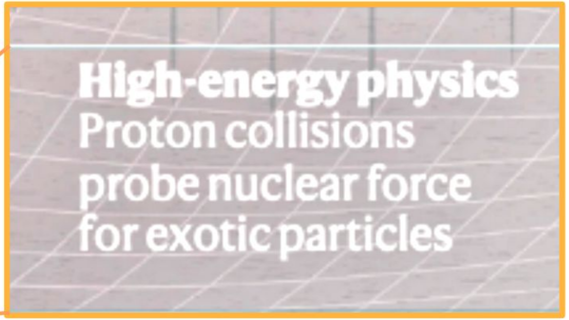
Precise tests of the hadron-hadron strong interaction via femtoscopy with ALICE

Otón Vázquez Doce
on behalf of the ALICE Collaboration

MESON 2021 16th International Workshop on Meson Physics, 17th - 20th May 2021

Unveiling the strong interaction among hadrons at the LHC

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



Outline

LHC

Small collision systems:

- pp $\sqrt{s}$ = 7, 13 TeV
- p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

⇒ size of particle source ~1 fm

Outline

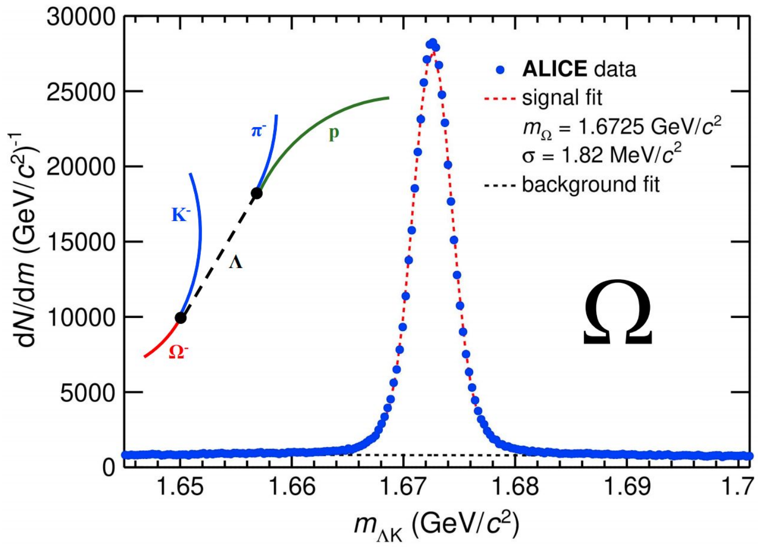
LHC

ALICE

Central barrel **tracking and PID**:

- Reconstruction of charged particles: p, π, K.
- Hyperon reconstruction through weak decays
  $\Lambda \to p\pi$, $\Xi \to \Lambda\pi$, $\Omega \to \Lambda K$

Correlation studies at small relative momentum

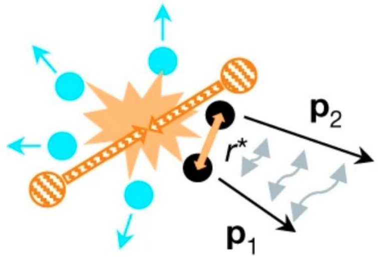


Outline

LHC

ALICE

Study of hadron strong interactions

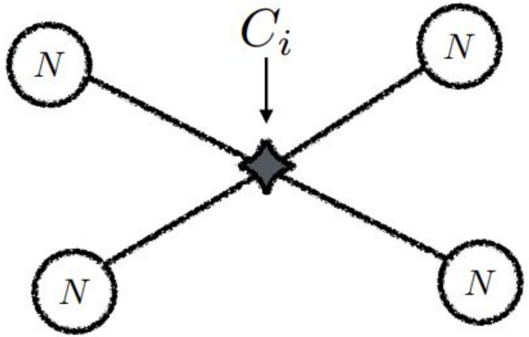


Femtoscopy: Precise data in the low momentum range, hardly accessible with other approaches

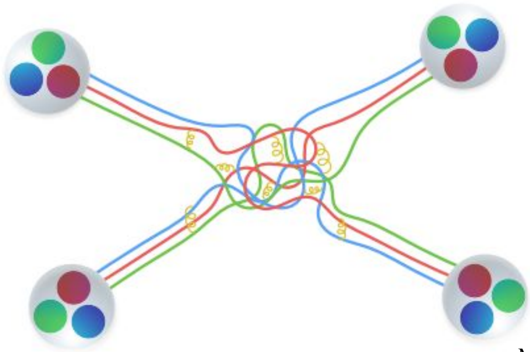
- **Test of first principle calculations** for unstable hadrons
- **Search for new bound states**
- **Equation of State of neutron stars**

Hadron-hadron strong interactions

Residual strong interaction among hadrons



$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$



Marc Illa
THEIA-STRONG2020

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

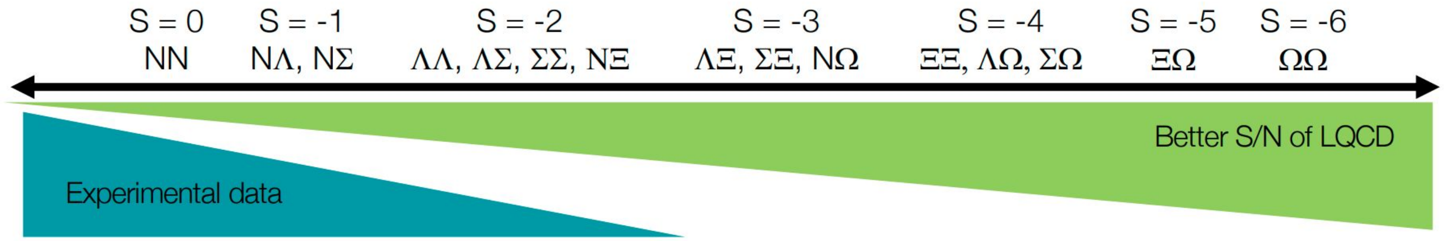
Non-perturbative region of QCD

- **Hadrons** as degrees of freedom
- **Effective theories** (EFT) with low-energy coefficients **constraint by data**

Lattice QCD

- Understanding of the interaction starting from **quark and gluons**

Hadron-hadron strong interactions



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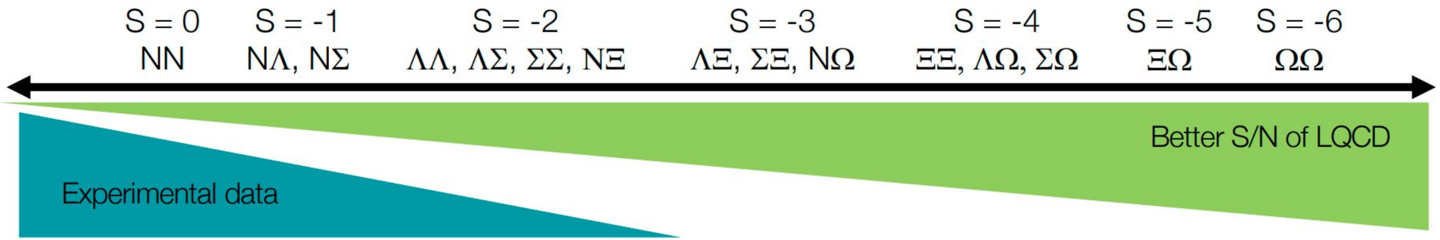
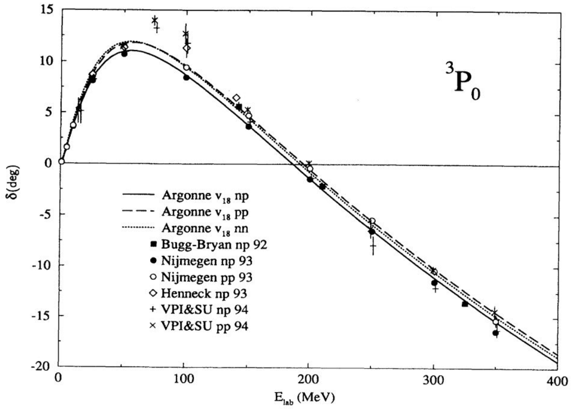
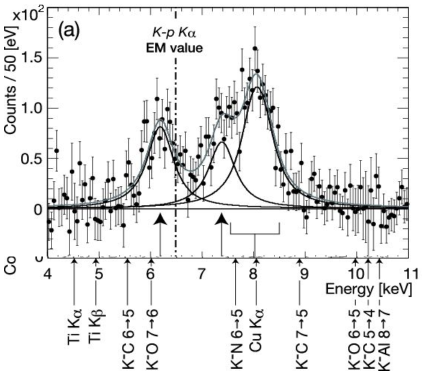


NN → NN



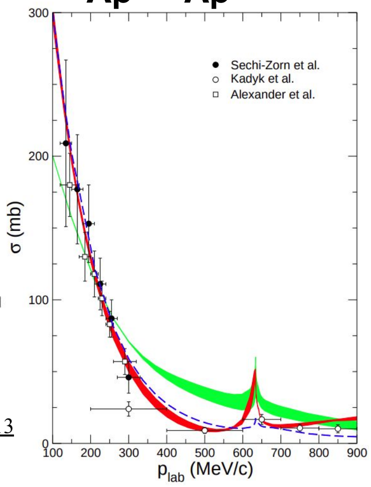
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Kaonic atoms



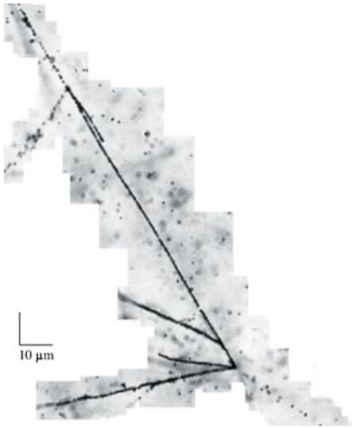
SIDDHARTA Coll. Phys.Lett.B 704 (2011) 113

Λp → Λp



LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

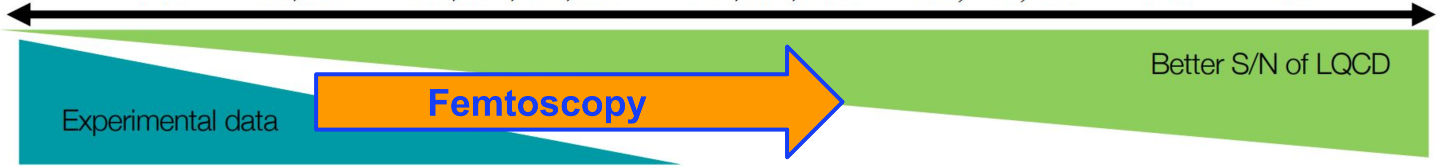
Ξ hypernuclei



KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

Hadron-hadron strong interactions

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



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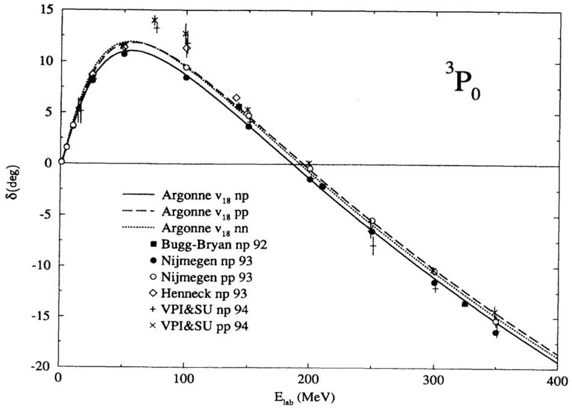

