Strong Interaction Studies in Λ– hadron systems up to $S = -3$ with ALICE

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on behalf of the ALICE Collaboration
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14th International Conference on Hypernuclear and Strange Particle Physics
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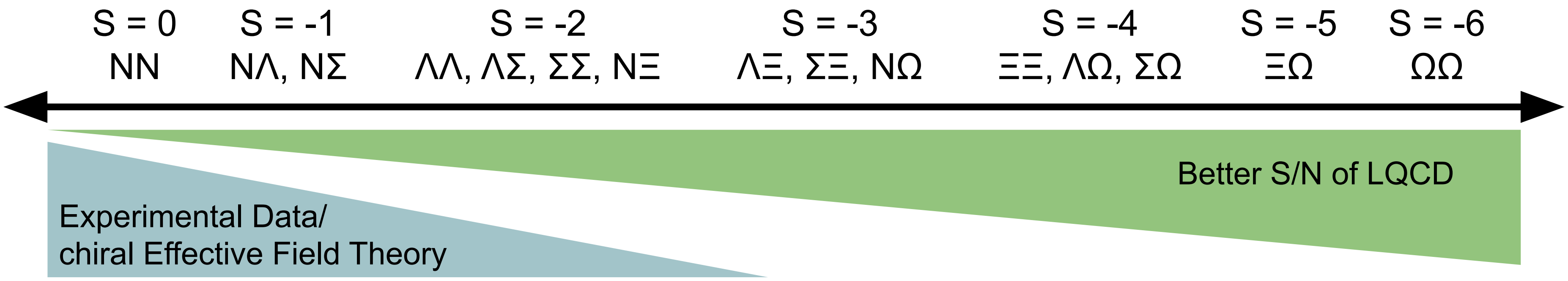
Prague, Czech Republic

The strong interaction with Λ-hadrons



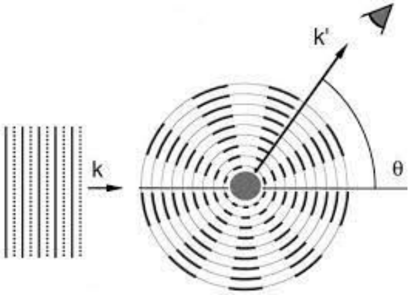
The strong interaction with Λ-hadrons

S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

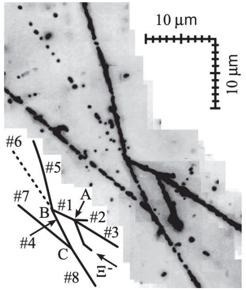
Better S/N of LQCD

Experimental Data/
chiral Effective Field Theory

scattering experiments

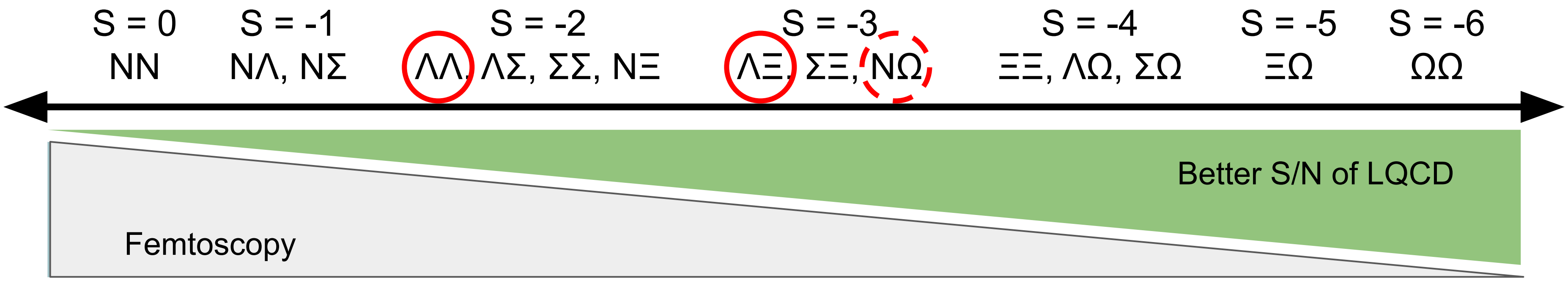


hypernuclei



H. Takahashi et al., PRL 87 (2001) 212502

The strong interaction with Λ-hadrons



A Bridge to overcome this misalignment

Method: Femtoscopy

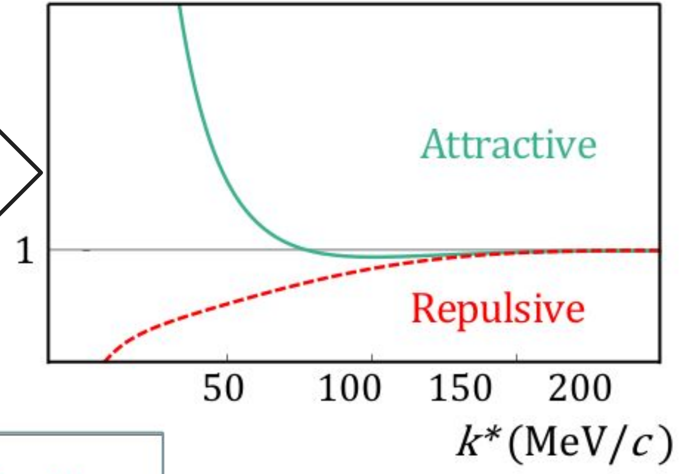
Figures: *Nature* 588, 232 (2020)

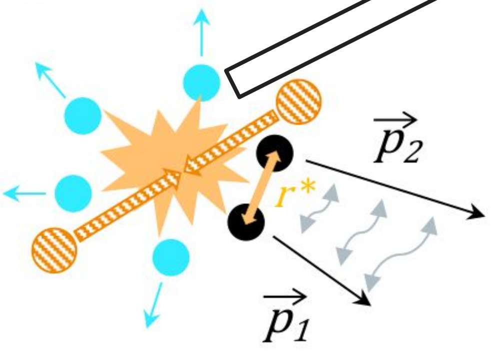
Central part: **The correlation function** in terms of the relative momentum k*

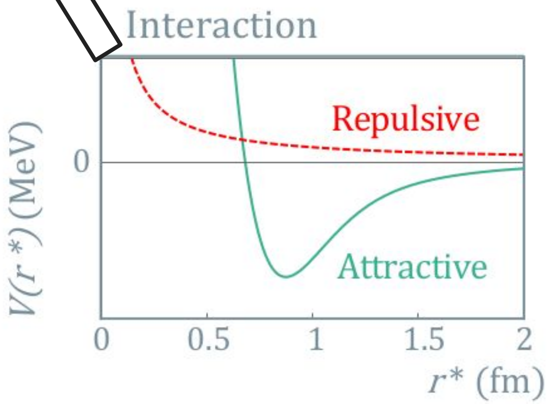
$$k^* = 1/2 \cdot |\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|$$

Correlation Function

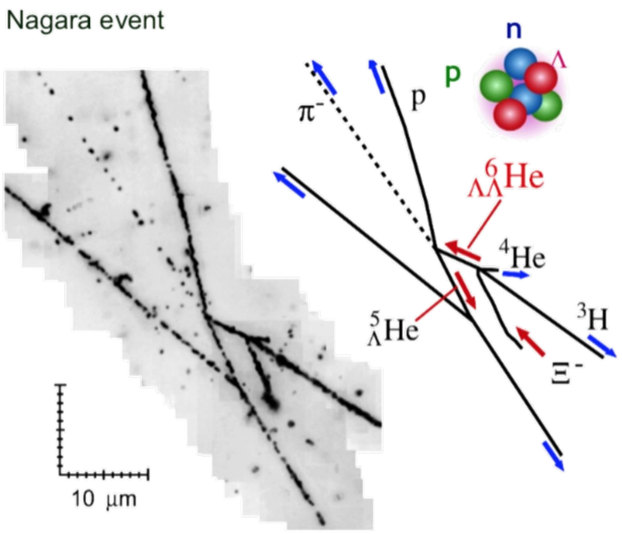
$$C(k^*) = \xi(k^*) \otimes \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = \int S(r^*) \left|\Psi(k^*, r^*)\right|^2 d^3r^*$$







|S| = 2: Λ-Λ interaction – before femtoscopy



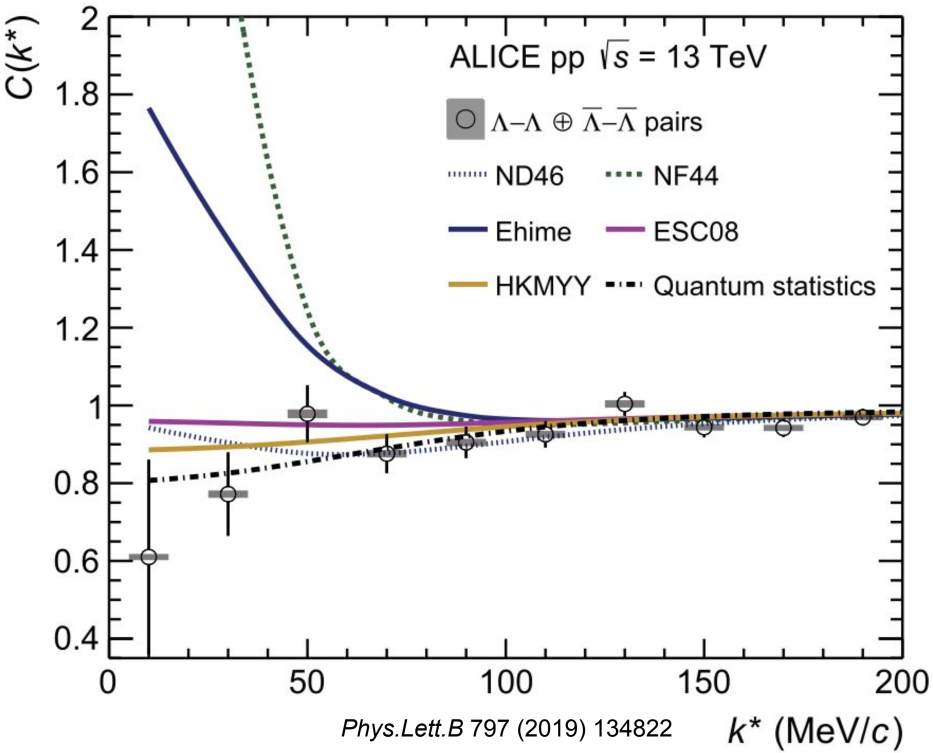
$^{6}{}_{\Lambda\Lambda}He \rightarrow {}^{5}{}_{\Lambda}He + p + \pi^-$

H. Takahashi et al., PRL 87 (2001) 212502

Search for H-dibaryon: bound state of *uussdd* (ΛΛ)

