Femtoscopy-for-interactions: a new tool to study low energy QCD

Laura Fabbietti Technische Universität München

FSP ALICE
Erforschung von
Universum und Materie

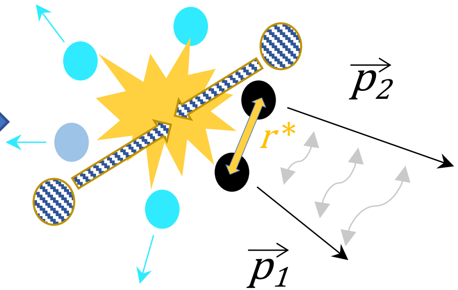
SFB 1258
Neutrinos
Dark Matter
Messengers

ORIGINS
Excellence Cluster

A new tool to study low energy QCD

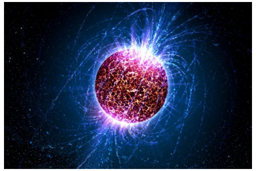
ALICE at the LHC

Femtoscopy in small systems



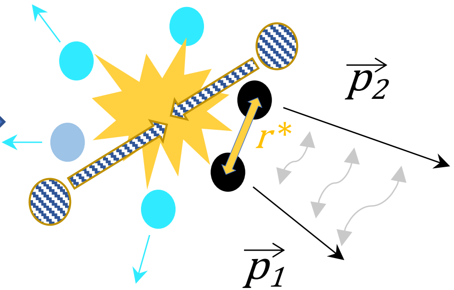
A new tool to study low energy QCD

Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



ALICE at the LHC

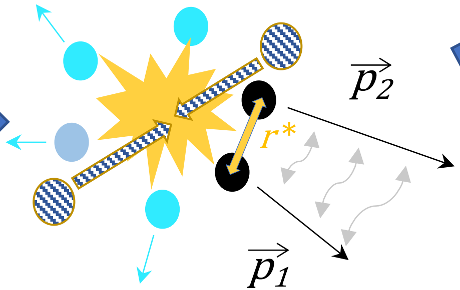
Femtoscopy in small systems



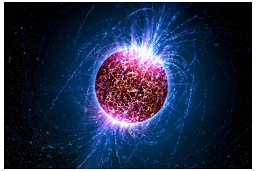
A new tool to study low energy QCD

ALICE at the LHC

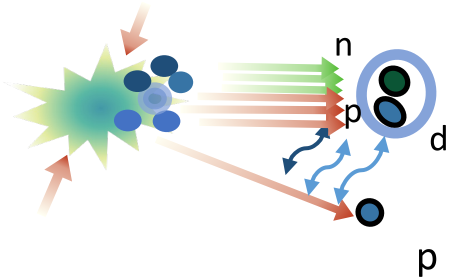
Femtoscopy in small systems



Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



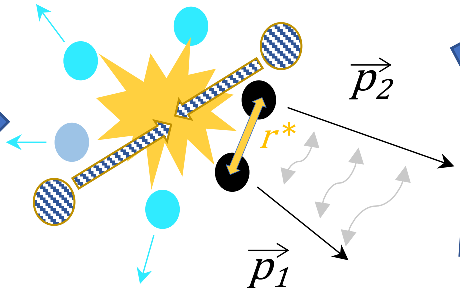
Nuclei formation



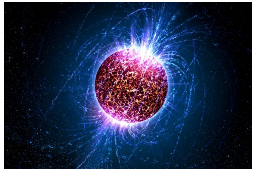
A new tool to study low energy QCD

ALICE at the LHC

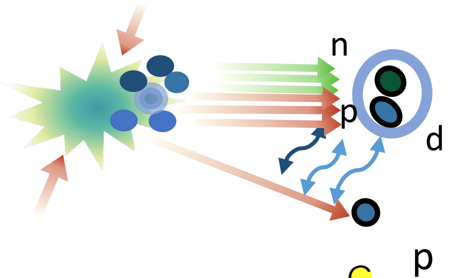
Femtoscopy in small systems



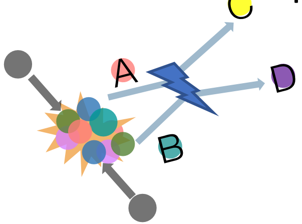
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



Nuclei formation



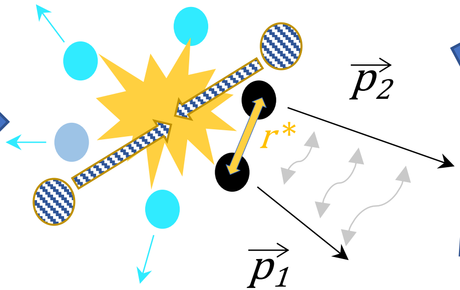
Direct access to coupled channels



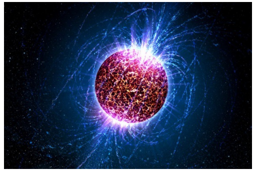
A new tool to study low energy QCD

ALICE at the LHC

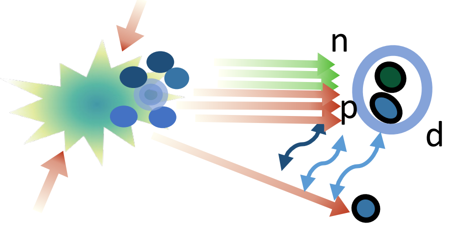
Femtoscopy in small systems



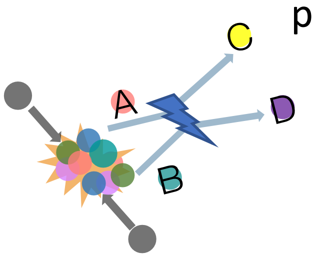
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



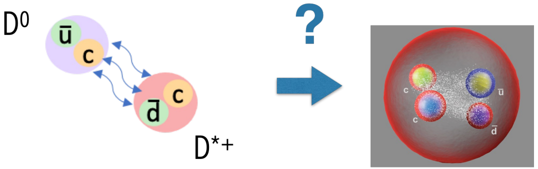
Nuclei formation



Direct access to coupled channels



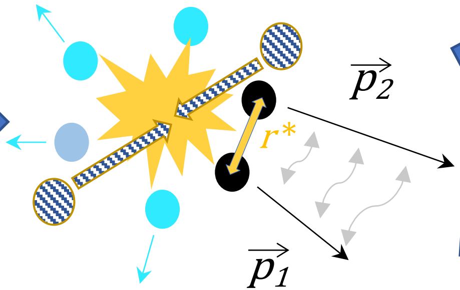
Final state interaction of charmed hadrons



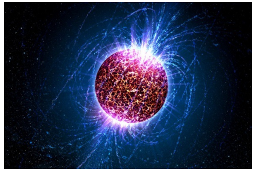
A new tool to study low energy QCD

ALICE at the LHC

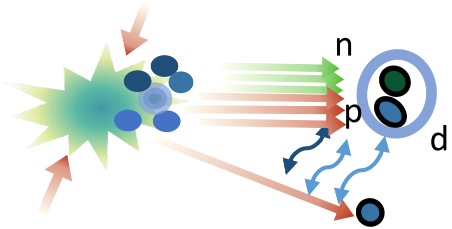
Femtoscopy in small systems



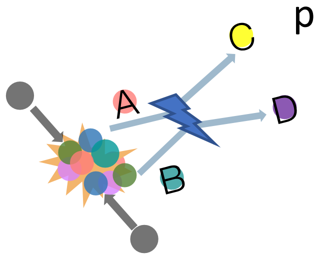
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



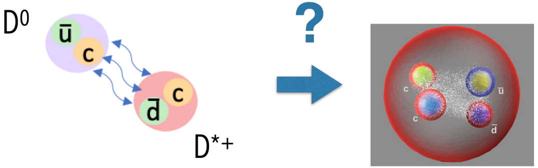
Nuclei formation



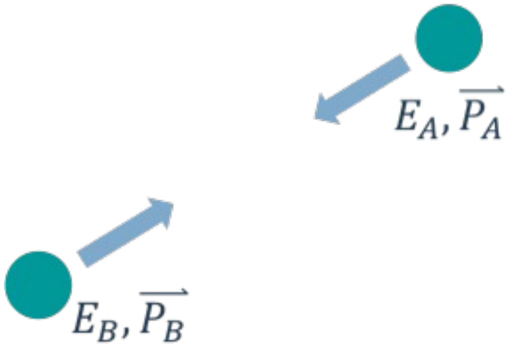
Direct access to coupled channels



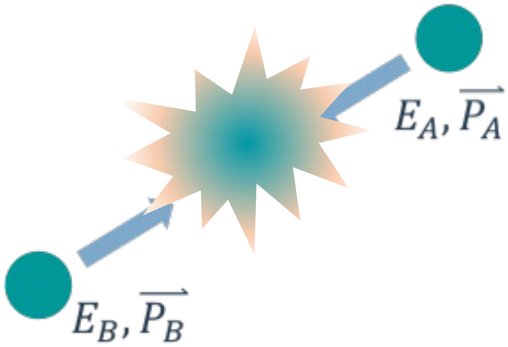
Final state interaction of charmed hadrons



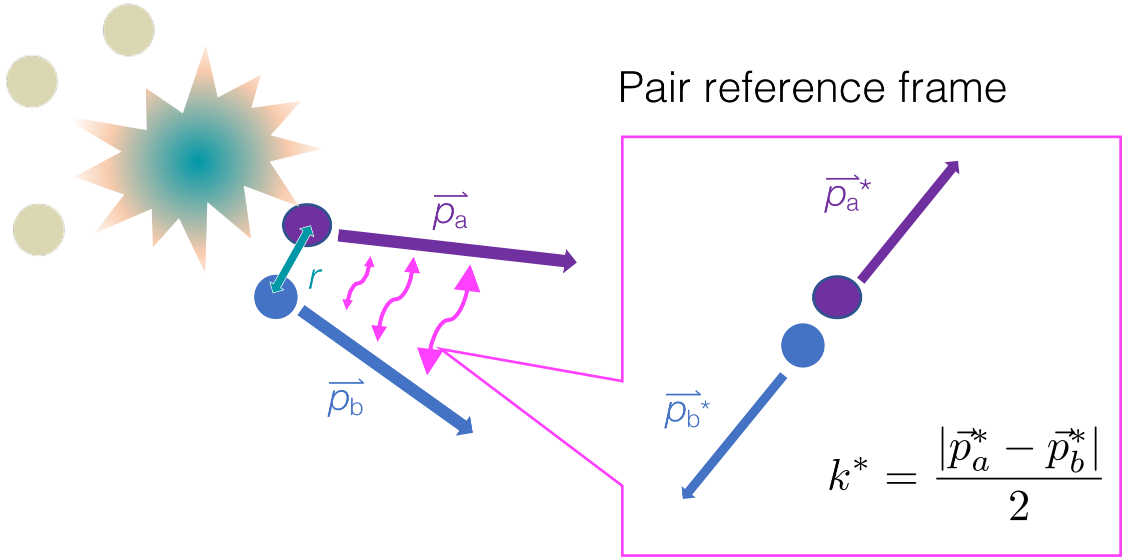
The femtoscopy technique



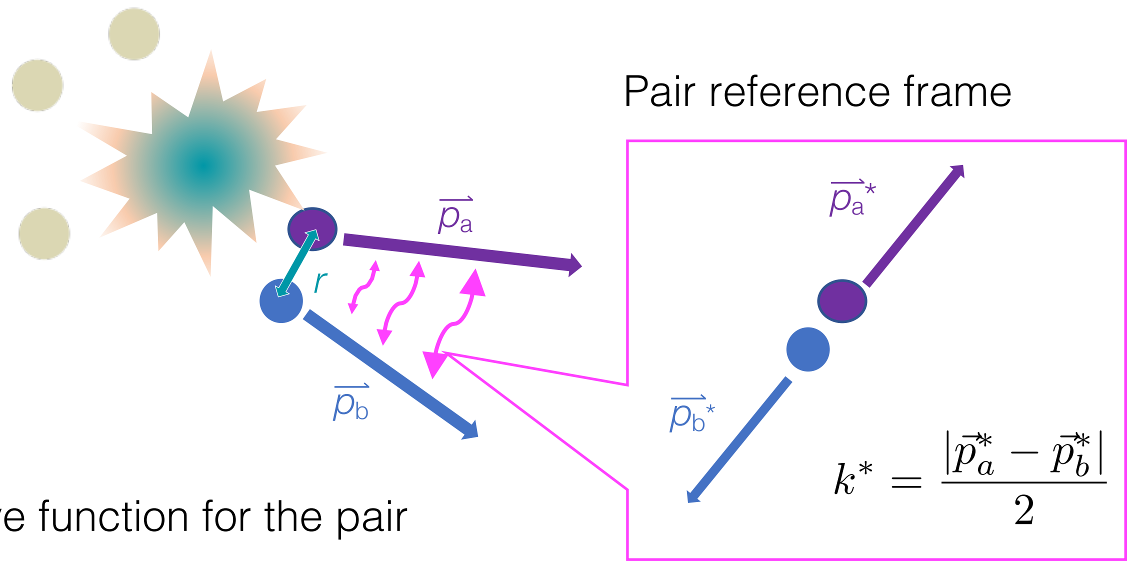
Nuclear collisions



Particle production and propagation



Particle production and propagation

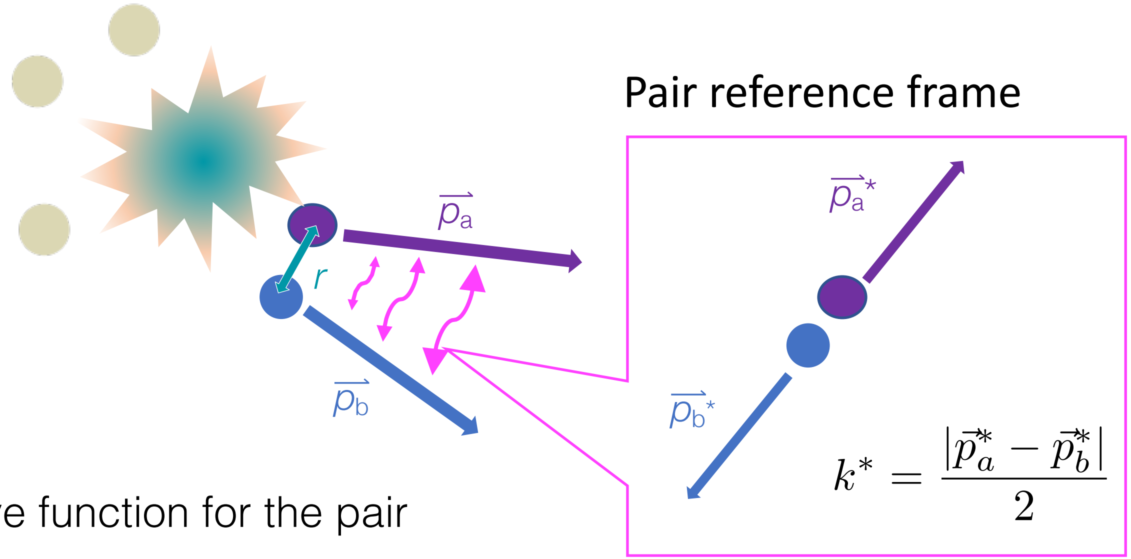


Schrödinger Equation:

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

The Koonin-Pratt formalism

S. E. Koonin, Phys. Lett. B 70, 43 (1977).



Schrödinger Equation:

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

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

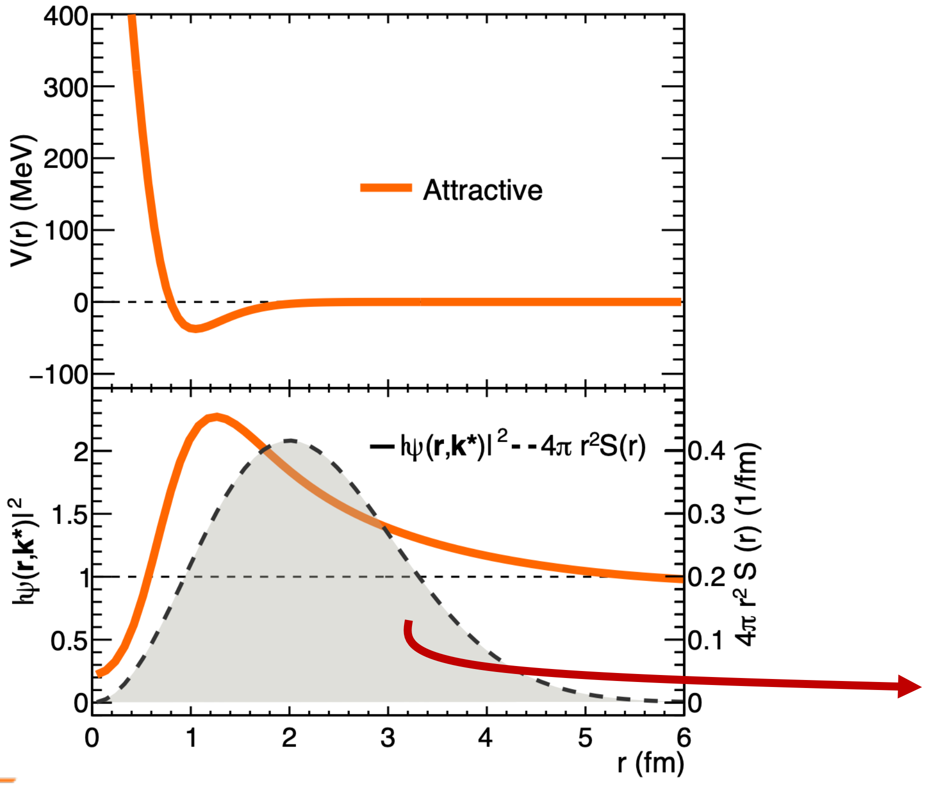
Emission source   Two-particle wave function

CATS (Correlation Analysis Tool using the Schödinger equation)

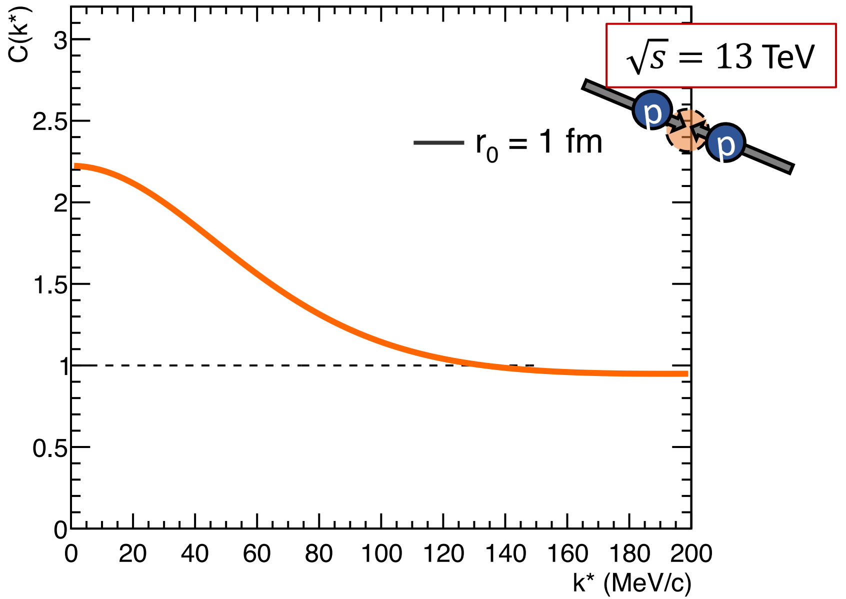
D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

