Precision studies of the strong interaction in Λ-hadron systems up to S=-3 with ALICE

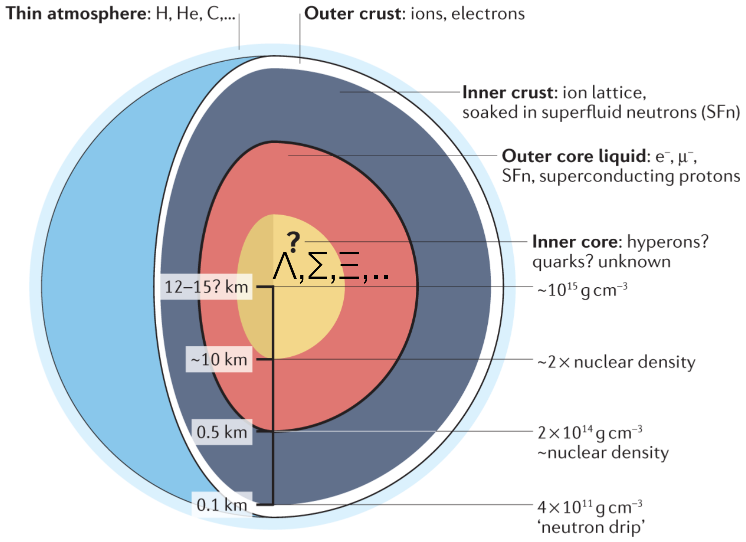
V. Mantovani Sarti on behalf of the ALICE Collaboration

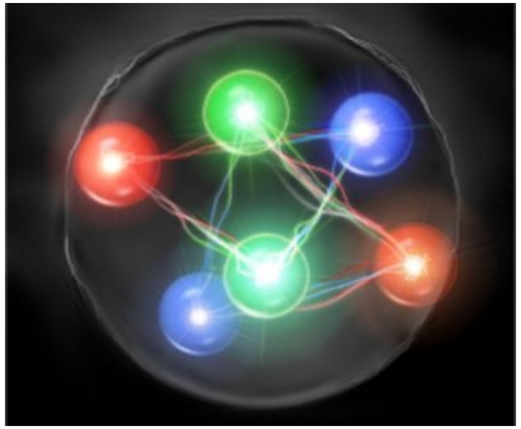
06.04.2022

Quark Matter 2022, Kraków

Strong interaction between Λ and hadrons

- Perfect probe for understanding strong interaction with strangeness
- |S| = 1: ΛN interaction
  - Equation of state of nuclear matter in neutron stars with hyperons
  - Input for three-body YNN
- |S| = 2 and |S| = 3 : ΛΛ and ΛΞ interaction
  - Constraints for hypernuclei and effective QCD theories in multi-strange sector
  - Exotic bound states as H-dibaryon and NΩ dibaryon

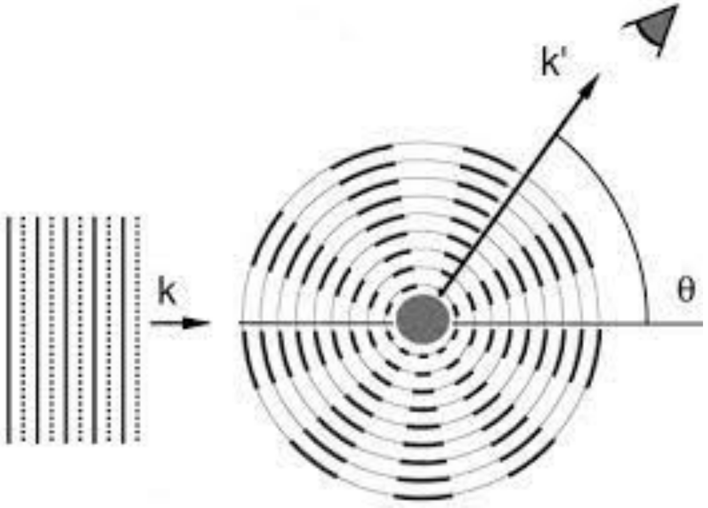




R.L Jaffe PRL 38 (1977) 195-198
HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737
HAL QCD Coll. Phys.Lett.B 792 (2019) 284-289

Λ-hadron interaction: theory and experiment

	$\|S\| = 0$ NN	$\|S\| = 1$ ΛN	$\|S\| = 2$ ΛΛ	$\|S\| = 3$ ΛΞ	$\|S\| > 3$ ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ
Scattering experiments					



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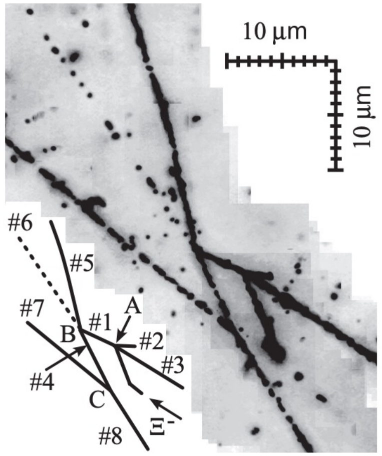
	|S| = 0 NN	|S| = 1 ΛN	|S| = 2 ΛΛ	|S| = 3 ΛΞ	|S| > 3 ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ

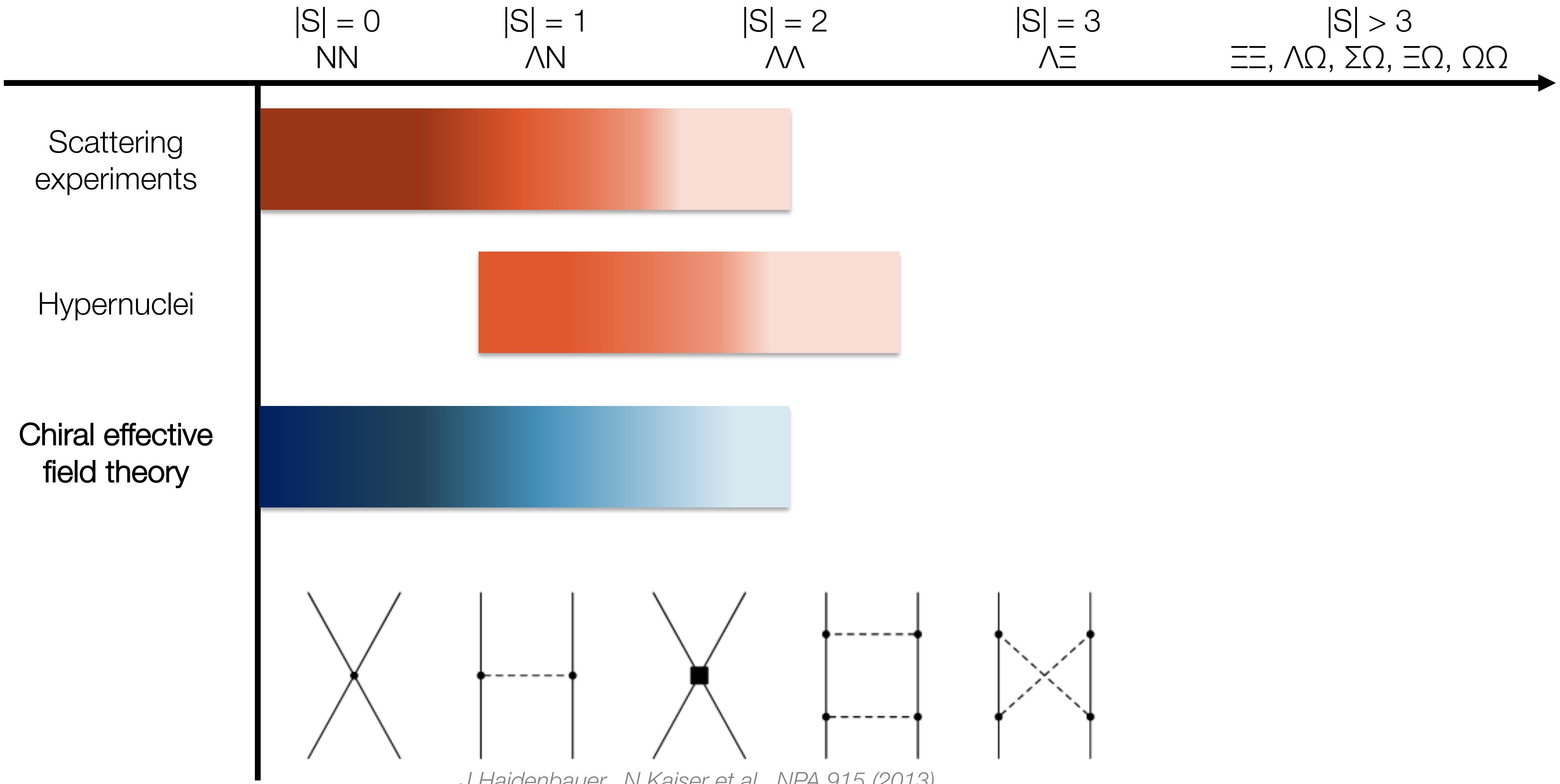
Scattering experiments

Hypernuclei



H. Takahashi et al., PRL 87 (2001) 212502
T. Nagae et al., PRL 80 (1998) 1605-1609
S.H. Hayakawa et al. PRL. 126 (2021), 062501
J.K Ahn et al., PRC 88 (2013), 014003

Λ-hadron interaction: theory and experiment



J.Haidenbauer., N.Kaiser et al., NPA 915 (2013)
J.Haidenbauer, U. Meißner, EPJ.A 56 (2020)

Λ-hadron interaction: theory and experiment

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Scattering experiments					
Hypernuclei					
Chiral effective field theory					
Lattice QCD					

HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737
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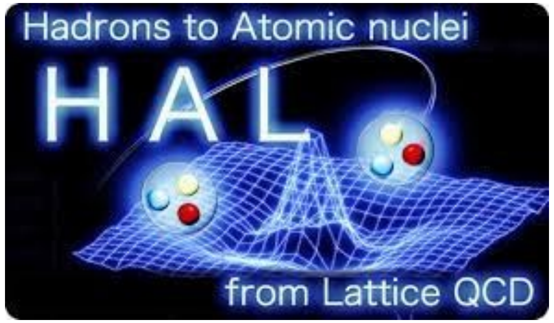

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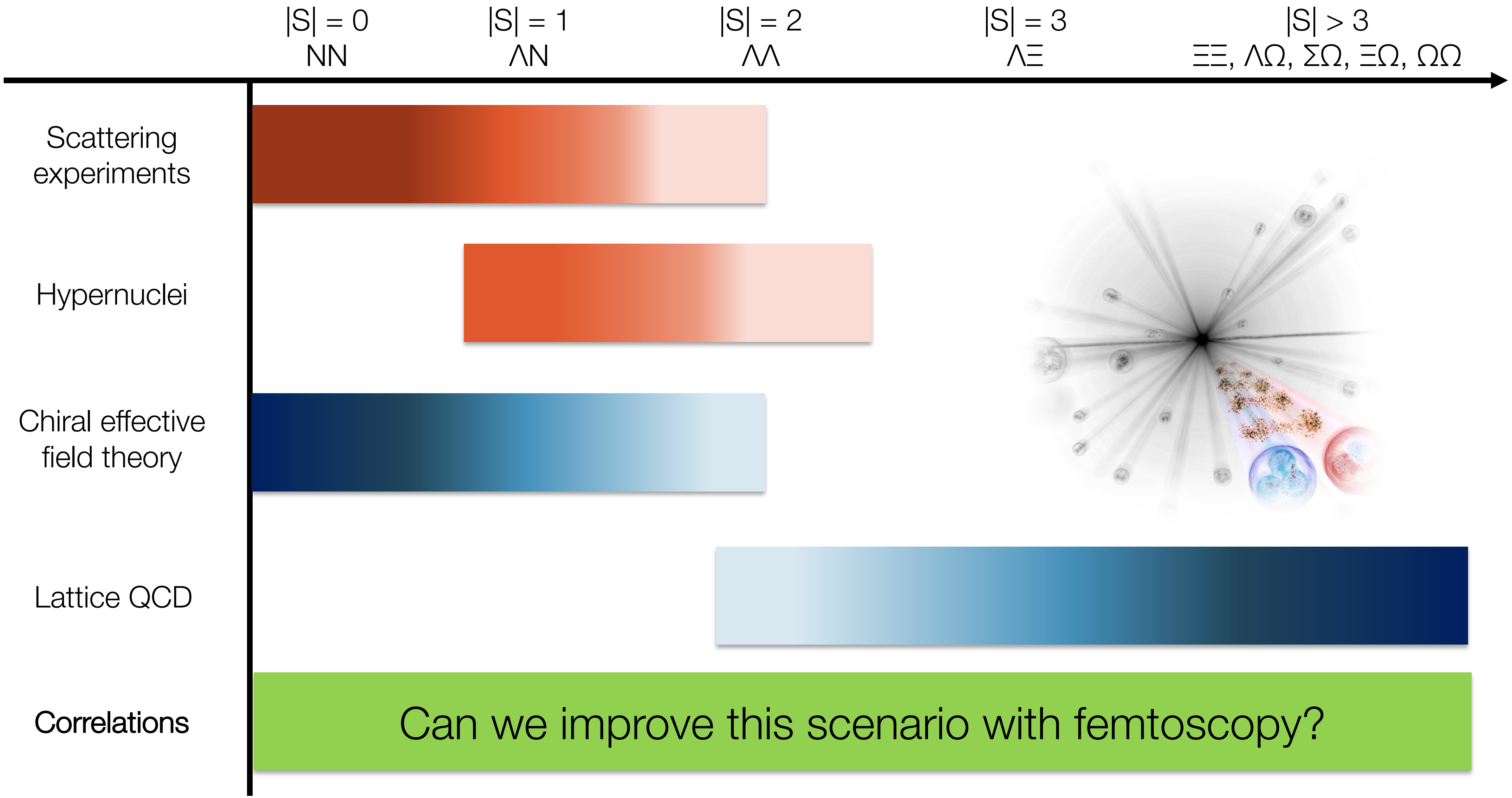
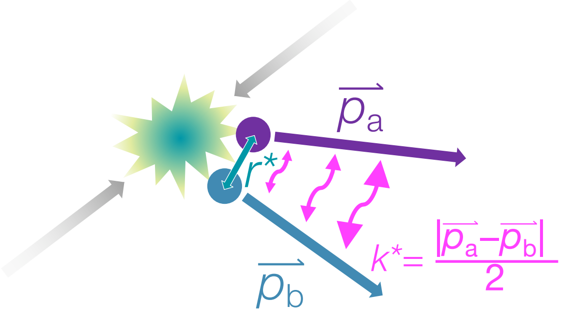
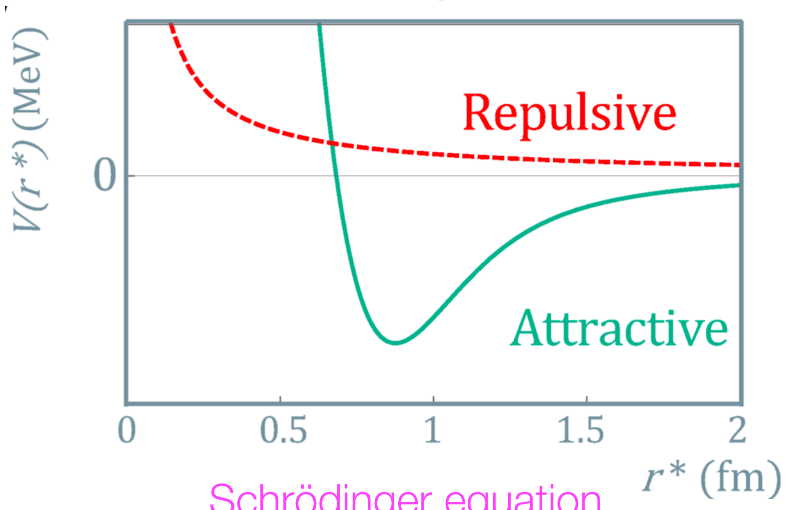


The femtoscopy technique at ALICE



Emission source S(r*)

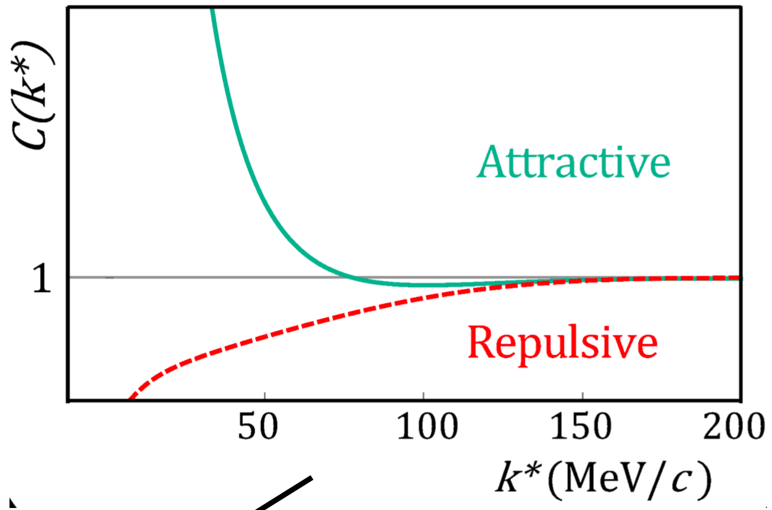
Interacting potential



Schrödinger equation

Two-particle wave function

Correlation function



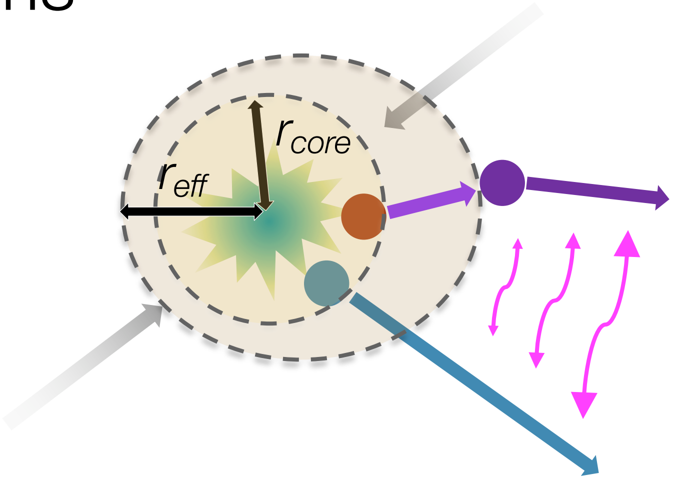
$$C(k^*) = \int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*) \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Measuring *C(k*)*, fixing the source **S(r*)**, study the interaction