- ➢ No evidence of a H decay in elementary e^+e^- collisions
- ➢ Nagara event: Double ΛΛ hypernuclei $_{\Lambda}{}^{6}{}_{\Lambda}He$
  - ○ Hints to a weak attractive interaction
  - ○ Limit on binding energy: $B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV

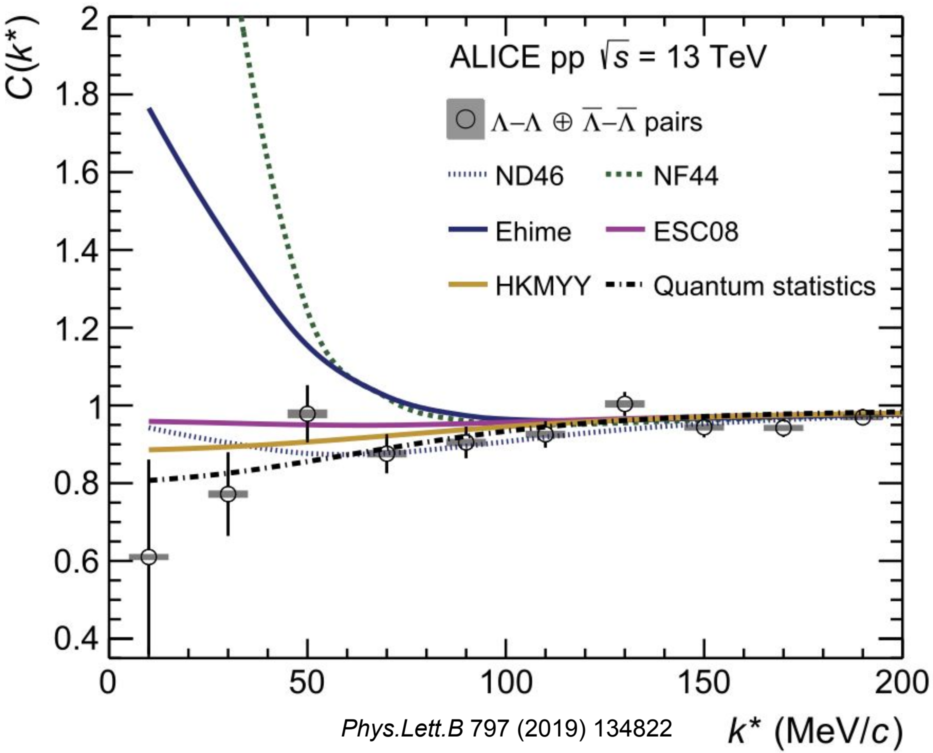
|S| = 2: Λ-Λ interaction – with femtoscopy



Phys.Lett.B 797 (2019) 134822

- Combined measurement of pp (@ 7,13 TeV) and p-Pb (@ 5.02 TeV) collisions:
- Incompatible predictions:
  - Ehime: strongly attractive interaction
  - NF44: shallow bound state
- Compatible predictions:
  - ESC08 and HKMYY: shallow attractive interaction
  - ND46: bound state

|S| = 2: Λ-Λ interaction – with femtoscopy



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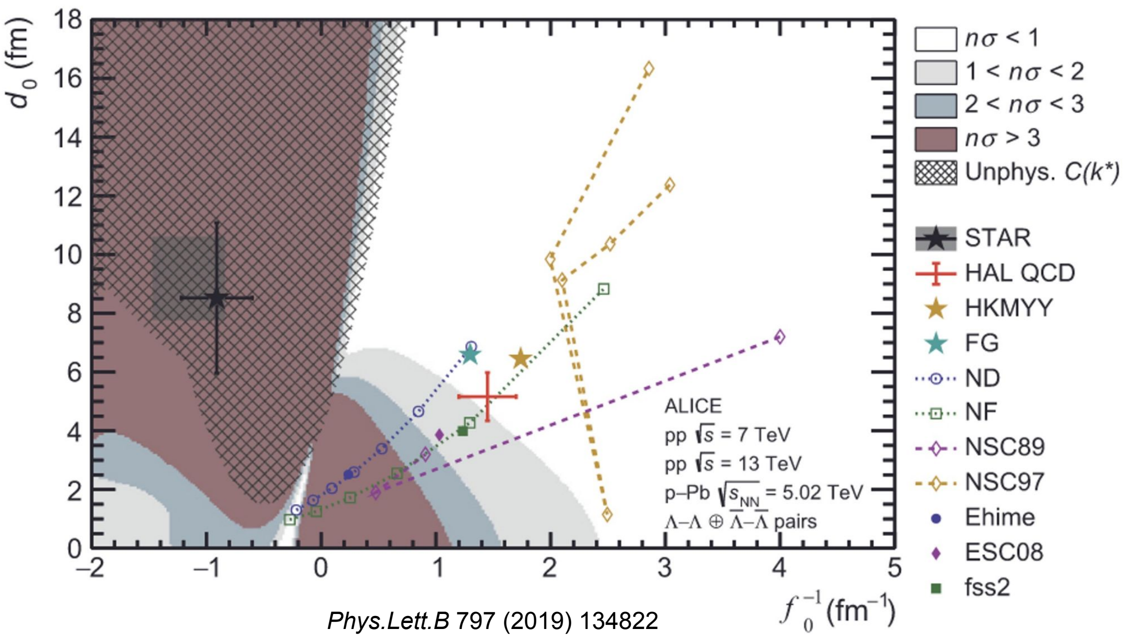
- ➢ Compatible predictions:
  - ○ ESC08 and HKMYY: shallow attractive interaction
  - ○ ND46: bound state

Effective-range expansion: d_0 and f_0:

- ➢ $f_0 > 0$: attractive interaction
- ➢ $f_0 < 0$: repulsive interaction
- ➢ $f_0 < 0$ and $d_0 > |f_0|/2$: bound state

|S| = 2: Λ-Λ interaction – with femtoscopy



Phys.Lett.B 797 (2019) 134822

- ➢ Scan the (f_0^{-1},d_0) parameter space with the Lednický Lyuboshits model in terms of nσ deviations
- ➢ Compatible with:
  - ○ Shallow attractive interaction
  - ○ Bound state

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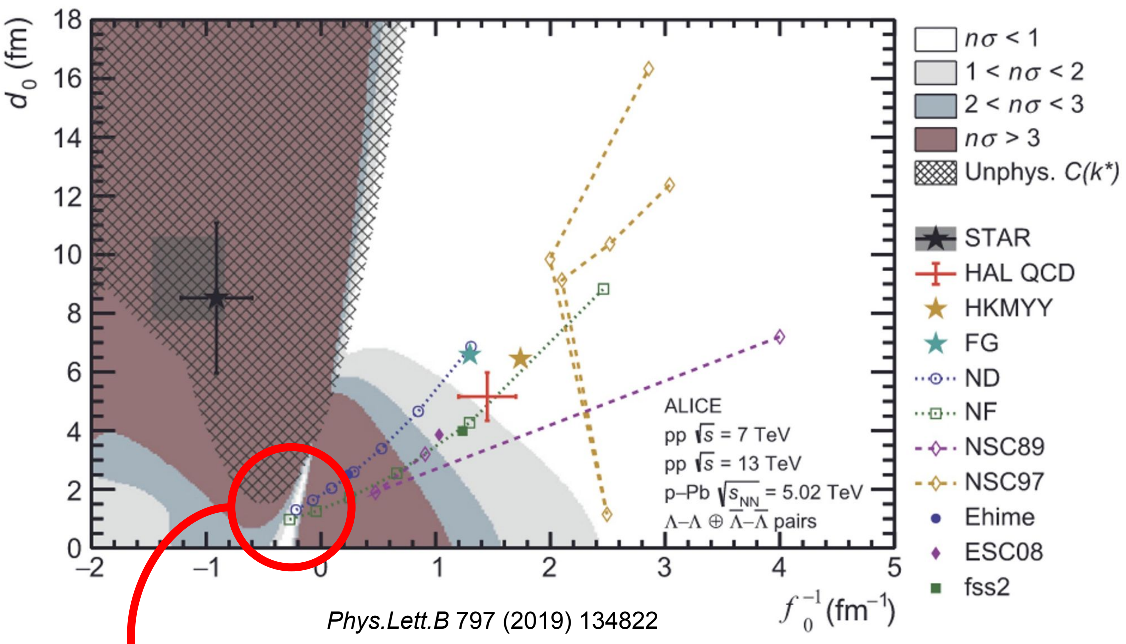


Phys.Lett.B 797 (2019) 134822

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

- ➢ Scan the (f_0^{-1},d_0) parameter space with the Lednický Lyuboshits model in terms of nσ deviations
- ➢ Compatible with:
  - ○ Shallow attractive interaction
  - ○ Bound state
- ➢ New upper limit on the binding energy of the H-dibaryon via a transformation from (f_0^{-1},d_0) to ($B_{\Lambda\Lambda}$,d_0) using

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

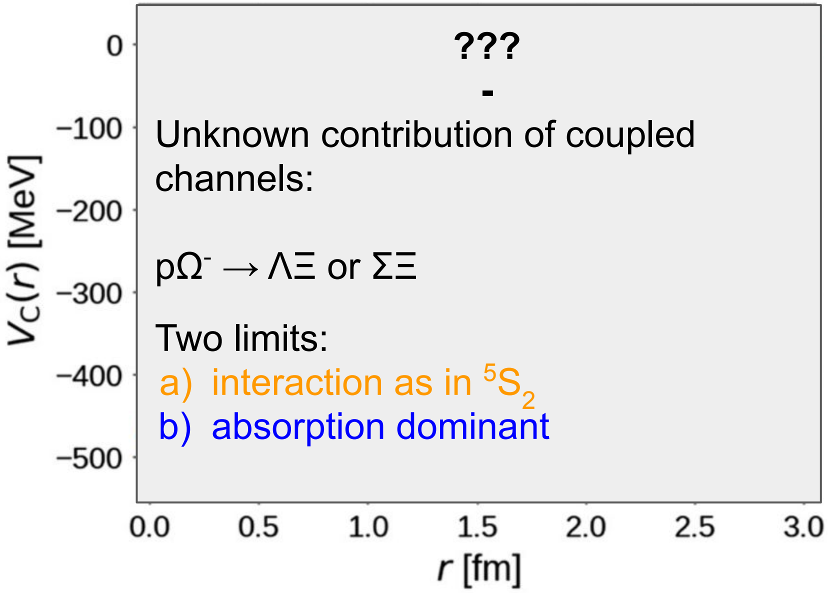
|S| = 3: Λ-Ξ⁻ interaction – before femtoscopy

Click here to insert text

|S| = 3: p-Ω⁻ interaction with femtoscopy

- Proton (J_p = 1/2) + Omega (J_Ω = 3/2)
  - angular momentum negligible

NΩ($^3S_1$)



???

