Recent Measurements of Hadron Interactions from Heavy-ion Collisions

Neha Shah

Indian Institute of Technology Patna, India

Outline:

- **Motivation**
- **Recent measurements:**
  Baryon-Baryon
  Baryon-meson
- **Summary**

Hadron Interactions

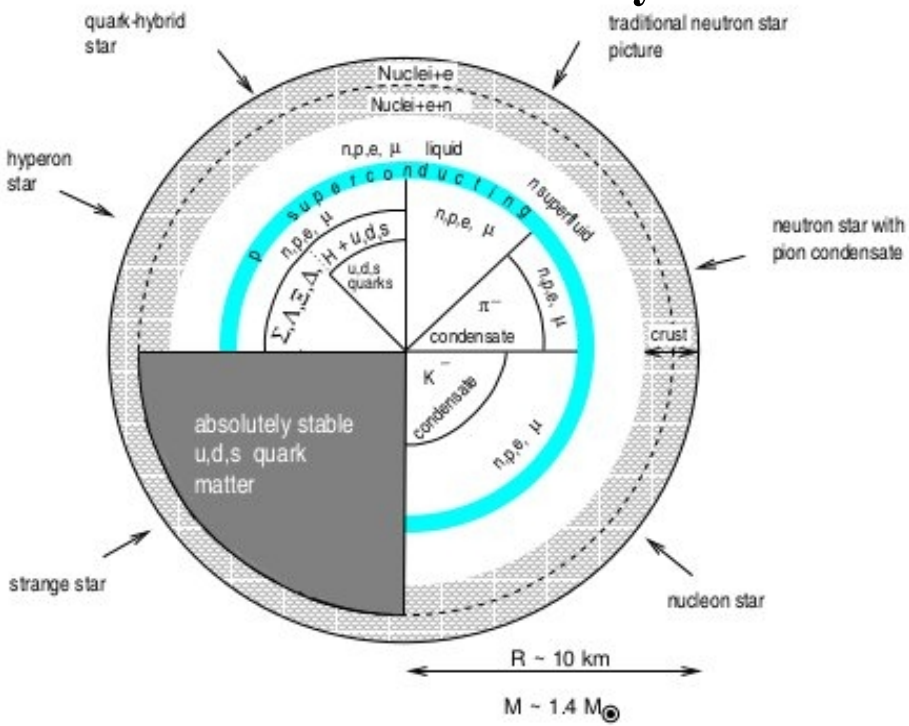
- **Hadron interactions are of fundamental interest in Nuclear Physics and Astrophysics**
- **Hypernuclear interactions - hyperon puzzle in Neutron stars**
- **Understanding production and the structure of hypernuclei**
- **Exotic hadrons (tetraquarks, pentaquark, dibaryons) – long standing challenge in hadron physics**

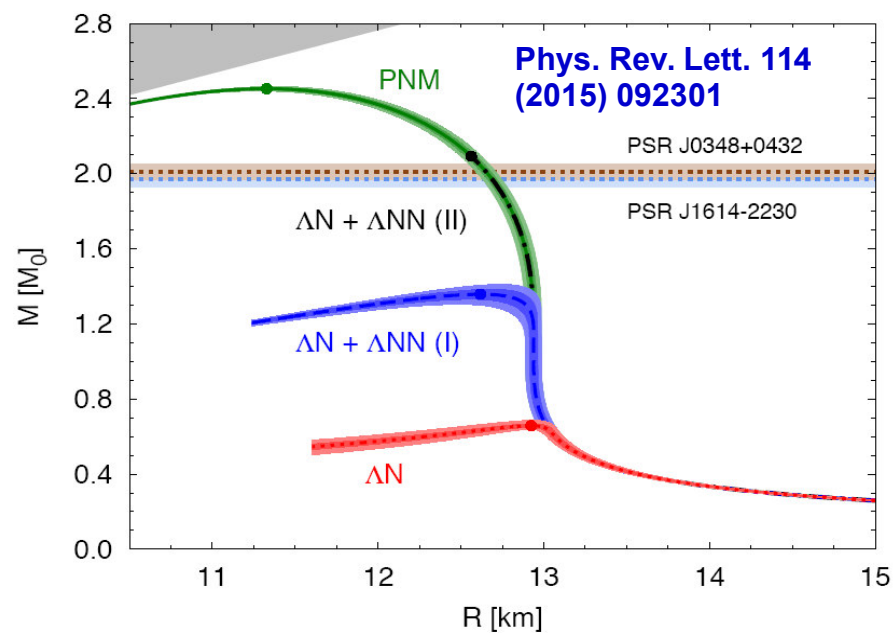
Hyperon Puzzle in Neutron Stars (NS)

- **Many hyperonic matter EOS models predict the presence of hyperons (Y) in the NS core and gives $M_{max} < 2M_{\odot}$, incompatible with measured NS masses**

- **This baffling problem likely originates from our incomplete knowledge (model dependence) of the hypernuclear interactions.**

- **Need for new experimental data to improve understanding of YN, YY two-body interaction and three-body forces: YNN, YYN, YYY**

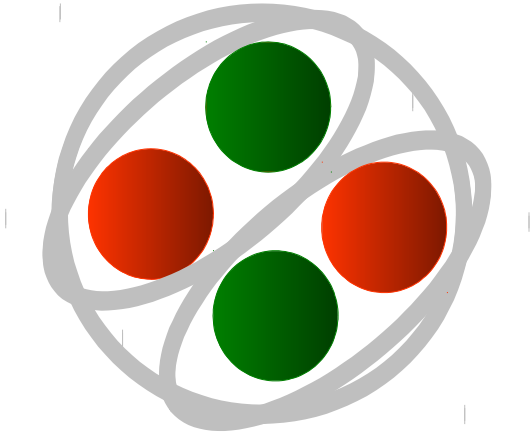




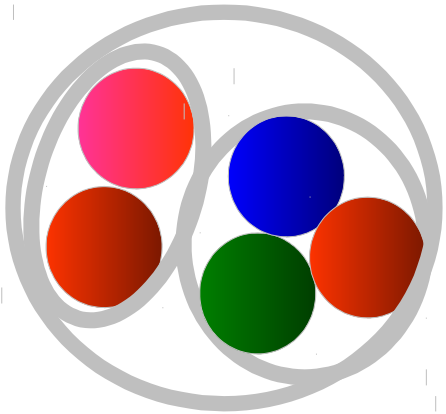
Exotic Hadrons

- **Within Standard Model, baryons are made up of 3 quarks and mesons are made up of a pair of quark-antiquark**
- **1977: using the Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss)** **(Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977))**
- **Exotic hadrons – long standing challenge in hadron physics**