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

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** (*)

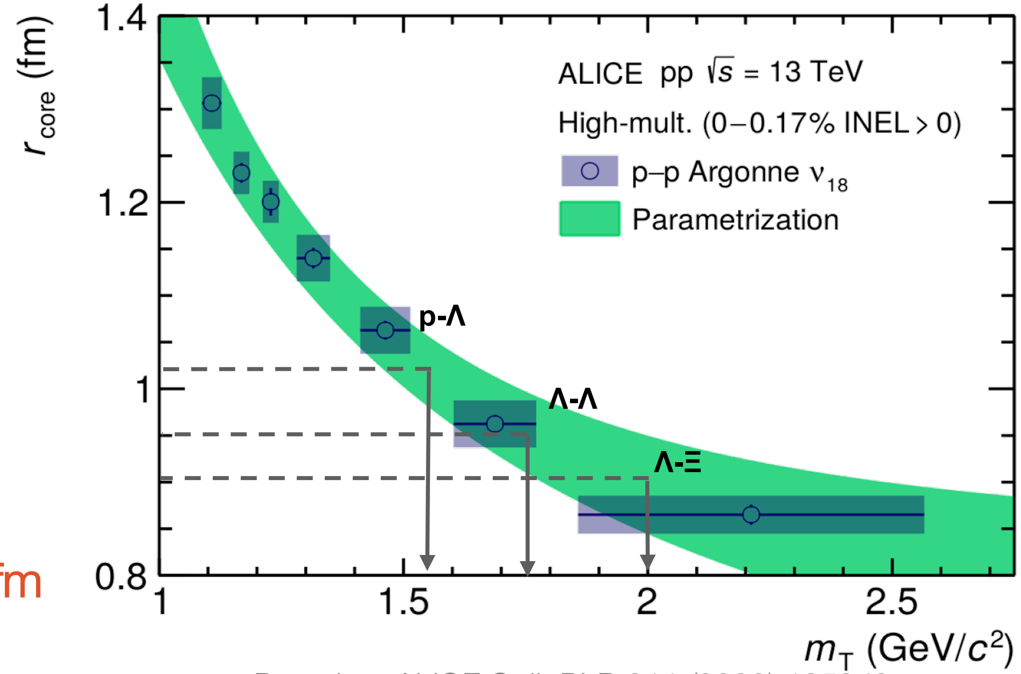


- Common universal core source for baryons

- Core constrained from p-p pairs
  - Fixing of the source at corresponding $\langle m_T \rangle$ ⟹ direct access to the interaction

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

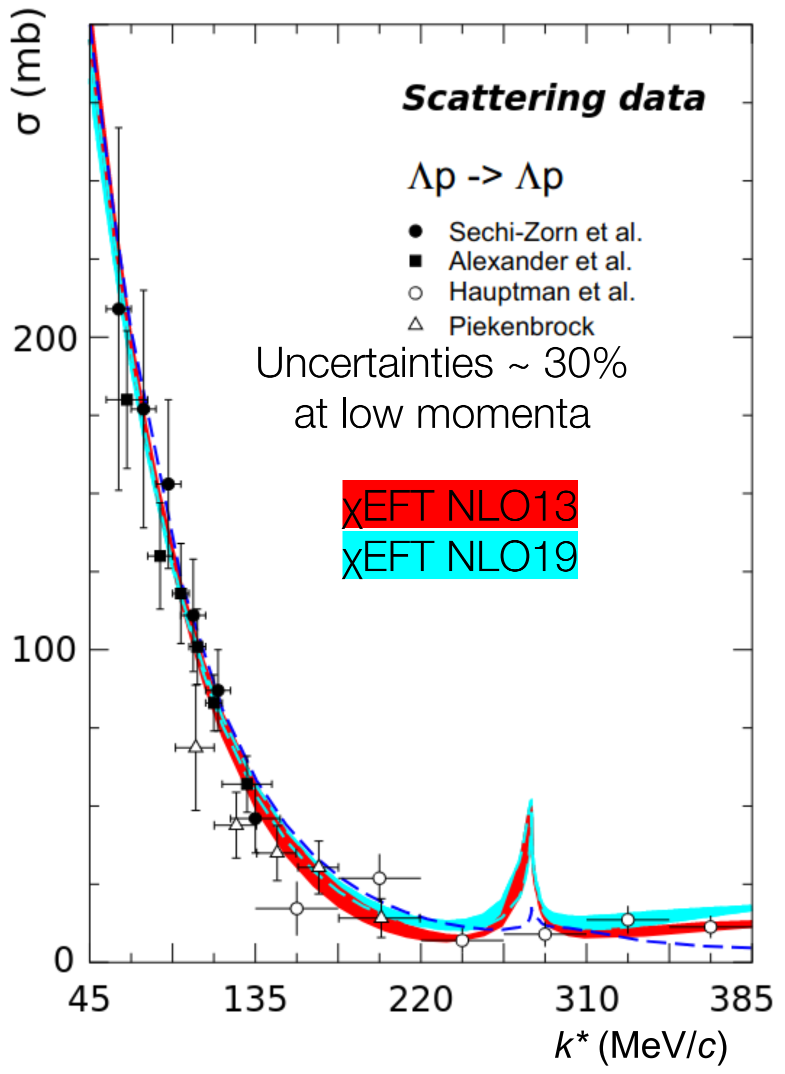
r_{eff} = 1 - 1.25 fm



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

|S| = 1: Λp interaction

- Low statistics and not available at low momenta



J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

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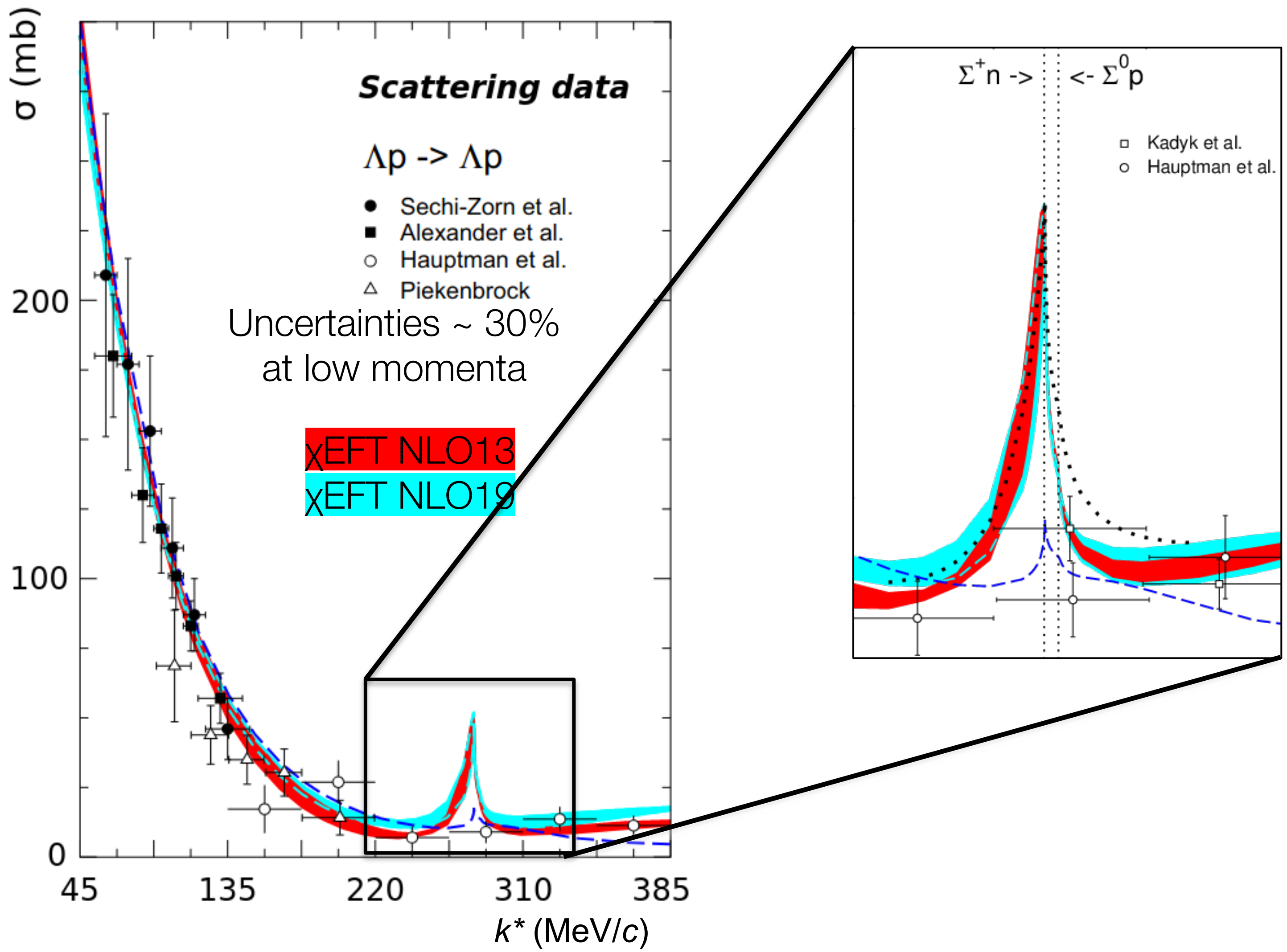
- ΛN-ΣN coupled system → 2-body coupling to ΣN is not (**yet**) measured



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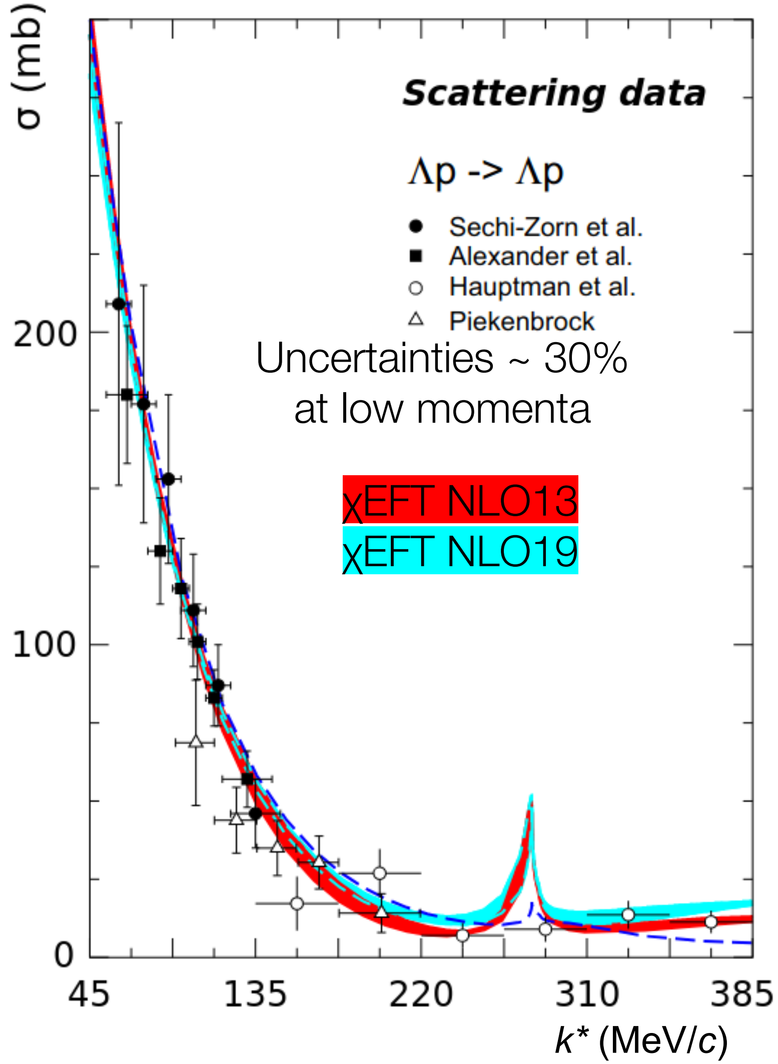
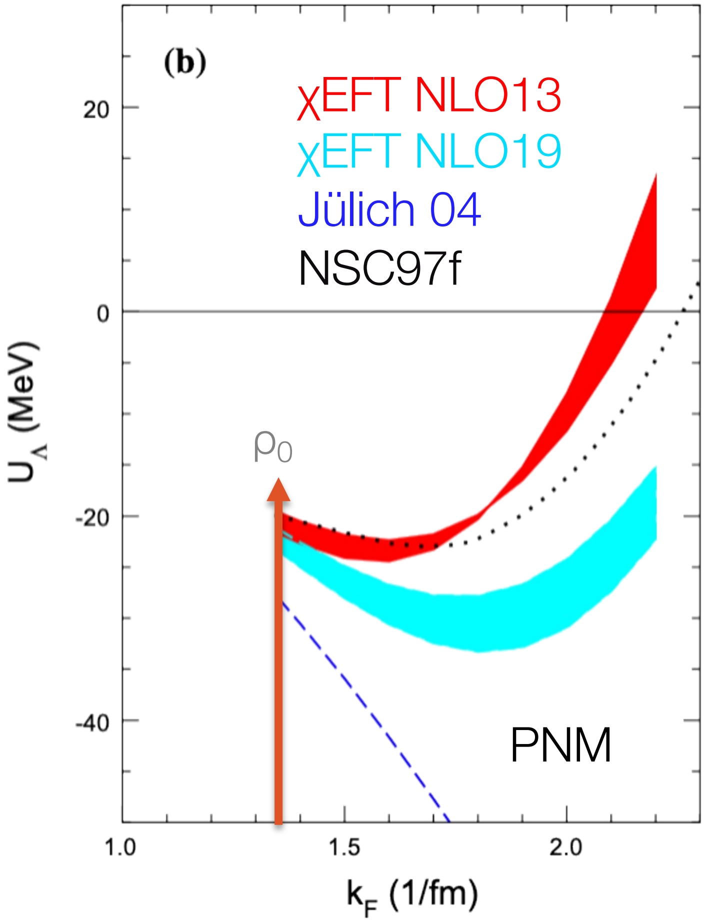
- ΣN coupling strength relevant for EoS
  - Strongly affects the behaviour of Λ a finite density
  - Implications for ΛNN interactions(*)

- NLO19 predicts weak coupling NΛ-NΣ
  - Attractive Λ interaction in neutron matter