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Unknown contribution of coupled channels:

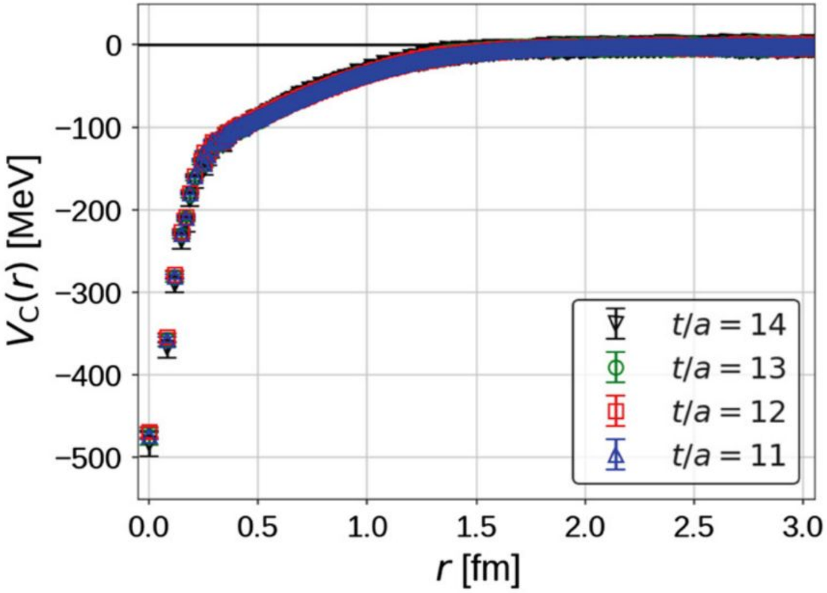
pΩ⁻ → ΛΞ or ΣΞ

Two limits:

a) interaction as in $^5S_2$

b) absorption dominant

NΩ($^5S_2$)

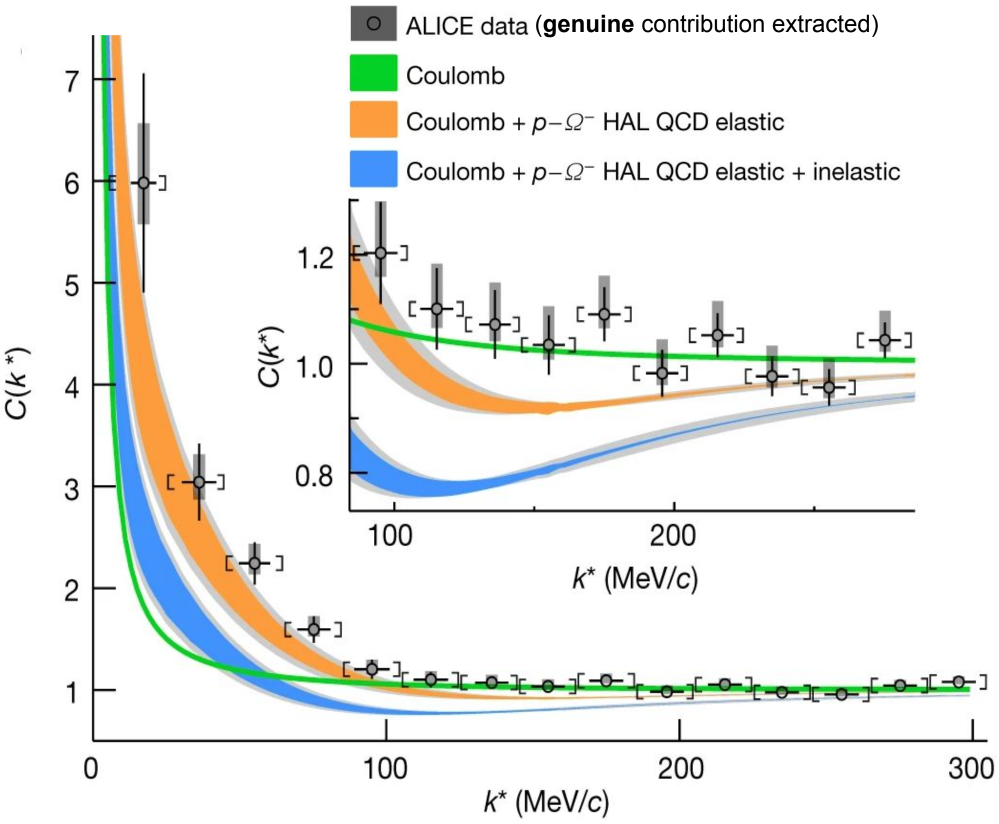


T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

|S| = 3: p-Ω^- interaction with femtoscopy

- Indication of missing attractive interaction when considering only Coulomb
- Better agreement of data without inelastic contributions
- Higher accuracy in the data than in the theoretical calculation
- Prediction of a bound state with binding energy **2.5 MeV**

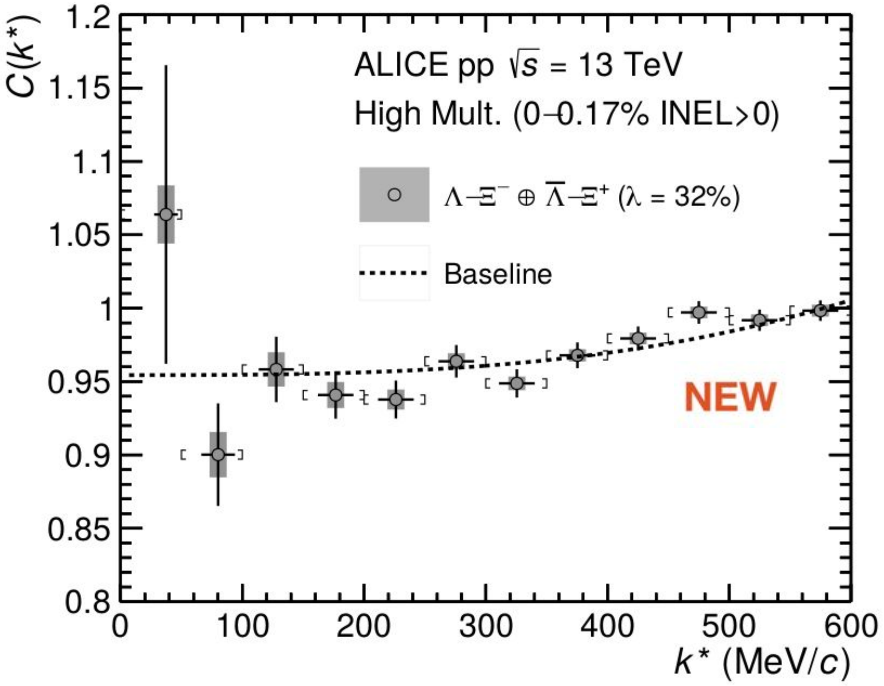
  ⇒ not reproduced by the data



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

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

Baseline (no interaction):



arXiv:2204.10258, submitted to PLB

First experimental observation of the Λ-Ξ⁻ interaction

Baseline (dotted line):

- Constrained at large k* ∈ [200,800] MeV/c
- Compatibility with the data @ k* < 200 MeV/c: **0.78 nσ**

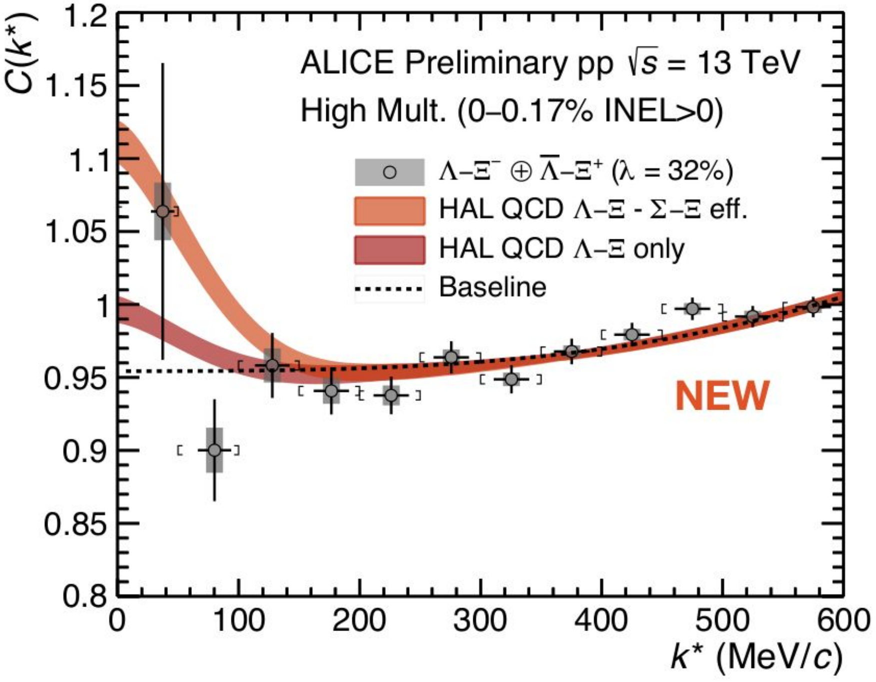
⇒ No significant deviation of the data from the baseline

⇒ Indication of shallow Λ-Ξ⁻ interaction

⇒ New publication: arXiv:2204.10258

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

Comparison with Lattice QCD(*)



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- Unknown contribution from coupled channels in Lattice QCD calculations (see p-Ω⁻ interaction)
  - Coupling ΛΞ–ΣΞ sizable in HAL QCD calculation
  - "No coupling" preferred: 0.64 nσ vs. 1.43 nσ but no sensitivity yet
- No NΩ cusp visible ⇒ hint to negligible coupling

