Searches for exotic bound states with femtoscopy

V. Mantovani Sarti (TUM)

SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms
ECT* Trento 13-17 May 2024

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SFB 1258 Neutrinos Dark Matter Messengers

Deutsche Forschungsgemeinschaft
MA 8660/1-1

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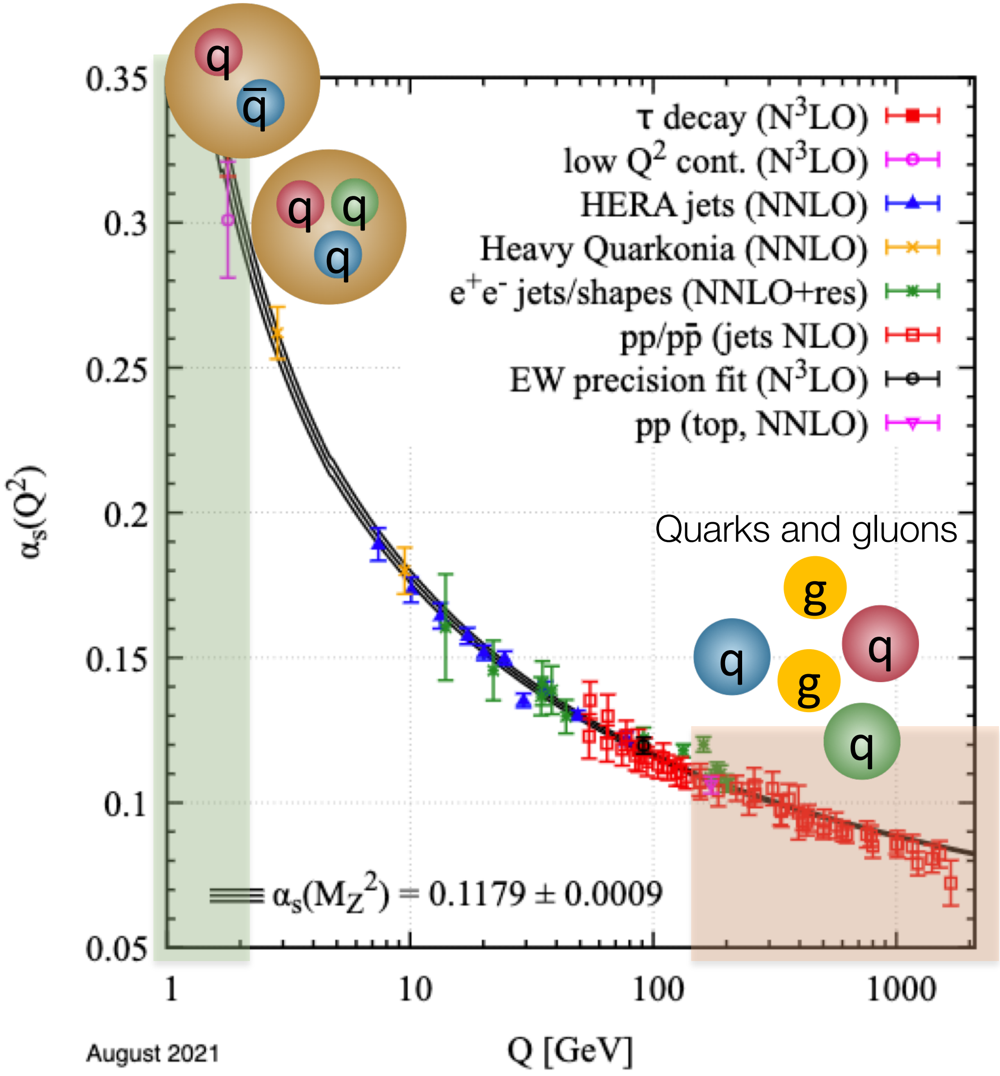
Strong interaction between hadrons

Mesons and baryons



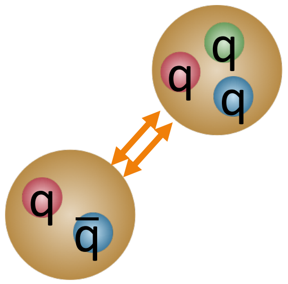
PDG, Prog.Theor.Exp.Phys 2022, 083C01(2022)

- Understanding how QCD evolves from high-energy to low-energy regime

How do hadrons emerge?

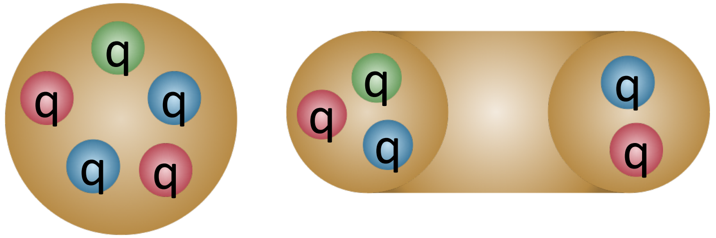
How do hadrons interact?

2-body and many-body interactions



How is the QCD spectrum organized?

Bound states/resonances
Conventional and exotic states



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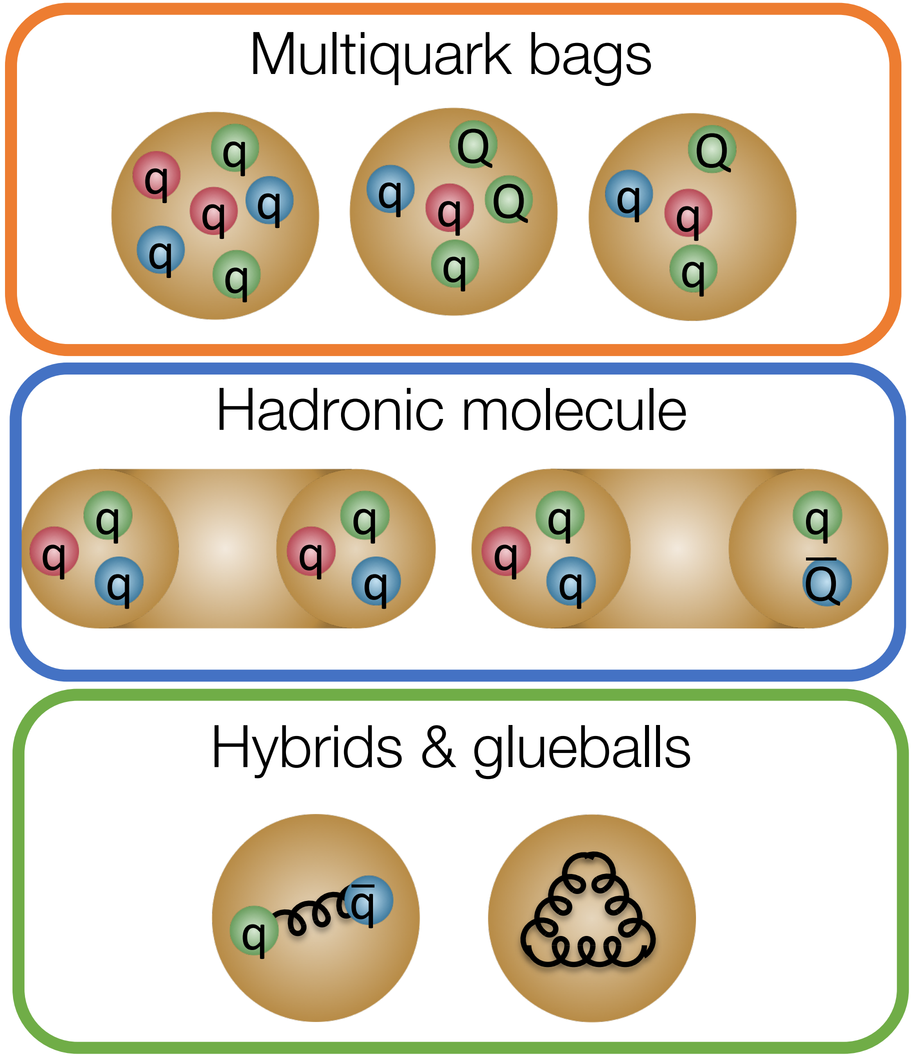
Exotic states in QCD and where to find them

- Multiquark bags
  - Many candidates in the **heavy-quark sector**
    $T^{a}_{cs0}(2900)^{++,0}$*: LHCb Coll. PRL 131 (2023) 4, 041902*
  - Candidates also in **light sector**
    → Very broad states, very challenging!
    PDG: Review on light meson spectroscopy
- Hadronic molecules
  - Candidates in heavy-quark sector, e.g T^{+}_{cc}
  - Case of the Λ(1405), similar candidates in other meson-baryon strangeness sectors, e.g. Ξ(1620)
- And more…

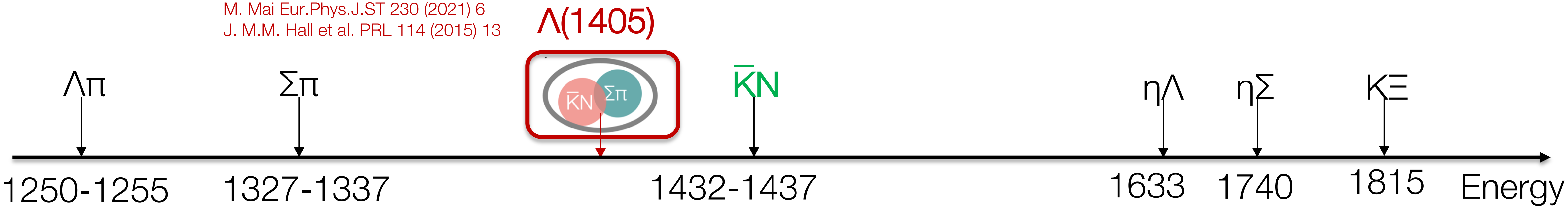
Today we will focus on strange molecular states!



Strange molecular states and where to find them

Interactions with rich coupled-channel dynamics → Typically observed close to channel thresholds

M. Mai Eur.Phys.J.ST 230 (2021) 6
J. M.M. Hall et al. PRL 114 (2015) 13



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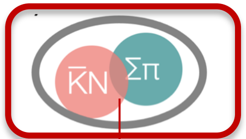
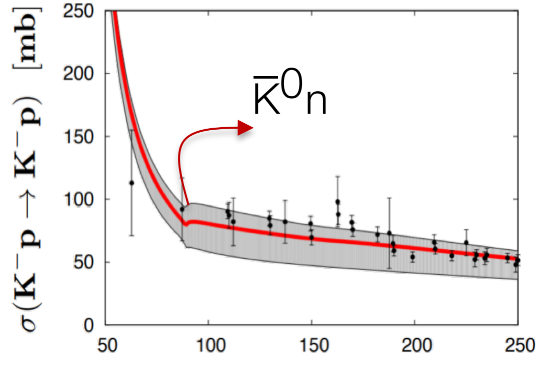
Λ(1405)

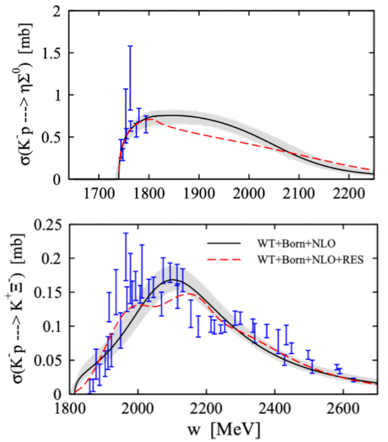


Kaonic hydrogen
SIDDHARTA PLB 704 (2011)

Scattering experiments

Ikeda et al. NPA 881 (2012)



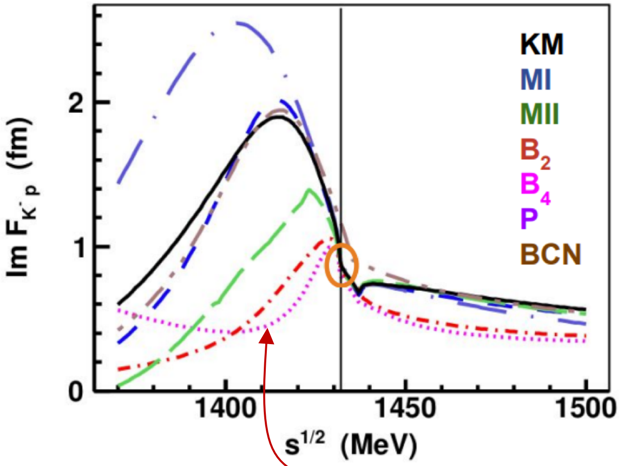


Data: K-p → X and NLO UχPT calculations
A. Feijoo, V. Magas, A. Ramos Phys.Rev.C 99 (2019) 3

Λπ — 1250-1255
Σπ — 1327-1337
K̄N — 1432-1437
ηΛ — 1633
ηΣ — 1740
KΞ — 1815
Energy

Strange molecular states and where to find them

Interactions with rich **coupled-channel dynamics** → Typically observed **close to channel thresholds**



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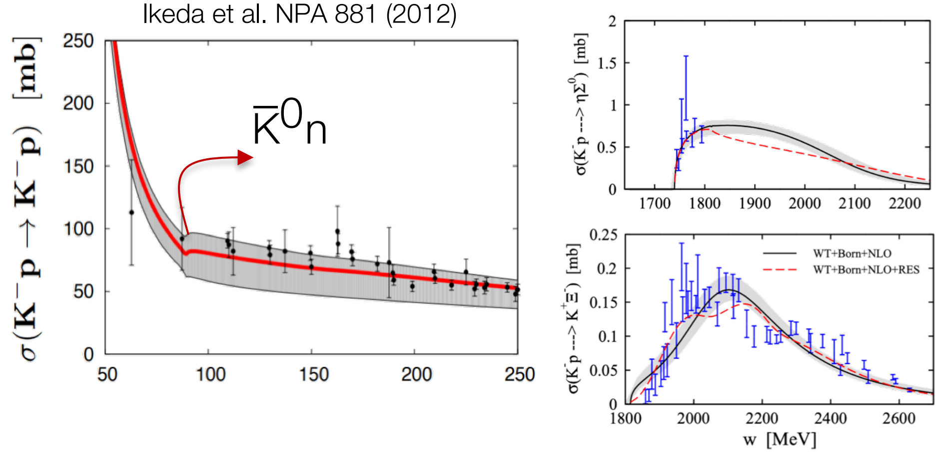

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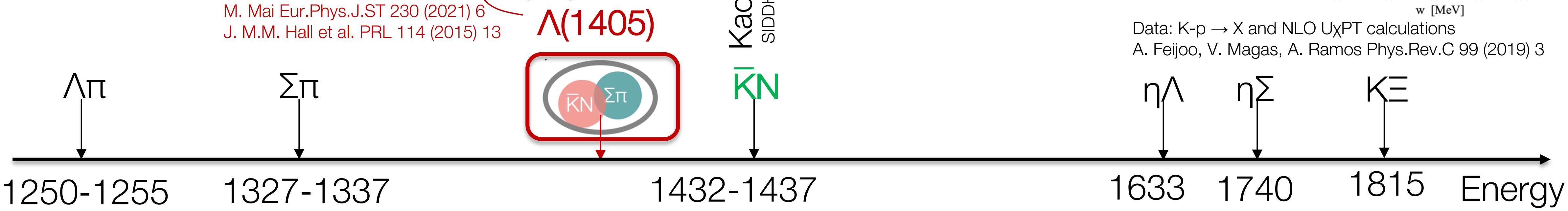
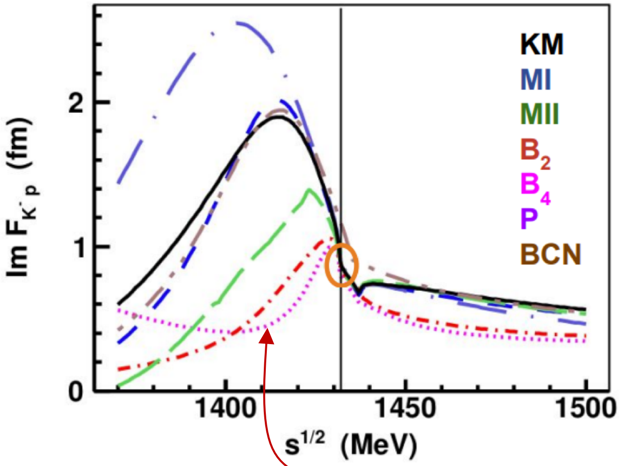


Strange molecular states and where to find them

Interactions with rich coupled-channel dynamics → Typically observed close to channel thresholds



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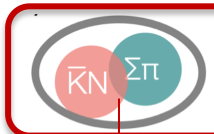
Λ(1405)

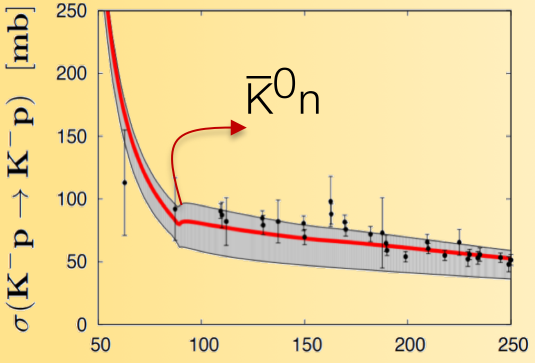


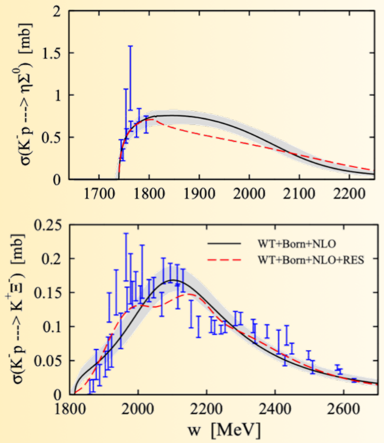
Kaonic hydrogen
SIDDHARTA PLB 704 (2011)

?

Scattering experiments

Ikeda et al. NPA 881 (2012)





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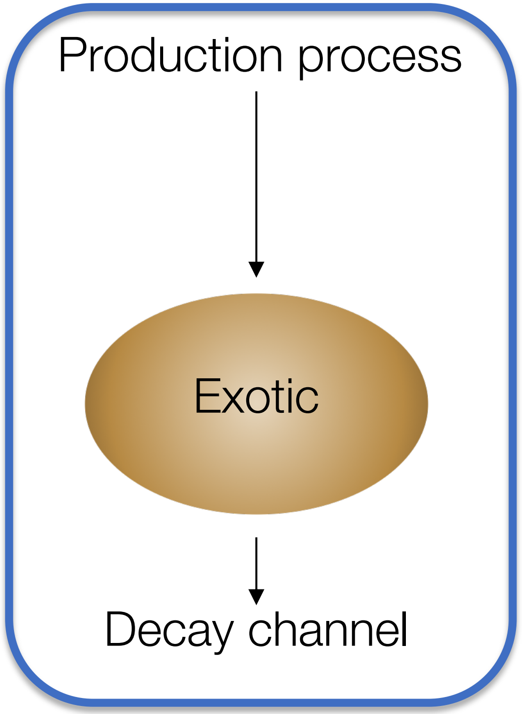
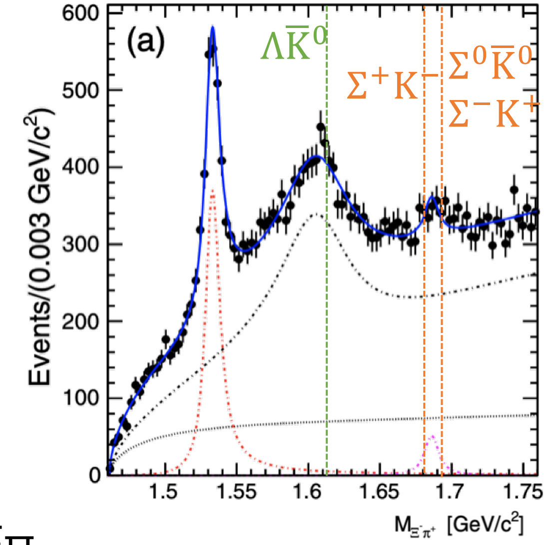
Λπ	Σπ	K̄N	ηΛ	ηΣ	KΞ	
1250-1255	1327-1337	1432-1437	1633	1740	1815	Energy

Need for experimental constraints on as many channels as possible

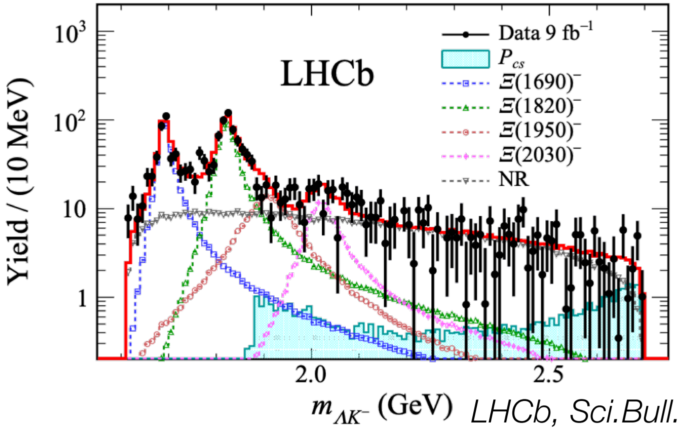
More strange molecular states and where to find them

Scattering experiments challenging with increasing strangeness
→ Intensive searches via spectroscopy measurements with different production mechanism





Belle, PRL 122 (2019)



LHCb, Sci.Bull. 66 (2021)

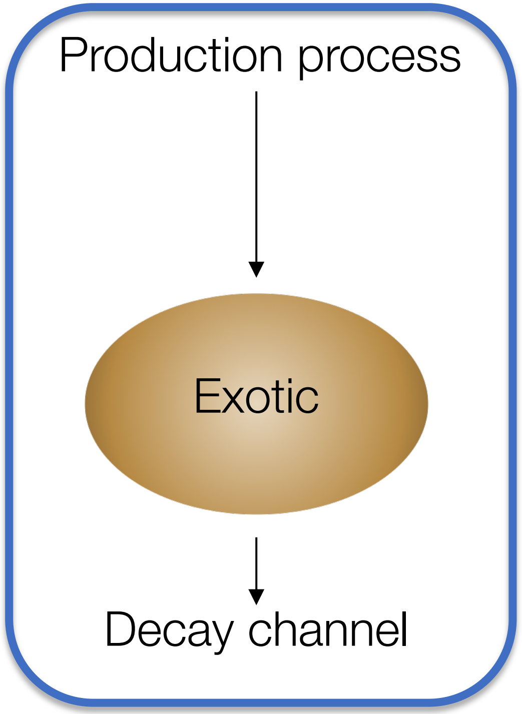
Ξ(1620) Ξ(1690)

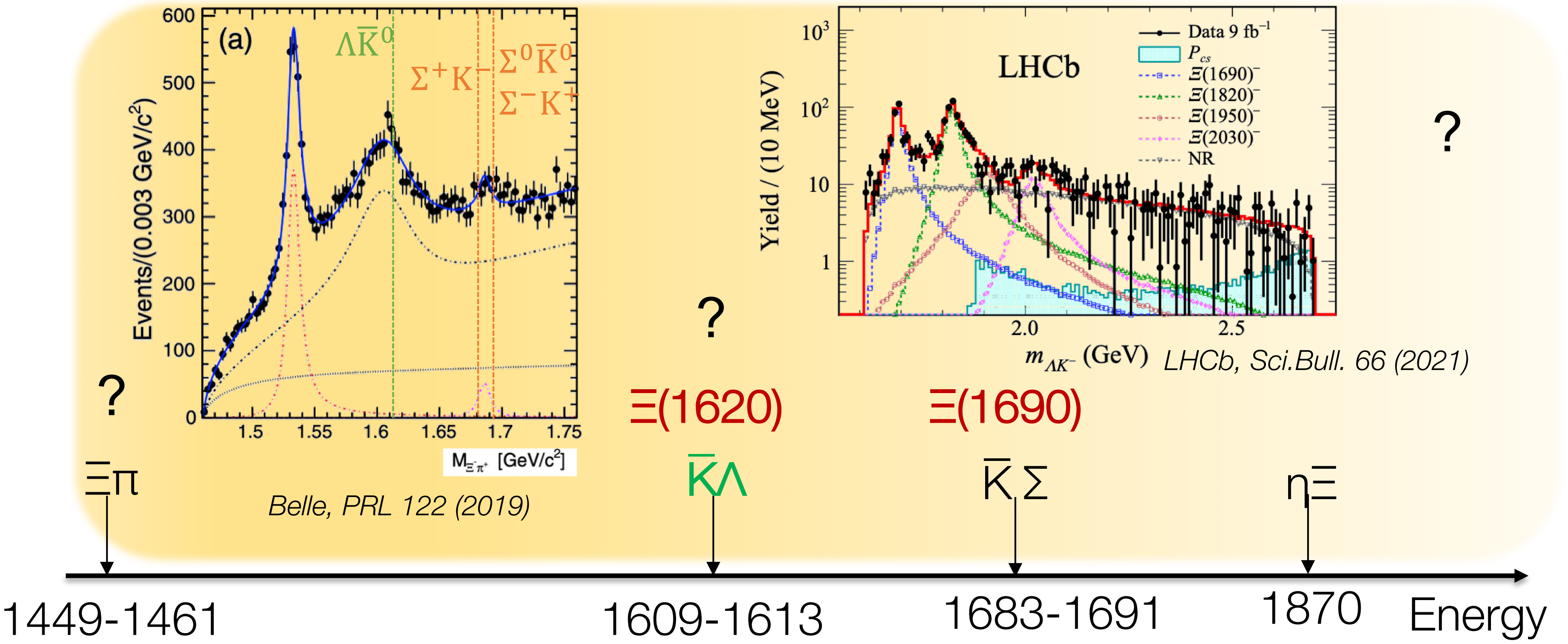
Ξπ	$\bar{K}\Lambda$	$\bar{K}\Sigma$	ηΞ	
1449-1461	1609-1613	1683-1691	1870	Energy

Combine different production mechanisms/decay channels to reveal the state's nature

More strange molecular states and where to find them

Scattering experiments challenging with increasing strangeness
→ Intensive searches via spectroscopy measurements with different production mechanism

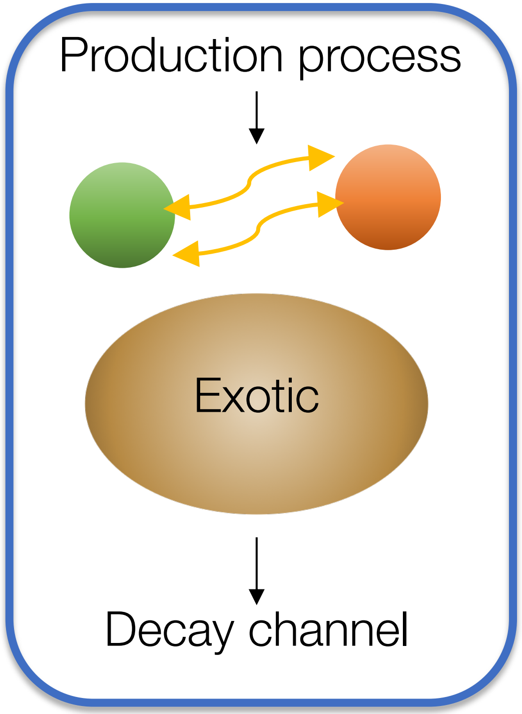


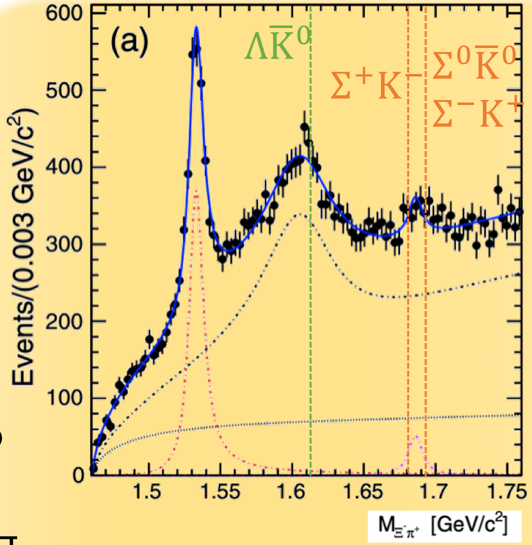


Combine different production mechanisms/decay channels to reveal the state's nature

More strange molecular states and where to find them

Scattering experiments challenging with increasing strangeness
→ Intensive searches via **spectroscopy measurements** with **different production mechanism**





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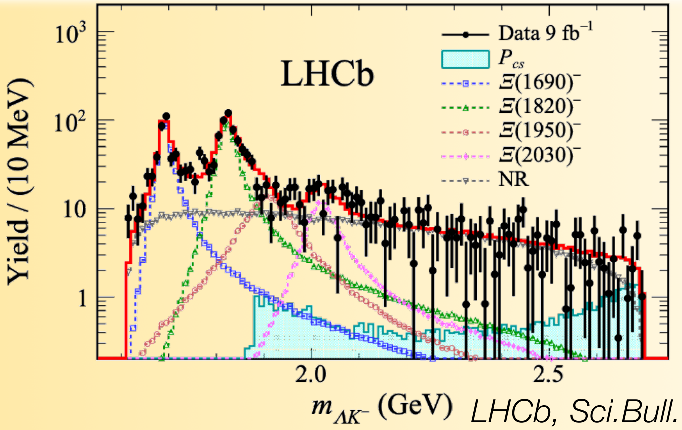


LHCb, Sci.Bull. 66 (2021)

Channel	$\Xi\pi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$
State	?	$\Xi(1620)$?	$\Xi(1690)$	?
Energy	1449-1461	1609-1613	1683-1691	1870

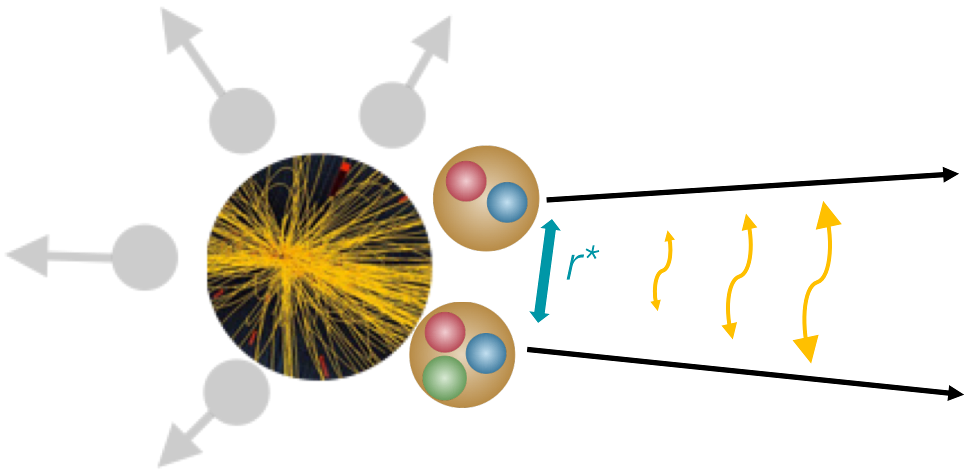
Energy

Accessing the interaction between the constituents

Investigating exotic states with correlations

- Accessing interaction between the constituents with correlation functions measured in pp collisions
  M.Lisa, S. Pratt et al, ARNPS. 55 (2005), 357-402, L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

$$C(k^*) = \int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*) \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$



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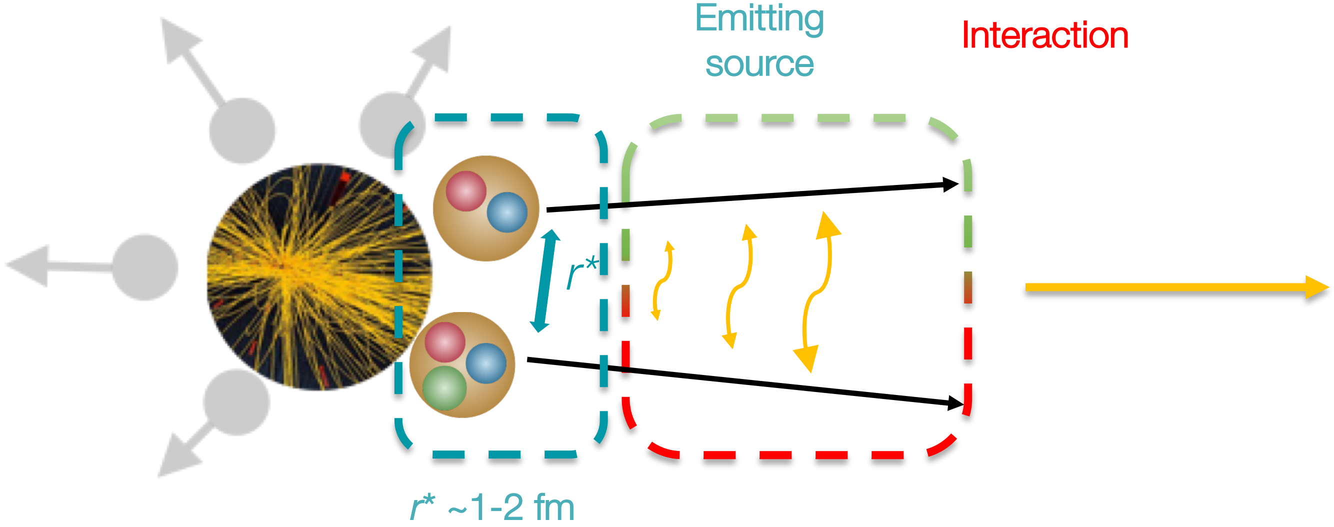
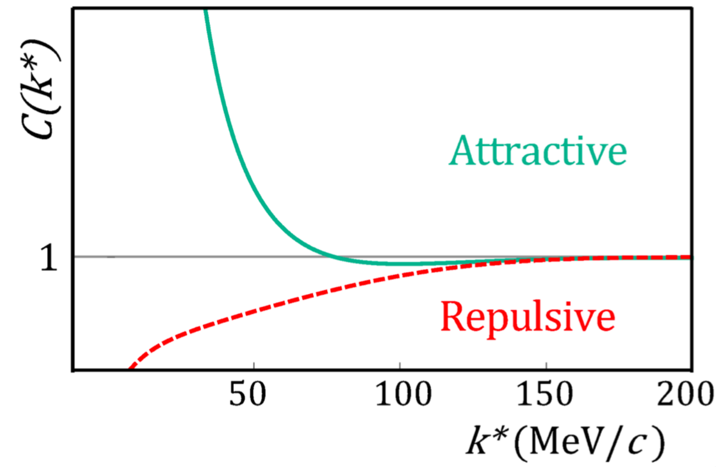
Emitting source

