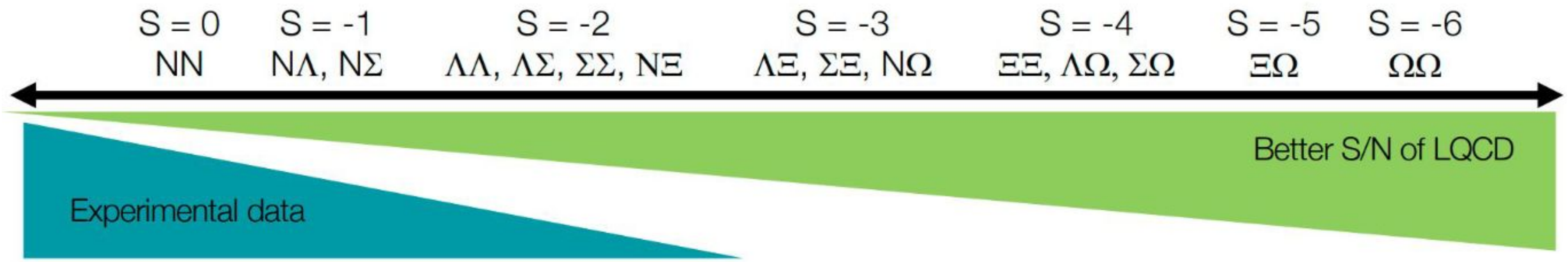
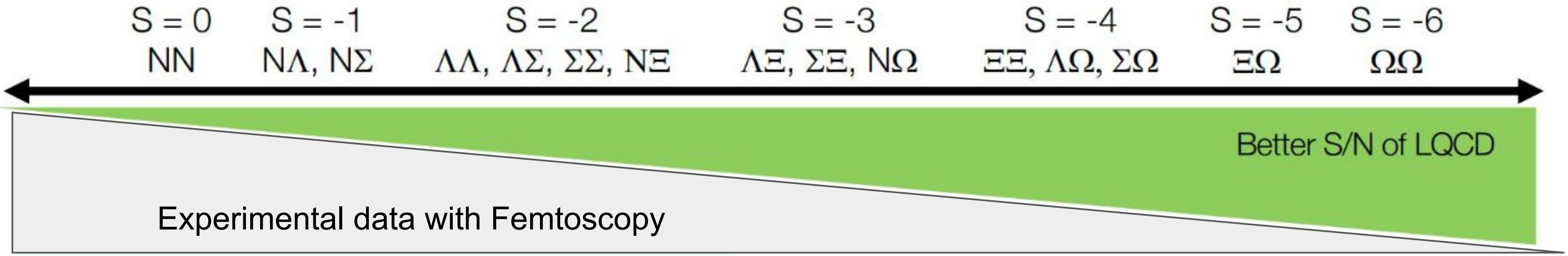
New experimental limits on the effective hadron interaction with strangeness = -3

Georgios Mantzaridis on behalf of the ALICE Collaboration
Technical University of Munich
STRANU 2021
26/05/2021

Entering the Hadronic S = -3 sector



Entering the Hadronic S = -3 sector

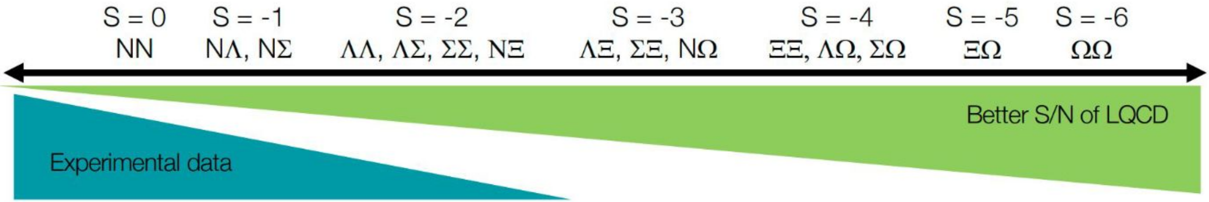


Femtoscopy pushes the boundary:

Experiment:	ALICE Experiment at CERN
Collision system:	pp
Energy:	$\sqrt{s}$ = 13 TeV
Type of events:	high multiplicity

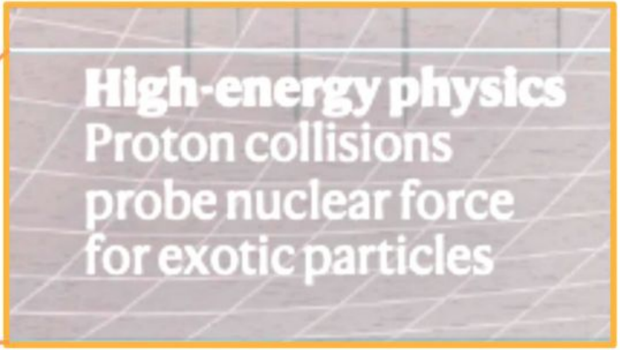
"Enhanced production of strange hadrons in high multiplicity (HM) pp collisions" ALICE Coll. Nature Physics 13, 535 (2017)

Entering the Hadronic S = -3 sector



Femtoscopy pushes the boundary

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



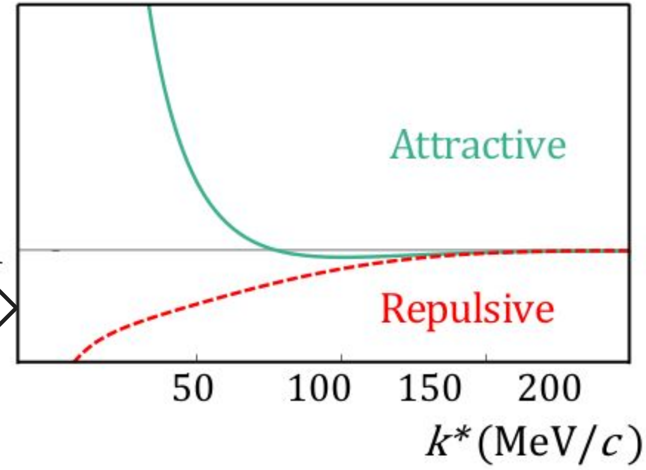
Method: Femtoscopy

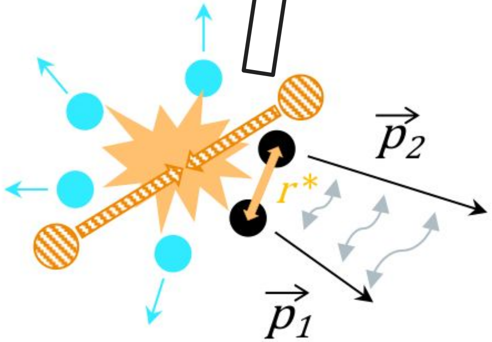
Central part: **The correlation function** in terms of the relative momentum k*