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

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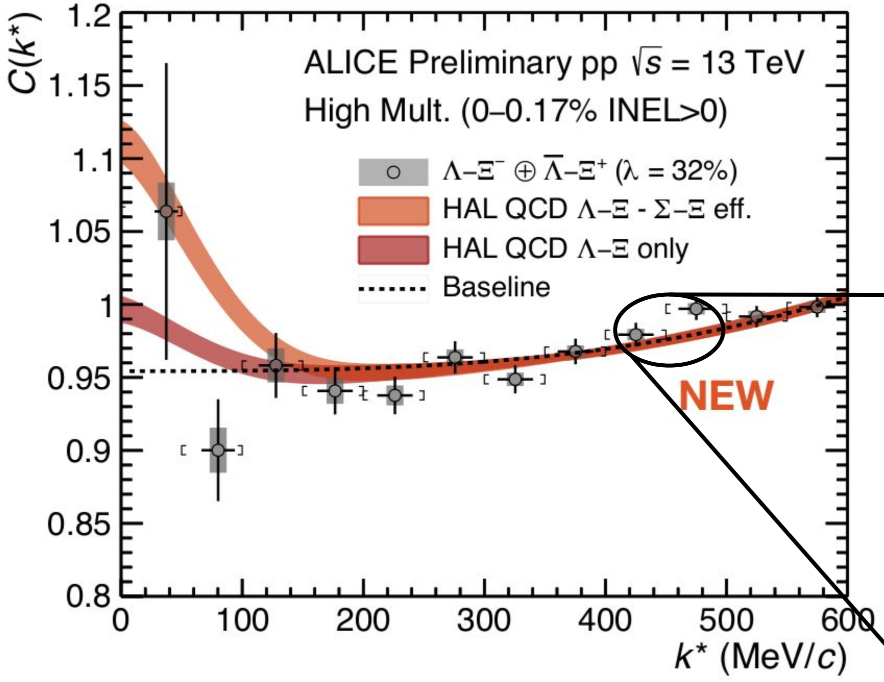

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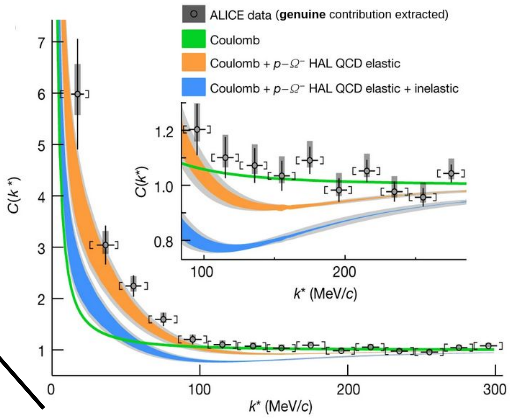
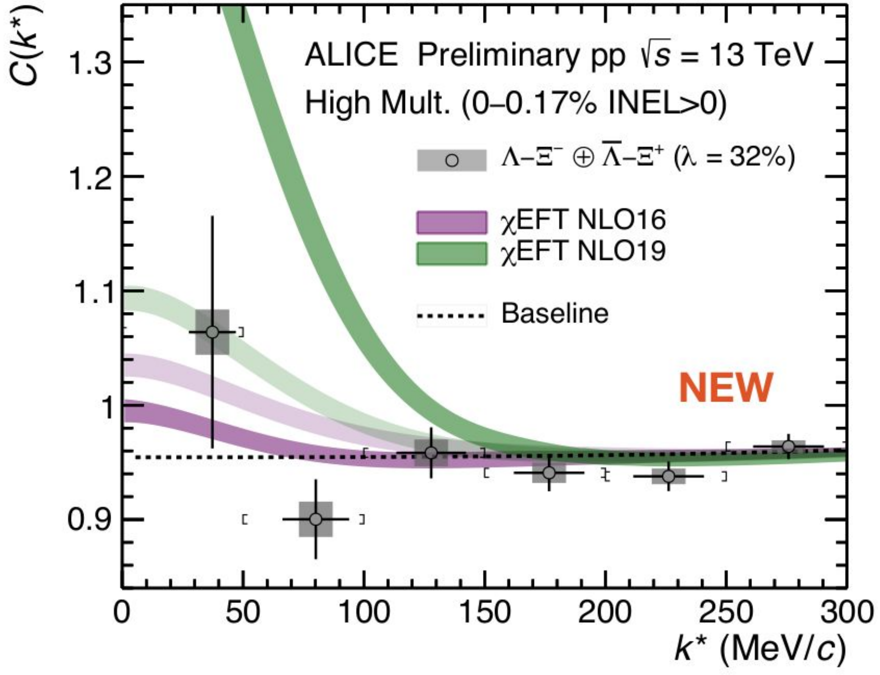
(expected at ~ 460 MeV/c)



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

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

Comparison with χEFT NLO$^{(*)}$



arXiv:2204.10258, submitted to PLB

potential (cut-off)	singlet		triplet		
	f_0	d_0	f_0	d_0	nσ
NLO16 (500)	0.99	5.77	–0.026	142.9	0.56 – 0.93
NLO16 (650)	0.91	4.63	0.12	32.02	0.91 – 1.61
NLO19 (500)	0.99	5.77	1.66	1.49	5.47 – 7.26
NLO19 (650)	0.91	4.63	0.42	6.33	1.30 – 2.10

** J. Haidenbauer, U.-G. Meißner, arXiv:2201.08238v1 [nucl-th] (2022)*

- ➢ Data favour with shallow interaction
- ➢ Best compatibility with lowest scattering lengths
- ➢ Constraints on SU(3) symmetry breaking parameters

Summary and Outlook

Λ-Λ interaction:

- Compatible with LQCD
- Bound state not excluded ⇒ new limit

p-Ω^{-} interaction:

- Most precise measurement of the interaction
- Bound state not observed

Λ-Ξ^{-} interaction:

- First observation of a shallow Λ-Ξ^{-} interaction and comparison to LQCD
- New paper public on arXiv

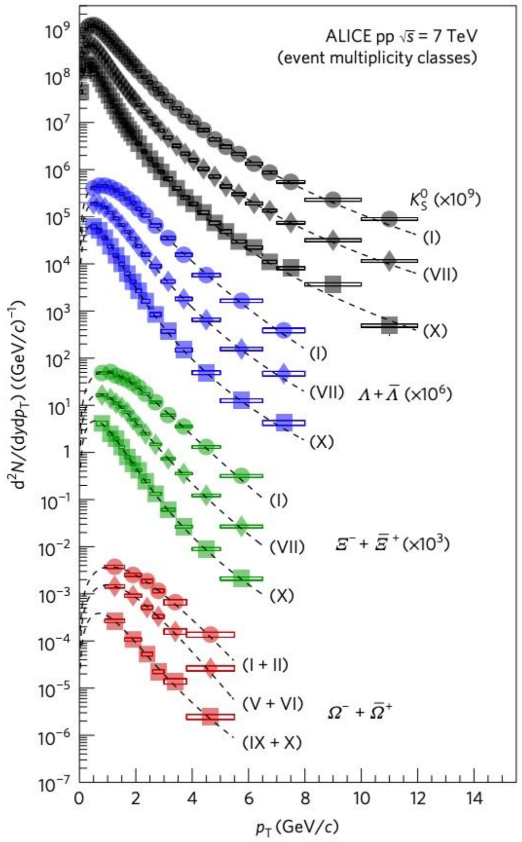
- Greater improvements expected in upcoming Run 3 and 4 of the LHC

Backup

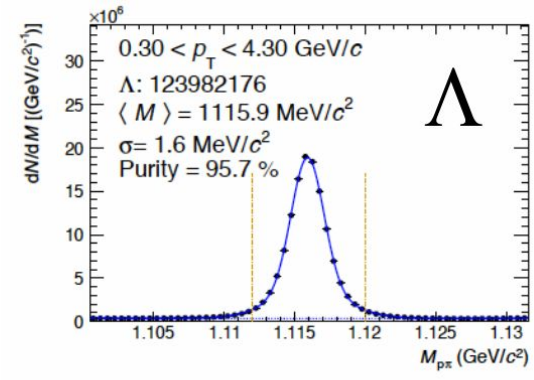
High multiplicity pp collisions

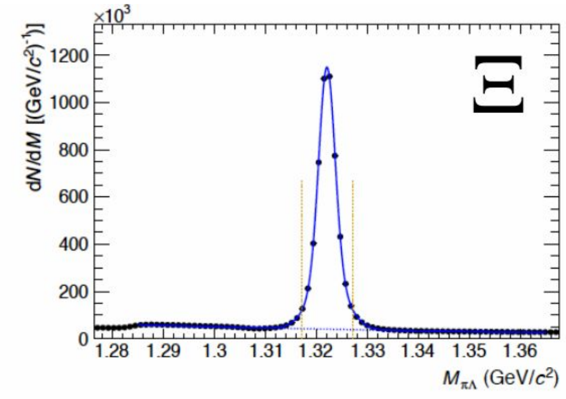
- pp collisions at ALICE are a perfect factory to produce a large amount of multi-strange hyperons
- enhanced strangeness containing particle yield detected in pp collisions at 13 TeV:

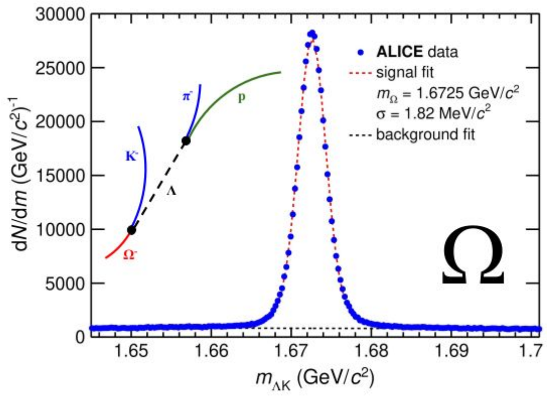
  ALICE Coll. Nature Phys. 13 (2017) 535-539
- Excellent particle reconstruction and identification capabilities of the ALICE detector
  - In particular: Detection of Hyperons via their weak decay
  - high purities and resolutions archived