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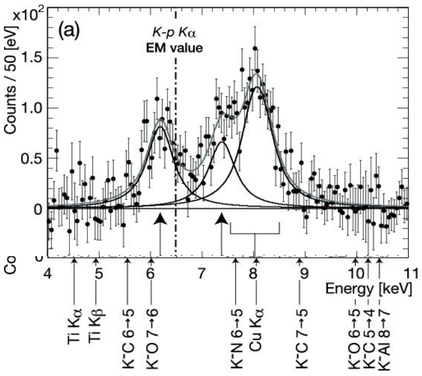

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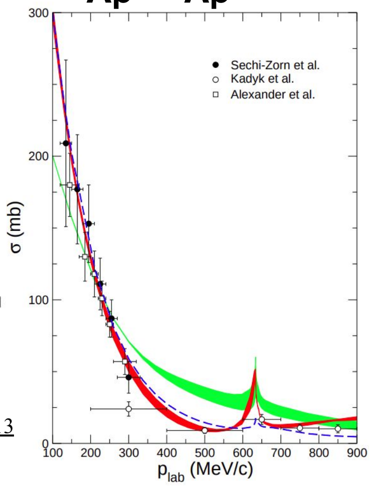

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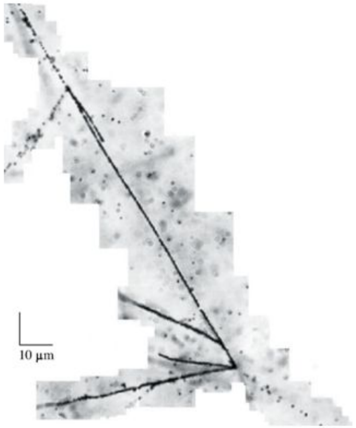

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Femtoscopy method in nuclear collisions

Femtoscopy method in nuclear collisions

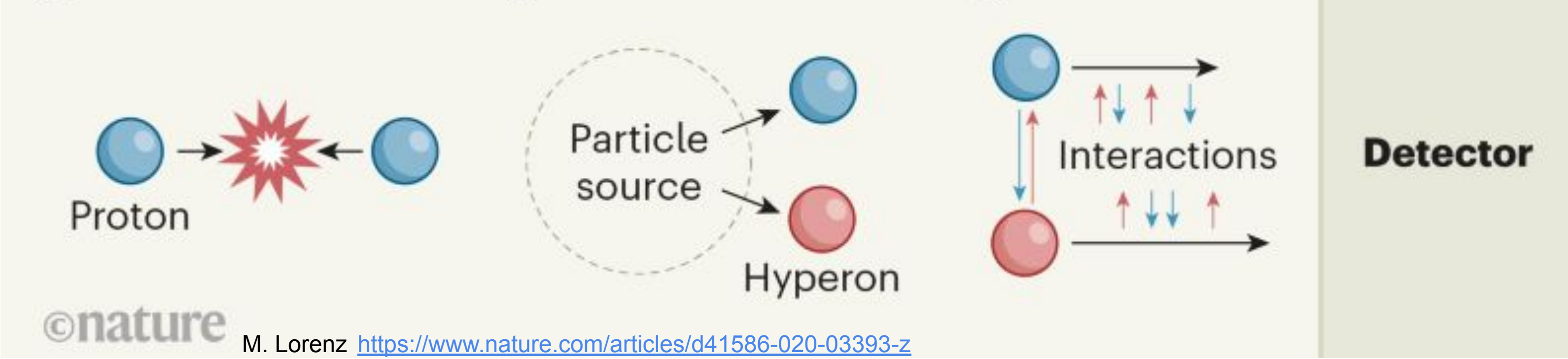
Based in the **measurement of the correlation function**

"Traditional" femtoscopy analyses in Heavy Ions Collisions:

- Study pairs of particles with "known" interaction
  ⇒ **Determine the characteristics of the source** (sizes 3-10 fm)

"Non-traditional" femtoscopy

- **Study the interaction** given a known source



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

Femtoscopy method in nuclear collisions

Measurement of the **correlation function,** $C(\overrightarrow{p_a}, \overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$

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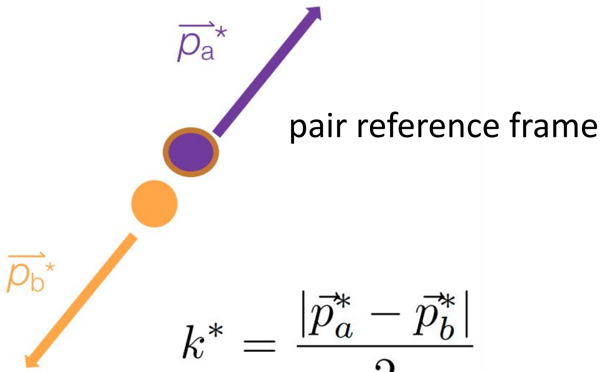
Experimentally:

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

→ Pairs of particles from same collision

→ Particles produced in different collisions



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

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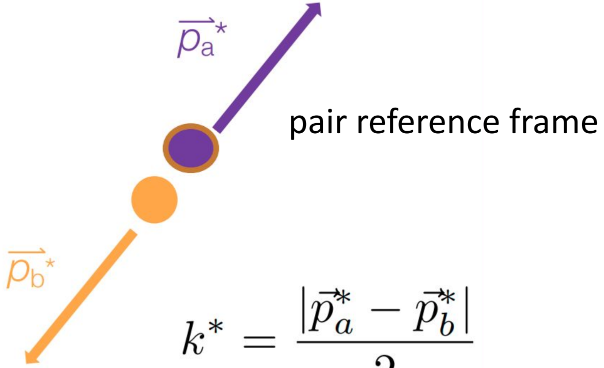
$N_{\mathrm{same}}(k^*)$ → Pairs of particles from same collision

$N_{\mathrm{mixed}}(k^*)$ → Particles produced in different collisions

$\xi(k^*)$ → Corrections to the experimental measurement:

- Normalization
- Resolution effects
- **Residual correlations**



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Theoretical correlation function

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

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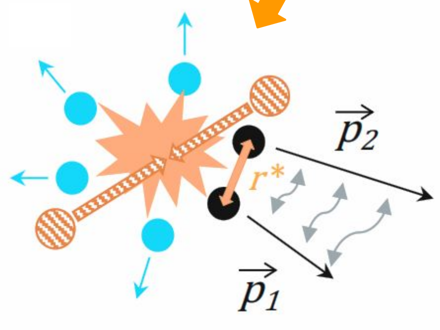

Object of study of standard femtoscopy

Theoretical correlation function

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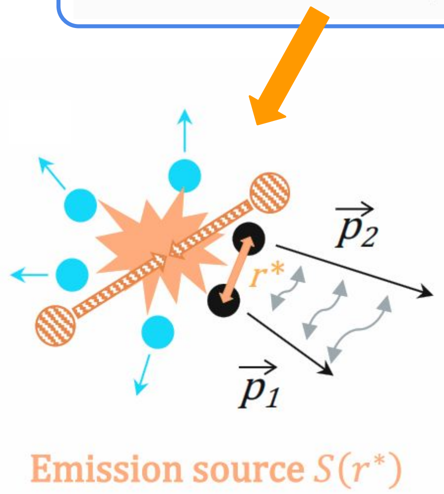

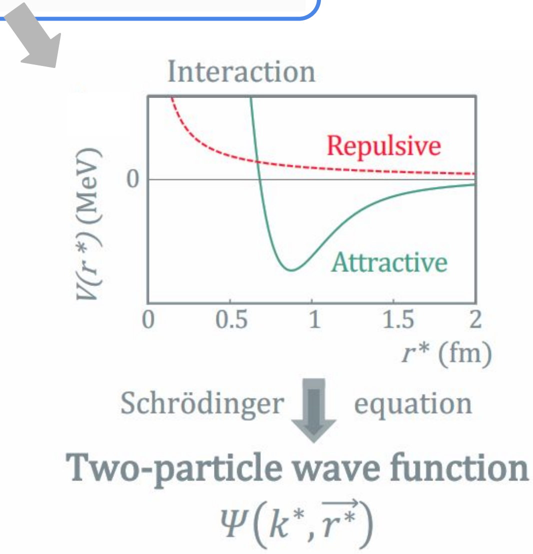

Object of study of standard femtoscopy

Object of study of “non-traditional” femtoscopy

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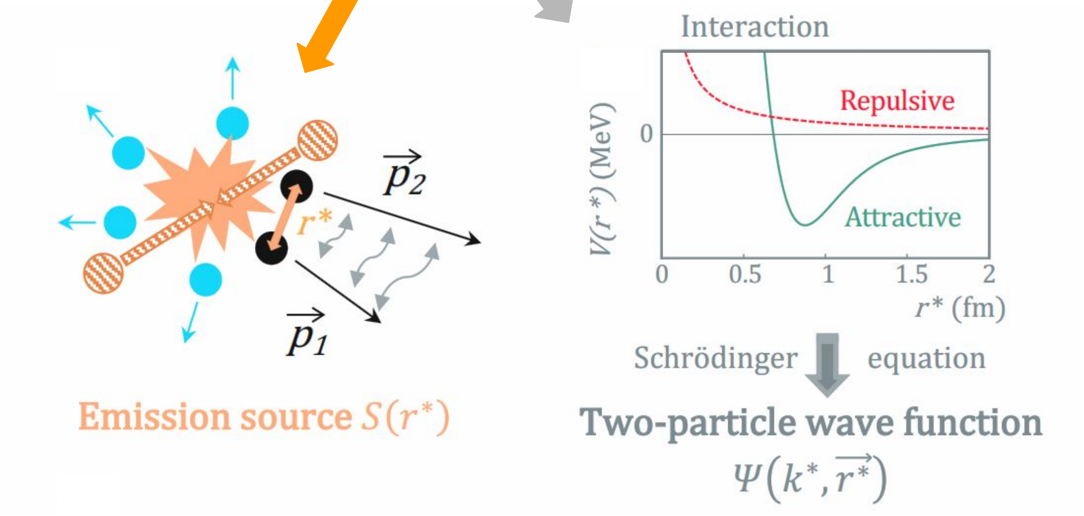

CATS: Schrödinger equation solver

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

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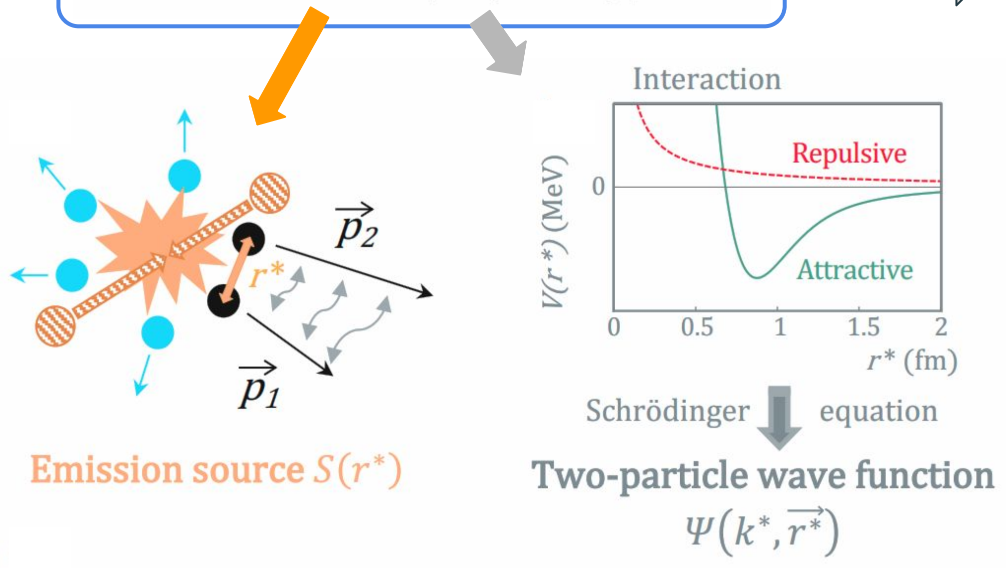