Examples of correlation functions

Predictions obtained using **CATS**



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

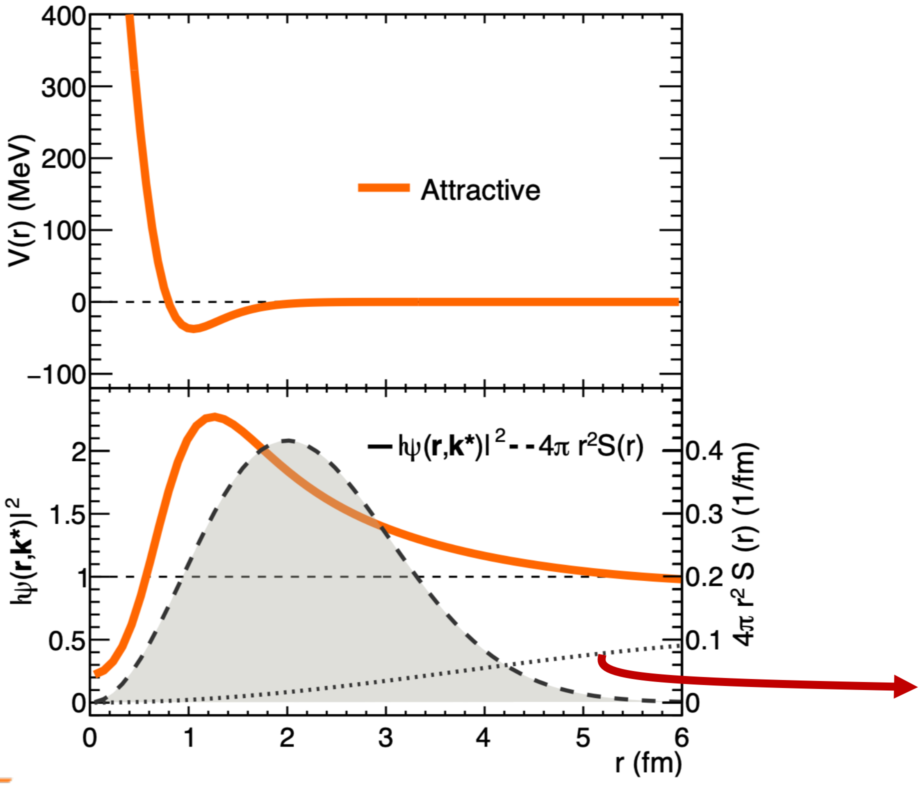


Accessing short-range dynamics in pp collisions

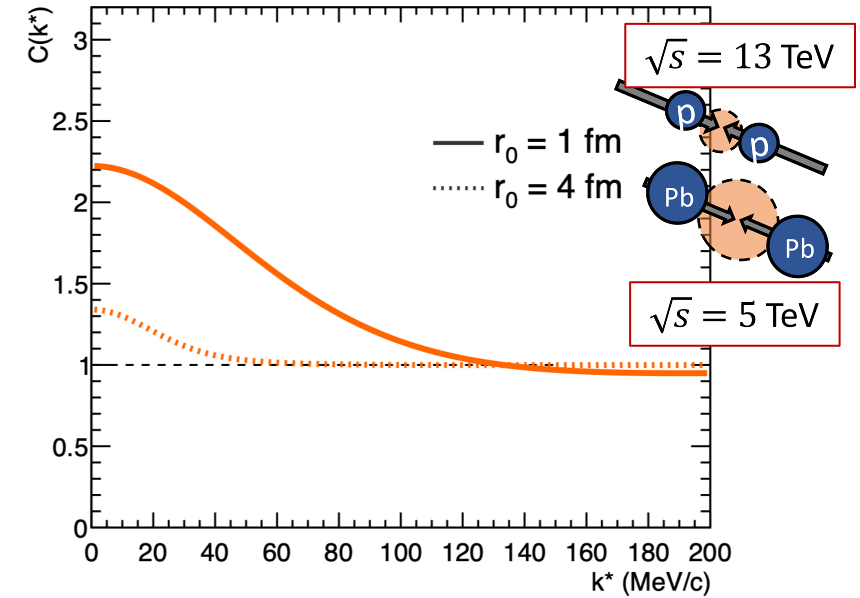
LF, V. Mantovani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

Examples of correlation functions

Predictions obtained using **CATS**



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

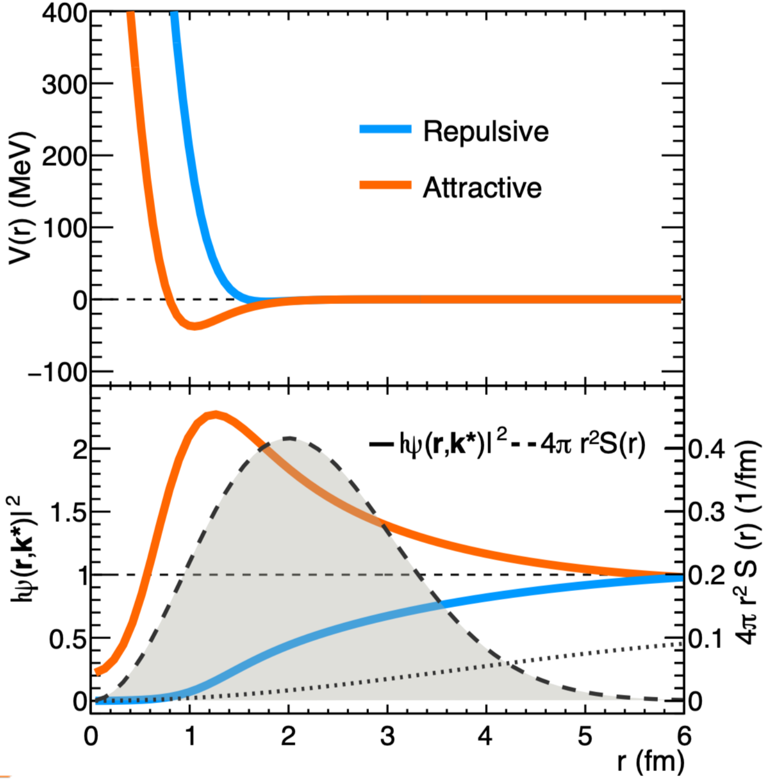


Decrease of signal strength for large source sizes

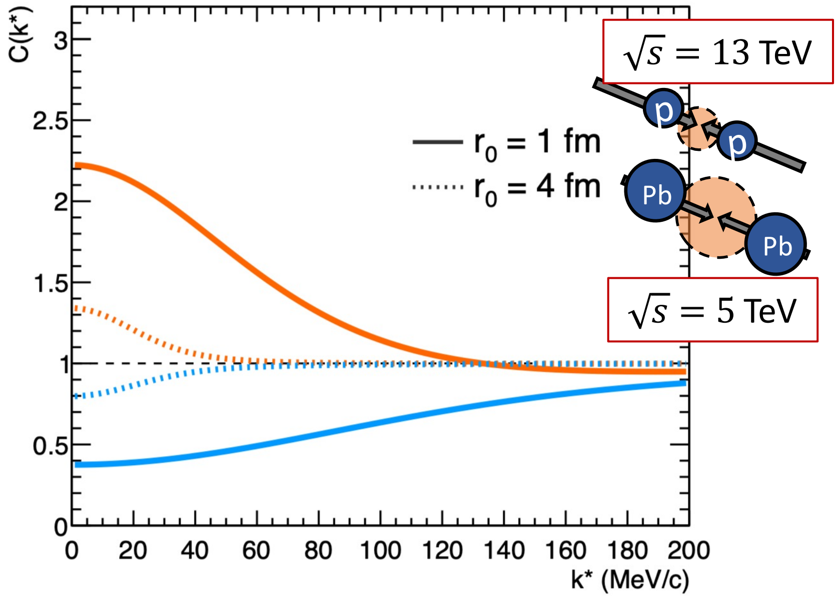
LF, V. Mantovani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

Examples of correlation functions

Predictions obtained using **CATS**



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

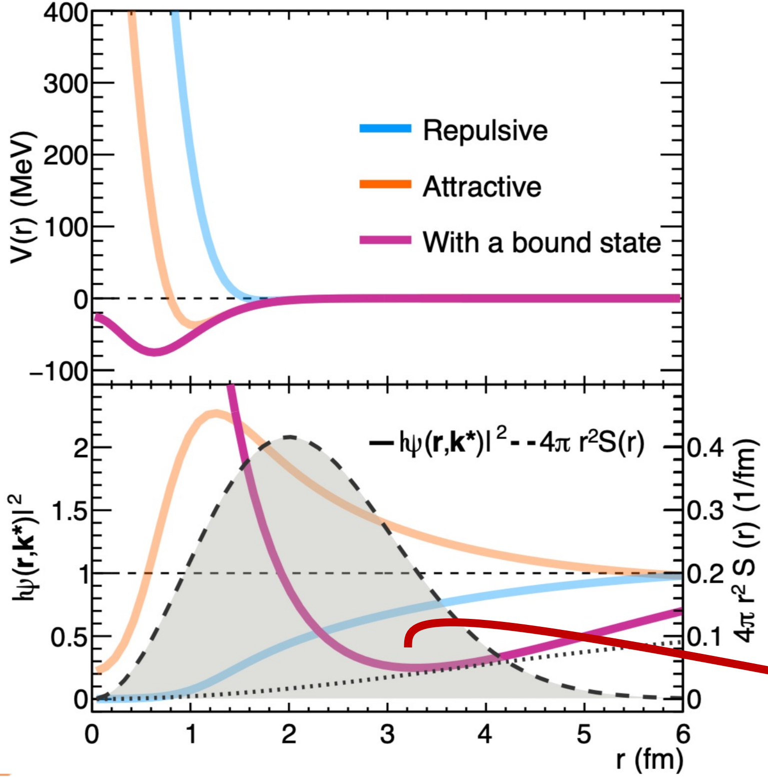


$$C(k^*) \begin{cases} > 1 & \text{Attractive (no BS)} \\ < 1 & \text{Repulsive} \end{cases}$$

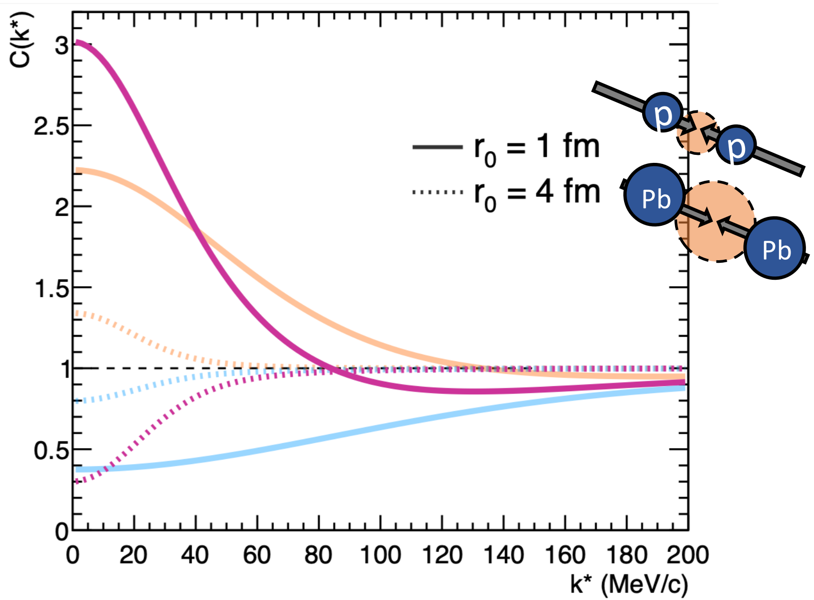
LF, V. Mantovani Sarti and O. Vazquez Doce ARNPS 71 (2021), 377-402

Examples of correlation functions

Predictions obtained using **CATS**



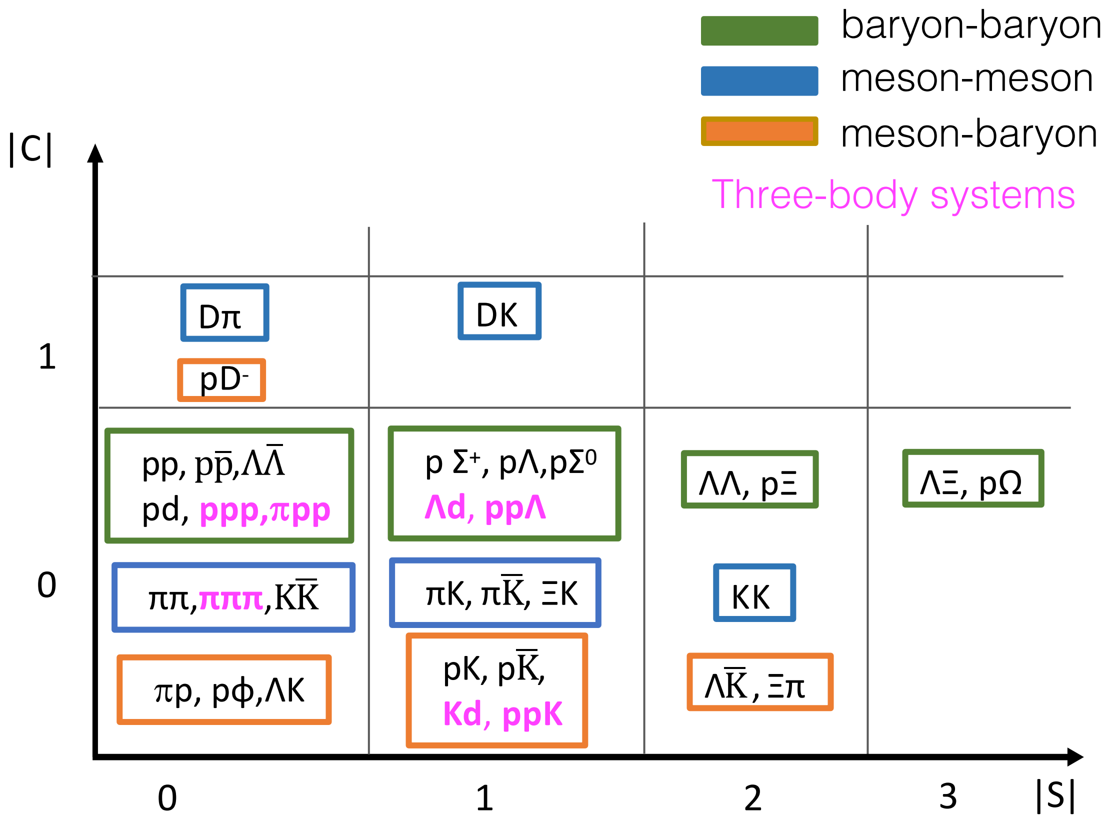
$$C(k^*) = \int S(\vec{r}^*)\ \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*$$



Correlation flips around unity when a bound state is present!

L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

What was measured in the last 5 years?



p-K: PRL 124 (2020) 9, 092301
PLB 822 (2021) 136708,
EPJC 83 (2023) 4, 340

p-p, p-Λ, Λ-Λ: PRC 99 (2019) 024001

Λ-Λ: PLB 797 (2019) 134822

p-Ξ^-: PRL. 123 (2019) 112002

p-Ξ^-, p-Ω^-: Nature 588 (2020) 232–238

p-Σ^0: PLB 805 (2020) 135419

p-φ: PRL 127 (2021) 172301

Baryon-Antibaryon: PLB 829 (2022) 137272

p-Λ: PLB 832 (2022) 137272

ΛΞ : PLB 844 (2023) 137223

D-p: PRD **106**, 052010 (2022)

p-p-p, p-p-Λ: EPJA 59 (2023) 7, 145

ppK: EPJA 59 (2023) 12, 298

D-π, D-K: PRD 110 (2024) 3, 032004

Λ -K: PLB 845 (2023) 138145

p-d, K-d: PRX 14 (2024) 3, 031051

π-p, πpp: arXiv:2502.20200v1

Source studies: PLB 811 (2020) 135849
arXiv:2311.14527

ALICE detector

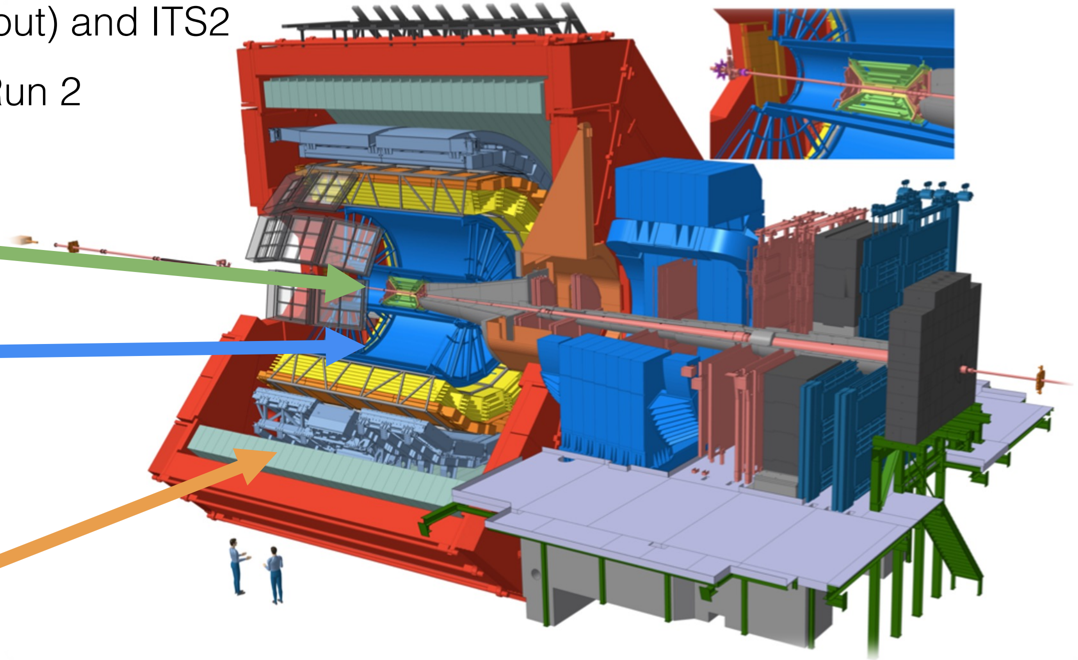
- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation
- Results in this talk refer to pp HM at 13 TeV, Run2
- Major upgrade of the TPC (GEM read out) and ITS2
- Factor 100 in data taking rate w.r.t to Run 2
- Run 3 started in 2022-(2025)

Inner Tracking System
Tracking, vertex, PID (dE/dx)

Time Projection Chamber
Tracking, PID (dE/dx)

Transition Radiation Detector

Time Of Flight detector
PID (TOF measurement)



Source function in pp collisions at the LHC

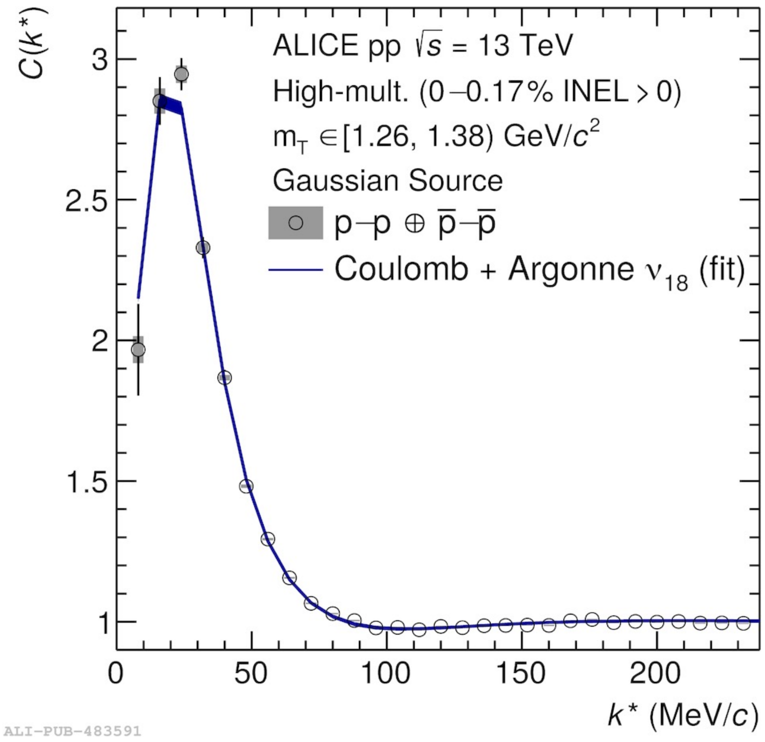
- Emitting source function anchored to p-p correlation function

$$\underbrace{C(k^*)}_{\text{measured}} = \int S(\vec{r}\,)\underbrace{\left|\psi(\vec{k}^*,\vec{r}\,)\right|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$ Effect of short lived resonances (cτ ~ 1 fm)