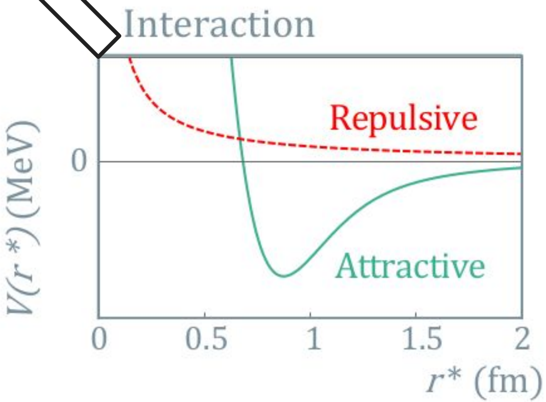
$$k^* = 1/2 \cdot |p_1^* - p_2^*|$$

Correlation Function

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







Same correlations between particle and antiparticle pairs:

$$\mathrm{p} - \Omega^- := \mathrm{p} - \Omega^- \oplus \overline{\mathrm{p}} - \Omega^+$$

$$\Lambda - \Xi^- := \Lambda - \Xi^- \oplus \overline{\Lambda} - \Xi^+$$

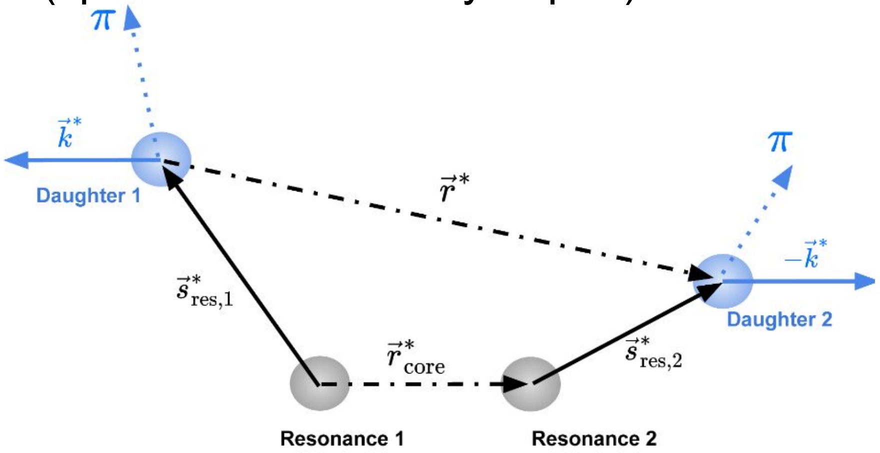
Figures: ALICE Coll. *Nature* 588, 232 (2020)

Source Function

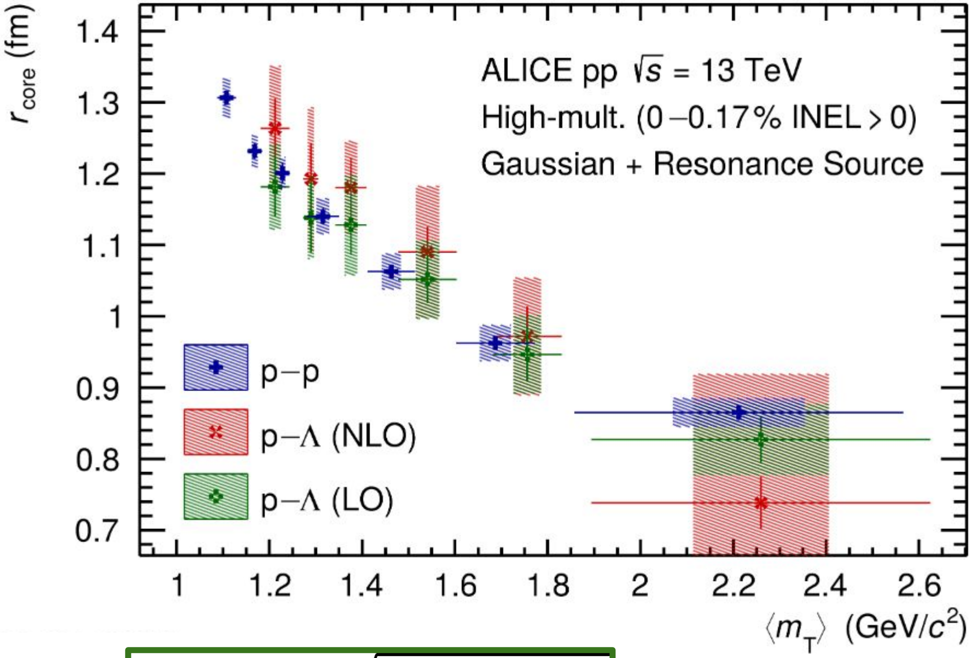
ALICE Coll., Physics Letters B, 811 (2920) 135849

Consists of two parts:

- Gaussian core $\mathbf{r}^*_{\text{Core}}$ (common for all baryon pairs)
- Extension to an effective source size $\mathbf{r}^*_{\text{eff}}$ by strongly decaying resonances (specific for each baryon pair)



Get $\mathbf{r}^*_{\text{Core}}$ from the transverse mass distribution:



$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m^2}$$

Modelling the Correlation Function

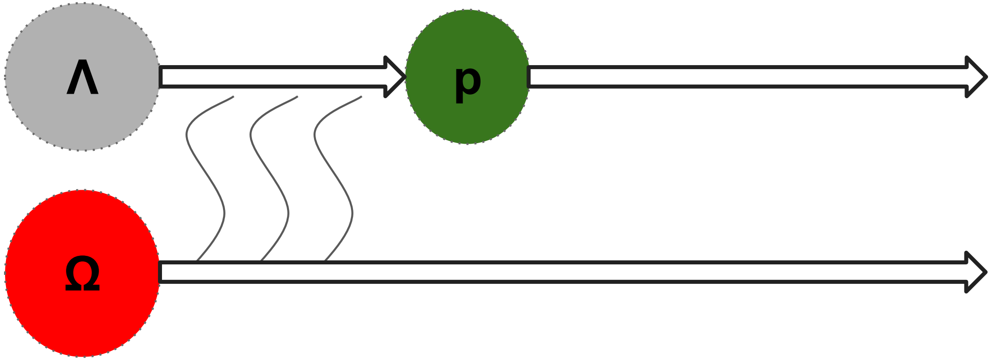
$$C_{\text{exp}}(k^*) = C_{\text{non-femto}}(k^*) \cdot C_{\text{femto}}(k^*)$$

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



p-Ω^-: Data analysis

Excellent particle reconstruction with ALICE:

Reconstruction:

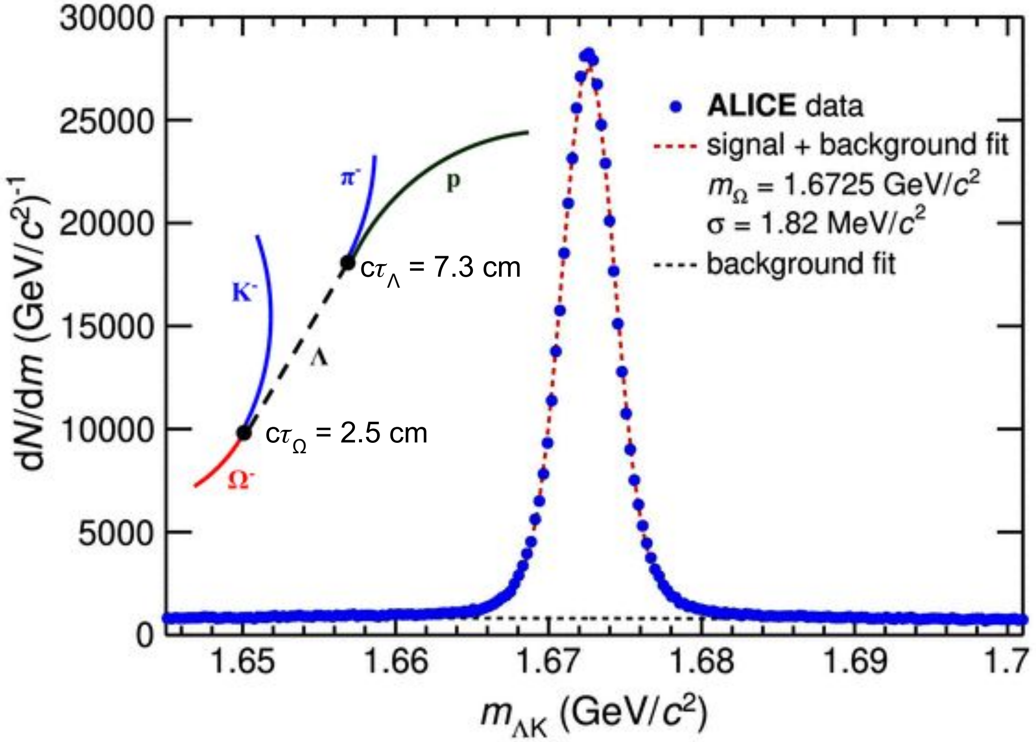
weak decay into K^- and Λ

Purity of Ω^- selection:

95%

p-Ω^- pairs:

$0.6 \cdot 10^6$ ($4 \cdot 10^3$ for k* < 200 MeV/c)



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

Experimental p-Ω^- correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$	79.0 %: Lattice QCD calculation
$C_{\mathrm{bgk}}(k^*)$	15.0 %: 3rd degree polynomial
$C_{\mathrm{feed}}(k^*)$	06.0 %: Flat

Experimental p-Ω^- correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$	79.0 %: Lattice QCD calculation
$C_{\mathrm{bgk}}(k^*)$	15.0 %: 3rd degree polynomial
$C_{\mathrm{feed}}(k^*)$	06.0 %: Flat

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

a) constant
b) 1st degree polynomial

Experimental p-Ω^- correlation function

Femto C(k*):

$C_{\text{gen}}(k^*)$	79.0 %: Lattice QCD calculation
$C_{\text{bgk}}(k^*)$	15.0 %: 3rd degree polynomial
$C_{\text{feed}}(k^*)$	06.0 %: Flat

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

a) constant

b) 1st degree polynomial

Source Function:

$\langle m_T \rangle$ = 2.2 GeV/c

r_{core} = 0.86 ± 0.06 fm

r_{eff} = 0.95 ± 0.06 fm

Experimental p-Ω^- correlation function

Femto C(k*):

$C_{\text{gen}}(k^*)$	79.0 %: Lattice QCD calculation
$C_{\text{bgk}}(k^*)$	15.0 %: 3rd degree polynomial
$C_{\text{feed}}(k^*)$	06.0 %: Flat

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

a) constant

b) 1st degree polynomial

Source Function:

$\langle m_T \rangle$ = 2.2 GeV/c

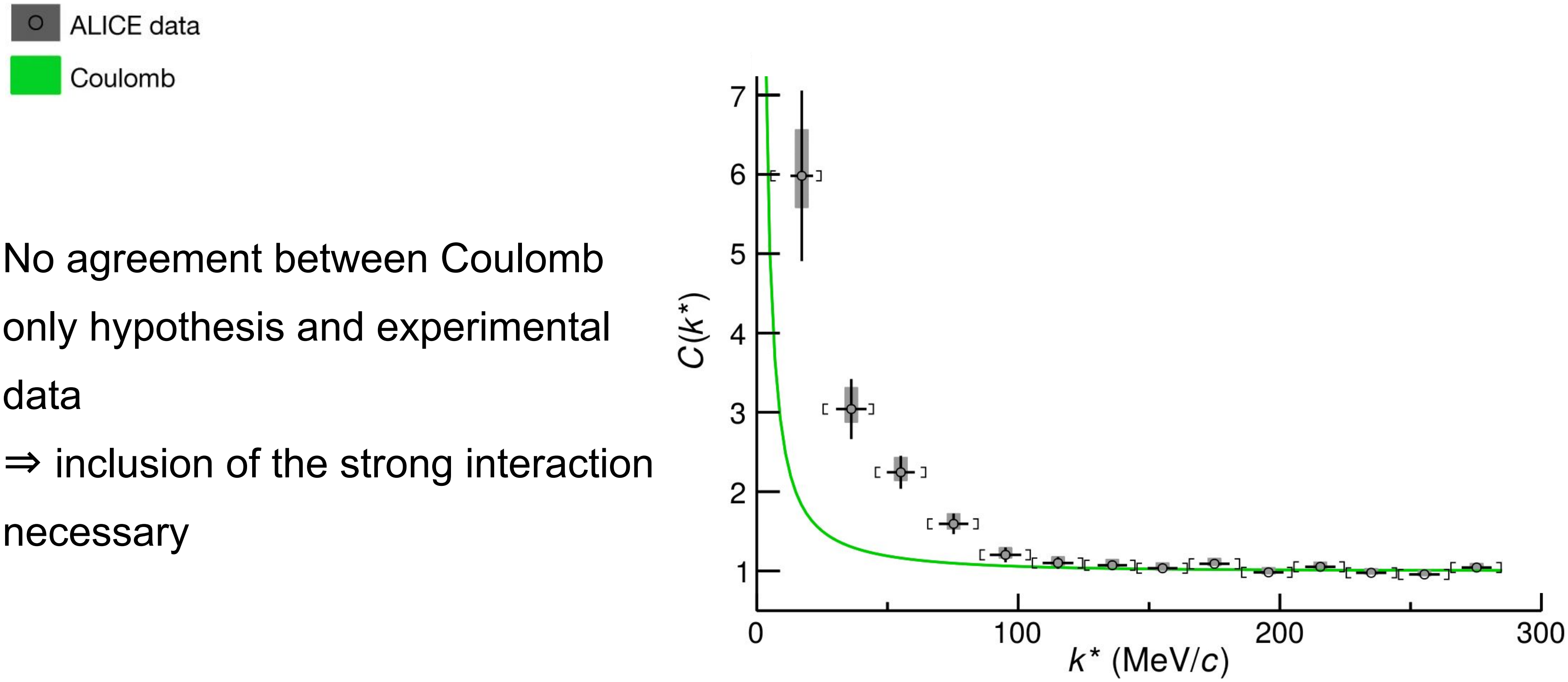
r_{core} = 0.86 ± 0.06 fm

r_{eff} = 0.95 ± 0.06 fm

Extract the genuine Correlation function:

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

p-Ω^-: Comparison with only Coulomb Potential



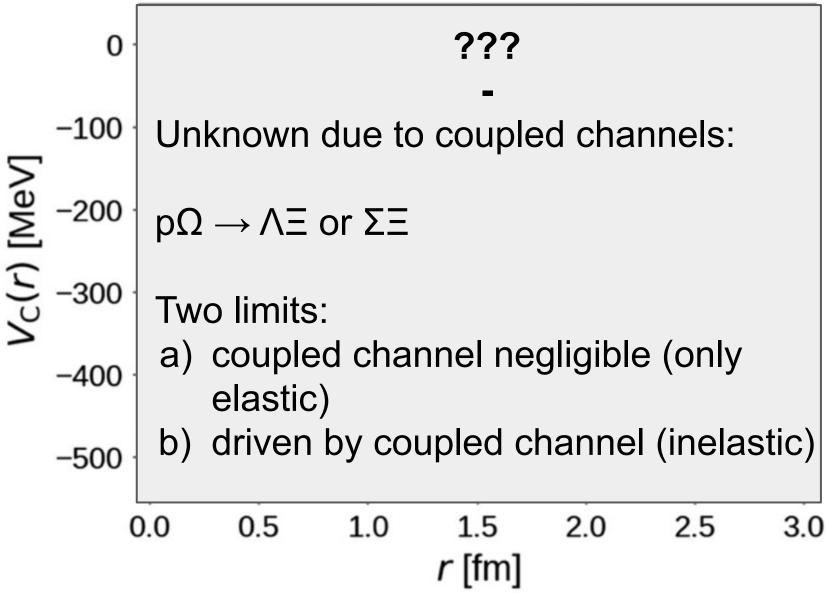
- No agreement between Coulomb only hypothesis and experimental data
  ⇒ inclusion of the strong interaction necessary