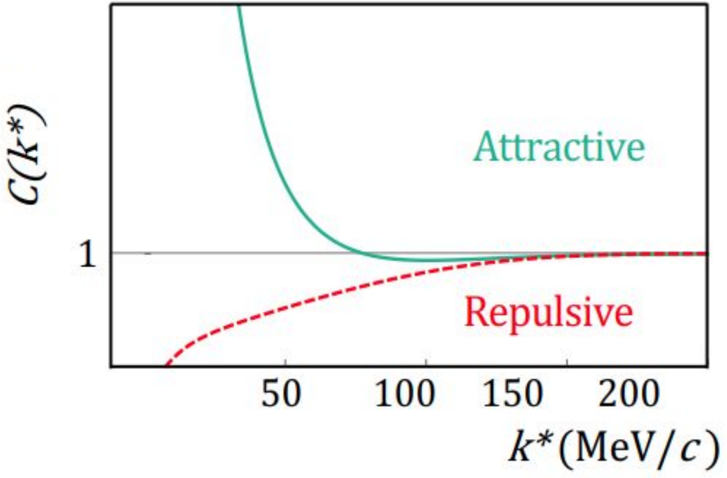

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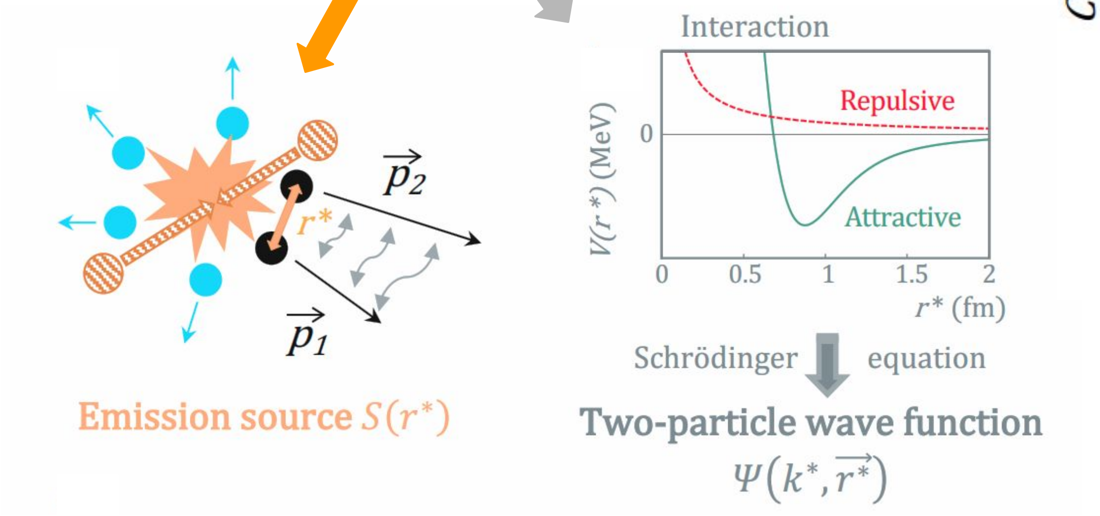
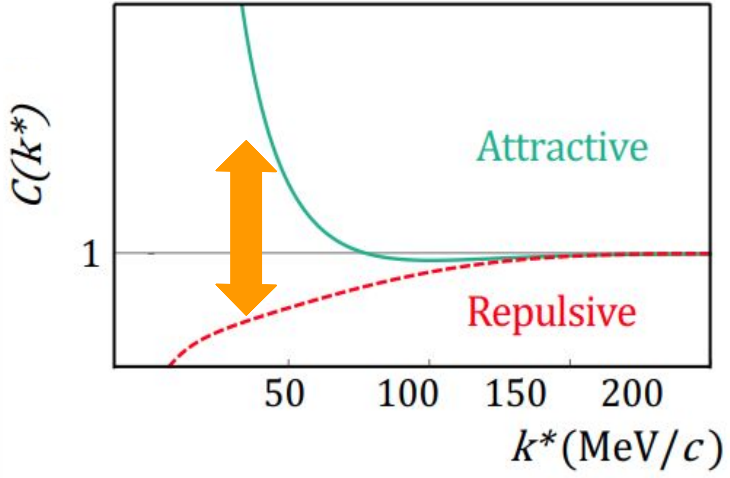
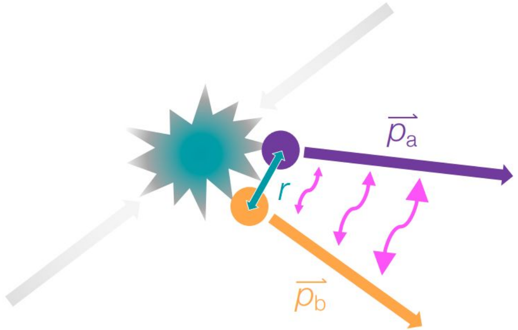


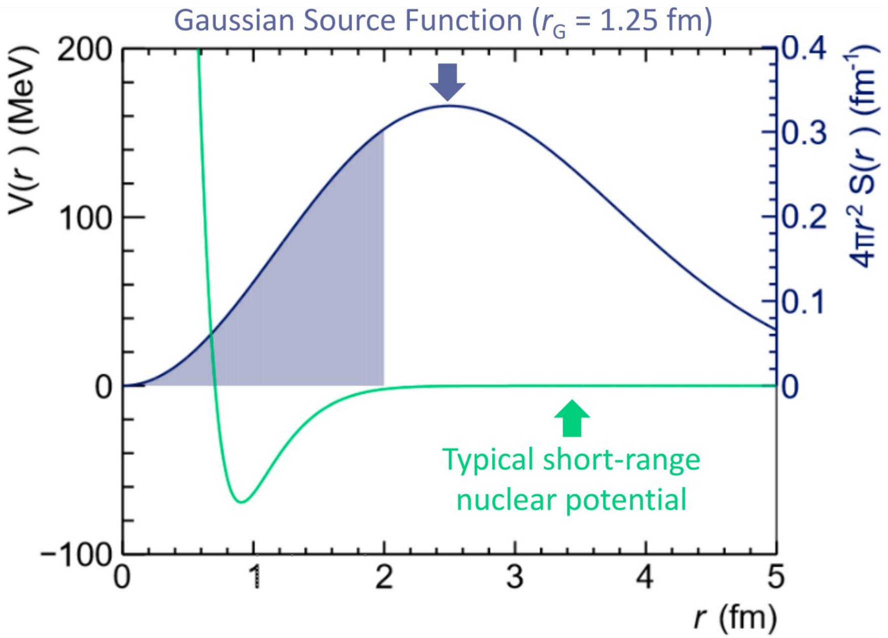


Femtoscopy with small sources

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

- Essential ingredient for detailed studies of the strong interaction





Determination of the source [ALICE Coll., Phys. Lett. B 811 (2020) 135849]

The first step is "traditional" femtoscopy: known interaction → determine source size

- p–p interaction: Argonne v18 potential
- crosscheck with p–Λ (χEFT)

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ALICE Coll., Phys. Lett. B 811 (2020) 135849

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- p−p interaction: Argonne v18 potential
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Determine **gaussian "core" radius**
- As a function of pair $<m_T>$
- **Common to all hadron-hadron pairs**

✖

Effect of strong short-lived resonances

Adds **exponential tail** to the source profile

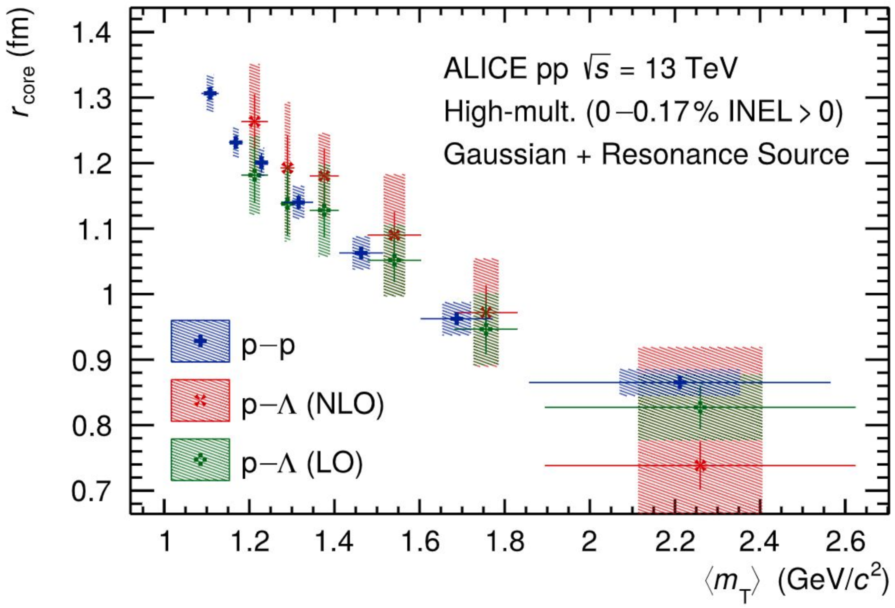
→ Angular distributions from EPOS

→ Production fraction from SHM

	Primordial	Resonances lifetime
p	35.8 %	1.65 fm
Λ	35.6 %	4.69 fm

Determination of the source

ALICE Coll., Phys. Lett. B 811 (2020) 135849



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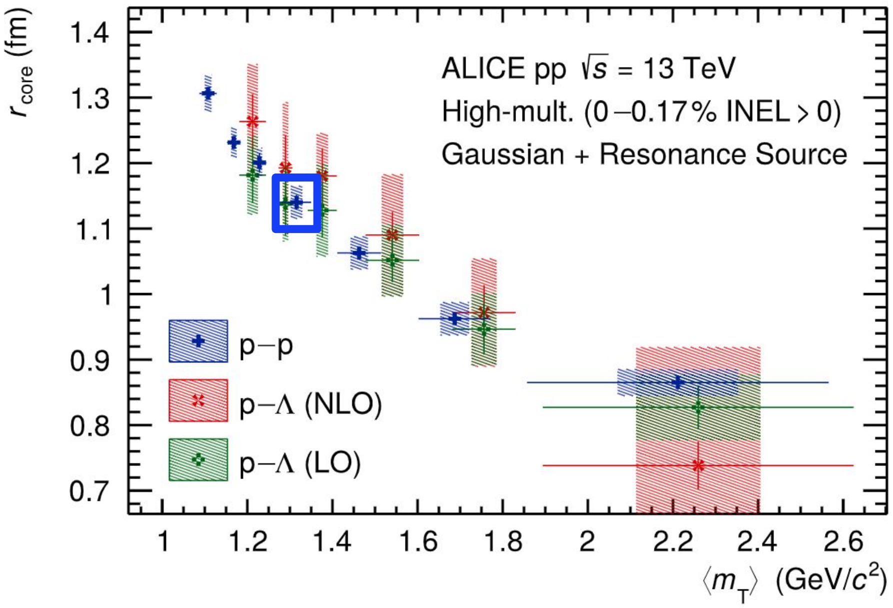