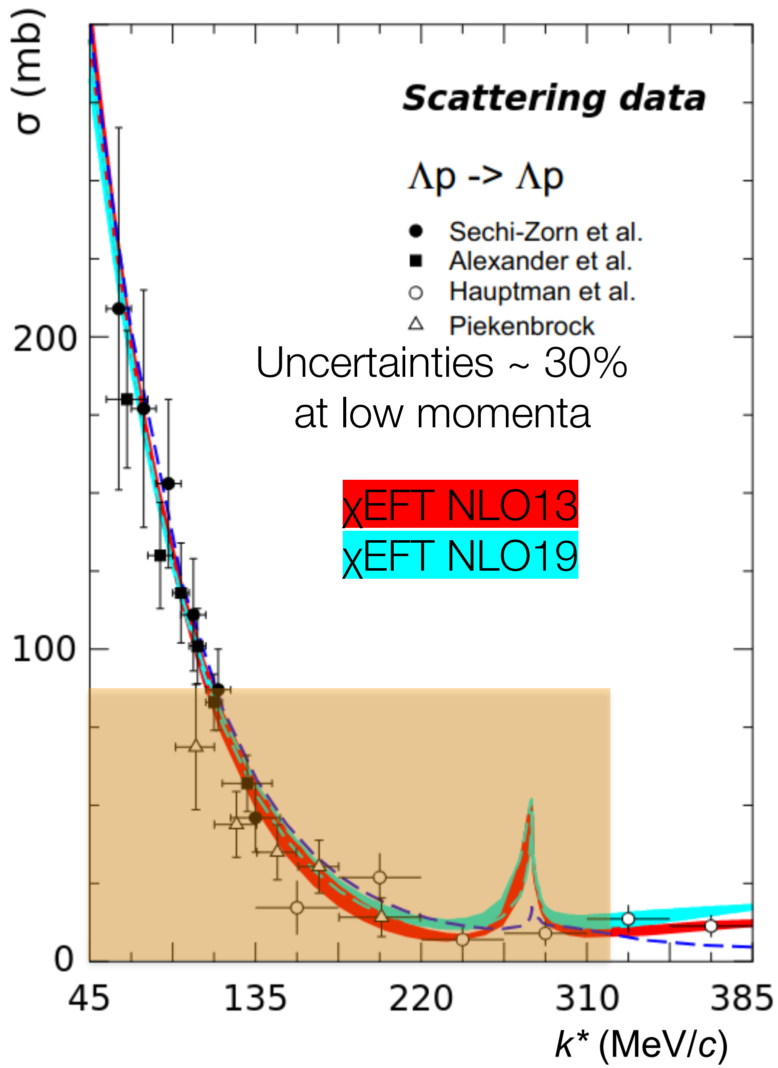


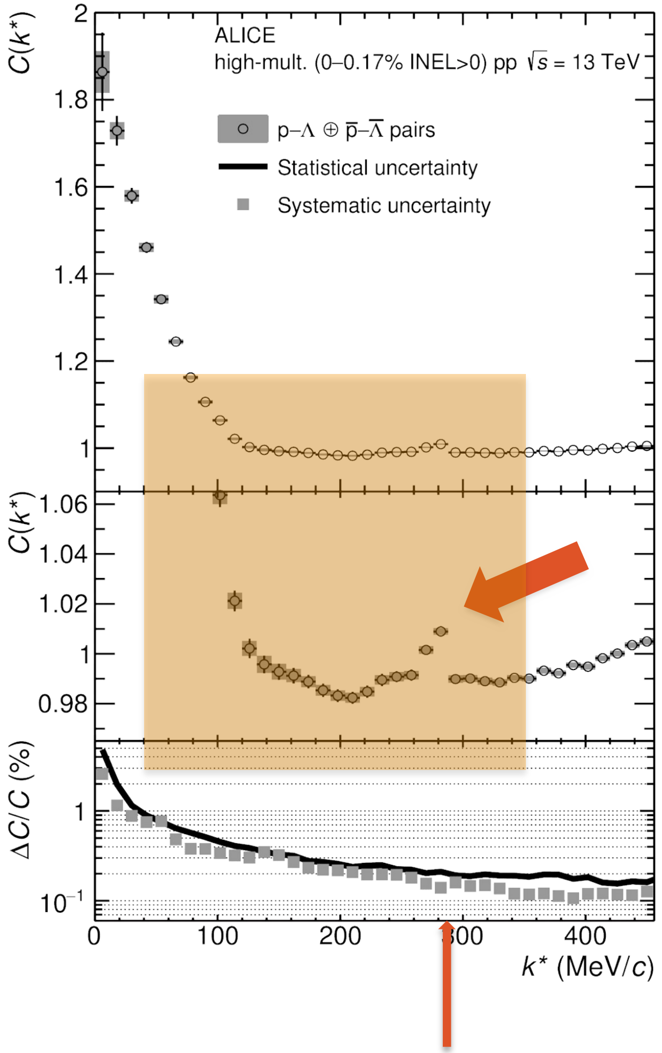


NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)
(*)D. Gerstung et al. Eur.Phys.J.A 56 (2020) 6, 175

|S| = 1: pΛ interaction in the femtoscopic era

- Factor 20-35 improved precision of the measurement (<1%)
- Most precise data available on the Λp interaction down to zero momenta
- First direct experimental evidence of ΣN cusp in 2-body channel





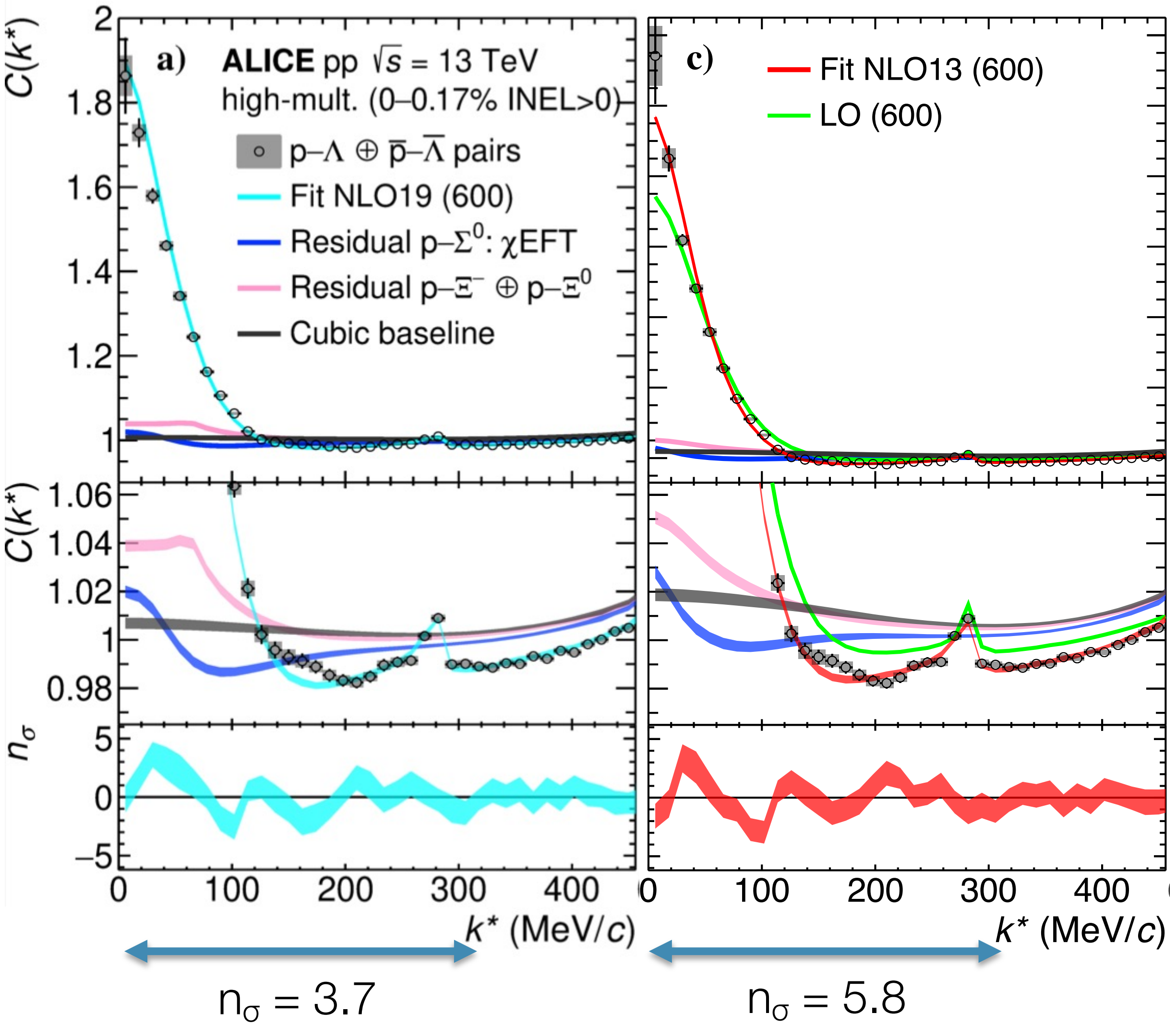
ALICE Coll. arXiv:2104.04427, submitted to PLB

|S| = 1: Λp interaction and access to the ΣN coupling

- Comparison with χEFT potentials
  - Sensitivity to different ΣN coupling strength
  - NLO19 favoured (n_σ = 3.9)→ attractive interaction of Λ at large densities
  - Larger ΛNN repulsion required to stiffen the Equation of State at large densities(*)

  Three-body correlations (R. Del Grande)
  Parallel Session T08 06/04 15:00

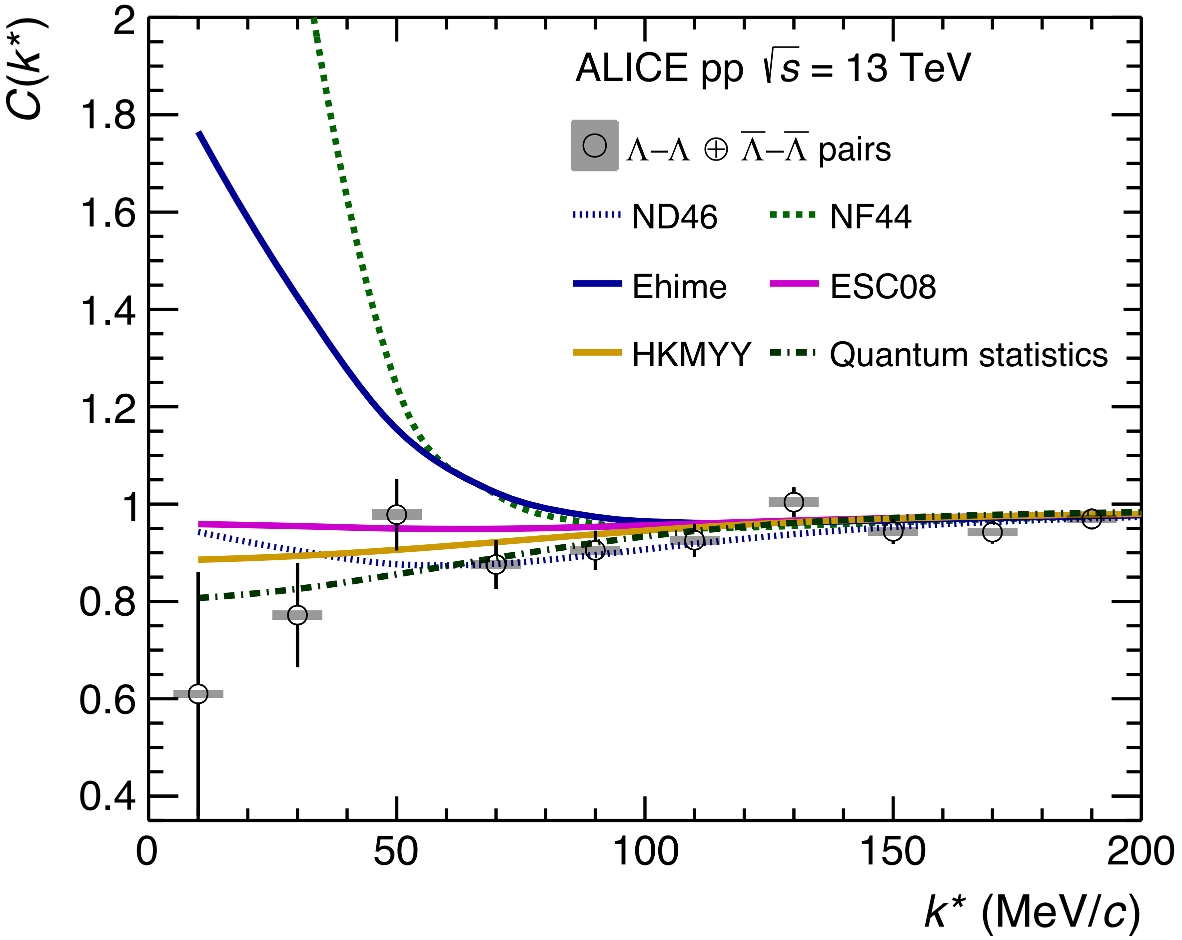
- New constraints to improve current theory



ALICE Coll. arXiv:2104.04427, submitted to PLB
(*)D. Gerstung et al. ", EPJ. A 56 (2020) 175

|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



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

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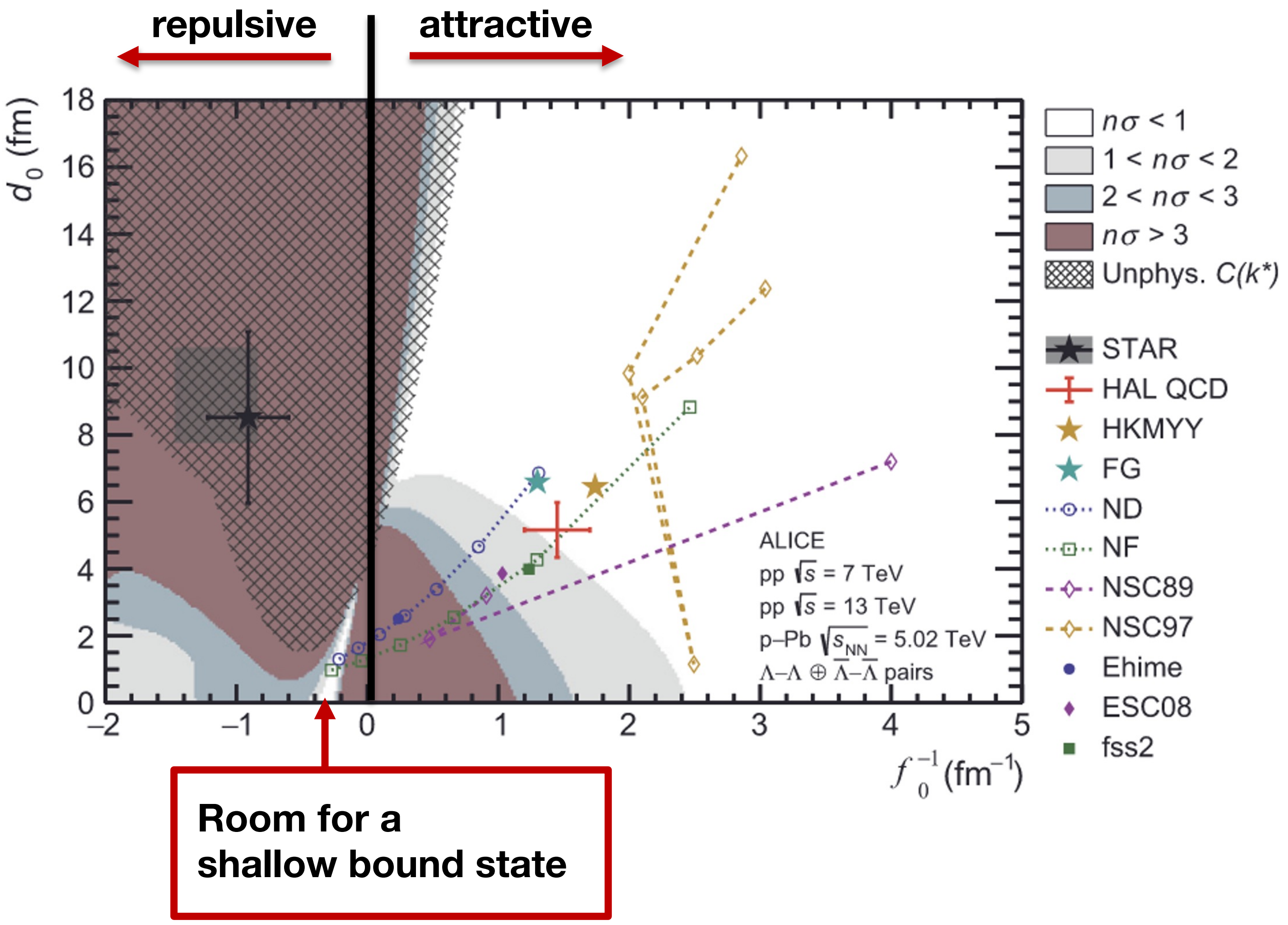
- ΛΛ correlation measured in pp MB 7, 13 TeV and p-Pb 5.02 TeV
- Scan in scattering parameter space (f_0^{-1}, d_0) and express agreement data/model in number of σ deviations
  - Agreement with hypernuclei data and lattice predictions
- Most precise upper limit on the binding energy of the H-dibaryon

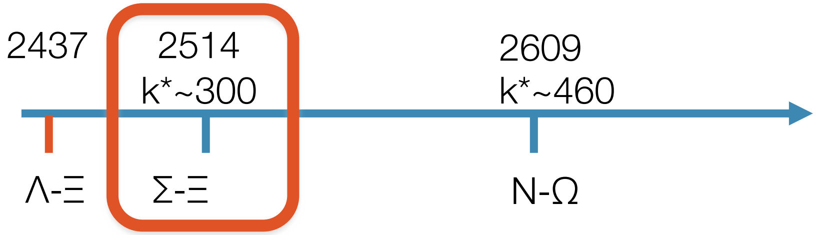
$$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat})^{+1.8}_{-1.0}(\text{syst})\ \text{MeV}$$



