Unveiling the strong interaction among hadrons at the LHC

Bernhard Hohlweger
Nuclear Physics Seminar - CRC Colloquium
19.11.2020

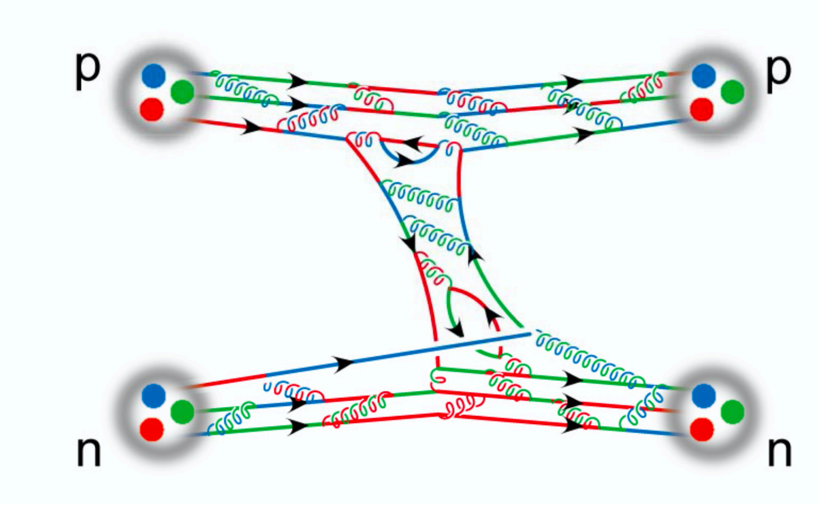
BMBF Forschungsschwerpunkt ALICE Experiment 202 ALICE

150 Jahre culture of excellence

SFB 1258 Neutrinos Dark Matter Messengers

ALICE

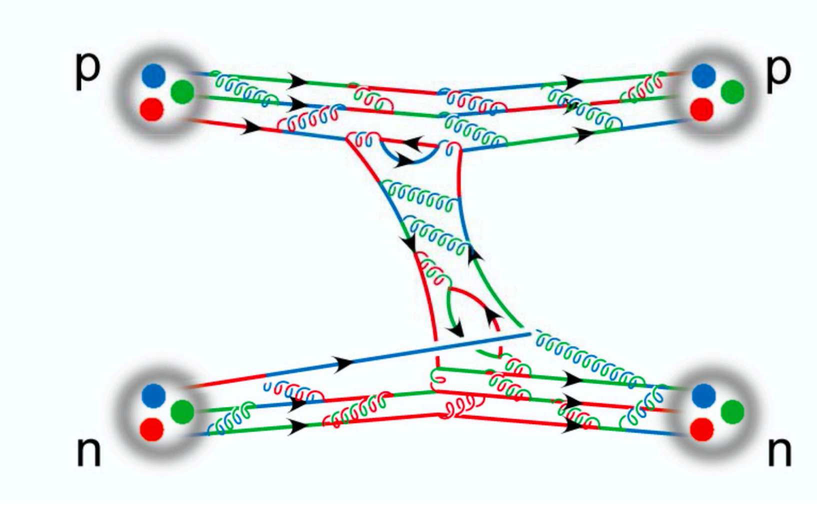
Nuclear interactions and QCD

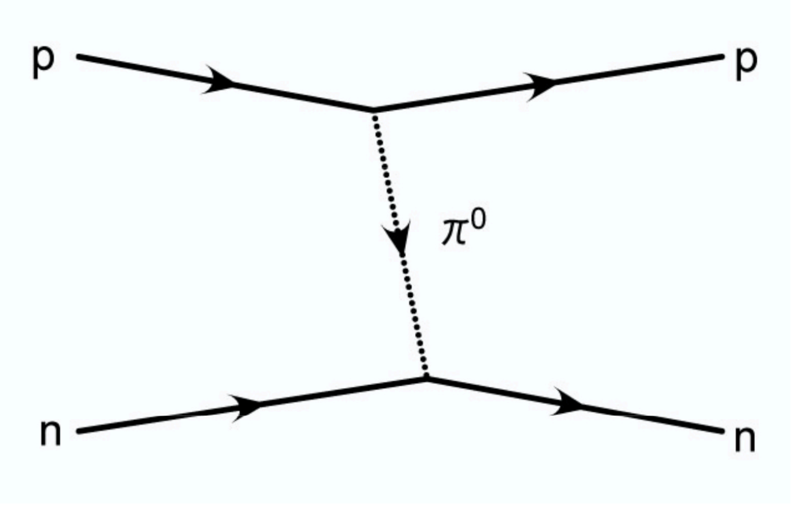


- Non-perturbative regime of QCD
  → calculations with lattice QCD
  - Computationally challenging
  - How to get hadronic observables
    e.g. Potentials?

https://www.int.washington.edu/PROGRAMS/talent13/Lectures.htm

Nuclear interactions and QCD





- Non-perturbative regime of QCD
  → calculations with lattice QCD
  - Computationally challenging
  - How to get hadronic observables e.g. Potentials?