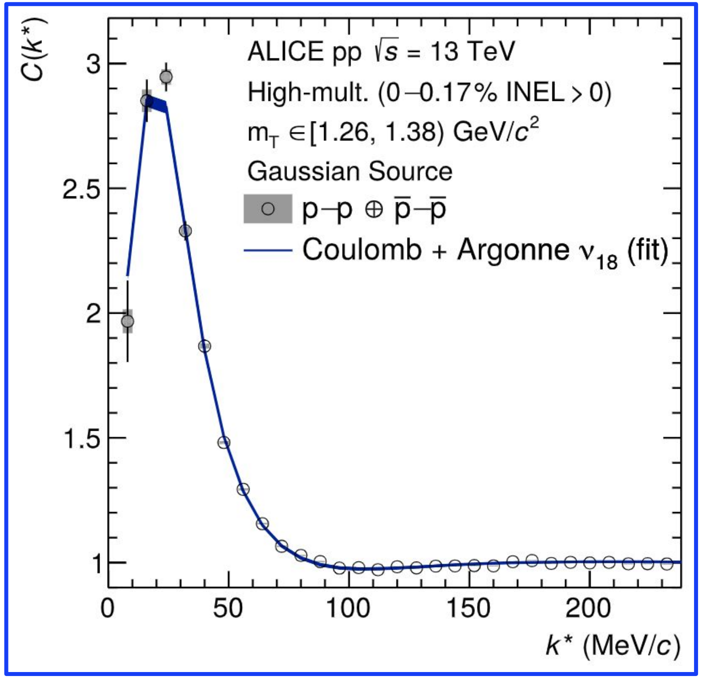

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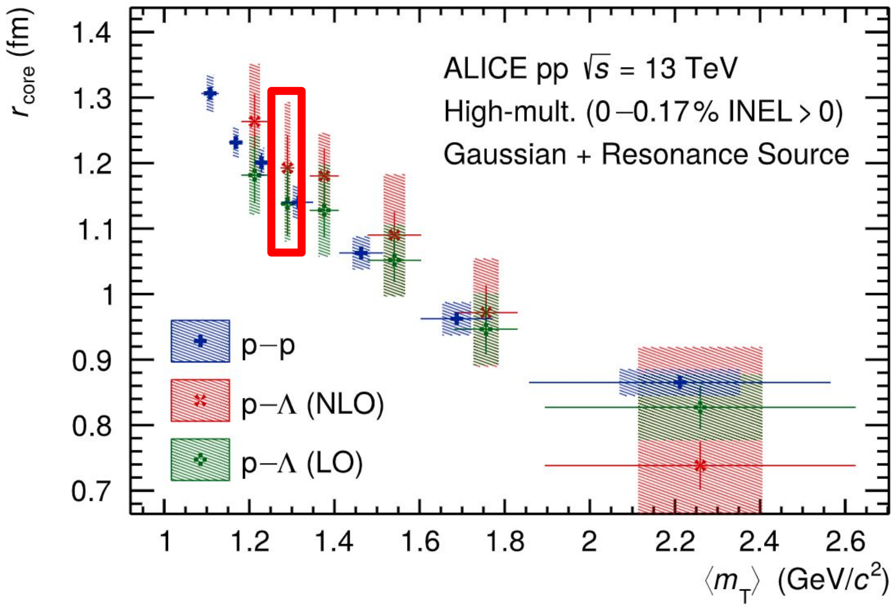

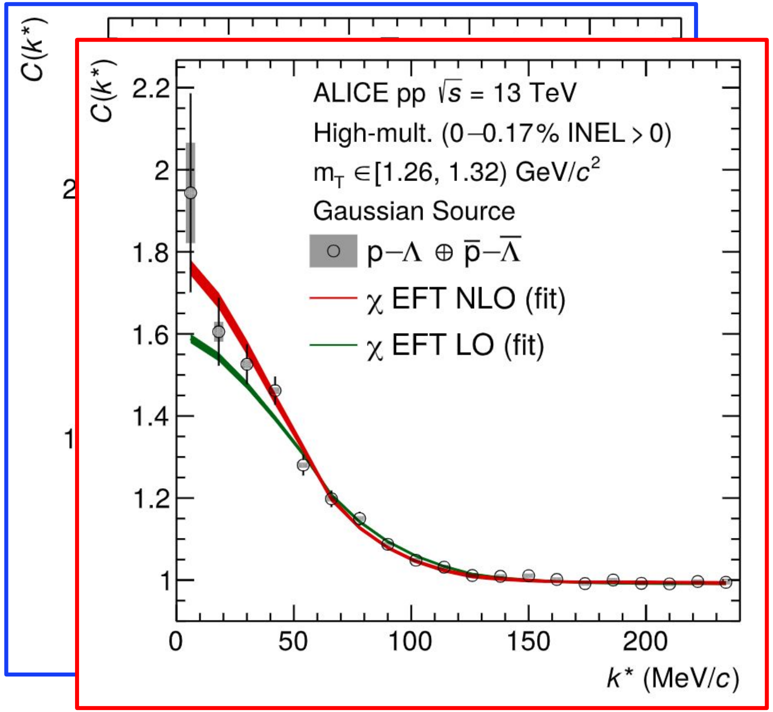

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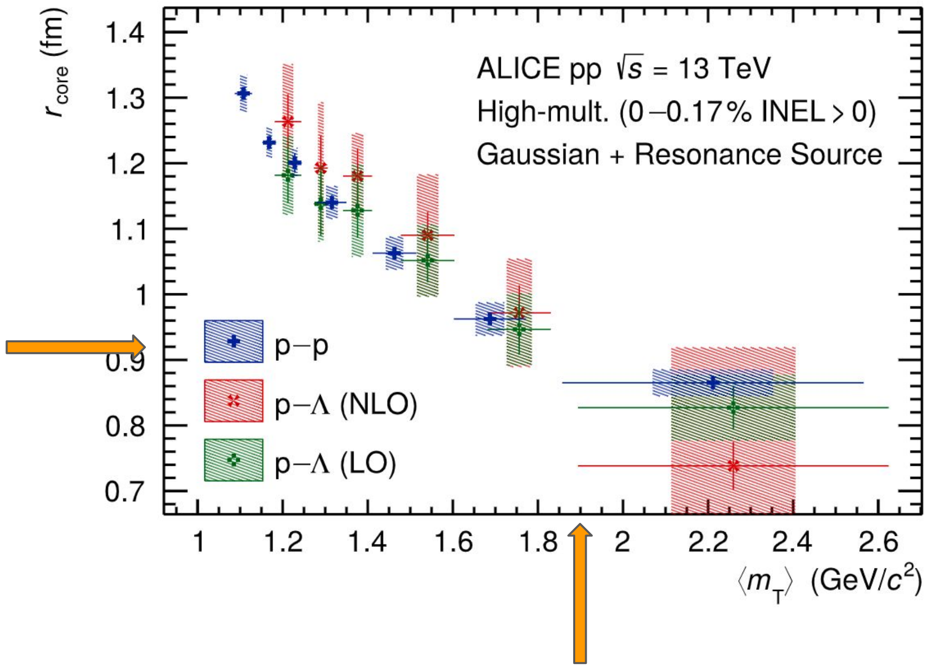


Source **size determined given the pair <m_T>** and **considering the effect of strong resonances** for the particles of the pair of interest

Example:

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

strong resonances effect

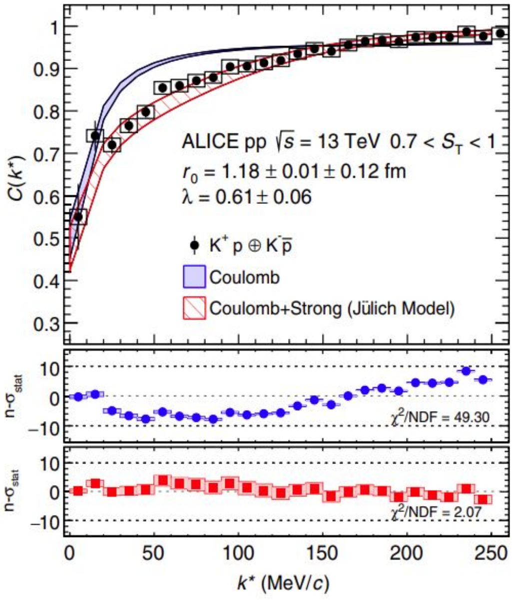
⇒ r_{gauss} = 1.02 ± 0.05 fm

Selected results

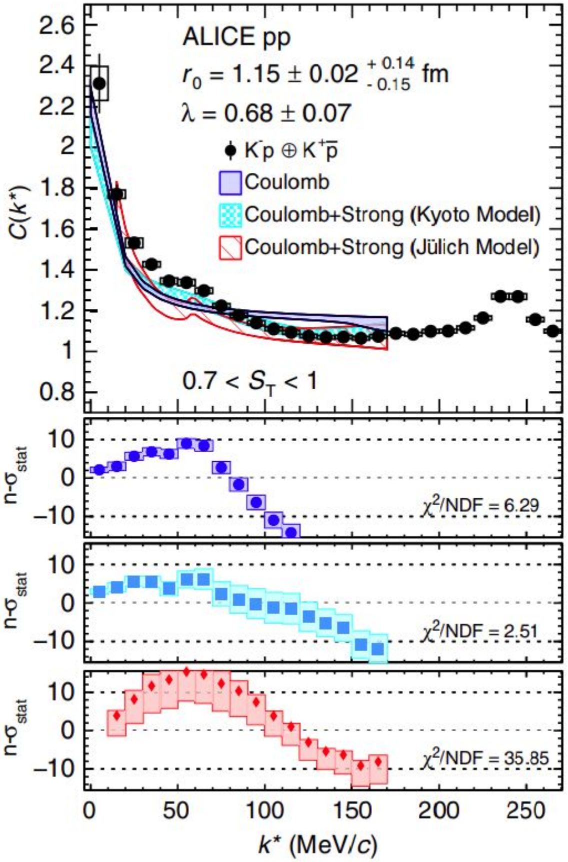
K-p correlations in pp collisions

ALICE Coll. Phys. Rev. Lett. 124 (2020) 092301

Well known K^+–p interaction
C(k*)<1 → Repulsive interaction



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



K^-–p correlation function

C(k*)>1→ attractive interaction

Coulomb potential only

Coulomb + Chiral Kyoto model

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

Coulomb + Jülich model

Nucl. Phys. A 981 (2019)

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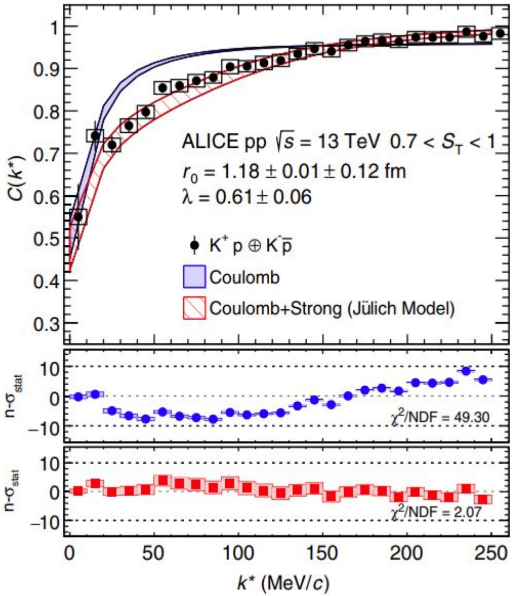