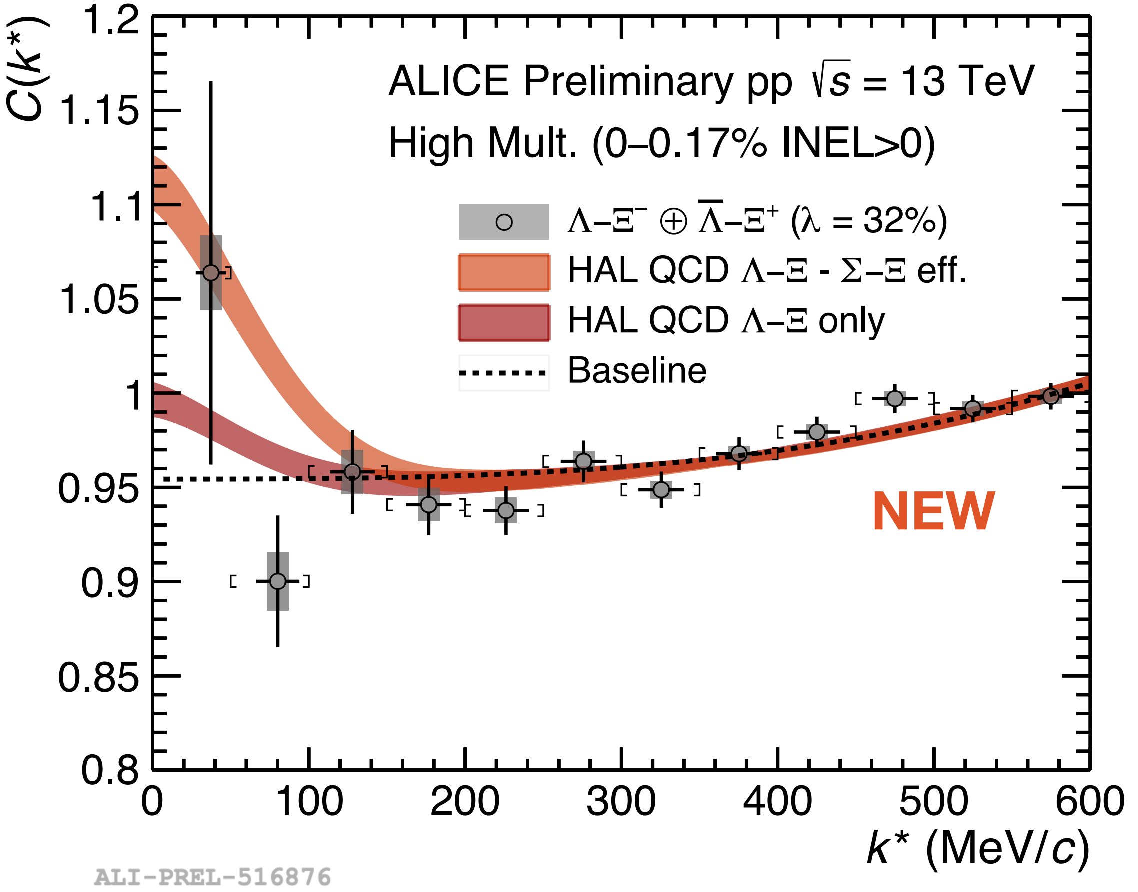
ALICE Coll. Phys.Lett.B 797 (2019) 134822

|S| = 3 : first measurements of the ΛΞ interaction

- ΛΞ⁻ correlation in high-multiplicity pp collisions 13 TeV
- Presence of inelastic channels:



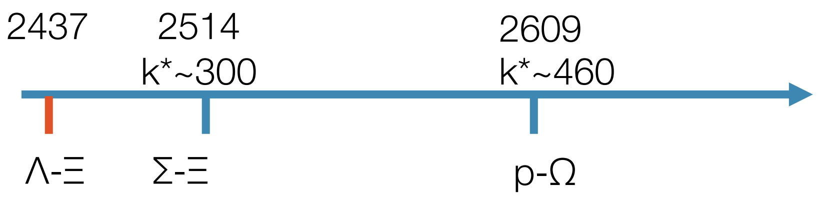
- Perfect test for lattice QCD potentials(*):
  - Sizeable ΛΞ-ΣΞ coupling from HAL QCD
    → data favour results with only ΛΞ elastic (nσ = 1.64)
    → data not yet sensitive to the coupling



ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489
(*) HAL QCD Coll. EPJ Web of Conferences 175, 05013 (2018)

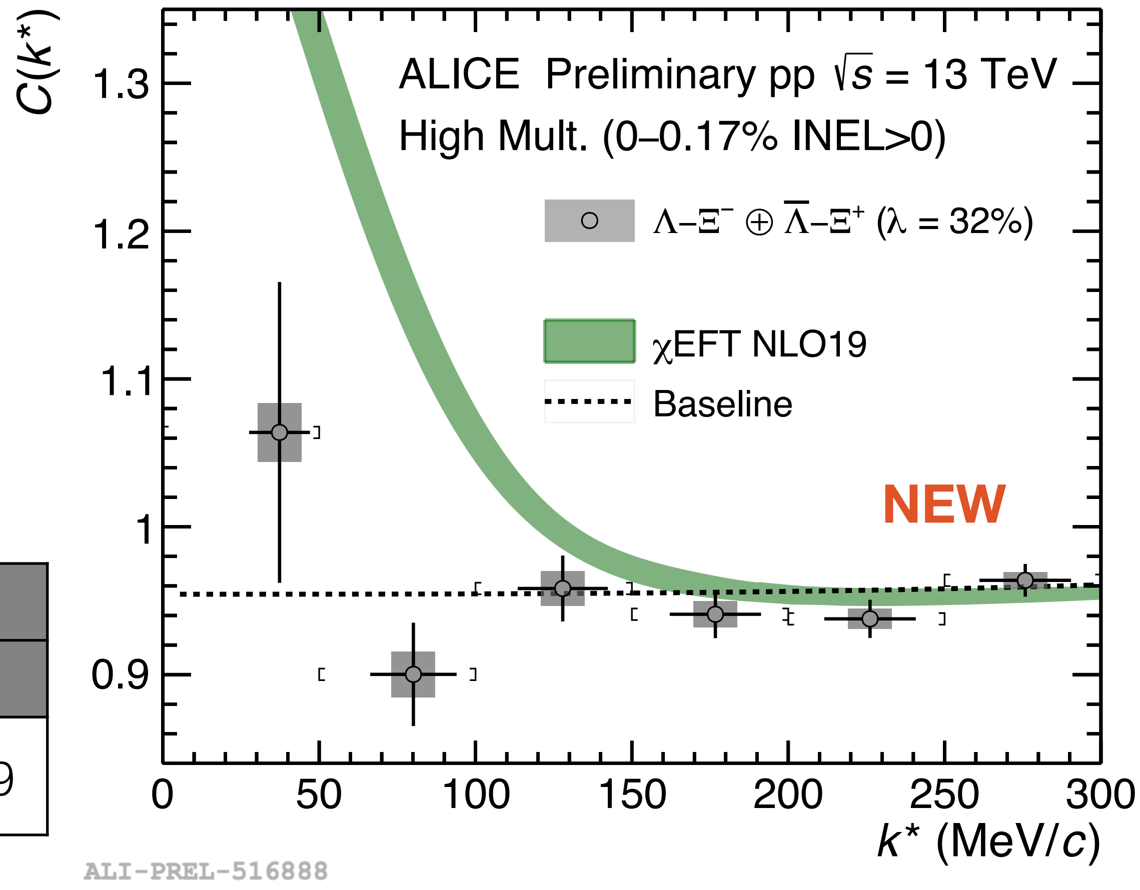
|S| = 3 : constraining chiral effective field theories

- ΛΞ⁻ correlation in high-multiplicity pp collisions 13 TeV



- Scattering parameters from state-of-the-art χEFT(*):
  – Potentials with large interaction overestimate the data

Model	Cut-off	Singlet (fm)		Triplet (fm)	
		f_0	d_0	f_0	d_0
NLO19	500	0.99	5.77	1.66	1.49



ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489
(*)J. Haidenbauer, U.G Meißner arXiV:2201.08238v1 (2022)

|S| = 3 : constraining chiral effective field theories

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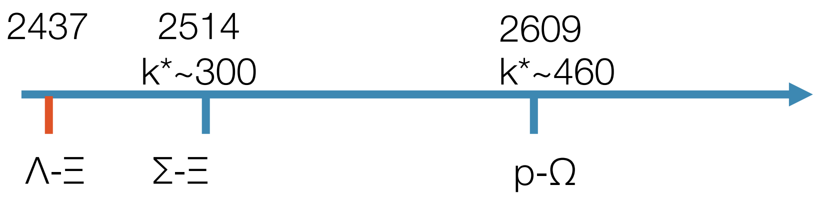
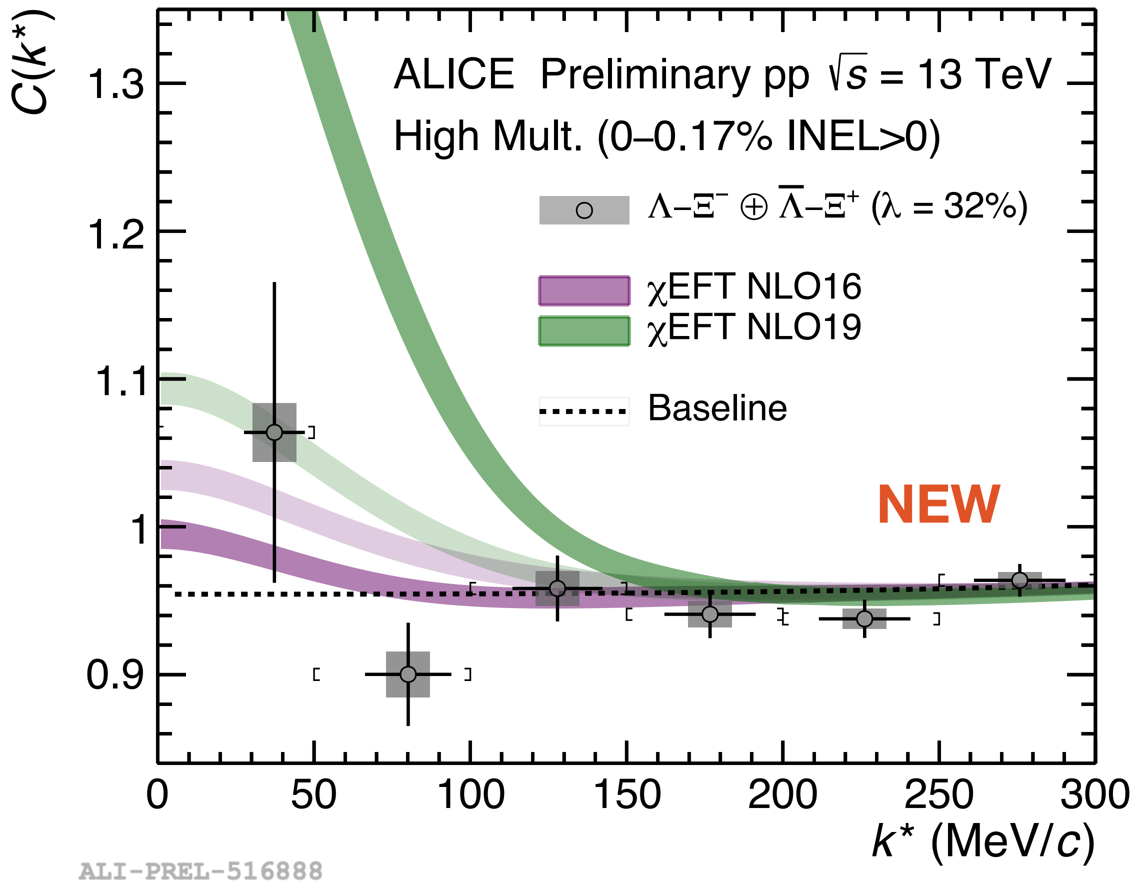


- Scattering parameters from state-of-the-art χEFT(*):
  - Potentials with large interaction overestimate the data
  - Data favour potentials with shallow interaction
- First experimental constraint in |S|=3 sector for χEFT



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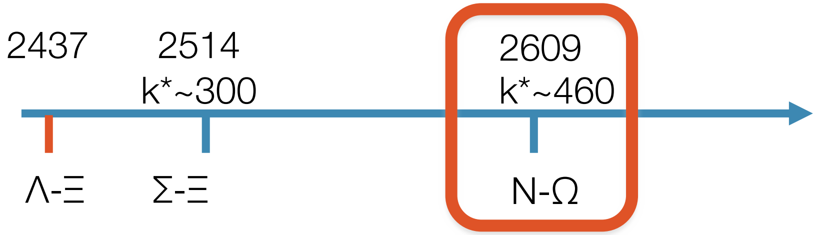
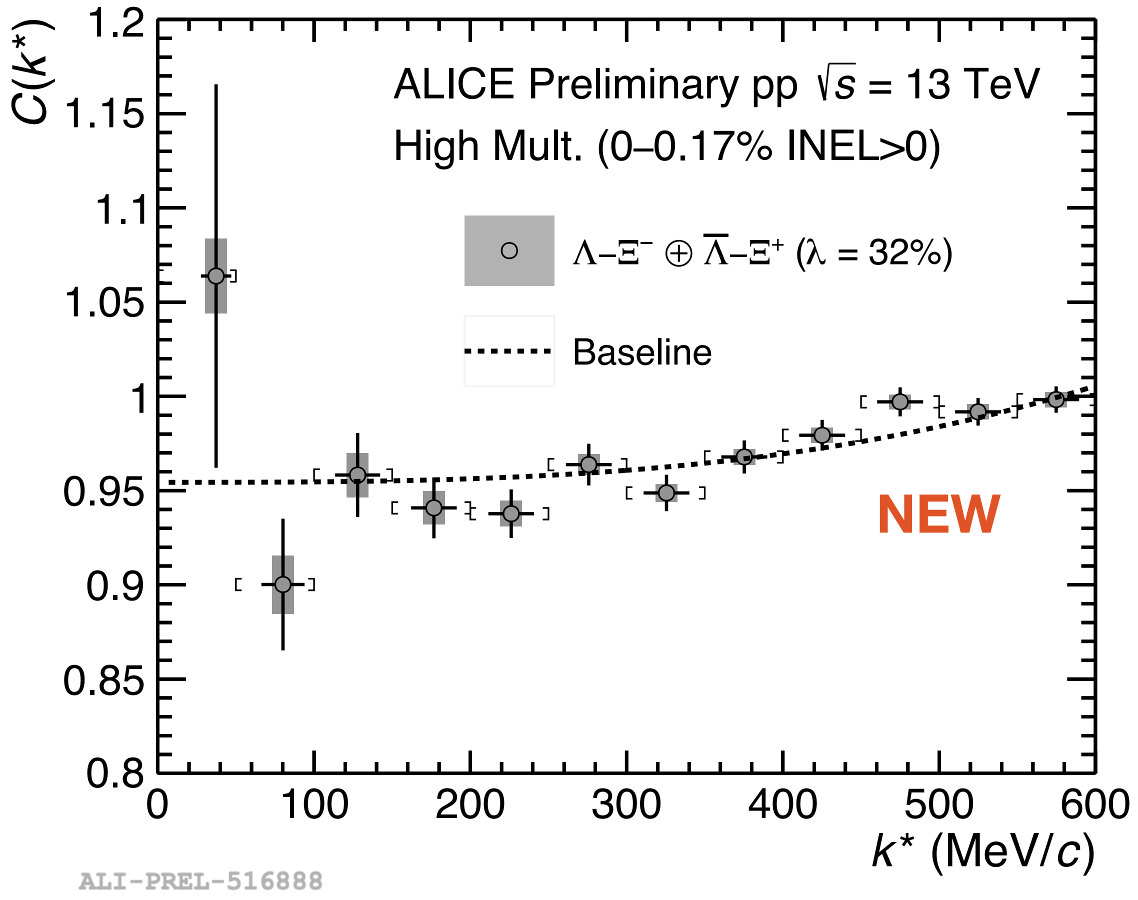
|S| = 3 : ΛΞ interaction and its role in pΩ interaction

- $\Lambda\Xi^-$ correlation in high-multiplicity pp collisions 13 TeV
- Presence of inelastic channels:



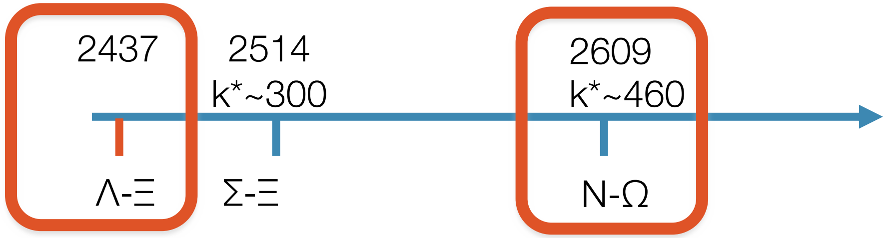
- No p-Ω cusp structure visible with current statistics → indications of a negligible coupling to NΩ



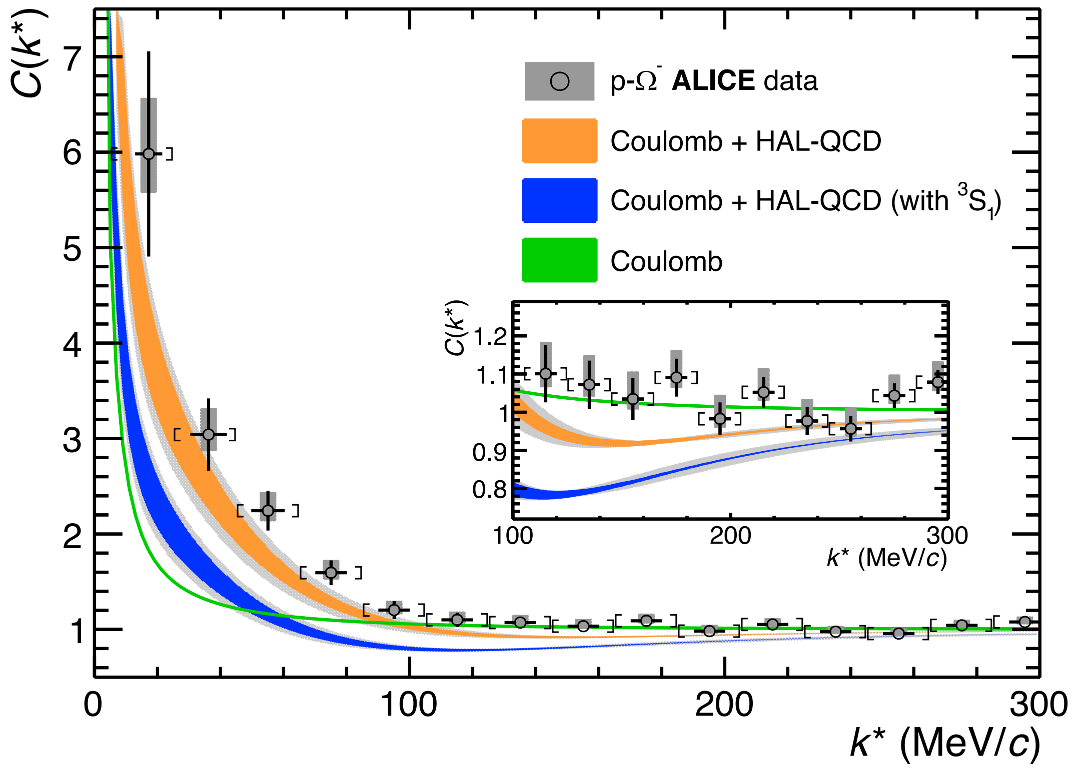
ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489

|S| = 3 : ΛΞ interaction and its role in pΩ interaction

- Attractive pΩ interaction → di-baryon with E_b~2.5 MeV
- Presence of inelastic channels:



- First measurements of pΩ in pp HM 13 TeV by ALICE
  - Strong attractive interaction
- Comparison with lattice predictions in two cases:
  - No / dominant inelastic contributions
- Data in agreement with
  - Negligible inelastic contributions → support the scenario obtained in ΛΞ measured correlations
  - No evidence of bound state



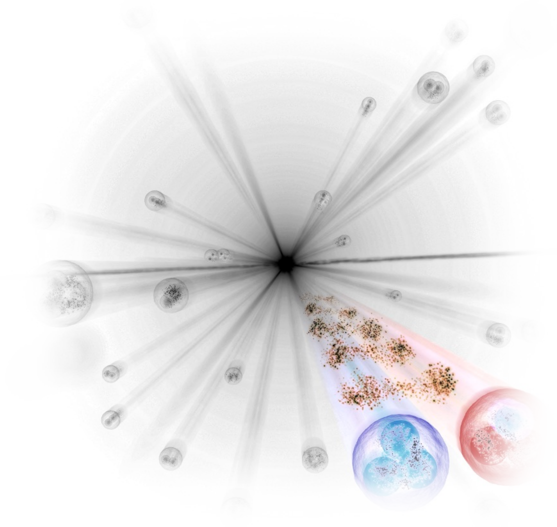
ALICE Coll. Nature 588 (2020) 232-238

Summary and Outlook

- Femtoscopy in small colliding systems → unique way to access multi-strange QCD sector

- Precision studies of |S| = 1,2,3 sector with Λ-hadrons correlations in ALICE
  - Most precise data on the Λp interaction → physics of neutron stars
  - Most precise upper limit on H-dibaryon energy
  - First measurements of $\Lambda\Xi^-$ interaction → constraints for lattice QCD calculations and chiral potentials

- More precision studies within reach with large statistics in Run 3 & 4!



For additional interesting femtoscopic results at ALICE:

Three-body interactions, R. Del Grande Parallel Session T08 06/04 15:00
Interaction with charmed mesons, F. Grosa Parallel Session T08 06/04 15:40

Additional slides

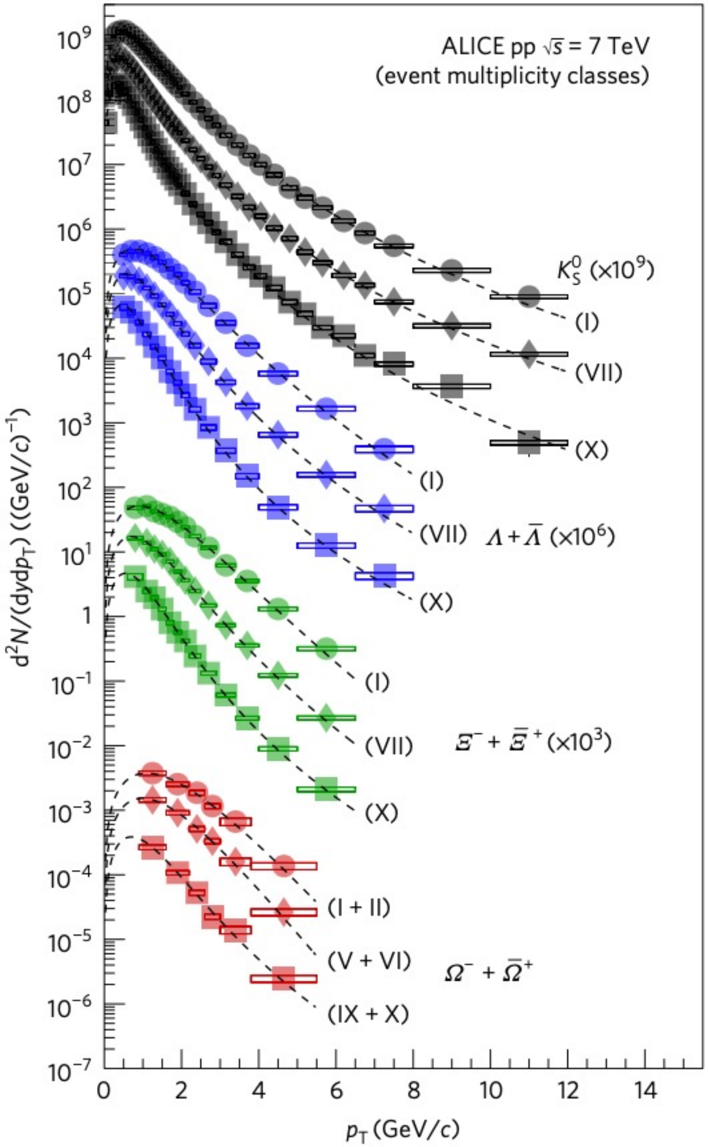
High multiplicity pp collisions

- pp collisions at ALICE are a perfect factory to produce a large amount of multi-strange hyperons
  ALICE Coll. Nature Phys. 13 (2017) 535-539
- In the paper:
  - High multiplicity events pp 13 TeV → enhanced yields of multi-strange hadrons
- High capability for particle identification at transverse momenta below 1 GeV/c
  - hyperons detected through weak decays

$$\Xi^- \rightarrow \Lambda\pi^-$$

$$\Omega^- \rightarrow \Lambda K^-$$

  - low contamination and high purity samples
-



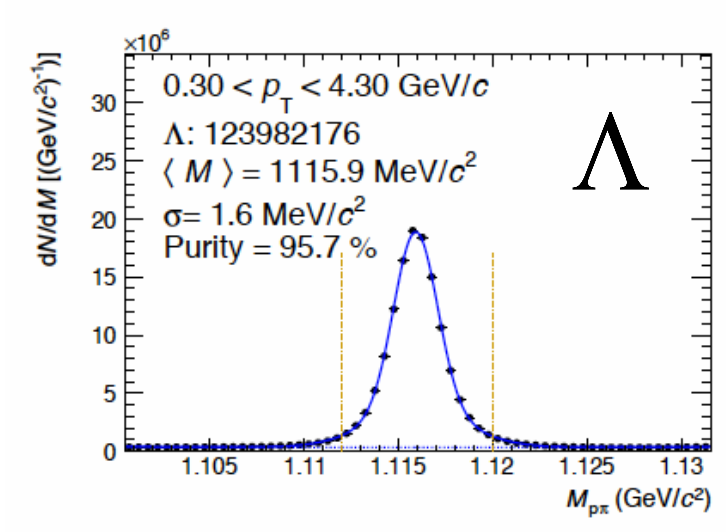
Hyperons @ ALICE in pp Collisions

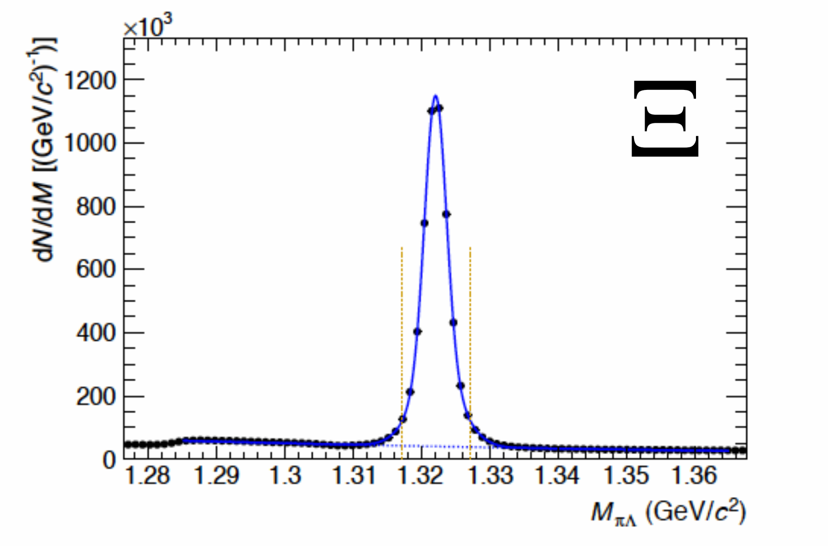
$\Lambda \to p\pi^-$

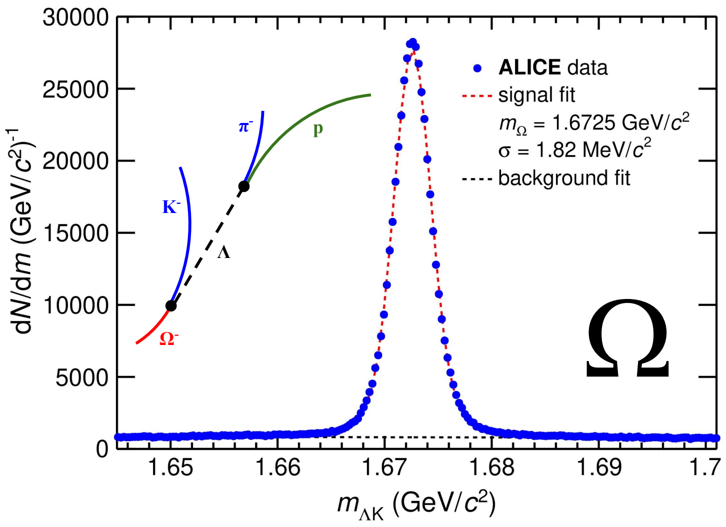
$\Xi^- \to \Lambda\pi^-$

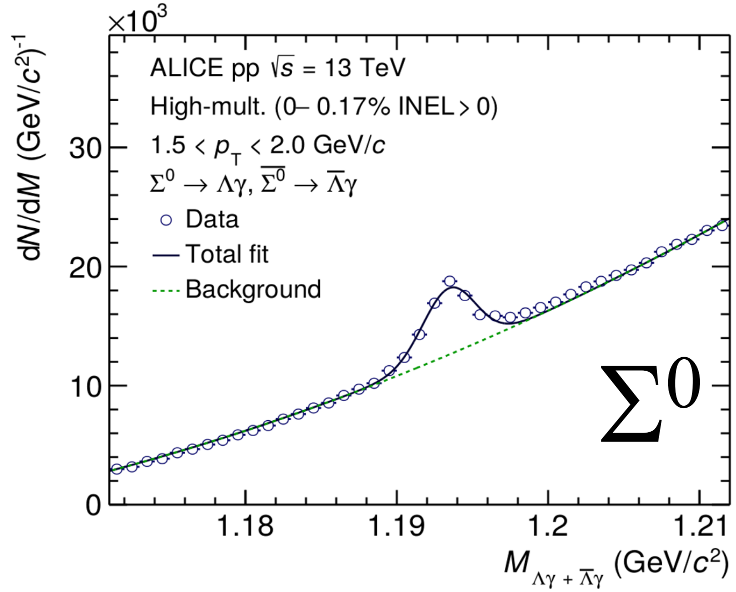
$\Omega^- \to \Lambda K^-$

$\Sigma^0 \to \Lambda\gamma$



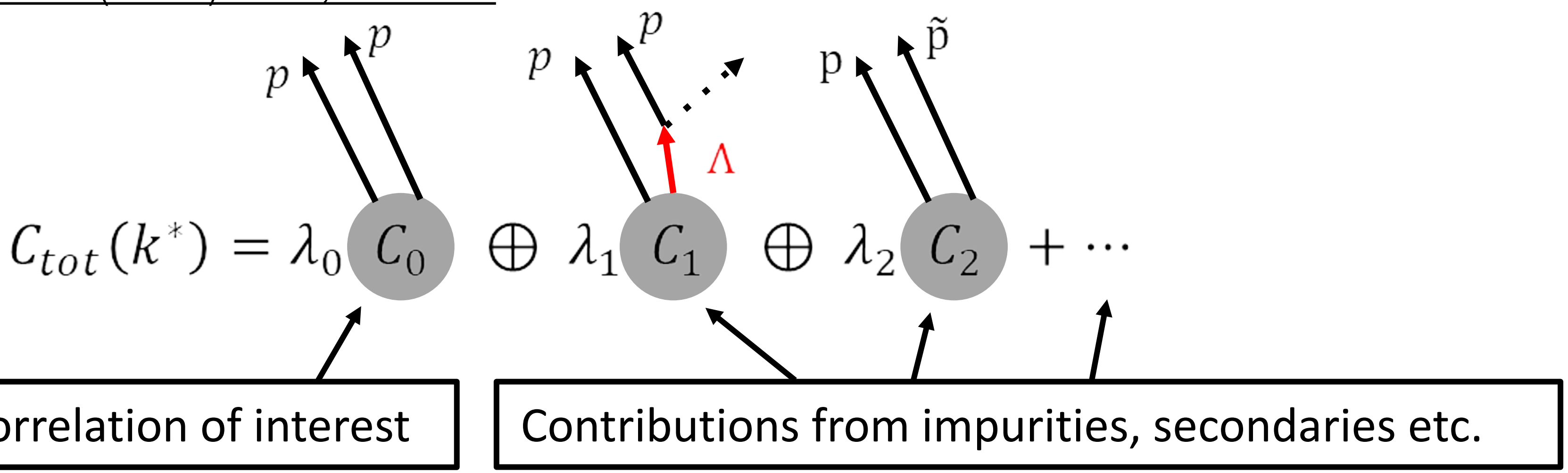






Femtoscopy - Decomposition of C(k*)

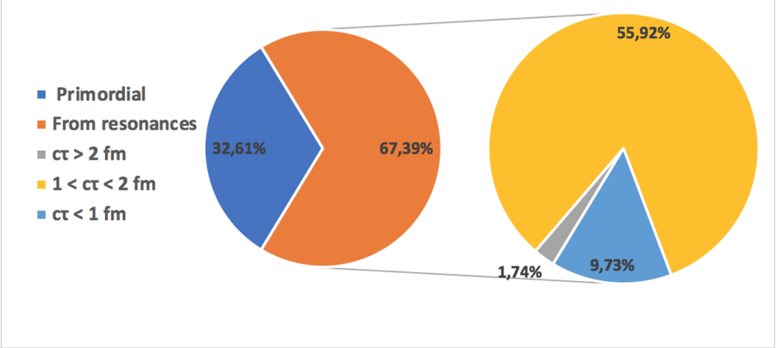
- Determine the amount of impurities and secondaries based on a data-driven MC study as done in Phys.Rev. C99 (2019) no.2, 024001



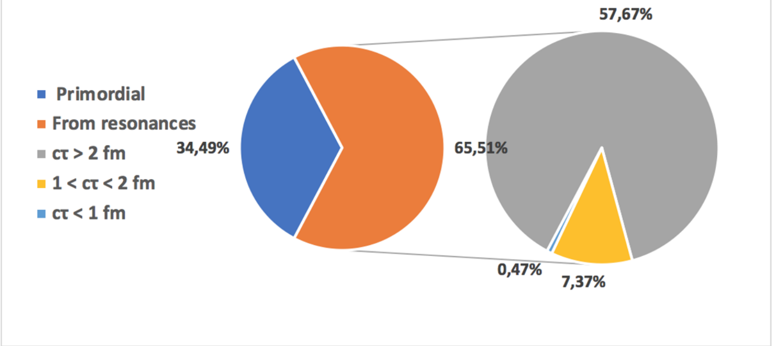
- Purity ($\mathcal{P}$) from fits to the invariant mass distribution or MC data
- Feed-down fractions (f) from MC template fits
- $\lambda_i = \mathcal{P}_{i_1} f_{i_1} \mathcal{P}_{i_2} f_{i_2}$, where $i_{1,2}$ denote the two particles of the i-th contribution