Interaction



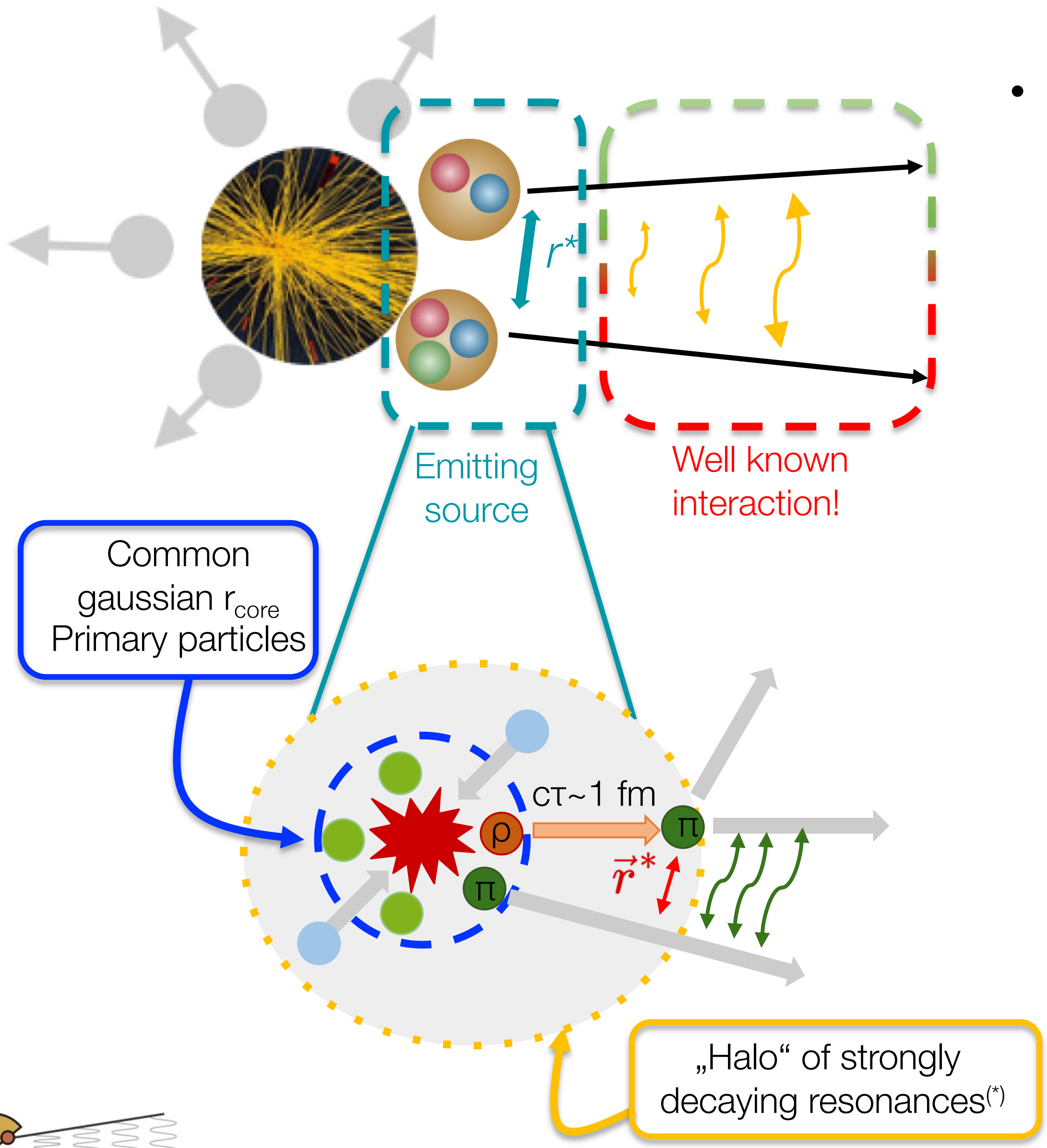
ALICE Coll. Nature 588 (2020) 232-238



Correlation mapping 1-to-1

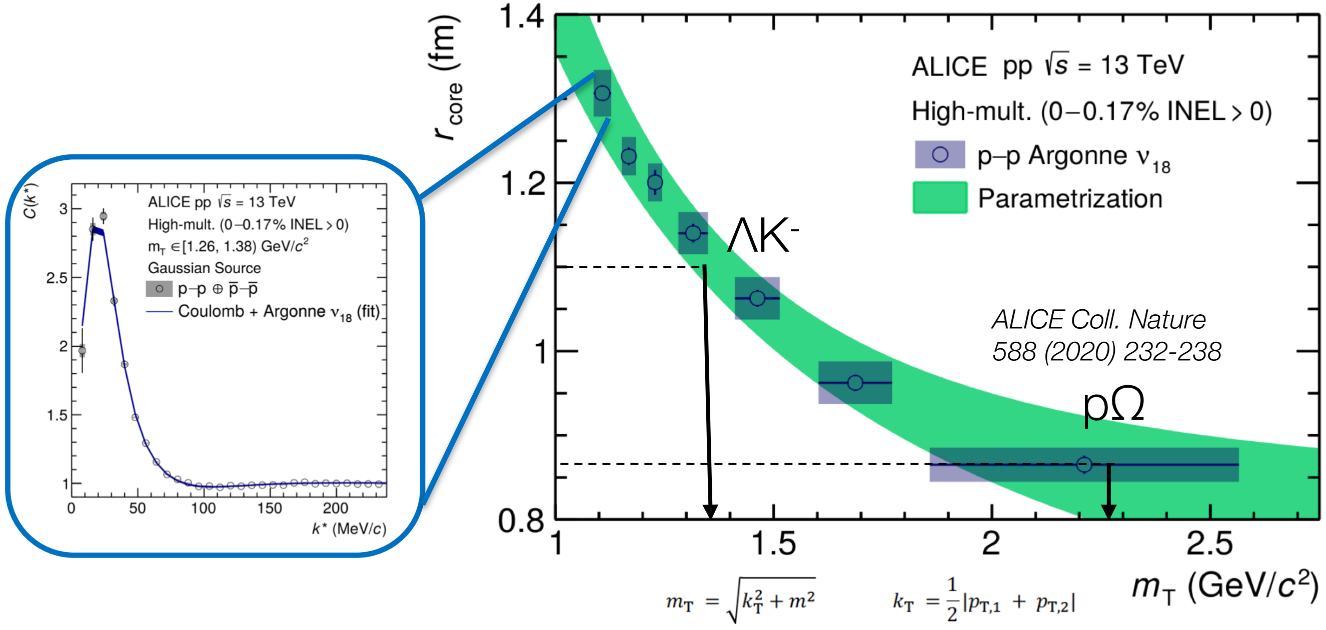
the nature of the interaction

The emitting source in pp collisions



- Modeled in a data-driven way using p-p correlations, most known interaction!!

Based on ALICE Coll. PLB 811 (2020) 135849
(*) U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)

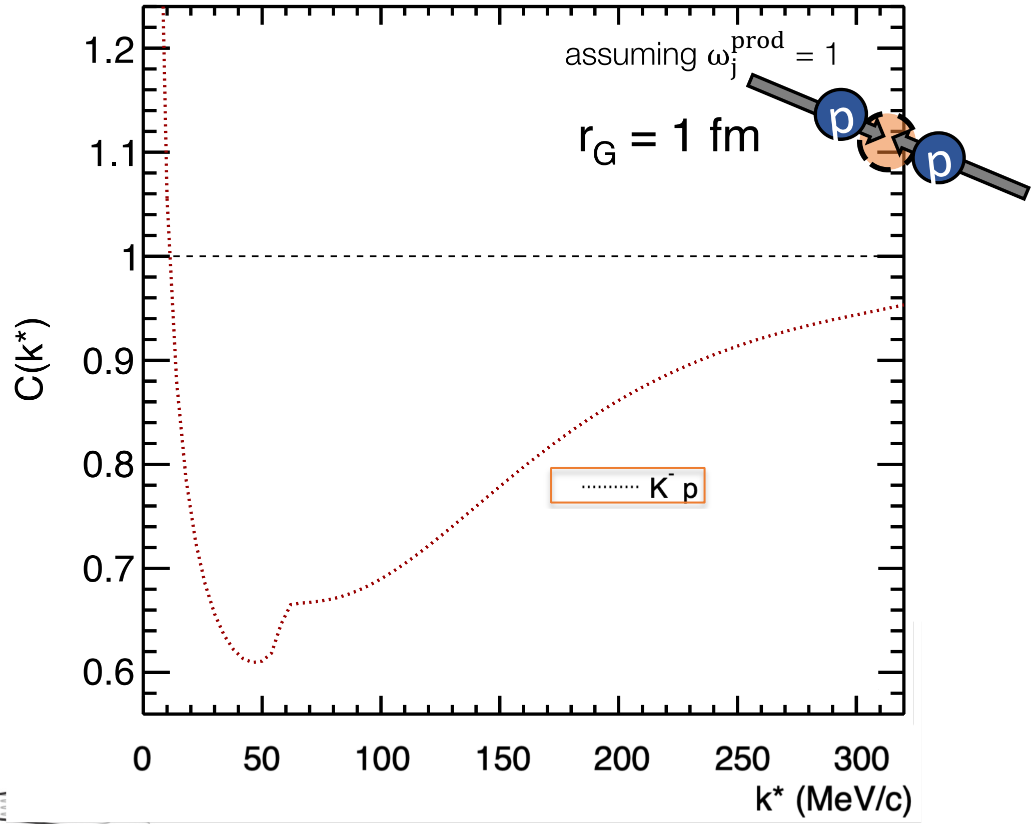


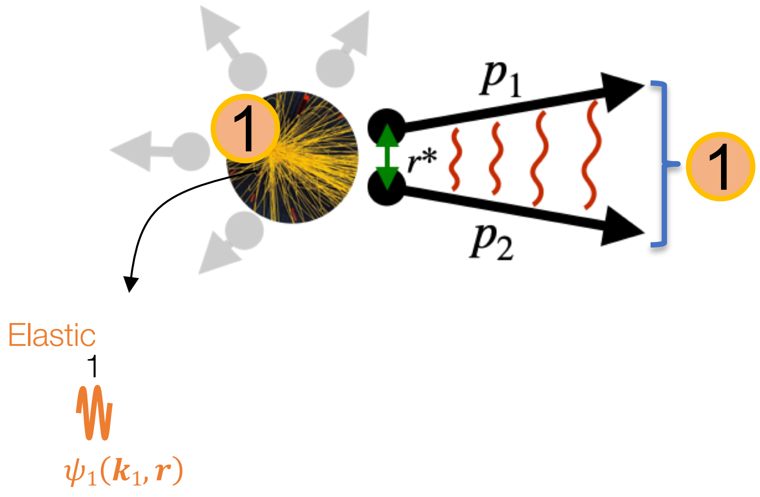
- Fixing of the source at corresponding <m_T>
  → Direct access to the interaction
  → Interparticle distances ~1-2 fm

Coupled-channels dynamics in correlations

$$C(k^*) = \int S_1(\vec{r}^*)\ \left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^*$$

elastic
1 → 1

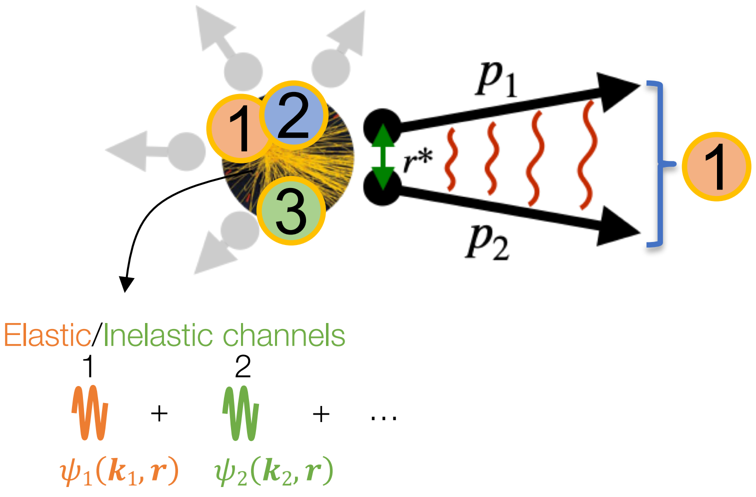


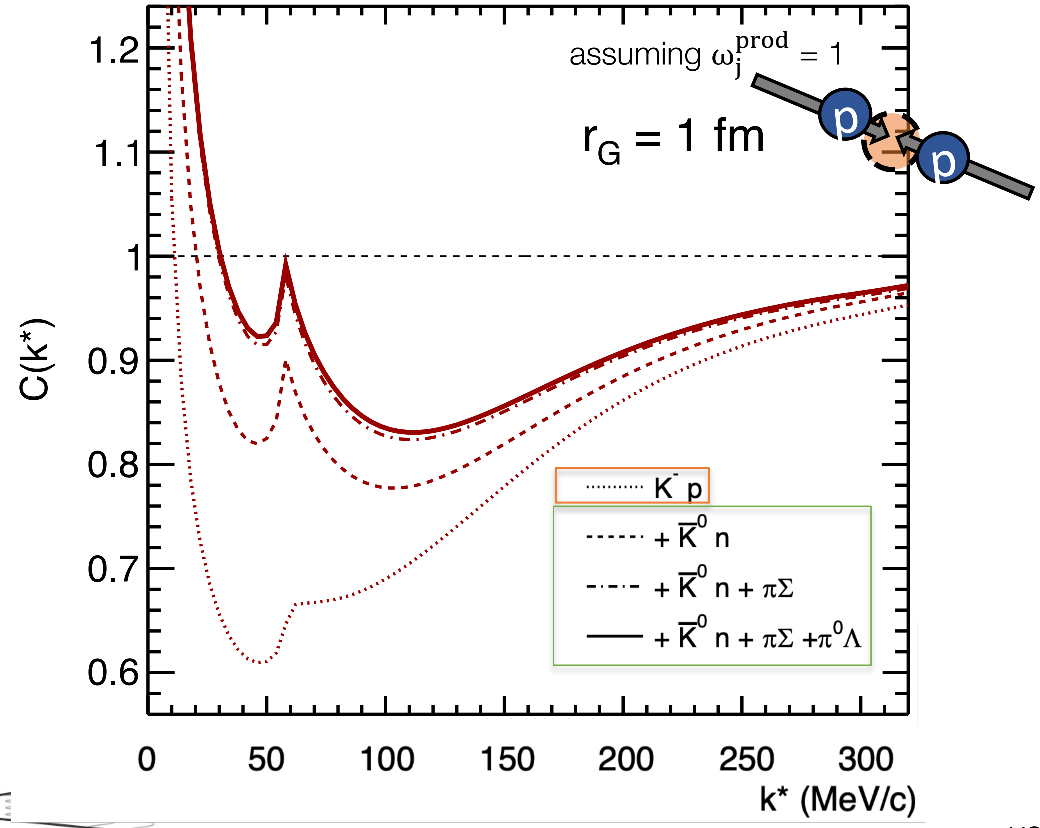


For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Coupled-channels dynamics in correlations

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



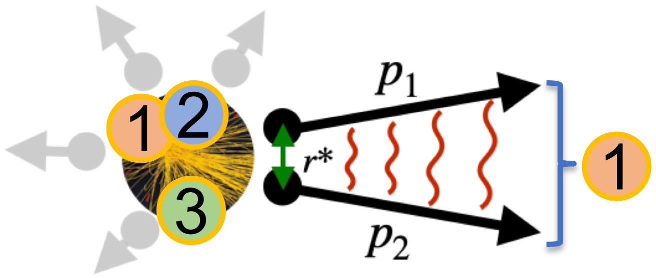


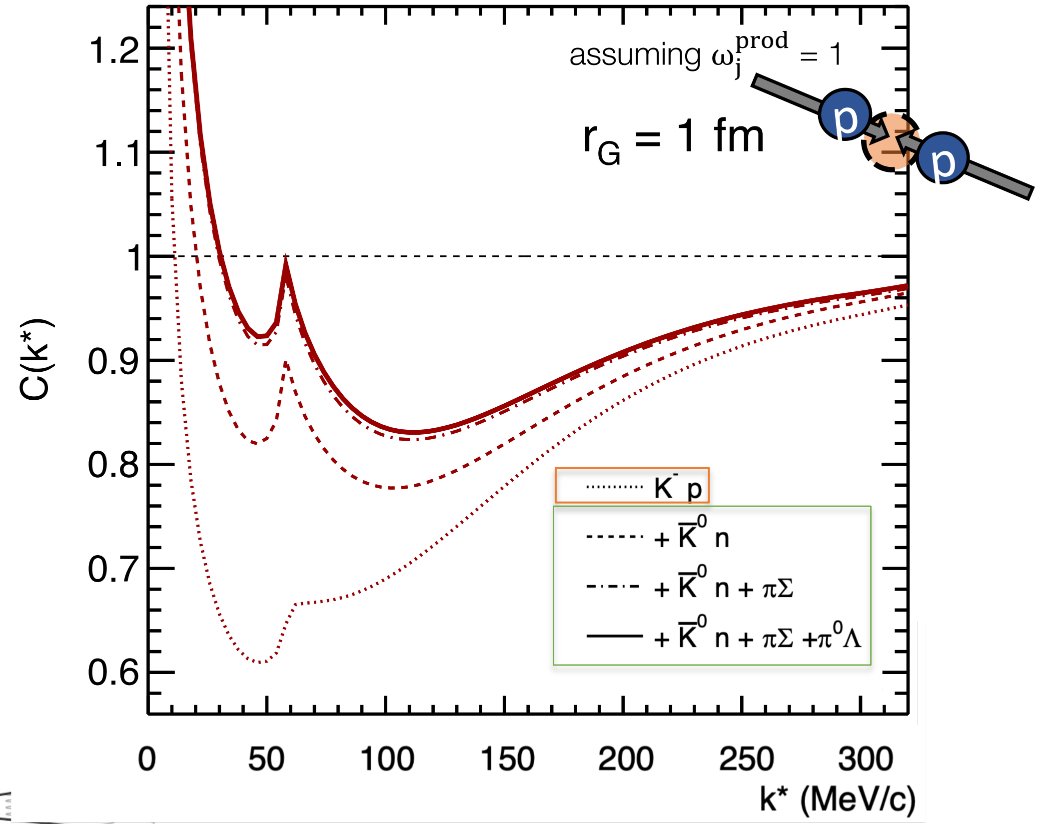
- Wavefunctions obtained in a coupled-channel approach
  - Above threshold: modify the shape of CF → cusp structure e.g. $\bar{K}^0 n$
  - Below threshold: increase the strength of CF → shift upward of CF e.g. $\Sigma\pi$
- Conversion weights ω_j^{prod}
  - How many j pairs are produced as initial states?
  - Obtained in a data-driven way using yields and kinematics

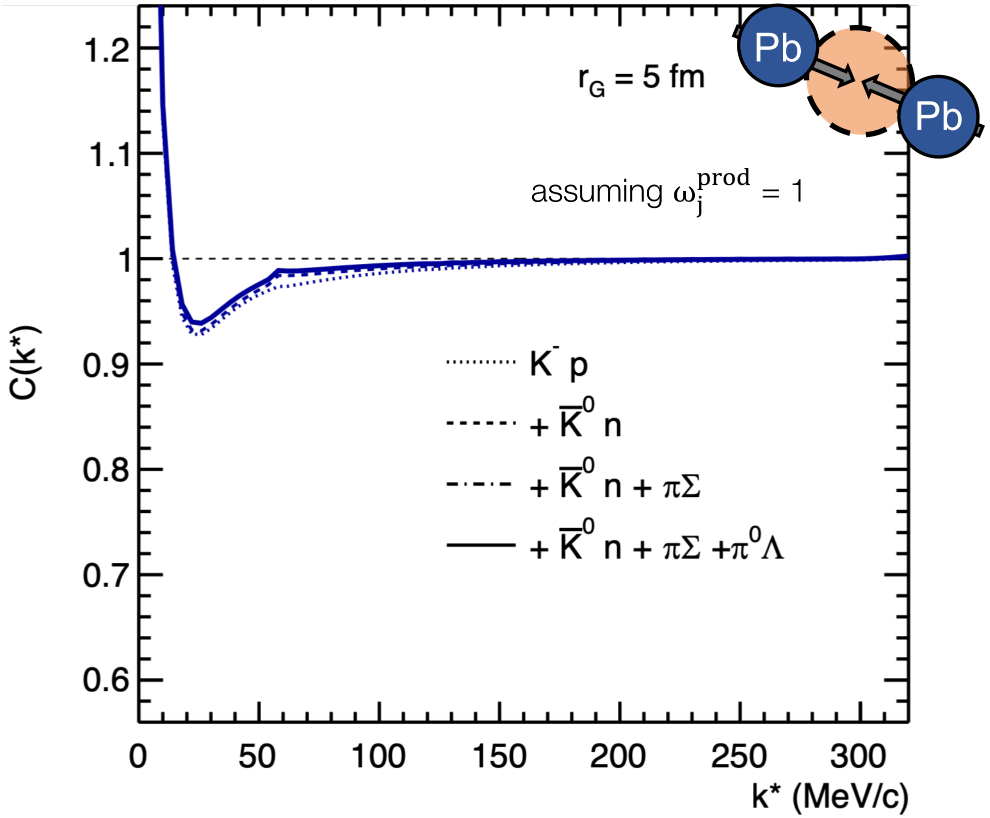
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020) L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Coupled-channels dynamics and source size

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





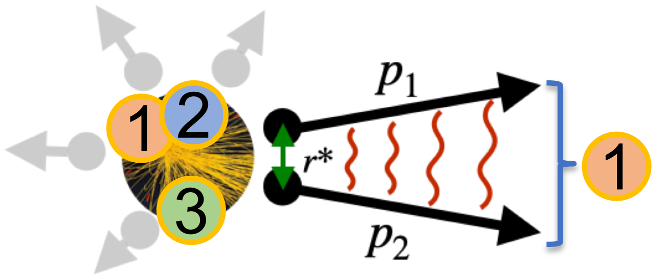


$K^{-}p$ femtoscopy: the game changer

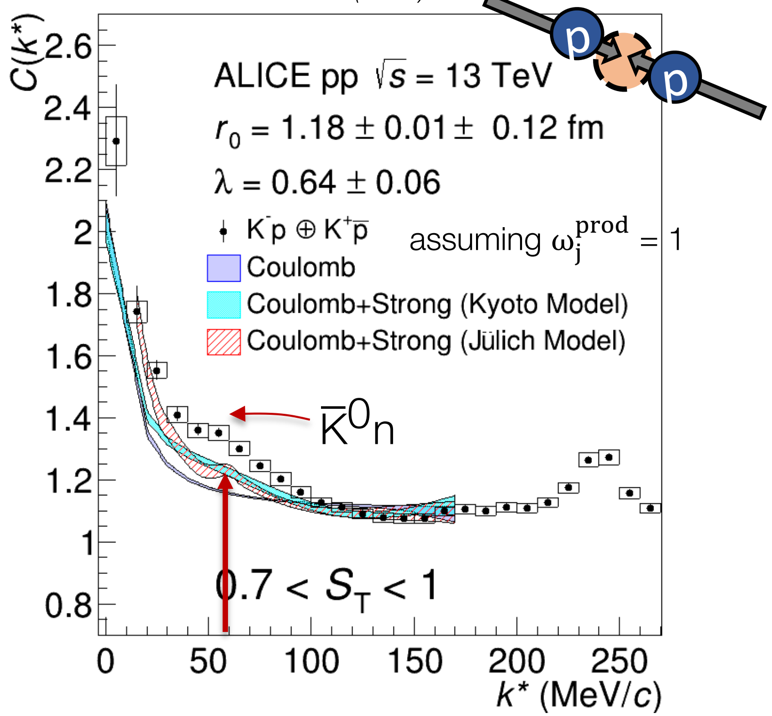
$$C(k^*) = \int S_1(\vec{r}^*)\, \left|\psi_{1\to1}(\vec{k}^*,\vec{r}^*)\right|^2 d^3r^* + \sum_{j\neq1} \omega_j^{\mathrm{prod}} \int S_j(\vec{r}^*)\, \left|\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)\right|^2 d^3r^*$$

elastic
1 → 1

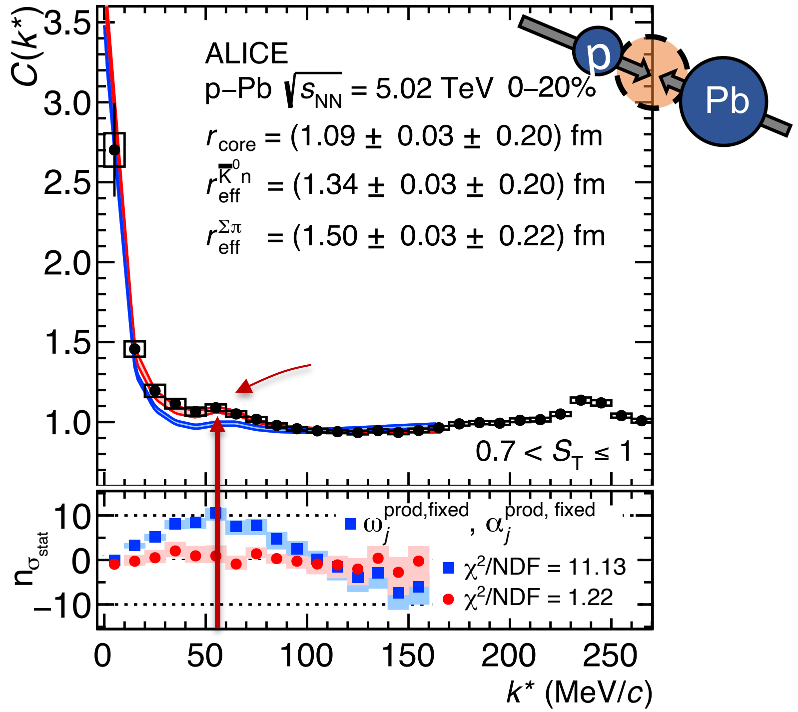
inelastic
2,3,… → 1



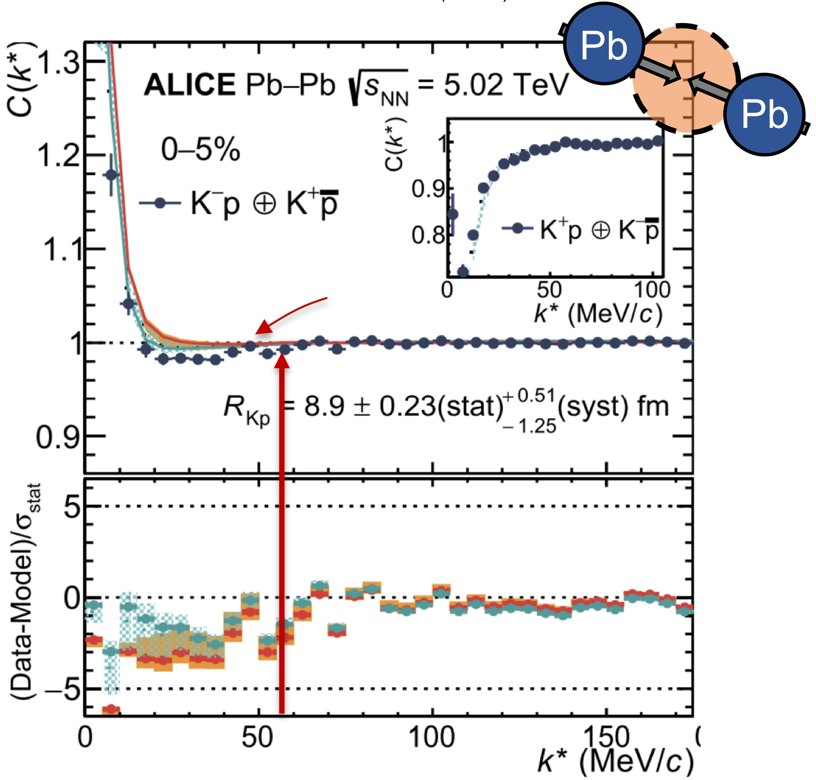
ALICE Coll. PRL124 (2020)



ALICE Coll. EPJC 83 (2023) 4



ALICE Coll. PLB 822 (2021)

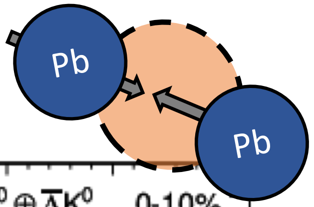


Moving to K$^-$Λ correlations…

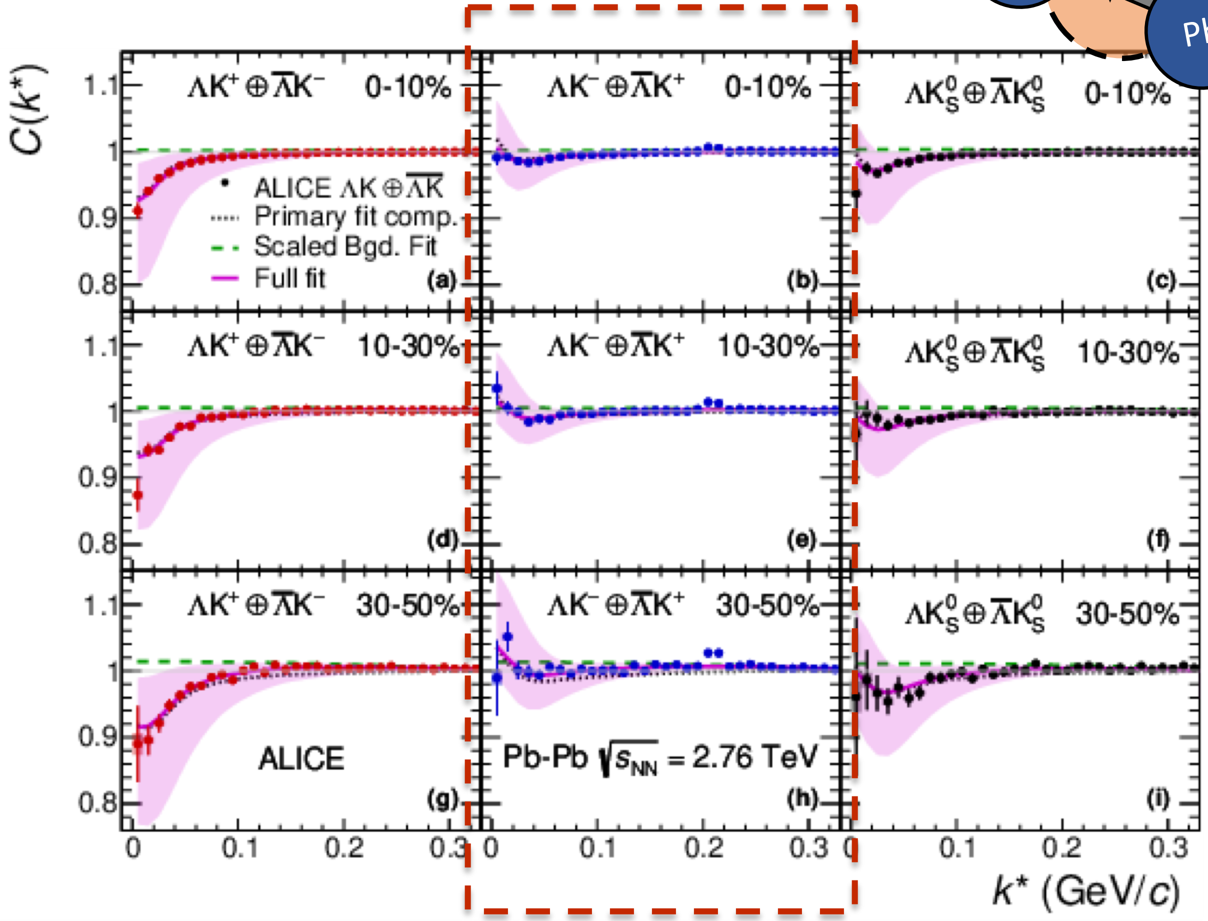
- Correlations measured in Pb-Pb collisions
  → No particular cusps or structure visible
  → First measurements of Λ$\overline{\text{K}}$ scattering parameters!

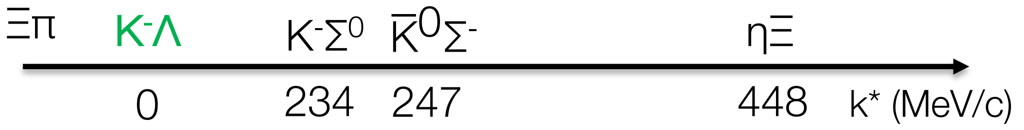
How does the correlation look like in pp collisions?

Can we shed light on the nature of Ξ(1620) and Ξ(1690) states with correlations?