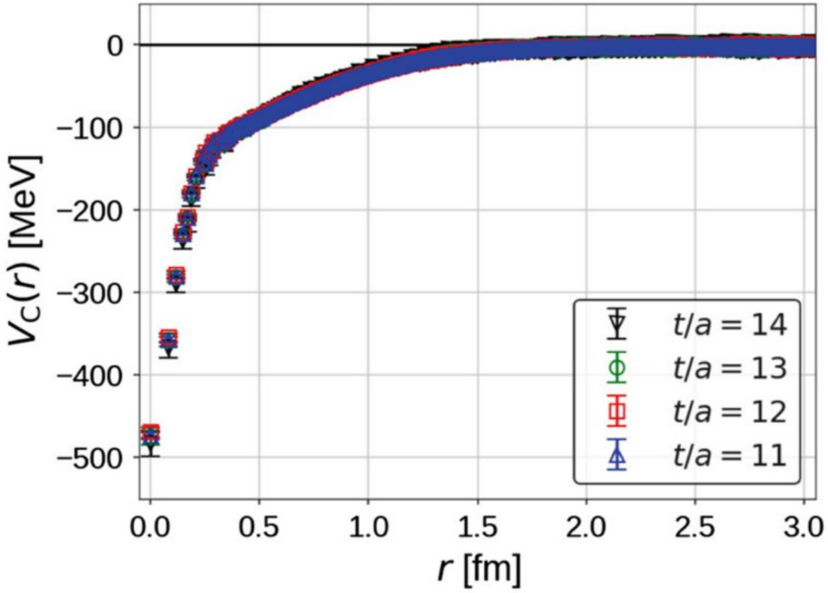
ALICE Coll. *Nature* 588, 232 (2020)