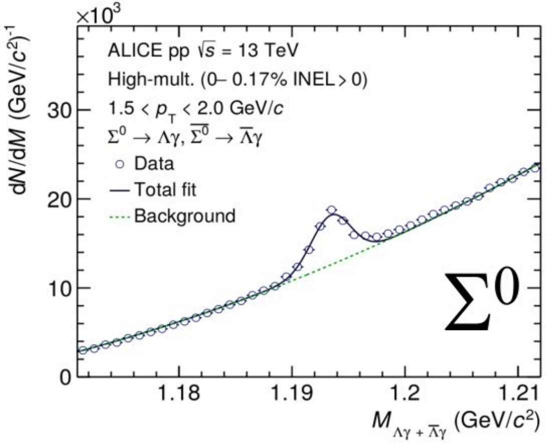


Hyperons at ALICE in pp Collisions







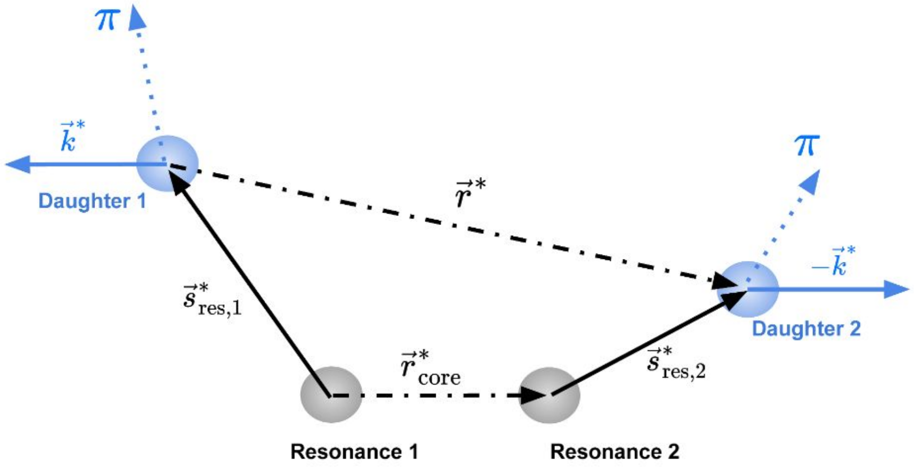


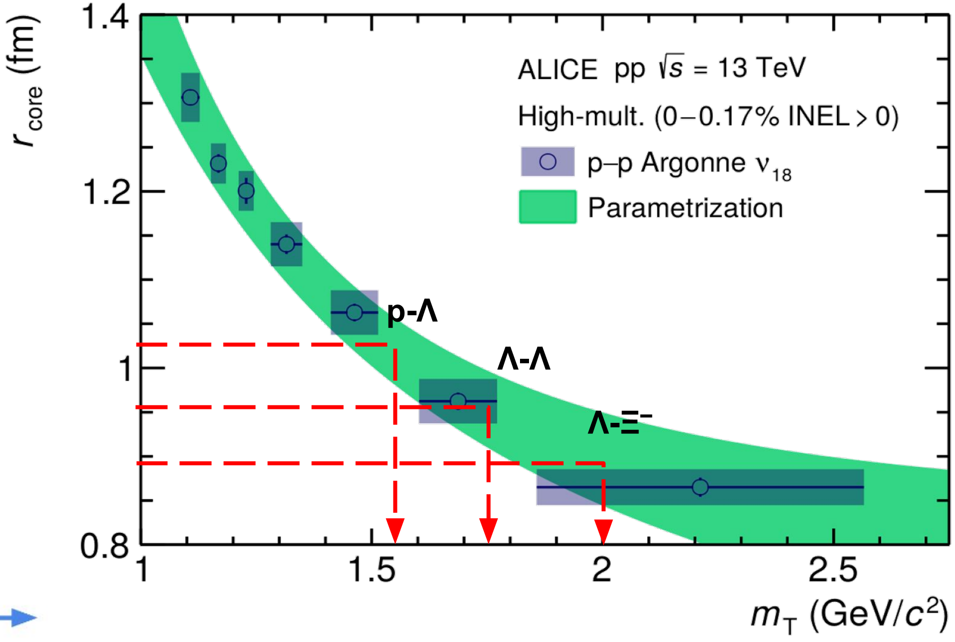
Source Function

ALICE Coll., Physics Letters B, 811 (2920) 135849

Consists of two parts:

- Common m_T scaling of the core radius $\mathbf{r^*}_{Core}$
- Extension to an effective source size $\mathbf{r^*}_{eff}$ by strongly decaying resonances (specific for each baryon pair)

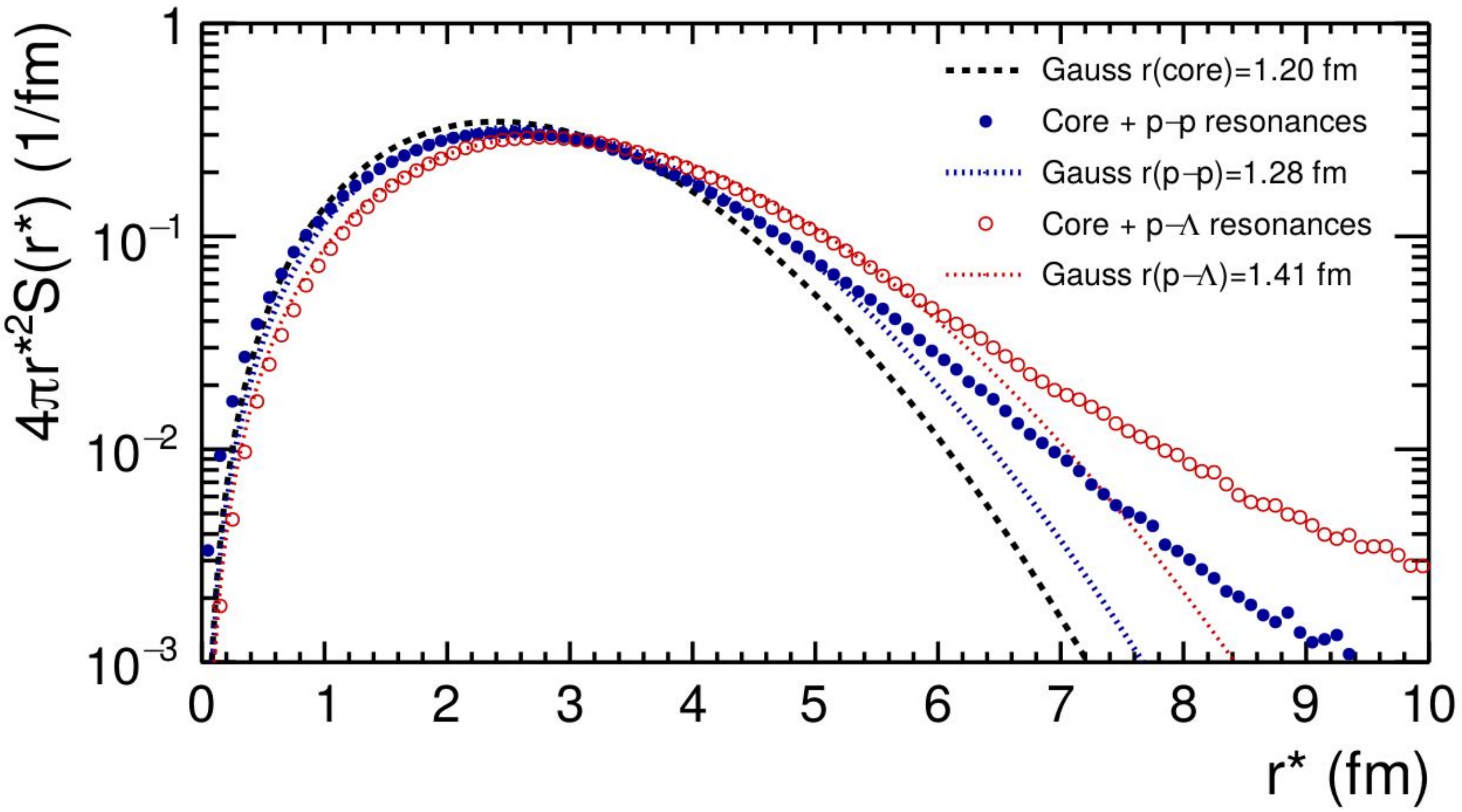




$$m_T = \sqrt{k_T^2 + m^2}$$

Source Function: Common source

ALICE Coll., Physics Letters B, 811 (2920) 135849



The Lednický-Lyuboshits model

Analytical approach to model CF for strong final state interactions with the scattering amplitude f_0

$$C(k^*)_{\text{Lednicky}} = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)^S}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2 \Re f(k^*)^S}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)^S}{r_0} F_2(2k^* r_0) \right]$$

d_0: effective range

f_0: scattering length

$$f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - i k^* \right)^{-1}$$

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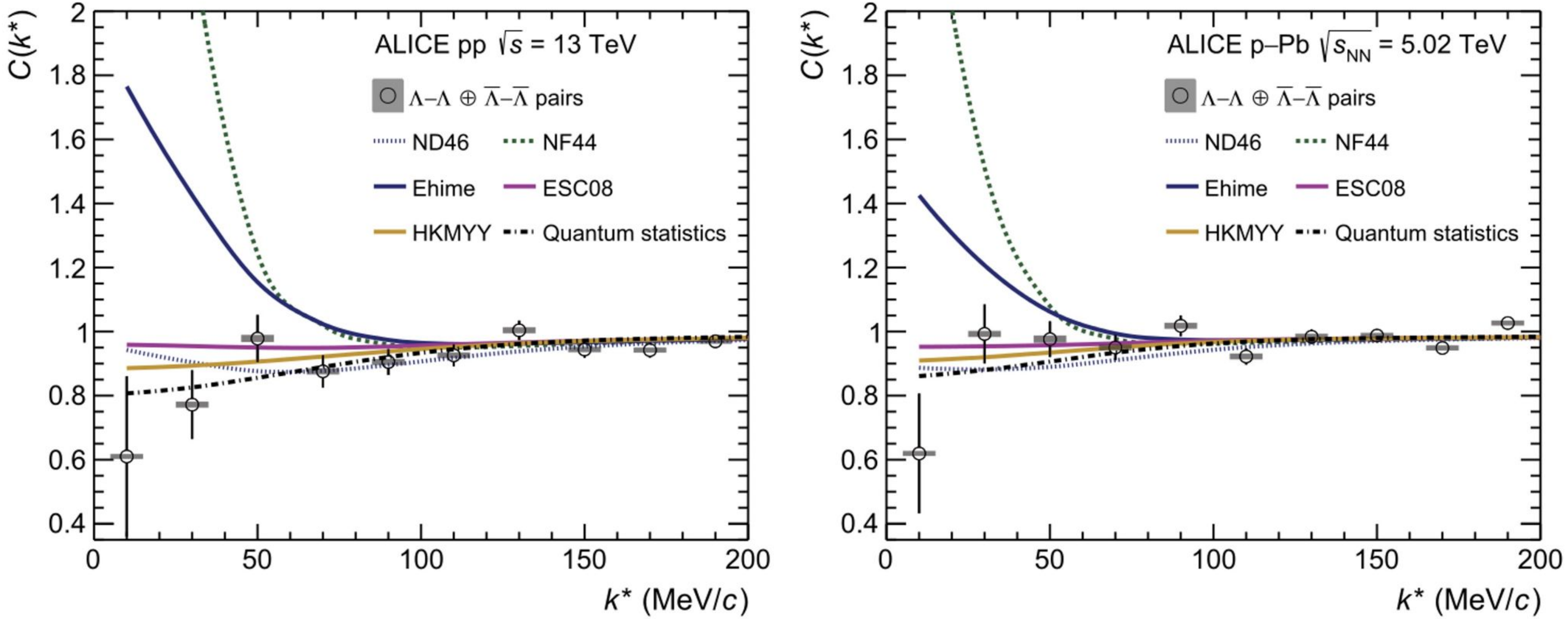
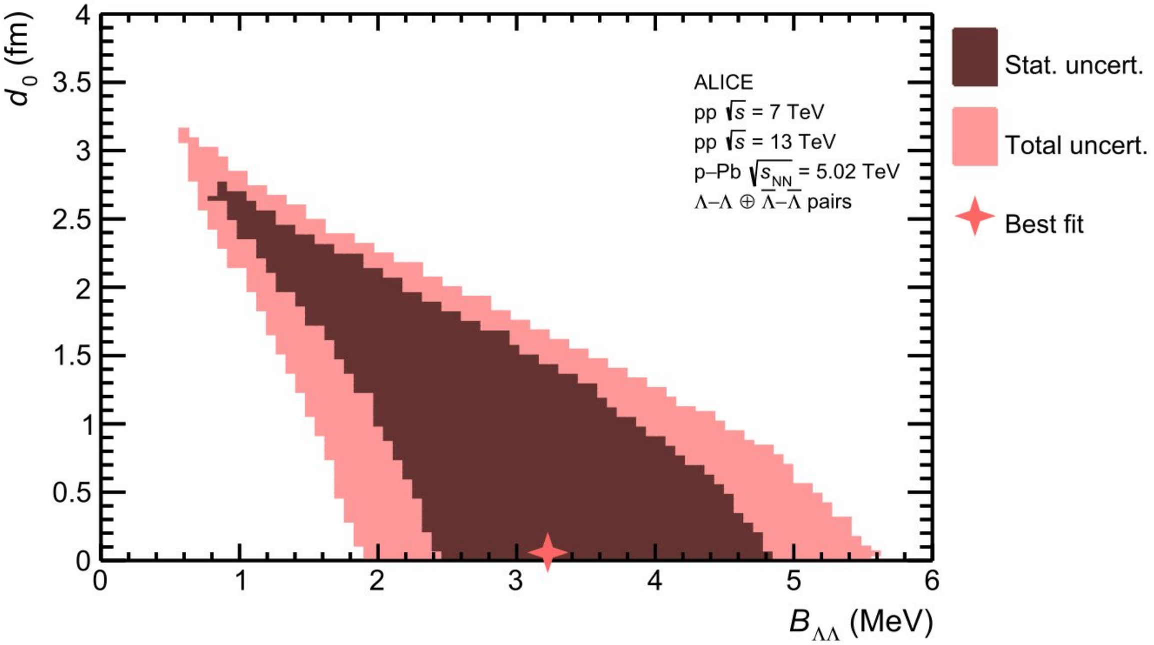
Λ-Λ Correlation function in different systems