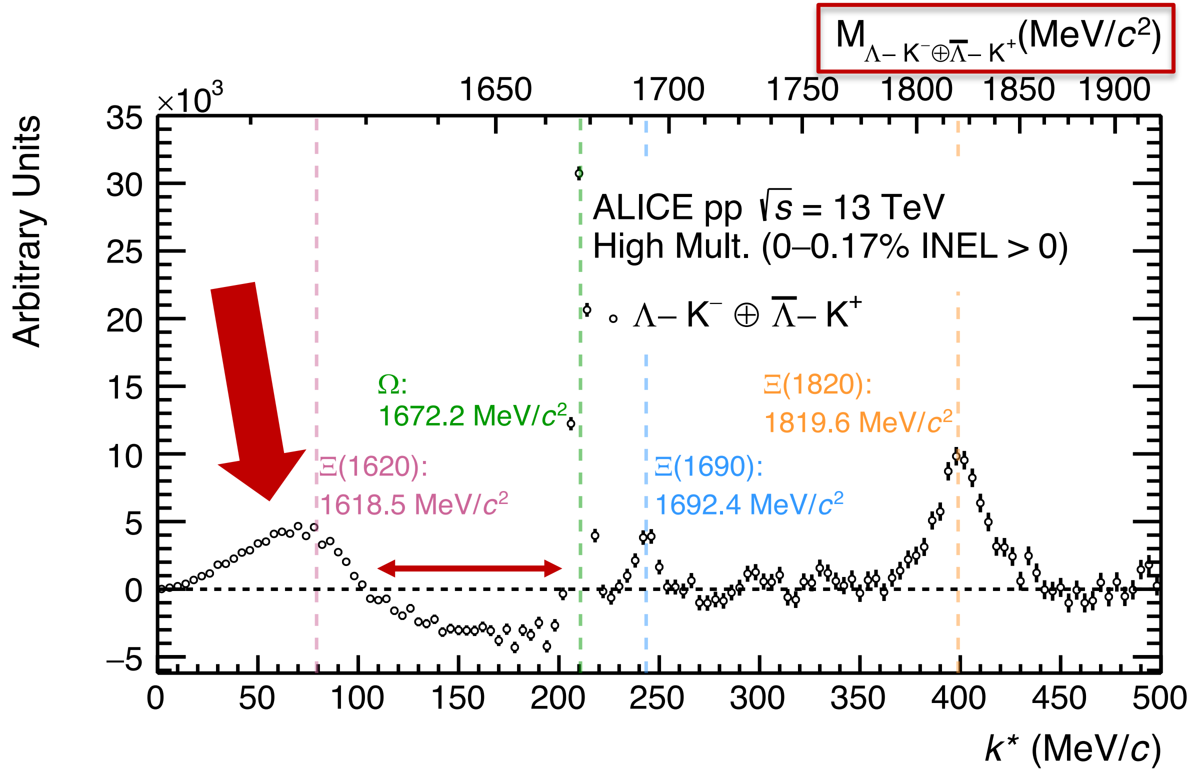
ALICE Coll. PRC 103 (2021)



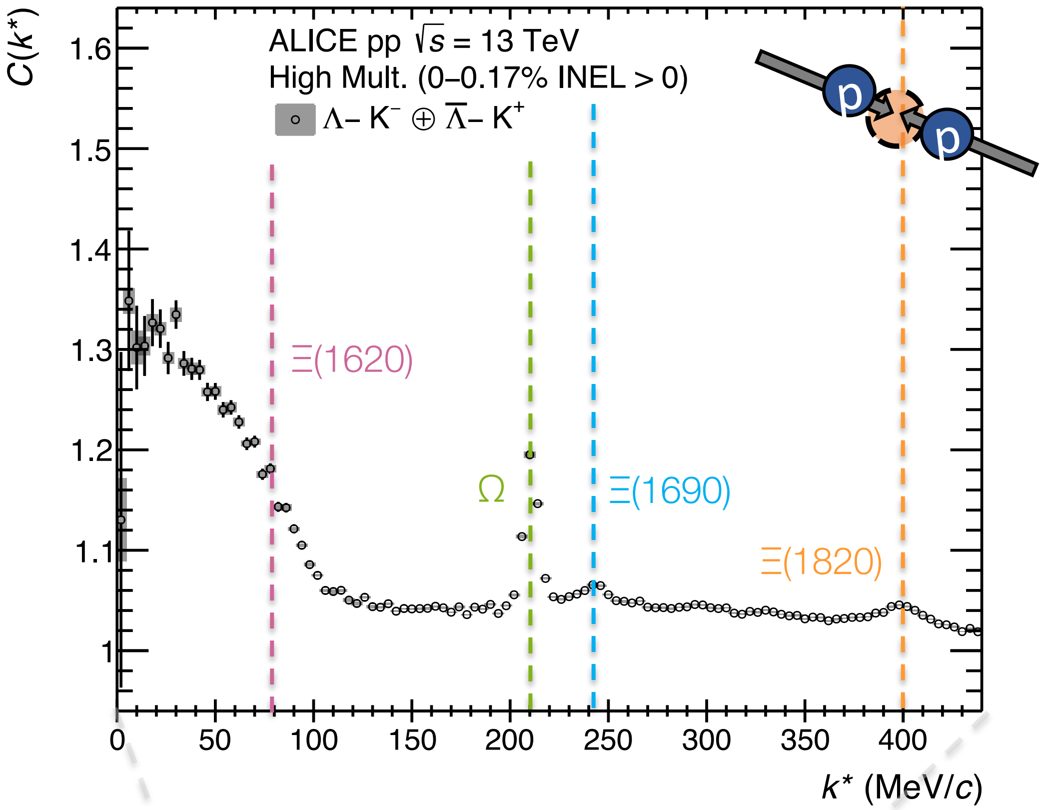


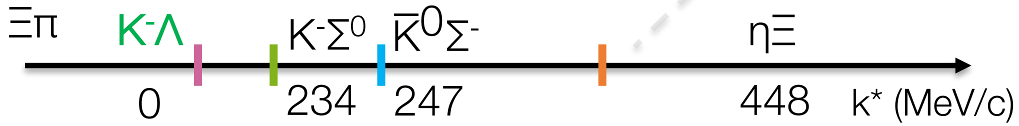
The ΛK^- correlation in pp collisions

- Several peak structures in the measured correlation
- Invariant mass from same and mixed event distributions used to build the correlation
  - $\Xi(1620)$ just above the threshold
    → First experimental evidence of decay into ΛK^-



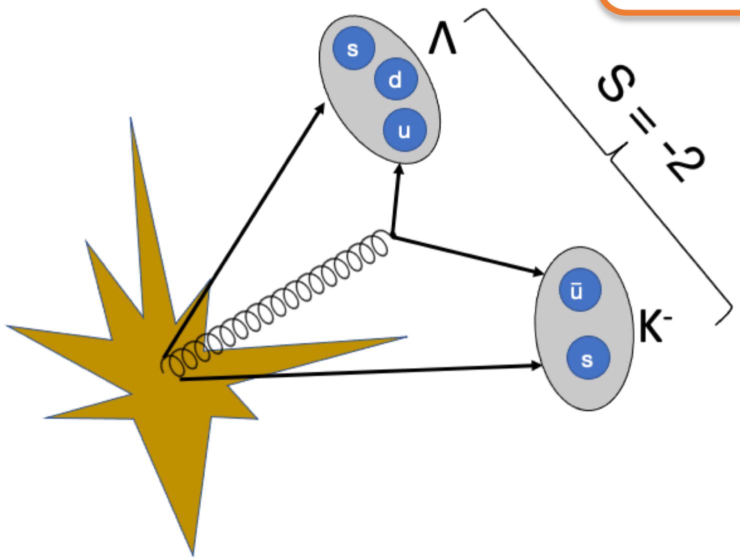
ALICE Coll. PLB 845 (2023) 138145





Modeling the correlation function

$$C(k^*) = N_D \cdot C_{model}(k^*) \cdot C_{bckg}(k^*)$$



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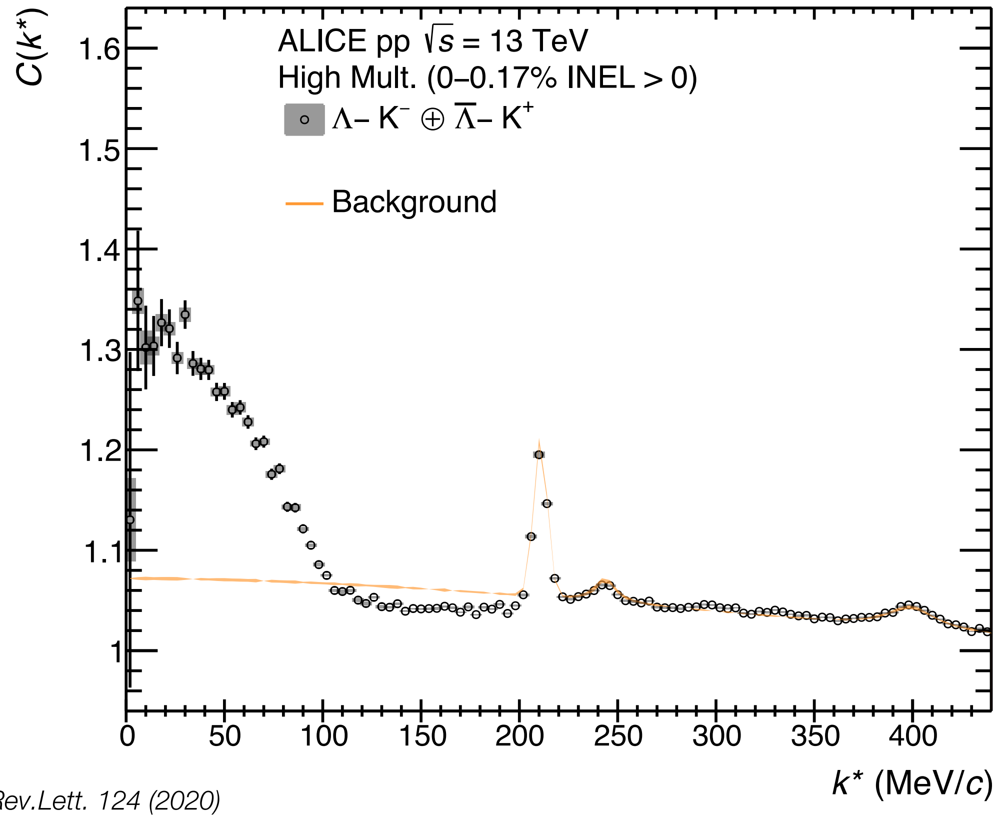


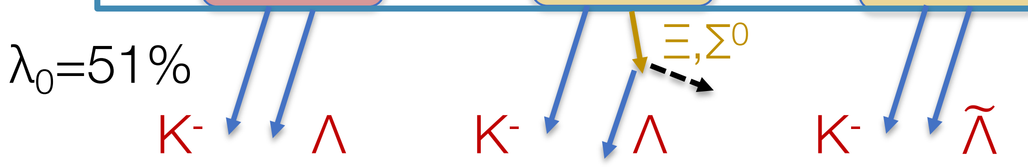
- Residual background due to initial parton scattering
  → Typically observed in meson-baryon correlations *ALICE Coll. Phys.Rev.Lett. 124 (2020)*
  → Modeled using Monte-carlo simulations

- Addition of Ω, Ξ* resonances observed in the CF modeled with BW
  → Values of (M,Γ) to be extracted with fit to the data

Modeling the correlation function

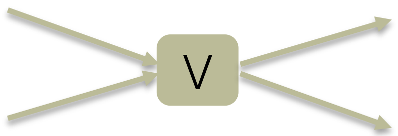
$$C(k^*) = N_D \cdot C_{model}(k^*) \cdot C_{bckg}(k^*)$$

$$\lambda_0\, C_0(k^*) + \lambda_1\, C_1(k^*) + \lambda_2\, C_1(k^*) + \cdots$$ [1]



- Genuine correlation of interest
  → Modeled with the Lednicky-Lyuboshits formula[2]

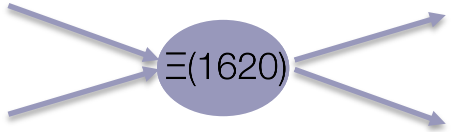
Non resonant



Assuming the effective-range expansion

+

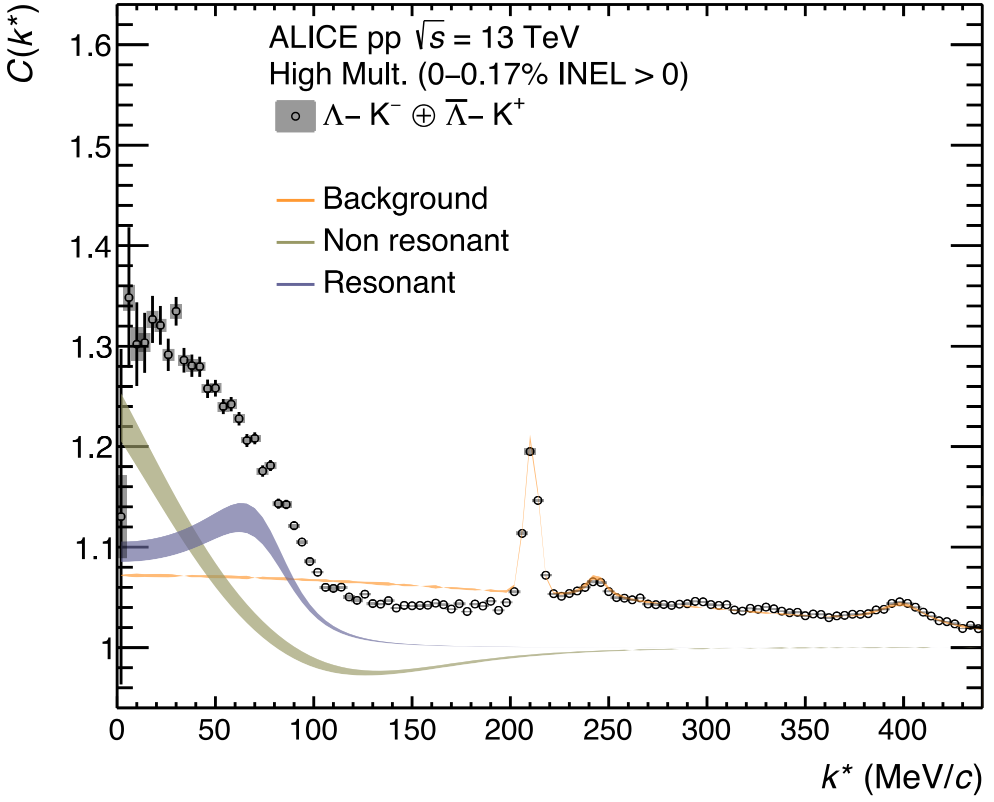
Resonant



Assuming a Flattè-like amplitude[3] for Ξ(1620)

- Contributions from secondaries, impurities, etc..
  → Modeled when possible[4] or assumed flat

ALICE Coll. PLB 845 (2023) 138145

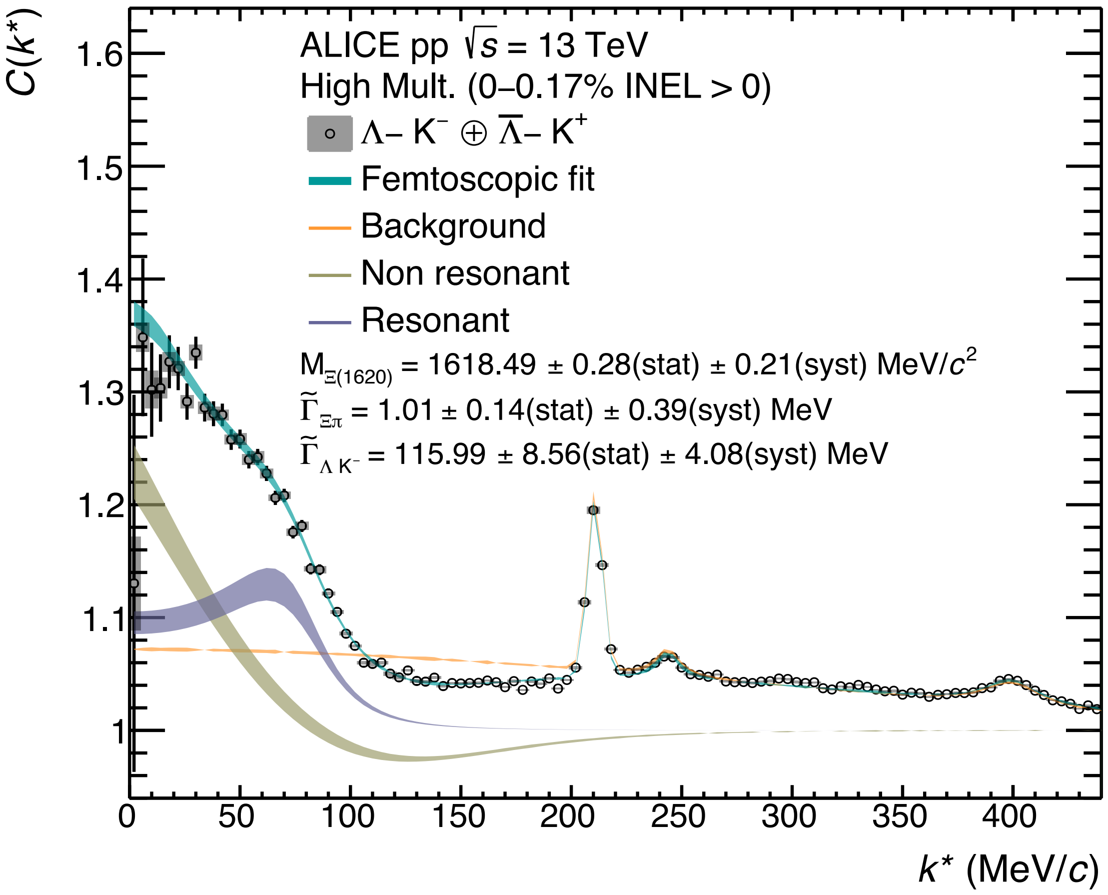


[1] ALICE coll. Phys.Rev. C99 (2019)
[2] R. Lednicky, V. Lyuboshits SJNP 35 (1982)
[2] F. Giacosa et al. EPJA 57 (2021), 12, 336
[4] CATS: D. Mihaylov et al., EPJC 78 (2018), 5, 394

The ΛK⁻ correlation in pp collisions

- Most precise data for ΛK⁻ down to threshold
- Model well reproduces the data in the whole k* region
  → Interplay between resonant and non-resonant interaction
- **Ξ(1620) properties**
  → Mass in agreement with Belle[1]
  → Indication of a large coupling of Ξ(1620) to ΛK⁻
- **Ξ(1690) properties** compatible with LHCb results and PDG informations

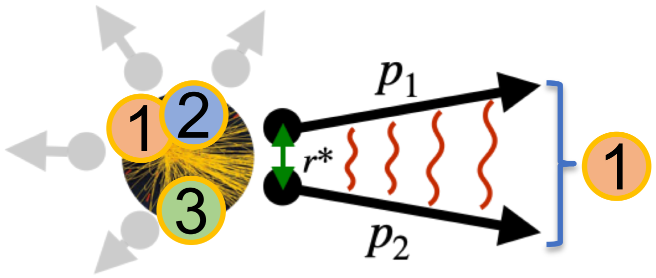
ALICE Coll. PLB 845 (2023) 138145

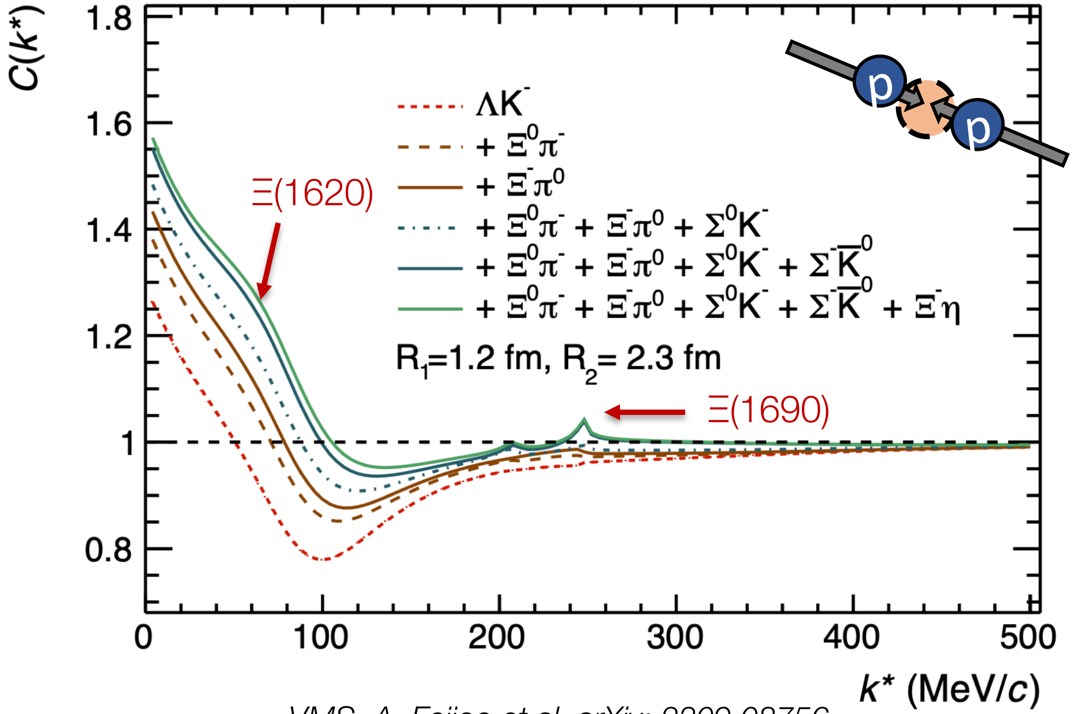


Can we use these femtoscopic data to constrain effective QCD models and investigate the Ξ(1620) nature?

Constraining effective QCD lagrangians with correlations

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





VMS, A. Feijoo et al. arXiv: 2309.08756

Wavefunctions obtained in a coupled-channel approach

- State-of-the-art NLO effective lagrangian in UχPT obtained in a coupled-channel approach
  A. Feijoo et al., PLB 841 (2023)

$$\mathcal{L}_{\phi B}^{(1)} = i\langle \bar{B}\gamma_\mu [D^\mu, B]\rangle - M_0\langle \bar{B}B\rangle - \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle - \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle\,,$$

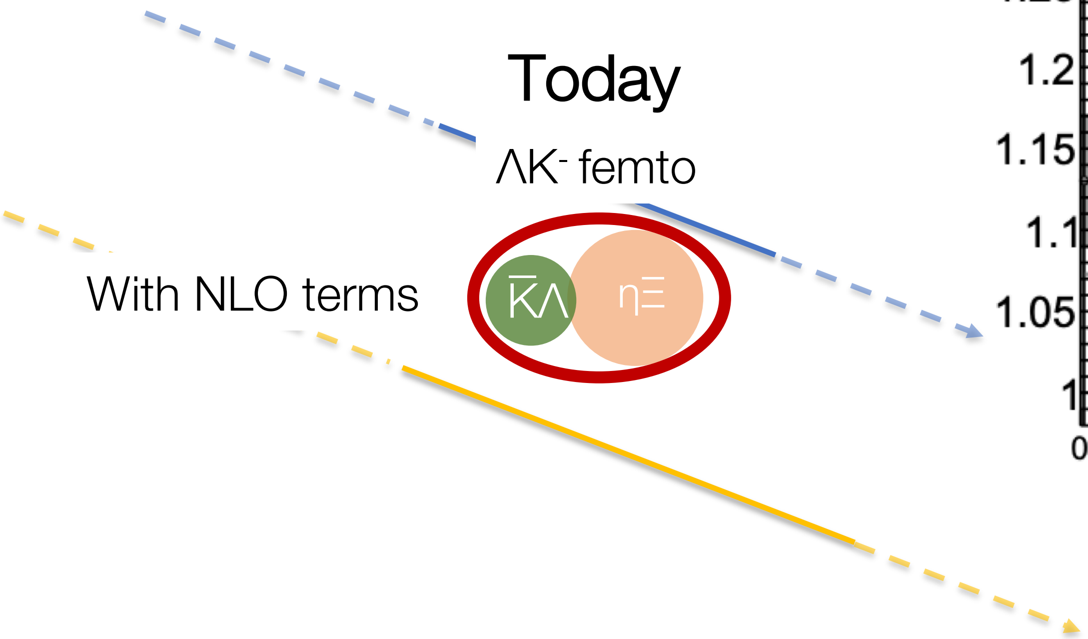
$$\mathcal{L}_{\phi B}^{(2)} = b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + d_1\langle \bar{B}\{u_\mu,[u^\mu,B]\}\rangle + d_2\langle \bar{B}[u_\mu,[u^\mu,B]]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle\,.$$

Conversion weights ω_j^{prod} and source studies for each channel

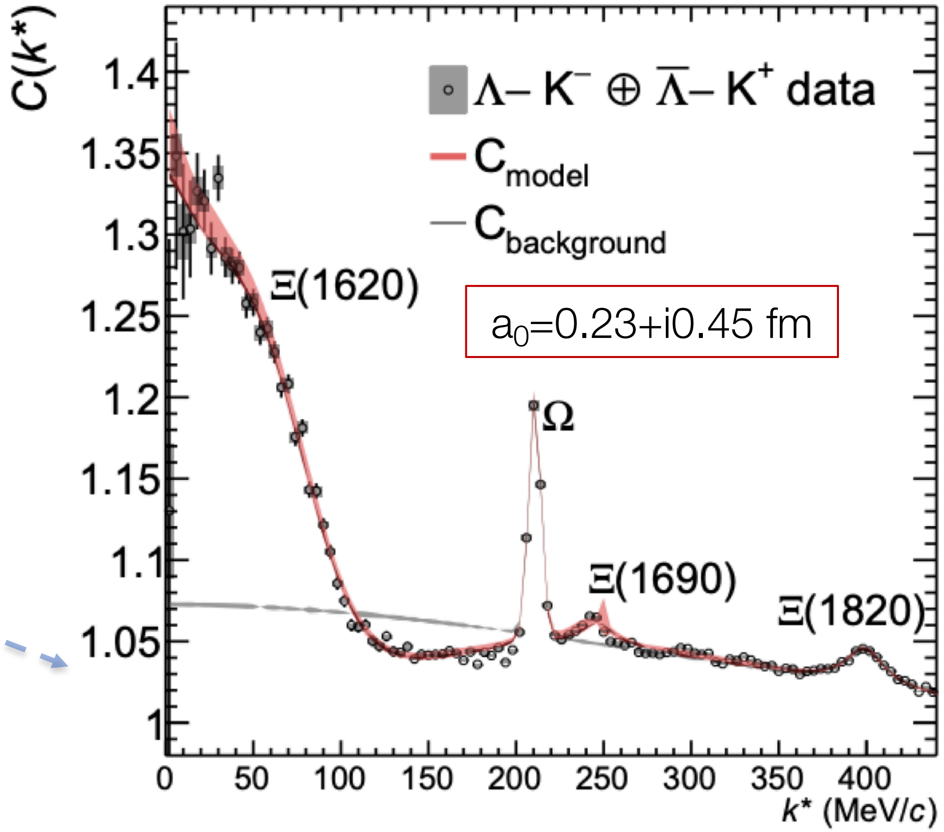
- Detailed data-driven study using thermal and transport models
  ALICE Coll. Eur.Phys.J.C 83 (2023), VMS, A. Feijoo et al. arXiv: 2309.08756

Femtoscopy era in the S=-2 meson-baryon sector

- First combined effort in constraining the low-energy constants of an effective chiral lagrangian to correlation data



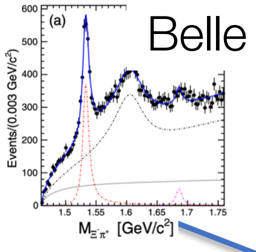
VMS, A. Feijoo et al. arXiv: 2309.08756



Work in collaboration with:
Dr. A. Feijoo, Dr. I. Vidana, Prof. A. Ramos, Prof. F. Giacosa,
Prof. T. Hyodo and Dr. Y. Kamiya

Femtoscopy era in the S=-2 meson-baryon sector

- First combined effort in constraining the low-energy constants of an effective chiral lagrangian to correlation data



Belle Coll.

K̄Λ Ξπ

A. Ramos, E. Oset PRL 89 (2002)

Only contact terms
|S|=1 data

K̄Λ Ξπ

With NLO terms
|S|=1 data

A. Feijoo et al. PLB 841 (2023)

Today

ΛK⁻ femto

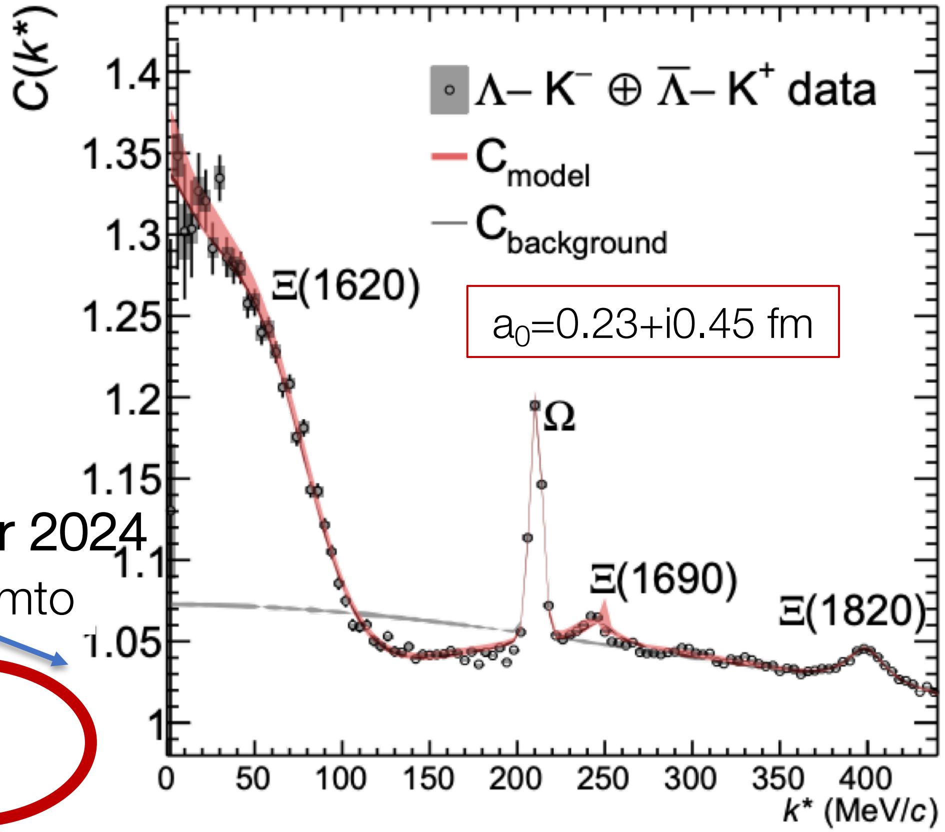
K̄Λ ηΞ

Summer 2024

Ξπ femto

...

VMS, A. Feijoo et al. arXiv: 2309.08756



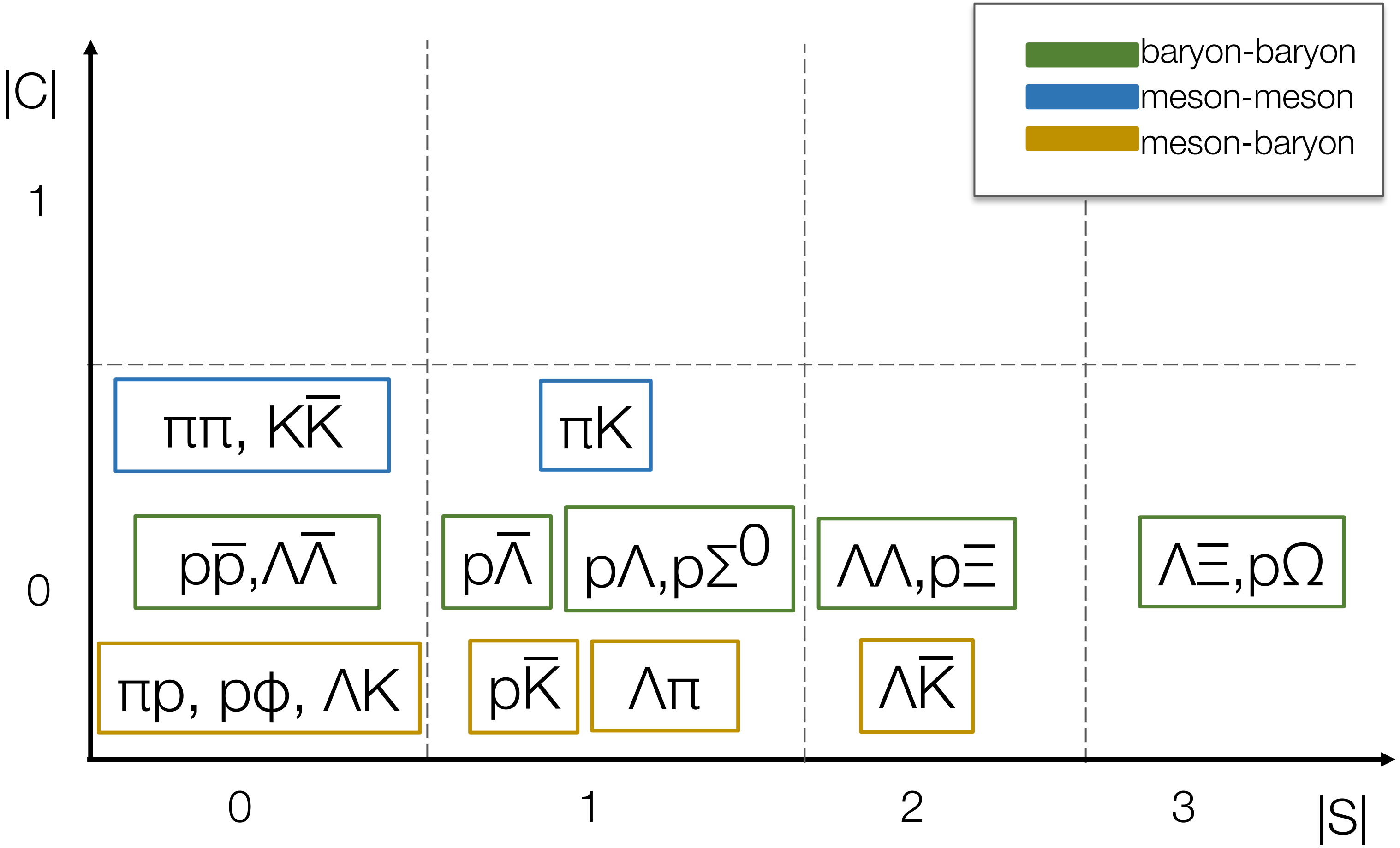
Towards a combined fit of all available data in this sector!!