ALICE Coll., PLB, 811 (2020), 135849



ALICE Coll., PLB, 811 (2020)

Source function in pp collisions at the LHC

- Emitting source function anchored to p-p correlation function

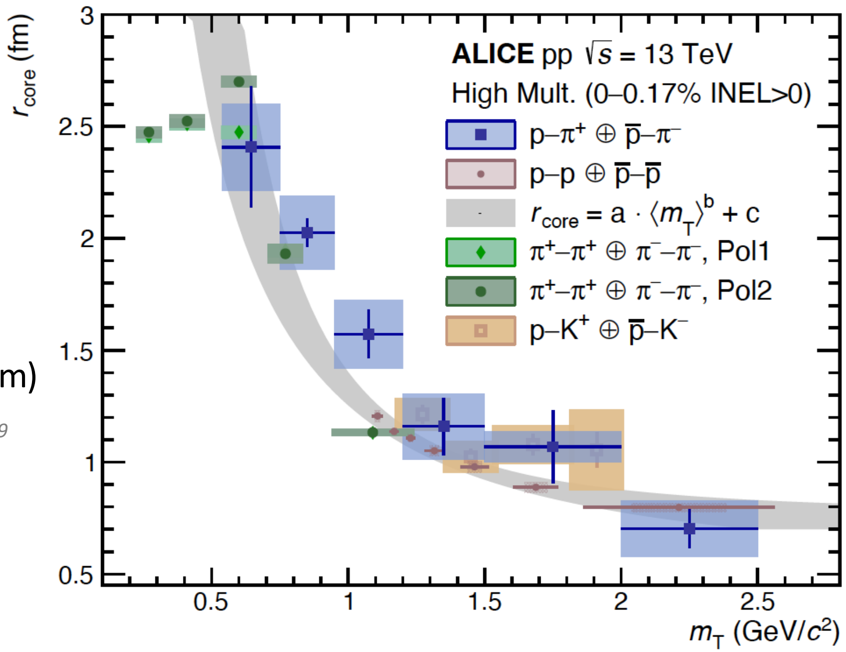
$$\underbrace{C(k^*)}_{\text{measured}} = \int S(\vec{r}\,) \underbrace{|\psi(\vec{k}^*,\vec{r}\,)|^2}_{\text{known interaction}} d^3\vec{r}$$

- Gaussian parametrization

$$S(r) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \times$$ Effect of short lived resonances (cτ ~ 1 fm)

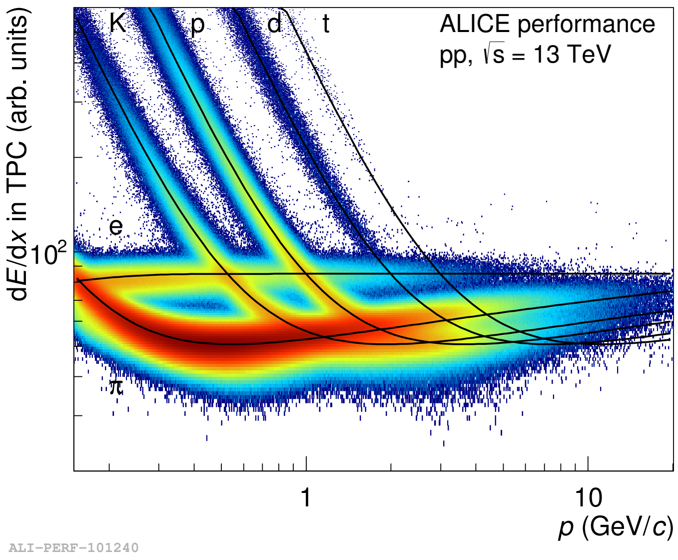
ALICE Coll., PLB, 811 (2020), 135849

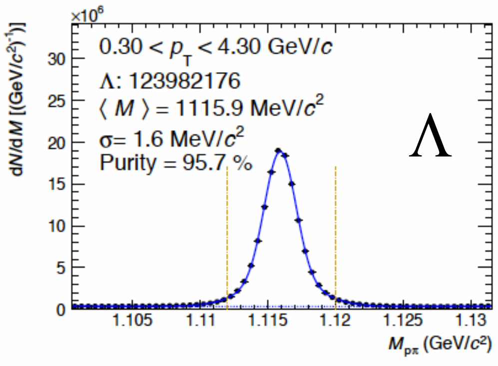
- Cross-check with K⁺-p, π-π, p-Λ, p-π
- One source that describes all systems with very different final state interactions



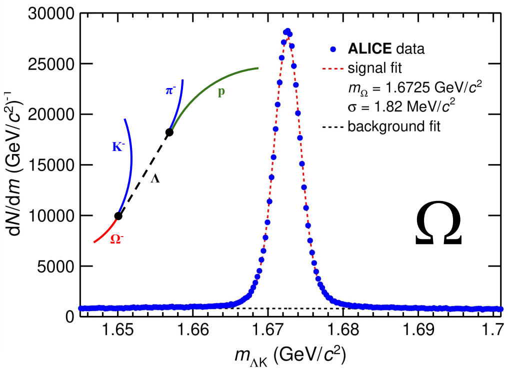
ALICE Coll., PLB, 811 (2020), 135849; ALICE Coll., arXiv:2311.14527, arXiv:2502.20200v1

Hyperons and charm hadrons @ ALICE



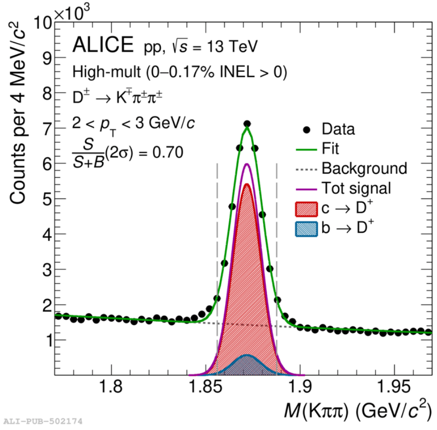


$\Lambda \rightarrow p\pi^-$



$\Omega^- \rightarrow \Lambda K^-$
$\hookrightarrow p\,\pi^-$

Λ, Ω :decay length ~cm
D meson: decay length ~100 μm

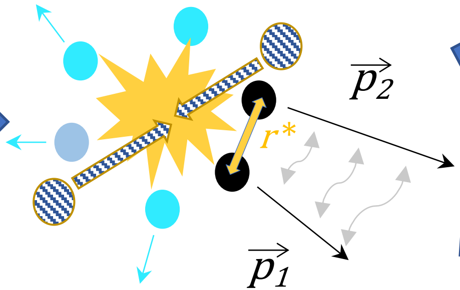


$D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$

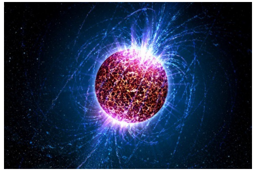
A new tool to study low energy QCD

ALICE at the LHC

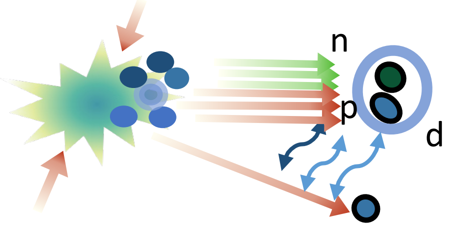
Femtoscopy in small systems



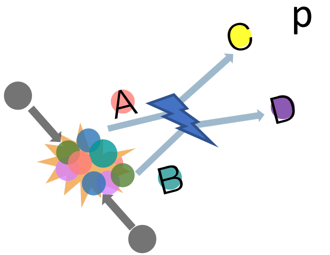
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



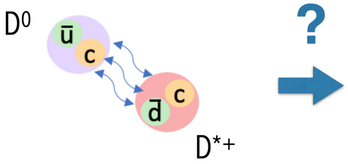
Nuclei formation

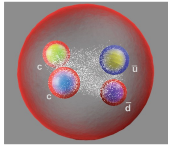


Direct access to coupled channels



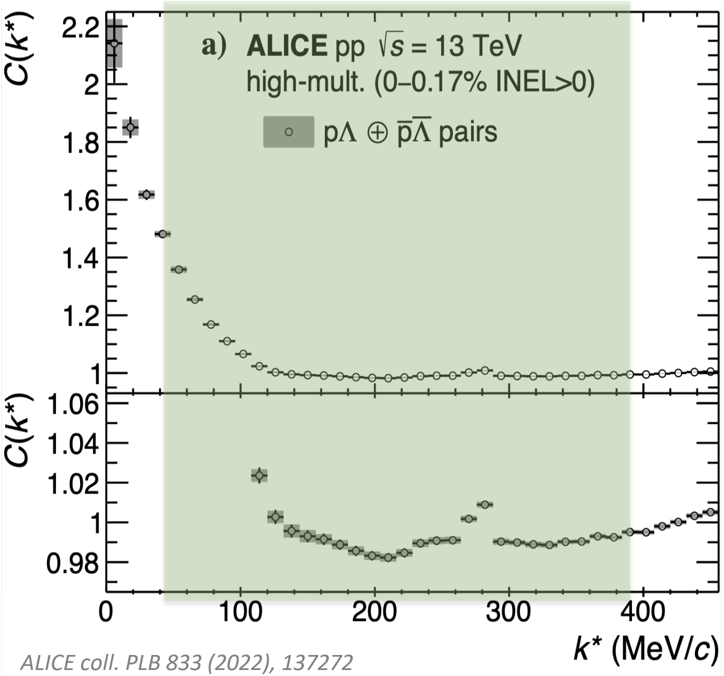
Final state interaction of charmed hadrons





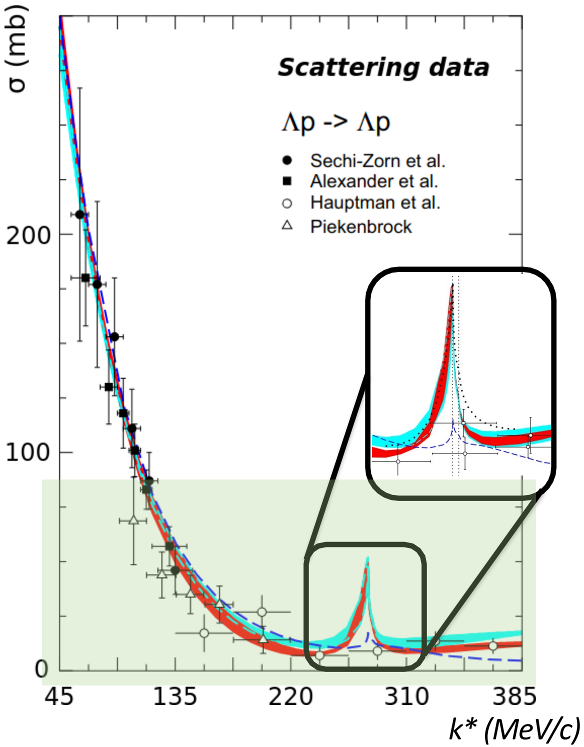
The pΛ femtoscopy correlation

~ $7 \cdot 10^5$ pΛ pairs with k*< 200 MeV/c



ALICE coll. PLB 833 (2022), 137272

- Measurement down to zero momentum
- Factor >20 improved precision (<1%)
- First experimental evidence of ΛN-ΣN opening in 2-body channel



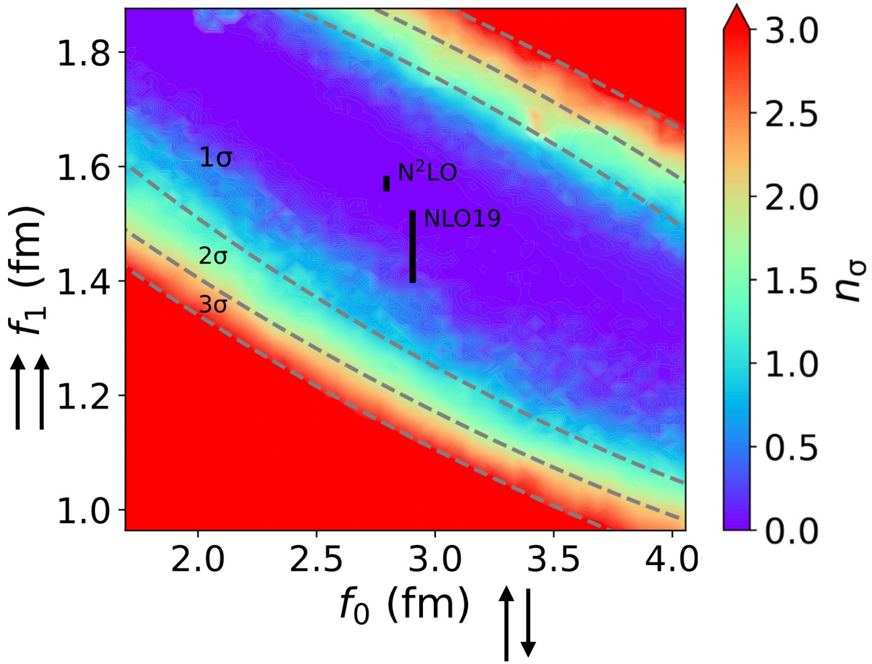
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

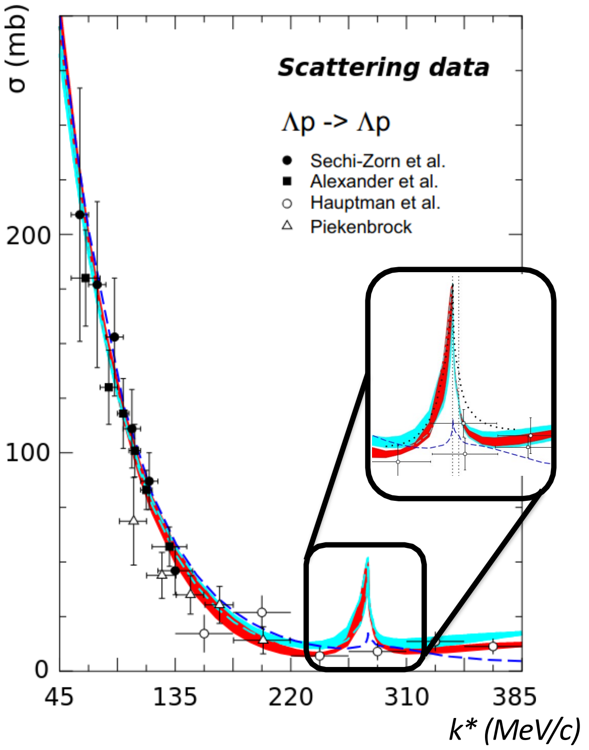
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

pΛ Scattering parameters

- Spin-0 and Spin-1 scattering length from scattering data
- Agreement with N2LO and NLO19

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550





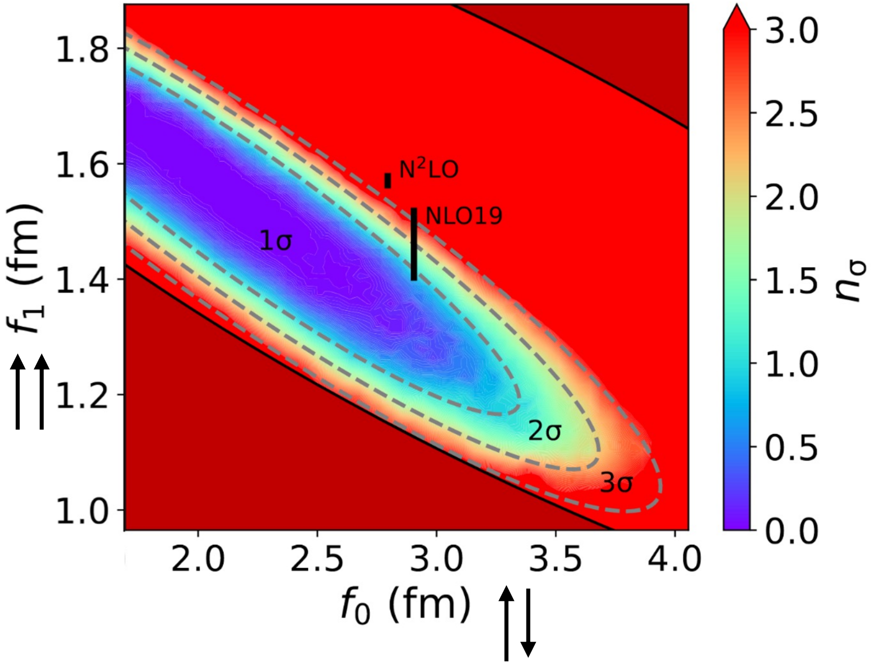
NLO19: J.Haidenbauer, U. Meißner, EPJA 56 (2020), 3, 91

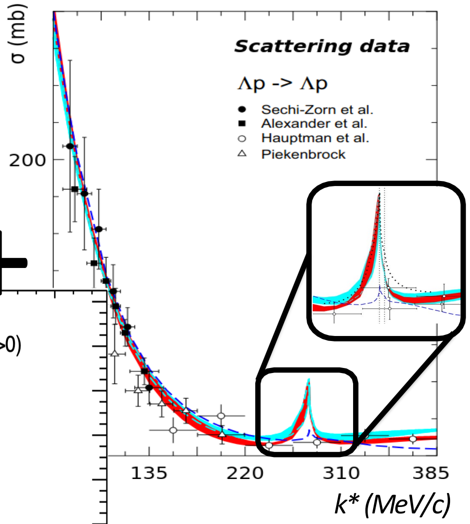
NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)

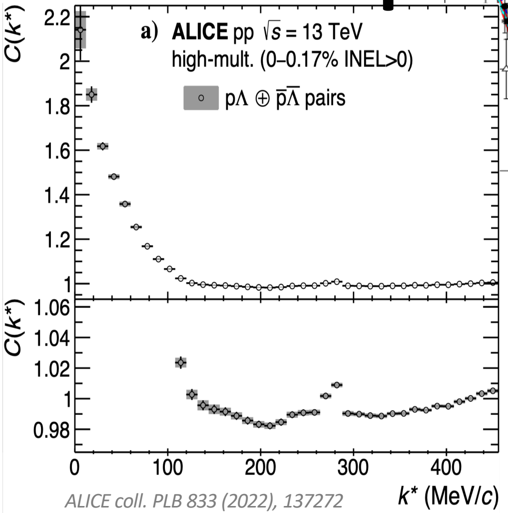
FIRST simultaneous Fit of scattering and femto data

- NEW: combined analysis of femtoscopic and scattering data
- Less attractive ΛN interaction

D. Mihaylov, J. Haidenbauer and V. Mantovani Sarti, PLB 850 (2024) 138550







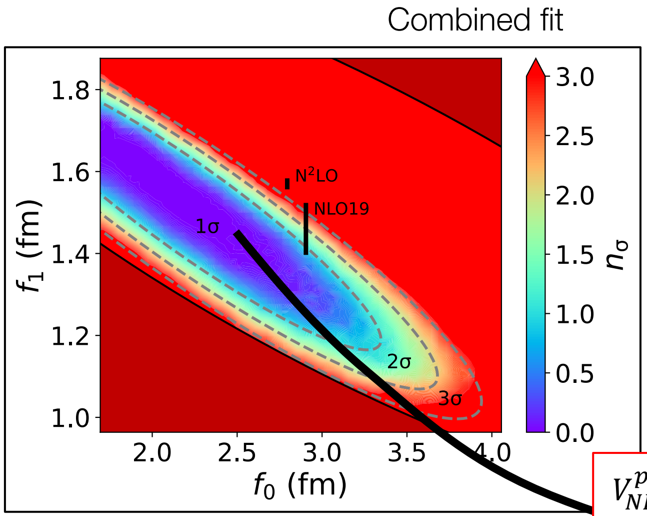
ALICE coll. PLB 833 (2022), 137272

WHAT about Neutron stars ?