p-Ω⁻: Detailed Look at the Interaction

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

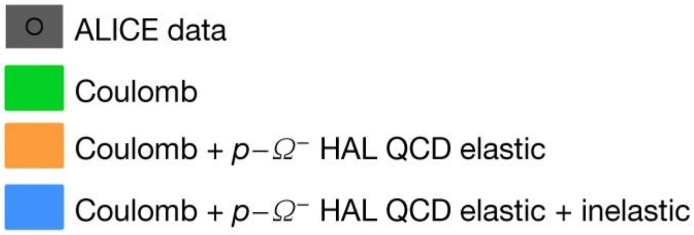
$N\Omega(^3S_2)$ | $N\Omega(^5S_2)$



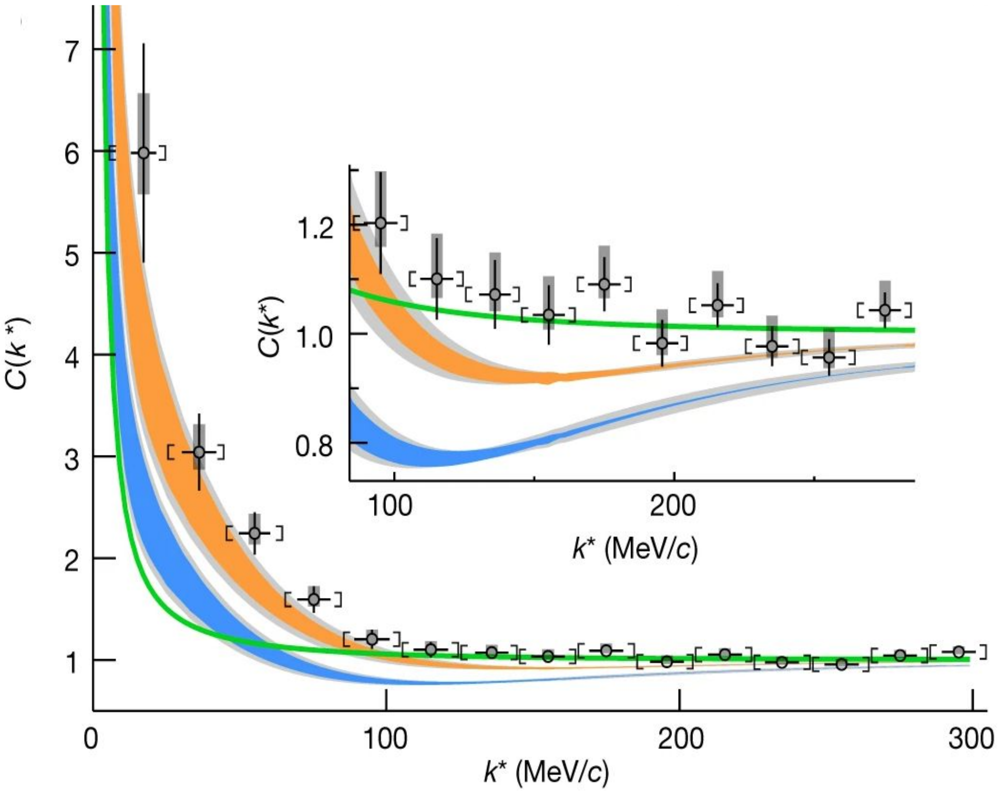


T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

p-Ω⁻: Comparison with Coulomb + HAL QCD

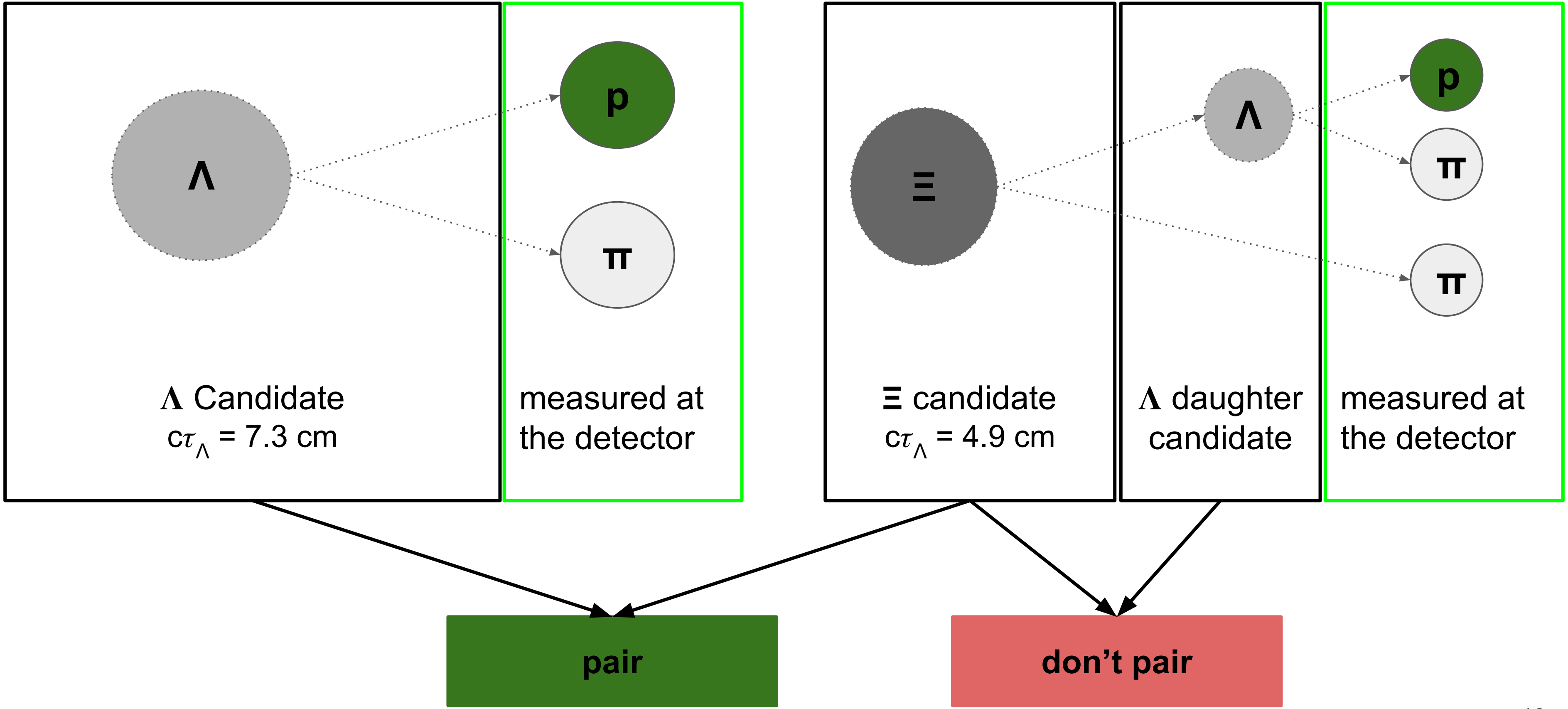


- Higher accuracy in the data than in the theoretical calculation
- Better agreement of data without inelastic contributions
- Prediction of a bound state with binding energy **2.5 MeV**
  ⇒ not reproduced by the data

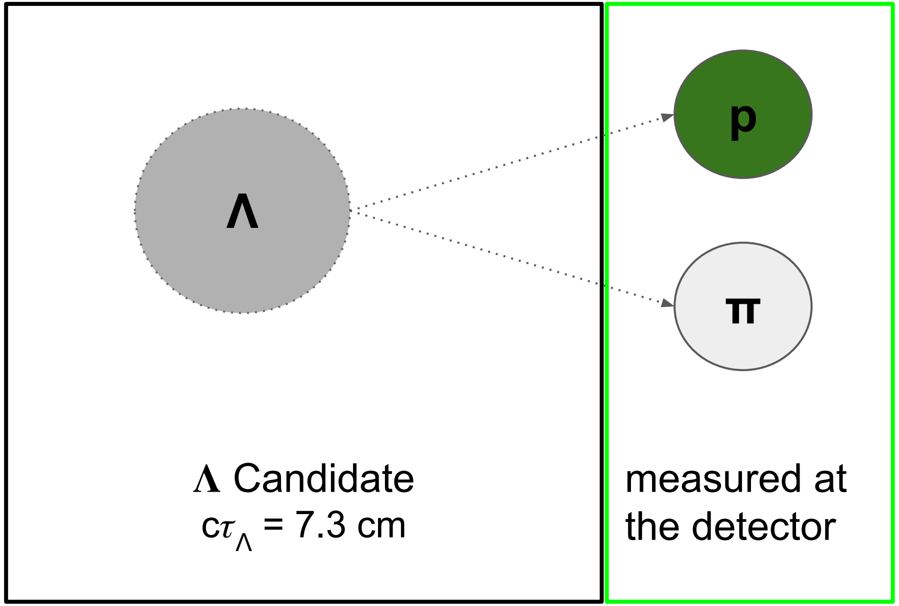


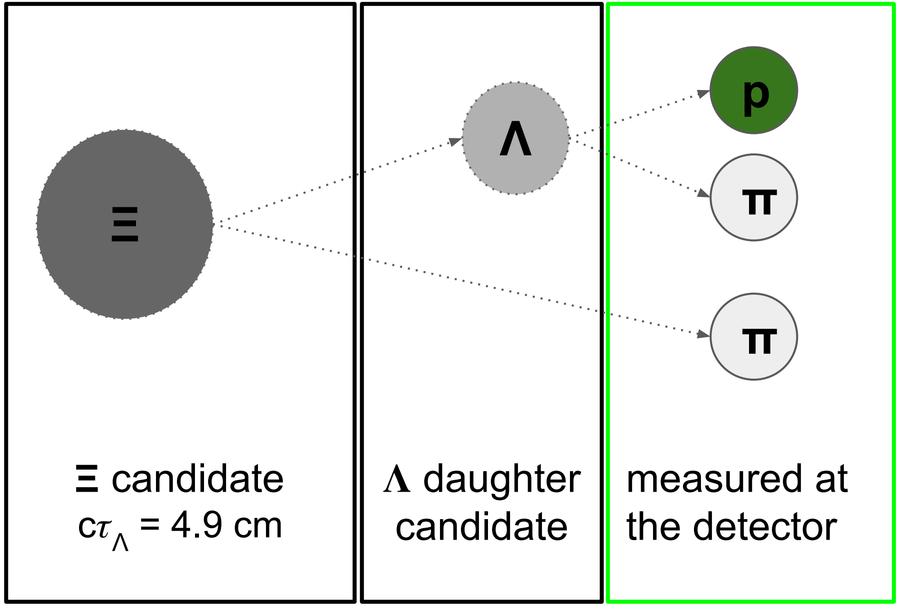
ALICE Coll. *Nature* 588, 232 (2020)

Data Analysis Λ-Ξ$^-$



Data Analysis Λ-Ξ⁻





Λ-Ξ⁻ pairs:

$1.1 \cdot 10^6$ ($5 \cdot 10^3$ for k* < 200 MeV/c)

Experimental Λ-Ξ⁻ correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$	36.01 %: Lednicky model
$C_{\mathrm{bgk}}(k^*)$	8.13 %: 2nd degree polynomial
$C_{\mathrm{feed}}(k^*)$	55.85 %: Flat

Experimental Λ-Ξ⁻ correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$	36.01 %: Lednicky model
$C_{\mathrm{bgk}}(k^*)$	8.13 %: 2nd degree polynomial
$C_{\mathrm{feed}}(k^*)$	55.85 %: Flat

Non- Femto:

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

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

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

Experimental Λ-Ξ^- correlation function

Femto C(k*):

$C_{\mathrm{gen}}(k^*)$ 36.01 %: Lednicky model

$C_{\mathrm{bgk}}(k^*)$ 8.13 %: 2nd degree polynomial

$C_{\mathrm{feed}}(k^*)$ 55.85 %: Flat

Non- Femto:

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

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

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

Source Function:

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

$r_{core} = 0.89 \pm 0.05$ fm

$r_{eff} = 1.03 \pm 0.05$ fm

Experimental Λ-Ξ⁻ correlation function

Femto C(k*):

$C_{\text{gen}}(k^*)$ 36.01 %: Lednicky model

$C_{\text{bgk}}(k^*)$ 8.13 %: 2nd degree polynomial

$C_{\text{feed}}(k^*)$ 55.85 %: Flat

Non- Femto:

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

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

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

Source Function:

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

$r_{core} = 0.89 \pm 0.05$ fm

$\mathbf{r_{eff} = 1.03 \pm 0.05}$ **fm**

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

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

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

The Lednicky-Lyuboshits model

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

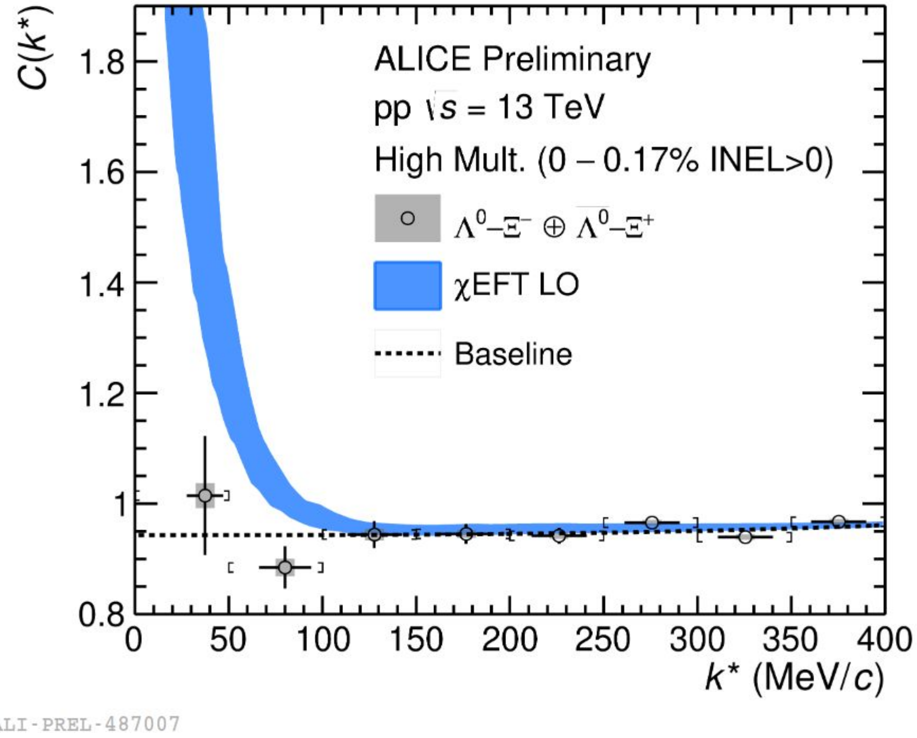
Analytical approach to model CF for strong final state interactions with the scattering amplitude f_0

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

d_0: effective range

f_0: scattering length

Model comparison χEFT LO



Scattering parameters

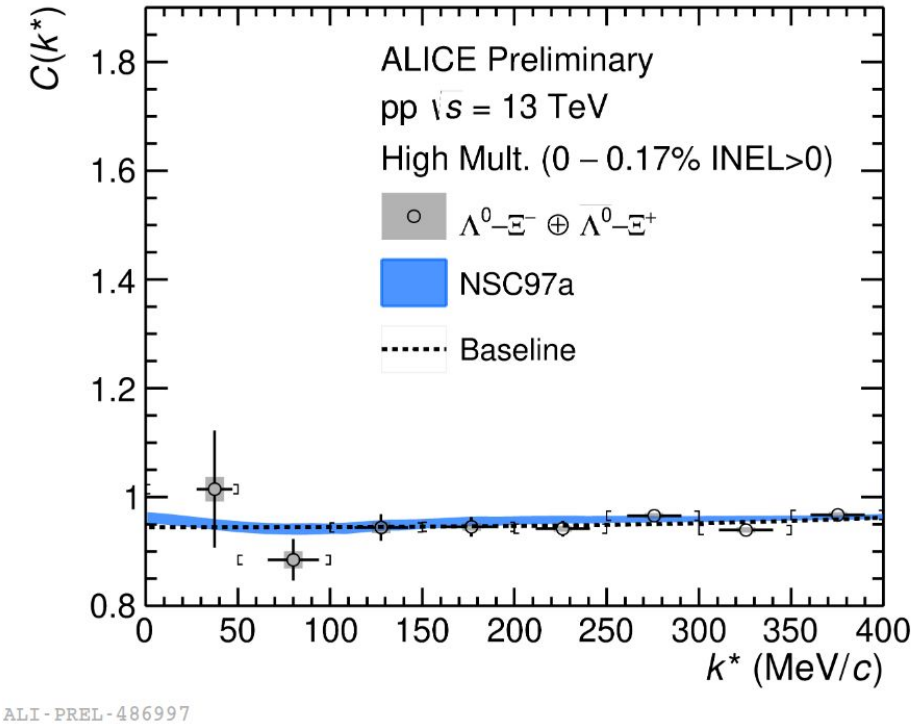
	EFT			
Λ (MeV)	550	600	650	700
singlet				
f_0^0	33.5	-35.4	-12.7	-9.07
d_0^0	1.00	0.93	0.87	0.87
triplet				
f_0^1	-0.33	- 0.33	- 0.32	-0.31
d_0^1	-0.36	-0.30	-0.29	-0.27

J. Haidenbauer and U.-G. Meissner, Phys. Lett. B 684 (2010) 275–280

Compatibility with theory

range	: 0 - 250 MeV/c	|	0 - 150 MeV/c
χ^2	: 10.93 - 78.31	|	10.67 - 75.80
nσ band	**: 1.94σ - 7.95σ**	**|**	**2.47σ - 8.20σ**

Model comparison NSC97a



Scattering parameters

	NSC97a
singlet	
f_0^0	0.80
d_0^0	4.71
triplet	
f_0^1	-0.54
d_0^1	-0.47

Th. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59 (1999) 21

Compatibility with theory

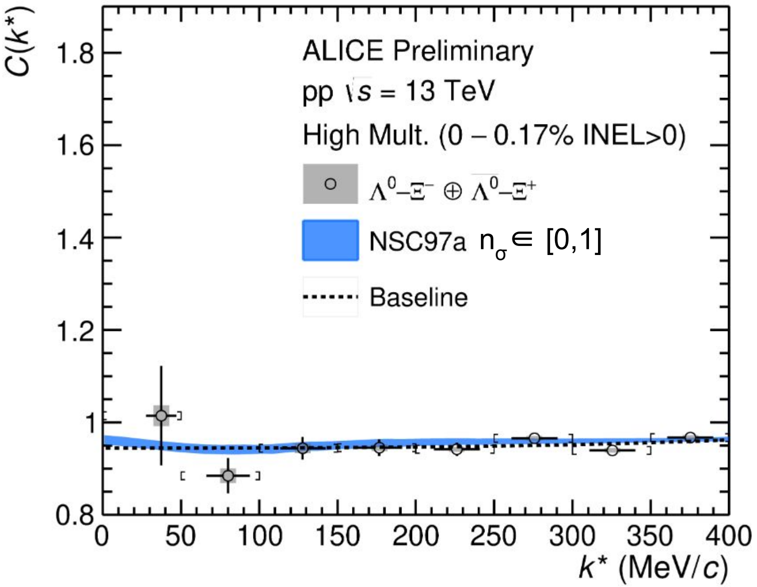
range	: 0 - 250 MeV/c	|	0 - 150 MeV/c
χ^2	: 2.17 - 6.45	|	1.77 - 3.17
nσ band	**: 0.22σ - 1.12σ**	**|**	**0.50σ - 0.90σ**

Results: Λ-Ξ^-

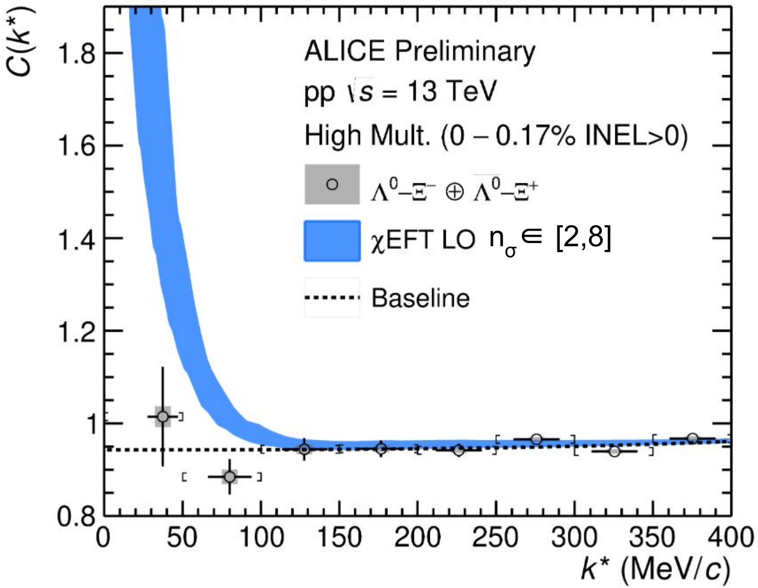
Comparison of ALICE data with meson exchange model and χEFT LO:

⇒ Suggests shallow strong interaction

⇒ Decrease of theoretical uncertainty of NΩ coupling



ALI-PREL-486997



ALI-PREL-487007

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

Summary

- First experimental constraints on the strangeness = -3 sector:
- First observation of the p-Ω interaction
    - published in nature last december
    - attractive strong interaction confirmed
    - Lattice QCD predicts a bound state <---> not seen in the data
    - theory missing the $^3S_2$ channel
- First observation of the Λ-Ξ interaction
    - shallow interaction potential
    - contradiction to χEFT LO calculations
    - first constraints for the $^3S_2$ channel of p-Ω^-: CC to Λ-Ξ^- seems negligable

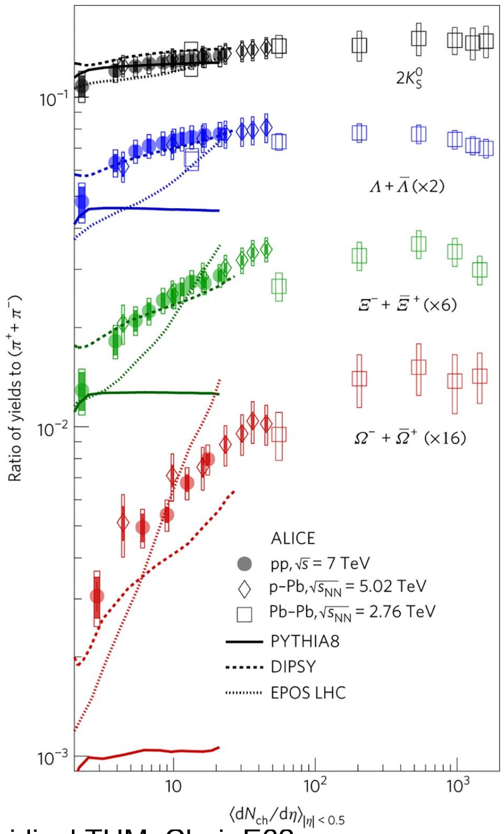
Outlook

- Further pair interactions to be explored in the future and further first principle calculations can be tested
- Run 3 and 4 will provide more data and the possibility for differential studies

Thank you for your attention

Backup

Enhanced strangeness production in HM events



Data sample:

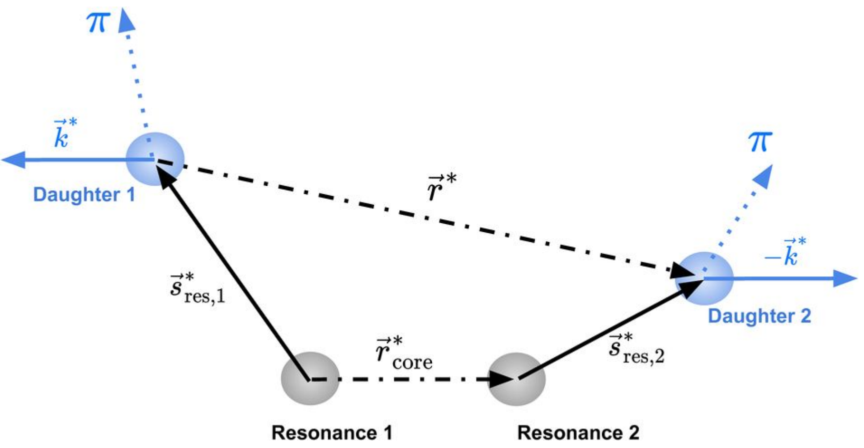
- pp 13 TeV (1000 M **high multiplicity** events)

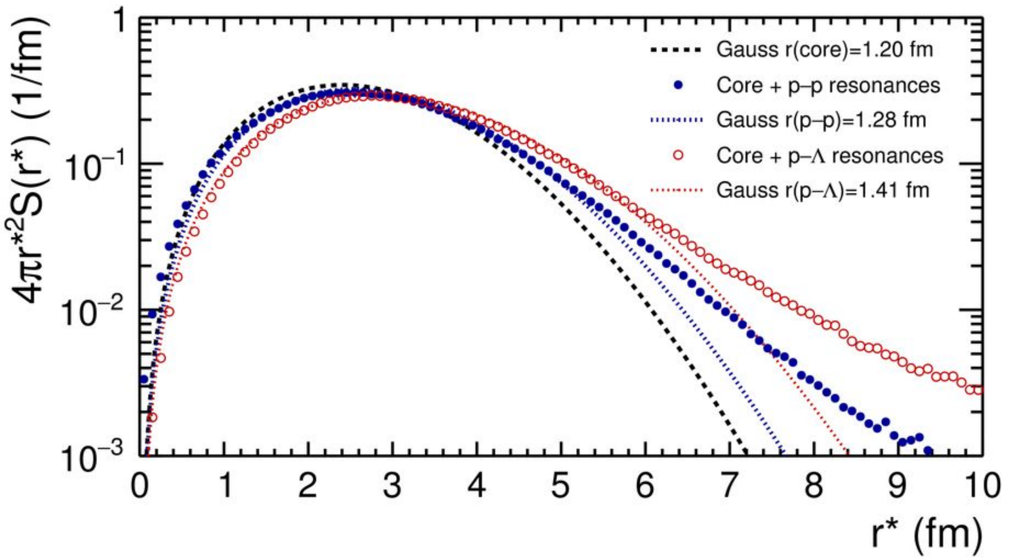
Tracking and PID:

- Hyperon reconstruction with purities >95%

Nature Physics volume 13, 535–539(2017)

Effect of the Resonances on the Source





The strong p-Ω^- interaction

Models of the p-Ω- interaction

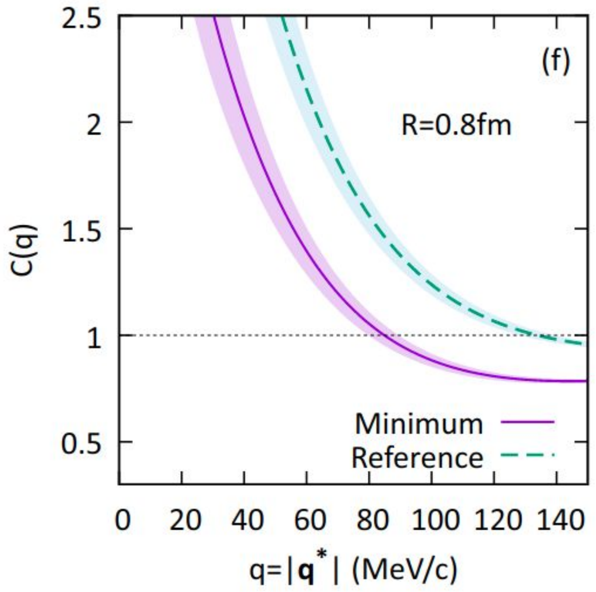
-> Calculations provide the potential shape for the $^5S_2$ channel (weight ⅝).

-> Currently, no model for the other channel in S-wave interaction, $^3S_1$ (weight ⅜). Requires coupled channel treatment.