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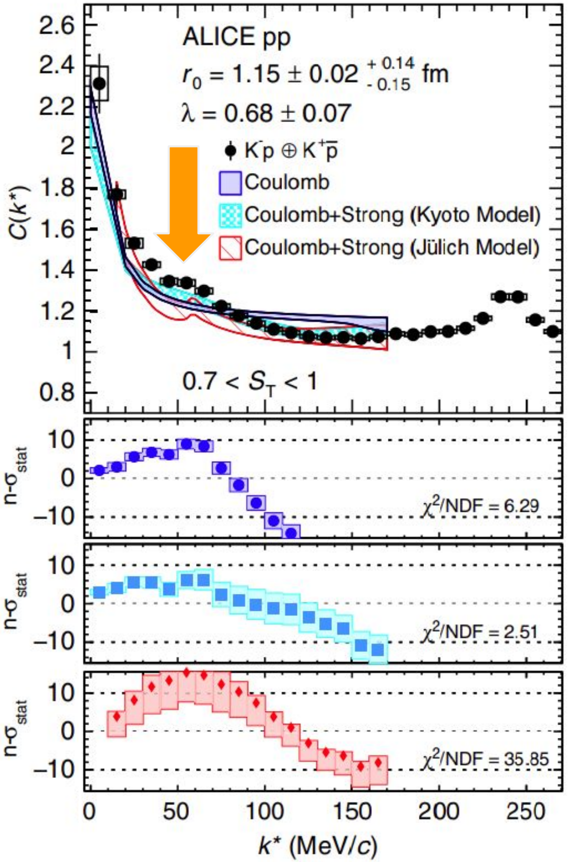

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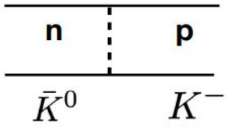
⇒ Evidence of the opening of the $\bar{K}^0$n isospin breaking channel

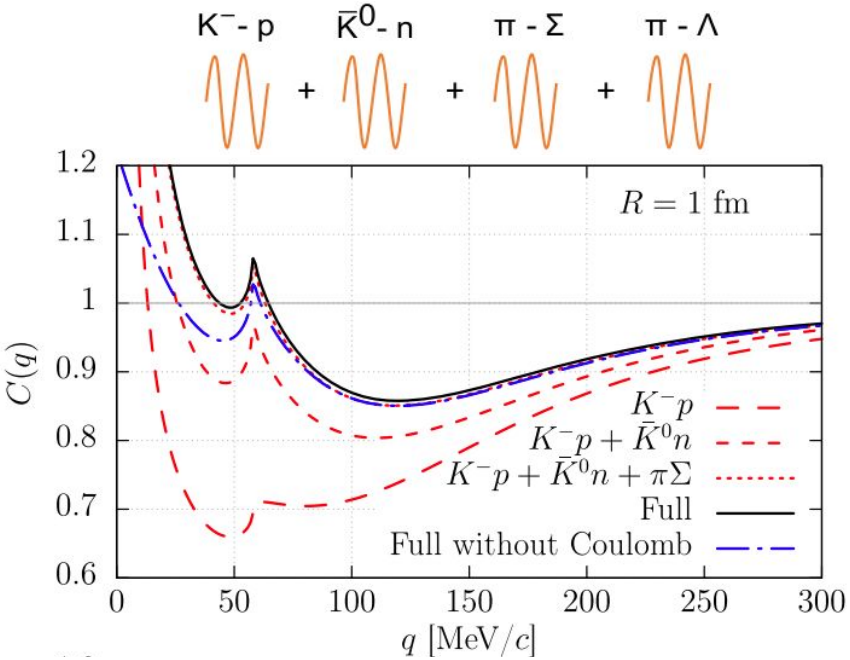


$$M(K^-p) + 5\,\mathrm{MeV} = M(n\bar{K}^0)$$

K-p correlations: Coupled channels

Kyoto model considering **coupled-channel effects reproduces ALICE data**

- Dependence on the system size



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

K-p correlations in pp, p-Pb, Pb-Pb collisions

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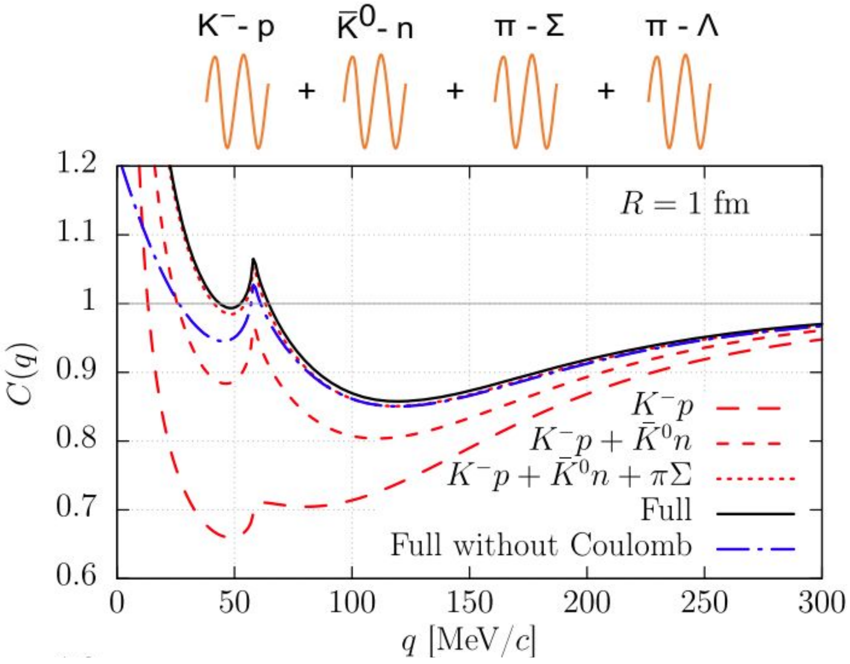
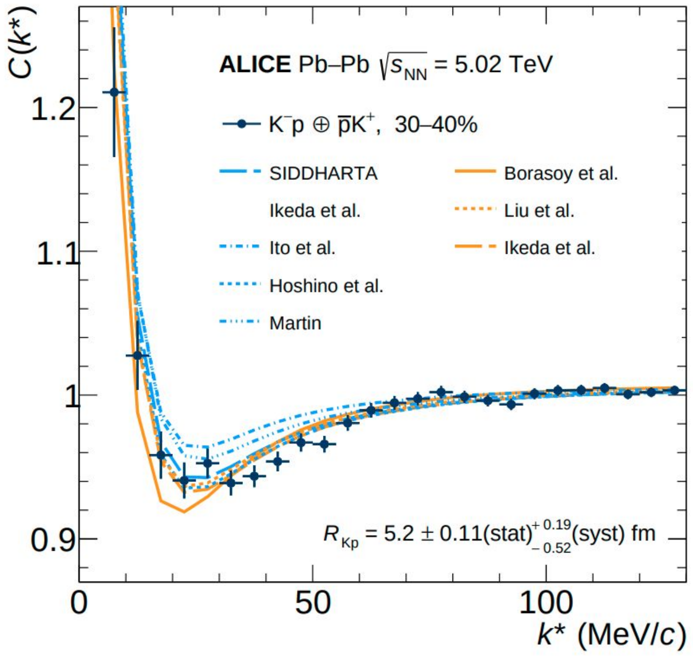
⇒ **Confirmed** by ALICE analysis in p-Pb, **Pb-Pb collisions**



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

ALICE Coll. arXiv:2105.05683 (submitted to PRX)



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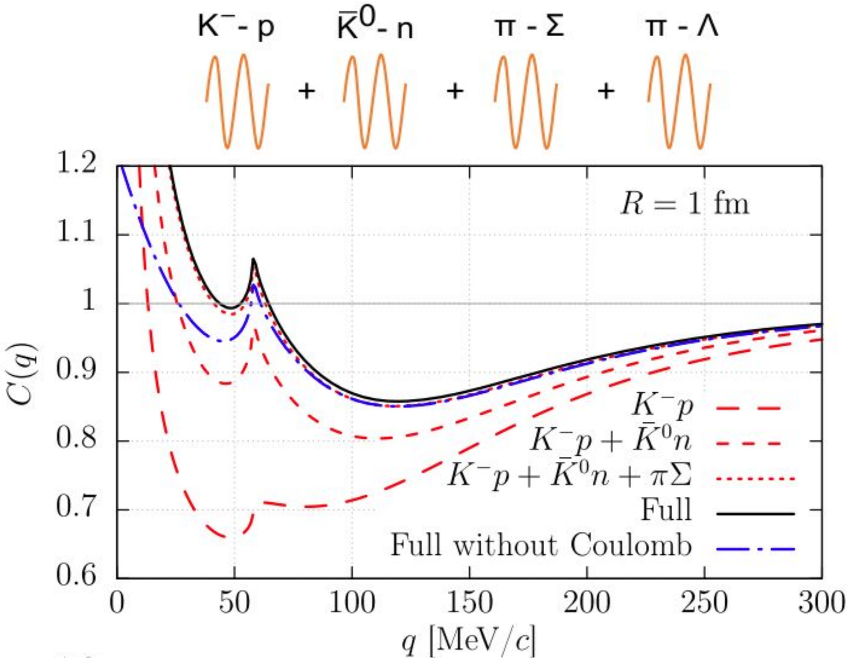

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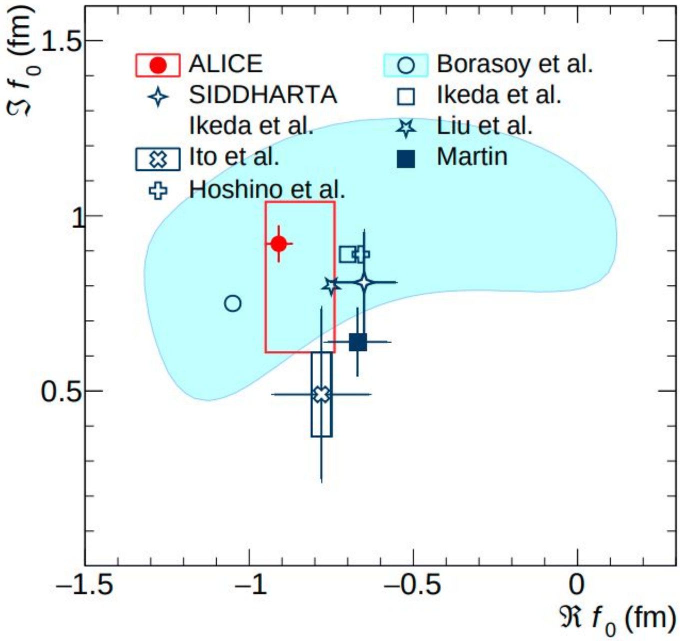
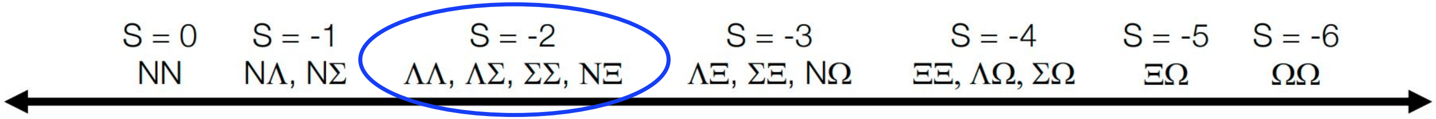
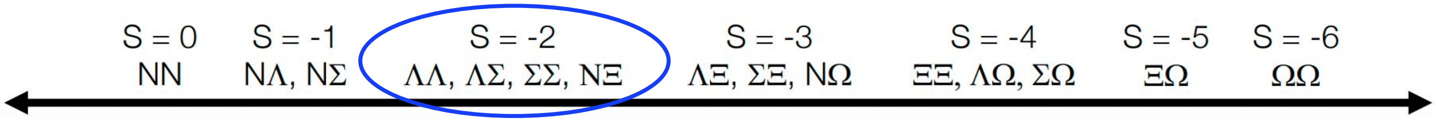