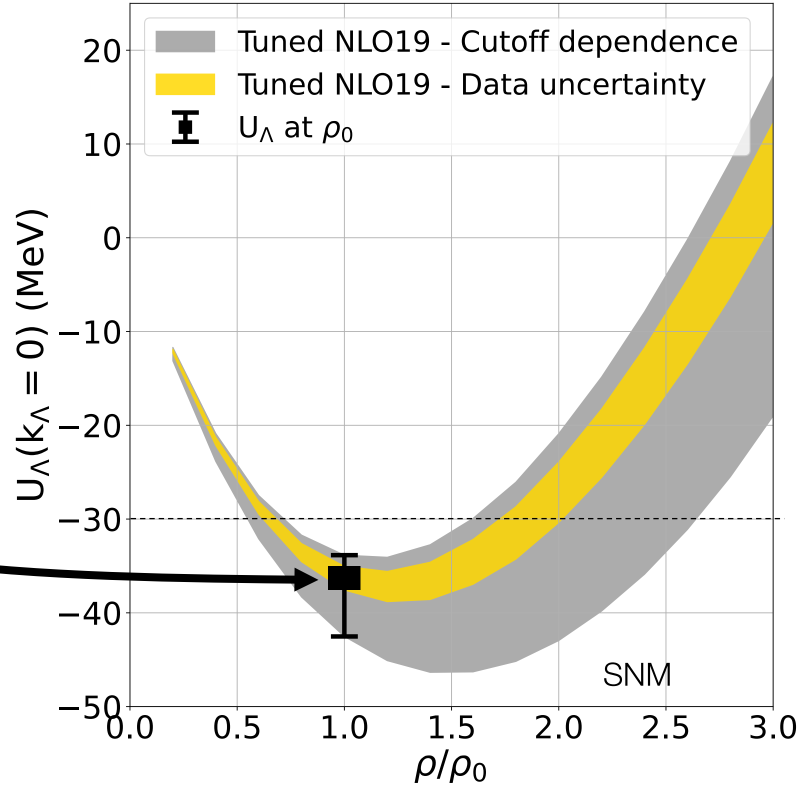
- Also interaction between other hyperons (Σ (uds), Ξ (ssd)) and nucleons, or between two hyperons ($\Lambda\Lambda$) are relevant for neutron stars.
- We have measured all the relevant two-baryon interactions with femtoscopy!

FROM scattering parameters to single particle potentials

D. Mihaylov, J. Haidenbauer and V. Mantonvani Sarti PLB 850 (2024) 138550



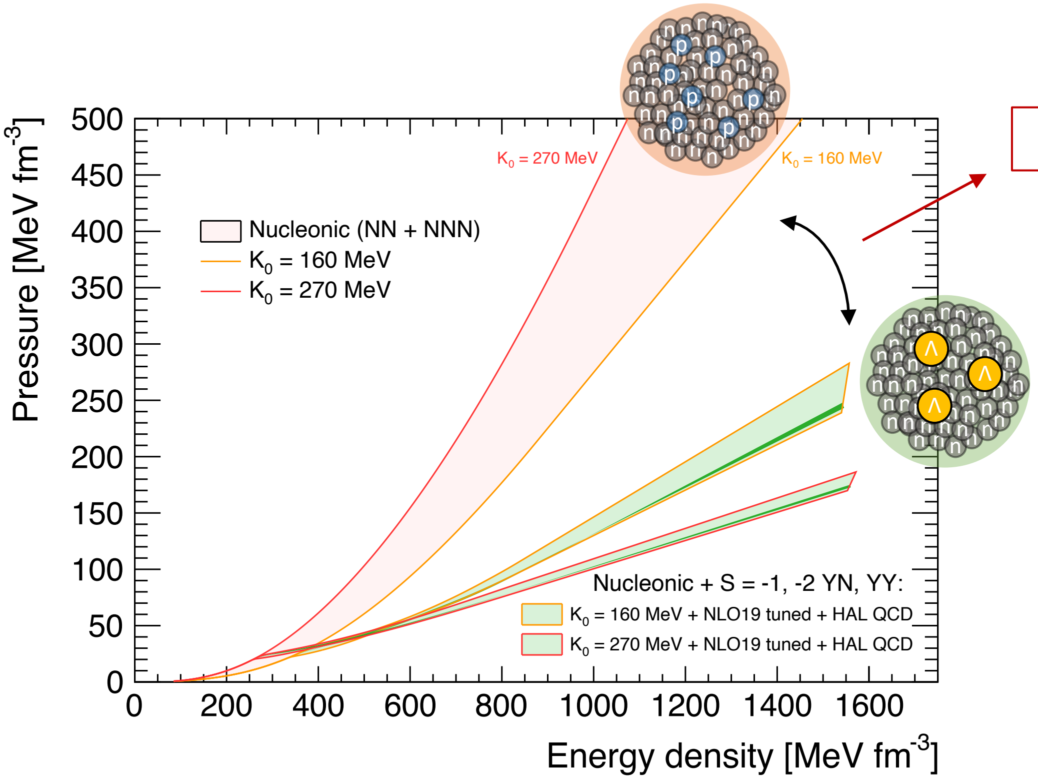
$V^{p\Lambda}_{NLO19}$ in mom. space via G-matrix approach



$U_\Lambda^{2BF}(\rho_0) = -36.3 \pm 1.3(stat)^{+2.5}_{-6.2}(syst)$ MeV

Quantitative estimate of repulsion from 3BF ΛNN at ρ_0 !

Impact on nuclear EOS and neutron stars



I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

Inclusion of S=-1, -2 YN softens the EoS!

Light shade: theoretical uncertainty (cut-off)

Dark shade: experimental uncertainty (comb. fit scatt. + femto)

Experiment

D.Mihaylov
TUM/Sofia
Uni

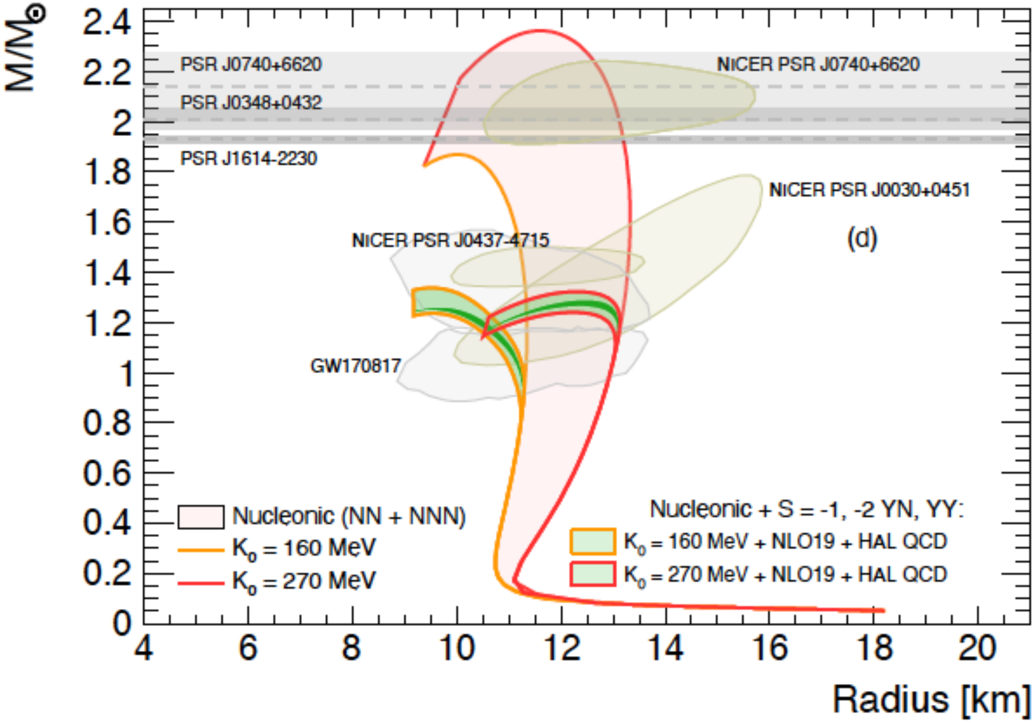
V. Mantovani
Sarti
TUM

Theory

J. Haidenbauer

I.Vidana
INFN Catania

Impact on nuclear EOS and neutron stars



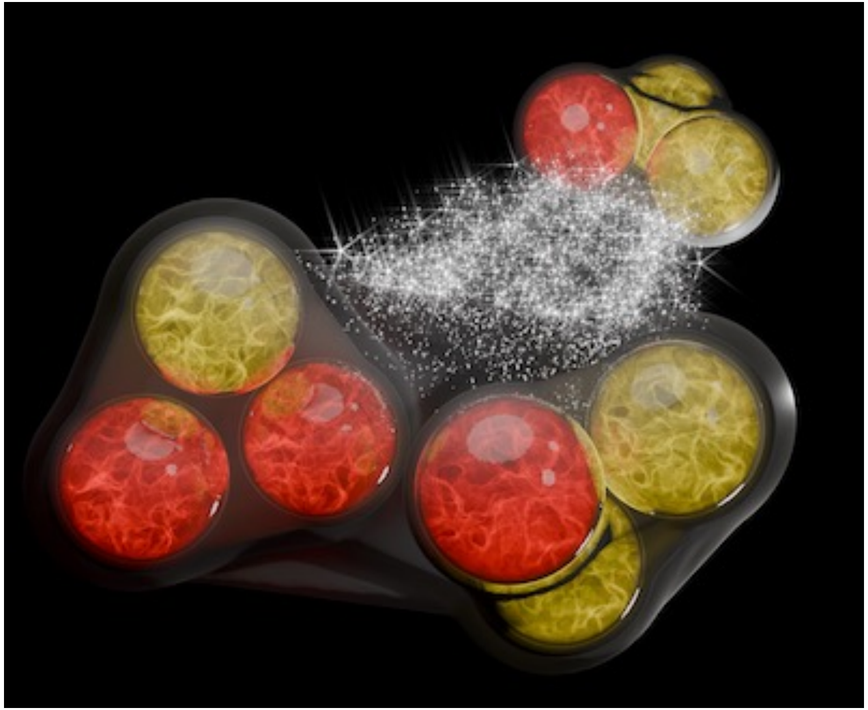
Upper limit of EoS with hyperons is too soft to reach 2M⊙

Additional repulsion among hadrons or new degree of freedom is needed

Three body hyperon nucleon interactions?

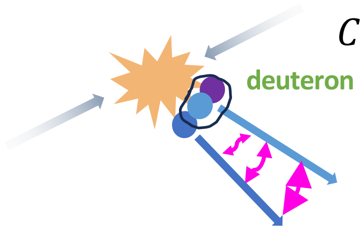
I.Vidana, V. Mantovani Sarti, J. Haidenbauer, D. L. Mihaylov, LF arXiv:2412.12729v1

Three body interaction at the LHC

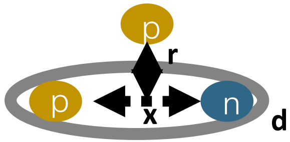


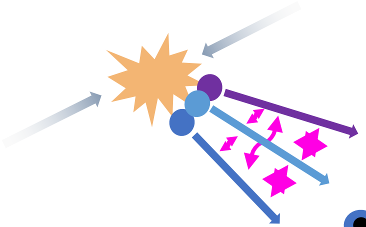
Two methods are currently studied

- Deuteron-baryon correlations
- Three-baryons correlations

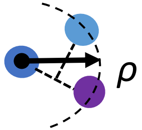


$$C(k^*) = \int S(r)|\psi(k^*, r)|^2\, 4\pi r^2\, dr$$





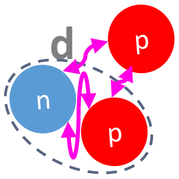
$$C(Q_3) = \int S(\rho)|\psi(Q_3, \rho)|^2\, \rho^5\, d\rho$$

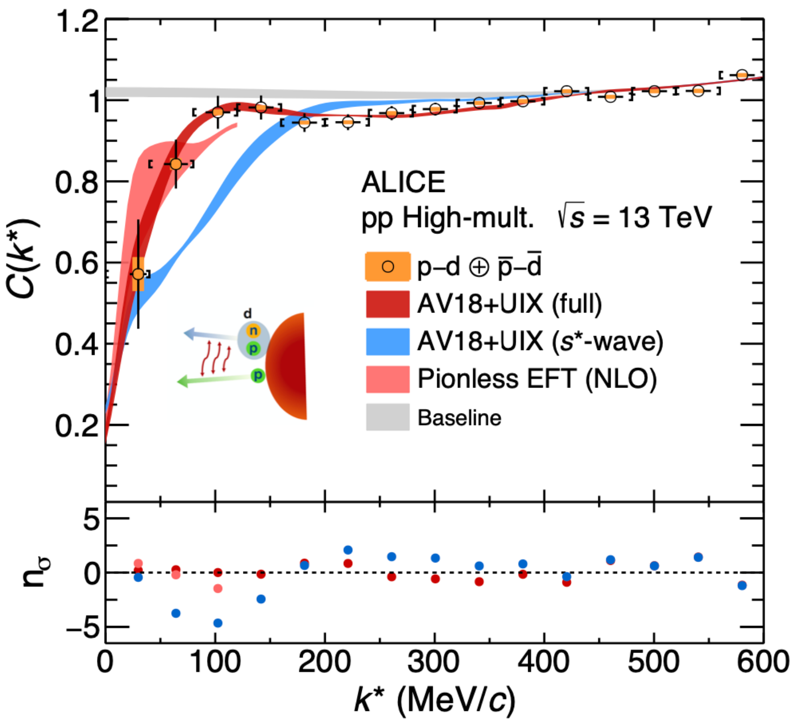


$$Q_3 = \sqrt{-q_{ij}^2 - -q_{ik}^2 - q_{kj}^2}$$

NNN using proton-deuteron correlations

- Full three-body calculations are required (NN + NNN + Quantum Statistics)



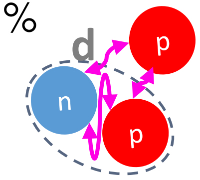


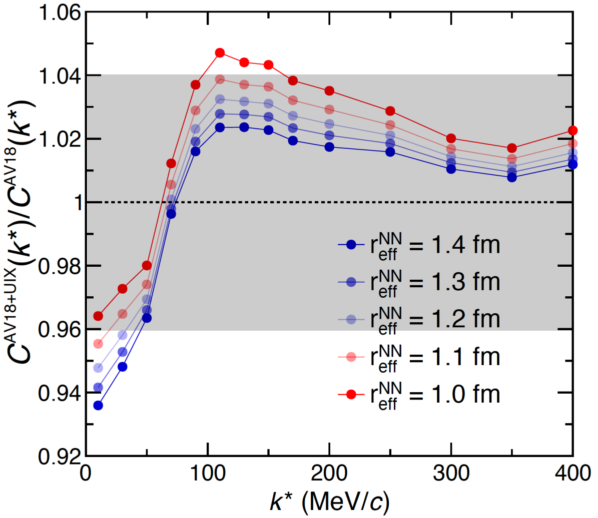
ALICE Coll., PRX 14 (2024) 3, 031051

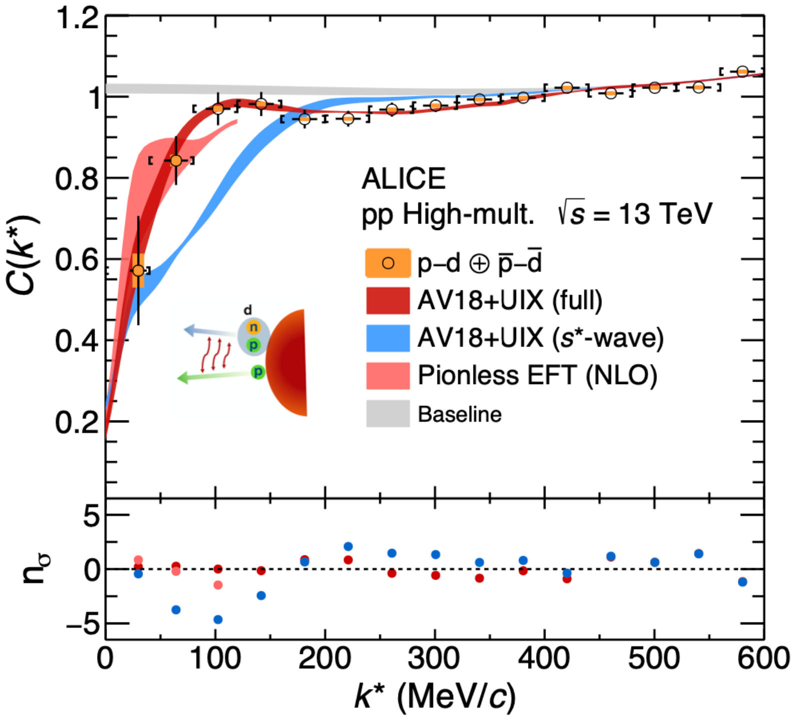
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity to three-body forces up to 5%





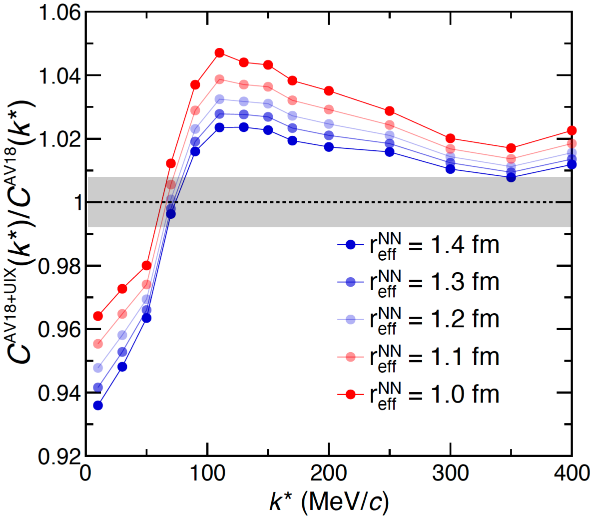


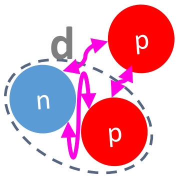
ALICE Coll., PRX 14 (2024) 3, 031051

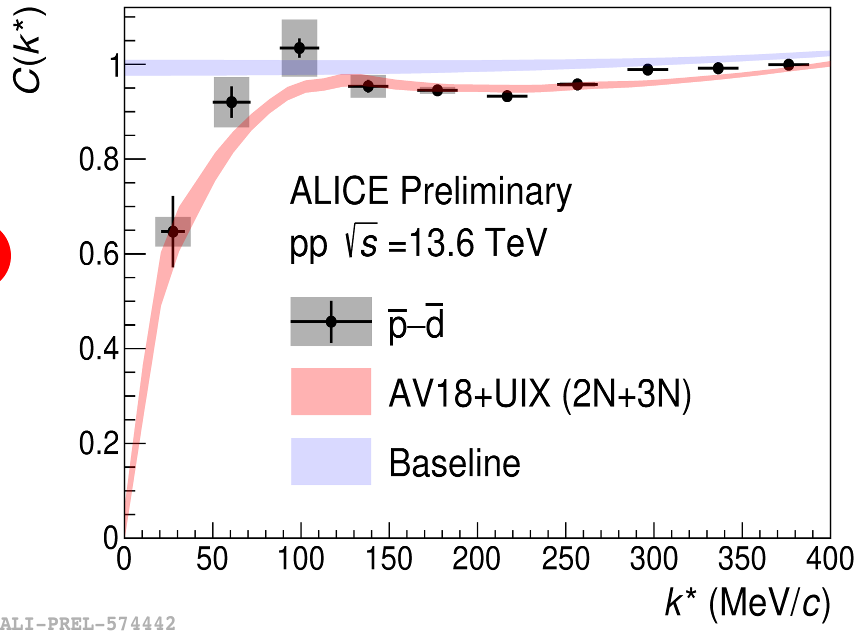
M. Viviani et al, Phys.Rev.C 108 (2023) 6, 064002

NNN using proton-deuteron correlations

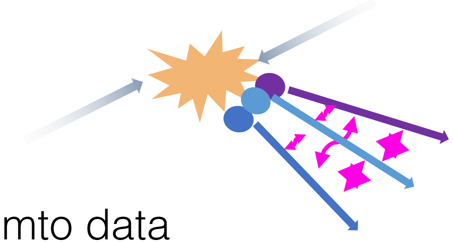
- Full three-body calculations are required (NN + NNN + Quantum Statistics)
- Hadron-nuclei correlations at the LHC can be used to study many-body dynamics
- Sensitivity for Run 3 ~1%