ALICE Coll., Physics Letters B, 811 (2920) 135849



Λ-Λ Limits for the binding energy from femtoscopy

ALICE Coll., Physics Letters B, 811 (2920) 135849

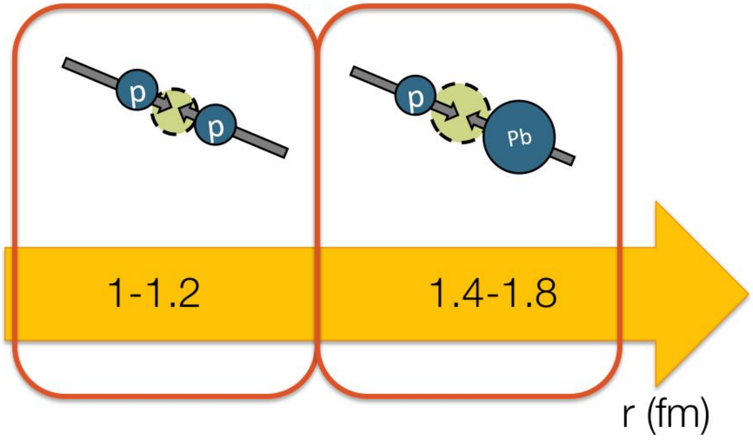


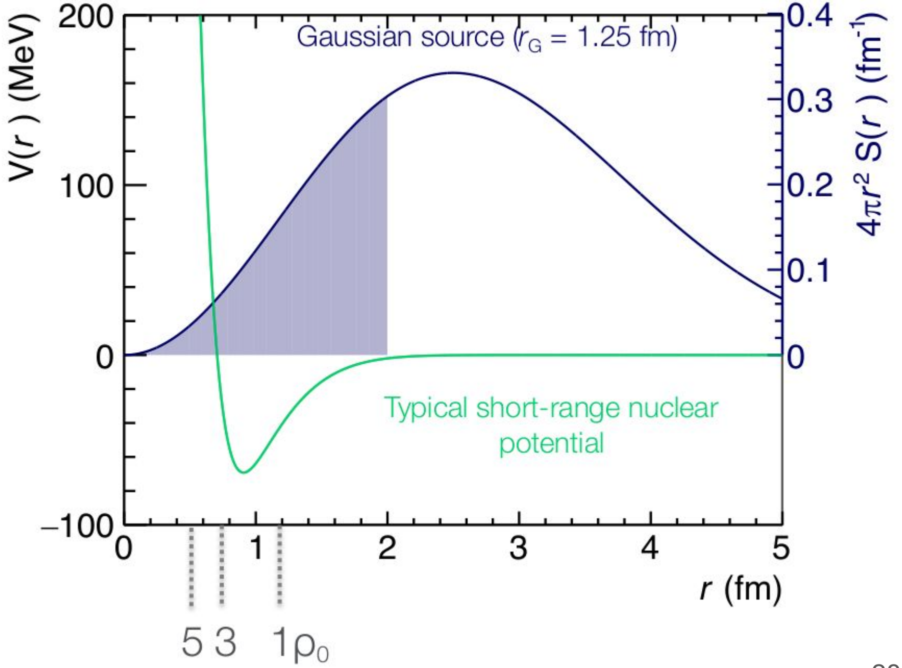
$$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}\ (\text{stat})^{+1.8}_{-1.0}\ (\text{syst})\ \text{MeV}$$

Femtoscopy in small colliding systems

V. M. S., L. Fabbietti and O. Vazquez-Doce nucl-ex 2012.09806

- ➢ small collision systems necessary to study the short ranged strong interaction
- ➢ short interparticle distances →mimic large densities

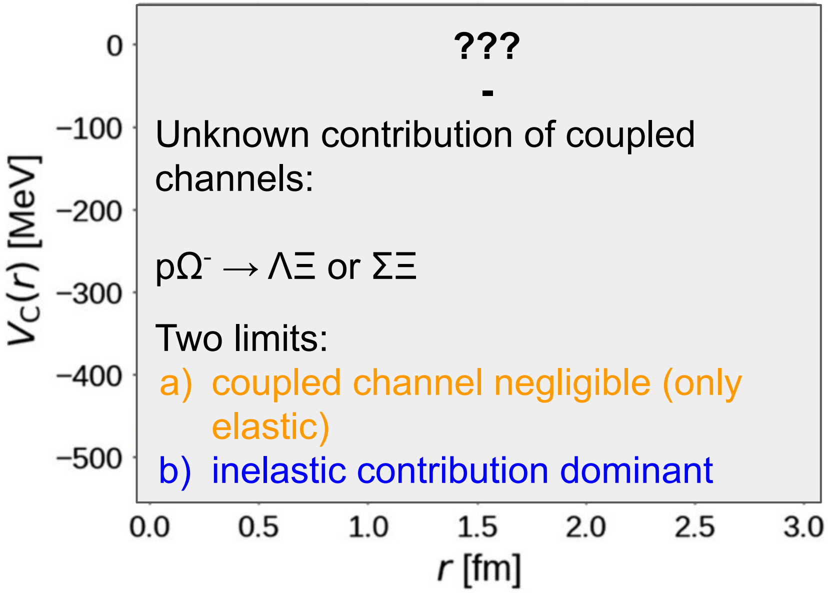




p-Ω⁻: Detailed look at the interaction

- Proton (J_p = 1/2) + Omega (J_Ω = 3/2)
  - angular momentum negligable

NΩ($^3S_2$) – inelastic



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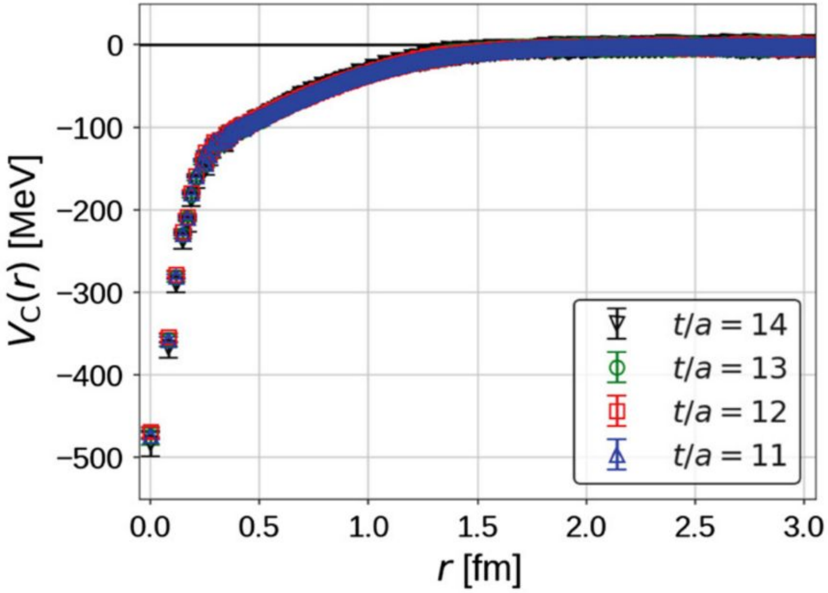
Unknown contribution of coupled channels:

pΩ⁻ → ΛΞ or ΣΞ

Two limits:

a) coupled channel negligible (only elastic)
b) inelastic contribution dominant

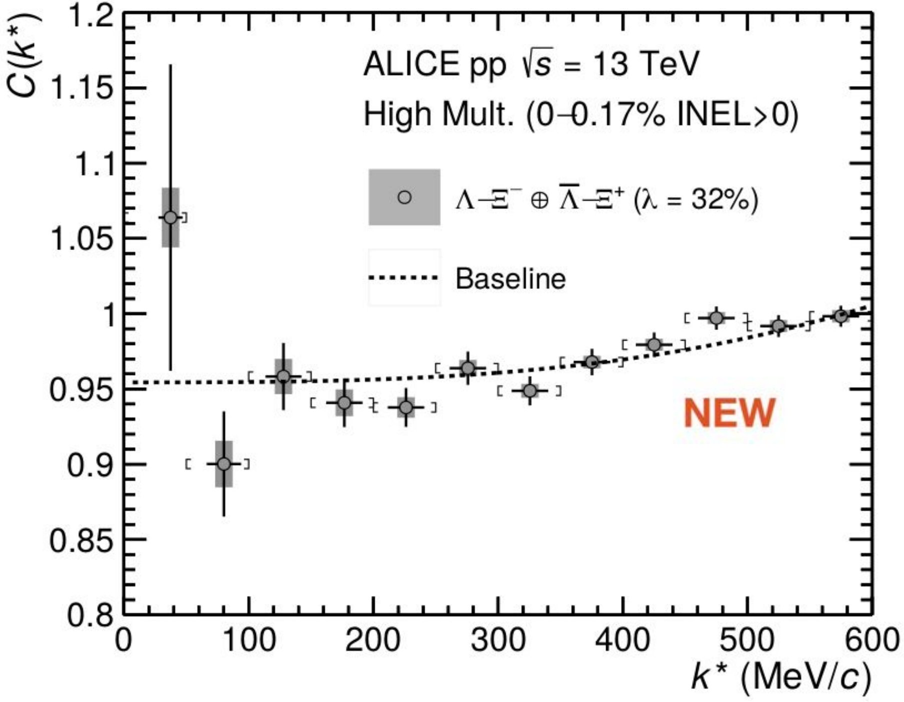
NΩ($^5S_2$) – elastic



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

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

Baseline (no interaction):