(Preliminary work done on contact terms for pΛ)
Mihaylov, Haidenbauer, VMS PLB 850 (2024) 138550

Work in collaboration with:
Dr. A. Feijoo, Dr. I. Vidana, Prof. A. Ramos, Prof. F. Giacosa,
Prof. T. Hyodo and Dr. Y. Kamiya

What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states



What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states

- Widely explored the light and strange sector with LHC Run 2

baryon-baryon
meson-meson
meson-baryon

|C|

1

0

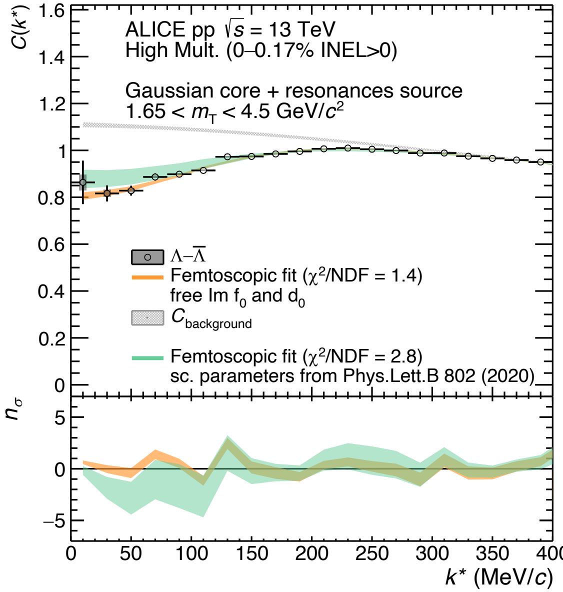
|S|

Tetraquark candidates in light meson sector
$a_0(980)$ with $K^0_S K^0_S$, $K^*_0(700)$ with $\pi^{\pm} K^0_S$
ALICE Coll. arXiv: 2312.12830
ALICE Coll. PLB 833, 137335 (2022);
PLB 790, 22 (2019); PLB 774, 64 (2017)

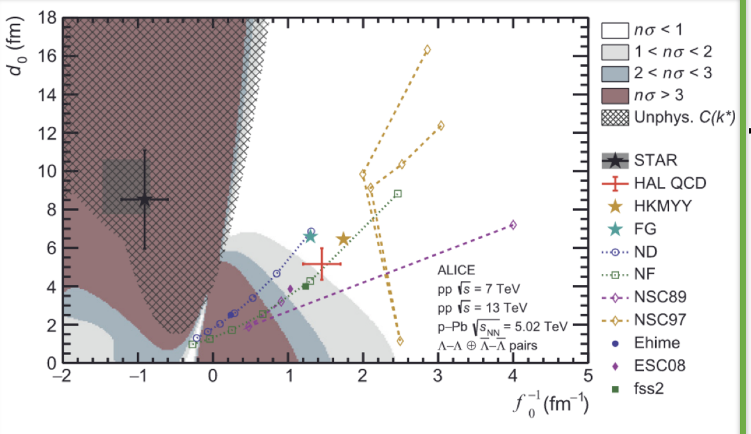
$\pi\pi$, $K\bar{K}$ | πK

$p\bar{p}$, $\Lambda\bar{\Lambda}$ | $p\bar{\Lambda}$ | $p\Lambda$, $p\Sigma^0$ | $\Lambda\Lambda$, $p\Xi$ | $\Lambda\Xi$, $p\Omega$

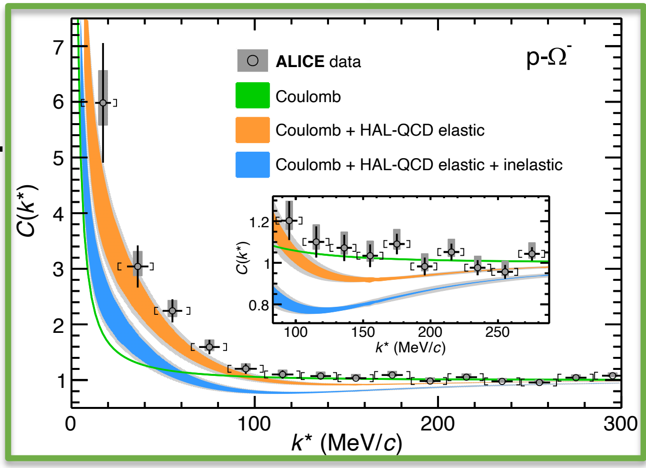
Dibaryon candidates
$B\bar{B}$, H-dibaryon, $N\Omega$



ALICE Coll. PLB 829 (2022), PLB 802 (2020)



ALICE Coll. PLB 797 (2019) 134822



ALICE Coll. Nature 588 (2020) 232-238

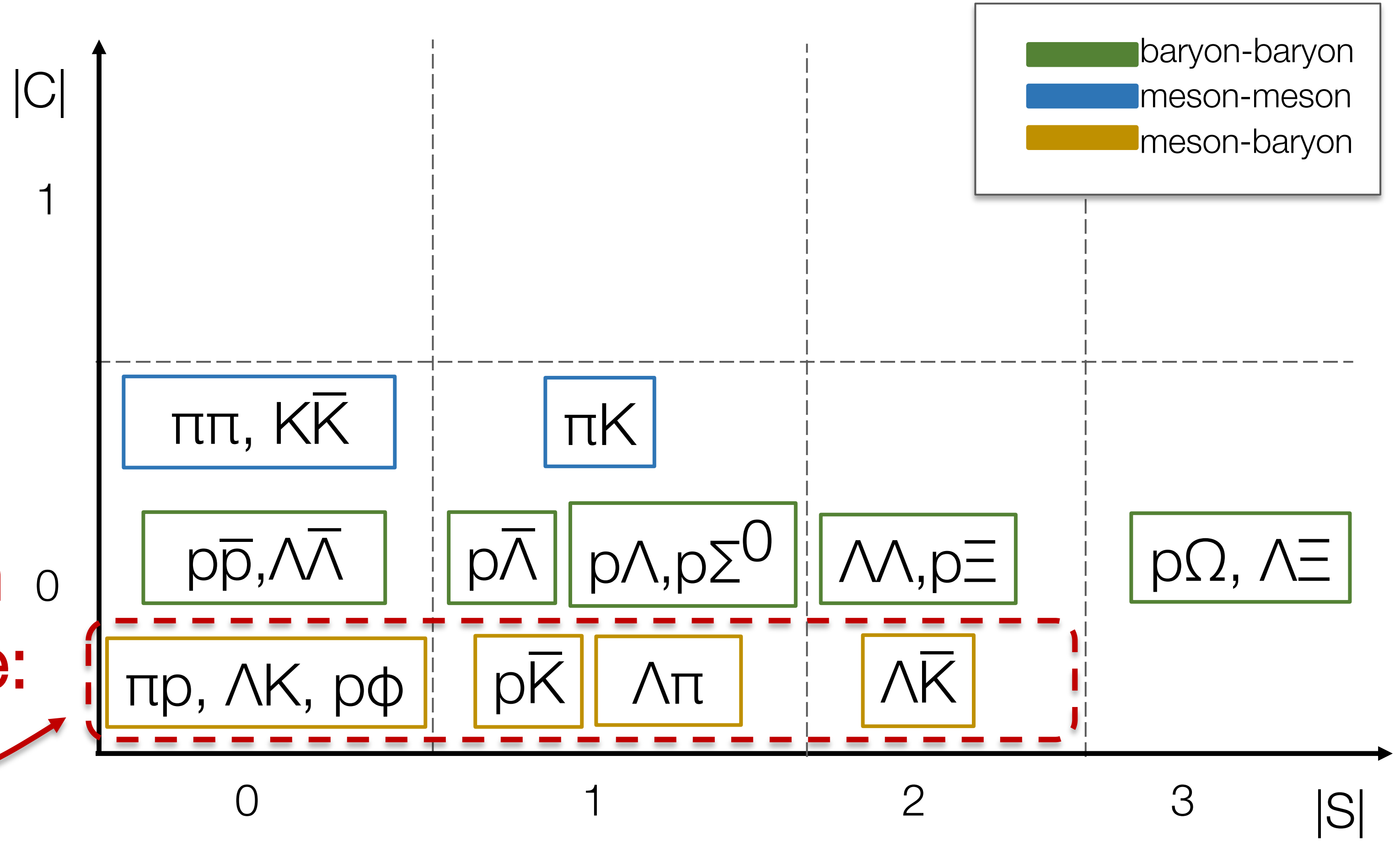
valentina.mantovani-sarti@tum.de

What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states

Novel data on |S|=0,1,2 meson-baryon interaction

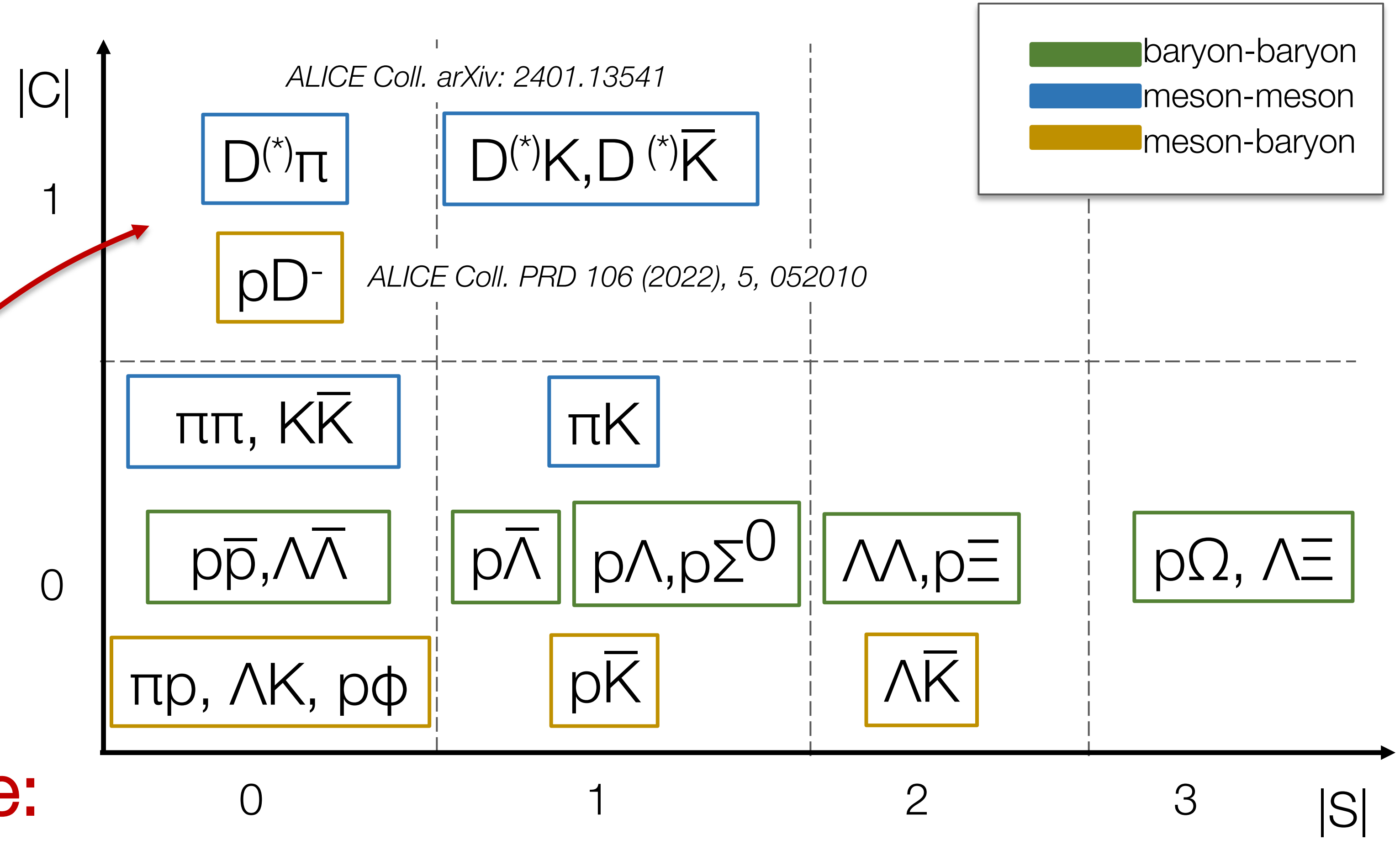
Molecular states and more: Λ(1405), Ξ*,N*,…



M. Mai Eur.Phys.J.ST 230 (2021) 6, 1593-1607
A. Feijoo et al. Phys.Lett.B 841 (2023) 137927
Y.-F. Wang et al. Phys.Rev.C 109 (2024) 1, 015202

What can correlations do for bound states and exotics

High-precision correlation data on many interactions involving exotic/bound states



First "scattering" data available also in the charm sector

Molecular states and more: Λ_c^*, $D_0^*(2300)$, $D_{s0}^*(2317)$, ...

Towards an even more charming future!!

ALICE 3 LOI: arXiv:2211.02491

Conclusions and outlooks

- Femtoscopy technique as a **complementary tool** to provide high-precision data on hadron-hadron interactions to study exotic states

- Access to strong interaction involving strange and charm hadrons
  - most precise data at low momenta available
  - input for **low-energy effective lagrangians**

- Possibility to constrain LECs of χEFT potentials thanks to the large statistics and high precision
  - Combined effort on the experimental side and theory side to deliver/employ the correlation data

ALICE Collaboration:
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
PRL 127 (2021), 172301
PLB 822 (2021), 136708
PRC 103 (2021) 5, 055201
PLB 833 (2022), 137272
PLB 829 (2022), 137060
PRD 106 (2022), 5, 05201
PL B 844 (2023) 137223
EPJA 59 (2023) 145
EPJC 83 (2023) 4, 340
PLB 845 (2023) 138145
EPJA (2023) 59:298
arXiv: 2311.14527 [hep-ph]
arXiv: 2401.13541 [nucl-ex]
arXiv:2308.16120 [nucl-ex]

STAR Collaboration:
Nature 527 (2015) 345-348
PRL 114 (2015), 022301
PLB 790 (2019) 490-497

HADES Collaboration:
PRC 82 (2010) 021901
PRC 94 (2016) 2, 025201

Latest theoretical studies on exotics and correlations:
Liu et al. Phys.Rev.D 107 (2023) 7, 074019
Albaladejo et al. Phys.Rev.D 108 (2023) 1, 014020
Kemchandani et al. arXiv:2312.11811
Ikeno et al. Phys.Lett.B 847 (2023) 138281
Torres-Rincon et al. Phys.Rev.D 108 (2023) 9, 096008
Kamiya et al. Eur.Phys.J.A 58 (2022) 7, 131
Vidaña, Feijoo et al. Phys.Lett.B 846 (2023) 138201
Albaladejo, Feijoo et al. arXiv:2307.09873
Liu et al. Phys.Rev.D 108 (2023) 3, L031503
Feijoo et al. Phys.Rev.D 109 (2024) 1, 016014
Liu et al. Phys.Rev.D 109 (2024) 1, 016014
M. Z. Liu et al. arXiv: 2404.06399 [hep-ph]
Li et al. arXIv: 2311.14365 [hep-ph]
Molina et al. Phys.Rev.D 109 (2024) 5, 054002
Krein Few Body Syst. 64 (2023) 3, 42

Many more correlations to come with on-going Run 3 and future LHC runs

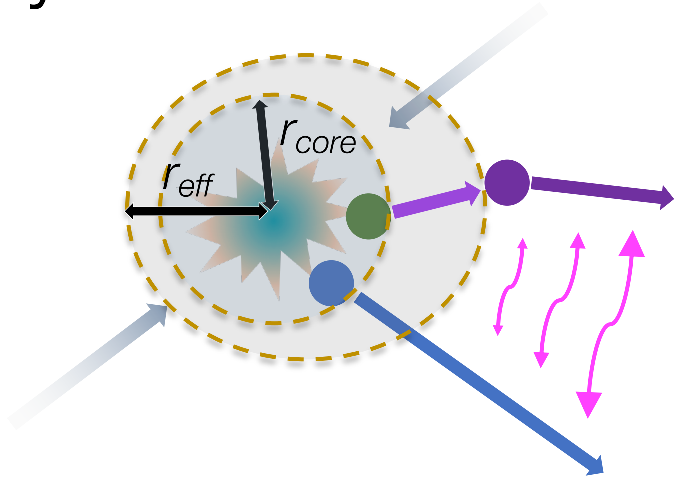
Additional slides

The emitting source in small colliding systems

- Data-driven analysis on p-p and p-Λ pairs
  - Possible presence of collective effects → m_T scaling of the core radius
  - Contribution of **strongly decaying resonances with cτ ~1 fm** (*)

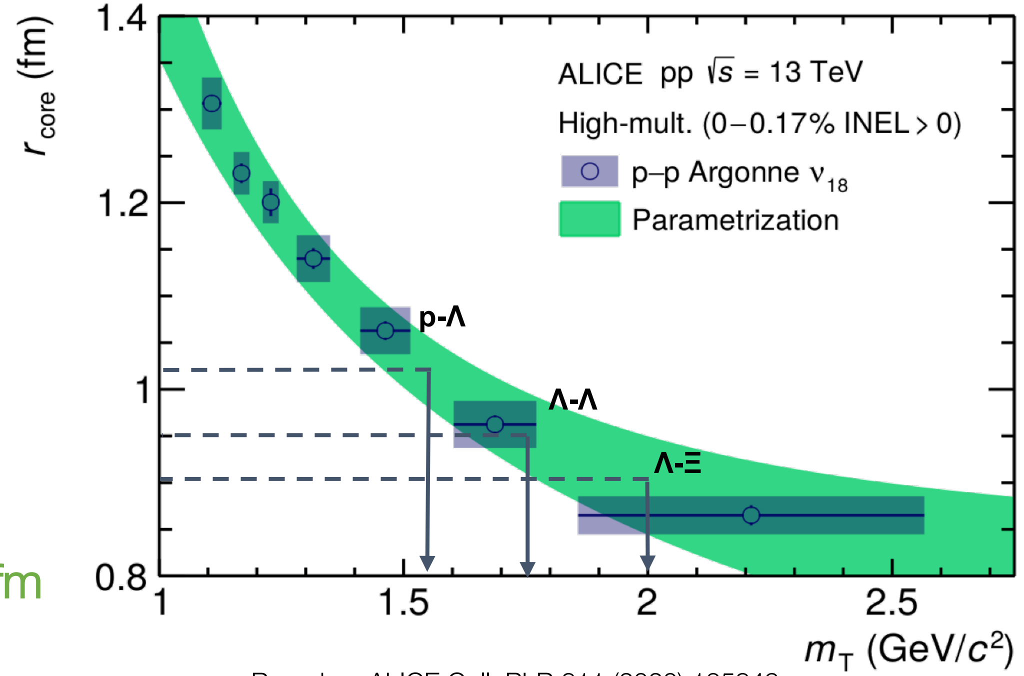
- Common universal core source for baryons

- Core constrained from p-p pairs
  - Fixing of the source at corresponding <m_T> ⟹ direct access to the interaction



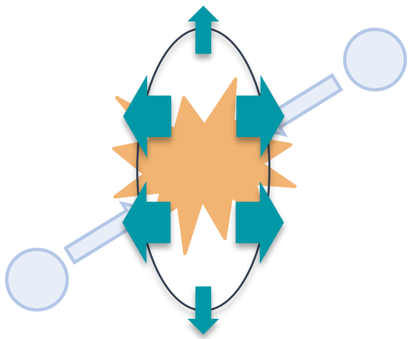
Particle	Res.	<cτ> (fm)
p	Δ,N*	1.6
Λ	Σ,Σ*	4.7

r_{eff} = 1 - 1.25 fm

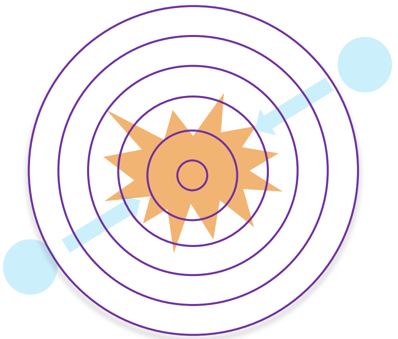


Based on ALICE Coll. PLB 811 (2020) 135849
(*) U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)

A source to rule them all



Anisotropic



Radial

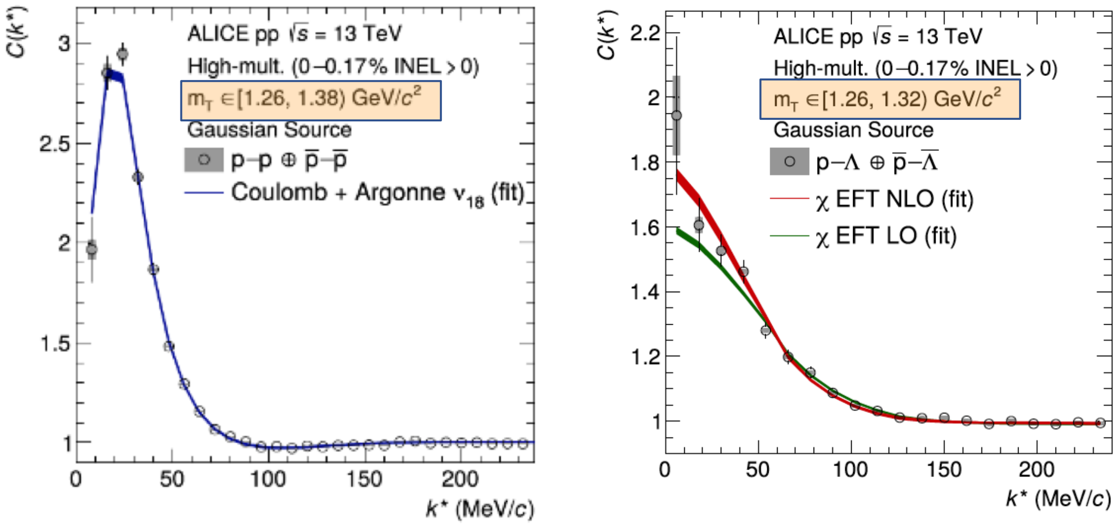
\+ pressure gradients

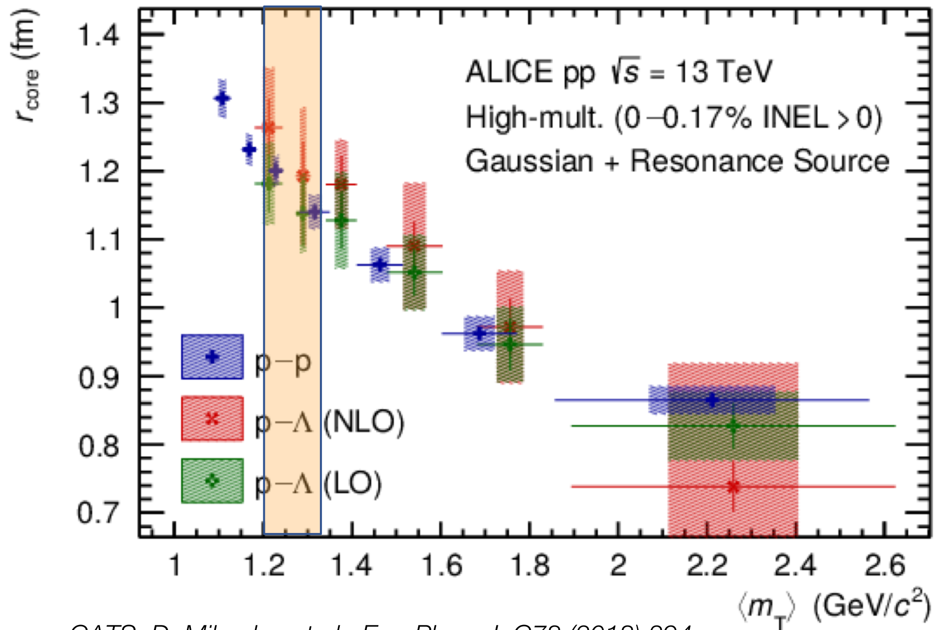
Different effect on different masses

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

$$S(r) = G(r, r_{core}\boxed{(m_T)}) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right) \otimes \frac{1}{s}\exp\left(-\frac{r}{s}\right)$$

ALICE Coll., PLB, 811 (2020)





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

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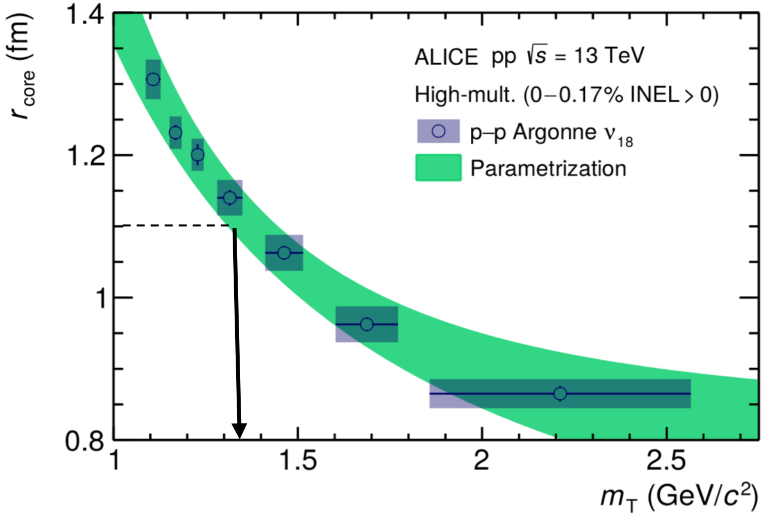
Fixing the source in ΛK correlations

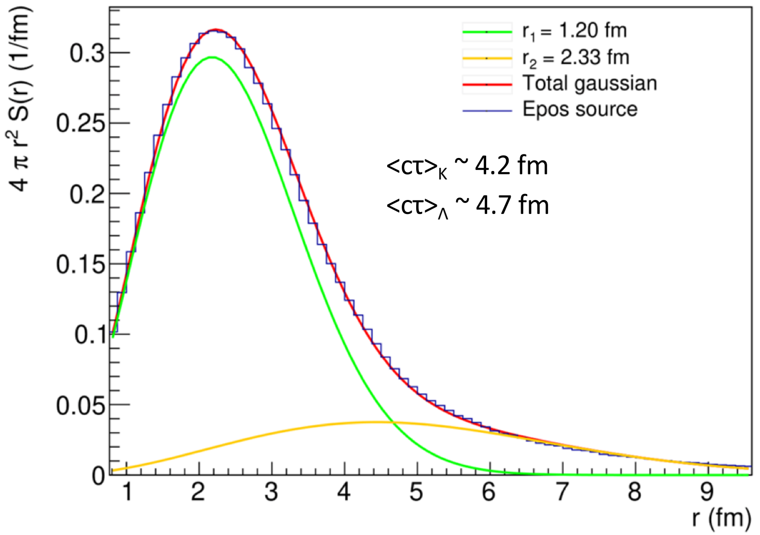
- Core-halo resonance model anchored to p-p CF
  - $r_{core} = 1.11 \pm 0.04$ ($\langle m_T \rangle_{\Lambda K} = 1.35$ GeV/c^2)
- Long-lived strongly decaying resonances feeding to Λ
  - fit with effective double gaussian

$$S_{tot}(r) = \lambda_s [\omega_S \cdot S(r_1) + (1-\omega_S) \cdot S(r_2)]$$

Parameter	Value
r_{core} [fm]	$1.11^{+0.04}_{-0.04}$
$r_{1,eff}$ [fm]	$1.202^{+0.043}_{-0.042}$
$r_{2,eff}$ [fm]	$2.330^{+0.050}_{-0.045}$
ω	$0.7993^{+0.0037}_{-0.0027}$
λ	$0.9806^{+0.0006}_{-0.0008}$

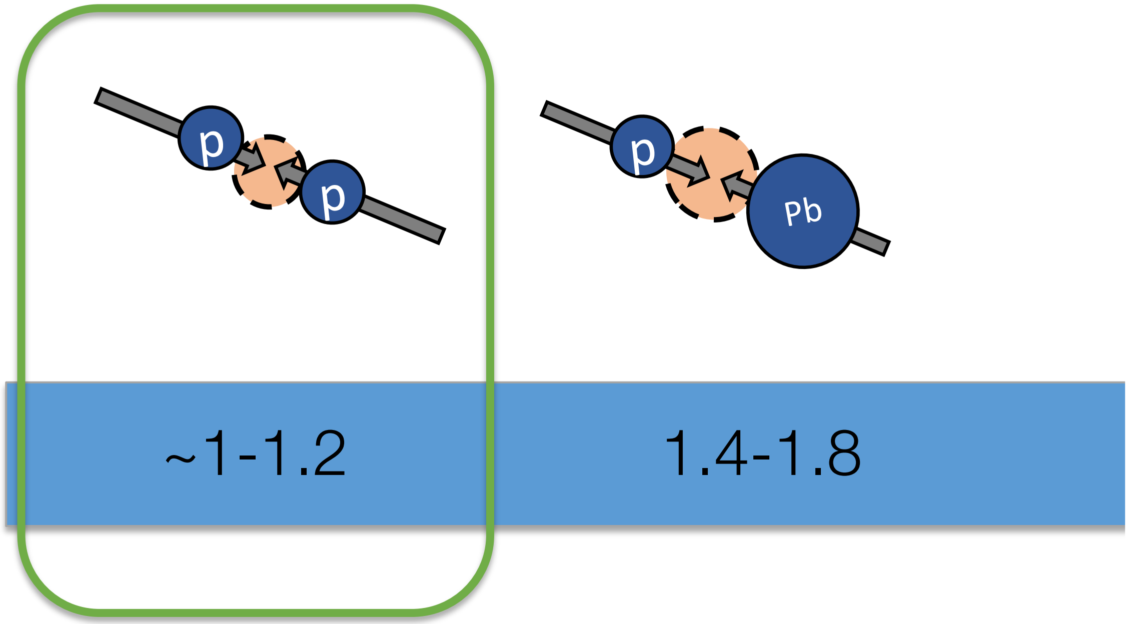
ALICE Collaboration Phys. Lett. B 811

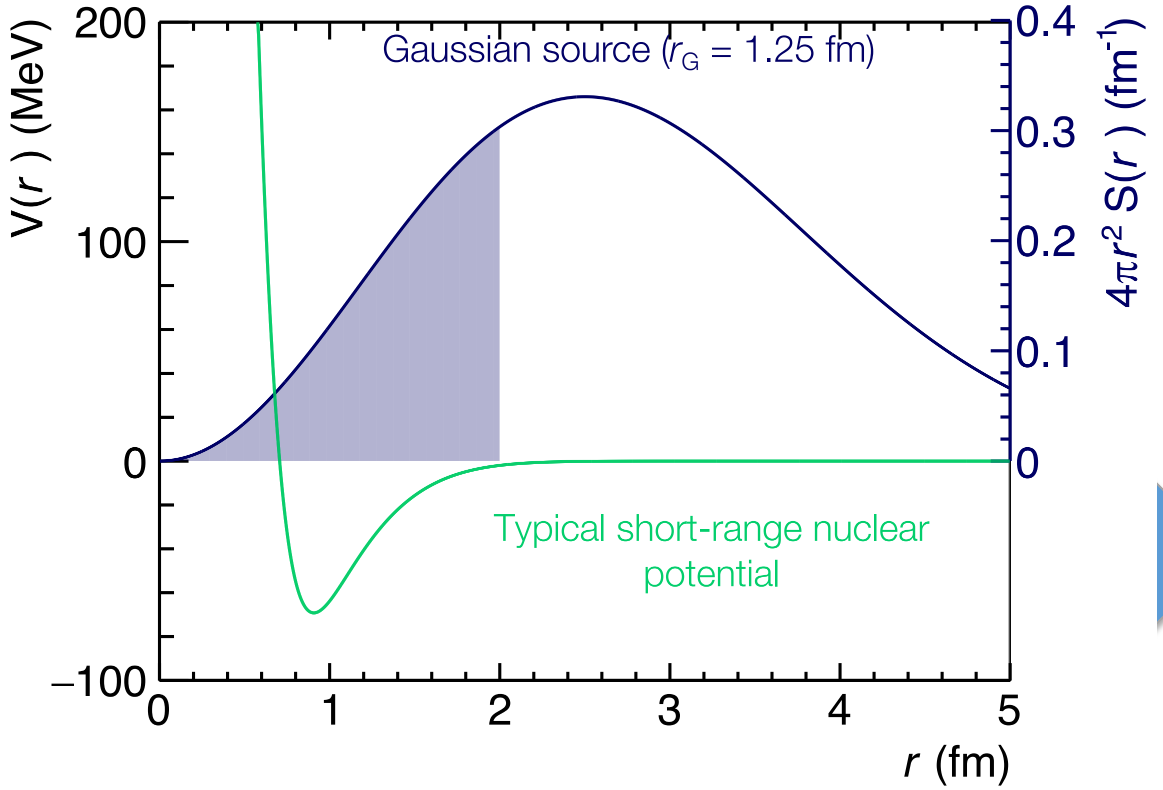




Correlation studies in small colliding systems

- By changing the colliding system we can probe distances ranging from 1 fm up to 10 fm
- Accessing the strong interaction → relative distances of ~1-2 fm → pp

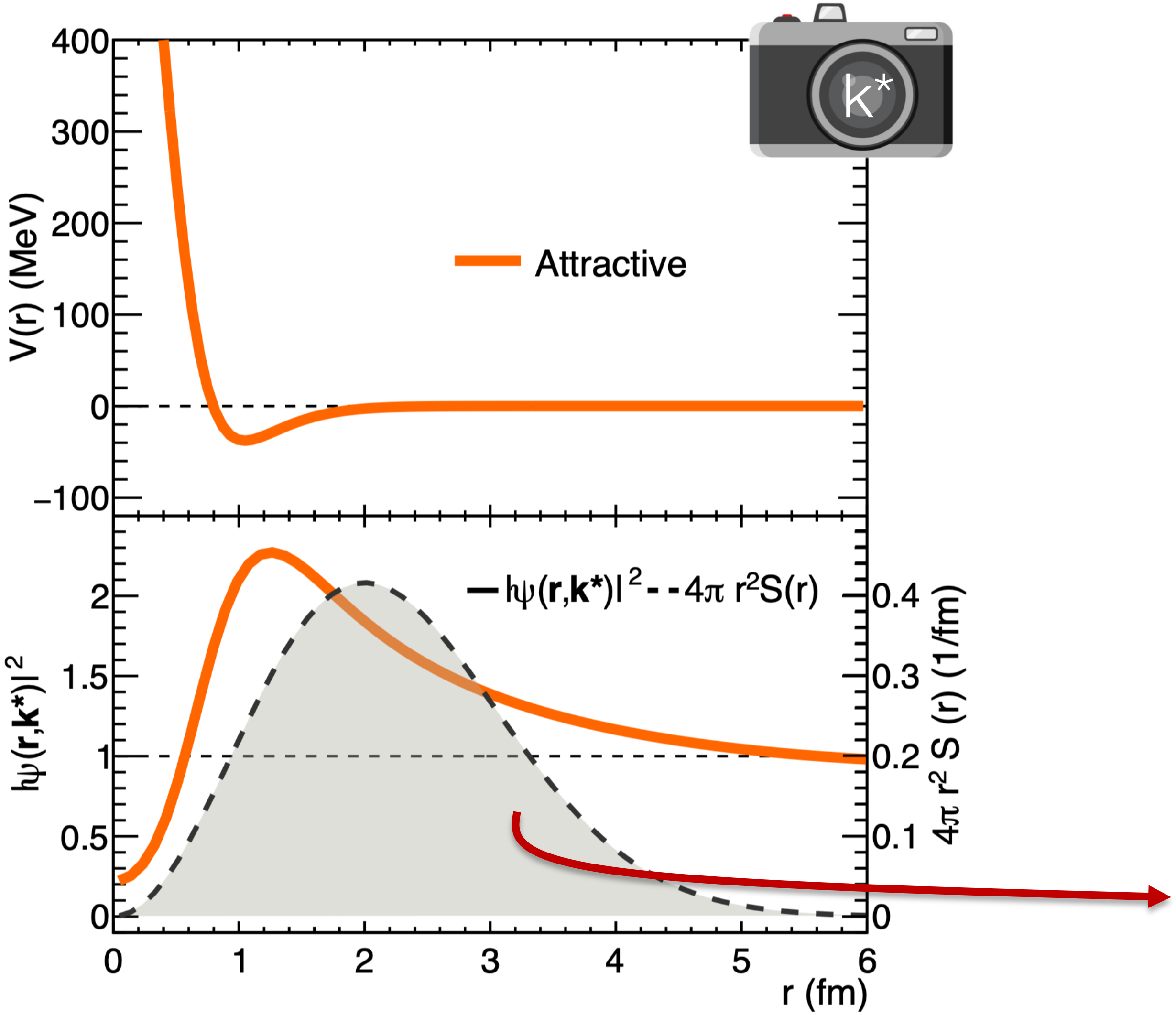




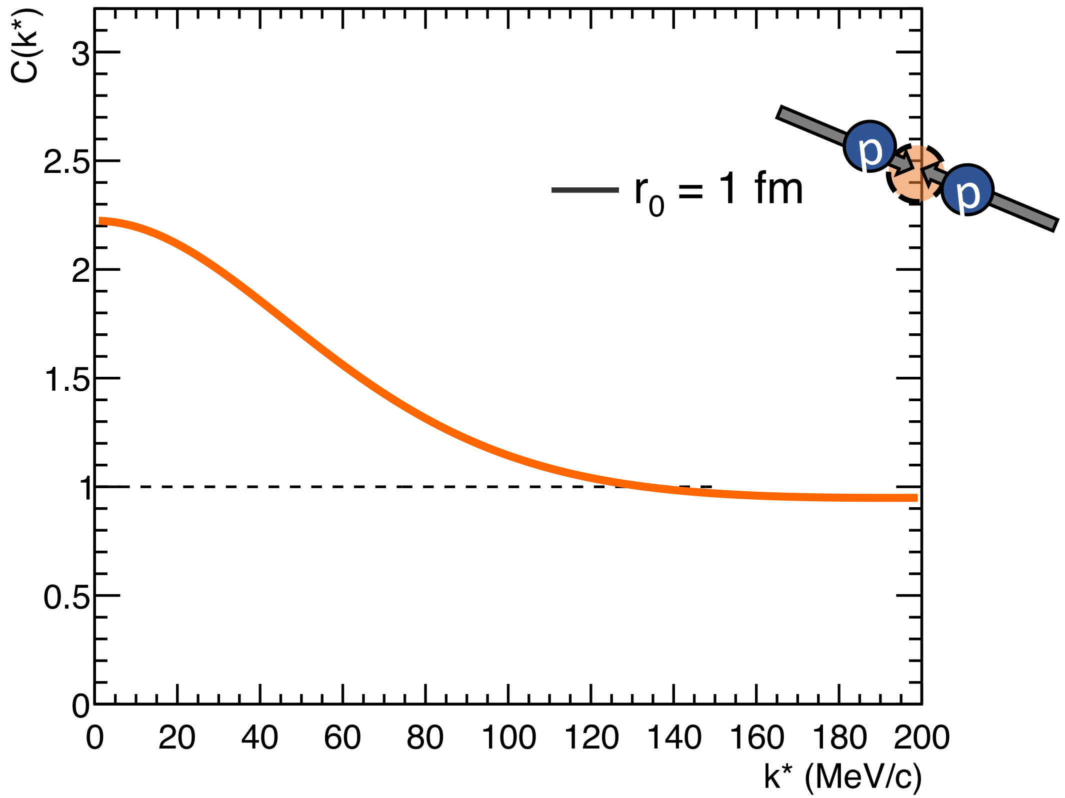
V. M. S., L. Fabbietti and O. Vazquez-Doce, Ann.Rev.Nucl.Part.Sci. 71 (2021)