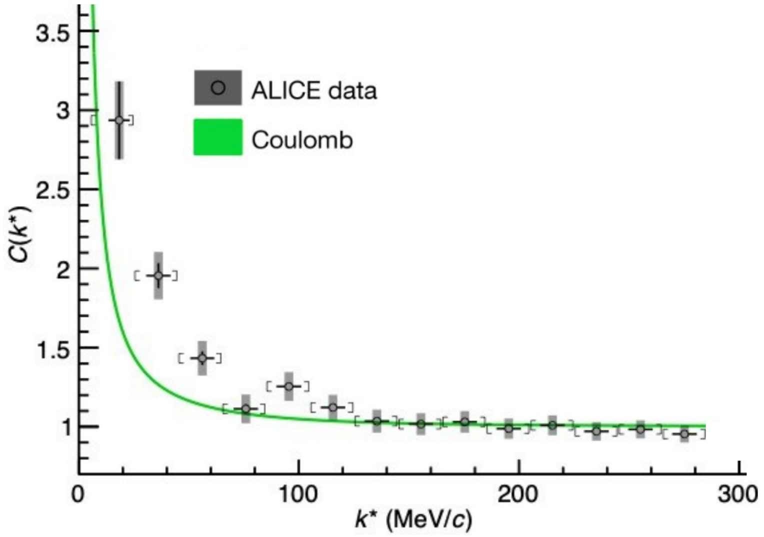
p–Ξ^- correlation function



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



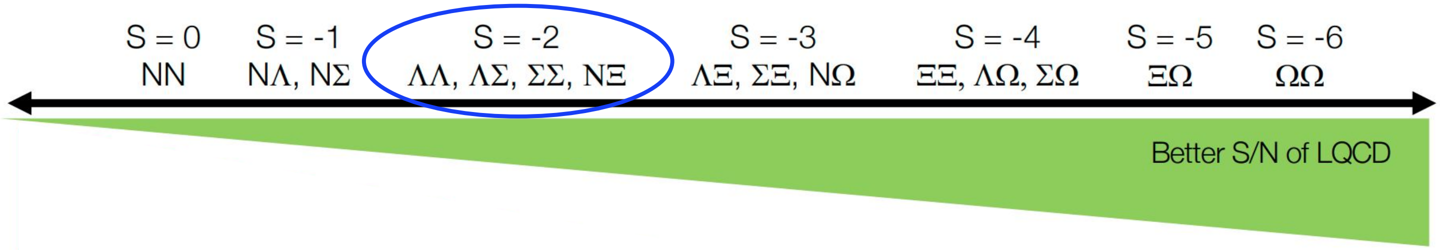
ALICE Coll. *Nature* **588**, 232 (2020)

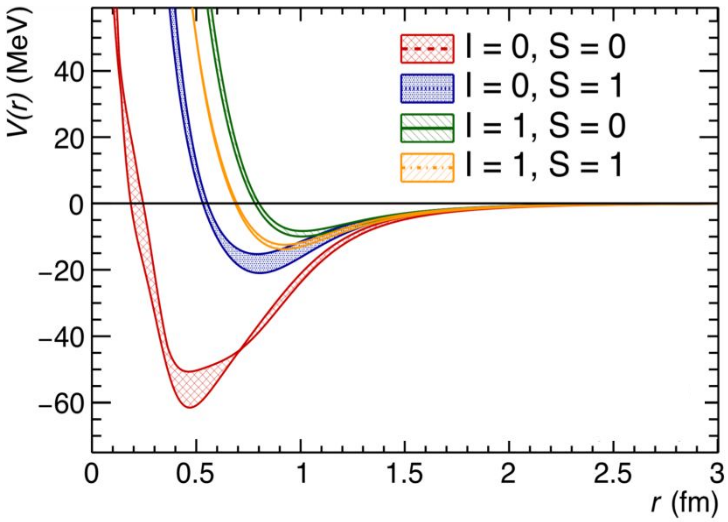


Enhancement above Coulomb-only prediction
⇒ Observation of the **attractive strong interaction**

- Continuation of the study in p-Pb coll.
  ALICE Coll. Phys. Rev. Lett. 123, 112002

p–Ξ⁻ potentials from Lattice QCD





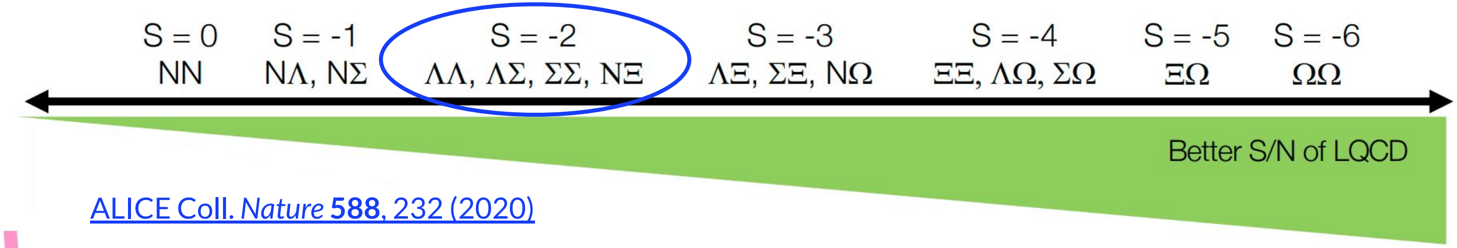
HAL QCD Collaboration

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

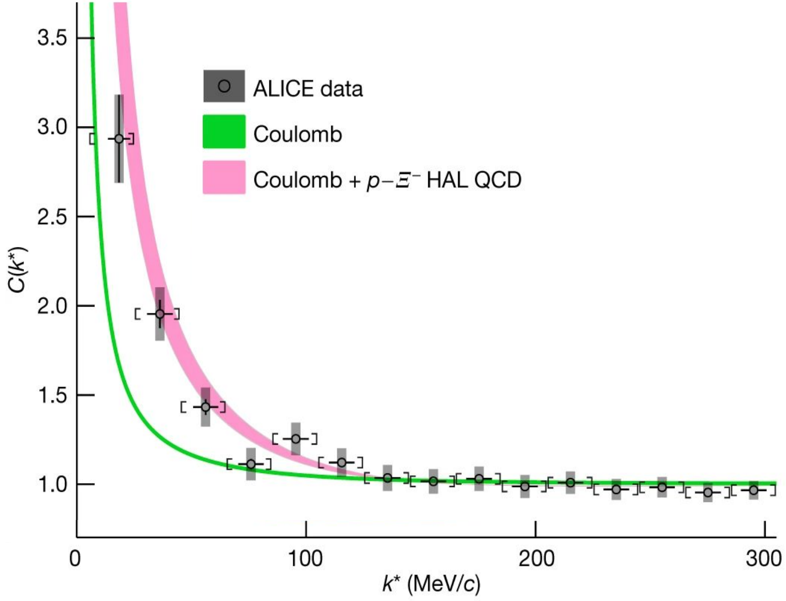
$$m_\pi = 146 \text{ MeV}/c^2$$
$$m_K = 525 \text{ MeV}/c^2$$

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

p–Ξ⁻ correlation function in pp at 13 TeV



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



Enhancement above Coulomb-only prediction
⇒ Observation of the **attractive strong interaction**

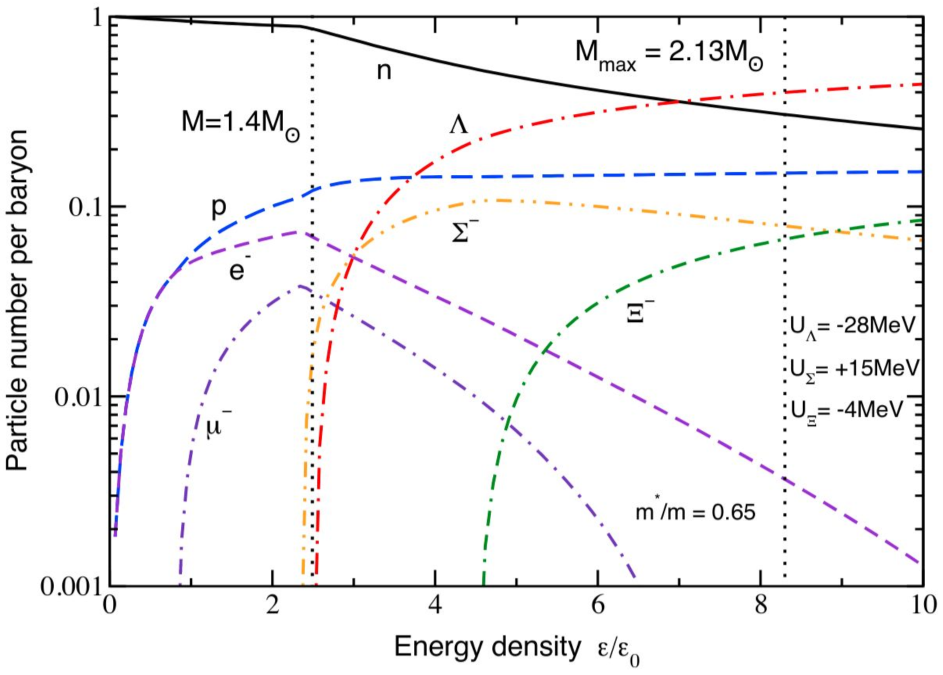
- Continuation of the study in p-Pb coll.
  ALICE Coll. Phys. Rev. Lett. 123, 112002

Excellent agreement with lattice predictions
⇒ Effect of validated Lattice QCD pΞ interaction
for the **Equation of State of Neutron Stars**

Hyperons in the core of Neutron Stars?