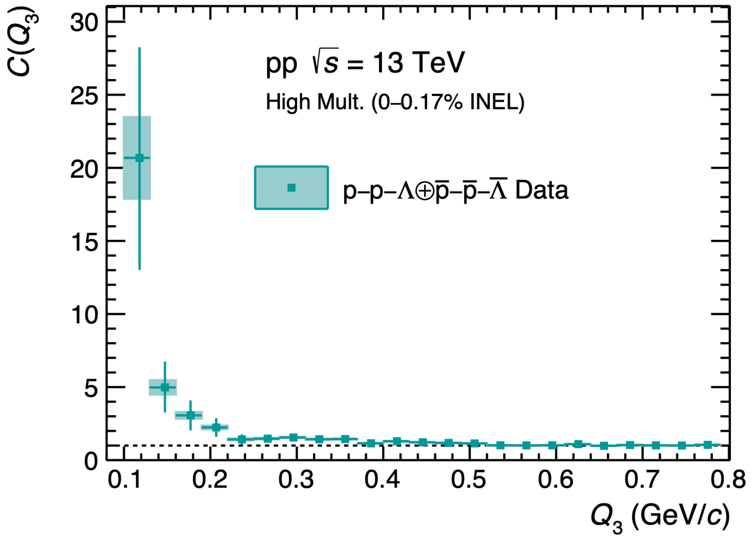




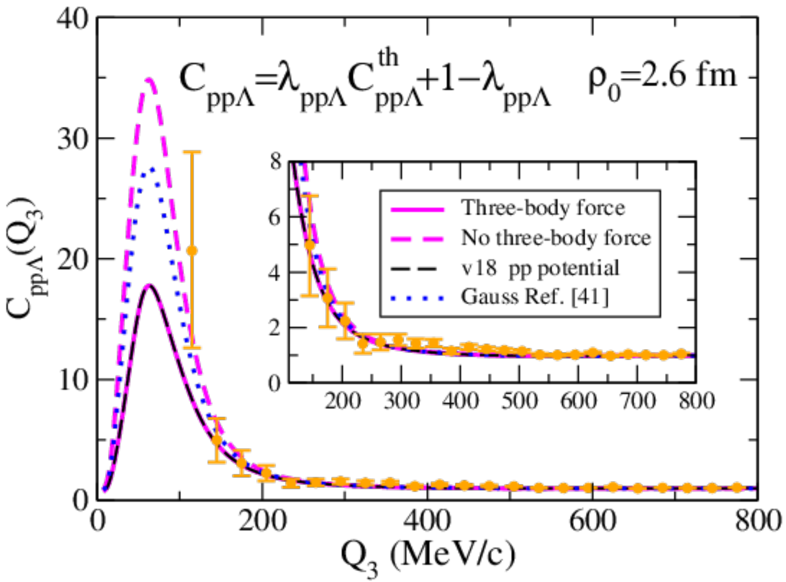
ppΛ correlation



Run 2 data limited in statistics
First calculation : → NΛ interaction from fit of scattering & femto data
→ hypertrition BE reproduced with 2B interaction

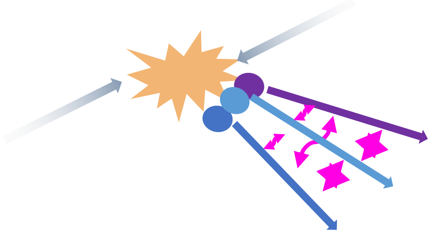


ALICE Coll., Eur.Phys.J.A 59 (2023) 7, 145



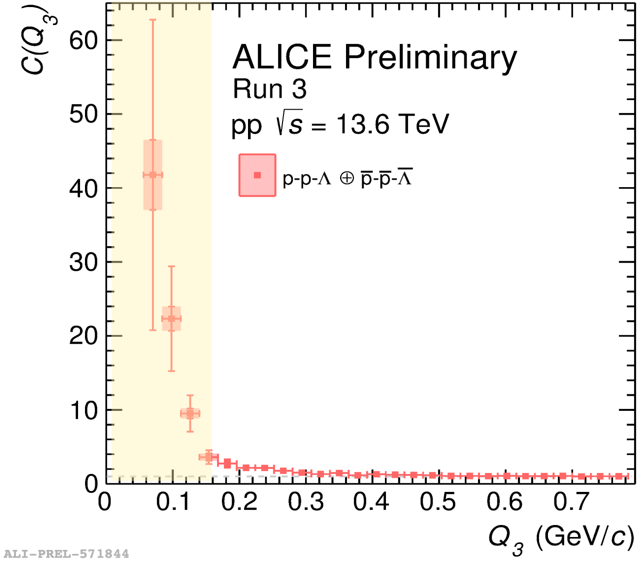
A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF arXiv:2408.01750

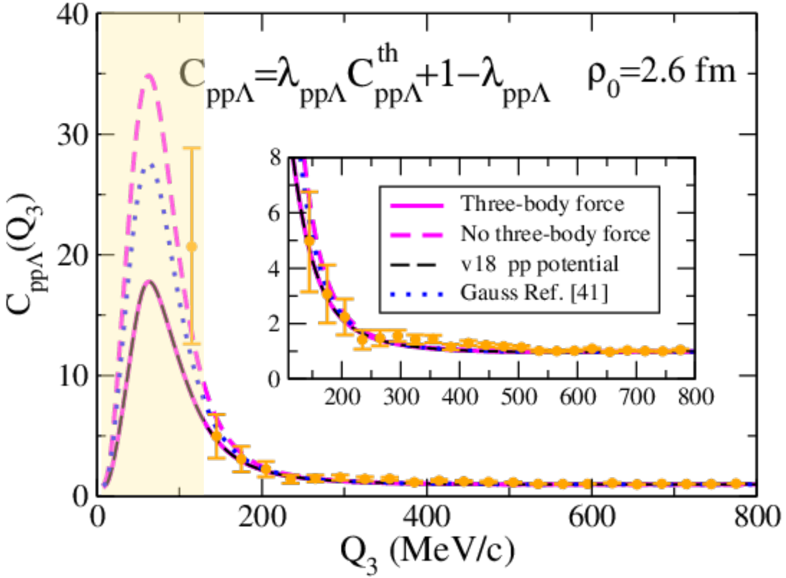
ppΛ correlation



Dedicated three body triggers for pp collisions at Run 3

By the end of 2026 100 times more statistics



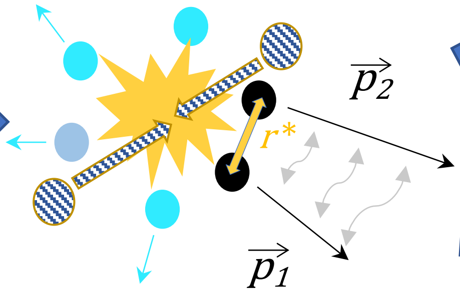


A. Kievsky and E. Garrido, Gattobigio, R. Del Grande, LF arXiv:2408.01750

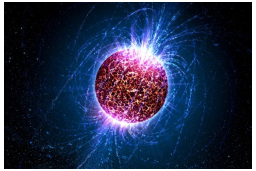
A new tool to study low energy QCD

ALICE at the LHC

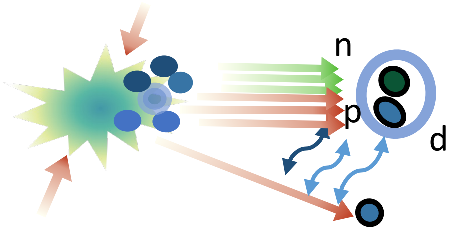
Femtoscopy in small systems



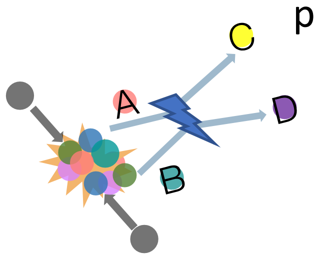
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



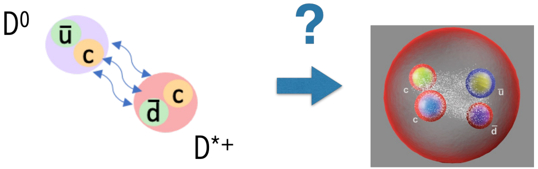
Nuclei formation



Direct access to coupled channels

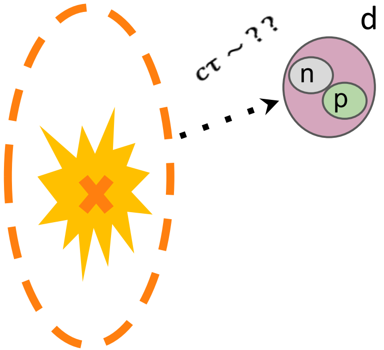


Final state interaction of charmed hadrons



Motivation

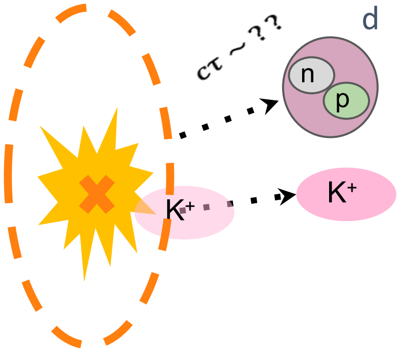
Solve a long-standing puzzle about the nuclei production mechanism in relativistic hadron-hadron collisions



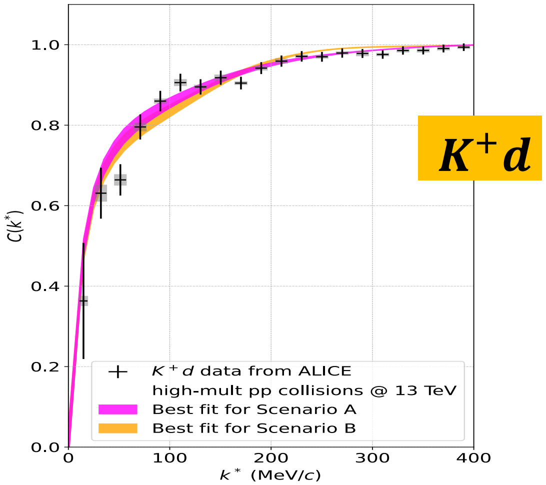
Motivation

Solve a long-standing puzzle about the nuclei production mechanism in relativistic hadron-hadron collisions

Evidence of K^+– d strong interaction at short distances

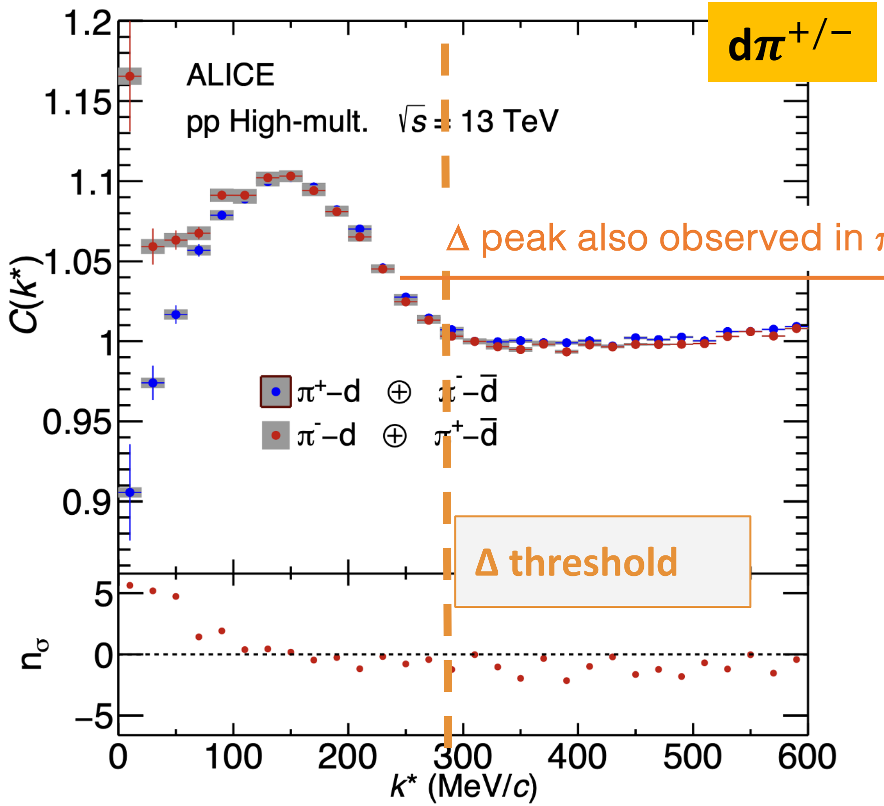


Data from ALICE Coll. Phys. Rev. X 14, 031051 (2024)
O. Vazquez Doce, D. Mihaylov, LF arXiv: 2412.04562

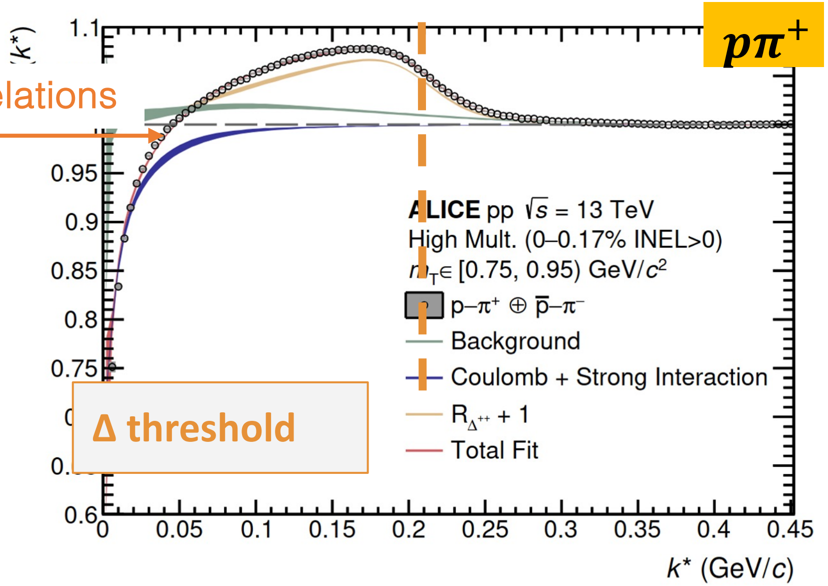


Considering K^+d correlations and the CECA source model it is possible to calculate an **upper limit** for the deuteron formation time : **4.75 fm/c**

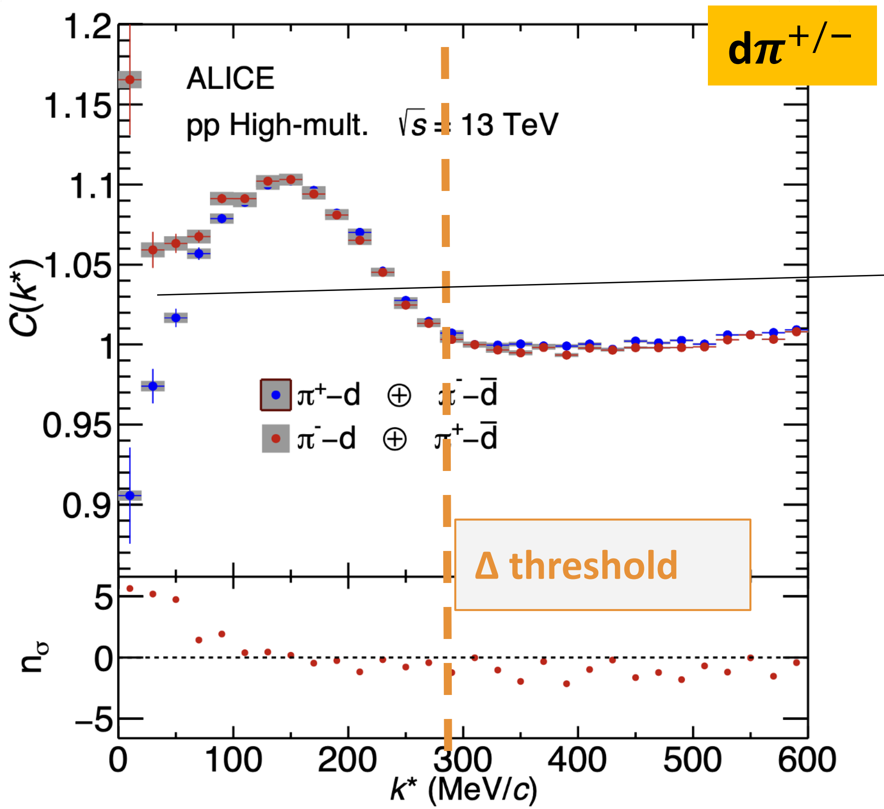
π-deuteron correlation functions in pp collisions at the LHC



Δ peak also observed in πp correlations



π-deuteron correlation functions in pp collisions at the LHC

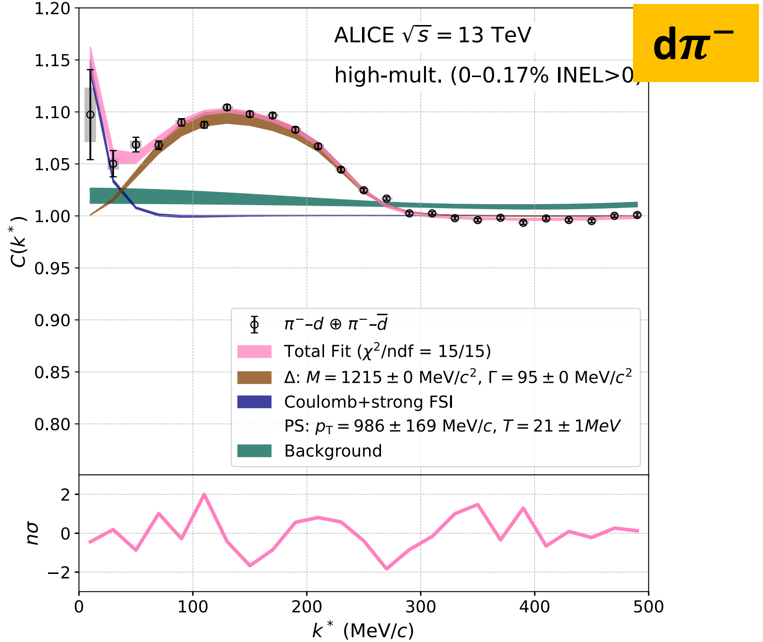


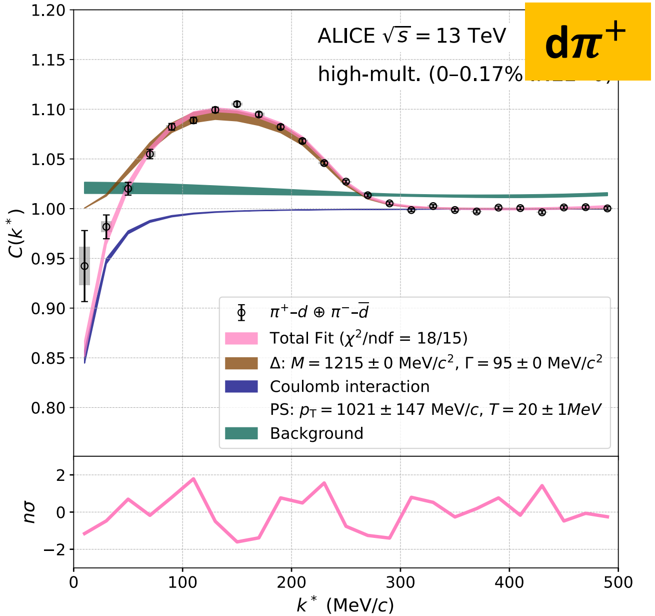
Attractive (π^{-} d)

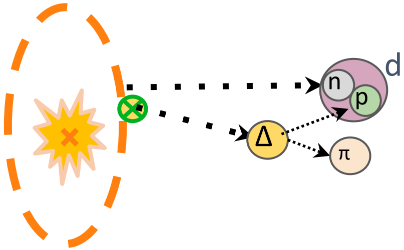
Repulsive (π^{+} d) final state interactions