From small to large colliding systems

"What's inside the integral"



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

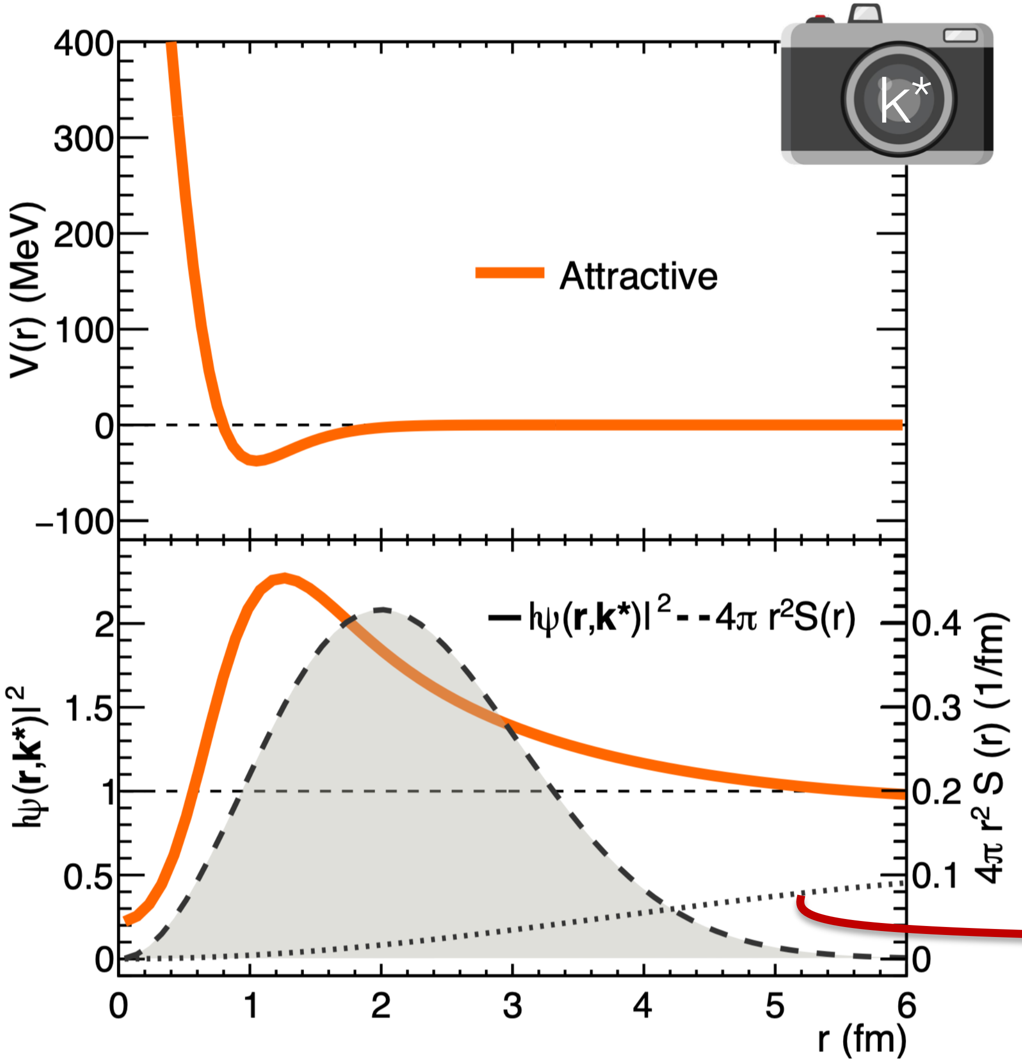


Accessing short-range dynamics in pp collisions

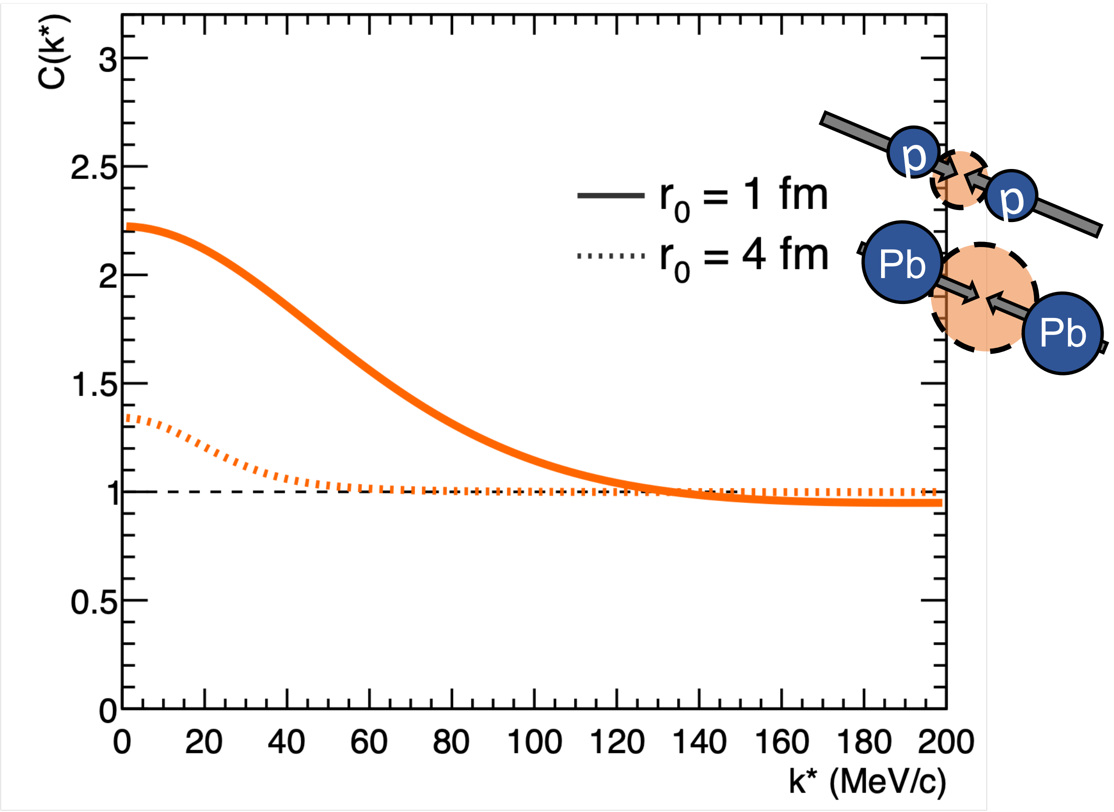
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

From small to large colliding systems

"What's inside the integral"



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

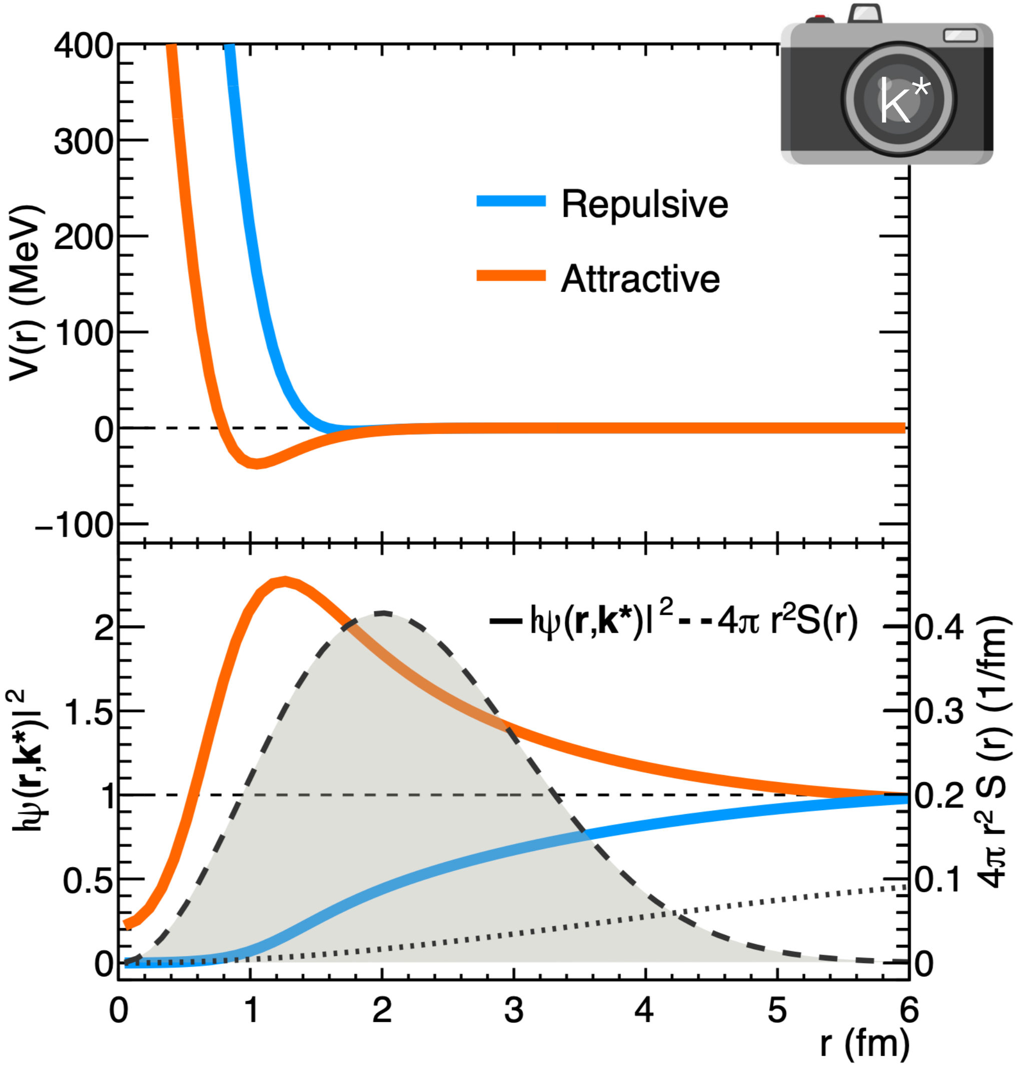


Decrease of signal strength for large source sizes

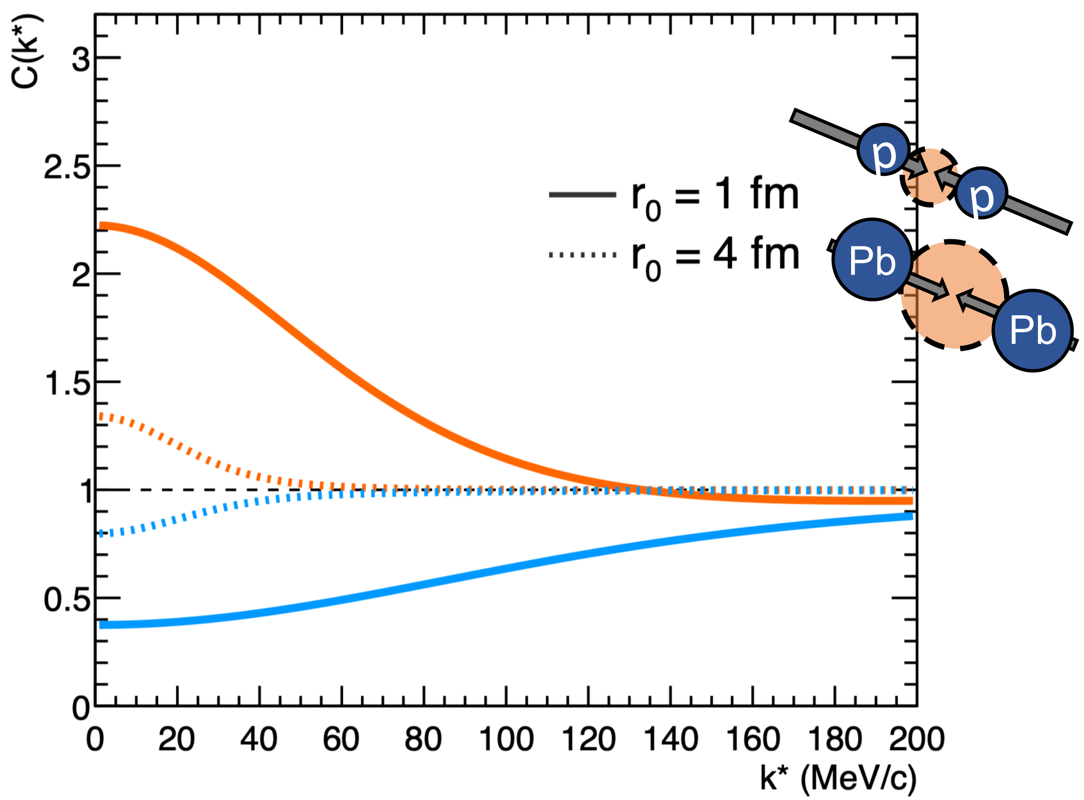
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

From small to large colliding systems

"What's inside the integral"



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

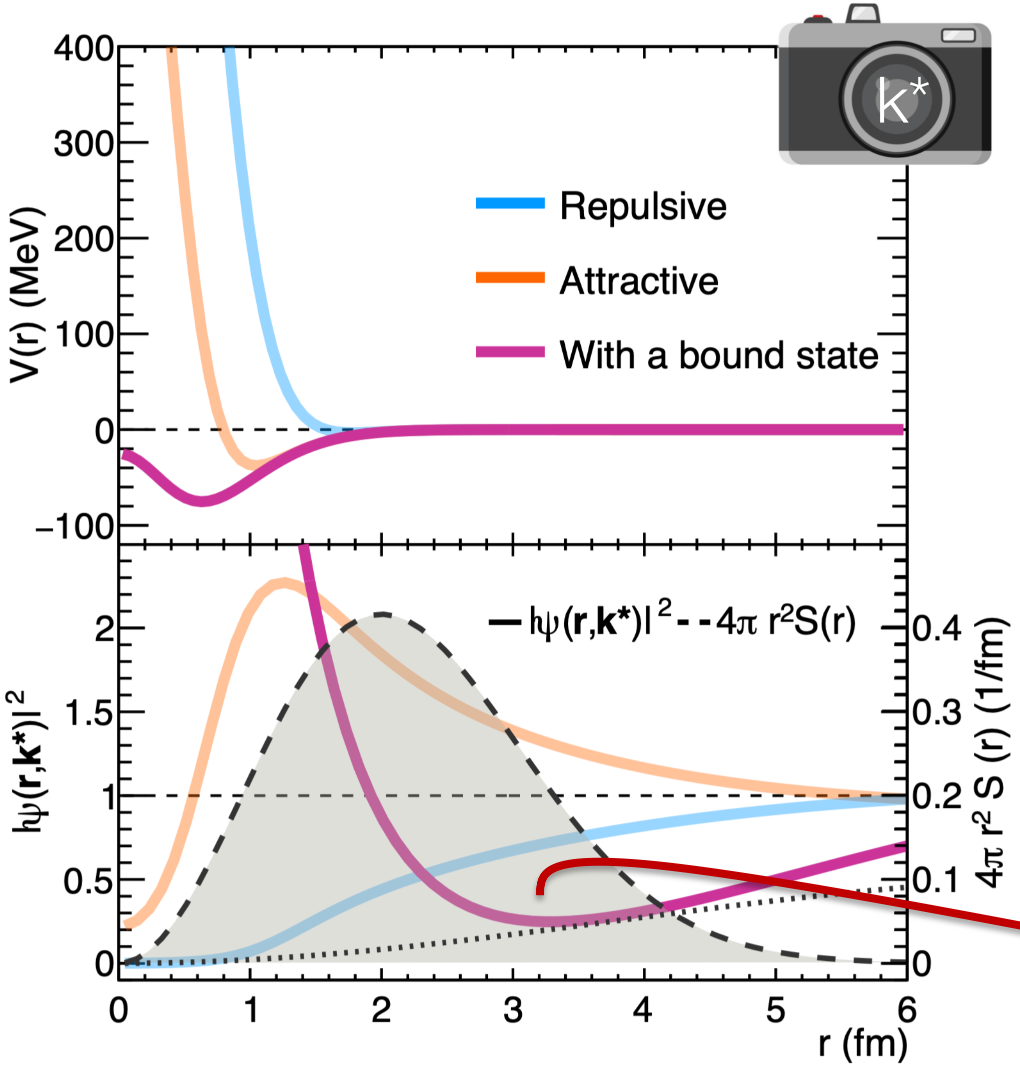


$$C(k^*) \begin{cases} > 1 & \text{Attractive (no BS)} \\ < 1 & \text{Repulsive} \end{cases}$$

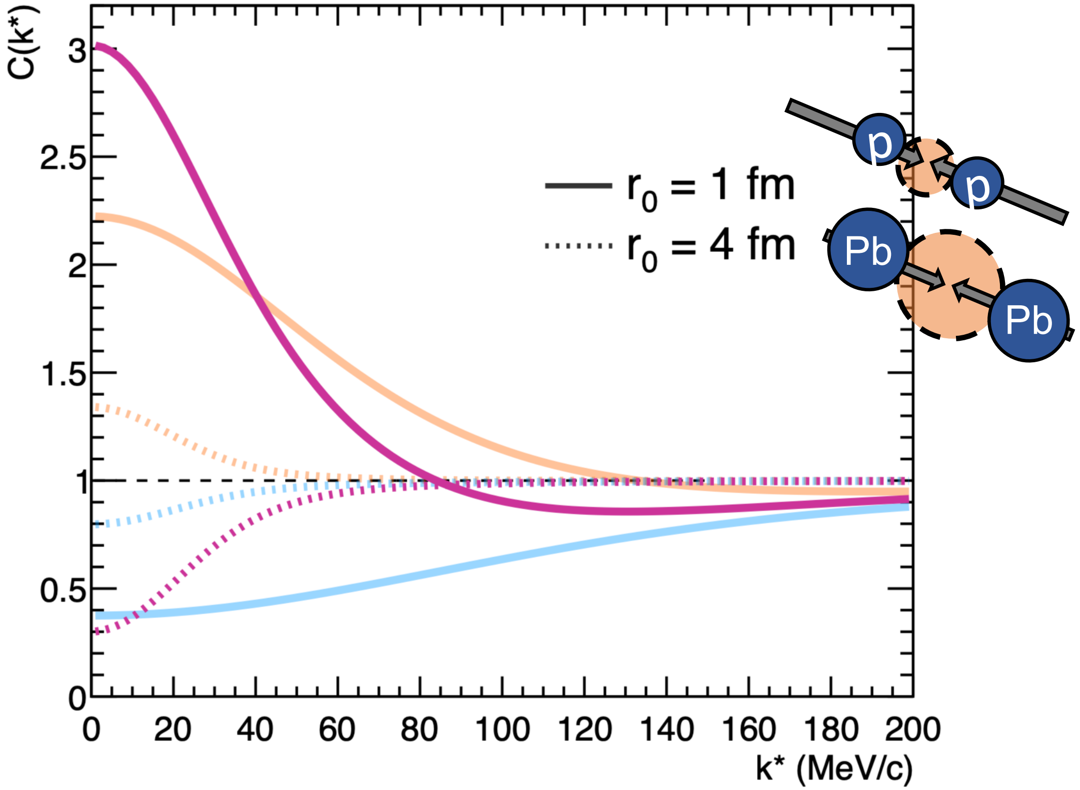
L. Fabbietti, VMS and O. Vazquez Doce ARNPS 71 (2021), 377-402

A clear signature for bound states

"What's inside the integral"



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



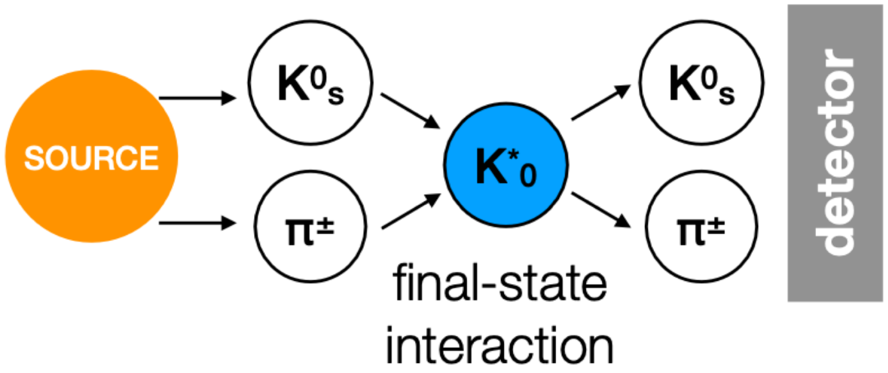
Correlation flips around unity when a bound state is present!

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

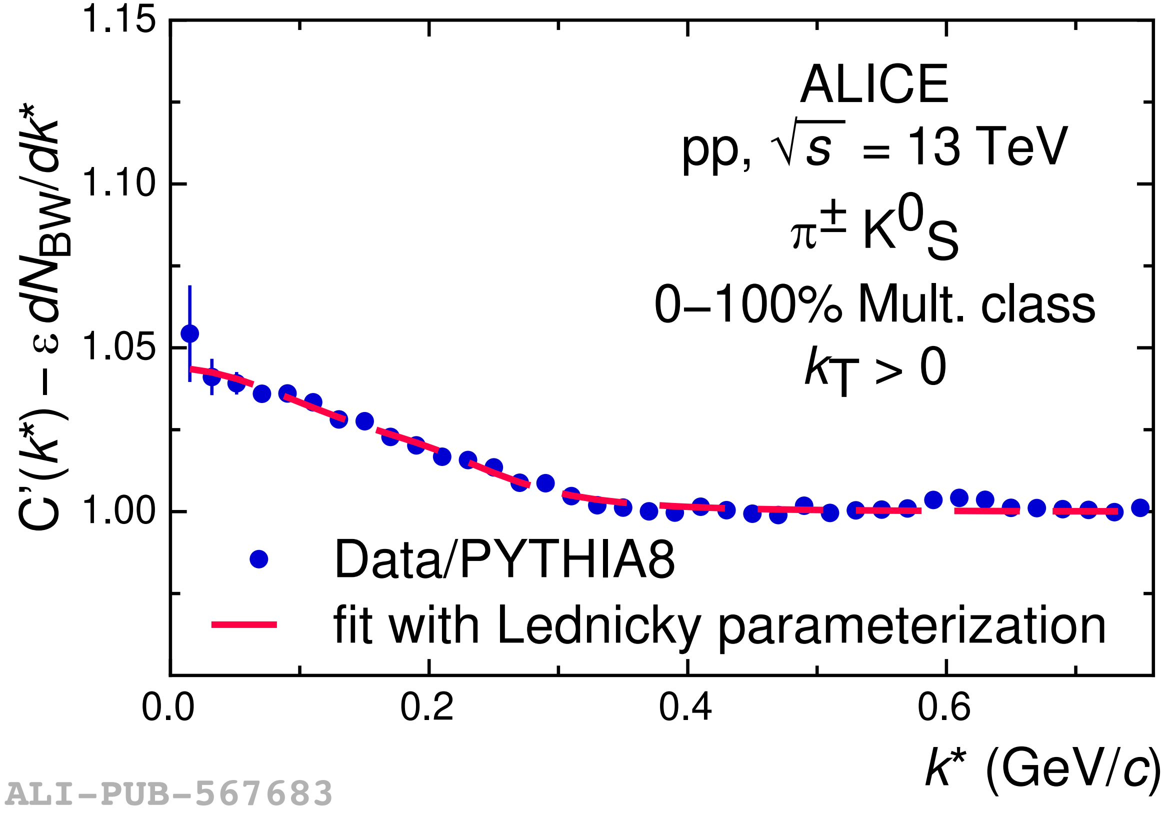
Studying the nature of the $K_0^*(700)$ state

- **First measurement** of $\pi^{\pm}K_s^0$ correlations in pp 13 TeV
  - similar studies with $K_s^0K_s^0$ and $K_s^0K^{\pm}$
    ALICE Coll. PLB 833, 137335 (2022); PLB 790, 22 (2019); PLB 774, 64 (2017)

- Agreement with $\pi^{\pm}K_s^0$ FSI via production of $K_0^*(700)$

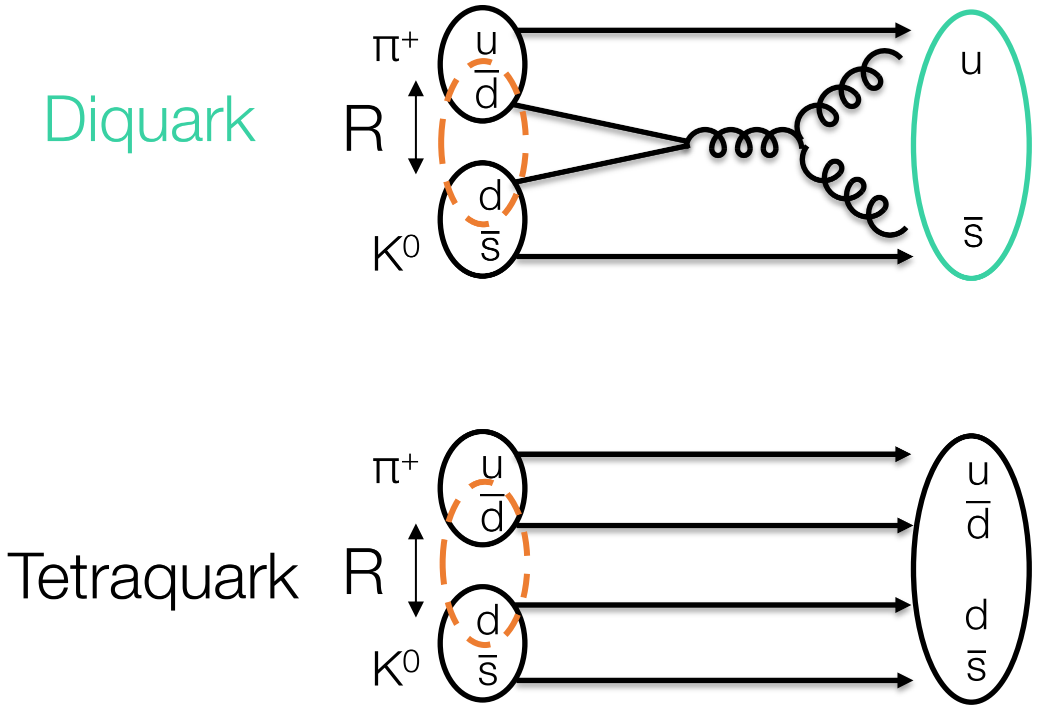


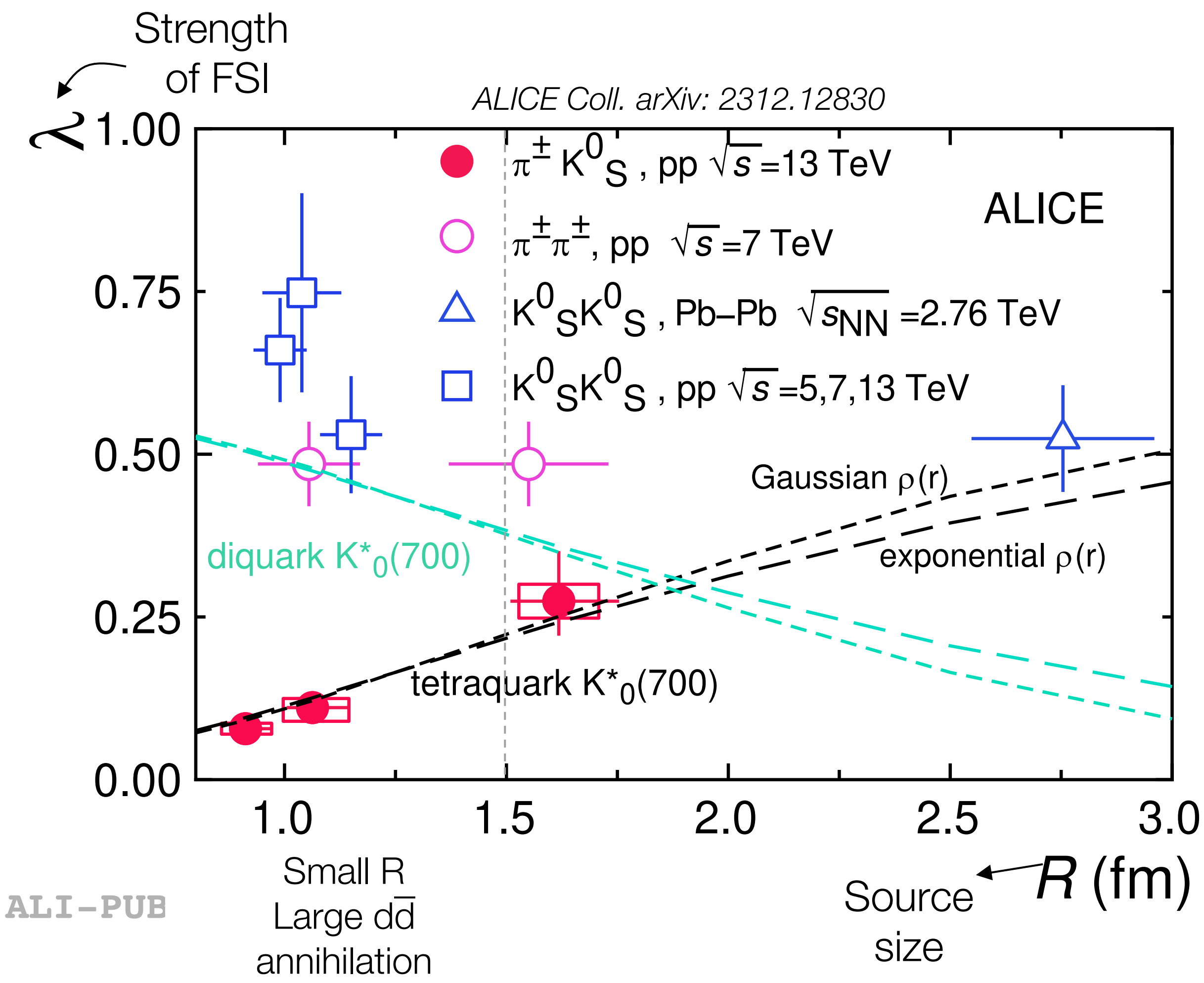
ALICE Coll. arXiv: 2312.12830



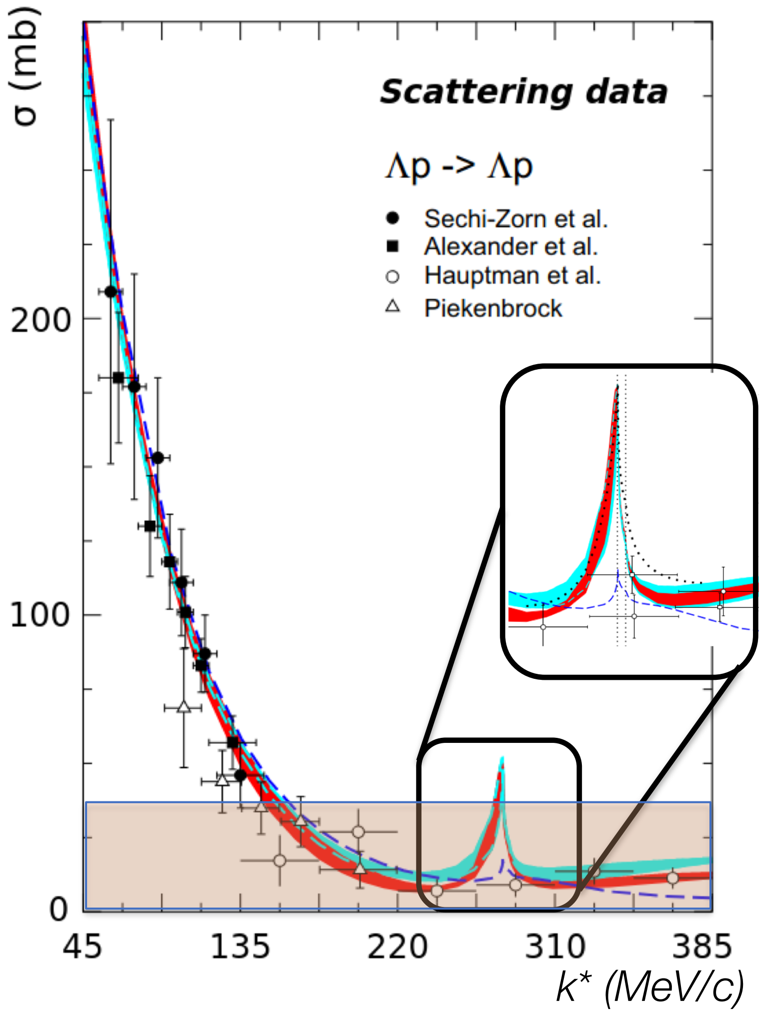
Studying the nature of the $K_0^*(700)$ state

- Testing **conventional or exotic structure** of $K_0^*(700)$
  - probing FSI strength vs source size via a simple geometrical approach



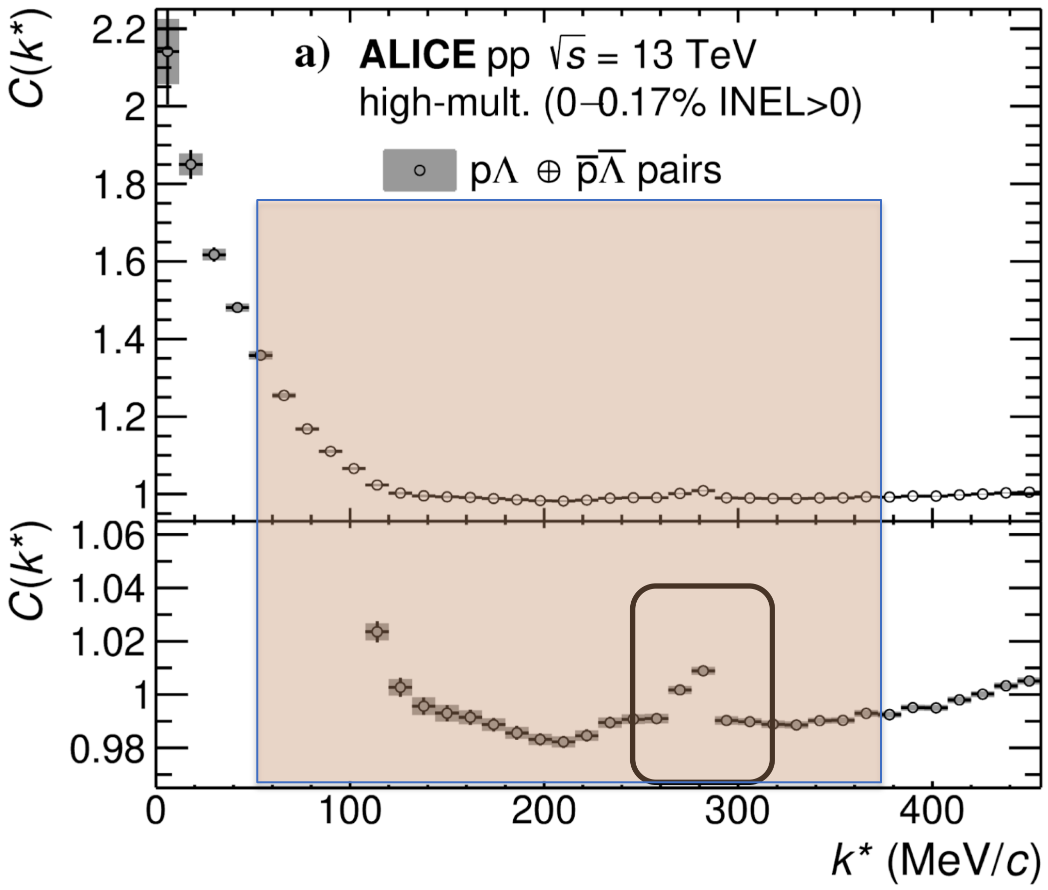


High-precision data on ΛN-ΣN interaction at LHC



NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)
(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