The source function - Effect of short-lived resonances

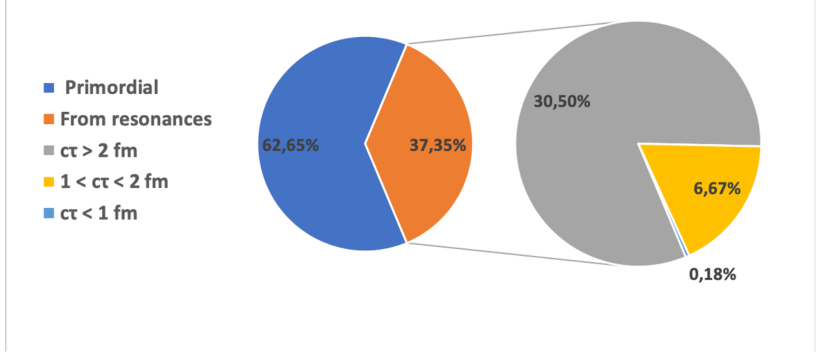
Protons



Λs



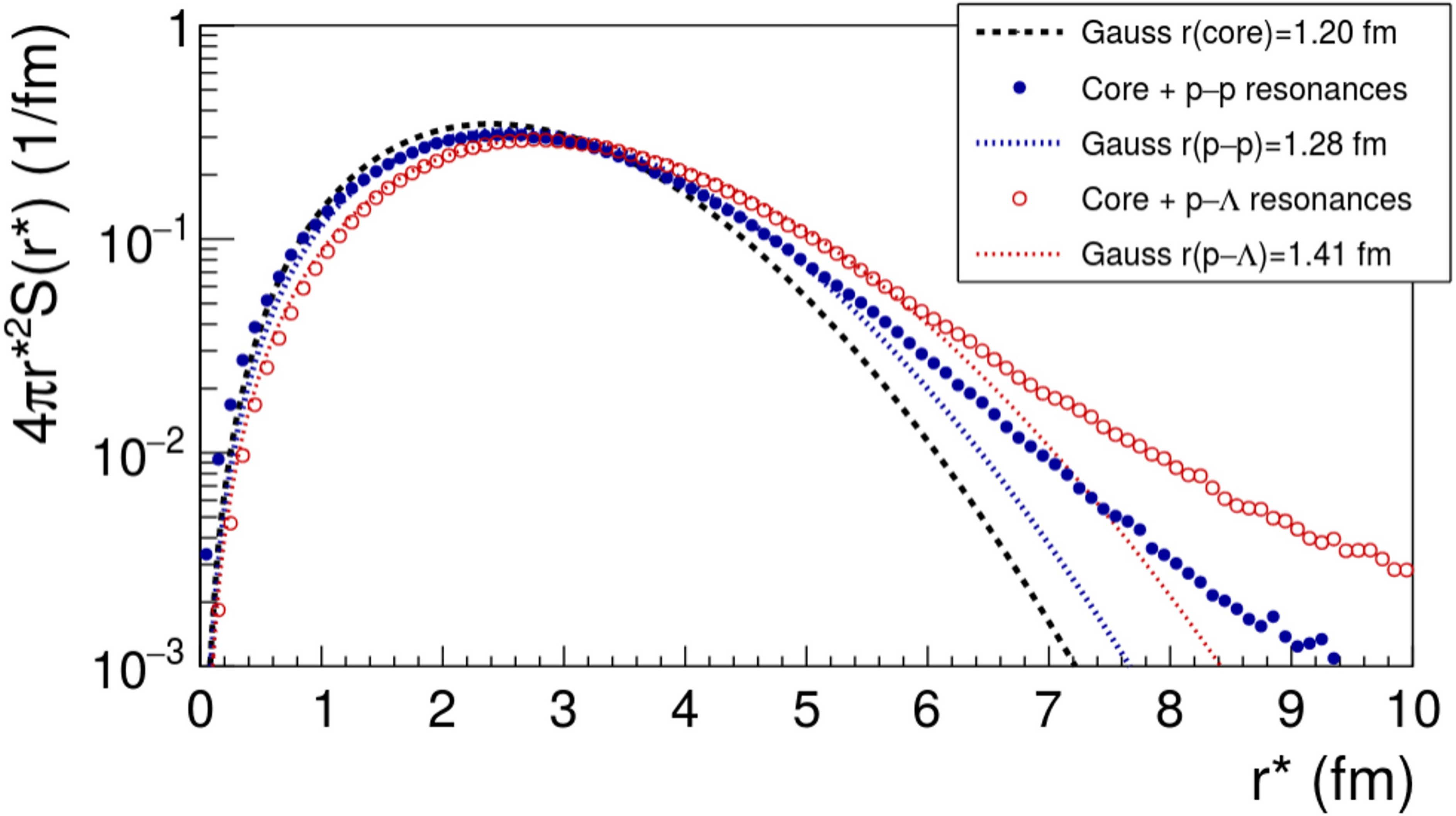
Σ^0s



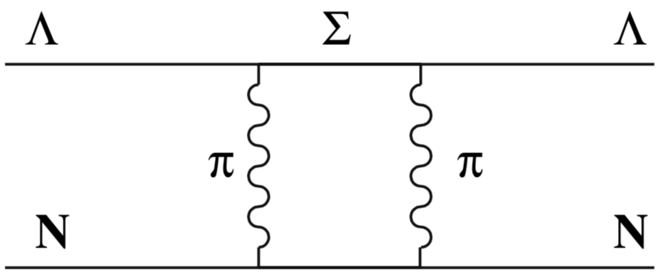
- For Ξ^- and Ω^- no contributions!
- Average mass and average cτ determined by the weighted average values of all resonances

Particle	M_{res} [MeV]	τ_{res} [fm]
p	1361.52	1.65
Λ	1462.93	4.69
Σ^0	1581.73	4.28

The common source - The source pdf

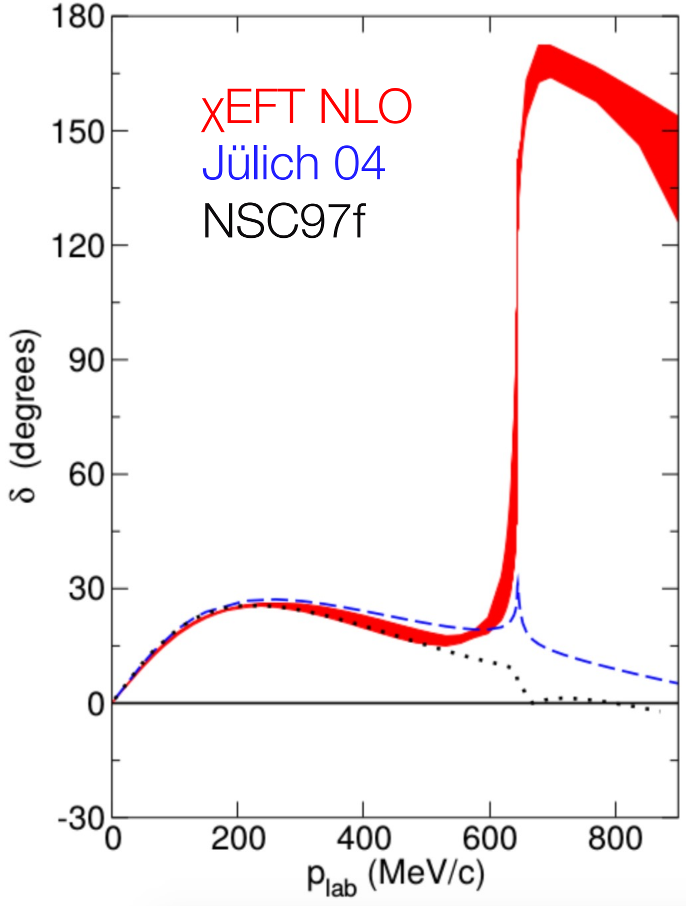


Influence of the ΛN – ΣN coupled channel

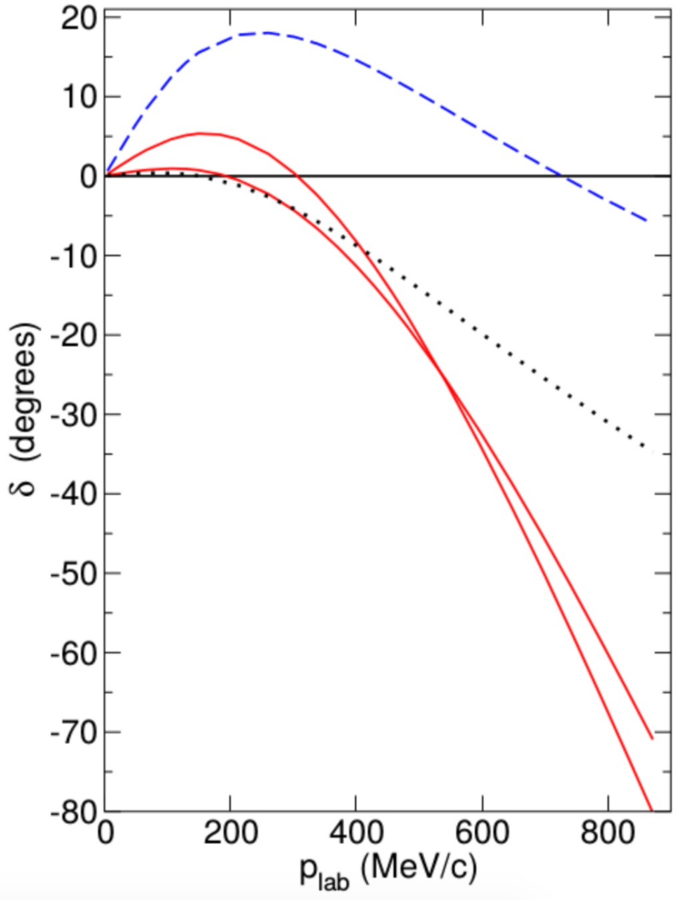


- ΣN-ΛN acts as an effective attraction
- Repulsion for Λ-p when the Σ-N – Λ-N coupled channel is neglected
  - strong coupling ⟹ dispersion repulsive effects ⟹ Shift of hyperon appearance towards higher densities
  - weak coupling ⟹ more attractive $U_{\Lambda}(\rho_0,0)$

Λ-p $^3S_1$
with the Σ-N – Λ-N coupling

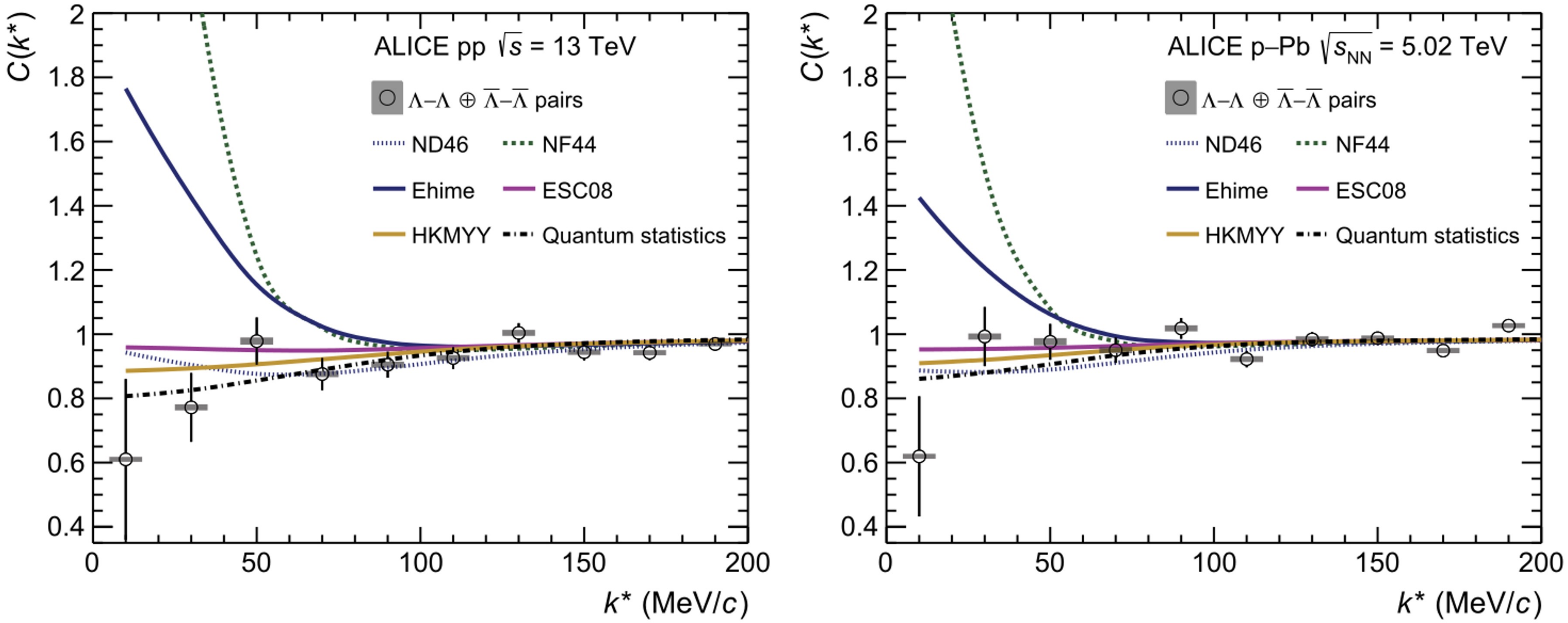


Λ-p $^3S_1$
w/o the Σ-N – Λ-N coupling



J. Haidenbauer *et al.*, Eur. Phys. A (2017) 53, 121.

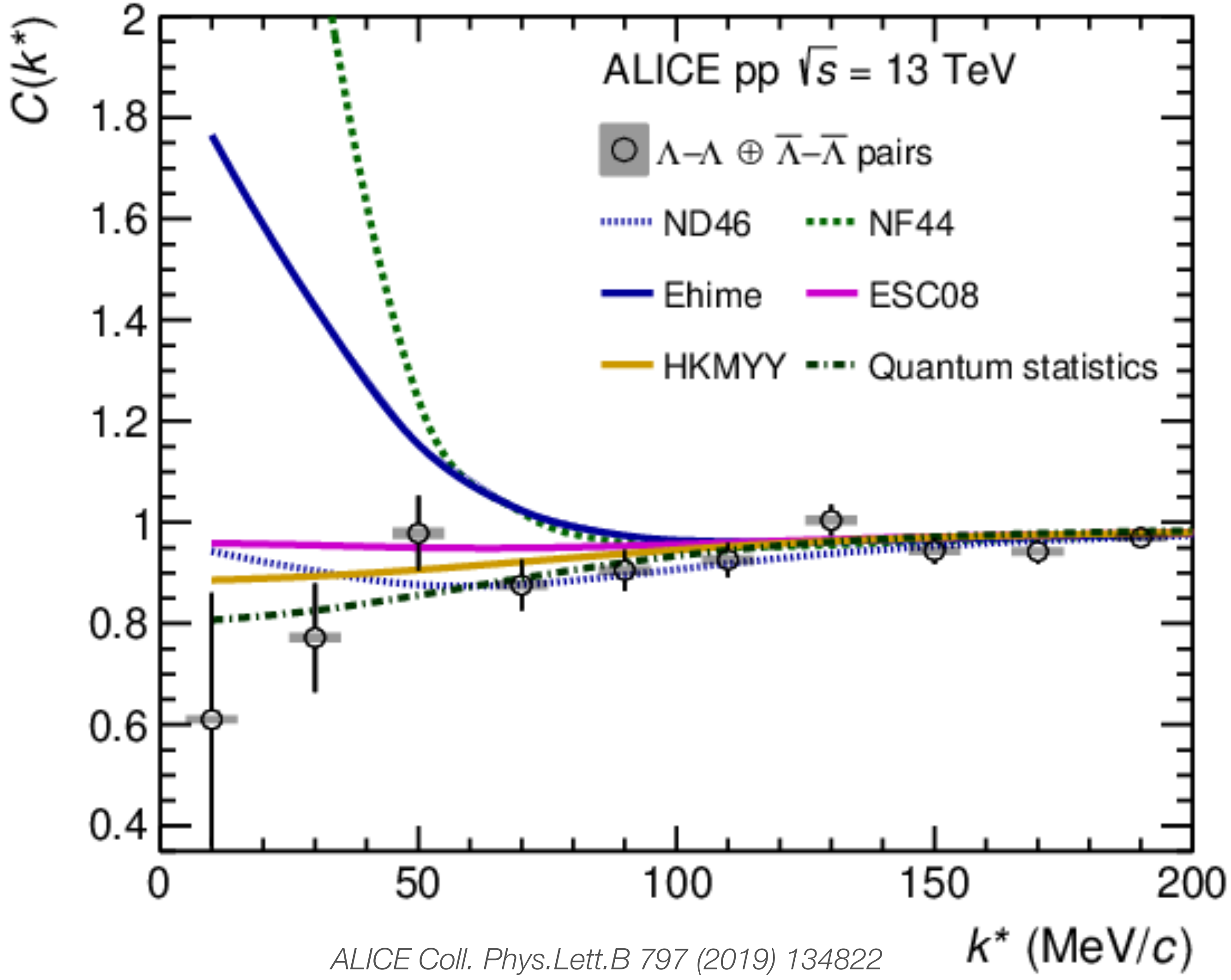
Λ-Λ correlations



Phys.Lett.B 805 (2020) 135419

|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



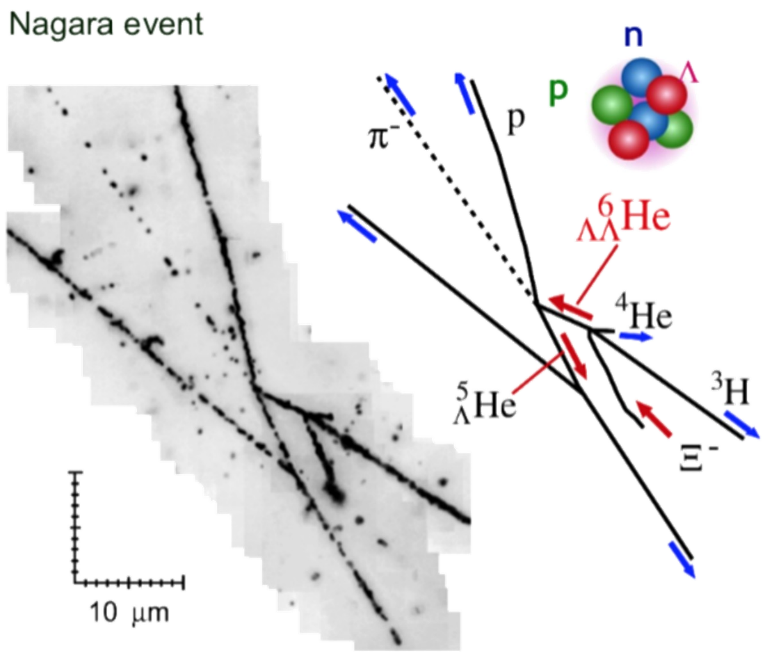
ALICE Coll. Phys.Lett.B 797 (2019) 134822

|S|=2 : ΛΛ interaction and the H-dibaryon

- H-dibaryon: hypothetical bound state of *uuddss*
  - No final experimental evidences so far
  - Recent lattice QCD calculations at physical point with ΛΛ-NΞ coupled-channel(*) → no bound state around ΛΛ or NΞ threshold (**)

- Double-Λ hypernuclei measurements
  - weak attractive interaction
  - H-dibaryon binding energy $B_{\Lambda\Lambda}$ = 6.91 ± 0.16 MeV

Can we improve the knowledge on the ΛΛ interaction and the fate of the H dibaryon?