Mainly Coulomb

Data Interpretation





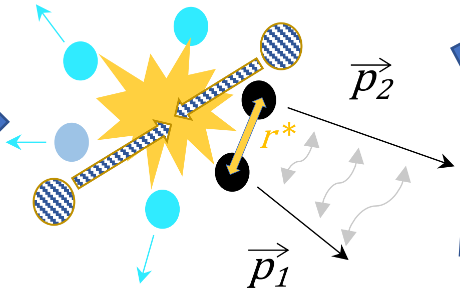


- The Δ peak in πd can <u>only</u> be explained as the residual correlation that is retained between the pion and the nucleon stemming from the same Δ decay
- This means that the deuteron formation occurs after the Δ decay and through rescattering/coalescence with an additional nucleon

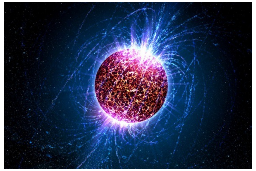
A new tool to study low energy QCD

ALICE at the LHC

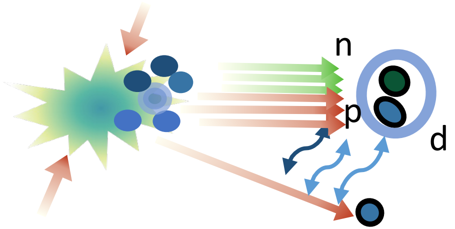
Femtoscopy in small systems



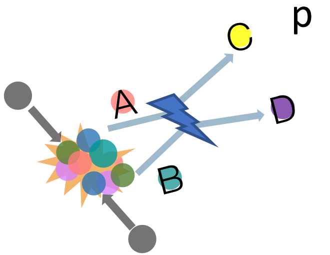
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



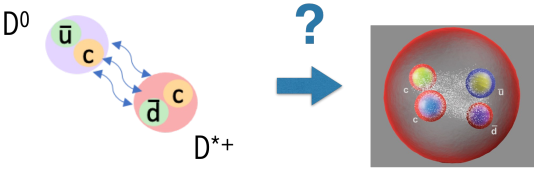
Nuclei formation



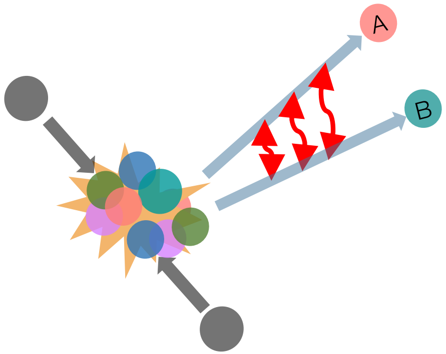
Direct access to coupled channels

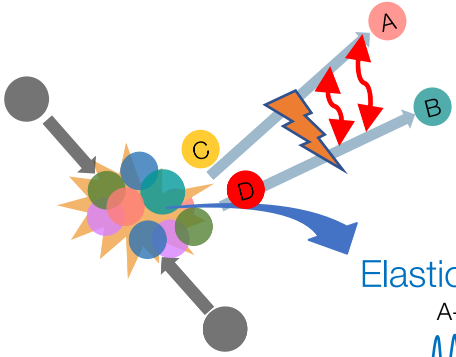


Final state interaction of charmed hadrons



Femtoscopy with coupled channels





Elastic/Inelastic channels

A-B C-D

$\psi_1(\boldsymbol{k}_1, \boldsymbol{r})$ + $\psi_2(\boldsymbol{k}_2, \boldsymbol{r})$

Elastic/Inelastic wave functions

$$C_{A-B}(k^*) = \underbrace{\int S(r)\, |\psi_{1\to 1}(k^*, r)|^2\, d^3r}_{\text{elastic}} + \underbrace{\sum_{j\neq 1} w_j \int S(r) \left|\psi_{j\to 1}\left(k_j^*, r\right)\right|^2 d^3r}_{\text{inelastic}} = \mathcal{N}(k*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

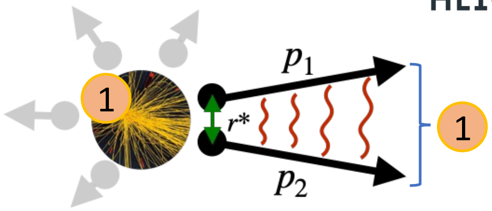
elastic
A-B → A-B

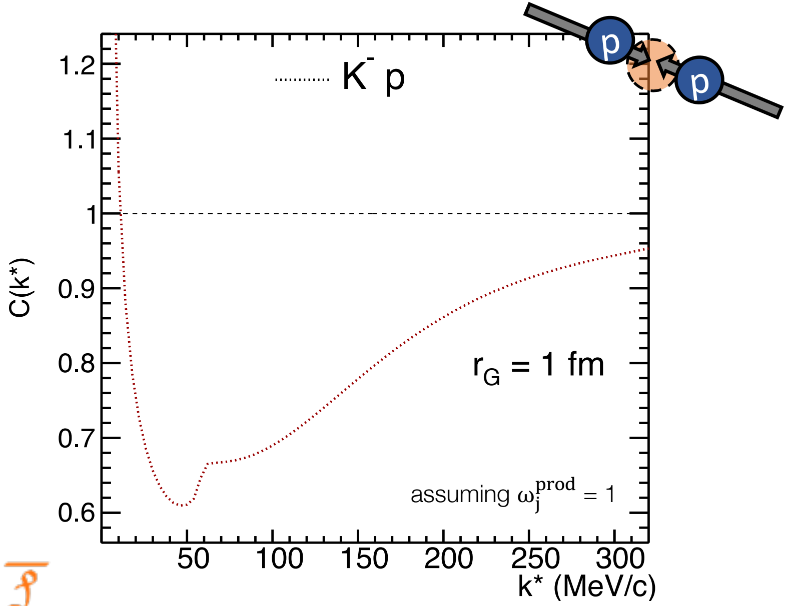
inelastic
C-D → A-B, …

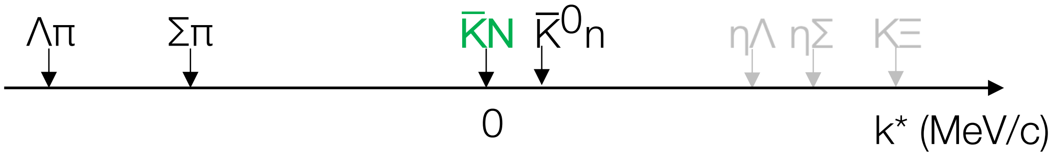
J. Haidenbauer Nucl.Phys.A 981 (2019)
Y. Kamiya et al. Phys.Rev.Lett. 124 (2020)
V.M.S., L. Fabbietti, O. Vazquez-Doce 2012.09806

Coupled-channels dynamics in femtoscopy

$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\ \left|\psi_{1\to 1}(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*}_{\substack{\text{elastic} \\ 1 \to 1}}$$





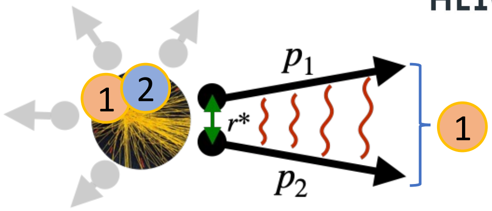


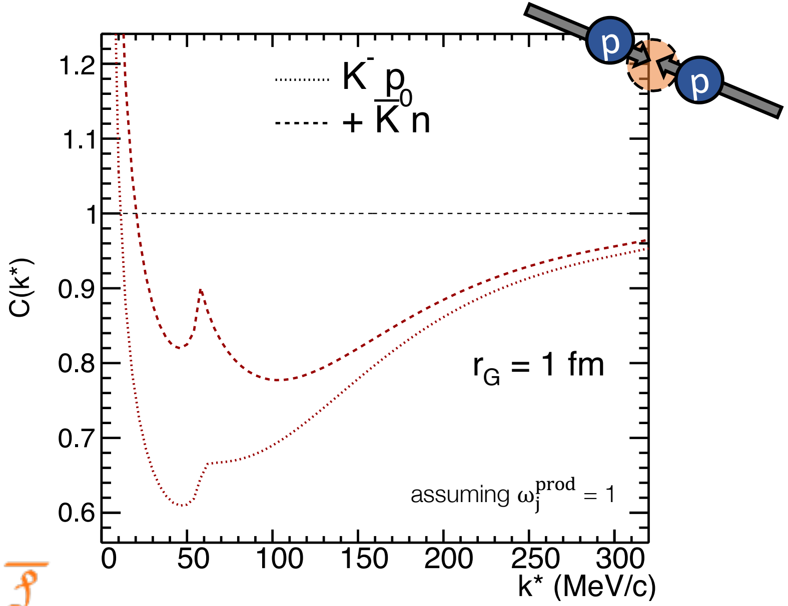
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)

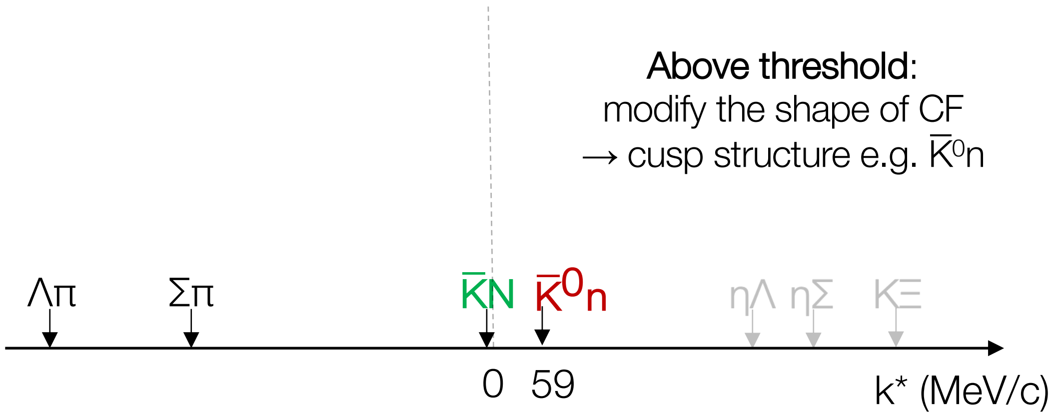
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Coupled-channels dynamics in femtoscopy

$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\,\left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^*}_{\substack{\text{elastic}\\ 1\,\to\,1}} + \underbrace{\sum_{j\neq1} \omega_j^{\text{prod}} \int S_j(\vec{r}^*)\,\left|\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)\right|^2 d^3r^*}_{\substack{\text{inelastic}\\ 2,..\,\to\,1}}$$





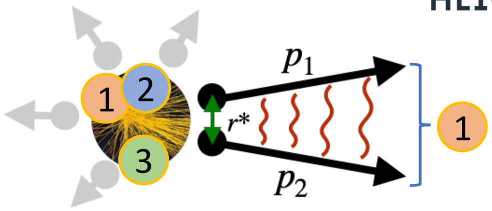


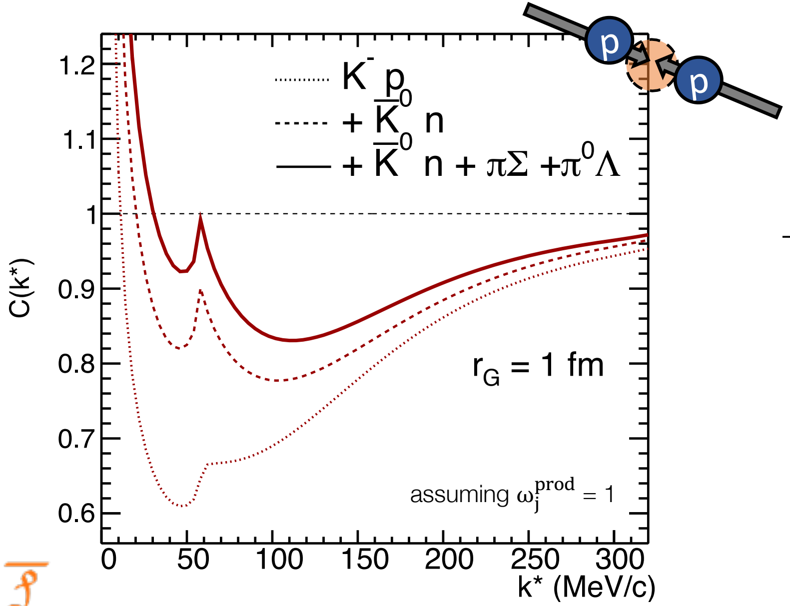
Above threshold:
modify the shape of CF
→ cusp structure e.g. $\overline{K}^0$n

For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Coupled-channels dynamics in femtoscopy

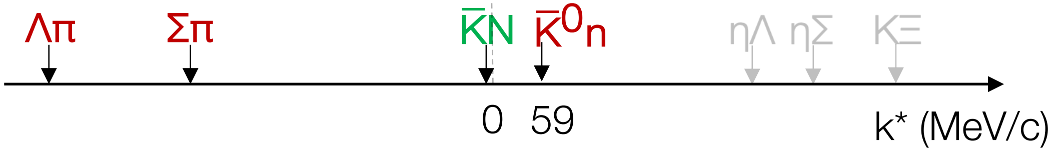
$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\,\left|\psi_{1\to1}\left(\vec{k}^*,\vec{r}^*\right)\right|^2 d^3r^*}_{\substack{\text{elastic} \\ 1\,\to\,1}} + \underbrace{\sum_{j\neq1}\omega_j^{\text{prod}}\int S_j(\vec{r}^*)\,\left|\psi_{j\to1}\left(\vec{k}_j^*,\vec{r}^*\right)\right|^2 d^3r^*}_{\substack{\text{inelastic} \\ 2,3,\ldots\,\to\,1}}$$





Below threshold:
increase the strength of CF
→ shift upward of CF e.g. Σπ

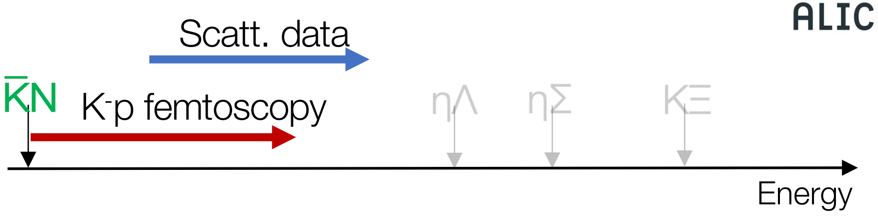
Above threshold:
modify the shape of CF
→ cusp structure e.g. $\bar{K}^0$n

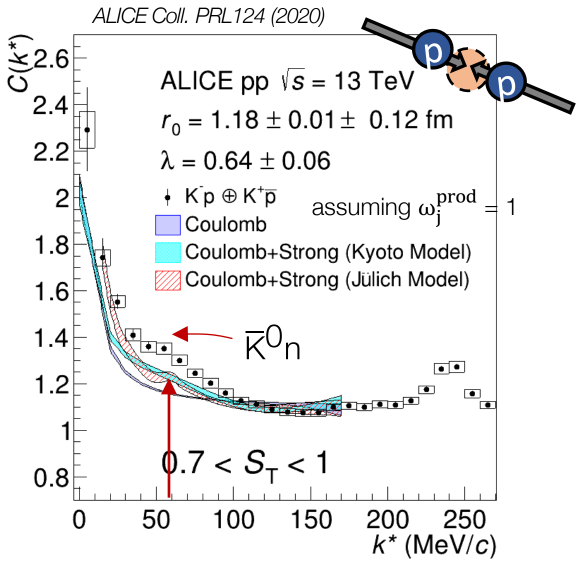


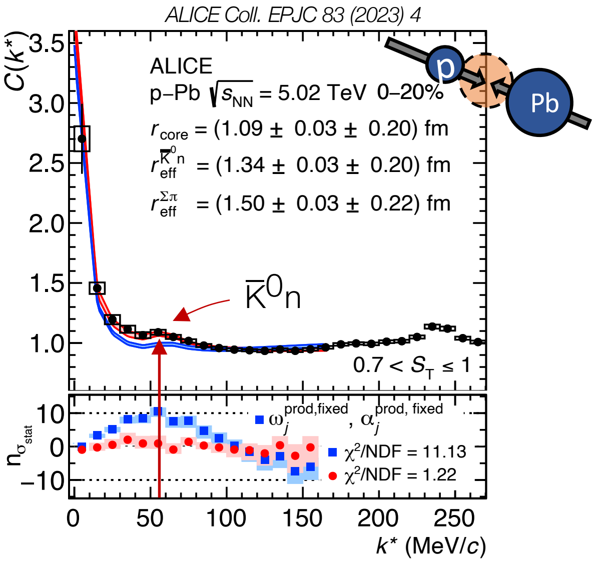
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

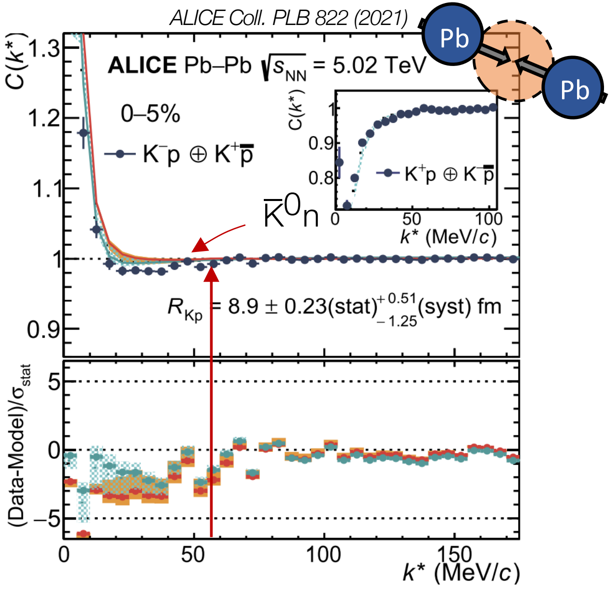
High-precision data on S=-1 sector

- Most precise data above K⁻p threshold with sensitivity to channels below threshold!
- Input for low-energy chiral effective potentials







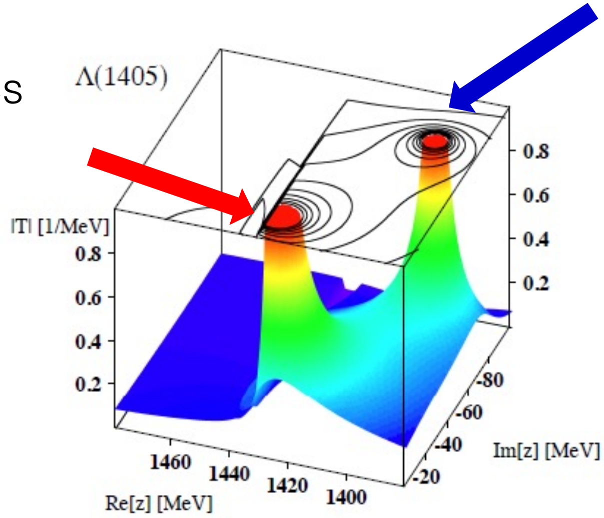


Molecular states

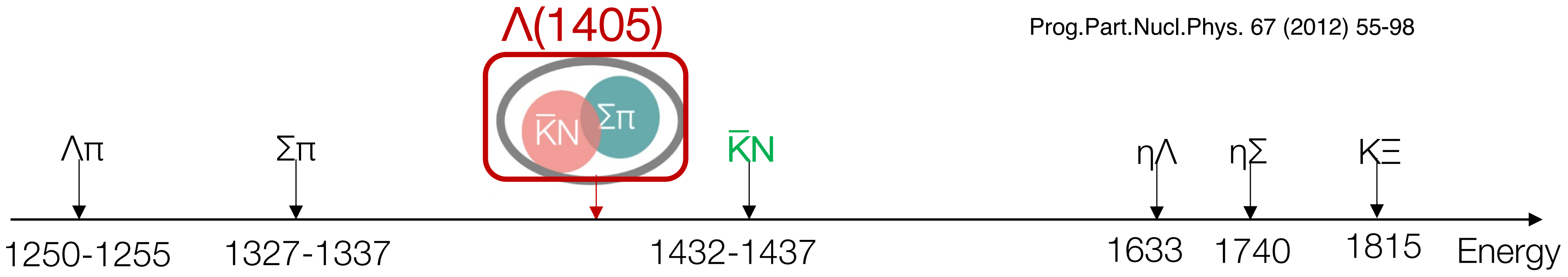
Λ(1405) is a dynamically generated resonances obtained solving coupled channel equation based on chiral dynamics (hadrons are the degrees of freedom)