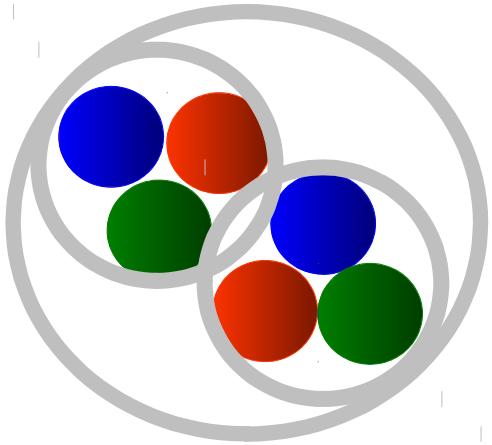
Tetraquark
Meson-Meson molecule



Pentaquark
Meson-Baryon molecule

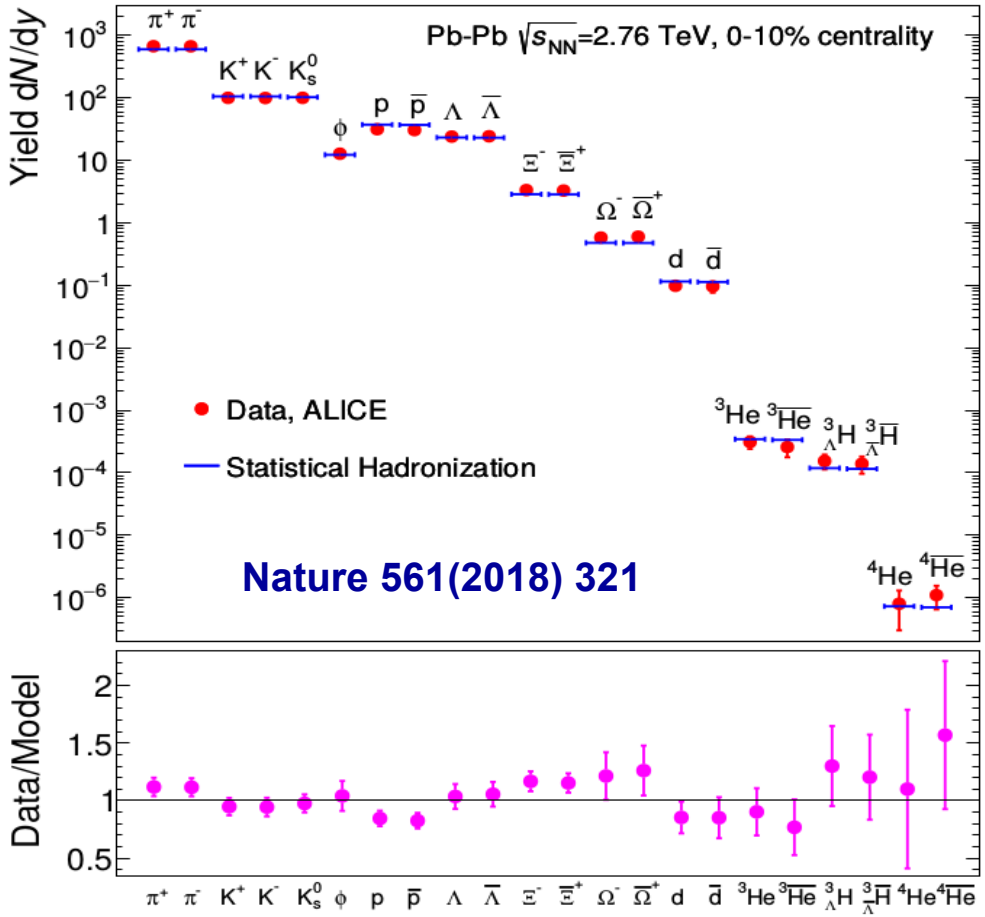


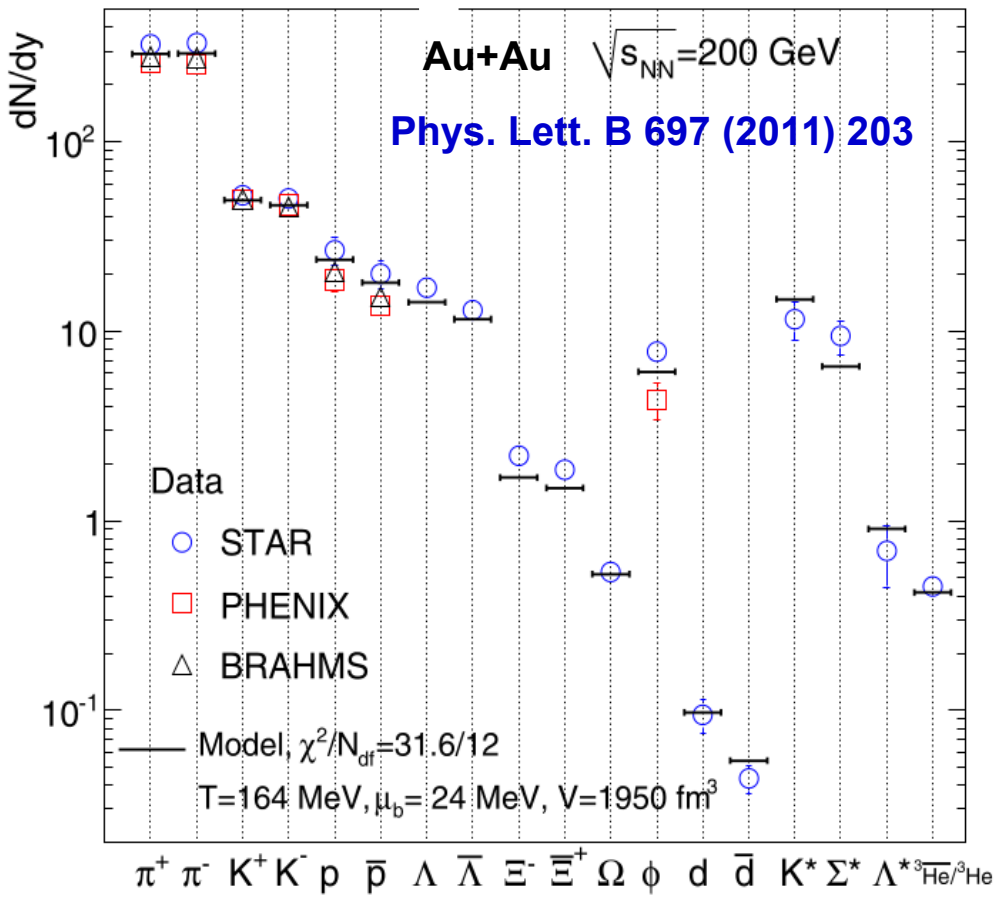
Hexaquark
Baryon-Baryon molecule



Baryons in HIC

- Hot and dense, strongly interacting partonic matter
- Comparable number of baryons and anti-baryons are produced in HIC





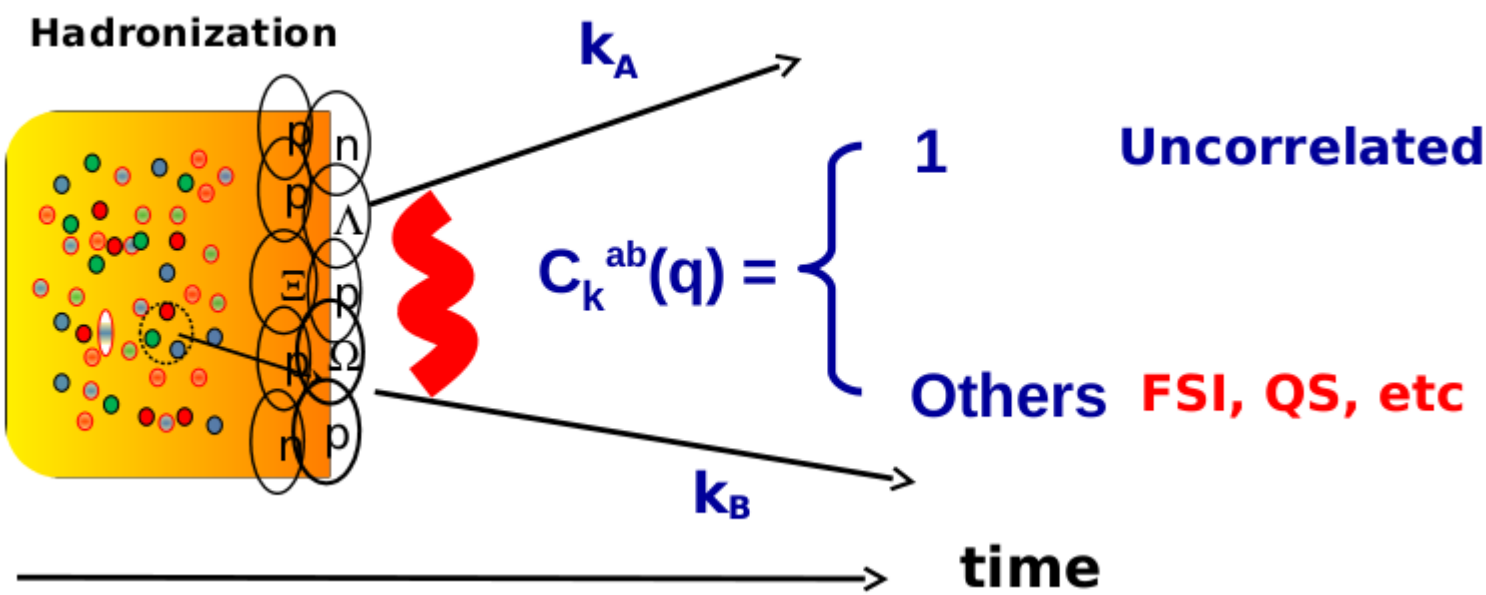
Two-particle Correlation Function

Femtoscopy: Probe the spatial and temporal extent of particle emitting source

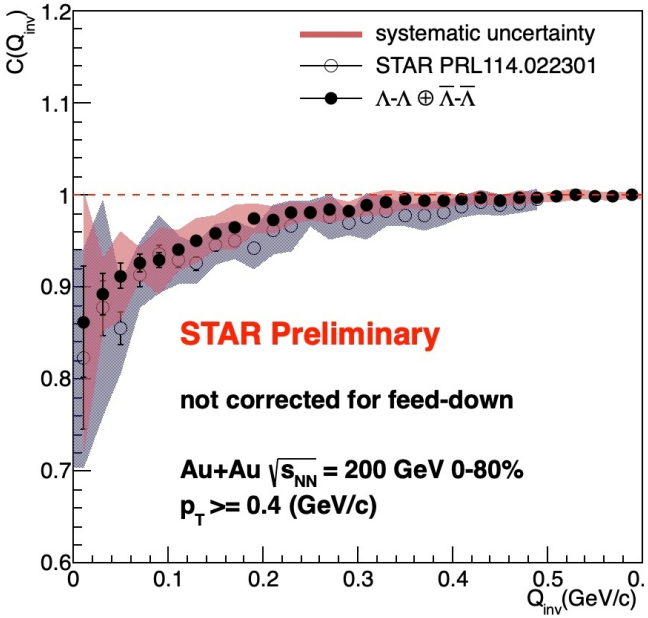
$$C_{\vec{K}}^{ab}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3 dp_b^3)}{(d^3N^a/dp_a^3)/(d^3N^b/dp_b^3)} = \int d^3\vec{r'} \cdot S_{\vec{K}}^{ab}(\vec{r'}) \cdot \left|f(\vec{q},\vec{r'})\right|^2$$