ALICE Coll. arXiv:2204.10258, submitted to PLB

Λ-Ξ⁻ pairs:

$1.3 \cdot 10^6$ ($6.1 \cdot 10^3$ for k* < 200 MeV/*c*)

Baseline (dotted line):

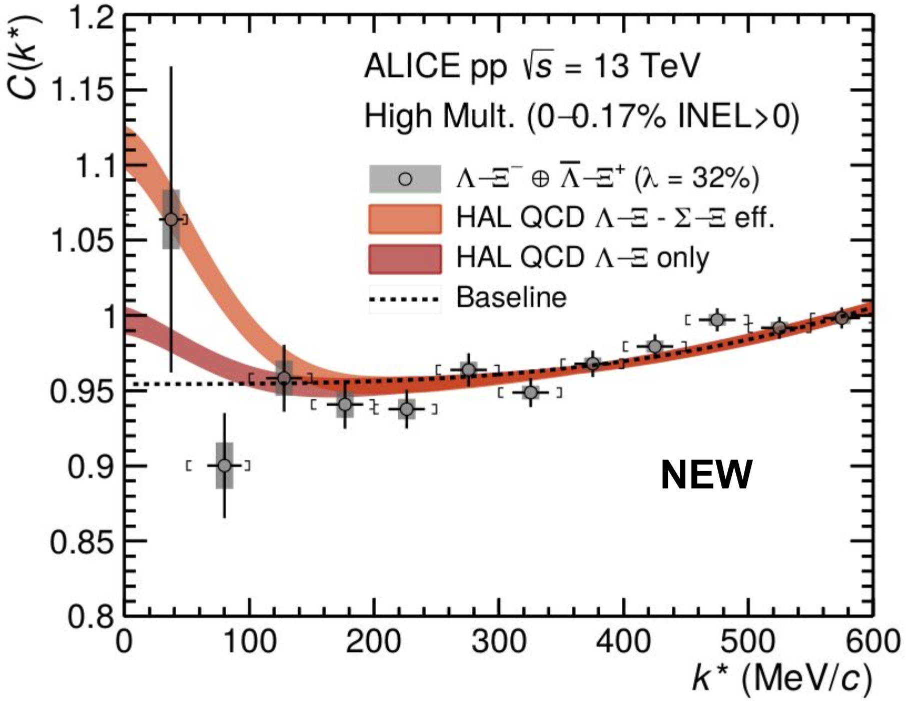
- constrained at large k* ∈ [200,800] MeV/*c*
- Compatibility with the data @ k* < 200 MeV/*c*: **0.78 nσ**

⇒ No significant deviation of the data from the baseline

⇒ indication of shallow ΛΞ interaction

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

Comparison with Lattice QCD:



Compatibility with theory

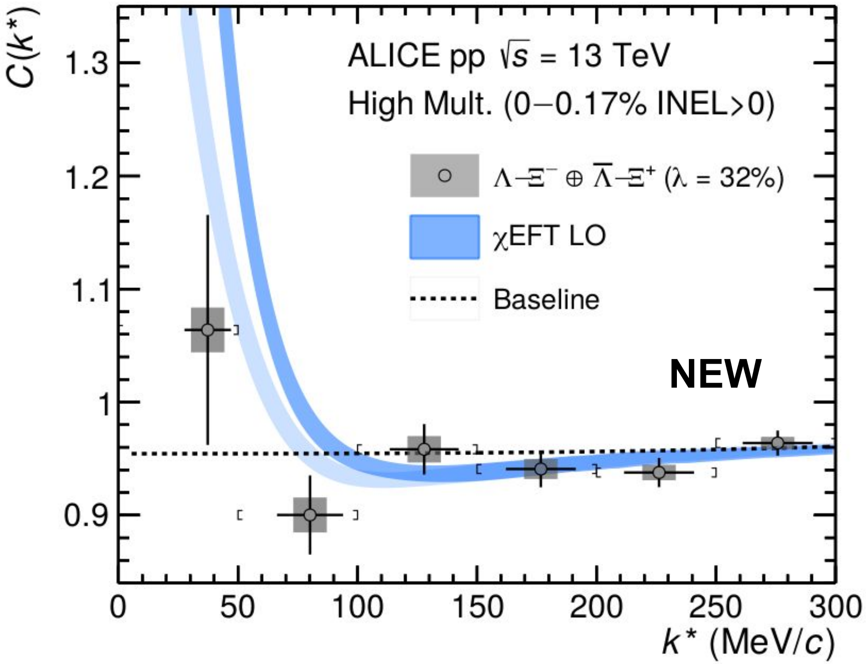
potential	nσ band
ΛΞ – ΣΞ effective	1.43 – 2.34
ΛΞ – ΛΞ only	0.64 – 1.04

Conclusions

- Noticeable ΛΞ – ΣΞ coupling in HAL QCD potential
- no experimental sensitivity on the coupling

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

Comparison with χEFT: LO



ALICE Coll. arXiv:2204.10258, submitted to PLB

Scattering parameters and compatibility

potential (cut-off)	singlet		triplet		
	f_0	d_0	f_0	d_0	nσ
LO (500)	33.5	1.00	–0.33	–0.36	3.06 – 5.12
LO (700)	–9.07	0.87	–0.31	–0.27	0.78 – 1.60

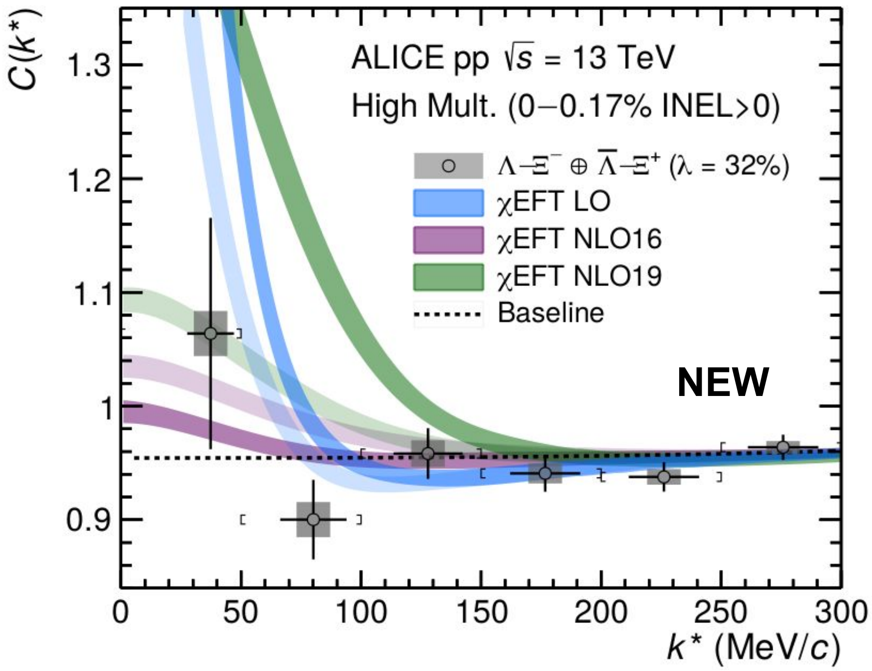
Conclusions:
- strong attraction in the singlet channel
- mild repulsion in the triplet channel
- for LO (700): bound state with 0.43 MeV

⇒ strong attraction of LO (500) excluded
⇒ better compatibility with smaller scattering length

** J. Haidenbauer, U.-G. Meißner, Phys. Lett. B, 684 (2010)*

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

Comparison with χEFT: NLO(*)



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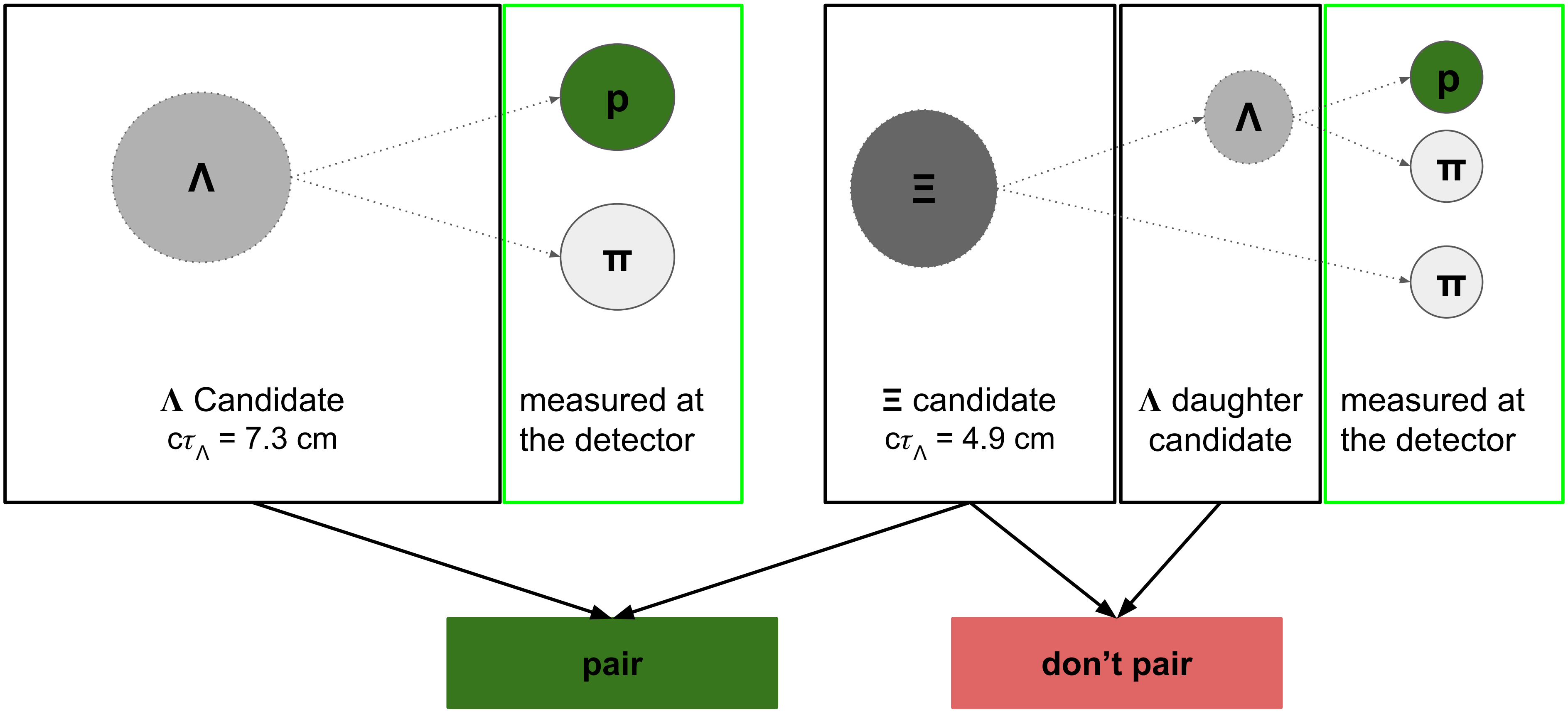
LO (500)	33.5	1.00	–0.33	–0.36	3.06 – 5.12
LO (700)	–9.07	0.87	–0.31	–0.27	0.78 – 1.60
NLO16 (500)	0.99	5.77	–0.026	142.9	0.56 – 0.93
NLO16 (650)	0.91	4.63	0.12	32.02	0.91 – 1.61
NLO19 (500)	0.99	5.77	1.66	1.49	5.47 – 7.26
NLO19 (650)	0.91	4.63	0.42	6.33	1.30 – 2.10