Lattice: slightly repulsive single particle potential in PNM for Ξ

⇒ **Ξ appears at larger densities** in NS



Courtesy J. Schaffner-Bielich (2021)

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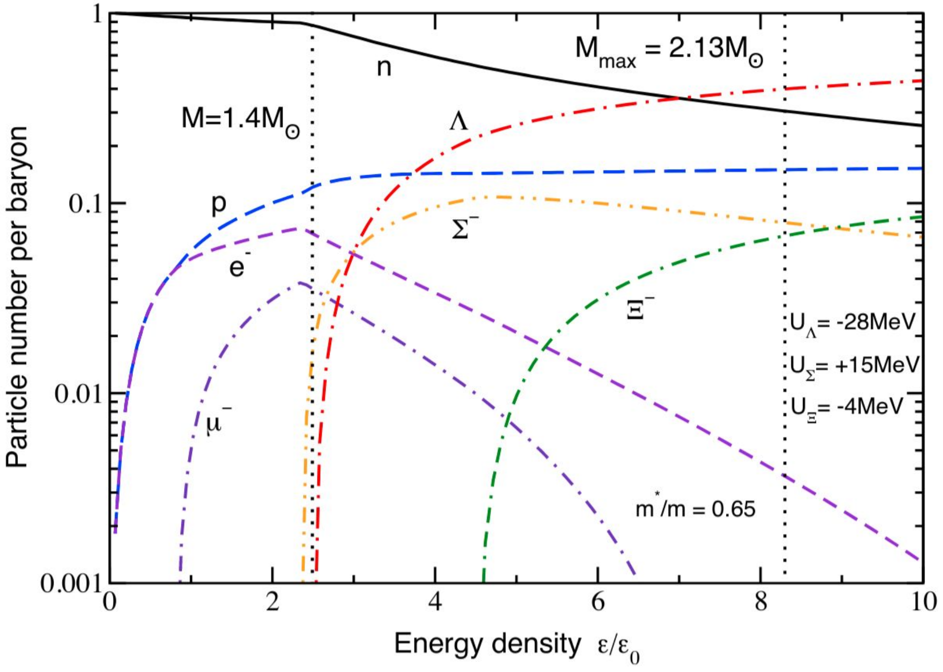
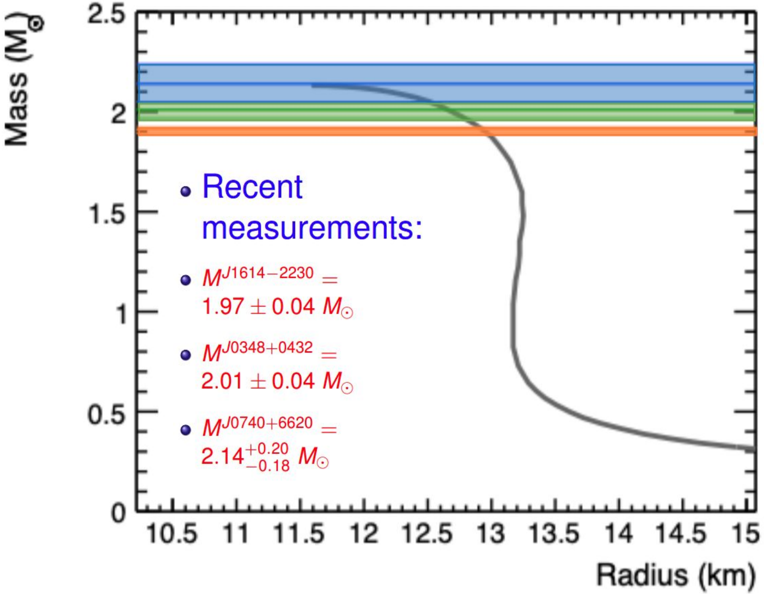
⇒ Ξ appears at larger densities in NS

⇒ **Stiffer EoS**





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Hyperons in the core of Neutron Stars?

Exact composition strongly depends on constituent interactions and couplings

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- **p–Λ** correlation function: **Critical test for χEFT**

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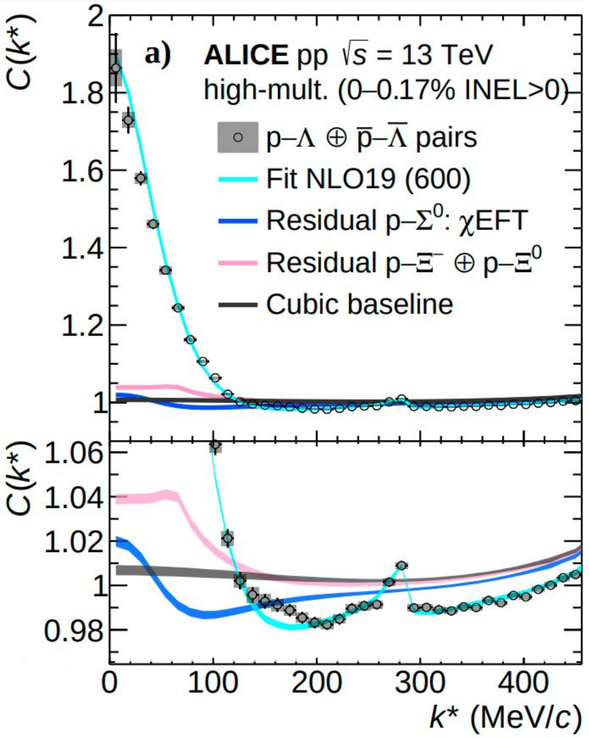

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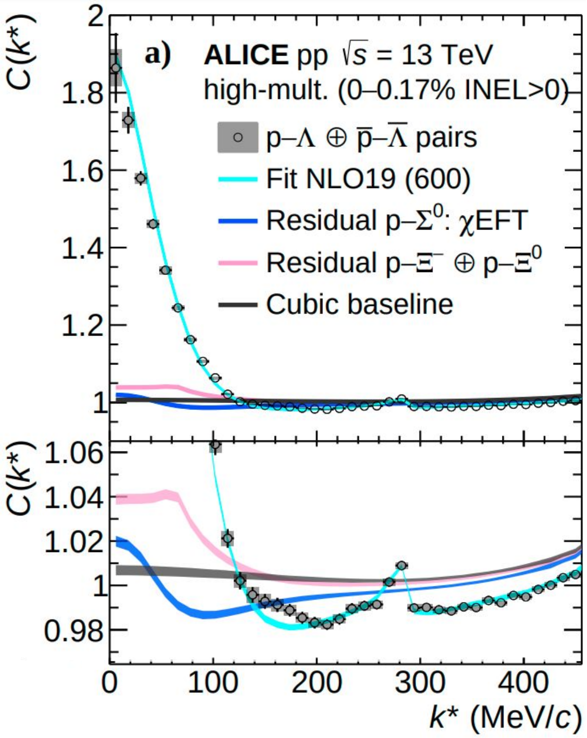
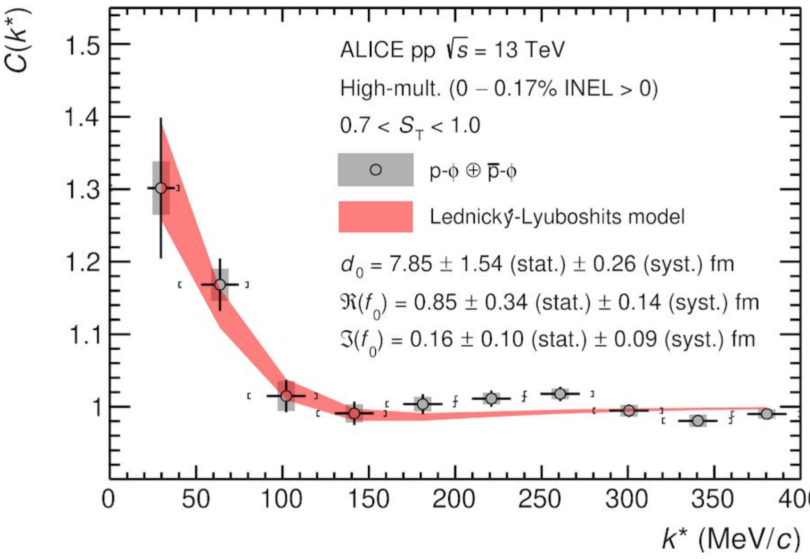


- **Attractive p–ϕ interaction demonstrated**

ALICE Coll., arXiv:2105.05578 (submitted to PRL)



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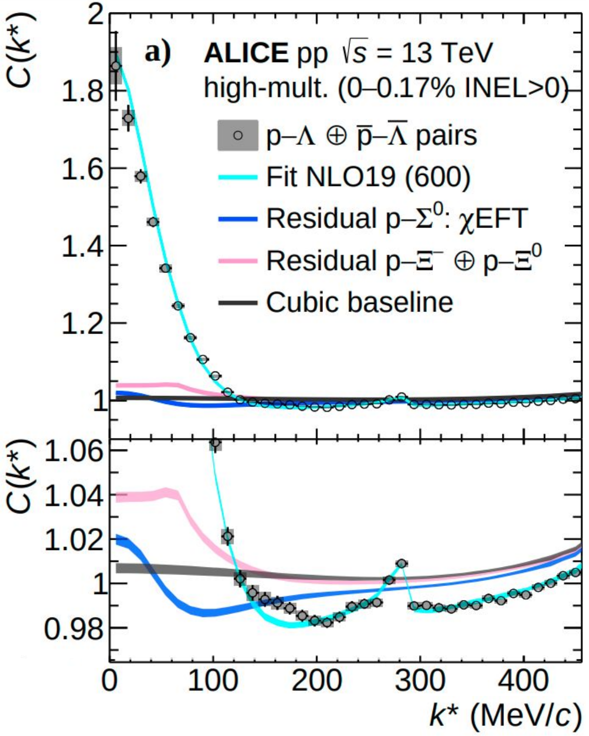

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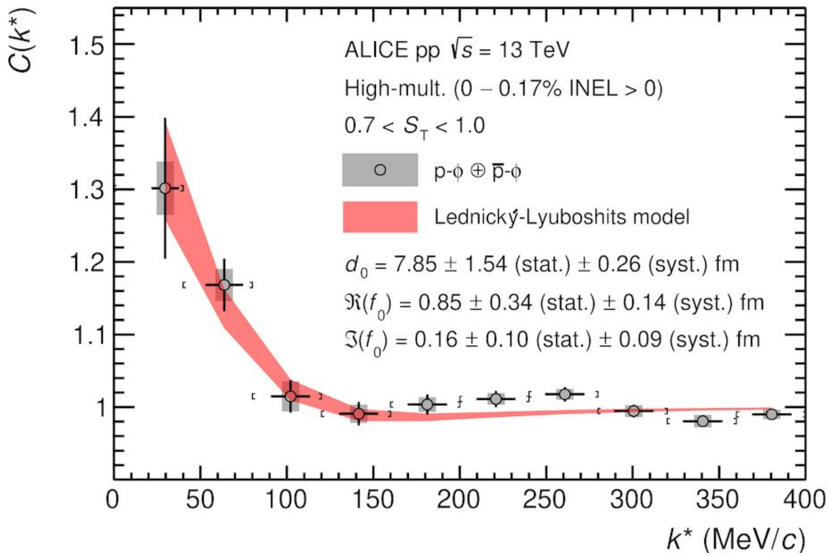
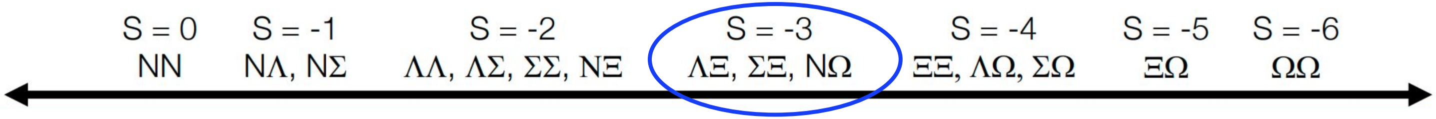