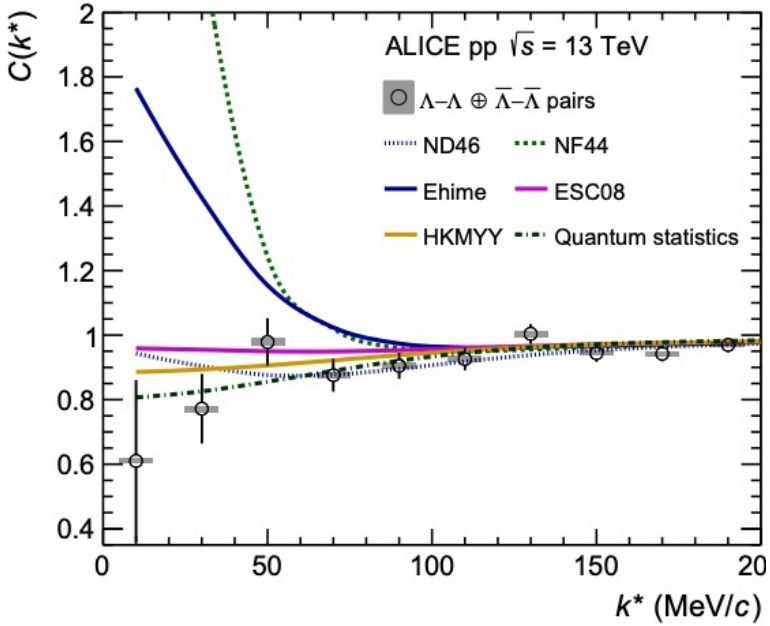
S(r') → normalized separation distribution

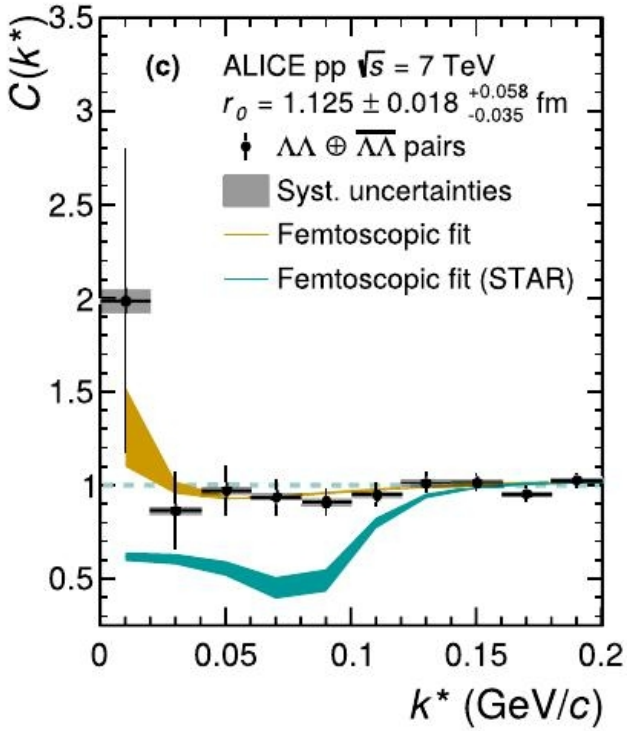
f(q, r') → two-particle wave function, where
(Quantum statistics (QS), FSI: Coulomb int., Strong int.)

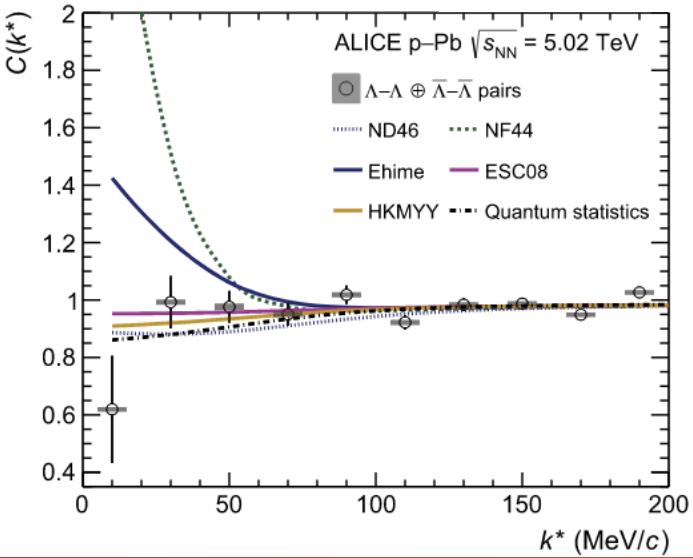


ΛΛ Correlation Function









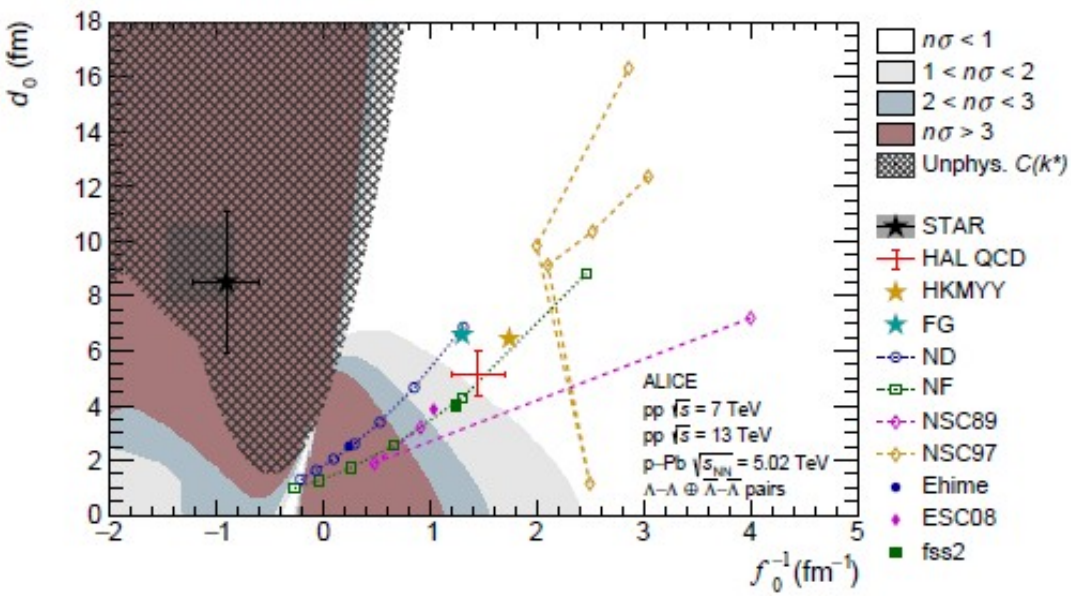
An attractive interaction allows to describe both STAR and ALICE experiment data

STAR Collaboration, Phys. Rev. Lett. 114 (2015) 022301

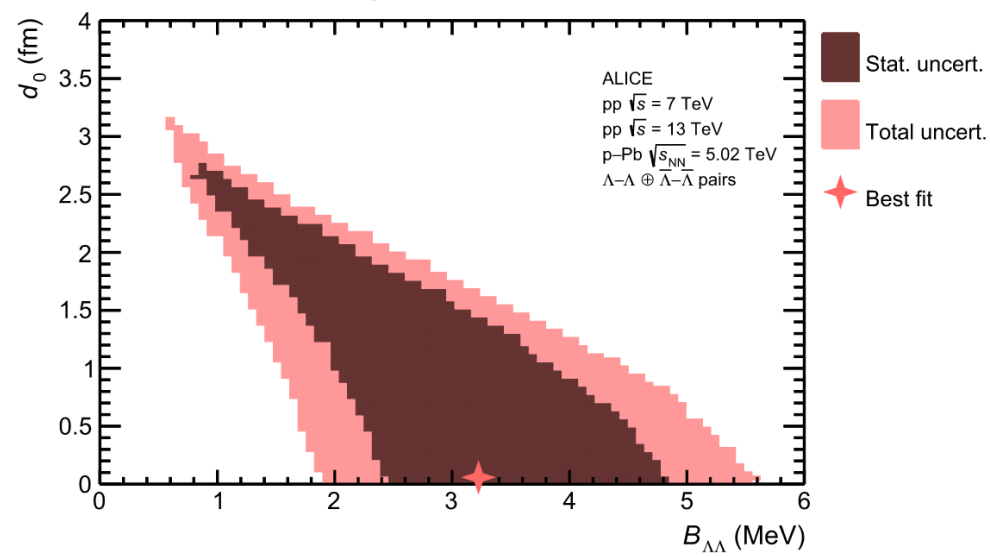
ALICE Collaboration, Phys. Rev. C 99 (2019) 024001
ALICE Collaboration, Phys. Lett. B 797 (2019) 134822

ΛΛ Correlation Function

- The scattering length is constrained to $f_0^{-1} < 0.8\ \mathrm{fm}^{-1}$
- A shallow attractive potential is in very good agreement with the experimental results
- The bindding energy, $B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\mathrm{stat})^{+1.8}_{-1.0}(\mathrm{syst})\ \mathrm{MeV}$
- Larger statistics data-sets at RHIC and LHC to yield a conclusive answer