- Extension of kinematic range
- Measurement down to zero momentum
- Factor 20 improved precision in data (<1%)
- First experimental evidence of ΣN cusp in 2-body channel

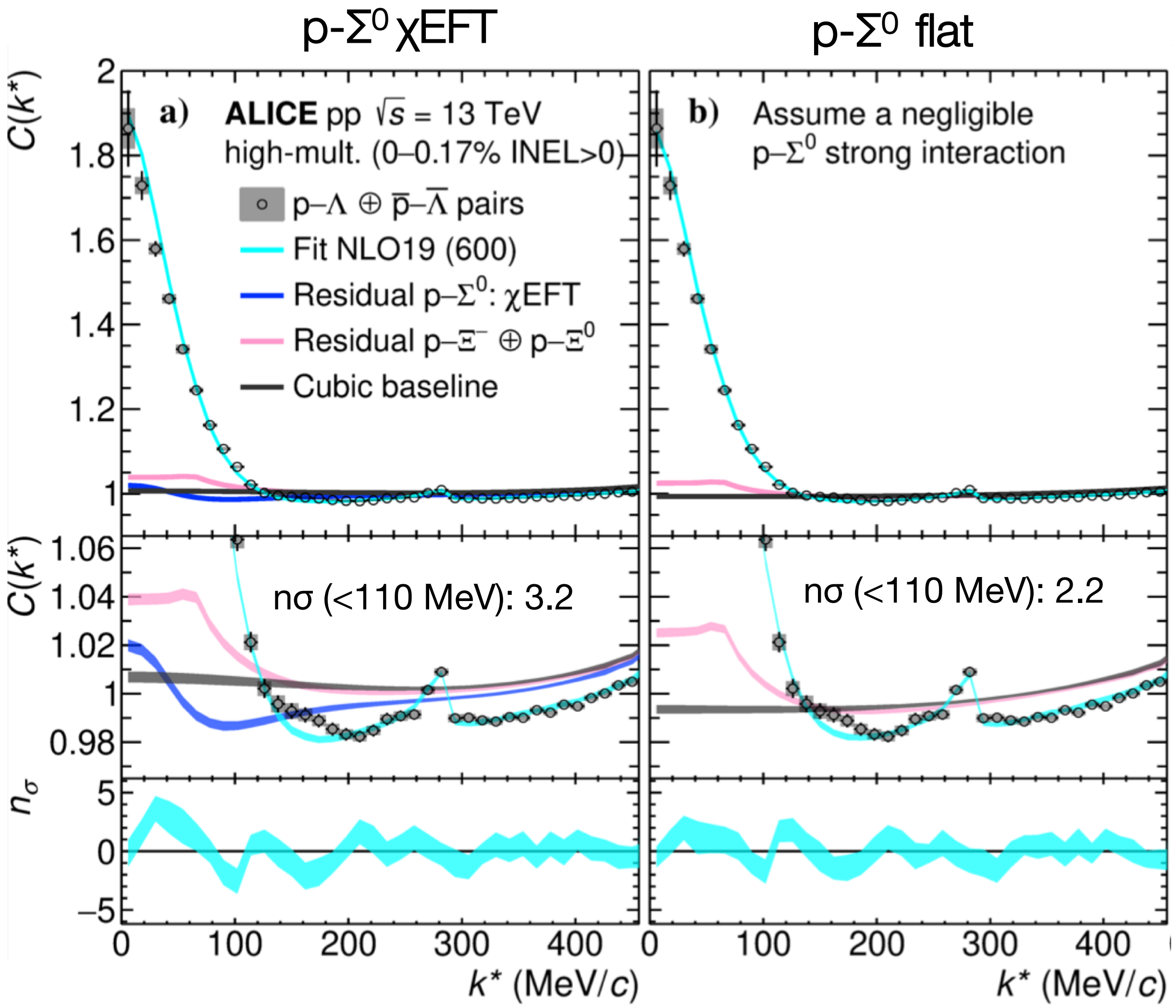


High-precision data on ΛN-ΣN interaction at LHC

- New scenario arising for ΛN-ΣN interaction
  - NLO19 potentials favoured
  - Sensitivity to residual p-Σ^0 interaction
  - Crucial input from several measurements:
    →p$\Sigma^{+,-}$ correlations in LHC Run 3
    →p$\Sigma^{+,-}$ scattering data J-PARC E40

- Deviations with correlation data observed

First-ever combined analysis using available pΛ scattering and correlation data



ALICE Coll. PLB 833 (2022), 137272

(1) D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175
(2) ALICE Coll. PLB 805 (2020) 135419

Combining scattering and correlation data on pΛ

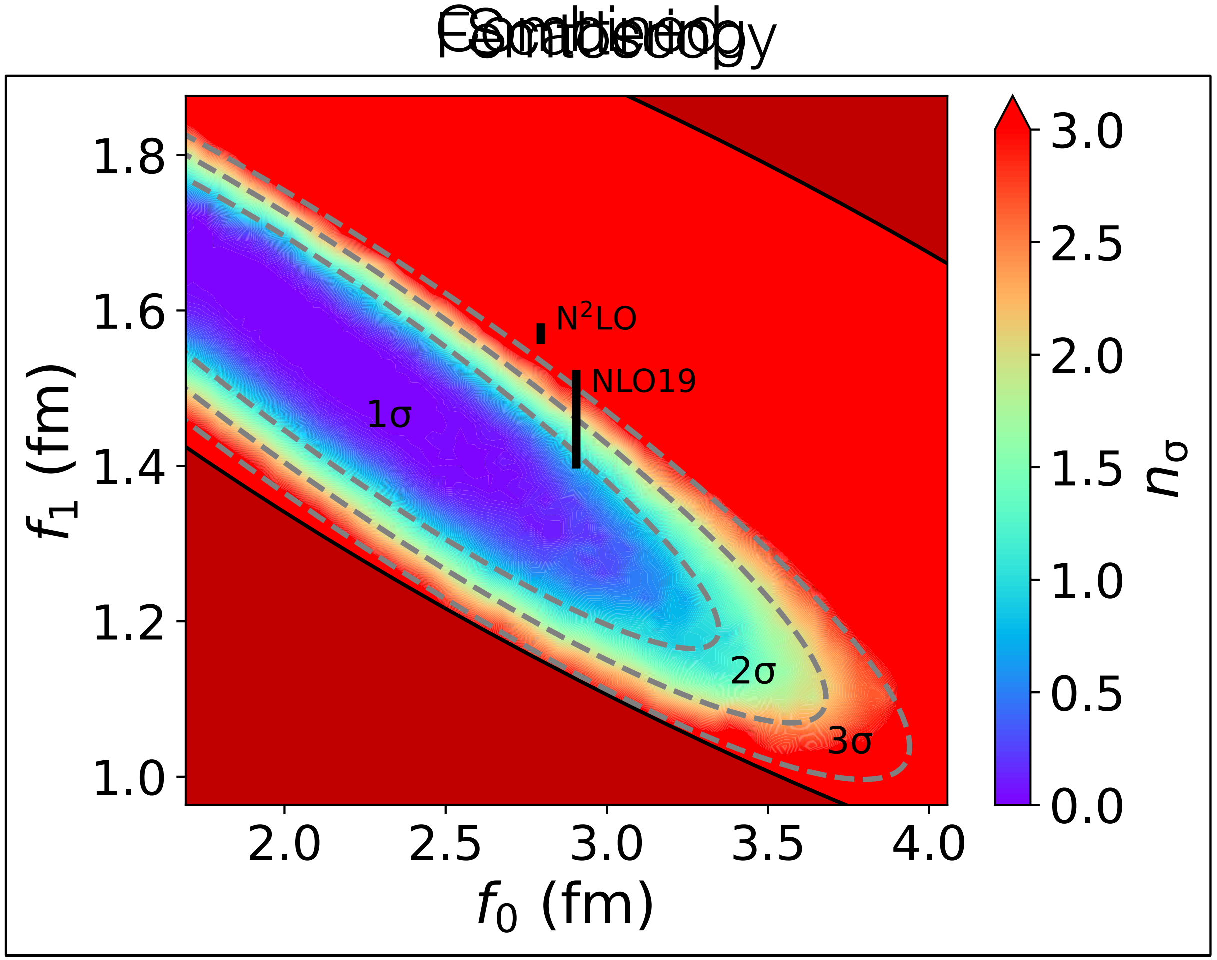
Mihaylov, Haidenbauer, VMS Phys.Lett.B 850 (2024) 138550

- First combined analysis of low-energy pΛ scattering and correlation data
  - 12 elastic pΛ cross-sections
  - pΛ correlation in 6 m_T ranges
    ALICE Coll. PLB 811 (2020) 135849
    CECA: D. Mihaylov et al. EPJC 83 (2023)

- Phenomenological potential tuned to reproduce scattering parameters of χEFT potentials at NLO[1]

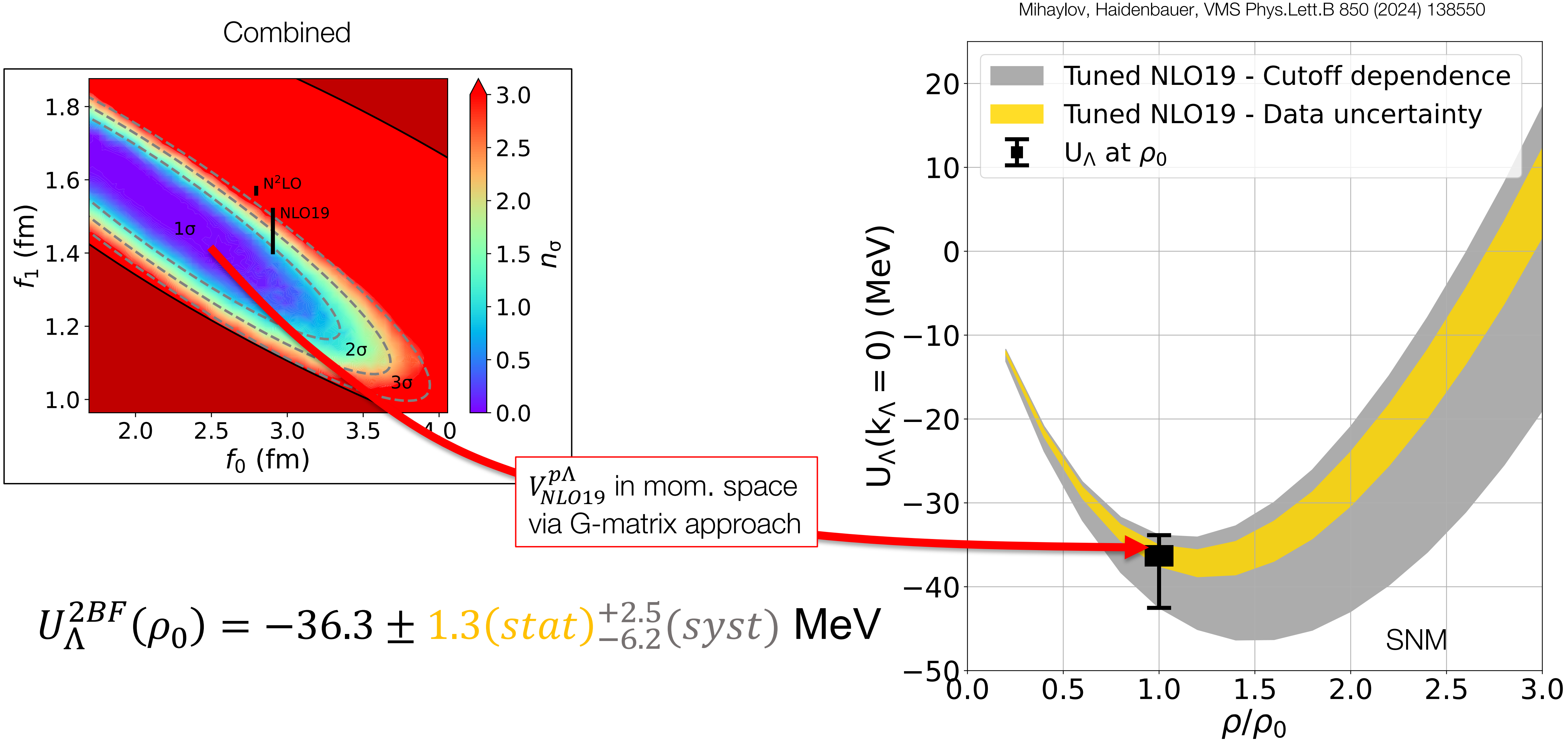
- Tightest constraints available on two-body pΛ scattering parameters

How does the current experimental uncertainty propagates to U_Λ at ρ_0?



(1) J. Haidenbauer et al., EPJA 56 (2020)

Quantifying the two-body contribution of U_Λ



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

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

Conversion weights in Kp femtoscopy

$$C(k^*) = \int S(r)\, \left|\psi_{1\to 1}(k^*, r)\right|^2 d^3r + \sum_{j=\Sigma\pi,\bar{K}^0 n} w_j^{prod} \int S_j(r)\, \left|\psi_{j\to 1}(k_j^*, r)\right|^2 d^3r$$

- Each coupled-channel is taken into account in ω_j weights
  - primary production yields fixed from thermal model (Thermal-FIST V. Vovchenko et al., PRC 100 no. 5 (2019))
  - estimate amount of pairs in kinematic region sensitive to final state interactions
  - distribute particles according to blast-wave model(*)
  - normalize to expected yield of K–p

(*) E. Schnedermann et al., PRC 48 (1993)
ALICE Coll., PLB 728 (2014)
ALICE Coll., PRC 101 no. 4 (2020)

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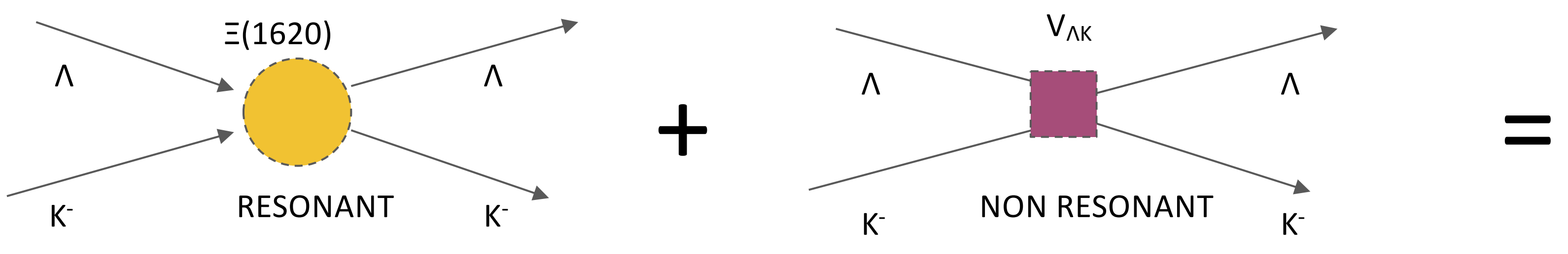
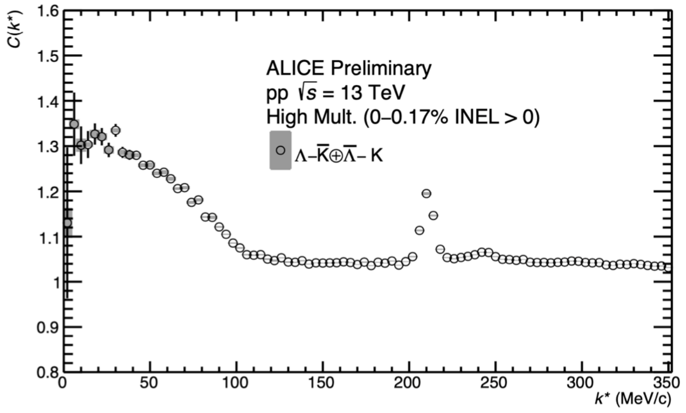
ΛK^- correlation: including the $\Xi(1620)$ resonance





$$C_{model}(k^*) = \lambda_{gen} C_{gen}(k^*) + \lambda_{\Xi K} C_{\Xi K}(k^*) + \lambda_{flat}$$

- Modeled with Lednicky-Lyuboshits analytical formula

$$C_{gen}(k^*) = w C_{non-res}(k^*) + (1-w) C_{res}(k^*)$$

- $C_{non-res}$ → LL with ERE scatt. amplitude
- C_{res} → LL with Flattè-like scatt. amplitude (F. Giacosa et al. Eur.Phys.J.A 57 (2021) 12, 336)

$$f(k^*) = \frac{-2\tilde{\Gamma}_2}{E^2 - M^2 + i\tilde{\Gamma}_1\sqrt{E^2 - E^2_{thr.1}} + i\tilde{\Gamma}_2\sqrt{E^2 - E^2_{thr.2}}}$$

ch. 1 = $\pi\Xi$
ch. 2 = ΛK^-

Thanks to Prof. F. Giacosa for the discussion

Scattering parameters for ΛK⁻

- Indication of an attractive non-resonant interaction
  → In agreement with ALICE Pb-Pb results[1]

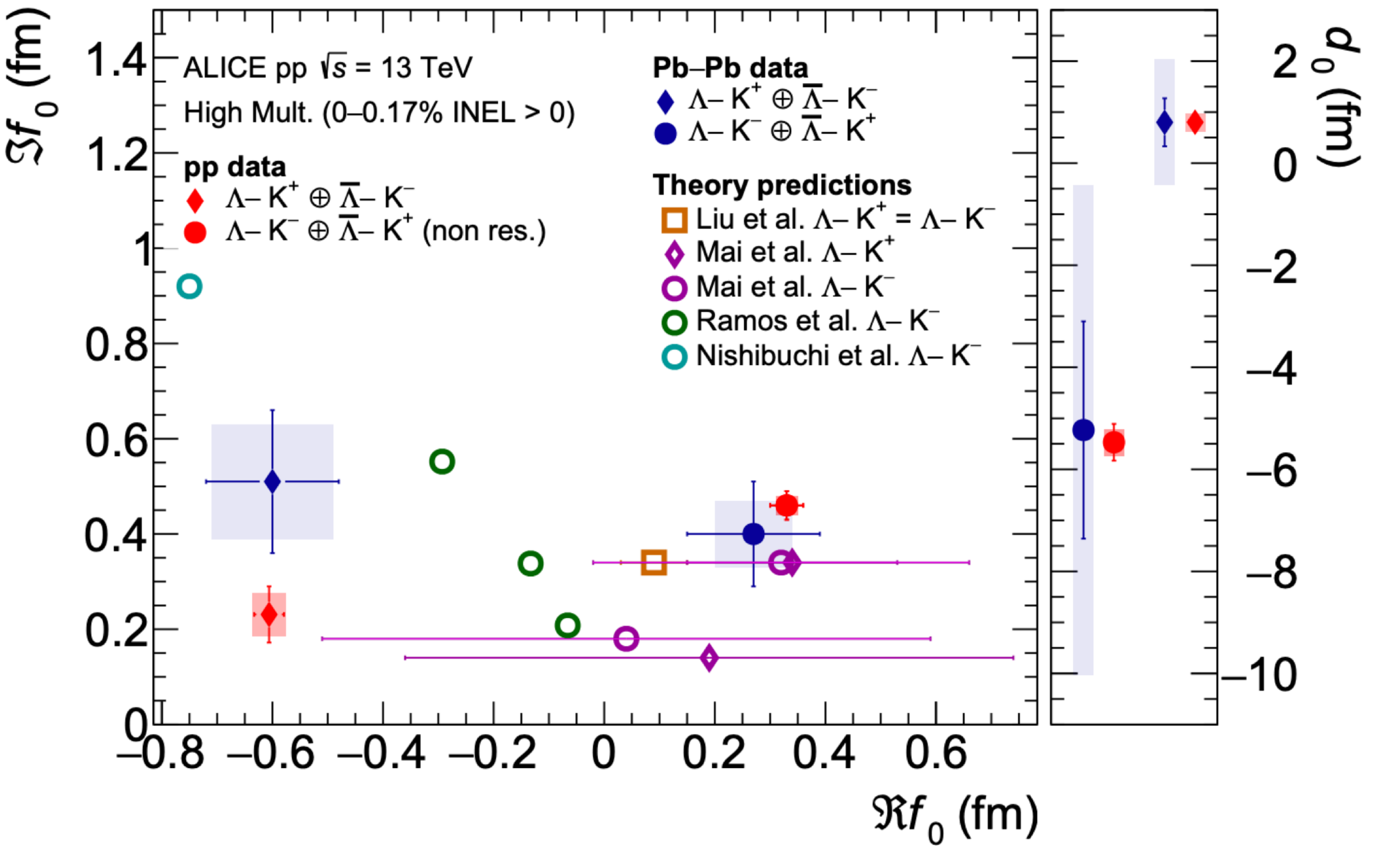
- Available models far from converging on similar results

  → Parameters fixed based on SU(3) flavour symmetry, isospin symmetry

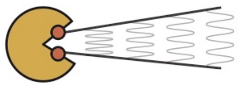
  → Mainly anchored to πN or K̄N data

  → Ξ(1620) typically lying below threshold

- High-precision data to constrain effective chiral theories and to understand the Ξ(1620) nature

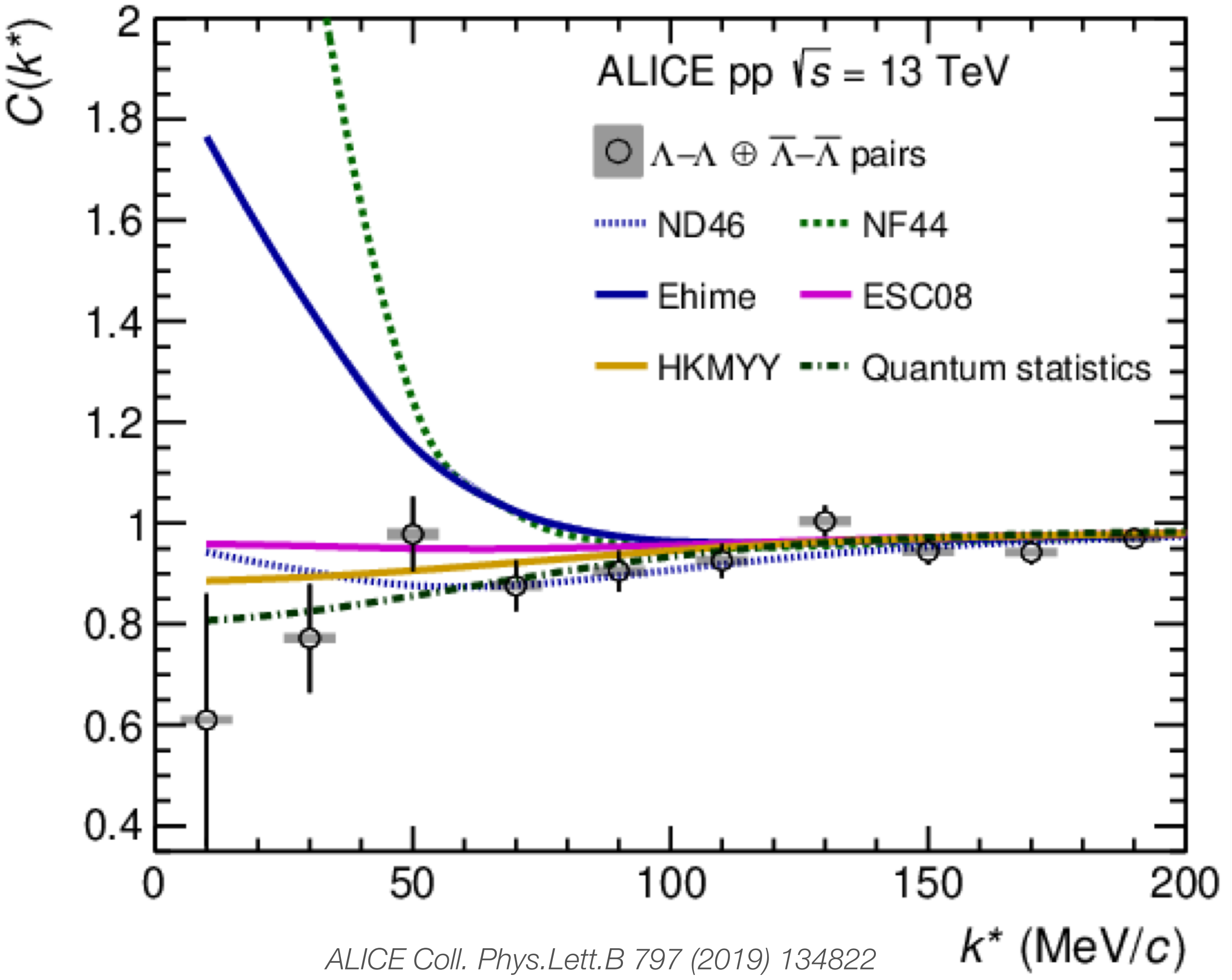


UχPT at LO: Ramos et al. PRL 89 (2002), Nishibuchi et al. EPJ Web Conf 271 (2022)
χPT at NLO: Liu et al. PRD 75 (2007), Mai et al. PRD 80 (2009)



|S|=2 : ΛΛ interaction models

- ΛΛ correlation measured in pp MB 13 TeV and p-Pb 5.02 TeV
- Comparison with available theoretical models
  - large attraction and very weakly bound state discarded
  - data compatible with a bound state (ND46) or shallow attraction (ESC08)
- Scan in scattering parameter space and express agreement data/model in number of σ deviations

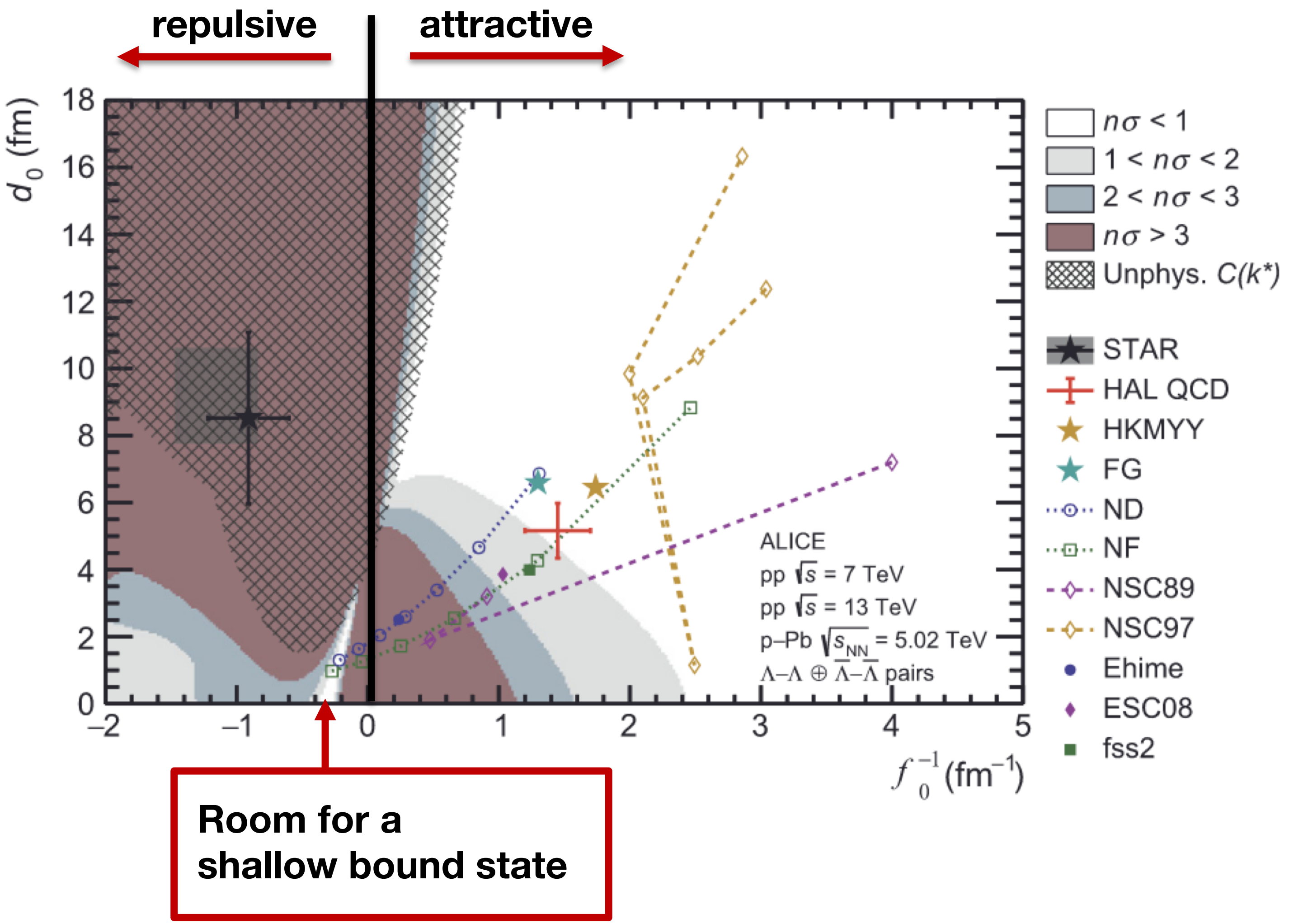


ALICE Coll. Phys.Lett.B 797 (2019) 134822

|S| = 2 : constraining the ΛΛ interaction with femtoscopy

- 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

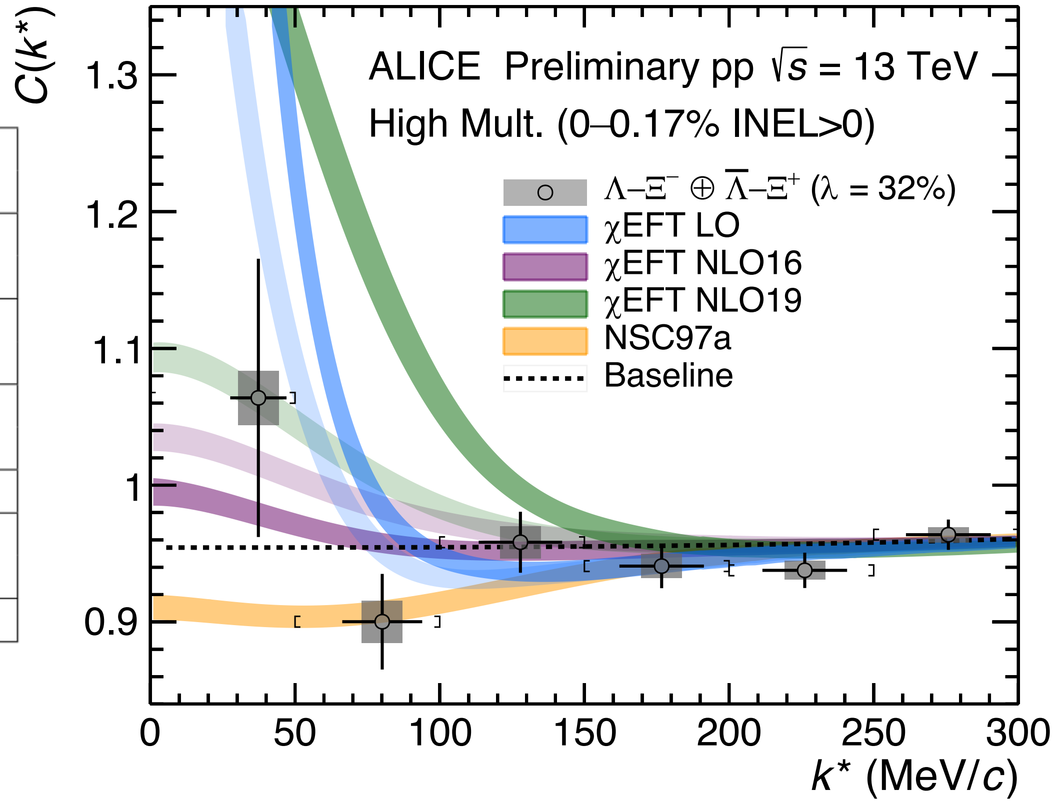
$$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat})^{+1.8}_{-1.0}(\text{syst})\ \text{MeV}$$



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

ΛΞ correlation in pp HM 13 TeV

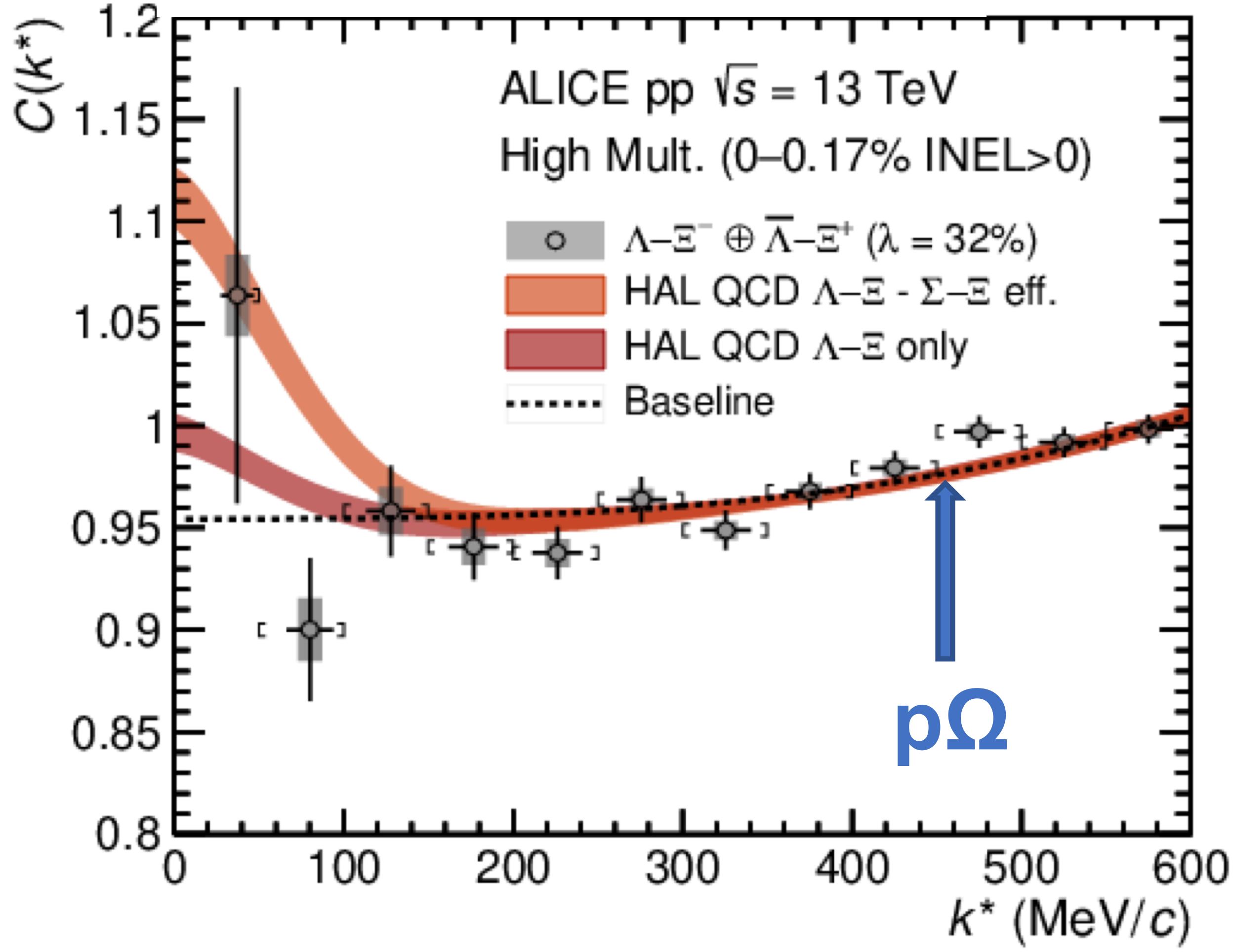
potential	cut-off (MeV) / version	singlet f_0^0	singlet d_0^0	triplet f_0^1	triplet d_0^1	n_σ
χEFT LO [11]	550	33.5	1.00	−0.33	−0.36	3.06 – 5.12
	700	−9.07	0.87	−0.31	−0.27	0.78 – 1.60
χEFT NLO16 [14]	500	0.99	5.77	−0.026	142.9	0.56 – 0.93
	650	0.91	4.63	0.12	32.02	0.91 – 1.61
χEFT NLO19 [15]	500	0.99	5.77	1.66	1.49	5.47 – 7.26
	650	0.91	4.63	0.42	6.33	1.30 – 2.10
NSC97a [12]		0.80	4.71	−0.54	−0.47	0.68 – 1.04
HAL QCD [2]	ΛΞ–ΣΞ eff.	0.60	6.01	0.50	5.36	1.43 – 2.34
	ΛΞ–ΛΞ only	–	–	–	–	0.64 – 1.04
Baseline		–	–	–	–	0.78