For I=0 KN and $\Sigma\pi$ are the main contributor

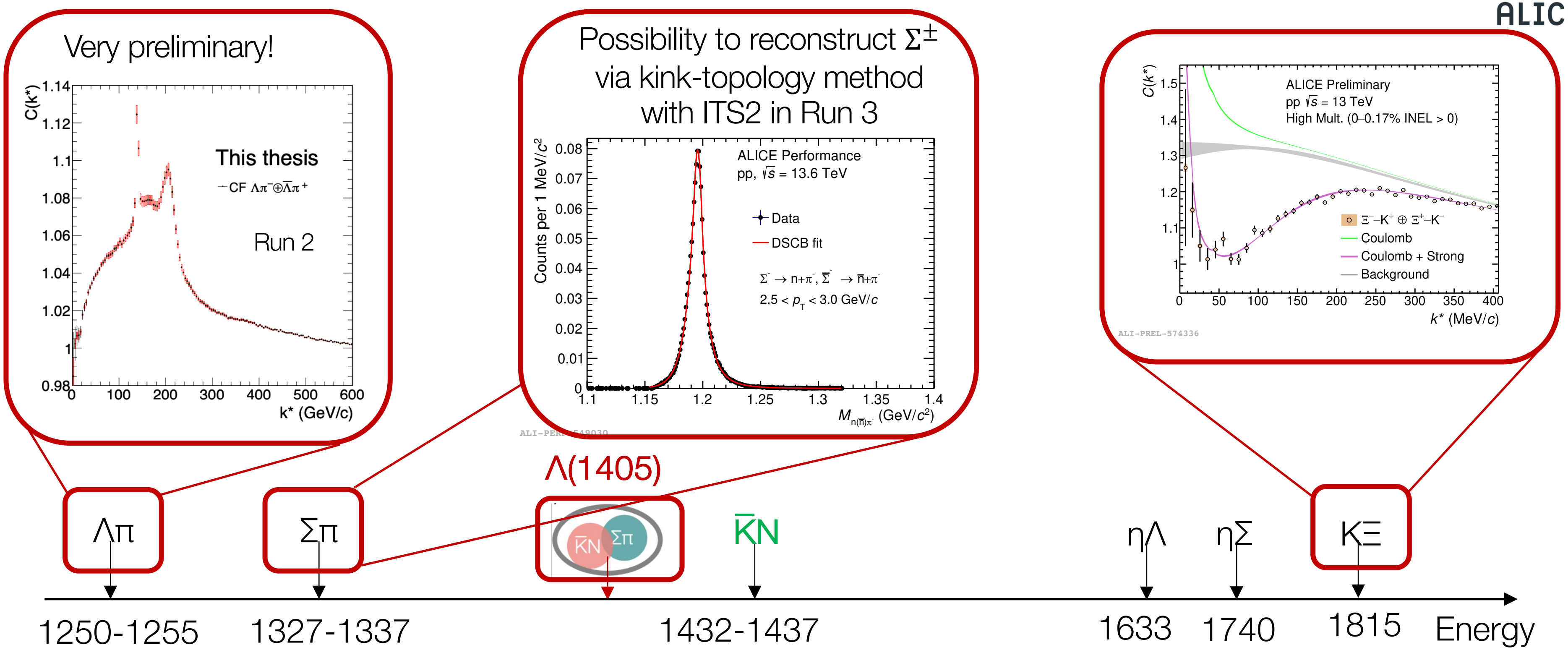
Two poles in complex energy plane:
m_1=1420 MeV (narrow quasi bound KN state)
m_2=1390 MeV (broad resonance in Sp)



Prog.Part.Nucl.Phys. 67 (2012) 55-98



Currently work in progress and outlooks for Run 3

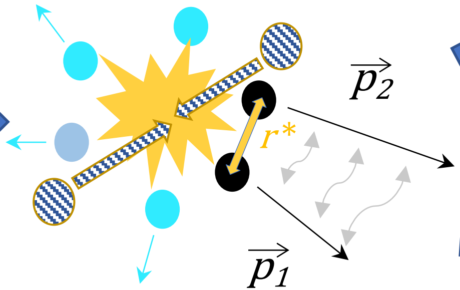


Pentaquark states in S=-3 sector with KΞ?
Feijoo, Vidaña arXiv: 2411.18248

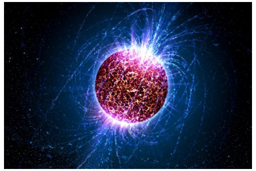
A new tool to study low energy QCD

ALICE at the LHC

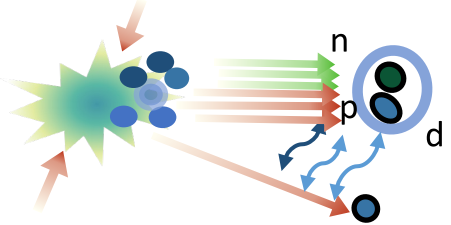
Femtoscopy in small systems



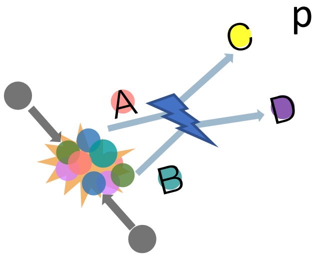
Study of Hyperon-nucleon, Hyperon-hyperon interactions relevant for Neutron Stars



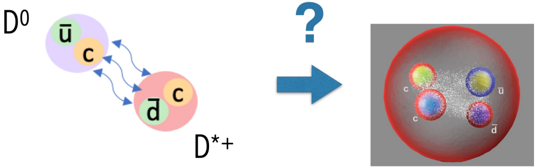
Nuclei formation



Direct access to coupled channels

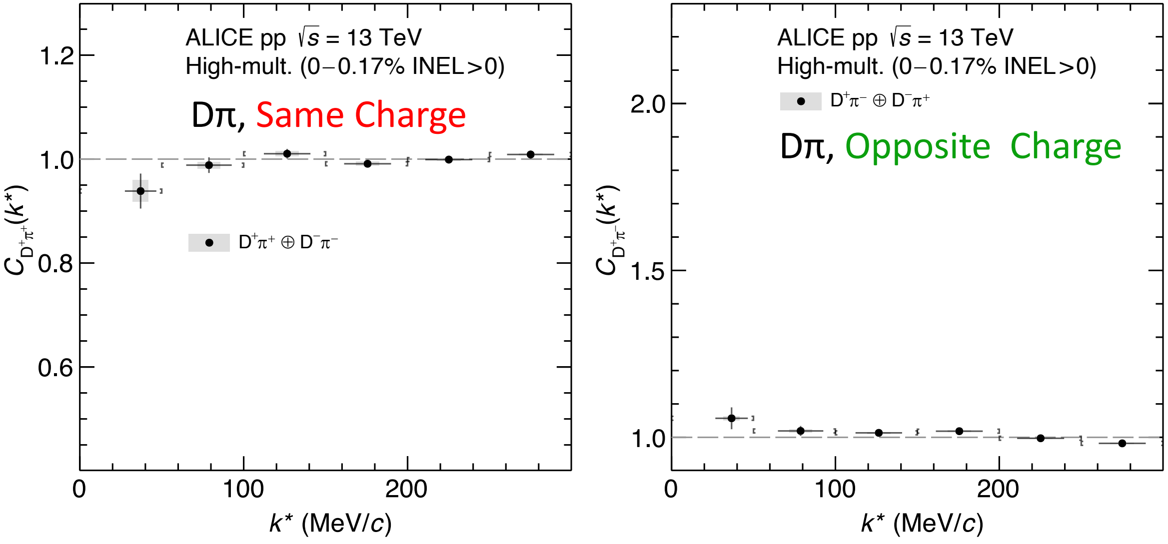


Final state interaction of charmed hadrons



D-π correlation function

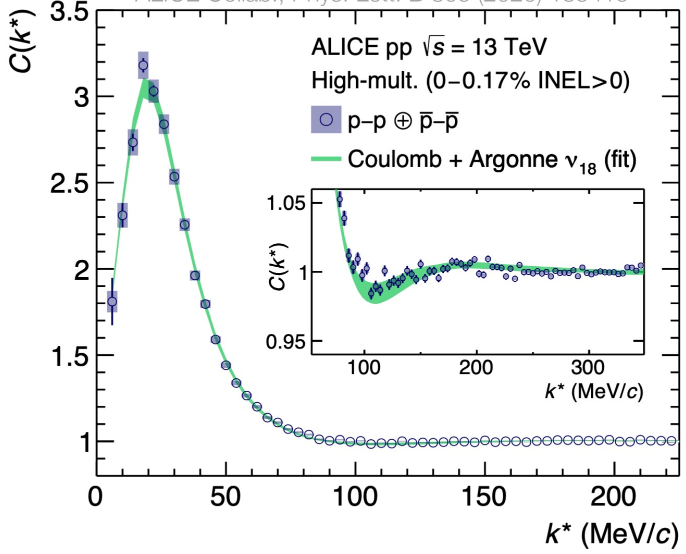
- Measurement of D(*)-K and D(*)-π correlation functions for same charge (SC) and opposite charge (OC) configuration
- Correction for feed-down, misidentifications etc. to extract **genuine CF** from data
- Sensitive to **Coulomb** and **strong** interaction



ALICE Coll. PRD **110** (2024) 032004

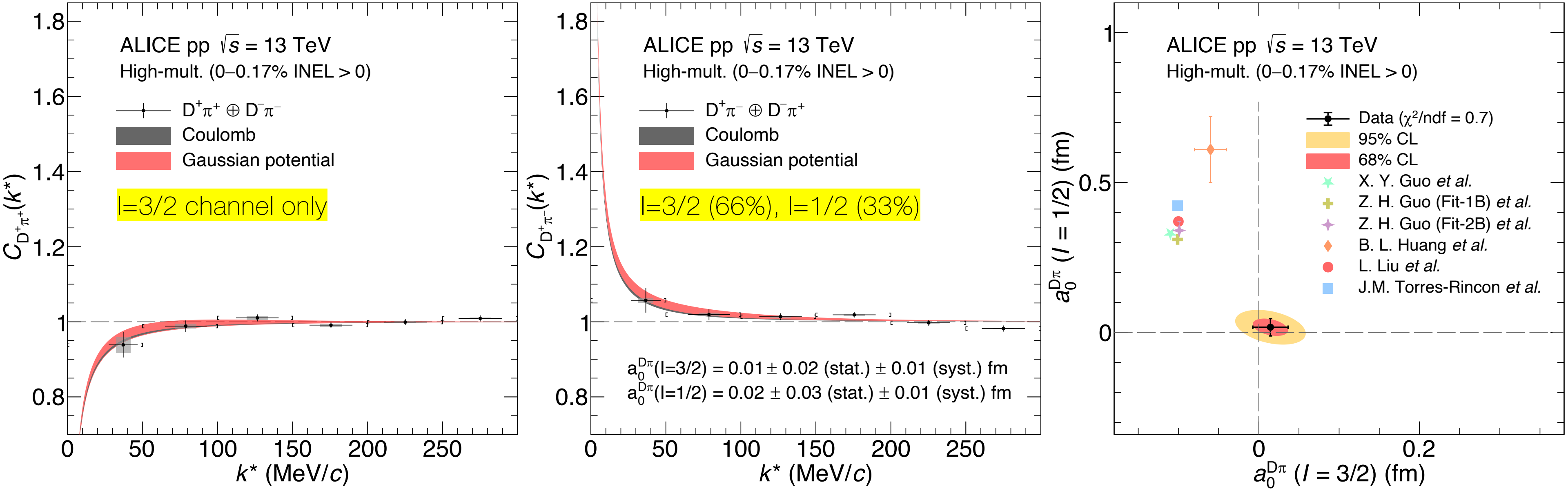
Comparison to NN system

ALICE Collab., Phys. Lett. B 805 (2020) 135419



Dπ correlation function fit

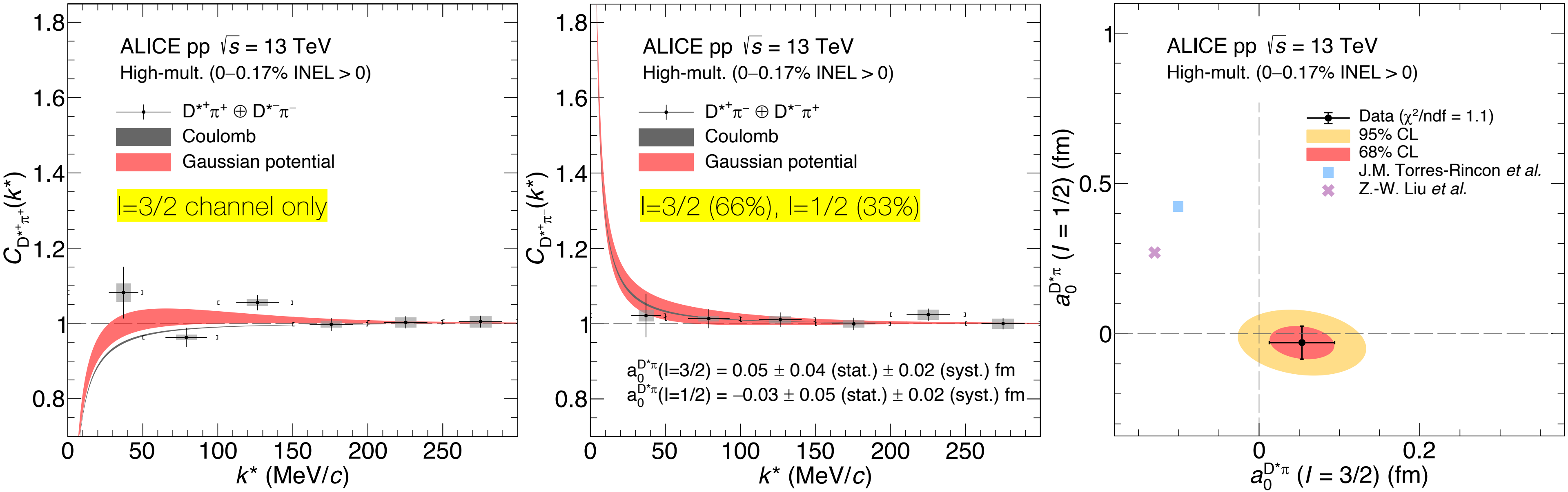
ALICE Coll., PRD **110** (2024) 032004



- Vanishing scattering parameters in both isospin channels
- Tension with theory especially in I=1/2 channel

D*π correlation function fit

ALICE Coll., PRD **110** (2024) 032004



- Vanishing scattering parameters within uncertainties
- Scattering parameters compatible with Dπ results → Heavy-quark spin symmetry

New theoretical approaches

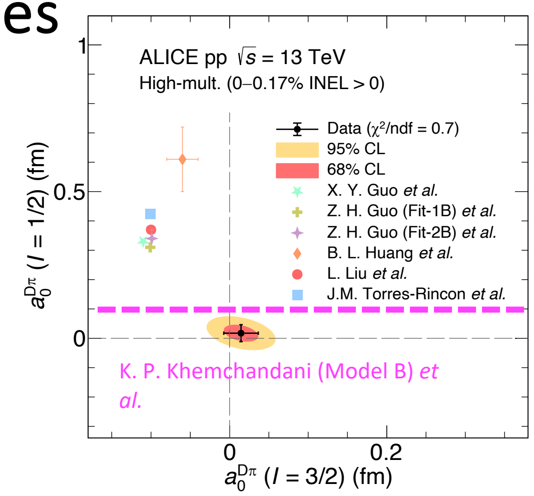
- Data inspired new theoretical calculations
- Smaller scattering length obtained $a_{D^*\pi}(I=1/2)=0.1$ fm, when considering molecular nature of D1 states (D1(2420) and D1(2430))

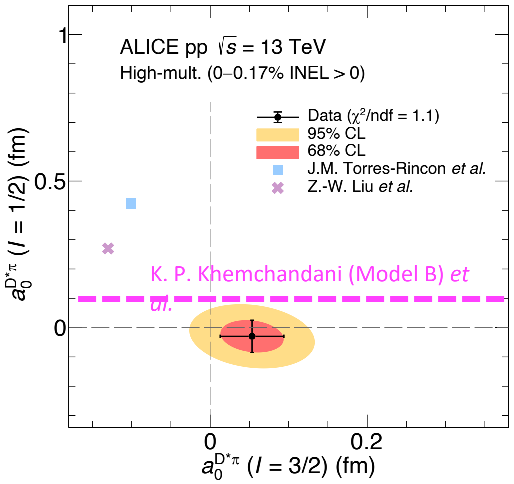
K. P. Khemchandani, L. M. Abreu, A. Martinez Torres, and F. S. Navarra, arXiv:2312.11811

  - Hidden gauge formalism with unitarization in coupled channels
  - D1(2430) explicitly added as bare quark-model pole structure to better accommodate it within experimental observations

  Belle Collaboration, Phys. Rev. D 69 (2004) 112002

  LHCb Collaboration Phys. Rev. D 92 (2015) 012012





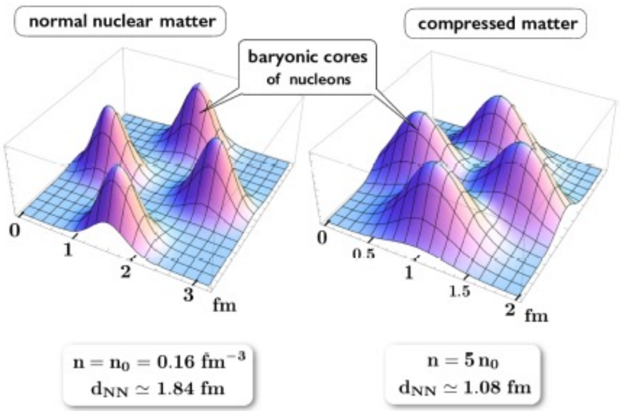
Summary

- The feasibility of the measurement of any hadron-hadron interaction at the LHC was demonstrated
- Three body systems are currently under investigation

- ALIC2@RUN3 : factor 100 more statistics in all channels

Stay tuned for much more to come…

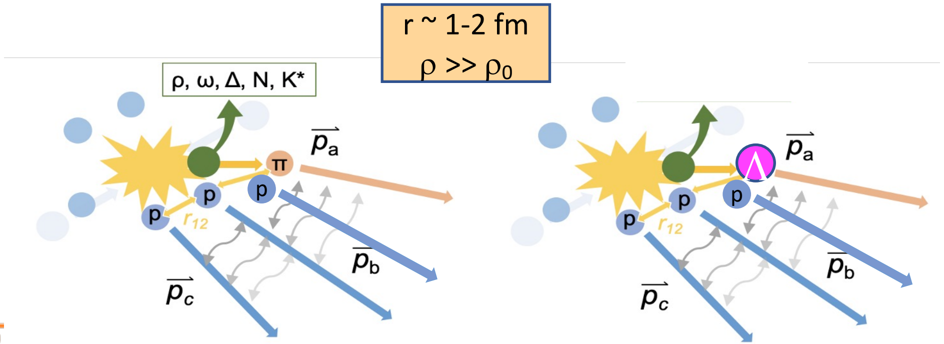
Short distances is the new high densities

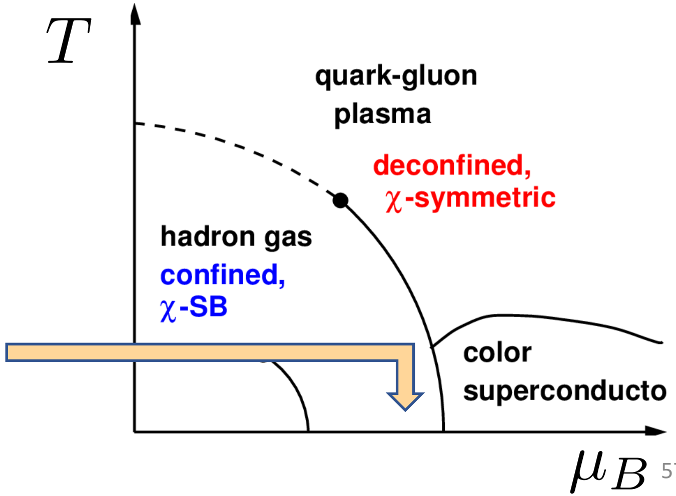


Future perspective:

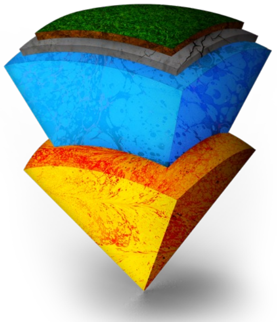
Three- and four-body interactions measured and intra-particle distances of ~1-1.5 fm will provide access to interaction at high densities and very low (?)b temperature

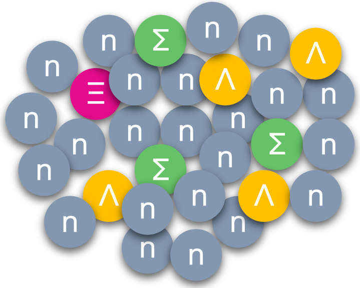
We can access the region of large μ_B at low temperatures





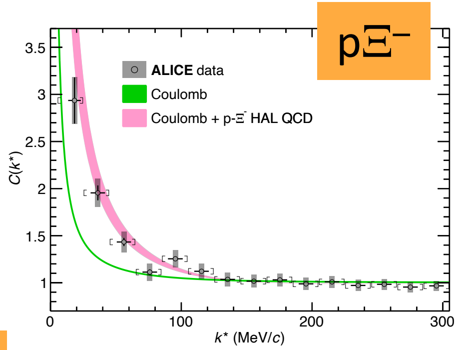
What is inside neutron stars?