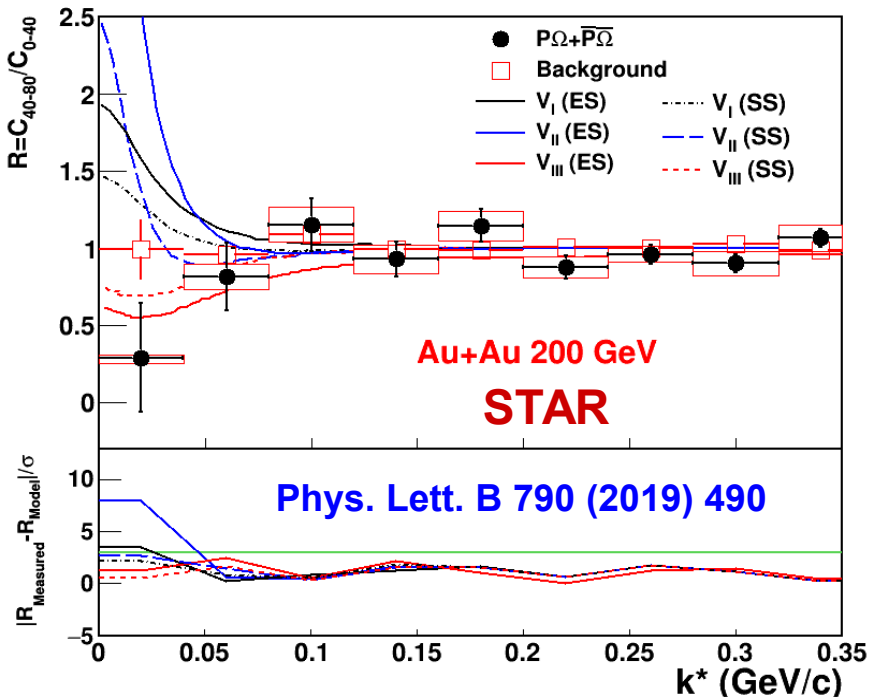


$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1 - \sqrt{1 + 2 d_0 f_0^{-1}}\right)^2 .$$



ALICE Collaboration, Phys. Lett. B 797 (2019) 134822

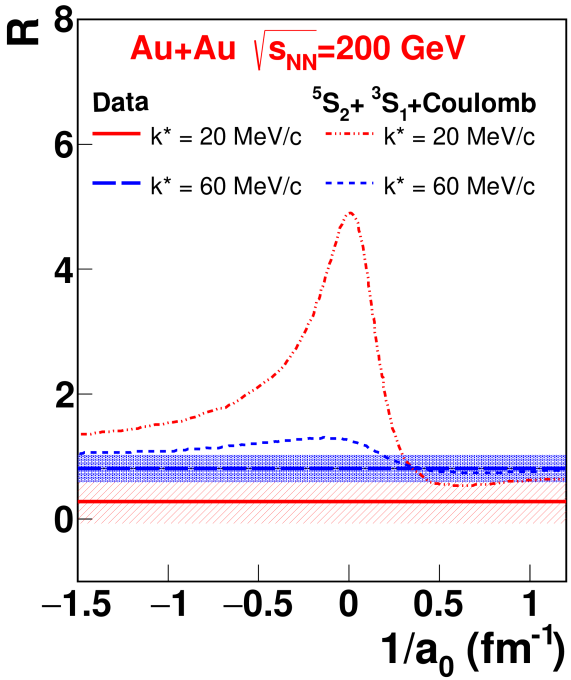
Proton-Ω Correlation Function



SS → Static source
ES → Expanding source
Background → Ω sideband is used
Boxes → systematic uncertainty

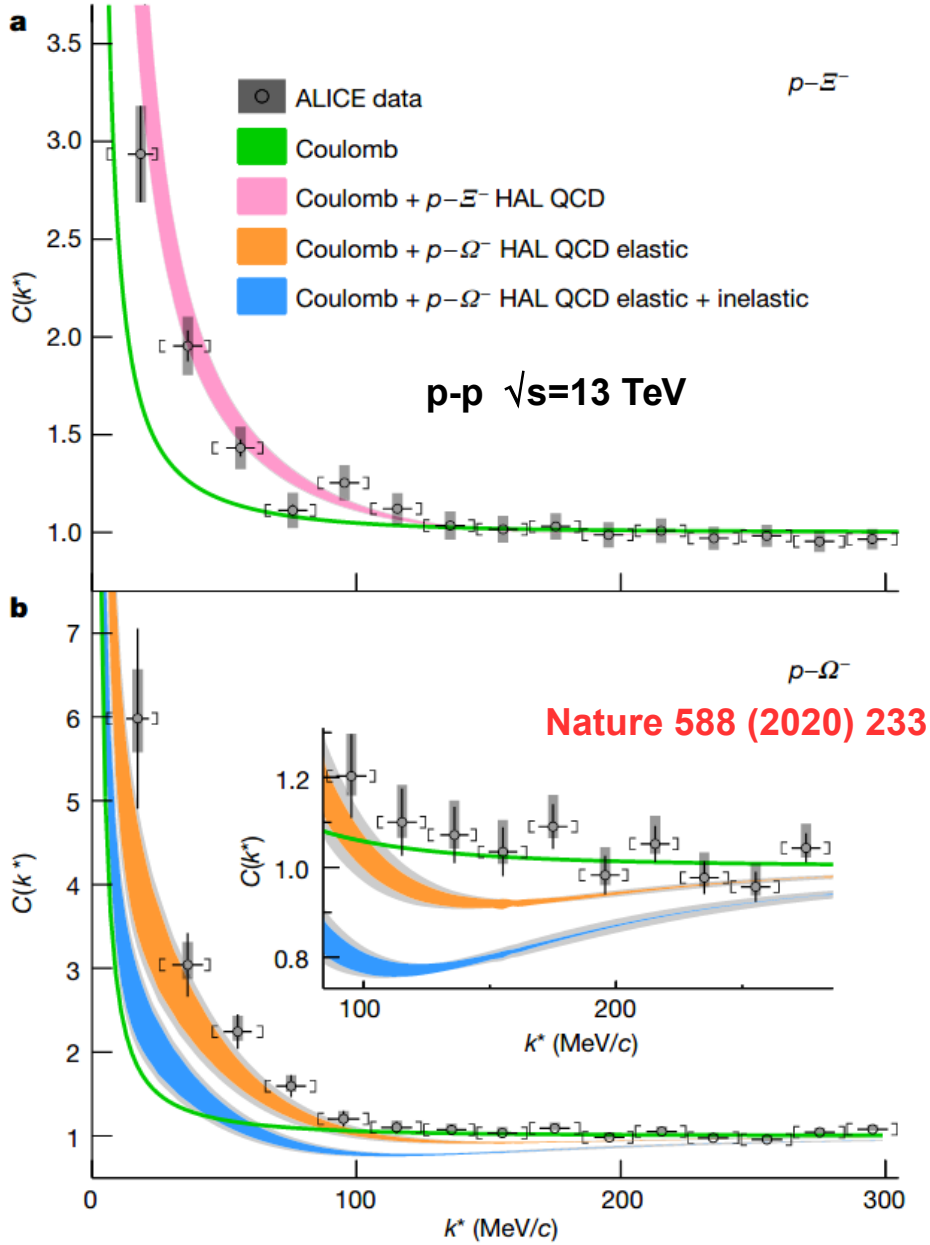
Spin-2 PΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

- ✓ The ratio of correlation function for the small (peripheral collisions) to large (central collisions) system is smaller than unity at low relative moment.
- ✓ Measurement supports the existence of a deeply bound state decaying into the proton Ω final state.