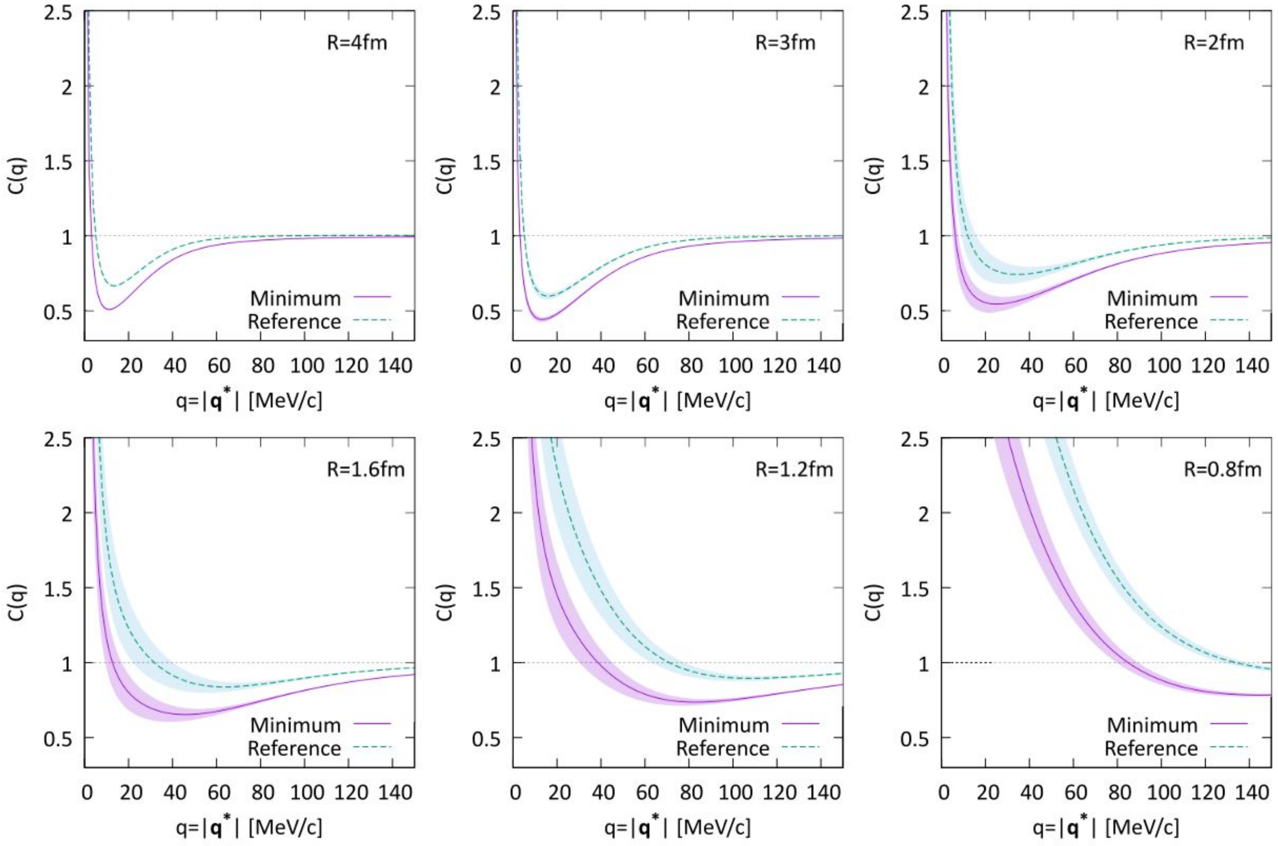
Assume two different (~extreme) scenarios:

1.- Complete absorption for distances r < r_0.
r_0 chosen from the condition $|V(^5S_2)| < |V(\text{Coulomb})|$ for r > r_0

2.- Complete elastic with a similar attraction as $^5S_2$
Kenji Morita et al., Phys. Rev. C101, 015201 (2020)

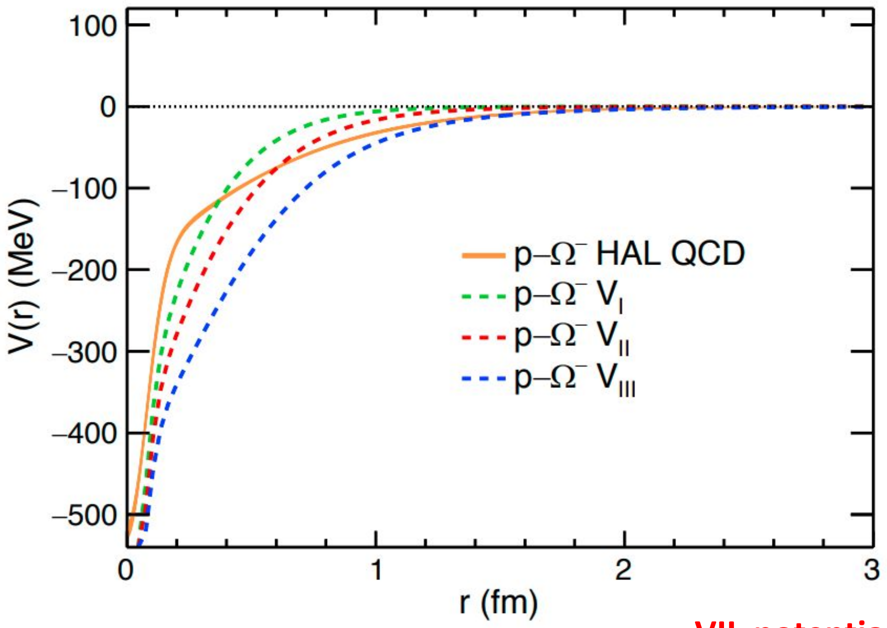


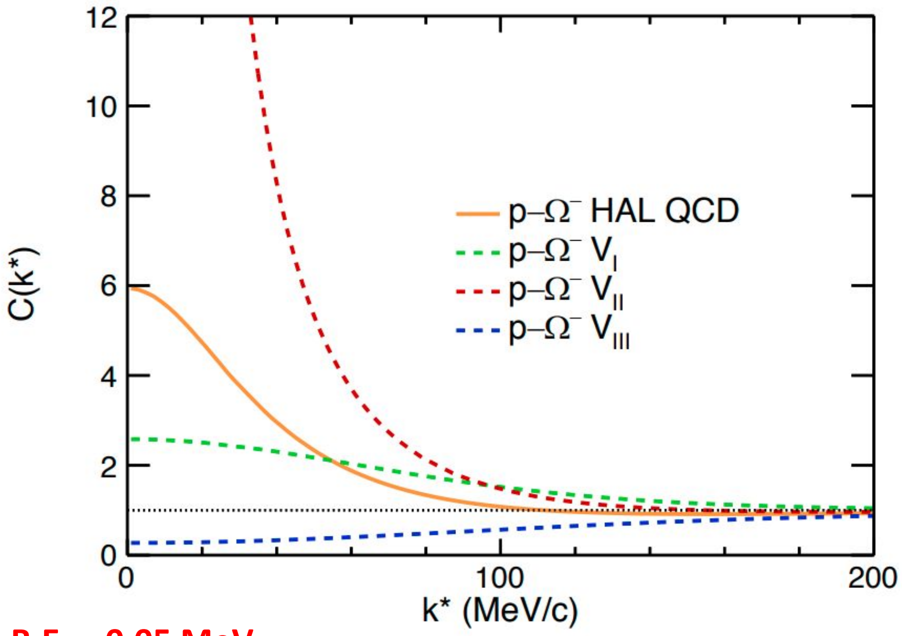
The strong p-Ω^- interaction



Effect of the boundstate on p-Ω^-

K. Morita et al., Phys. Rev. C 101, 015201 (2020)





VII potential: B.E. = 0.05 MeV

VI potential: No Bound state

VIII potential: B.E. = 24.8 MeV

HAL QCD B.E. = 1.5 MeV