ALI-PREL-516888

|S| = 3: Λ-Ξ⁻ interaction – with femtoscopy

ALICE Coll., arXiv:2204.10258, accepted by PLB

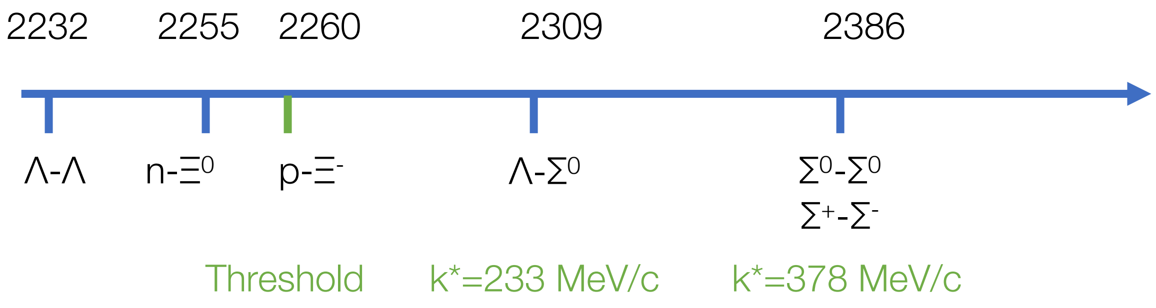


- Unknown contribution from coupled channels in Lattice QCD calculations
  → Coupling ΛΞ–ΣΞ sizable in HAL QCD calculation
  → No sensitivity yet ("No coupling" 0.64 nσ vs. „Coupling“ 1.43 nσ)
- No NΩ cusp visible
  → Hint to negligible NΩ-ΛΞ coupling

(*) *N. Ishii et al.. EPJ Web of Conferences 175, 05013 (2018)*

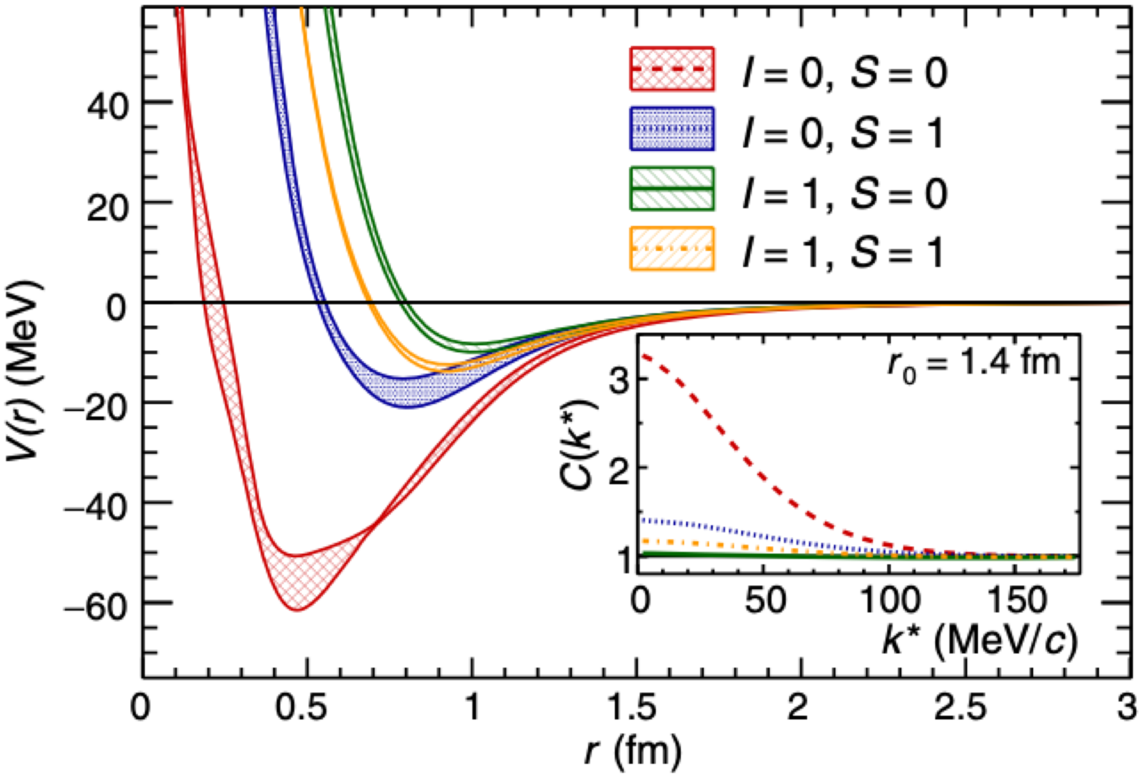
Lattice QCD potentials of the |S| = 2 sector: p-Ξ^- interaction

- Direct comparison to HAL QCD potentials near physical quark masses(*)
- Presence of coupled-channels



- Weak coupling to Λ-Λ channels expected from HAL QCD potentials
  - confirmed from femtoscopic (**) and hypernuclei measurements (***)

p-Ξ^- interaction

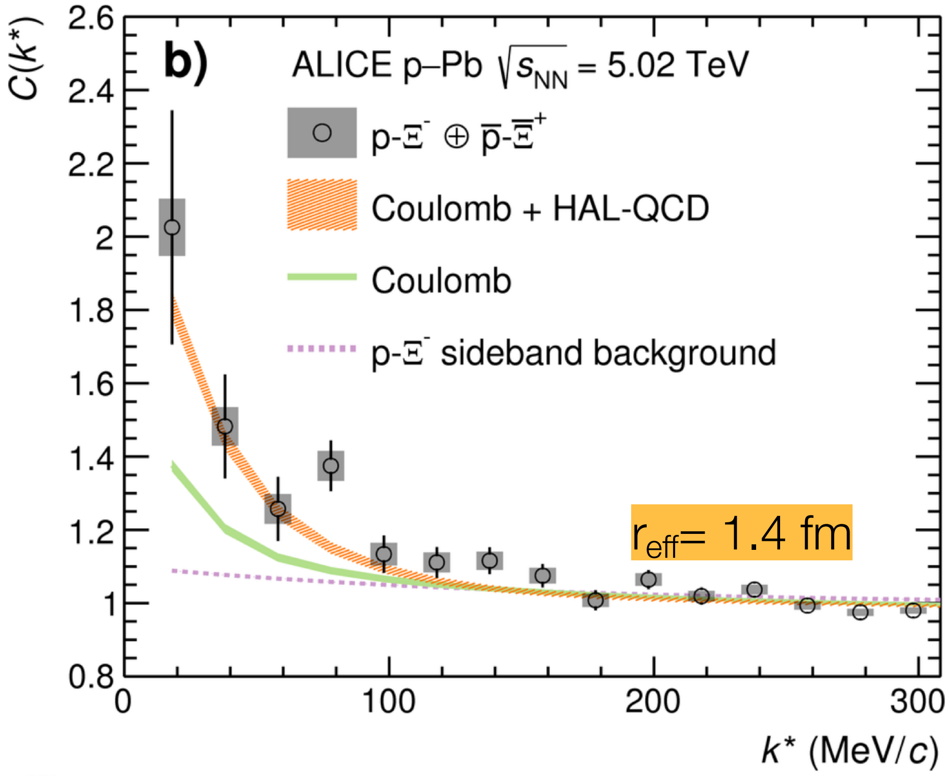


(*) T. Hatsuda Front. Phys. 13(6), 132105 (2018)
(**) ALICE Coll. Phys. Lett. B 797 (2019) 134822
(***) Hayakawa et al. Phys. Rev. Lett. 126, 062501 (2021)

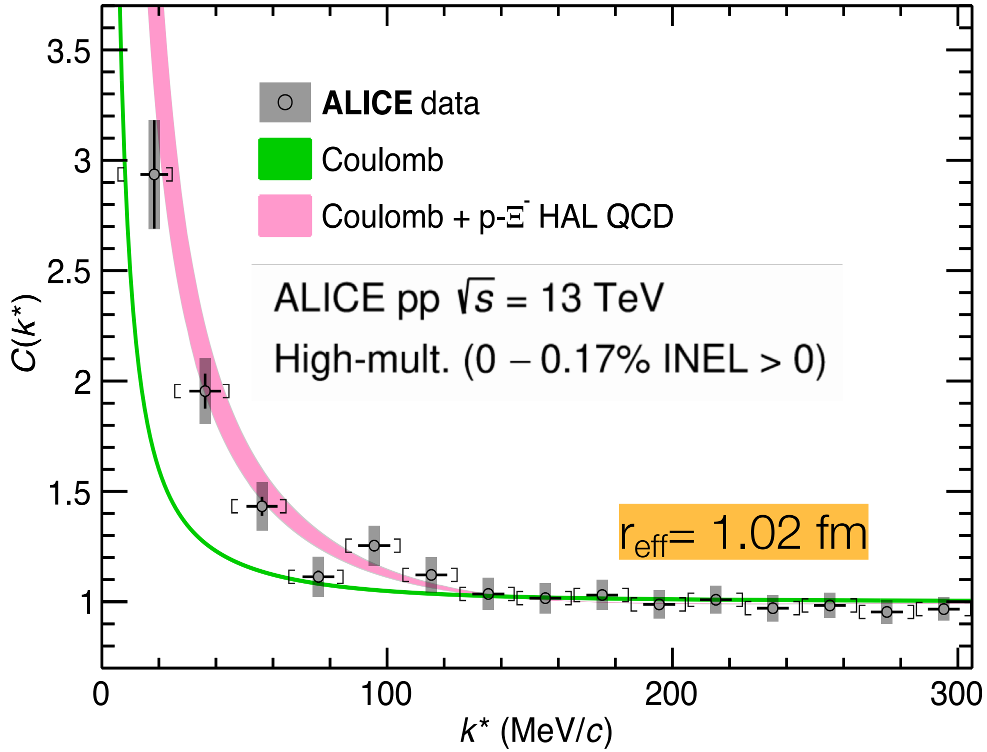
First measurements of the p-Ξ^- interaction at LHC

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems
- **At finite density HAL QCD potentials predict in PNM a slightly repulsive U_Ξ ~+6 MeV(*) → stiffening of the EoS**

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



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



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

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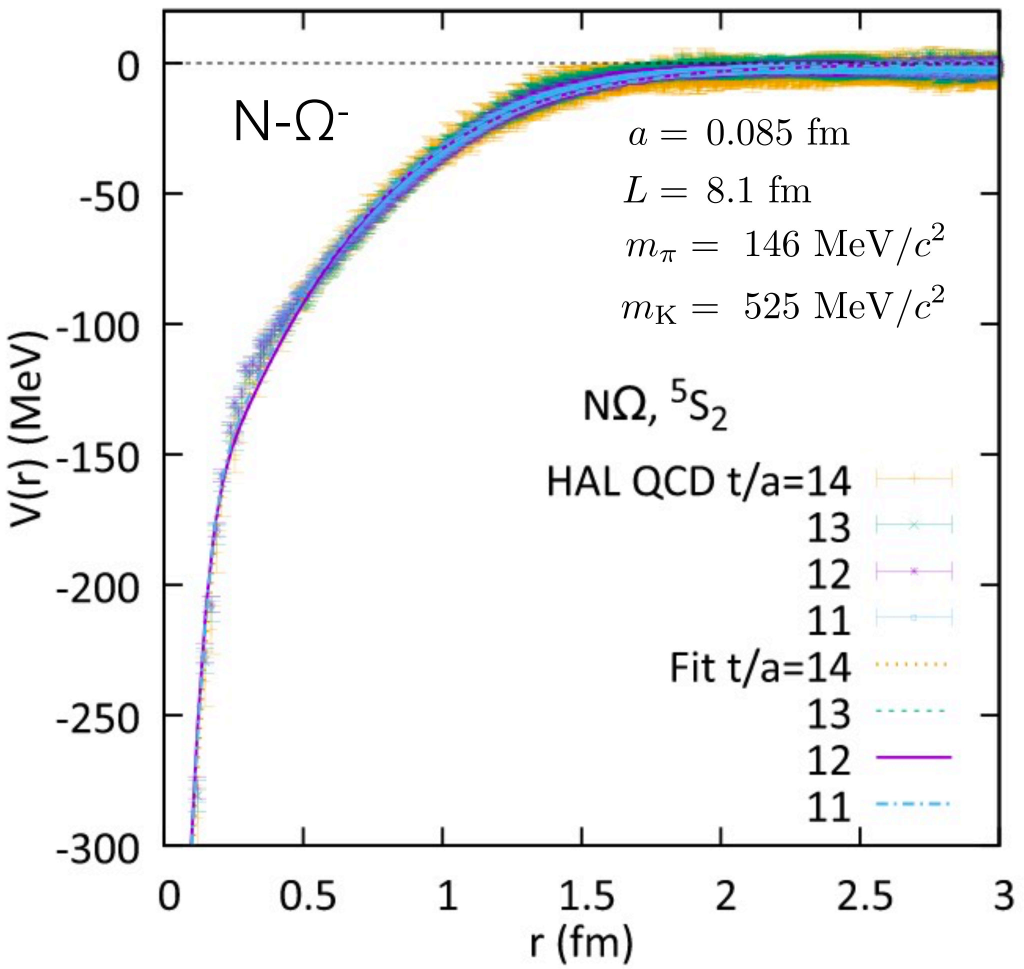
The $p\Omega^-$ interaction and first test of lattice potentials

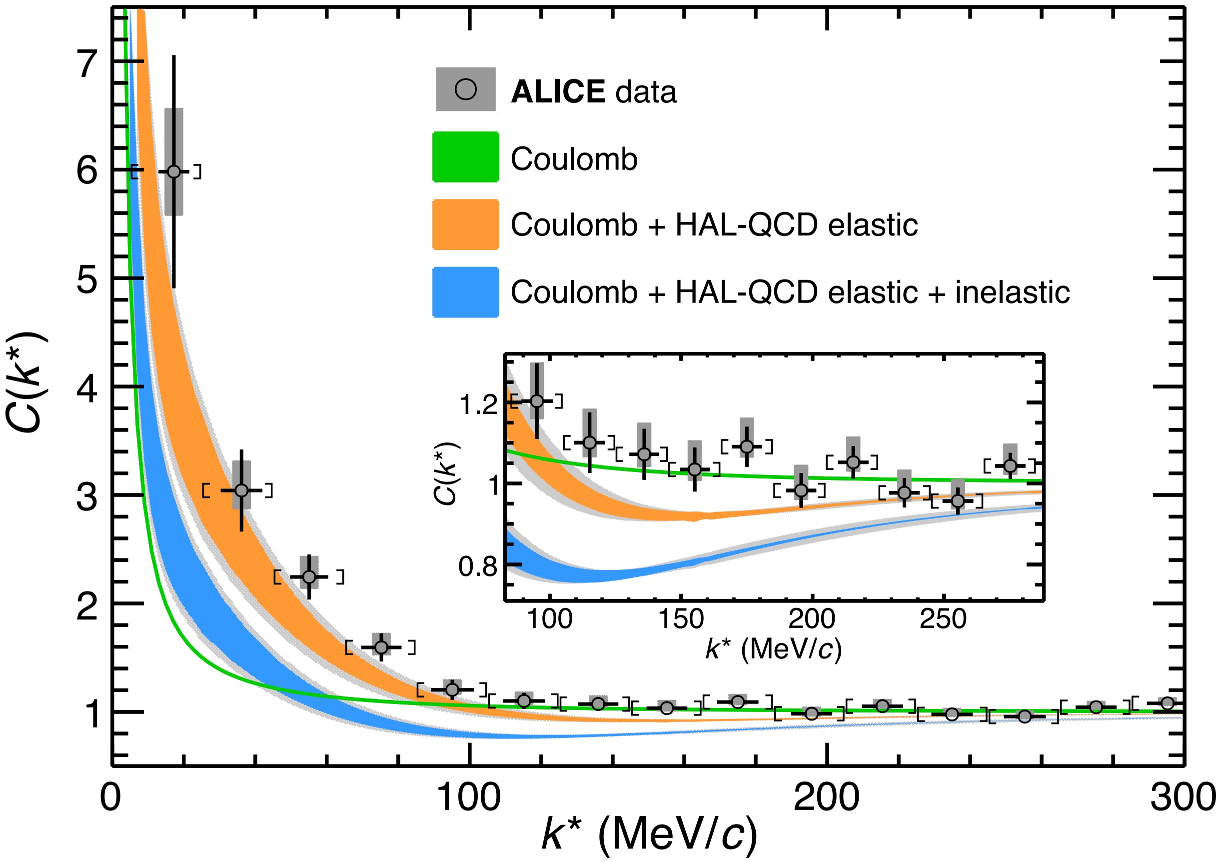
- Available NΩ lattice potentials at physical quark masses[1]
- Very attractive potential in $^5S_2$ state
  → Formation of a loose bound state with B.E~1.5 MeV
  → Looking for another dibaryon after deuteron!
- Inelastic channels (e.g. $p\Omega^- \rightarrow \Lambda\Xi^-$) in $^3S_1$ not yet calculated on the lattice
  → First measurements of $\Lambda\Xi^-$ by ALICE indicates a weak coupling[2]



[1] HAL QCD Coll. PLB 792 (2019)
[2] ALICE Coll. arXiv:2204.10258, accepted by PLB

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

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

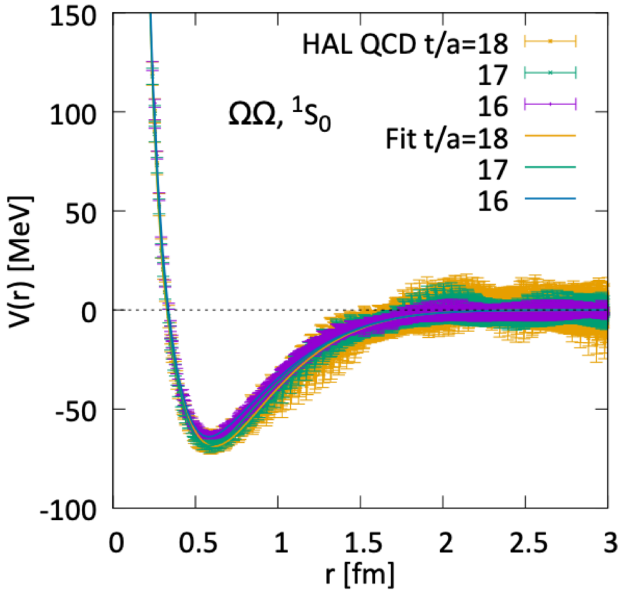


- Enhancement above Coulomb
  → Observation of the strong interaction
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  - Inelastic channels dominated by absorption
  - Neglecting inelastic channels
    → Favoured!
- So far, no indication of a bound state
  → Extend the measurements to p-Pb and Pb-Pb in Run 3 and Run 4
- Access to Ω-Ω in Run 3 and Run 4 with ALICE[1]

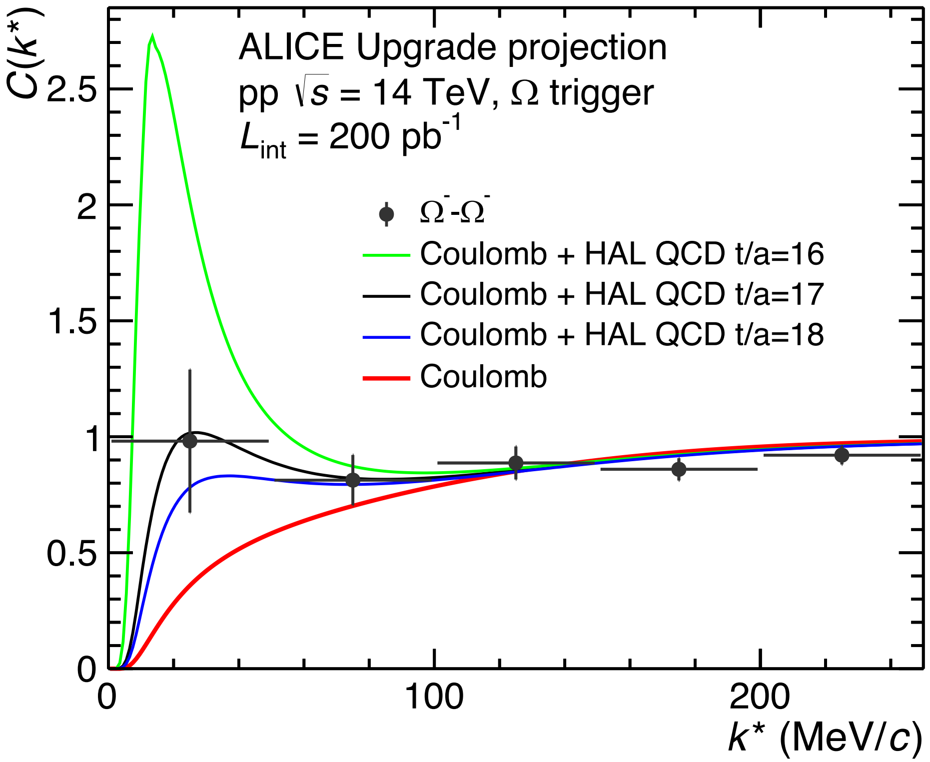
[1] ALICE Public Note ALICE-PUBLIC-2020-005

ΩΩ correlation with future LHC runs

- Most strange dibaryon predicted by lattice potentials[1]
  → B. E ~1.6 MeV



- Thanks to enhanced statistics of Run 3
  → similar precision to the current p–Ω Run 2 (30% at k* = 50 MeV/c)



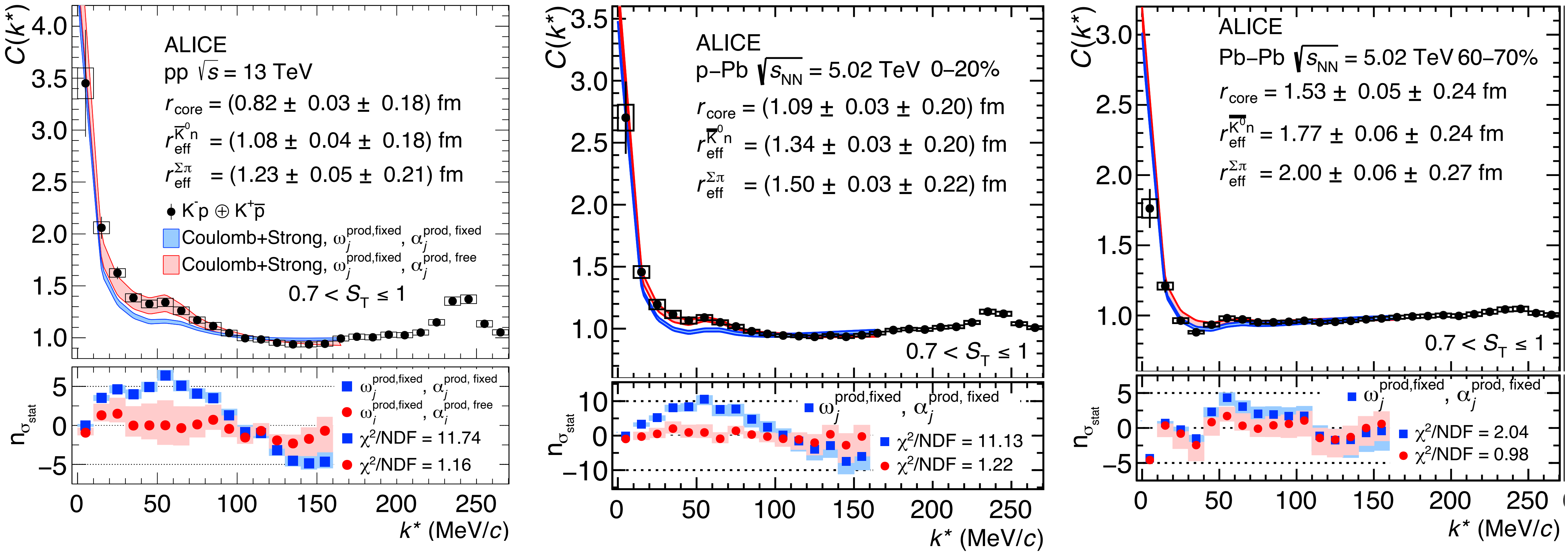
CERN-LHCC-2020-018 ; LHCC-G-179
Future high-energy pp programme with ALICE

K⁻–p femtoscopy in different colliding systems

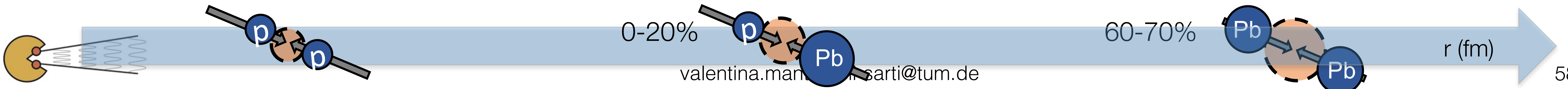
Fit the scaling factor needed for the model to reproduce the data

$$C(k^*) = \int S(r)\, |\psi_{1\to1}(k^*, r)|^2\, d^3r + \sum_{j=\Sigma\pi,\bar{K}^0 n} \alpha_j \cdot \omega_j^{prod} \int S_j(r)\, |\psi_{j\to1}(k_j^*, r)|^2\, d^3r$$

χEFT Kyoto model:
Ikeda et al. NPA 881 (2012), PLB706 (2011)
Kamiya et al. PRL 124 (2020)
Mihayara et al. PRC95 (2017)



ALICE Coll. Eur.Phys.J.C 83 (2023) 4, 340



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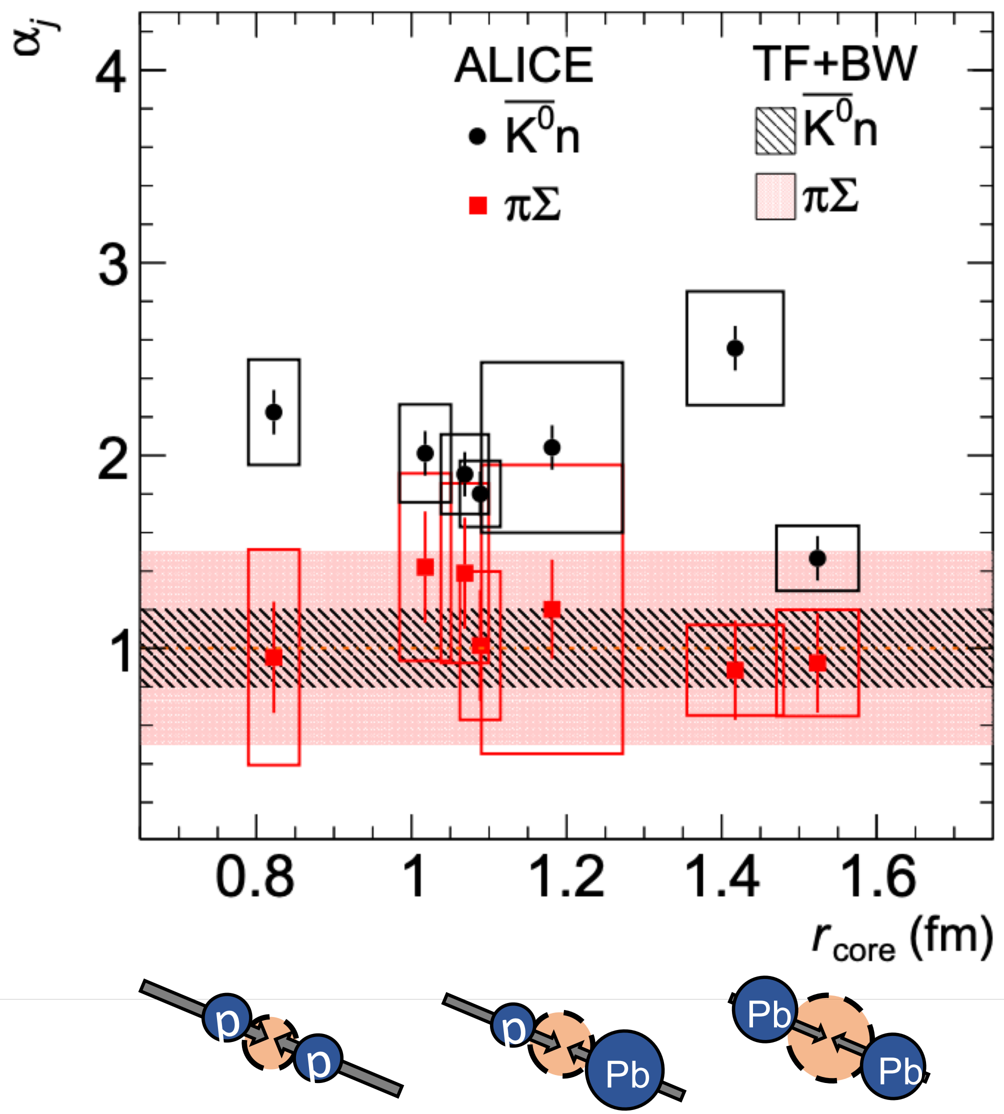
Extracted strong weights for $\Sigma\pi$ and $\overline{K}^0$ n channels

Unique constraint and direct access to $K^-p \leftrightarrow \overline{K}^0 n$ and $K^-p \leftrightarrow \Sigma\pi$ dynamics

- $\Sigma\pi$ consistent with unity
- deviation from unity for $\overline{K}^0$ n
  - K^-p - $\overline{K}^0$ n coupling too weak in chiral potentials
  - update the scattering amplitude of KN–πΣ–πΛ system by including correlation measurements to available kaonic hydrogen and scattering data

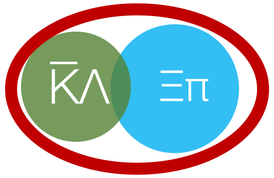
ALICE Coll. Eur.Phys.J.C 83 (2023) 4, 340



Constraining the S=-2 meson-baryon sector

- State-of-the-art UχPT at NLO available[1]
  - Ξ(1620) and Ξ(1690) dynamically generated states

Ξ(1620)



  - Low energy constants (LECs) fixed to S=-1 sector[2]
  - Two sets of subtraction constants (SCs) values
  - Widths of Ξ(1620) too large wrt to Belle´s results[3]

Use the high-precision femtoscopic data to fix LECs!

Work in collaboration with:
Dr. A. Feijoo, Dr. I. Vidana, Prof. A. Ramos,
Prof. F. Giacosa,
Prof. T. Hyodo and Dr. Y. Kamiya

[1] A. Feijoo et al., PLB 841 (2023)

Table 3: Comparison of the pole positions between the models: Model I and Model II (in MeV) with their couplings g_i and the corresponding modulus found in $J^P = \frac{1}{2}^-, (I, S) = (\frac{1}{2}, -2)$.