K. Morita et al., Phys. Rev. C 94, 031901 (2016)

Proton-Ω Correlation Function



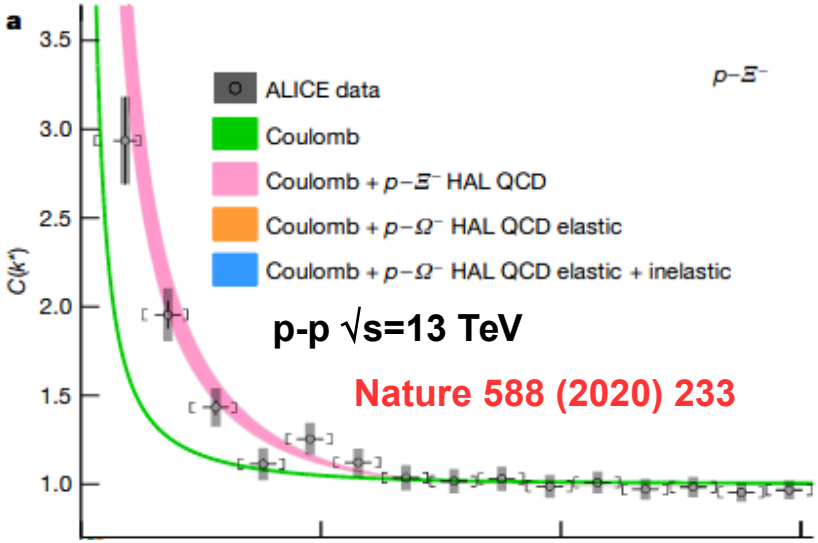
- **An attractive interaction exists and exceeds the strength of the Coulomb interaction.**

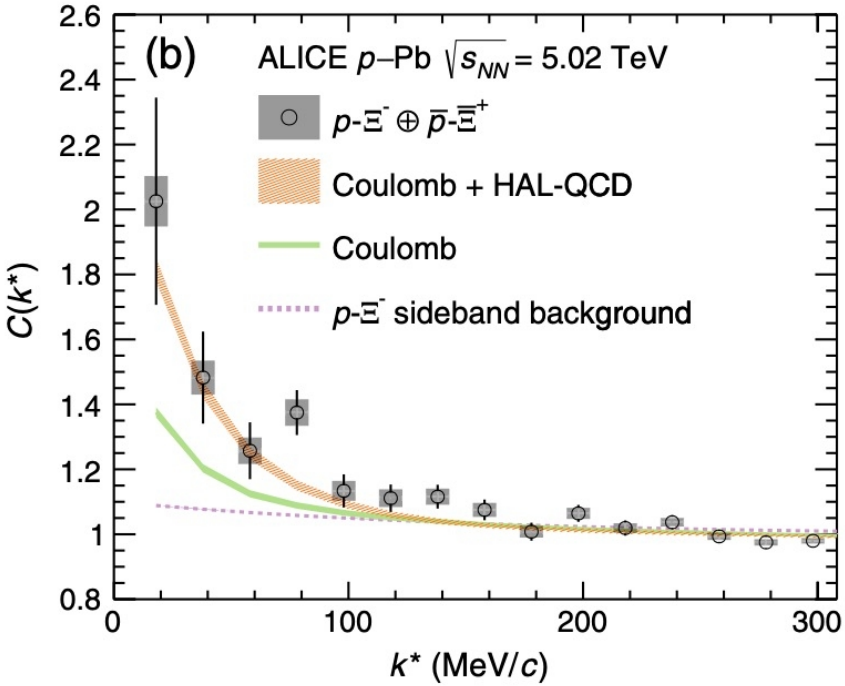
- **The theoretical calculations predict the existence of a p–Ω⁻ bound state with a binding energy of 2.5 MeV, which causes a depletion in the correlation function in the k* region between 100 and 300 MeV/c.**

- **The lattice QCD predictions underestimate the data.**

- **Additional measurements are necessary to draw a firm conclusion on the existence of the bound state.**

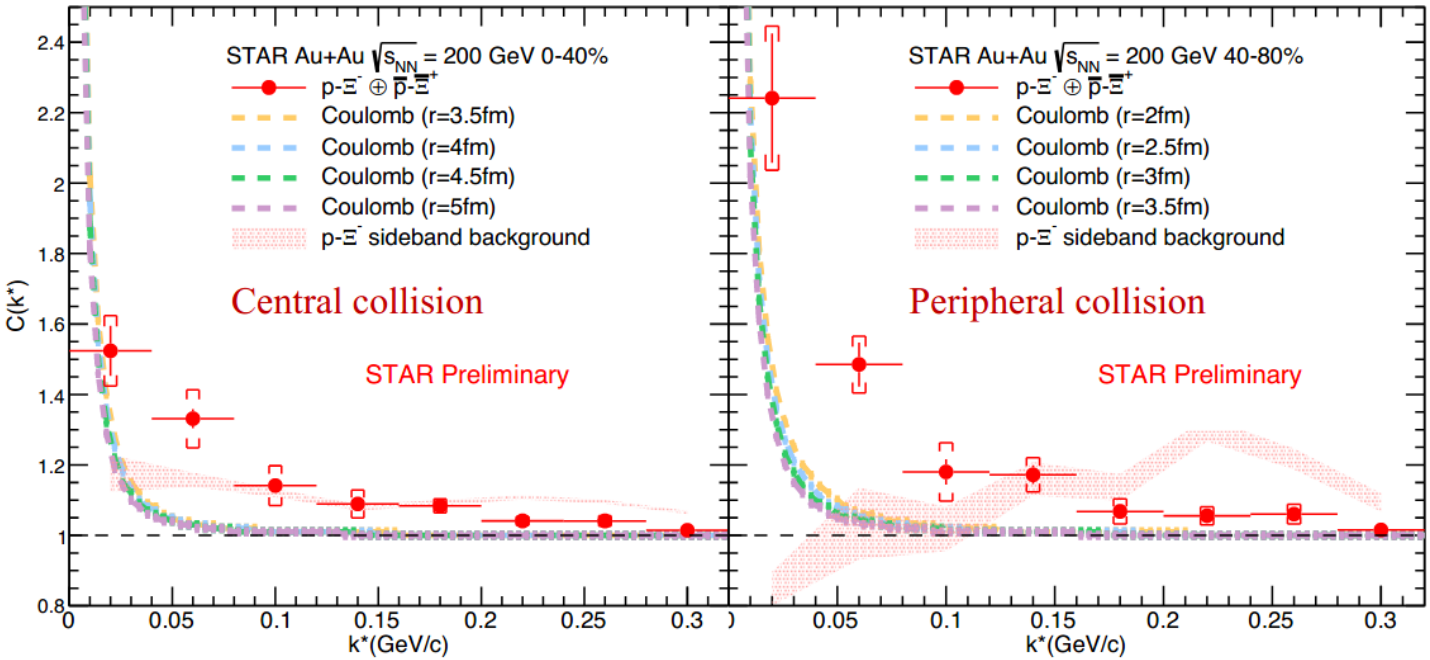
Proton-Ξ Correlation Function





- The measured p-Ξ correlation function show deviation from expection based on the Coulomb interactions.
- An attractive p-Ξ strong interaction is observed.
- The p-Ξ interactions from HAL-QCD collaboration are found to be consistent with the measurement.

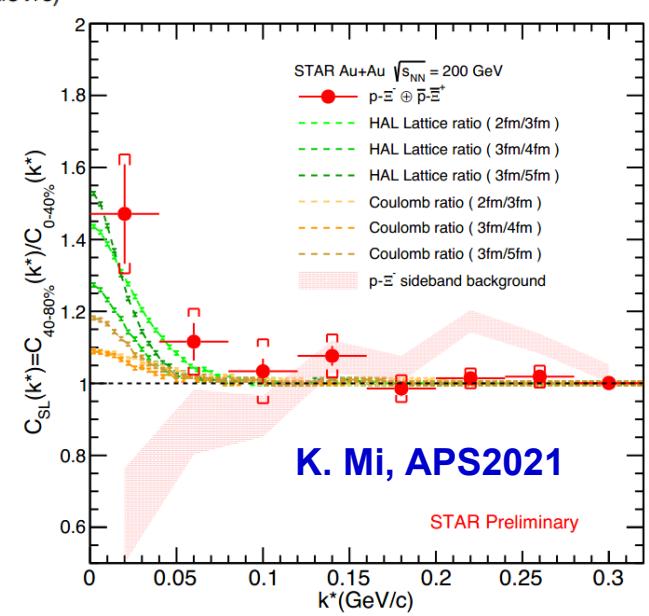
Proton-Ξ Correlation Function



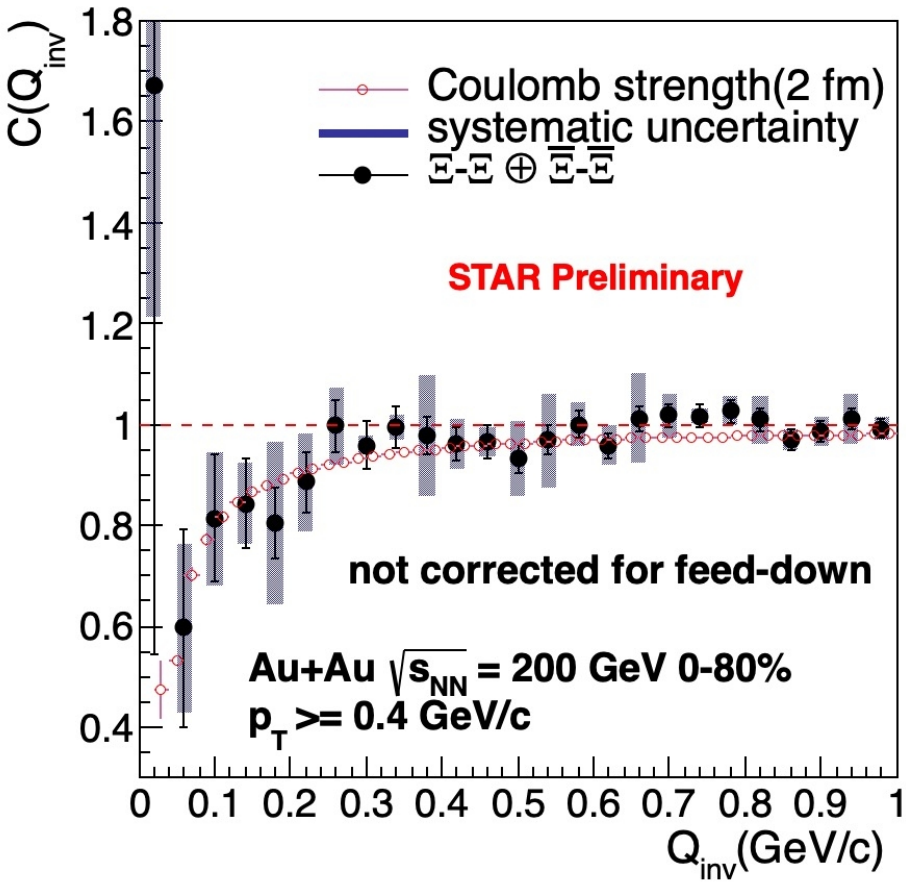
- **The measured p-Ξ correlation function show deviation from expection based on the Coulomb interactions.**

