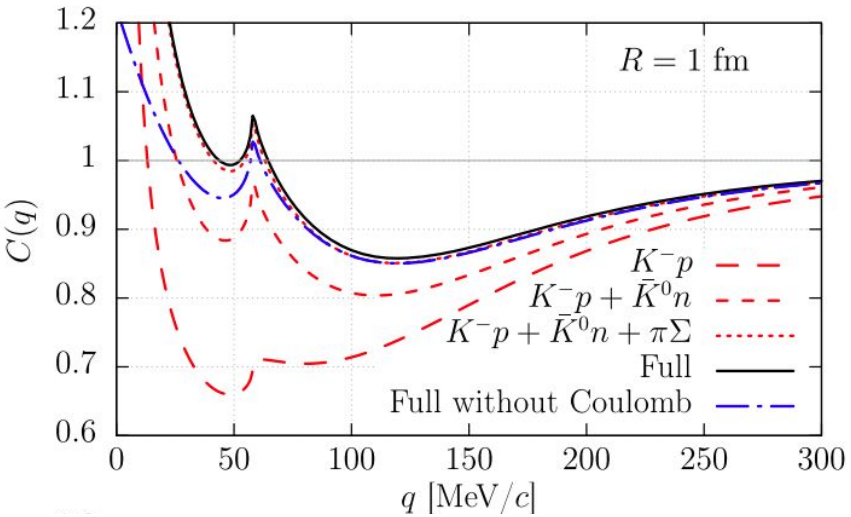
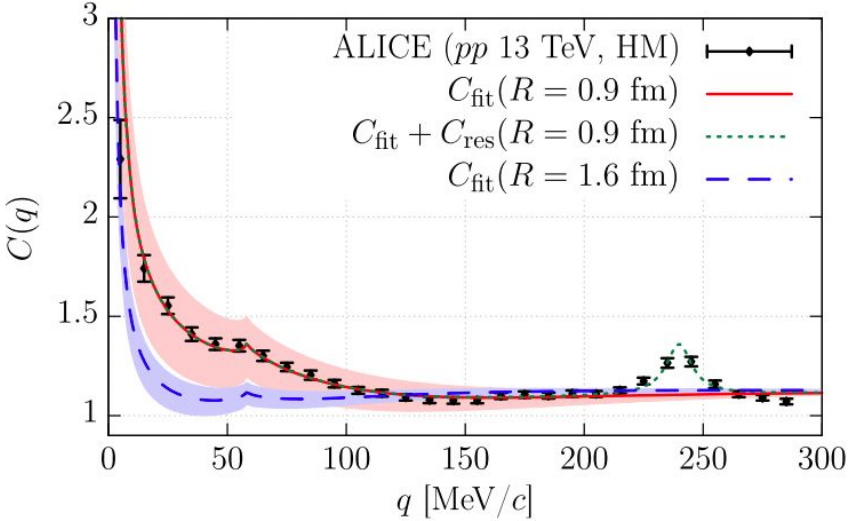
K-p correlations: model constraint

Update of the Kyoto model: **coupled-channel effects**

- Dependence on the system size

Y. Kamiya et al., Phys. Rev. Lett. 124, 132501 (2020)





Lattice QCD with S=-3

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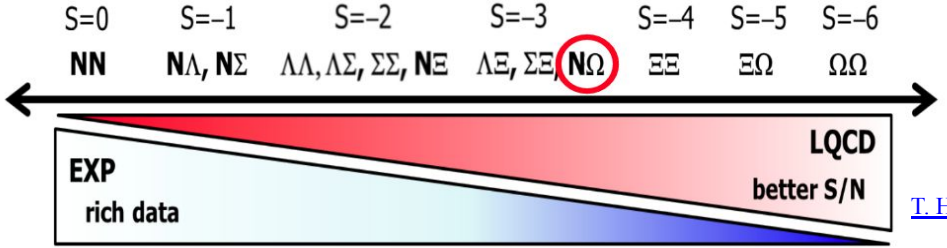


T. Hatsuda@SQM19Bari

- **First principle calculations** in the strangeness sector:
  - Recent developments by lattice QCD at the physical point
- baryon-baryon sector:
  - models constrained by **data with limited precision** (in contrast with N-N interactions)
- Difficulties to produce beams of hyperons

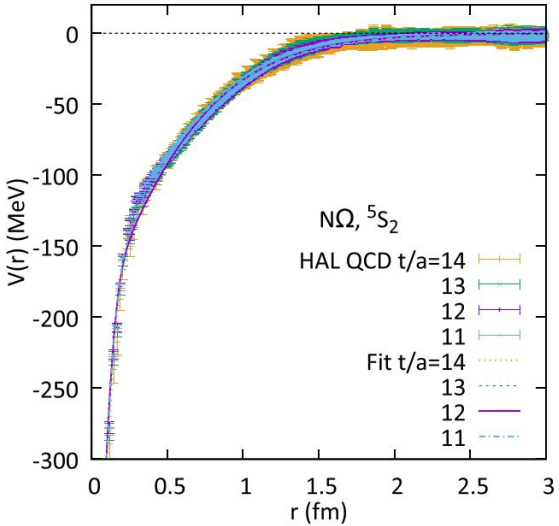
⇒ Correlation studies can bring balance experiment-theory