$^{6}_{\Lambda\Lambda}$He -> $^{5}_{\Lambda}$He + p + π−

$\Delta B_{\Lambda\Lambda}$ = 0.67 ± 0.17 MeV

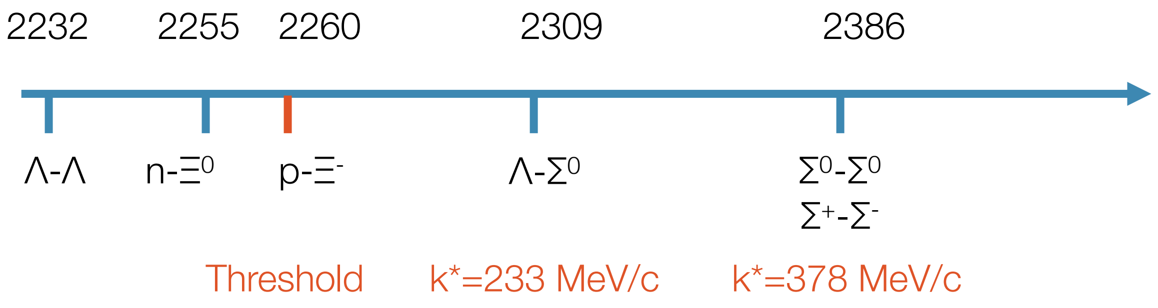
H. Takahashi et al., PRL 87 (2001) 212502

(*) HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737
A. Ohnishi et al., Few Body Syst. 62 (2021) 3, 42
Y. Kamiya et al., PRC 105 (2022)

(**) ALICE Coll. Phys. Rev. Lett 123, (2019) 112002
ALICE Coll. Nature 588, 232–238 (2020)

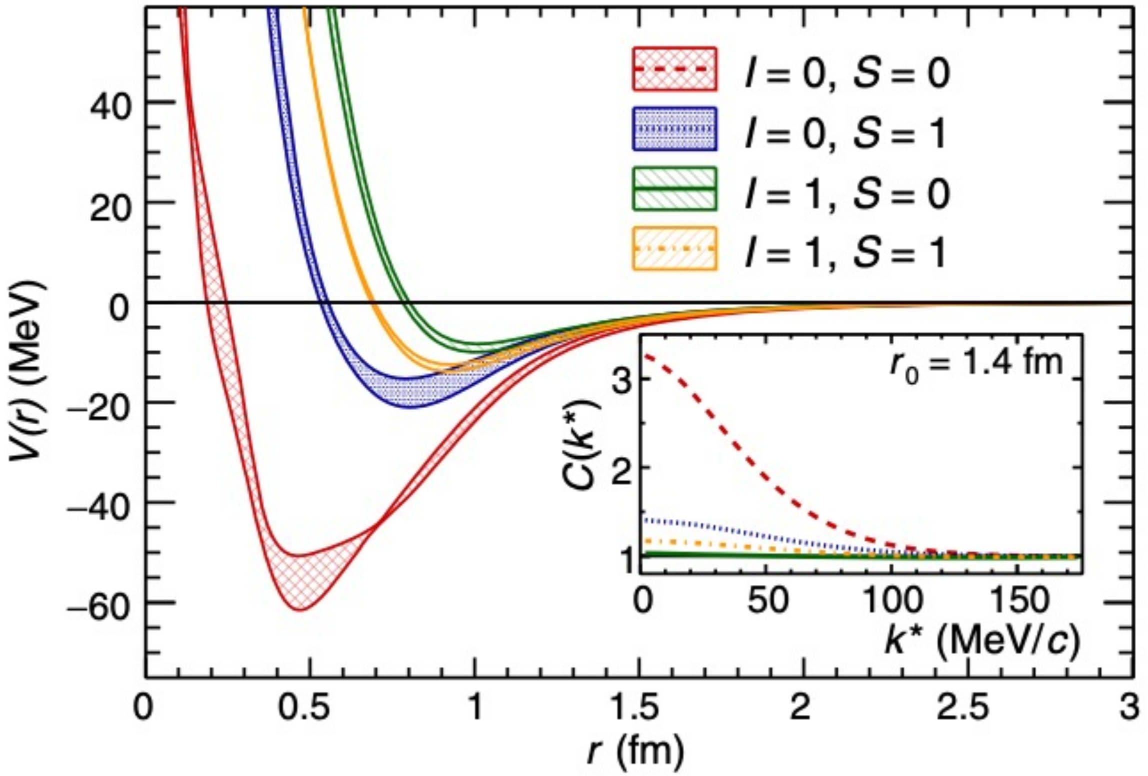
Lattice QCD potentials of the |S| = 2 sector: p-Ξ^- interaction

- 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

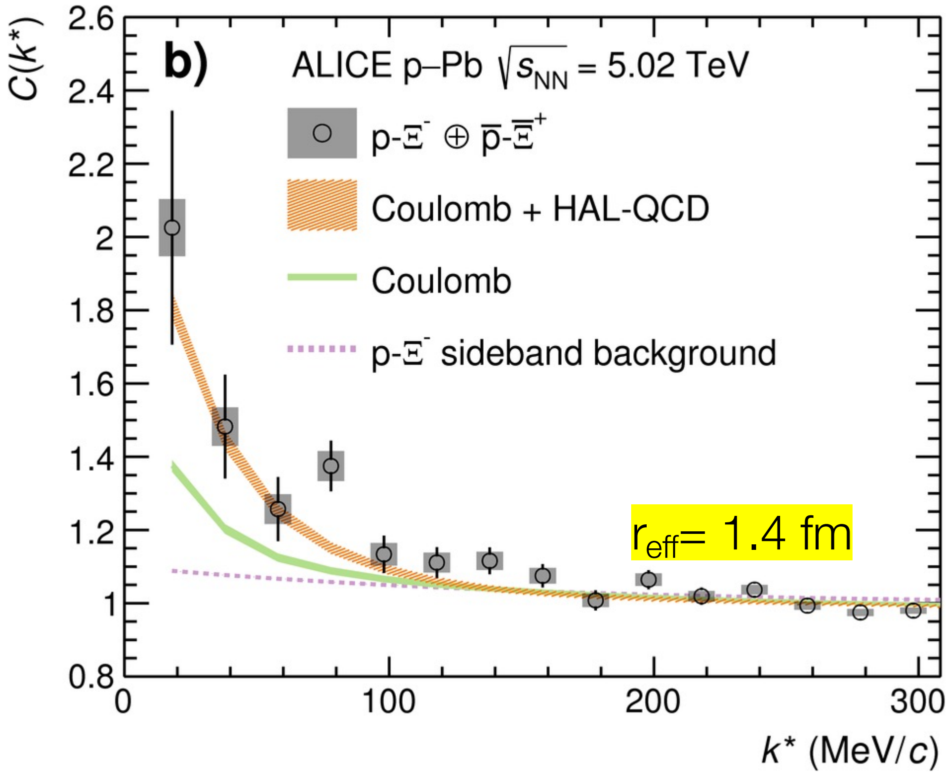


(*) T. Hatsuda Front. Phys. 13(6), 132105 (2018)
(**) ALICE Coll. Phys. Lett. B 797 (2019) 134822
(***) Hayakawa et al. Phys. Rev. Lett. 126, 062501 (2021)

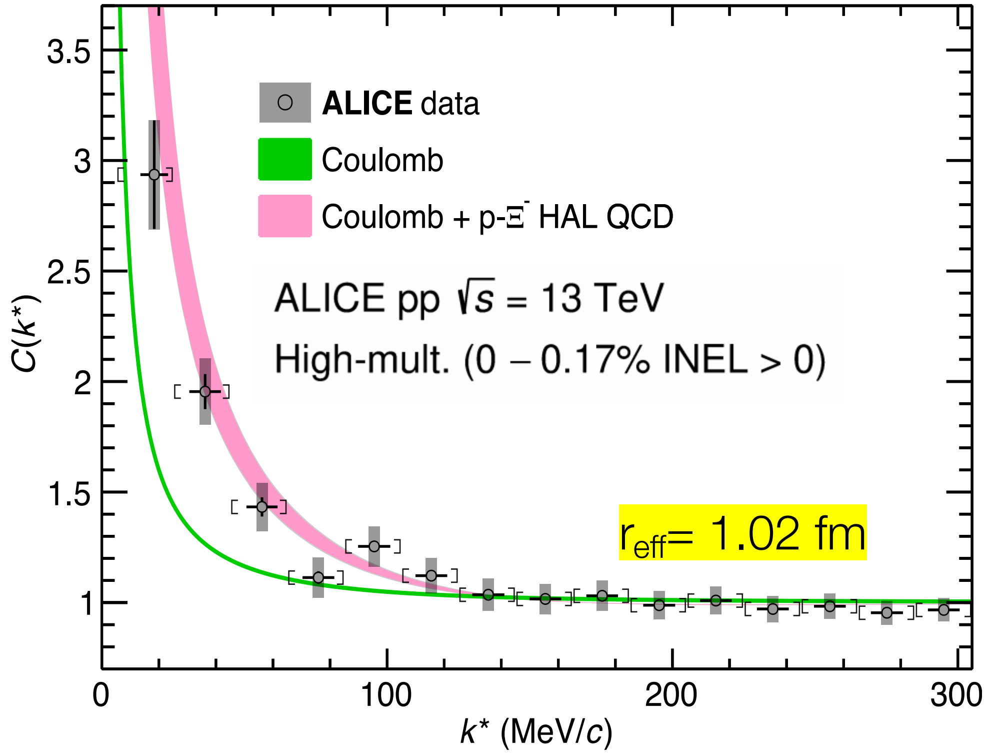
|S|=2 sector: p-Ξ⁻ interaction and first test of LQCD

- 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)

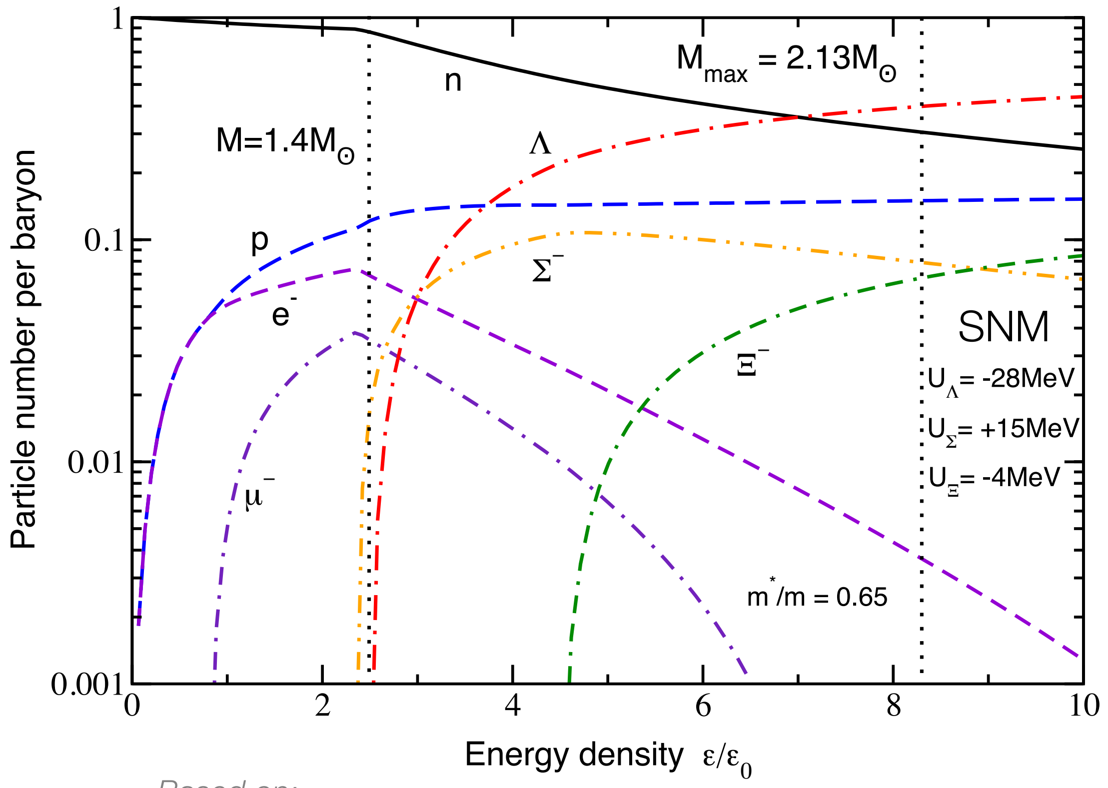


(*) HAL QCD Coll., PoS INPC2016 (2016) 277

Implications for neutron stars

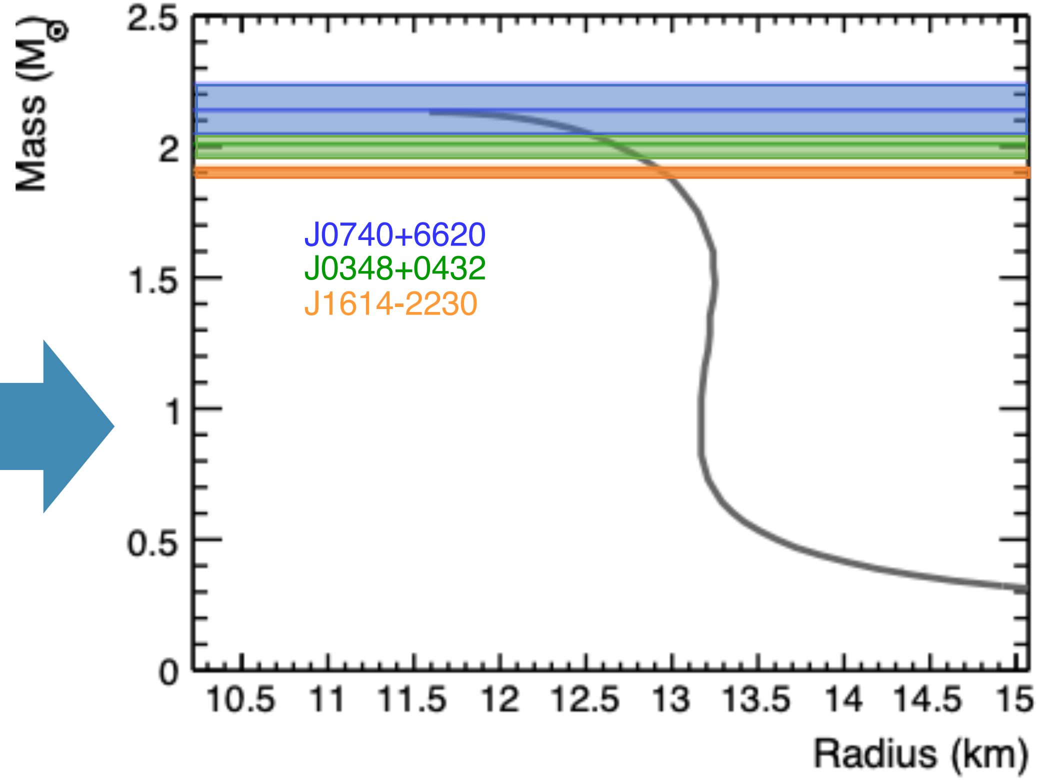
- Using HAL QCD predictions at finite density → Ξ production pushed to higher densities → stiffening of EoS compatible with current measurements
- What about the three-body interactions?