- **An attractive p-Ξ strong interaction is observed.**

- **The ratio of p-Ξ correlation function for the perpheral to central collisions is consistent with the p-Ξ interactions from HAL-QCD collaboration.**



Ξ–Ξ Correlation Function



M. Isshiki, Talk on Tuesday

- **Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state.**

- **The result shows anti-correlation at Q_{inv}< 0.25 GeV/c.**

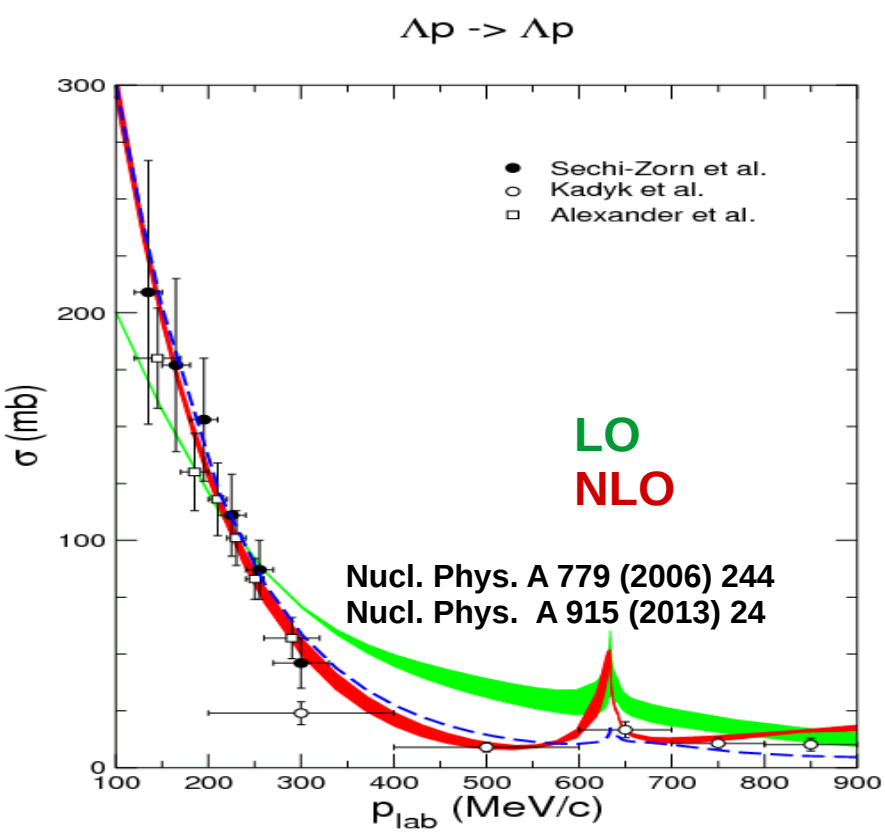
  - qualitatively matches with coulomb strength.

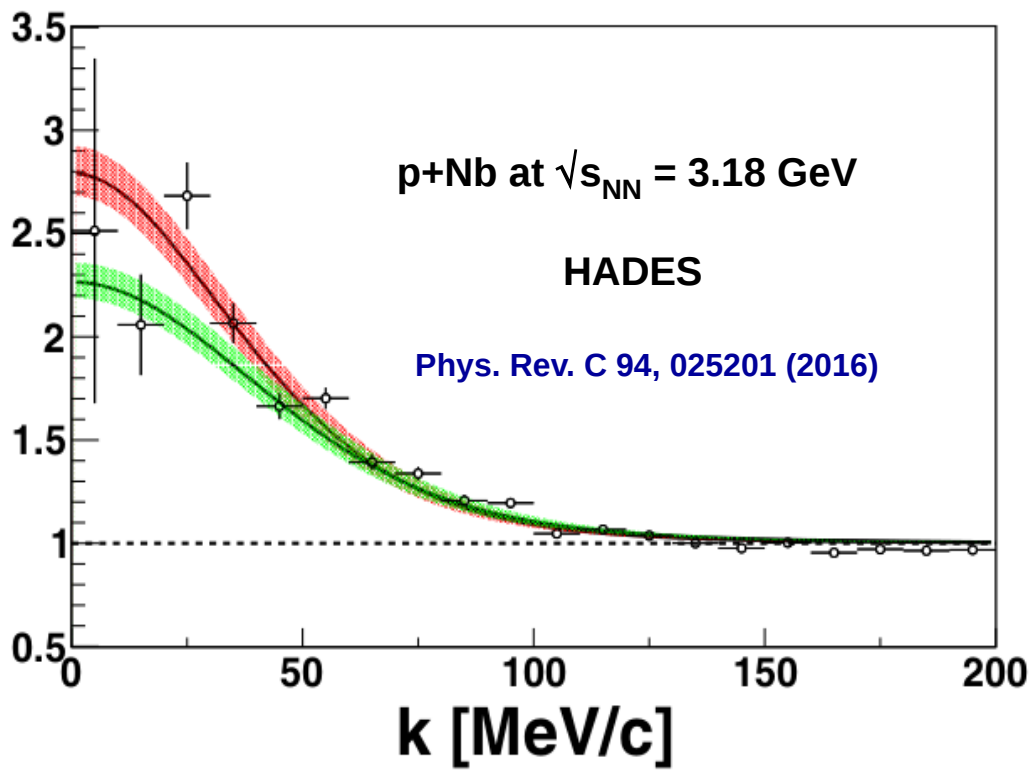
  - to cancel quantum statistics (negative correlation), strong interaction needs to be positive correlation.

Proton-Λ Correlation Function

- Calculations based on chiral effect field theory predicts a repulsive core of the interaction potential for NLO

- Discrimination of the LO and NLO not possible due to the lack of data

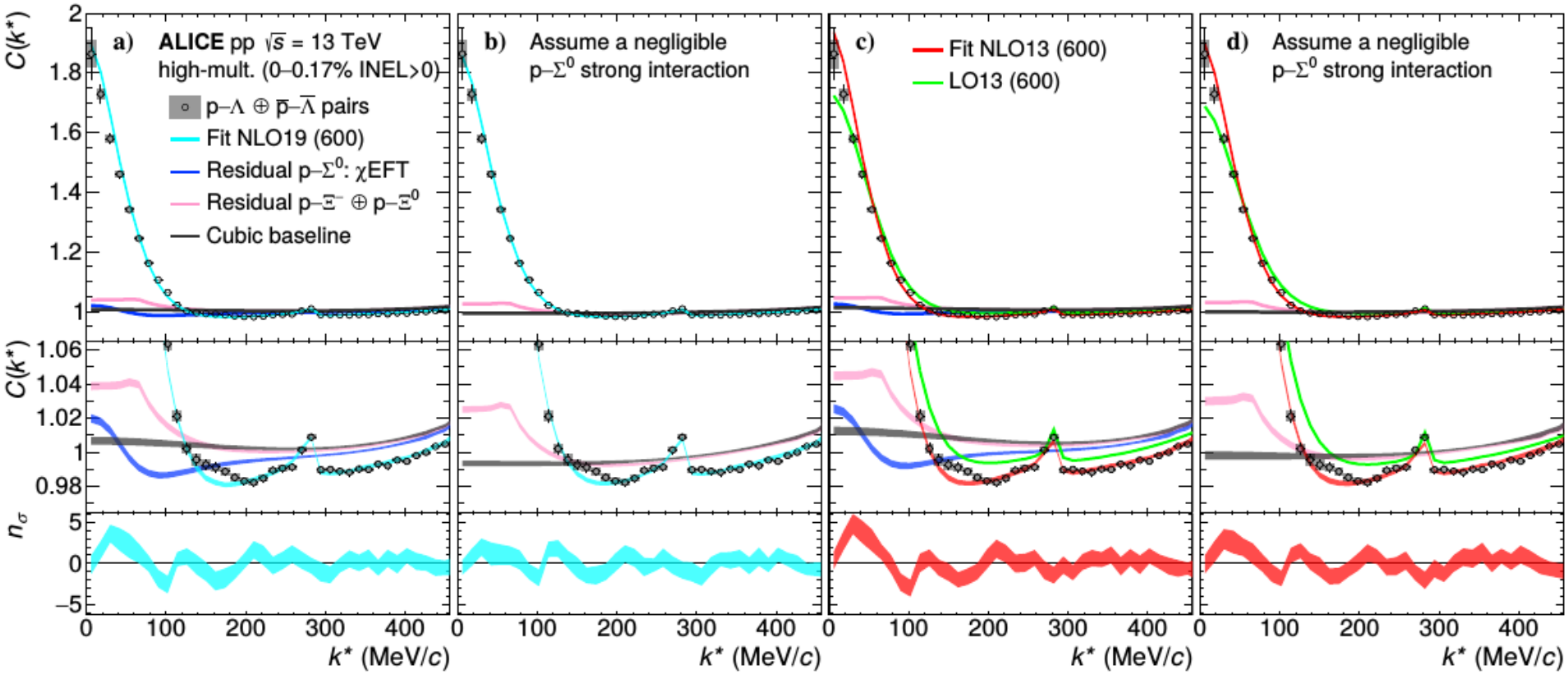




Proton-Λ Correlation Function

- The coupling of pΛ to NΣ is manifested as a cusp-like enhancement present at the corresponding threshold energy.