Model I	Ξ(1620)		Ξ(1690)	
M [MeV]	1599.95		1683.04	
Γ [MeV]	158.88		11.51	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi\Xi$	$2.09 + i1.00$	2.32	$-0.30 - i0.12$	0.33
$\bar{K}\Lambda$	$-2.11 - i0.09$	2.11	$-0.49 + i0.05$	0.50
$\bar{K}\Sigma$	$-0.90 + i0.34$	0.97	$1.57 - i0.24$	1.59
$\eta\Xi$	$-0.23 + i0.13$	0.26	$0.74 - i0.11$	0.74
Model II	Ξ(1620)		Ξ(1690)	
M [MeV]	1608.51		1686.17	
Γ [MeV]	170.00		29.72	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi\Xi$	$2.11 + i1.07$	2.37	$-0.36 - i0.24$	0.43
$\bar{K}\Lambda$	$-2.10 - i0.09$	2.10	$-0.81 + i0.02$	0.81
$\bar{K}\Sigma$	$-0.86 + i0.38$	0.94	$2.26 + i0.03$	2.26
$\eta\Xi$	$-0.19 + i0.12$	0.23	$1.04 - i0.07$	1.04

[2] A.Feijoo et al PRC 99 (2019)
[3] Belle coll. PRL 122 (2019)

Femtoscopy era in the S=-2 meson-baryon sector

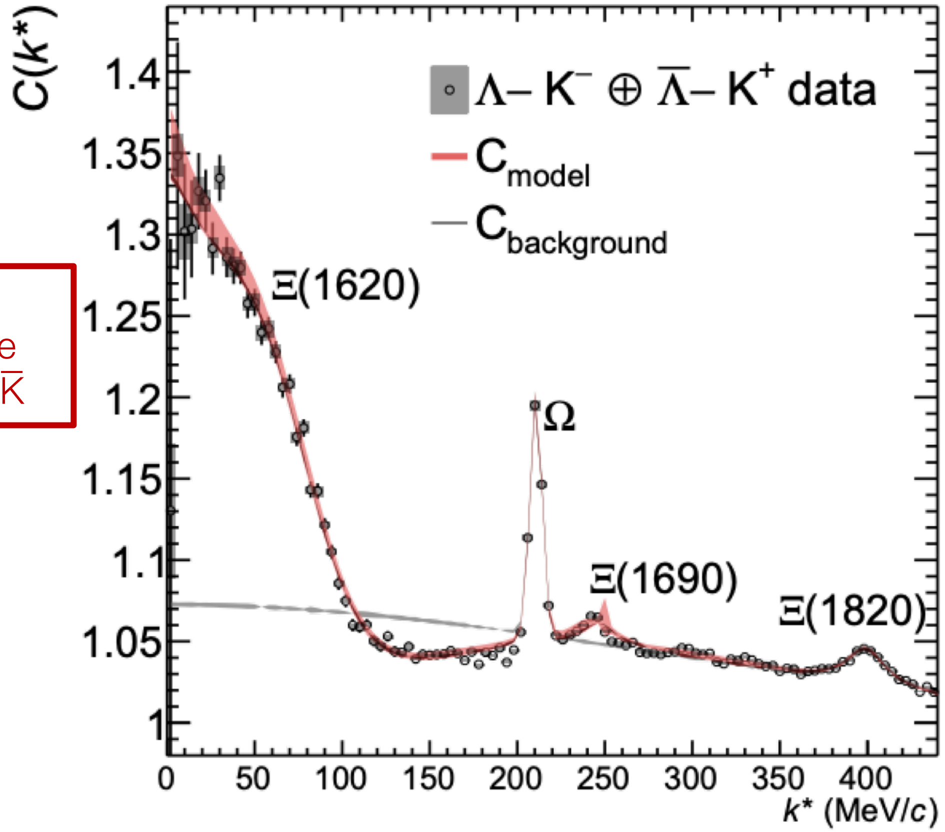
- First combined effort in constraining the input parameters of an effective chiral lagrangian to correlation data
- How does the Ξ(1620) pole scenario look like?

mass M:	1612.68 MeV		1670.28 MeV	
width Γ:	24.57 MeV		7.44 MeV	
Riemann sheet:	$(---+++)$		$(---+++)$	
	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$
$\pi^-\Xi^0(1454)$	0.51	0.014	0.22	0.002
$\pi^0\Xi^-(1456)$	0.36	0.007	0.39	0.007
$K^-\Lambda(1609)$	0.94	0.162	0.07	0.000
$K^-\Sigma^0(1686)$	0.17	0.002	2.20	0.761
$\bar{K}^0\Sigma^-(1695)$	0.21	0.003	1.37	0.230
$\eta\Xi^-(1868)$	5.86	0.937	0.05	0.000
Experimental Ξ^*:	Ξ(1620) [18]		Ξ(1690) [56]	
mass M:	$1610.4 \pm 6.0^{+5.9}_{-3.5}$ MeV		1690 ± 10 MeV	
width Γ:	$59.9 \pm 4.8^{+2.8}_{-3.0}$ MeV		20 ± 15 MeV	

Ξ(1620) pole
Mainly molecular nature
composed of ηΞ and $\Lambda\bar{K}$

Ξ(1690) pole
Virtual state
Mainly coupled to $\bar{K}\Sigma$

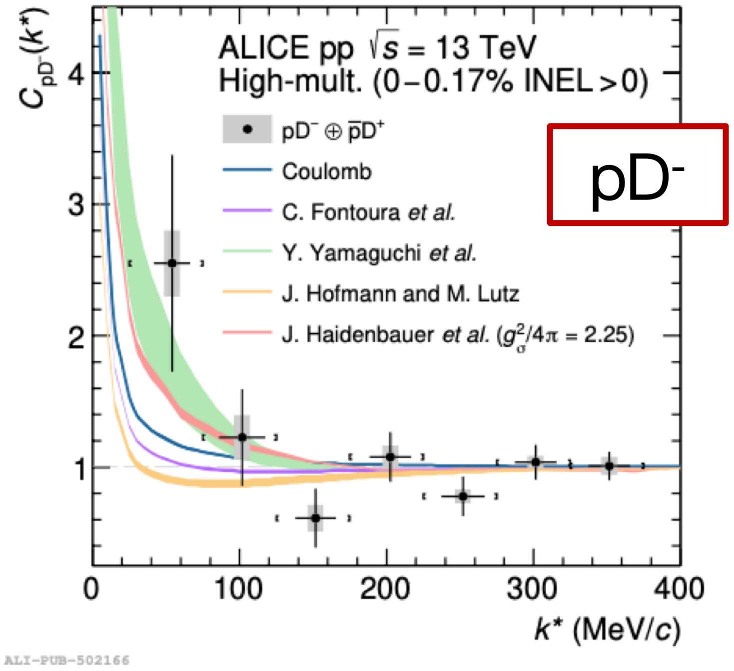
VMS, A. Feijoo et al. arXiv: 2309.08756



Work in collaboration with:
Dr. A. Feijoo, Dr. I. Vidana, Prof. A. Ramos,
Prof. F. Giacosa,
Prof. T. Hyodo and Dr. Y. Kamiya

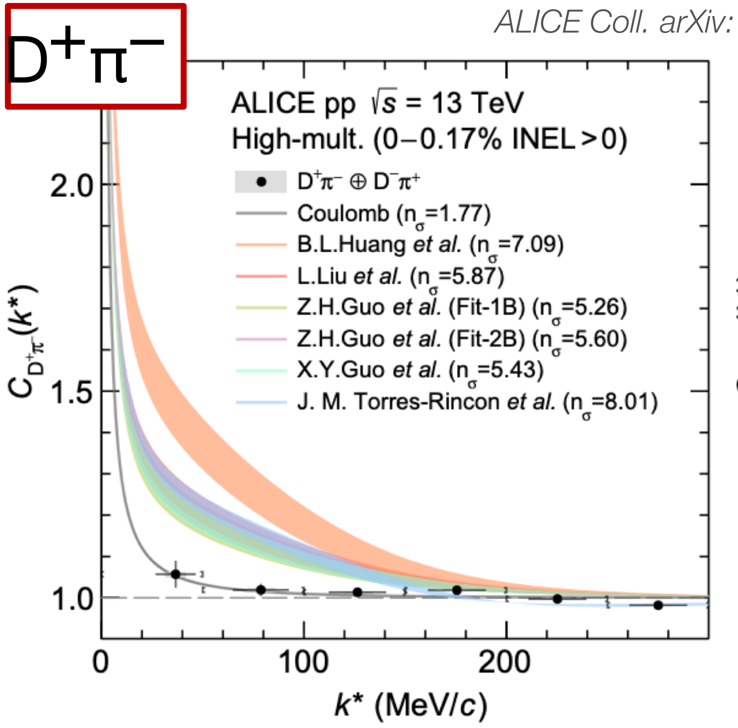
Accessing the interaction between light and charm hadrons

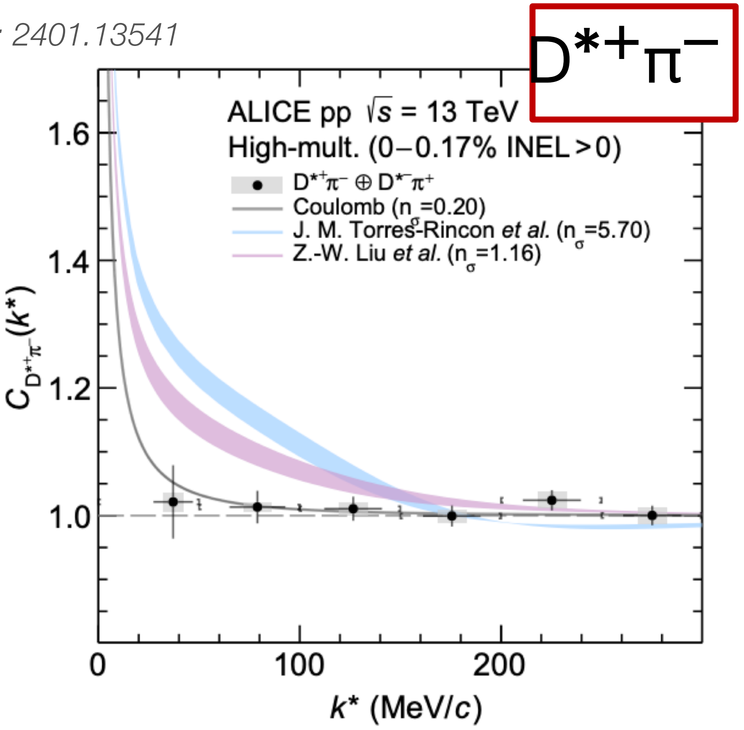
ALICE Coll. PRD 106 (2022), 5, 052010



- First measurements of interaction between D(*) mesons and light hadrons
  - Several predictions of exotic states, crucial input for charm nuclei and heavy-flavor observables in heavy-ions
- Femtoscopy can be extended to the charm sector
  - More results to come with the LHC Run 3 and Run 4 statistics

ALICE Coll. arXiv: 2401.13541

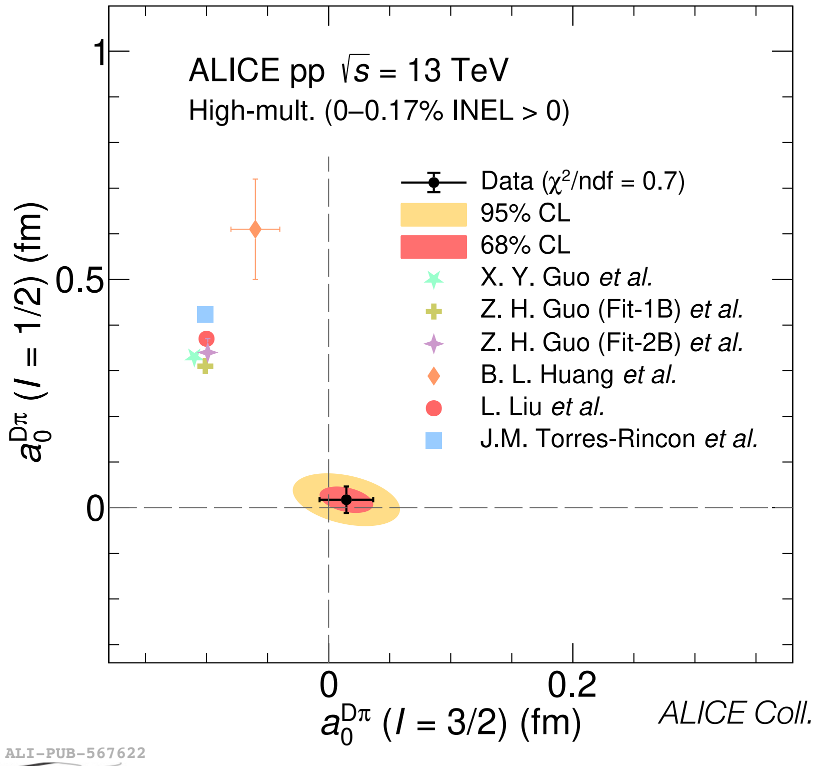




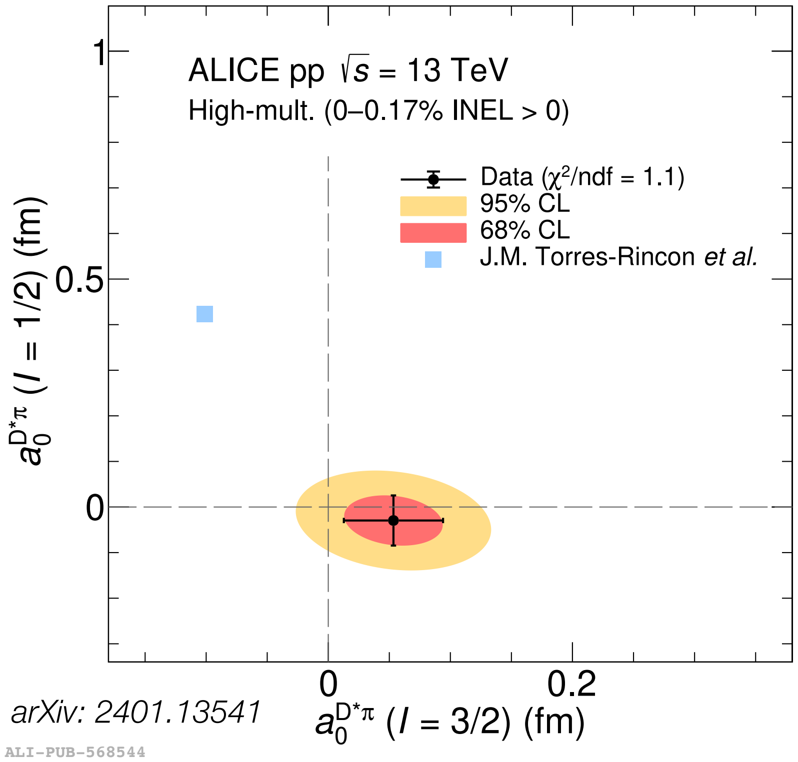
Measuring the scattering length for Dπ and D*π systems

- Extracted **scattering lengths compatible with zero**
  → No influence of the hadronic phase on heavy-flavour observables in heavy-ions
- Tension with available theoretical models
  → Novel possibility to constrain effective QCD models in the charm sector!

Dπ system



D*π system



ALICE Coll. arXiv: 2401.13541

First experimental constraints available for $D^{(*)}$ - light mesons dynamics

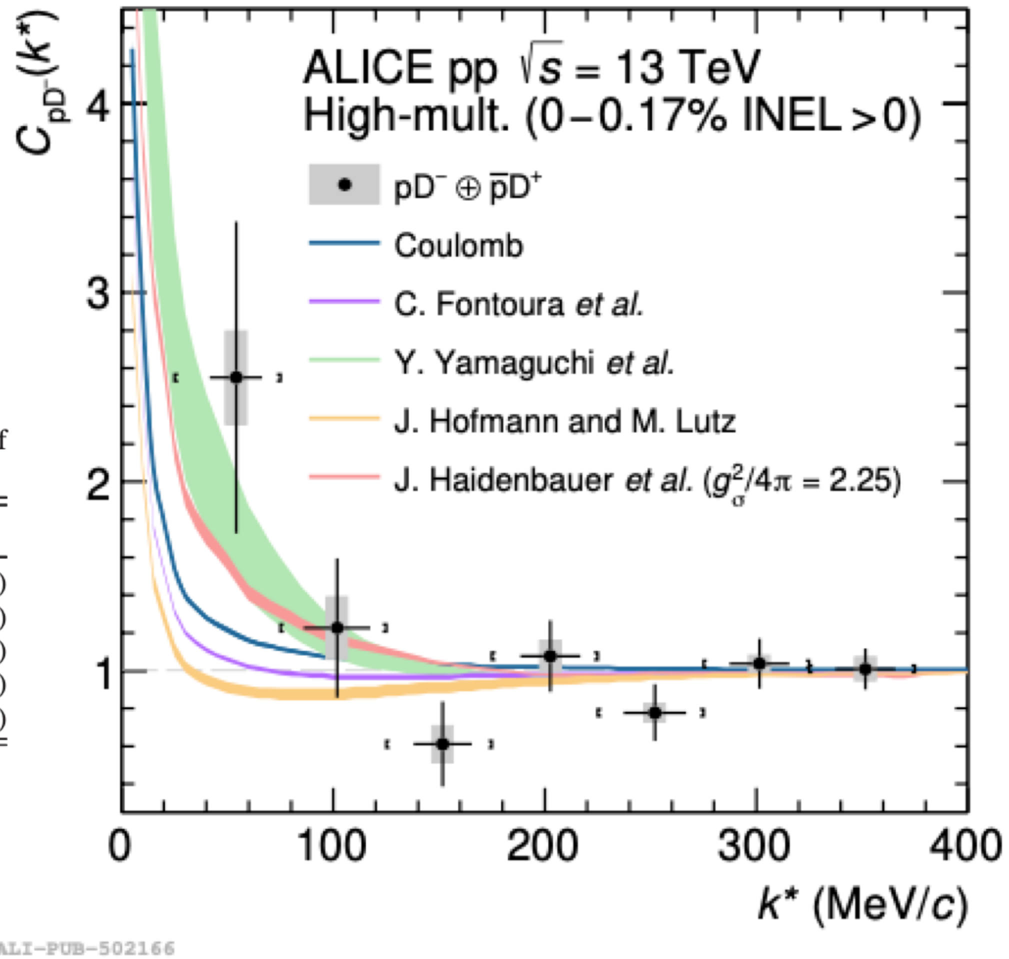
Accessing the strong interaction with charm hadrons

- First measurement of the genuine correlation between protons and D⁻ mesons
  → Important input in studies and searches for charm nuclear states[1]
- Comparison with available models
  → Indication of an attractive interaction
  → Compatible also with the formation of bound state

TABLE I. Scattering parameters of the different theoretical models for the $N\bar{D}$ interaction [22–25] and degree of consistency with the experimental data computed in the range $k^* < 200$ MeV/c.

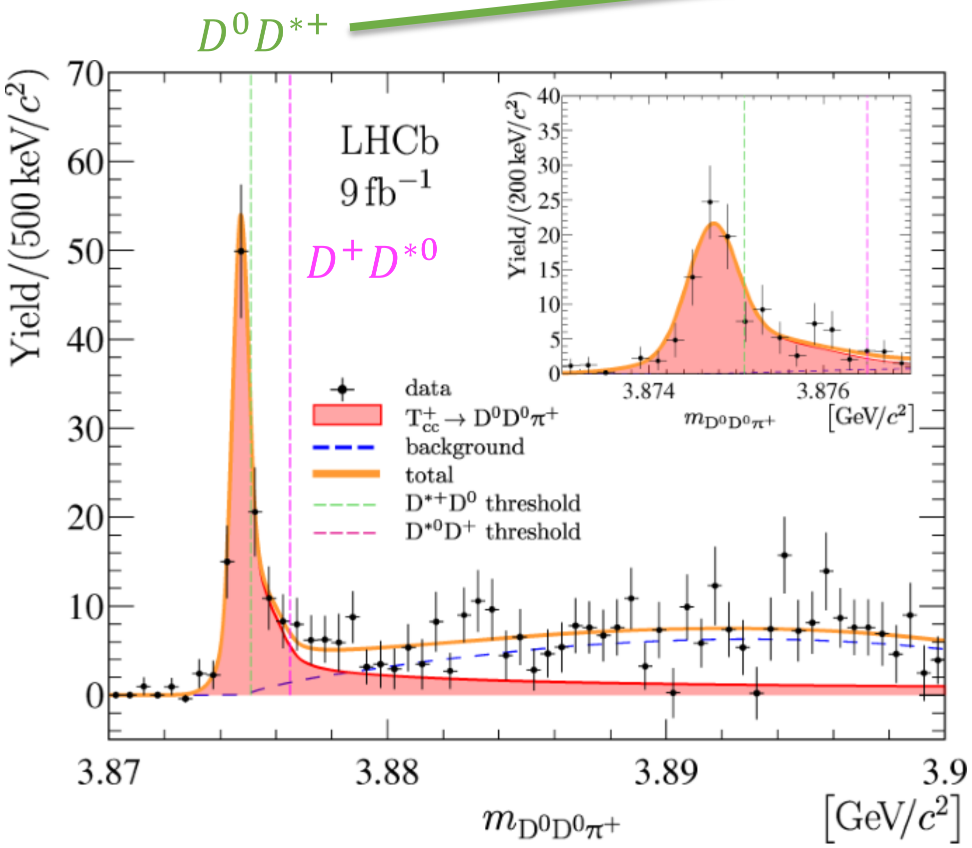
Model	$f_0(\mathrm{I}=0)$	$f_0(\mathrm{I}=1)$	n_σ
Coulomb			(1.1–1.5)
Haidenbauer *et al.* [22] ($g_\sigma^2/4\pi = 2.25$)	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [23]	−0.16	−0.26	(1.3–1.6)
Yamaguchi *et al.* [25]	−4.38	−0.07	(0.6–1.1)
Fontoura *et al.* [24]	0.16	−0.25	(1.1–1.5)

ALICE coll. PRD 106 (2022), 5, 052010



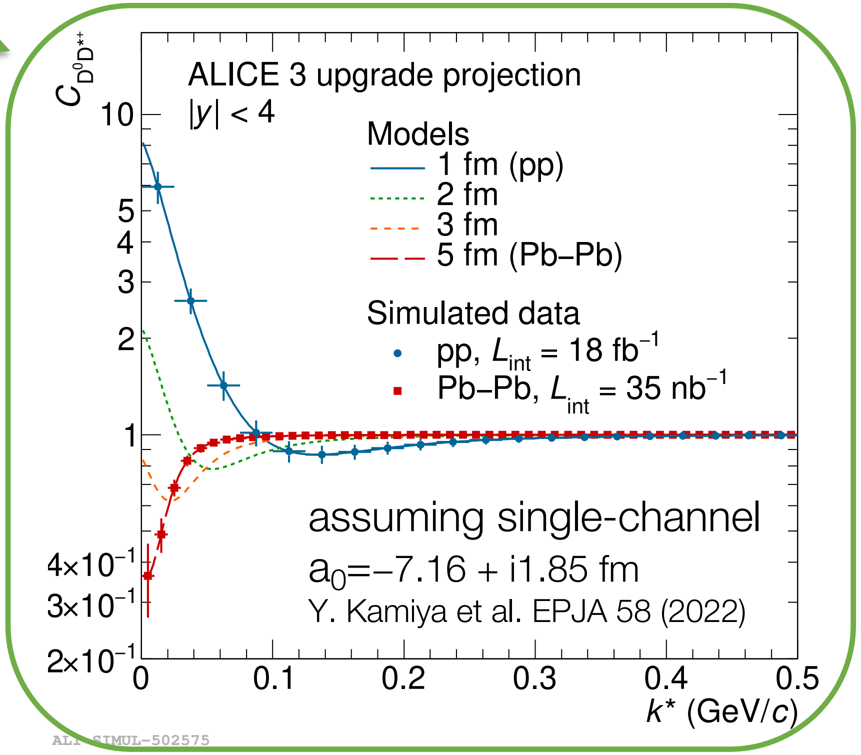
[1] A. Hosaka et al. Prog. Part. Nucl. Phys. 96 (2017), 6, 062C01

- Exotic charm states as T_{cc}^{+} observed at LHCb
  - Possible molecular candidate



LHCb, Nature Physics 18 (2022), Nature Comm. 13 (2022)

- Investigate its nature with ALICE 3 in Run 5 and Run 6 (from 2035) via DD* correlations

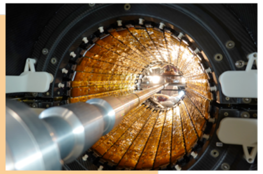


ALICE 3 LOI, CERN-LHCC-2022-009

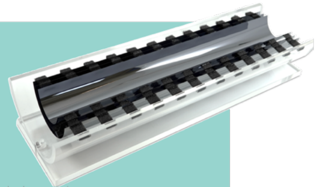
Future complementarity between spectroscopy and femtoscopy

ALICE 3 detector

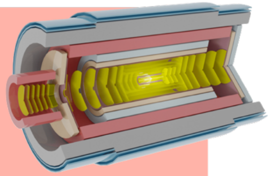
GEM-based TPC, ITS2, MFT
50x readout capability
3x tracking precision

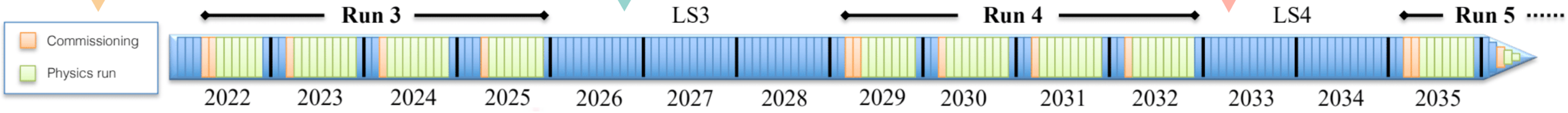


ITS3, FoCal
3x tracking precision
2x efficiency at low p_T + forward γ

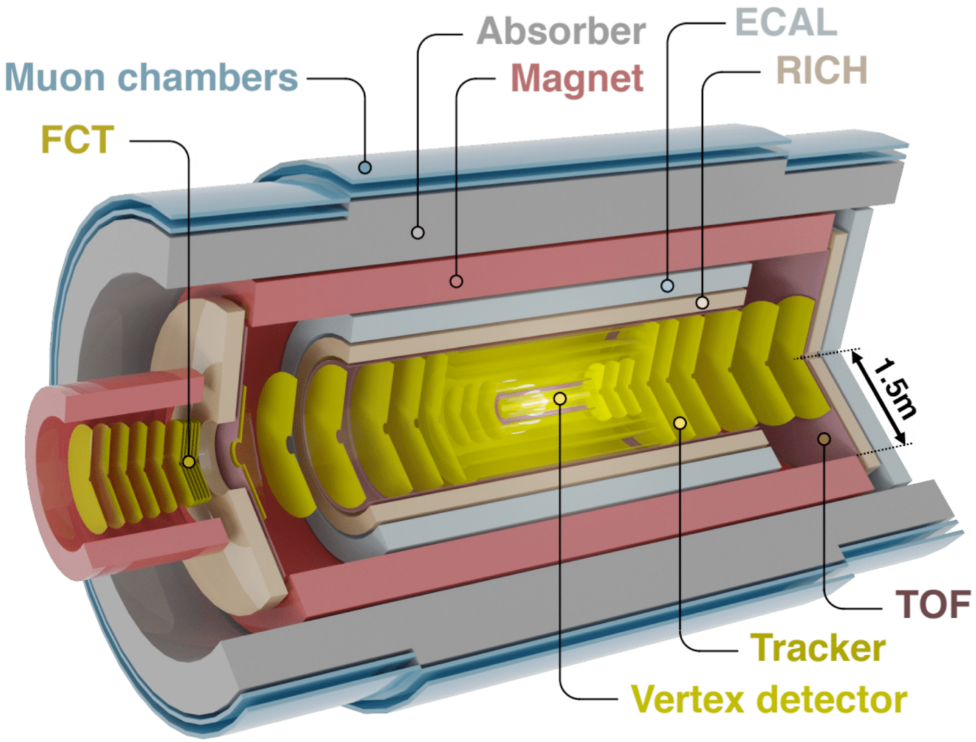


ALICE 3
Ultra-thin dedicated heavy-ion experiment





- Each upgrade improves
  1. Spatial resolution (improves reconstruction of weakly-decaying particles)
  2. Readout capability (improves integrated luminosity)
- Excellent pointing resolution (~10μm, p= 200 MeV/c) + large acceptance (|η| < 4)
  → secondary vertices and decay chains
  - All silicon tracker with σ_p/p ~1%
  - First tracking layer at 5 mm from primary vertex
- Excellent hadron and lepton PID
  - Silicon-based TOF and RICH
  - Muon chambers with absorber
- x5 more AA luminosity than Run 3&4 → DD* correlations!!



Modeling the charm correlations

- DD^* and $D\bar{D}^*$ sector

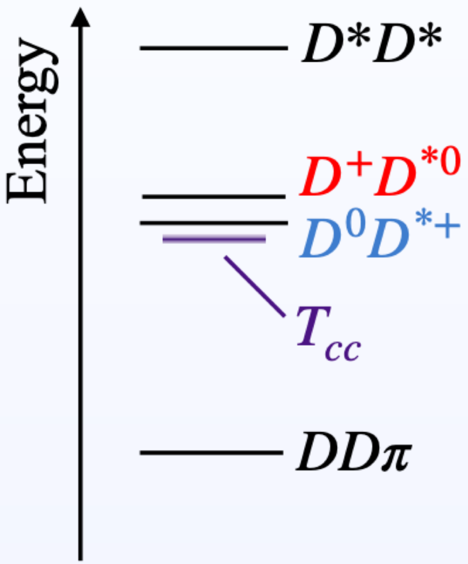
$a_0 \equiv \mathscr{F}(E = E_{th})$

+ : attractive w/o bound

- : repulsive or attractive w/ bound

$C = 2$

LHCb, Nature Com. 13 (2022) 1



$$E_{T_{cc}} = \delta_m - \frac{i}{2}\Gamma$$

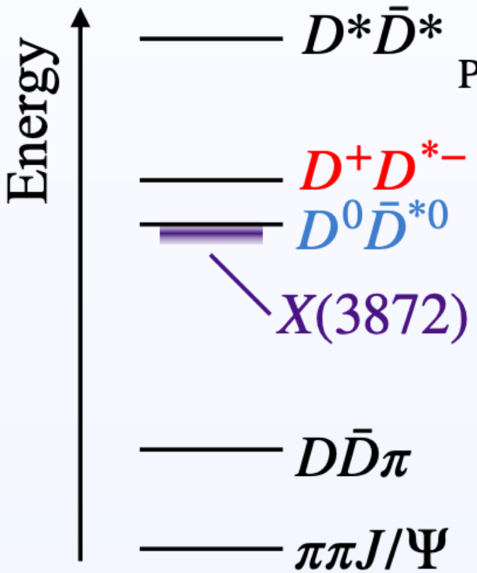
$\delta m = -0.36$ MeV

$\Gamma = 0.048$ MeV

$a_0 = -7.16 + i1.85$ fm

$C = 0$

PDG, PTEP 2020, 083C01 (2020).



$$E_{X(3872)} = \delta_m - \frac{i}{2}\Gamma$$

$\delta m = -0.04$ MeV

$\Gamma = 1.19$ MeV

↓

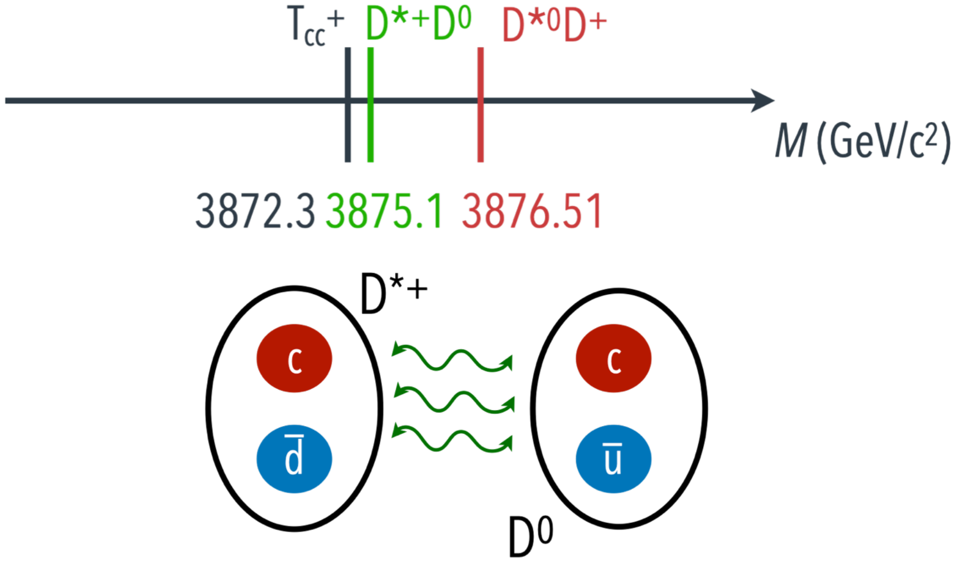
$a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95$fm

- T_{cc}/ $X(3872)$ lies nearby $DD^*/D\bar{D}^*$

==> meson-meson molecule?

==>Strong attractive interaction

Expected performance for the measurement of DD* correlations



- D^{*+} meson: reconstructed in $D^{*+} \rightarrow D^0\pi^+$ channel
- D^0 meson: reconstructed in $D^0 \rightarrow K^-\pi^+$ channel
  - Challenge: significant contribution from decays of resonances

$$BR(D^{*+} \rightarrow D^0\pi^+) = (66.7 \pm 0.5)\%$$
$$BR(D^{*0} \rightarrow D^0\pi^0) = (64.7 \pm 0.9)\%$$
$$BR(D^{*0} \rightarrow D^0\gamma) = (35.3 \pm 0.9)\%$$

PDG, Prog. Theor. Exp. Phys. 2020 083C01

- Fast simulation strategy
  - Simulate PYTHIA8 events and select events with D^{*+} and D^0 meson pairs
  - Combine pairs of D^{*+} and D^0 mesons from same events and mixed events, weighting according to their efficiency
  - D^0 from D^{*+} decays are excluded (assuming that experimentally we can set an invariant-mass veto on $D^0\pi$ pairs)
  - Scale same event and mixed event distributions according to expected number of events
  - Scale same event distribution according to theoretical predictions
  - Compute expected statistical uncertainty according to expected signal and background yields

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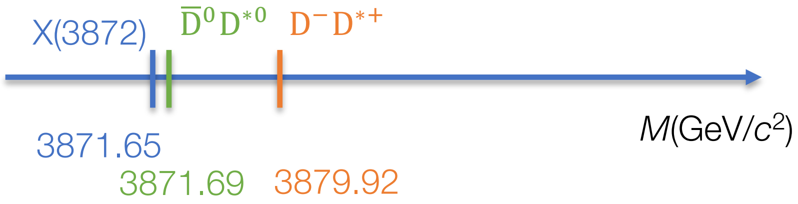
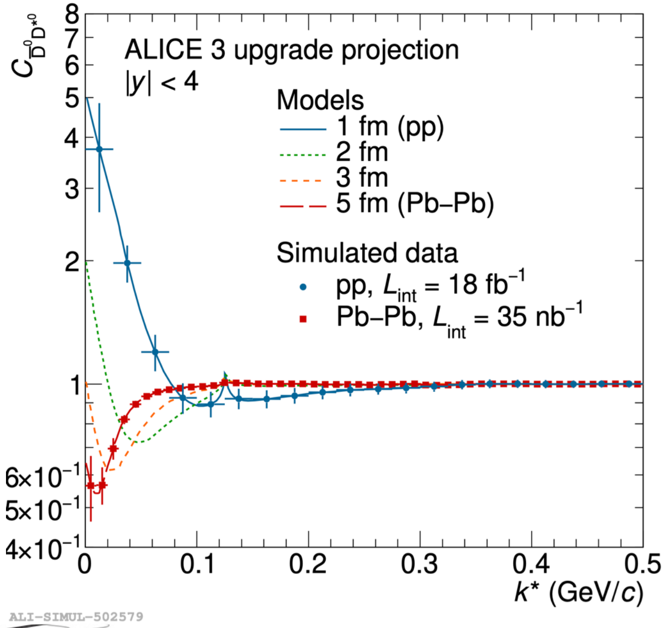
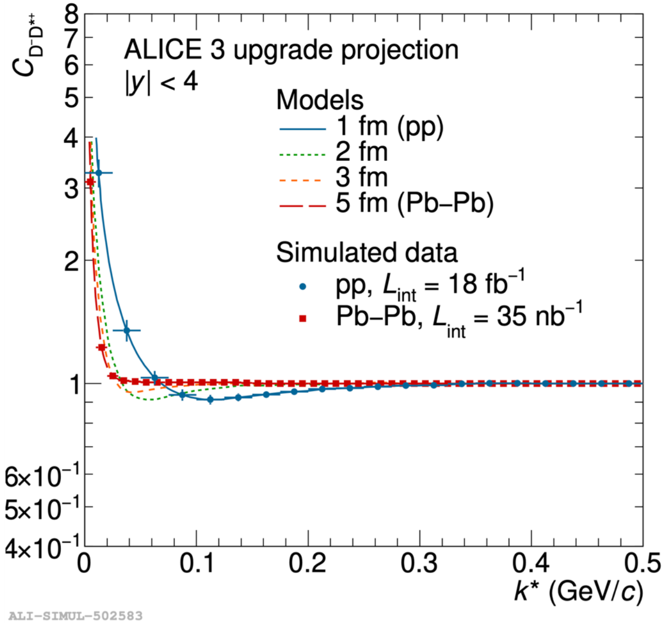
$D\bar{D}^*$ correlations



D^{*+} meson: reconstructed in $D^{*+} \rightarrow D^0\pi^+$ channel
D^0 meson: reconstructed in $D^0 \rightarrow K^-\pi^+$ channel
D^+ meson: reconstructed in $D^+ \rightarrow K^-\pi^+\pi^+$ channel
D^{*0} meson: reconstructed in $D^{*0} \rightarrow D^0\gamma$ channel

- $D^{*-}D^+$:
  - Smaller contribution from decays of resonances
    $$BR(D^{*+} \rightarrow D^+\pi^0) = (31.3 \pm 0.5)\%$$
  - Further from X(3872) mass and with Coulomb interaction
- $D^{*0}D^0$:
  - Challenge: reconstruction of photons





- Inversion of the correlation function not observed for D^-D^{*+} because the X(3872) is 'far' (148 MeV) from the mass threshold with respect to $\bar{D}^0D^{*0}$ (~200 KeV).