Courtesy J. Schaffner-Bielich 2020



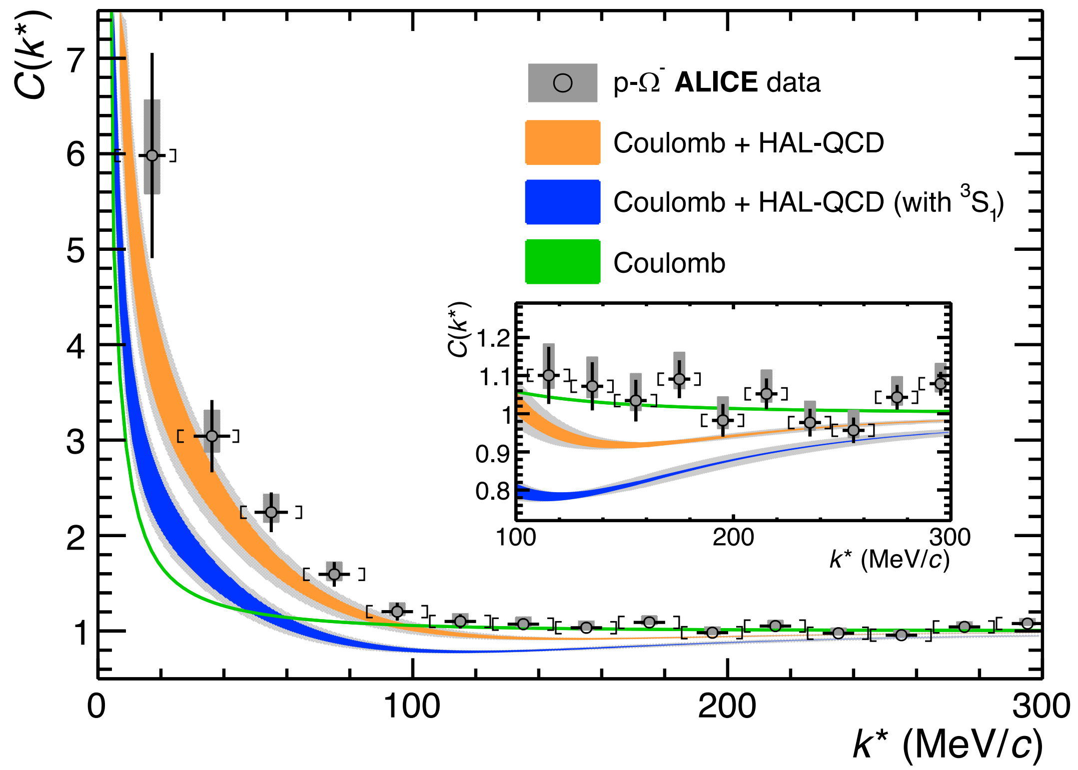
Based on:
Weissenborn S, Chatterjee D, Schaffner-Bielich J. Nucl. Phys. A881:62 (2012)
Schaffner J, Mishustin IN. Phys. Rev. C 53:1416 (1996)
Haidenbauer J, et al. Phys. Rev. C 98:065804 (2018)

Courtesy J. Schaffner-Bielich and B. Dönigus 2020



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

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

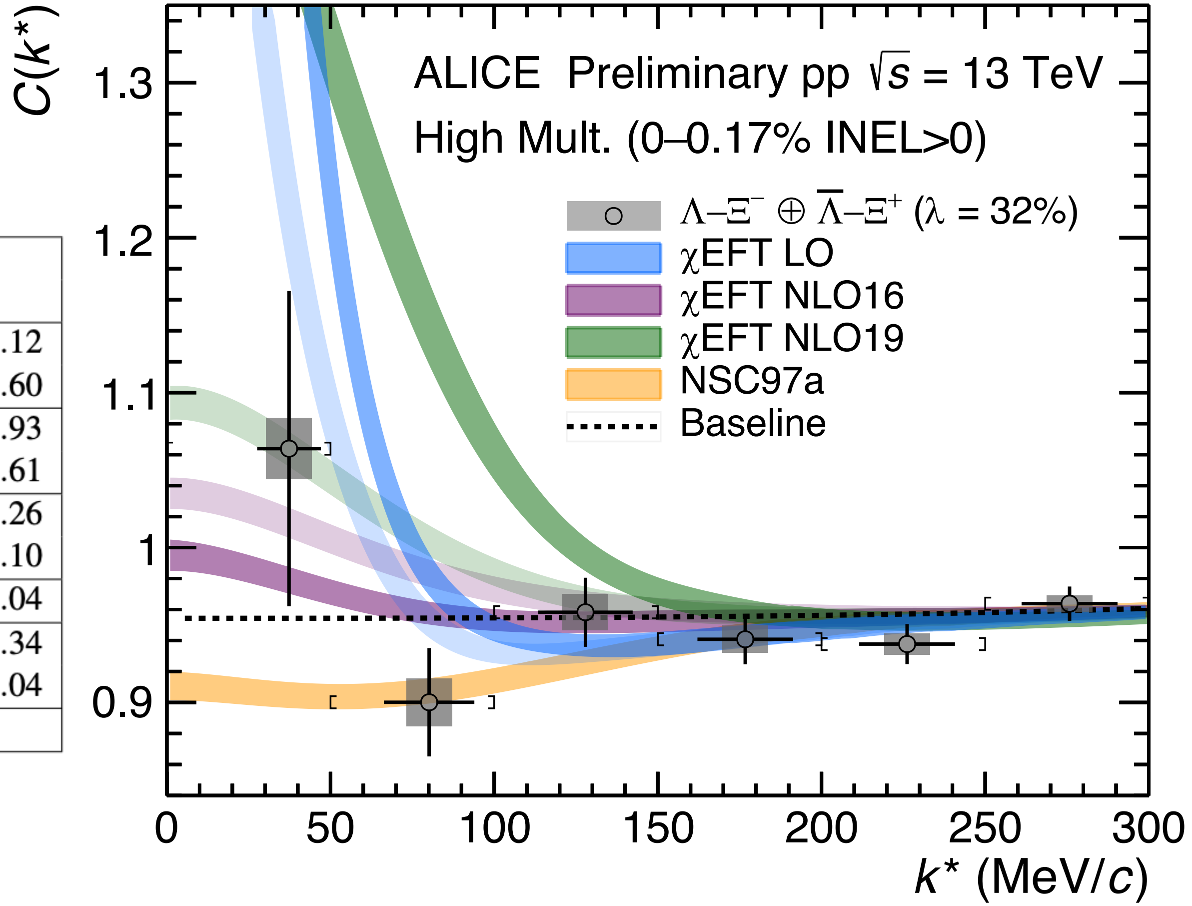


ALICE Collaboration Nature 588 (2020) 232-238

- – Model corrected for residual correlations and corrections
- – Radius extracted from m_T differential p-p correlations (r ~ 0.9 fm)
- Enhancement above Coulomb
  → Observation of the strong interaction
- Agreement of lattice prediction depends on the treatment of inelastic channels
  - – No clear depletion corresponding in the data

ΛΞ correlation in pp HM 13 TeV

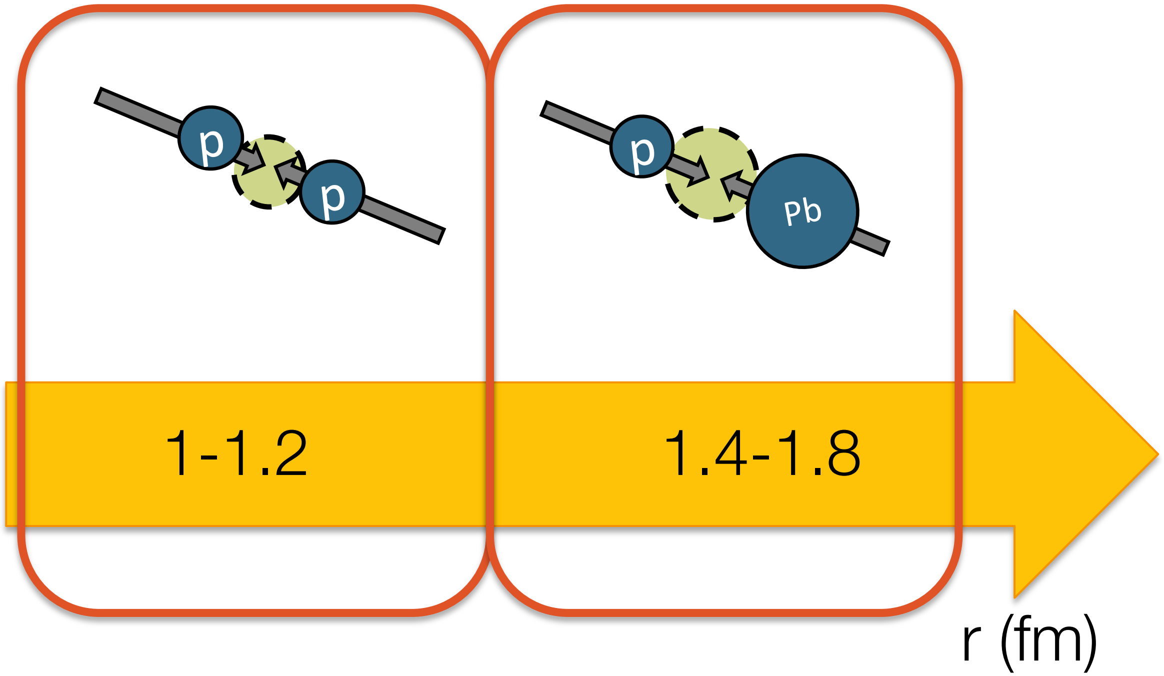
potential	cut-off (MeV) / version	singlet f_0^0	singlet d_0^0	triplet f_0^1	triplet d_0^1	n_σ
χEFT LO [11]	550	33.5	1.00	−0.33	−0.36	3.06 – 5.12
	700	−9.07	0.87	−0.31	−0.27	0.78 – 1.60
χEFT NLO16 [14]	500	0.99	5.77	−0.026	142.9	0.56 – 0.93
	650	0.91	4.63	0.12	32.02	0.91 – 1.61
χEFT NLO19 [15]	500	0.99	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



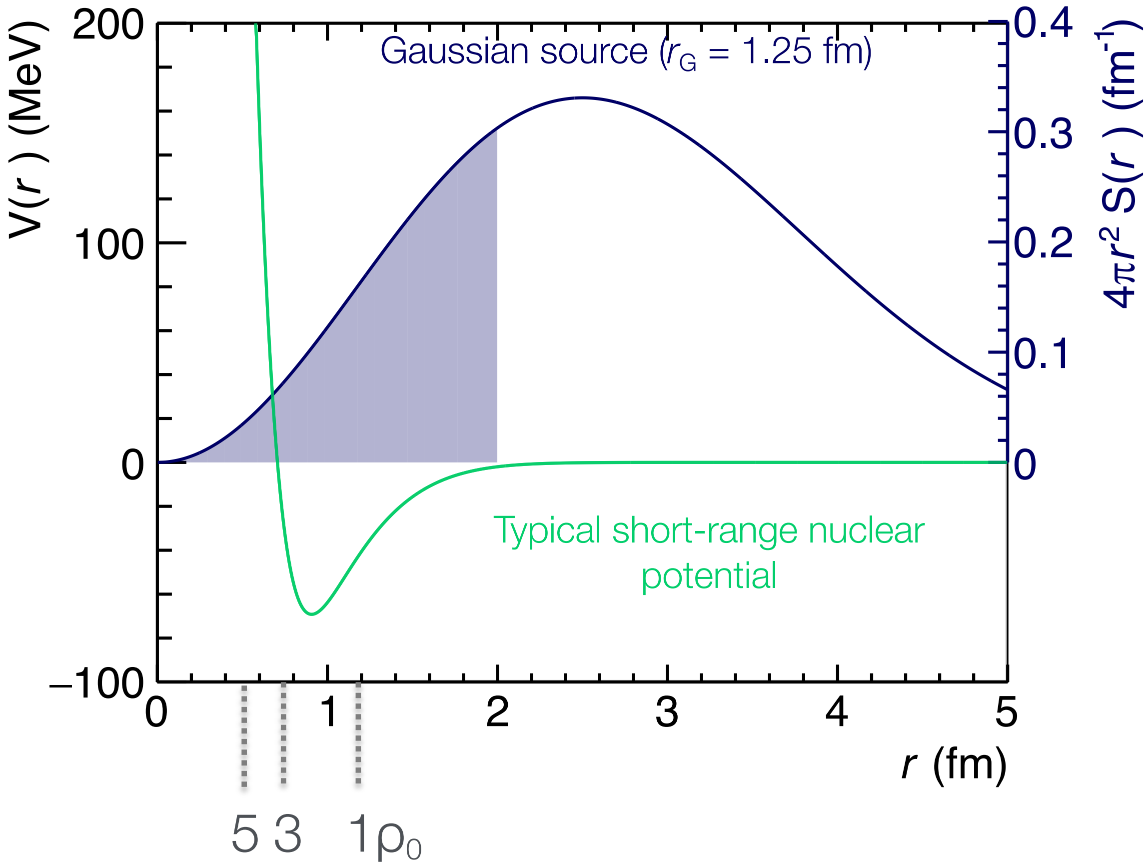
ALI-PREL-516888

Femtoscopy in small colliding systems

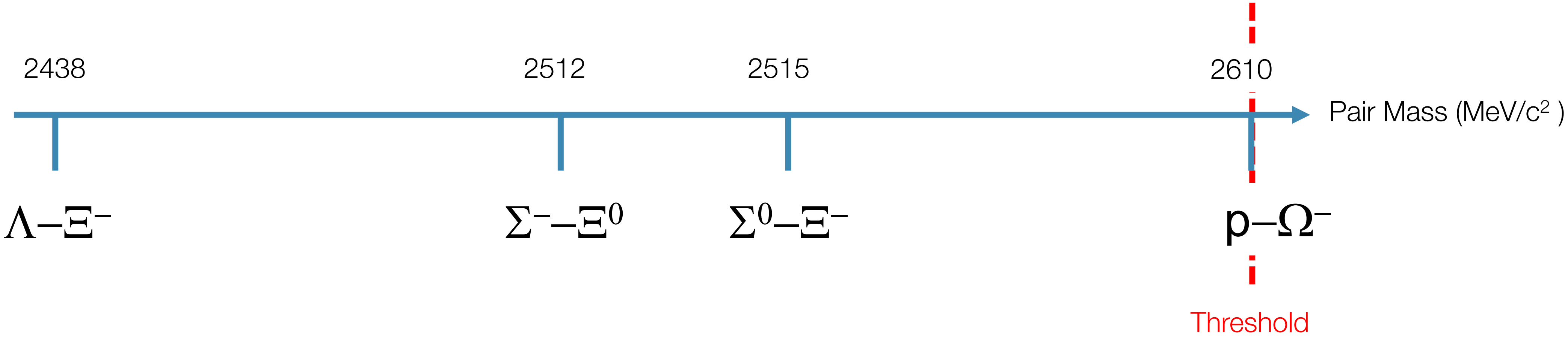
- Accessing the strong interaction → relative distances of ~1-1.4 fm → pp and p-Pb collisions
- Small interparticle distance → doorway to studying large densities



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



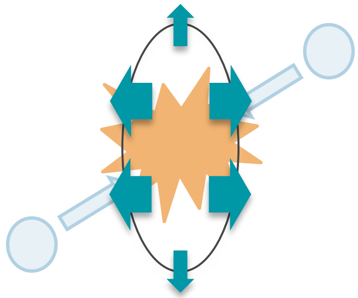
Couple channels in |S| = 3



- Absorption of p–Ω^- pairs in $^3S_1$ ($^{2S+1}L_J$)configuration by the channels below threshold dominate interaction
  - Not included in the lattice calculations so far → Test of two cases:
    - Total absorption of all J = 1 pairs: $V^{J=1}(r) = -i\theta(r0 - r)\, V_0$ with $V_0 \rightarrow \infty$ for r < 2 fm
    - Neglecting the absorption and same behavior as in the $^5S_2$ configuration
  - Coupled channel treatment missing so far
- Inelastic interactions suppressed for p–Ω^- pairs in $^5S_2$ configuration

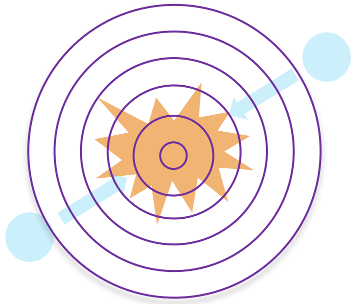
Small Sources: Collective Effects and Strong Resonances

Elliptic flow



Anisotropic pressure gradients within the source

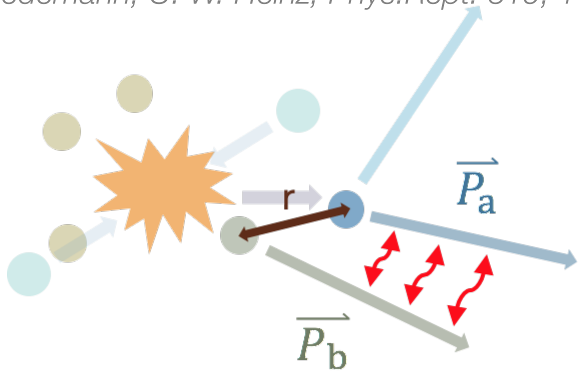
Radial flow



- Expanding source with constant velocity
- Different effect on different masses

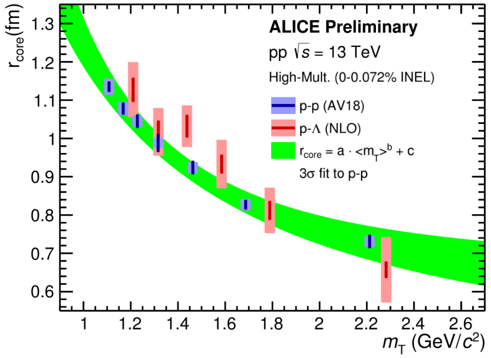
Strong decays of broad resonances

U. A. Wiedemann, U. W. Heinz, Phys.Rept. 319, 145-230 (1999)



- Resonances with cτ ~ r_0 ~ 1 fm (Δ^*, N^*, Σ^*) introduce an exponential tail to the source
- Different for each particle species

Core Radius



⊗

Strong decays of specific resonances