- **Different modelling for the p–Σ^0 feed-down leads to modification of the measured pΛ correlation, implying an indirect sensitivity to the genuine p–Σ^0 correlation.**



ALICE Collaboration, arXiv:2104.04427

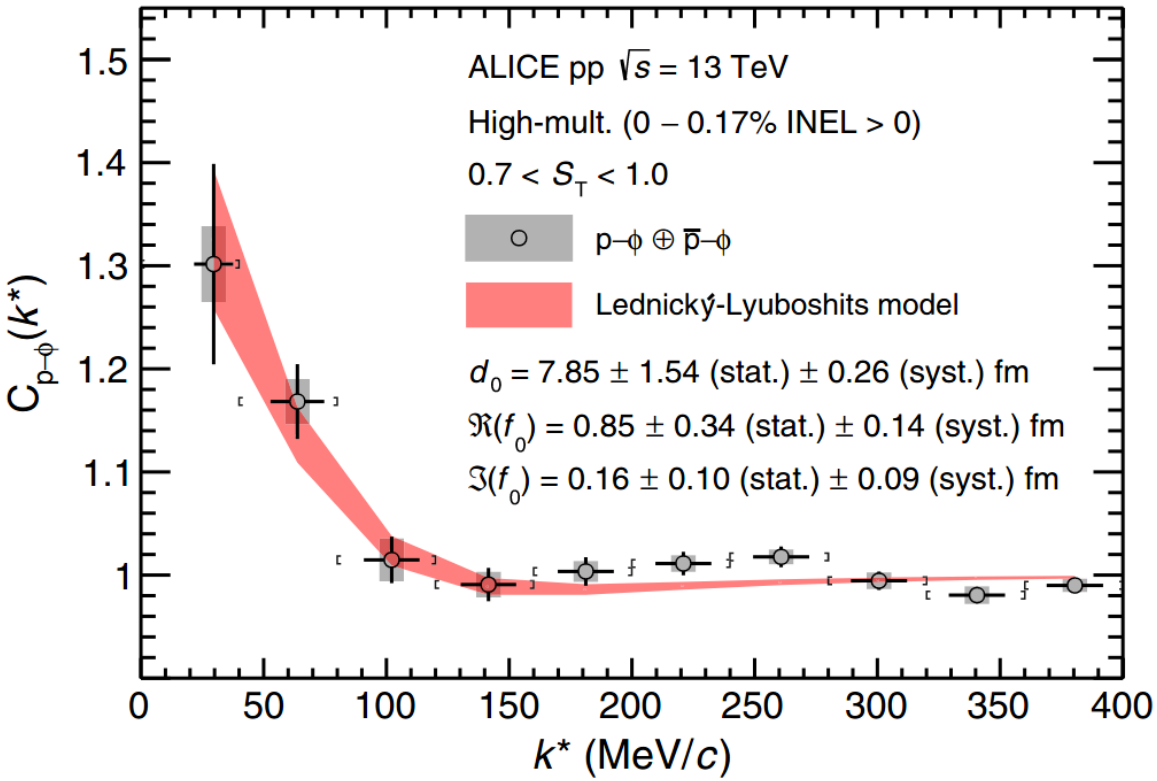
Proton-φ Correlation Function

- The imaginary part of the scattering length vanishes within uncertainties, indicating that inelastic processes do not play a prominent role for the p-φ interaction

- The p-φ interaction in vacuum is attractive and dominated by elastic scattering.

- The N-φ Coupling constant, using Yukawa-type potential, is

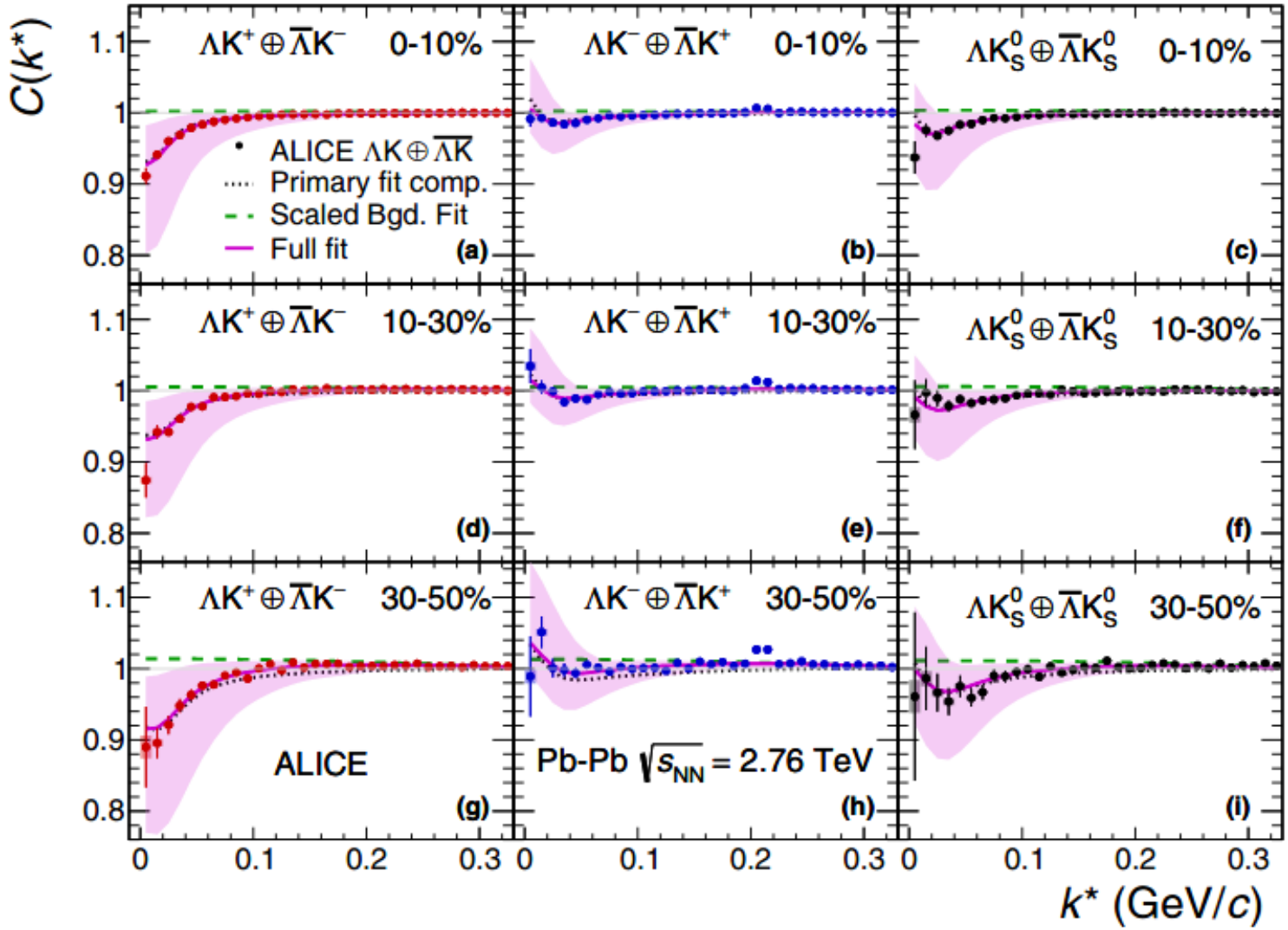
$$g_{N\text{-}\phi} = 0.14 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$$



ALICE Collaboration, Phys. Rev. Lett. 127 (2021) 172301

Λ–Kaon Correlation Function

- The measurement suggest that the ΛK^+ interaction is repulsive, the ΛK^- and ΛK_0^S interaction is attractive.