ALICE make use of high-multiplicity pp collisions with an **enhanced production of strangeness**

ALICE Coll, Nature Physics 13, 535 (2017)

p-Ω⁻ interaction

- **HAL QCD p-Ω⁻ potential** with physical quark masses [T. Iritani et al., Phys. Lett. B 792 (2019) 284-289]
  - m_π = 146 MeV/c^2, m_K = 525 MeV/c^2



⇒ p-Ω⁻ attractive interaction at all distances
- No pauli blocking

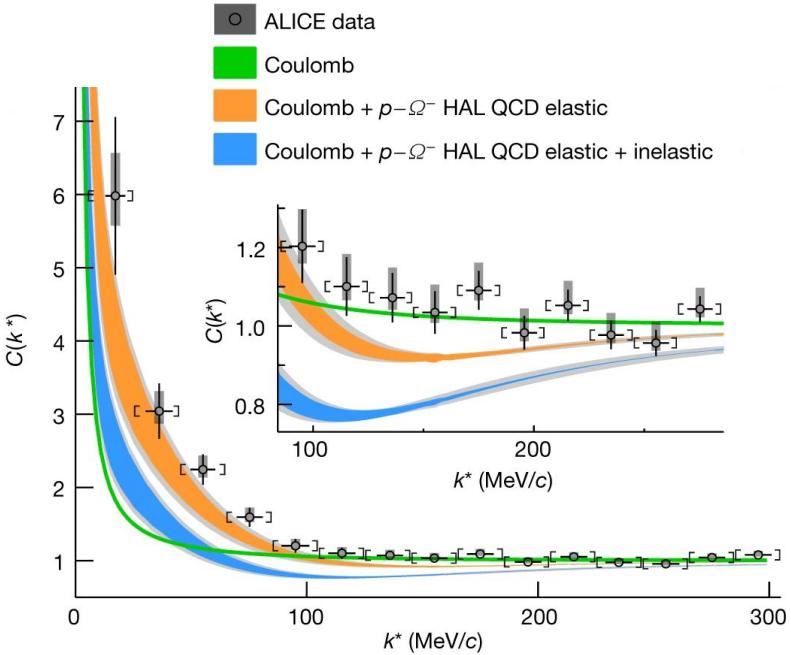
Same behaviour predicted by meson exchange models [T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)]

- Predicts the formation of a **p-Ω⁻ di-baryon**:

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

p-Ω⁻ correlation function in pp at 13 TeV

"Unveiling the strong interaction among hadrons at the LHC",
ALICE Coll., Nature 588, 232 (2020)



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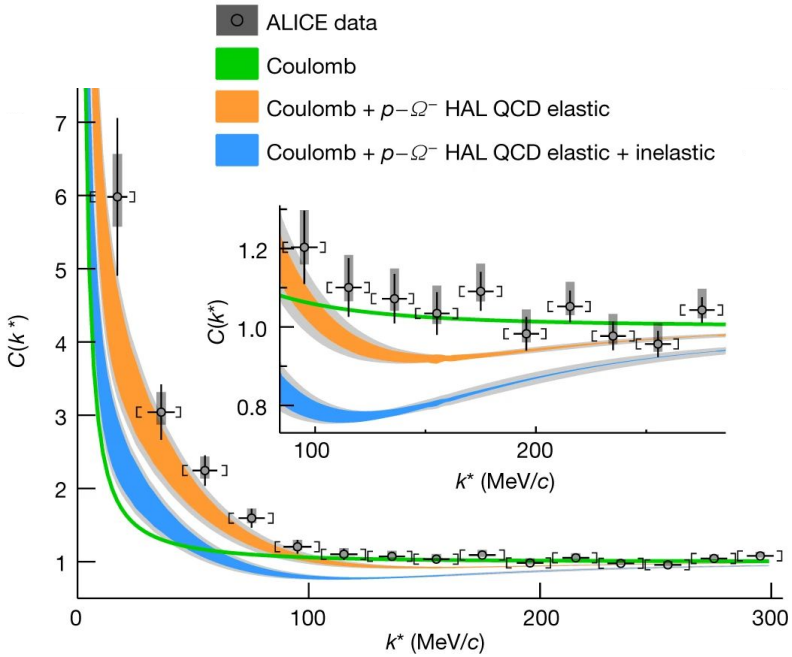
ALICE Coll., Nature 588, 232 (2020)



⇒ Evidence of **attractive** strong **interaction** p-Ω⁻ system
- p-Ω⁻ correlation function enhanced with respect to p-Λ, p-Ξ⁻

⇒ The correlation function in pp collisions at the LHC sensitive to small differences among the interaction potentials (very small sources samples short distances)

⇒ Precise p-Ω⁻ experimental correlation function provide **first constraint for lattice QCD** calculations:
- Inelastic channels not accounted for quantitatively within the lattice ⇒ two extreme assumptions

⇒ The **data do not follow the depletion** in the correlation function expected due to the p-Ω⁻ bound states:
- Dependence on the system size

Outlook

- The LHC provides precise testing of the hadron-hadron interaction at distances lower than 1 fm.
- Correlation data complements other approaches.
  - For some channels (multi-strange particles) constitute the only precise data
- 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.
- Upcoming LHC data taking will provide the possibility of carrying out new and differential studies and investigate 3-body interactions.

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