⇒ ALICE measured p–Σ^0, Λ–Λ, p–d

p–Ω⁻ correlation function in pp at 13 TeV



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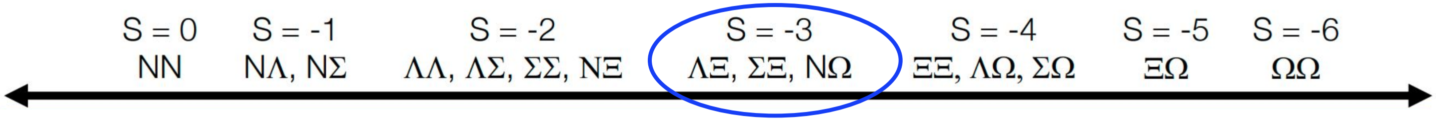
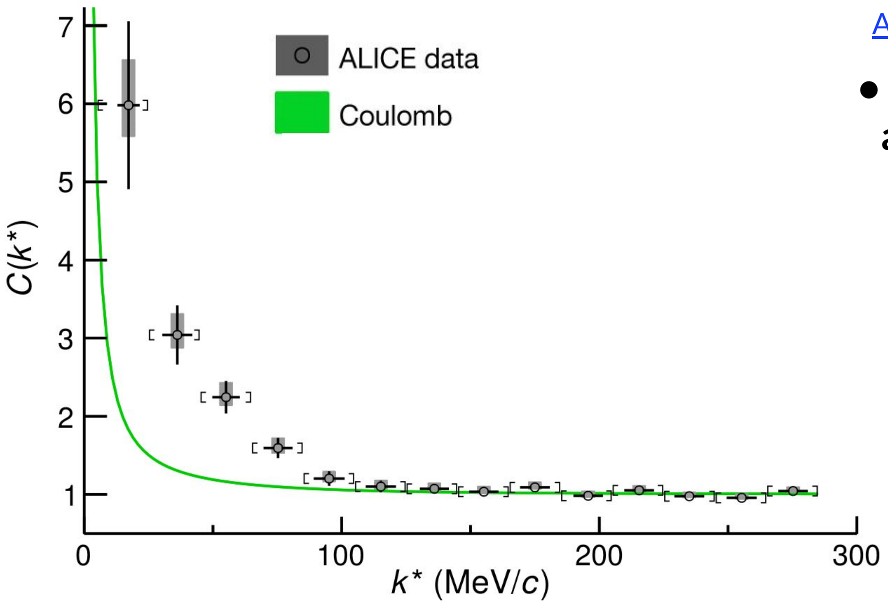
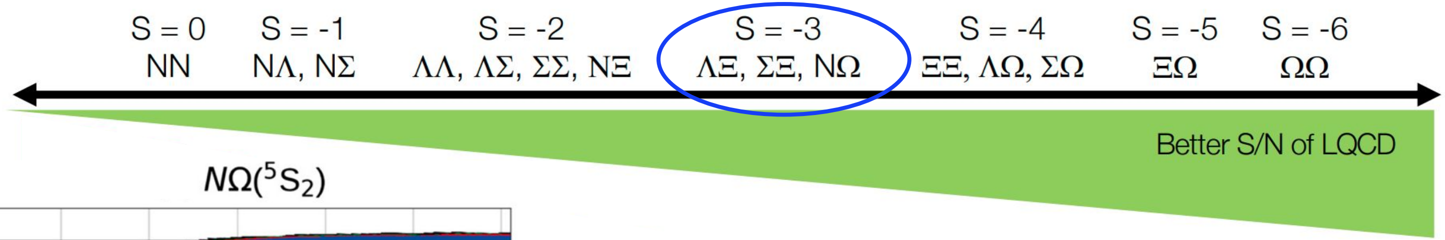


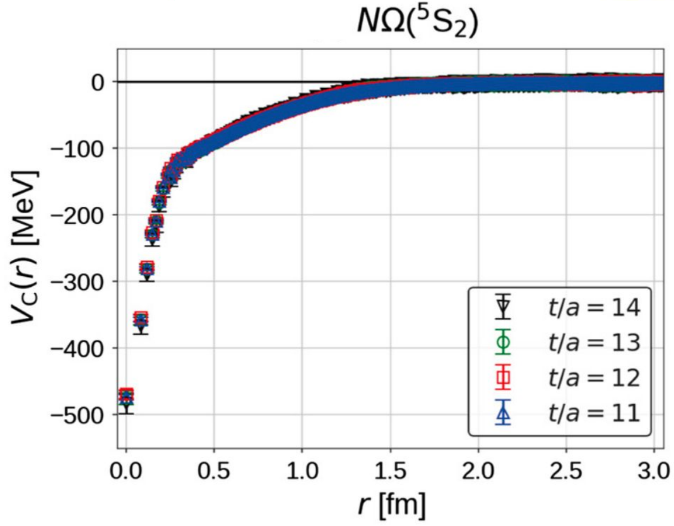


[ALICE Coll. *Nature* **588**, 232 (2020)]

- Observation of the **attractive strong interaction**

Lattice QCD NΩ potential





T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

$$m_\pi = 146\ \mathrm{MeV}/c^2$$
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Interaction of p–Ω⁻ pairs in $^5S_2$ state by HAL QCD

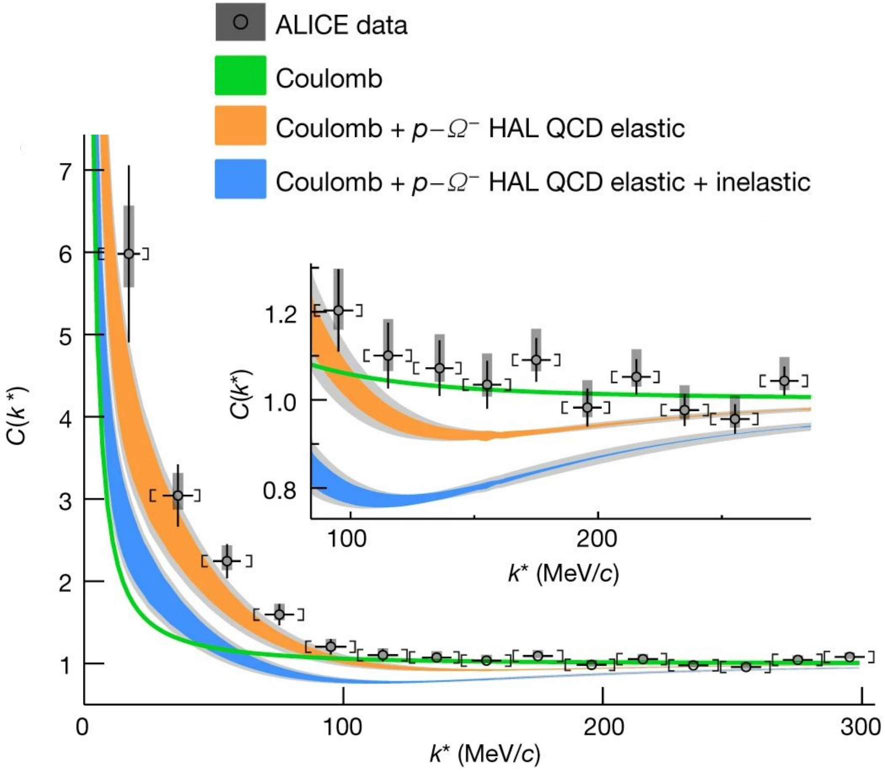
$^3S_1$ channel not calculated:
Could be influenced by inelastic channels NΩ →ΛΞ, ΣΞ

Predicts the formation of a p–Ω⁻ di-baryon

⇒ depletion in the correlation function

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

p–Ω⁻ correlation function in pp at 13 TeV



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

- **Data more precise** than lattice calculations
  ⇒ First constraints in the S=-3 sector
- So far, **no indication of a bound state**
  No visible depletion of C(k*)

Uncertainty of calculations:
→ Two extreme assumptions for the $^3S_1$ channel
- Attractive as $^5S_2$
- Dominated by **inelastic channels**

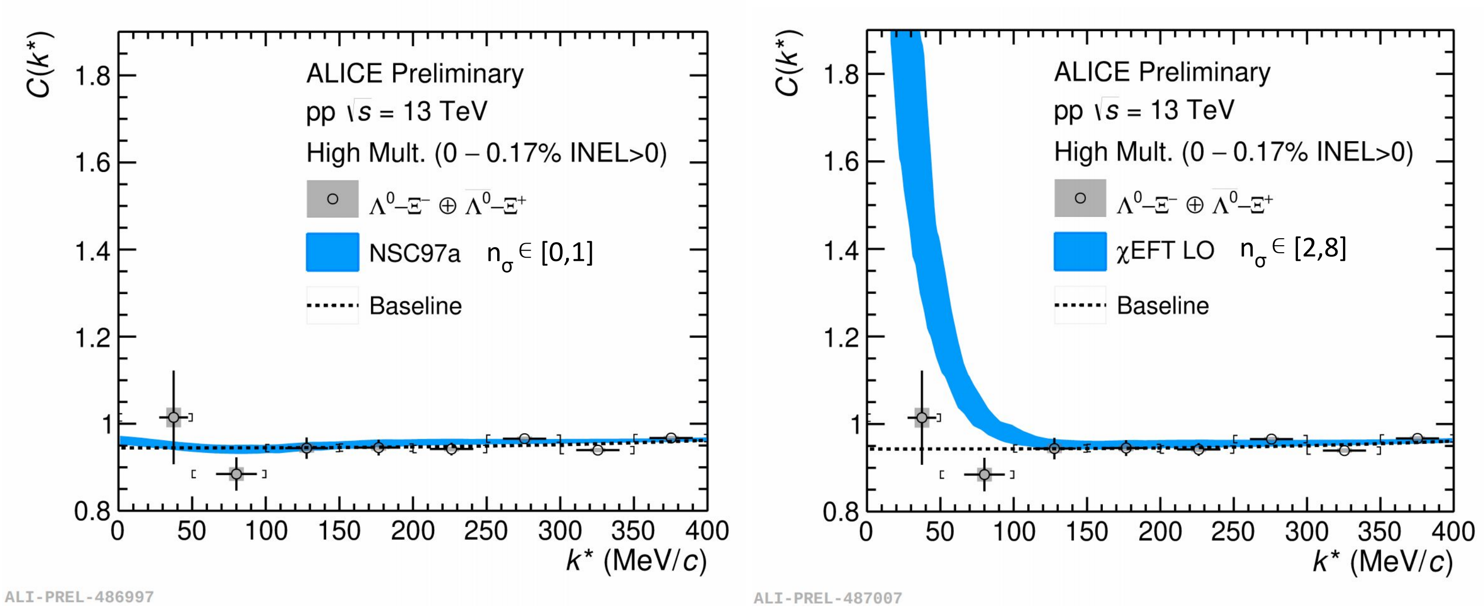
First measurement of the Λ–Ξ⁻ correlation function

ALICE data compared with EFT and meson exchange model

J. Haidenbauer and U.-G. Meissner, Phys. Lett. B 684 (2010) 275–280
Th. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59 (1999) 21

⇒ **Suggests shallow strong interaction**

⇒ Decrease of theoretical uncertainty of NΩ coupling



$r_{gauss} = 1.03$ fm
$\lambda_{\Lambda\Xi} = 0.36$

Outlook

The LHC provides precise testing of the hadron-hadron interaction at distances lower than 1 fm.

Femtoscopy data provide unprecedented constraints on hadron-hadron interactions

→ We test lattice calculations
→ We can study bound states
→ We provide constraints to the equation of state of neutron stars

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Since last MESON conference:

- ALICE Coll. PRL 123, 112002 (2019) p-Ξ
- ALICE Coll. PLB 797, 134822 (2019) Λ-Λ
- ALICE Coll. PRL 124, 092301 (2020) p-K
- ALICE Coll. PLB 805, 135419 (2020) p-Σ^0
- ALICE Coll. PLB 811, 135849 (2020) p-p, p-Λ
- ALICE Coll. Nature 588, 232–238 (2020) p-Ξ, p-Ω
- ALICE Coll. arXiv:2104.04427 (2021, submitted to PRL)p-Λ
- ALICE Coll. arXiv:2105.05578 (2021, submitted to PRL)p-ϕ
- ALICE Coll. arXiv:2105.05190 (2021, submitted to PRL)B-antiB
- Preliminary 2021 p-d
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Data from **Run 3 and Run 4 of the LHC** will provide many more possibilities

THANK YOU!