Conclusions:
- no bound state in NLO potentials
- best compatibility with lowest scattering lengths

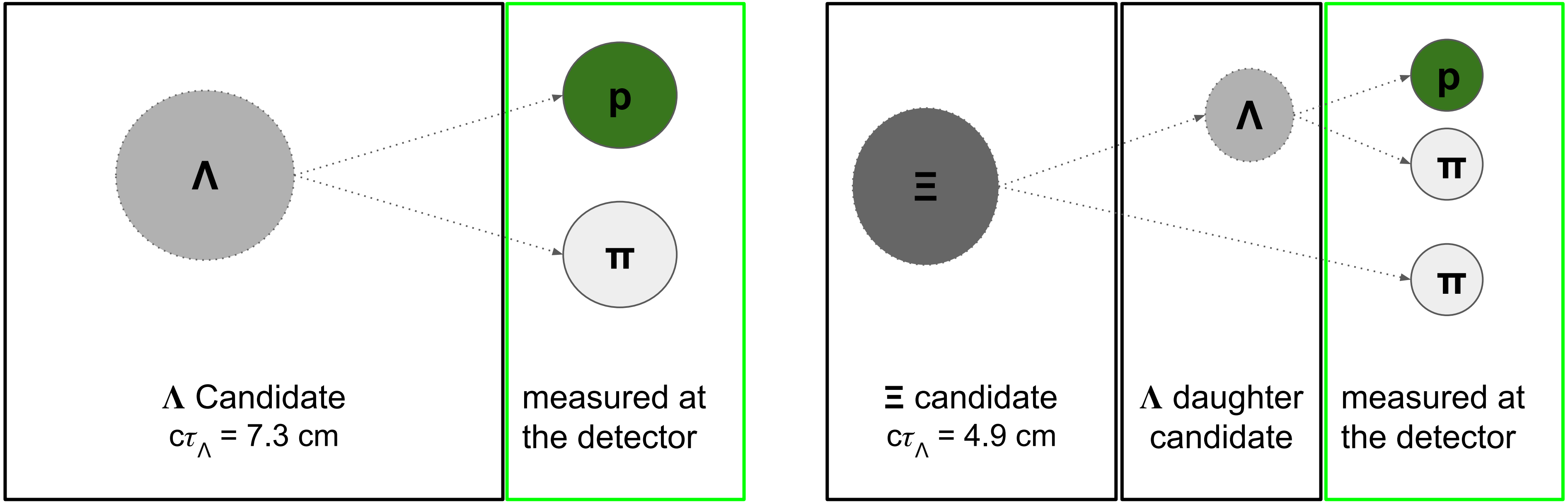
⇒ important constraints for free SU(3) breaking parameters in the potentials by ALICE

** J. Haidenbauer, U.-G. Meißner, arXiv:2201.08238v1 [nucl-th] (2022)*

Data analysis Λ-Ξ^-



Data analysis Λ-Ξ⁻



Λ-Ξ⁻ pairs:

$1.3 \cdot 10^6$ ($6.1 \cdot 10^3$ for $k^* < 200$ MeV/c)

Modelling the correlation function

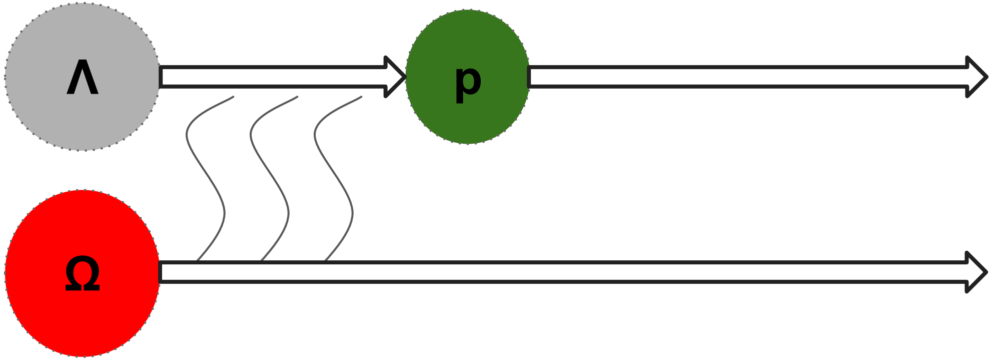
$$C_{\text{exp}}(k^*) = C_{\text{non-femto}}(k^*) \cdot C_{\text{femto}}(k^*)$$

$C_{\text{non-femto}}(k^*)$ Baseline from non-femto effects such as energy conservation

$C_{\text{femto}}(k^*)$ Final state interactions, depending on the analysed baryon pairs

$$C_{\text{femto}}(k^*) = \lambda_{\text{gen}} \cdot C_{\text{gen}}(k^*) + \lambda_{\text{bkg}} \cdot C_{\text{bkg}}(k^*) + \lambda_{\text{feed}} \cdot C_{\text{feed}}(k^*)$$

Example for feeddown correlation:



Experimental Λ-Ξ⁻ correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$	33%:	Lednický model
$C_{\mathrm{bgk}}(k^*)$	11%:	2nd degree polynomial
$C_{\mathrm{feed}}(k^*)$	56%:	Flat

$C_{\text{non-femto}}(k^*)$:

a) $A(1+ p\, k^{*2})$

b) $A(1+ p\, k^{*3})$

Source Function:

$\langle m_T \rangle$ = 2.0 GeV/c

r_{core} = 0.89 ± 0.05 fm

r_{eff} = 1.03 ± 0.05 fm

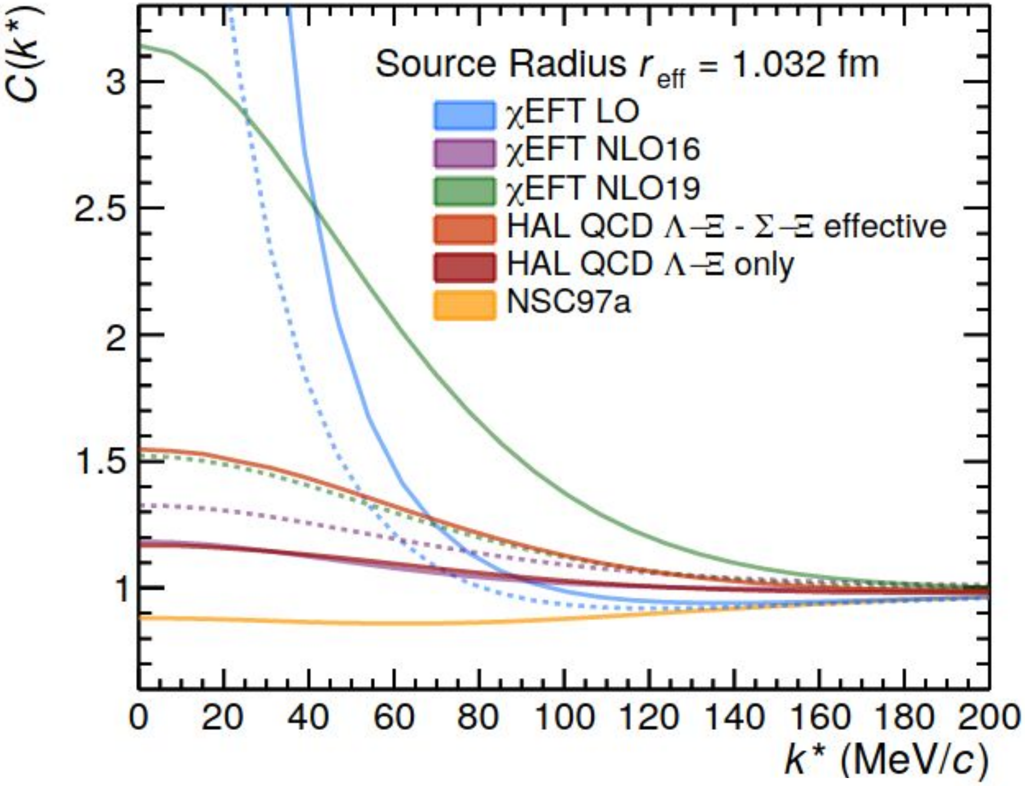
Correct the genuine theoretical calculated C(k*) for the additional contributions:

$$C_{\mathrm{femto}}(k^*) = \lambda_{\mathrm{gen}} \cdot C_{\mathrm{gen}}(k^*) + \lambda_{\mathrm{bkg}} \cdot C_{\mathrm{bkg}}(k^*) + \lambda_{\mathrm{feed}} \cdot C_{\mathrm{feed}}(k^*)$$

$$C_{\mathrm{exp}}(k^*) = C_{\text{non-femto}}(k^*) \cdot C_{\mathrm{femto}}(k^*)$$

Genuine $\Lambda\Xi^-$ interaction

- ➢ Theoretical correlation functions from the discussed potentials
- ➢ dotted lines correspond to the larger cut-off version in χEFT potentials



ALICE Coll. arXiv:2204.10258, submitted to PLB