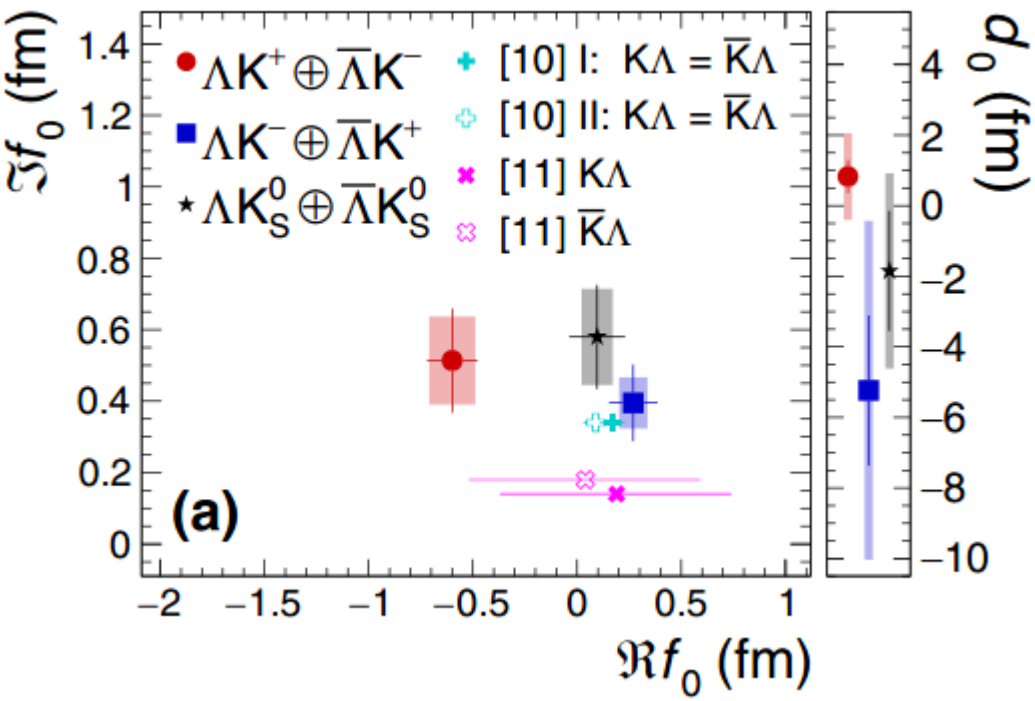


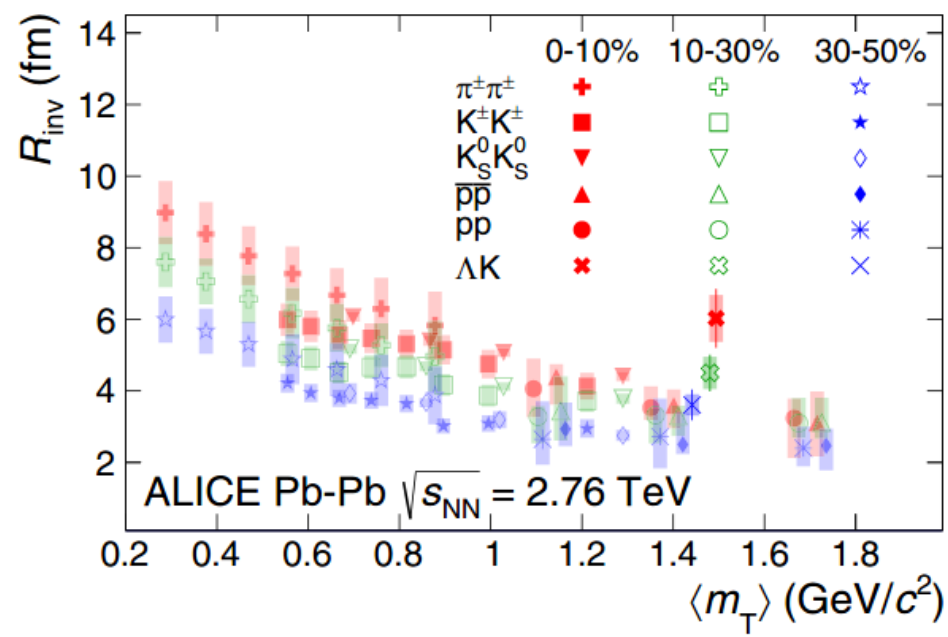
ALICE Collaboration, Phy. Rev. C103 (2021) 055201

Λ–Kaon Correlation Function

- **The ΛK systems source radii is larger than expected from extrapolation from identical particle femtoscopic studies.**

- **The larger radii arising from the separation in space-time of the single particle source distributions of Λ and K.**





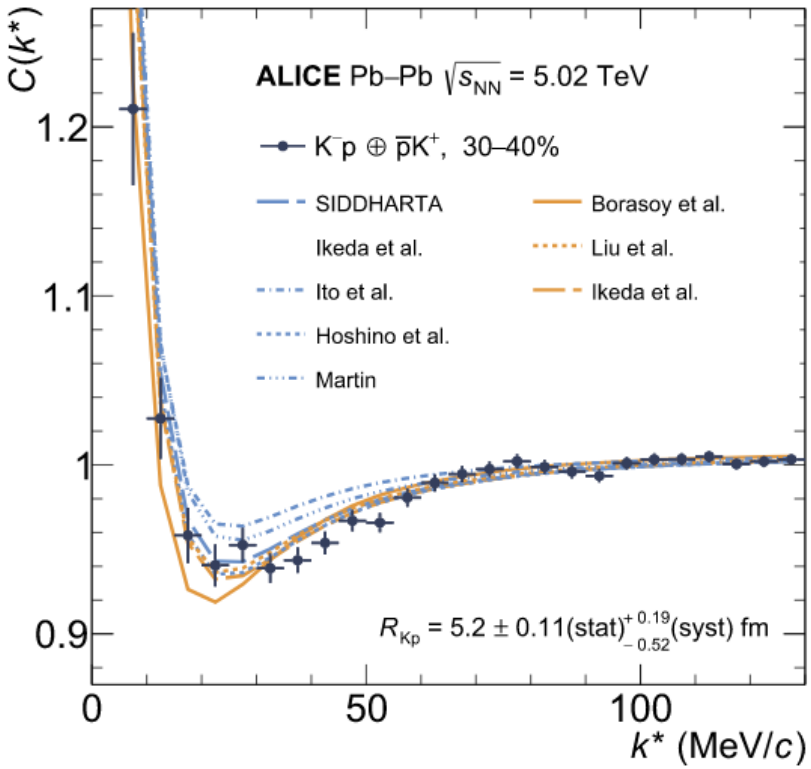
ALICE Collaboration, Phy. Rev. C103 (2021) 055201

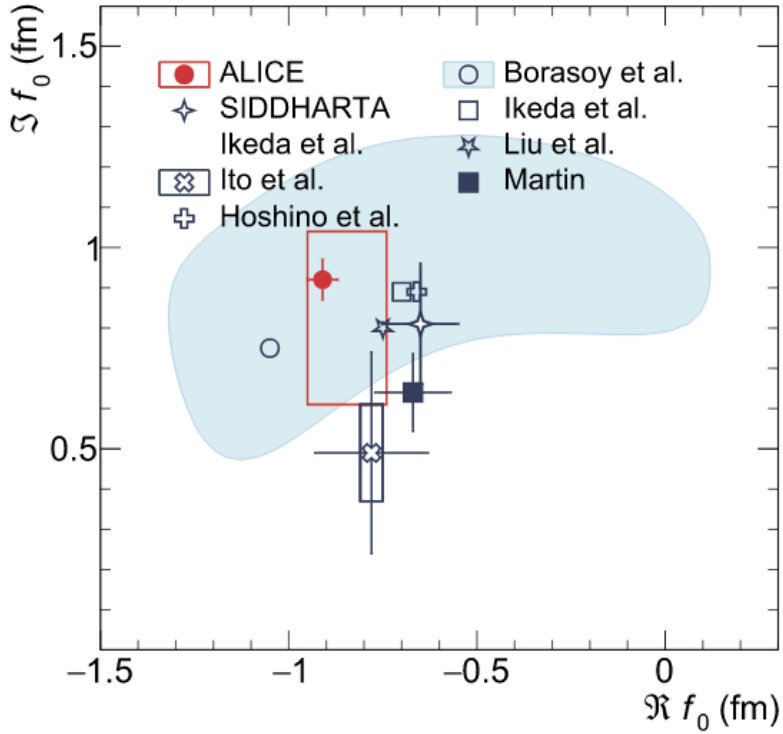
Kaon-Proton Correlation Function

- An accurate measurement of kaon–proton scattering parameters at low relative momentum, allowing precise access to the K−p →K−p process.

- A complementary tool to the study of exotic atoms with comparable precision.

- The obtained scattering length is comparable to the values from scattering and exotic kaonic atoms experiment as well as model calculations.





ALICE Collaboration, Phys. Lett. B 822 (2021) 136708

Summary

- **The femtoscopy measurements from heavy-ion collisions provides a unique opportunity to explore strong interactions and search for exotics.**

- **The upcoming high luminosity Run-3 and Run-4 at LHC and planned data taking for Au+Au at 200 GeV in 2023 and 2025 at RHIC will allow us to significantly improve the precision of the extracted inter-action parameters for many hadron pairs.**

Thank you!