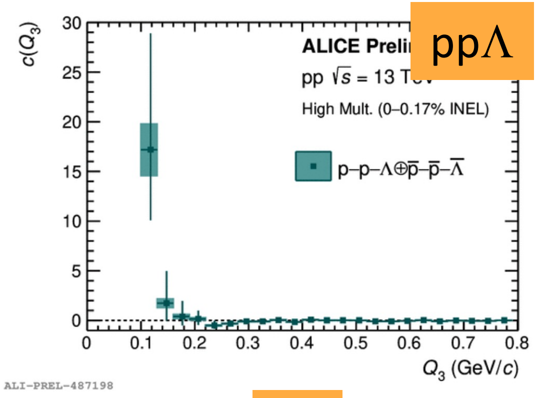


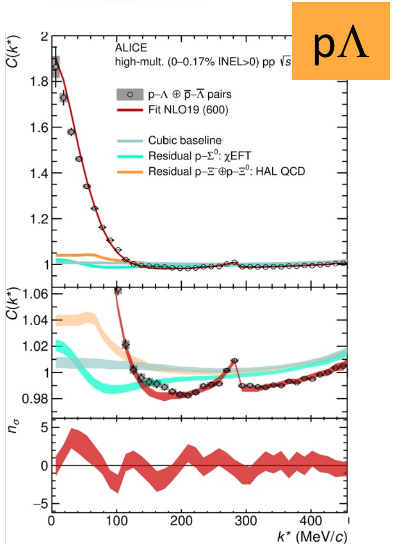


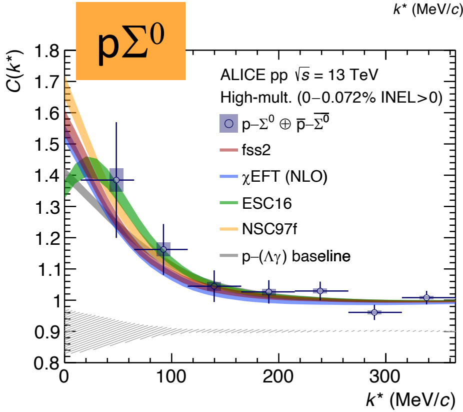
?

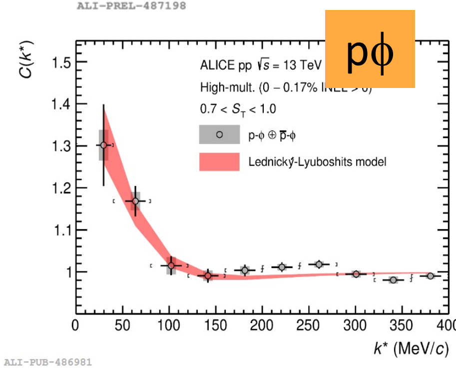
All two- and three-particle strong interactions can be measured at the LHC!



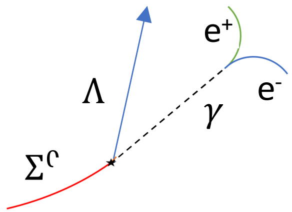


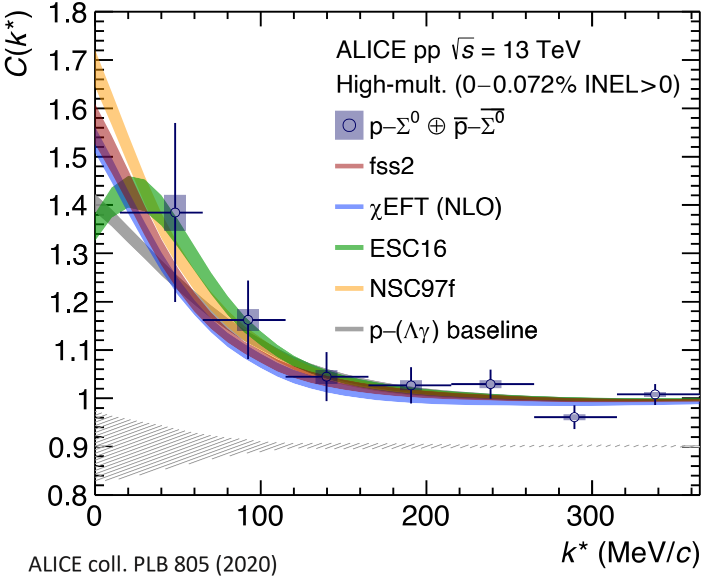




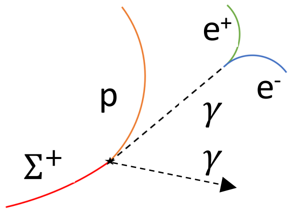


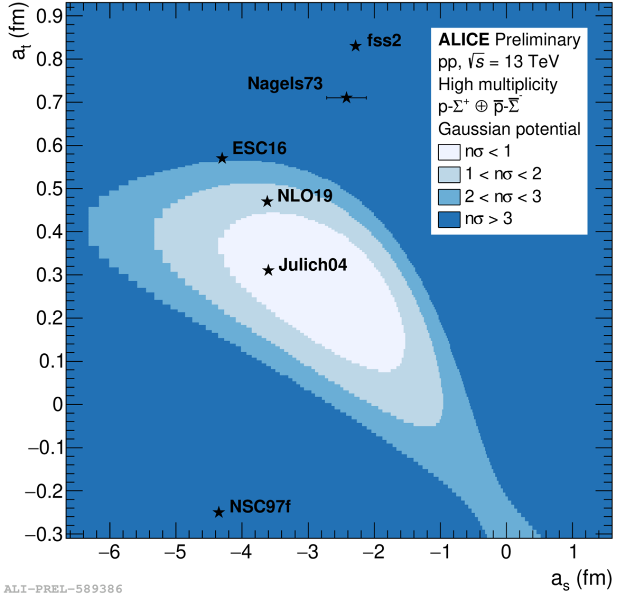
$|S|=1$: PΣ^0 and PΣ^+





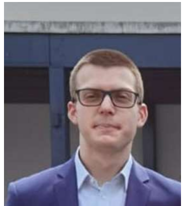
ALICE coll. PLB 805 (2020)





A. Mathis
TUM

B. Heybeck
Uni. Frankfurt



D-light meson scattering lengths

Pair	(S,I)	L. Liu et al.	X.-Y. Guo et al.	Z.-H. Guo et al. Fit-1B	Z.-H. Guo et al. Fit-2B	B.-L. Huang et al.	J. M. Torres-Rincon et al.	Z.-W. Liu et al.
D(*)π	(0,3/2)	-0.10 fm	-0.11 fm	-0.101 fm	-0.099 fm	-0.06 fm	-0.101 fm	-0.12-i0.00036 fm
	(0,1/2)	0.37 fm	0.33 fm	0.31 fm	0.34 fm	0.61 fm	0.423 fm	0.27-i0.00036i fm
D(*)K	(1,1)	0.07+i0.17 fm	-0.05 fm	0.06+i0.30 fm	0.05+i0.17 fm	-0.01 fm	-0.027+i0.083 fm	-0.22+i0.18 fm
D(*)$\bar{K}$	(-1,0)	0.84 fm	0.46 fm	0.96 fm	0.68 fm	1.81 fm	0.399 fm	-0.19-i1.7*10^{-6} fm
	(-1,1)	-0.20 fm	-0.22 fm	-0.18 fm	-0.19 fm	-0.24 fm	-0.233 fm	0.29+i5.2*10^{-6} fm

D-mesons

D*-mesons

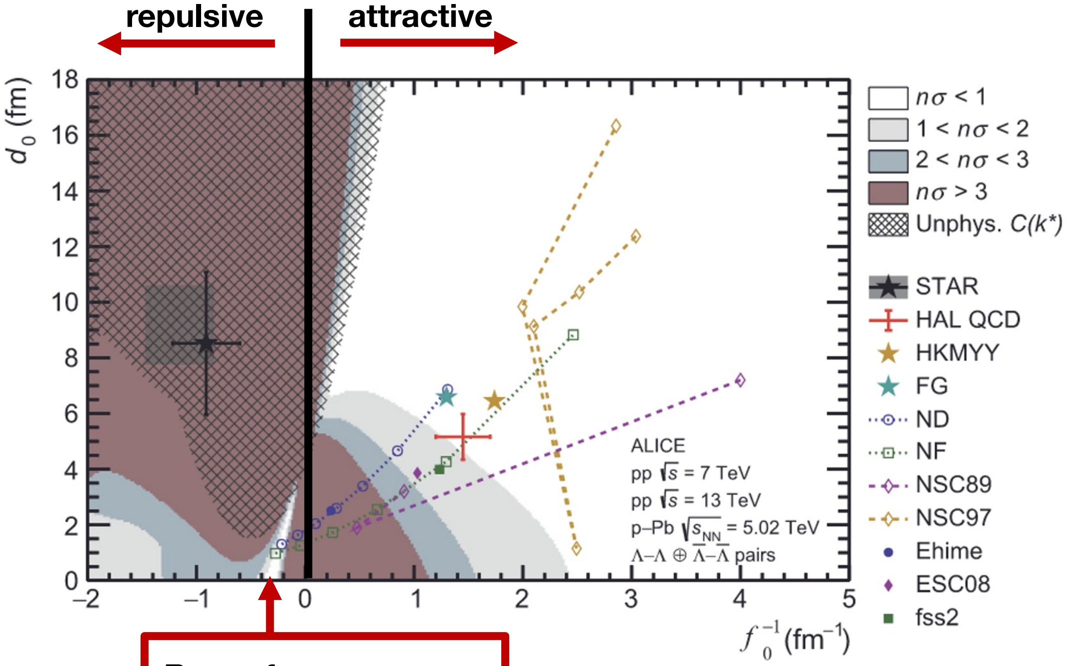
Go from isospin (theory) to charge (data) basis using Clebsch-Gordan coefficients

L. Liu et al., Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al., Phys. Rev. D 98 (2018) 014510
Z.-H. Guo et al., Eur. Phys. J. C 79 (2019) 13
B.-L. Huang et al., Phys. Rev. D 105 (2022) 036016
J. M. Torres-Rincon et al., Phys. Rev. D 108 (2023) 096008
Z.-W. Liu et al., Phys. Rev. D 84 (2011) 034002

|S|=2 : ΛΛ scattering parameters

- Important for existence of H-dibaryon
- ΛΛ correlation measured in pp MB 7, 13 TeV and p-Pb 5.02 TeV
- Scan in scattering parameter space (f_0^{-1}, d_0) and express agreement data/model in number of σ deviations
  - Agreement with hypernuclei data and lattice predictions
- Most precise upper limit on the binding energy of the H-dibaryon

$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\mathrm{stat})^{+1.8}_{-1.0}(\mathrm{syst})$ MeV



Room for a shallow bound state

ALICE Coll. Phys.Lett.B 797 (2019) 134822

D.Mihaylov
TUM/Sofia Uni

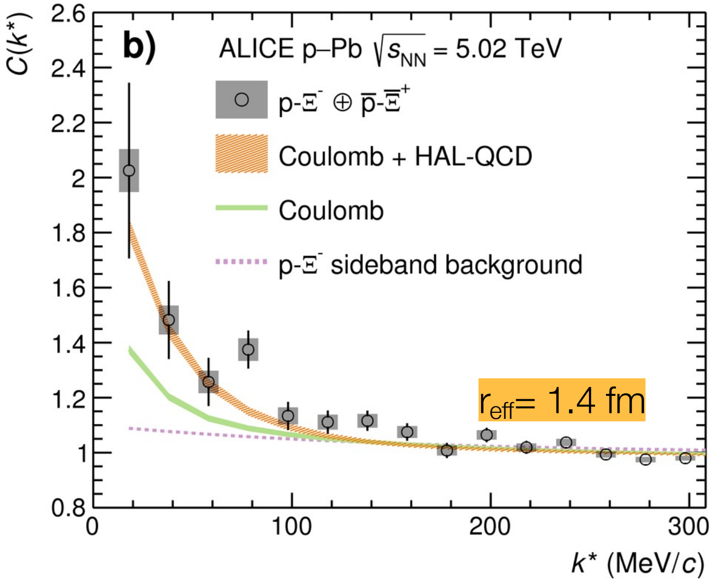
|S|=2: PΞ^- test lattice potentials

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems

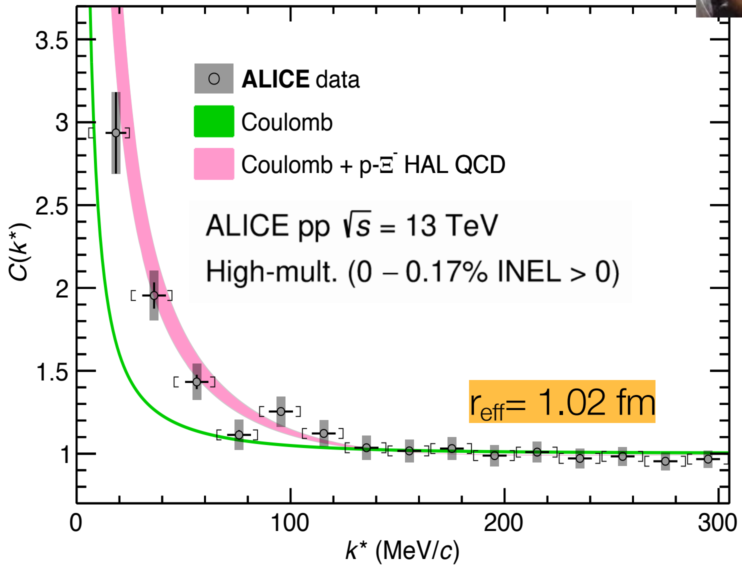
O. Vazquez-Doce
INFN Frascati

B. Holweger
TUM

ALICE Coll, Phys. Rev. Lett 123, (2019) 112002



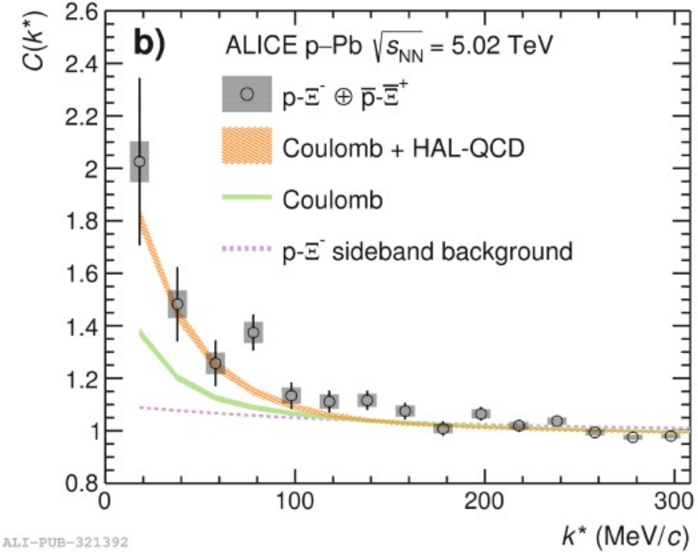
ALICE Coll. Nature 588, 232–238 (2020)

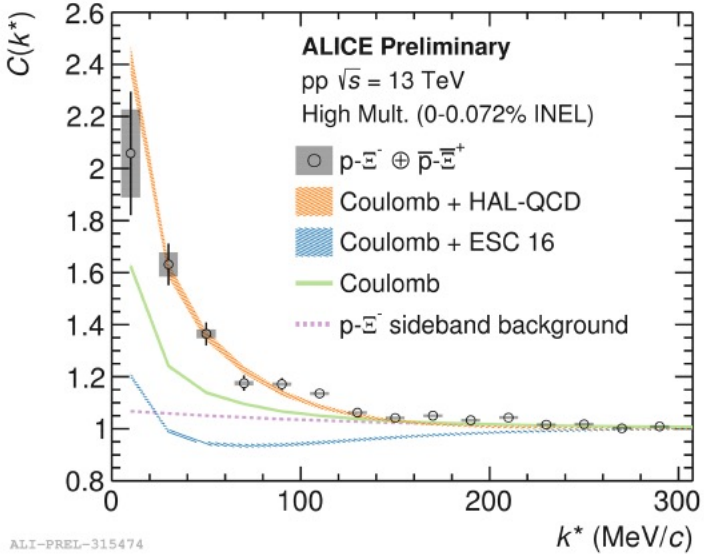


(*) HAL QCD Coll., PoS INPC2016 (2016) 277

pΞ^- Comparisons to ESC08

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

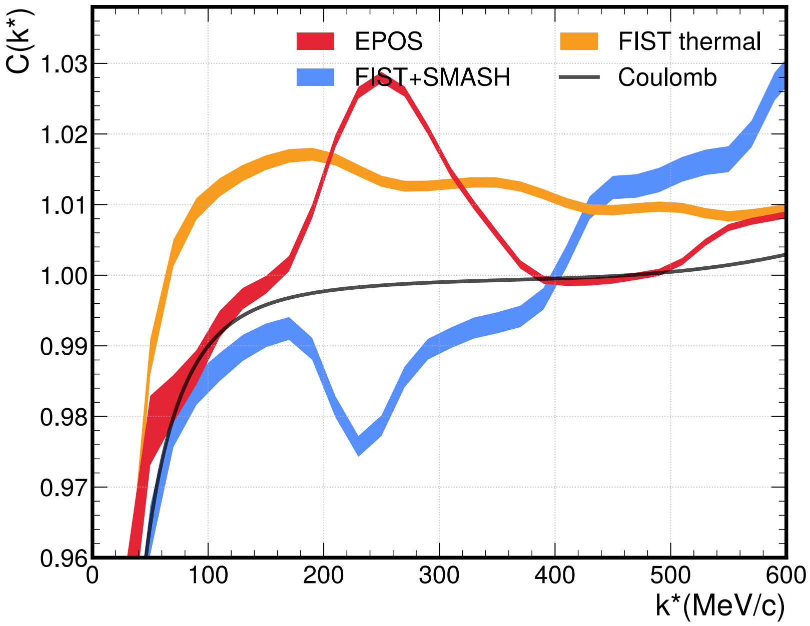




Model Studies

EPOS 3+Coalescence, FIST + π+d-scattering

[1] Mahlein et al., EPJC 83 (2023) 9, 804



- Predictions of πd correlation function using thermal and coalescence models
- **Coalescence[1]** model that reproduces the deuteron spectra from the same data set without any free fit parameter is employed.
- **EPOS+ Coalescence[1]** clear bump (Δ-yields tuned to ThermalFIST)
- **Thermal FIST** input leads to a trivial baseline
- **Removing pairs** where the π and one Nucleon stem from a Δ removed the bump entirely
- **Only elastic** interaction: no enhancement. Due to momentum conservation **no change in k* is expected**
- **Elastic+Inelastic**: massive reduction due to deuteron **destruction**