- Calculations starting from an effective Lagrangian (chiral effective field theory)
  - Hadrons as degrees of freedom
  - ➢ Chiral Perturbation theory

https://www.int.washington.edu/PROGRAMS/talent13/Lectures.htm

Strong interaction among (strange) baryons

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

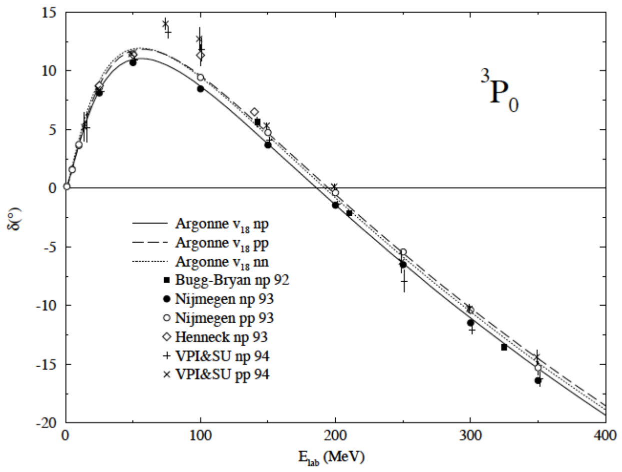
Strong interaction among (strange) baryons

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

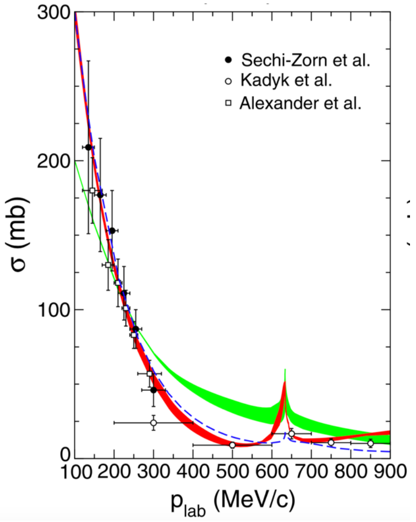
Experimental data

N–N → N–N



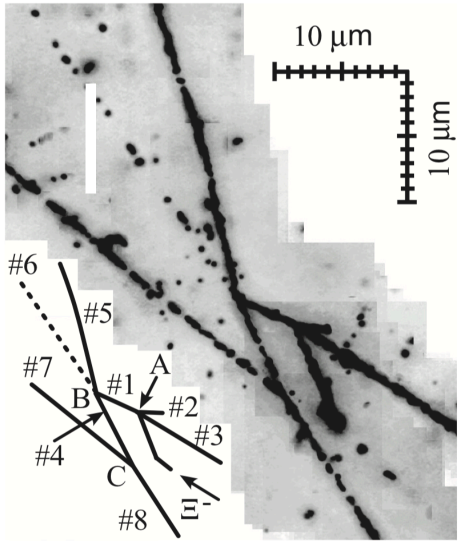
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, PRC 51 (1995) 38-51.

p–Λ → p–Λ



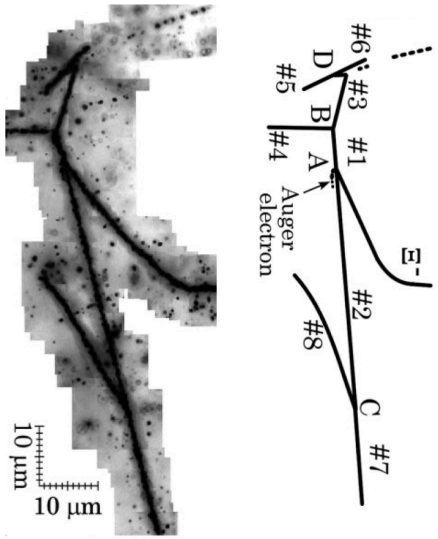
LO from H. Polinder, J.Haidenbauer, U. Meiβner, NPA 779 (2006) 244 and NLO from J.Haidenbauer., N.Kaiser et al., NPA 915 (2013) 24.

Double Λ Hypernucleus



J. K. Ahn et al., PRC 88, 014003 (2013)

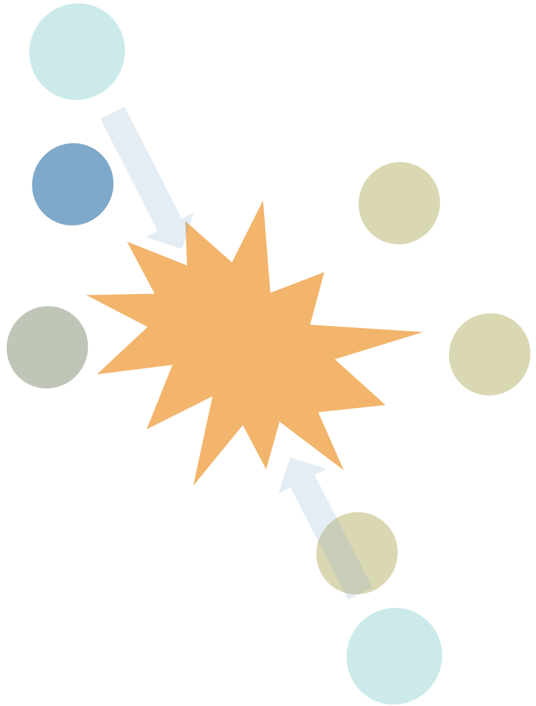
Ξ Hypernucleus



K. Nakazawa et al. PTEP 2015, 033D02

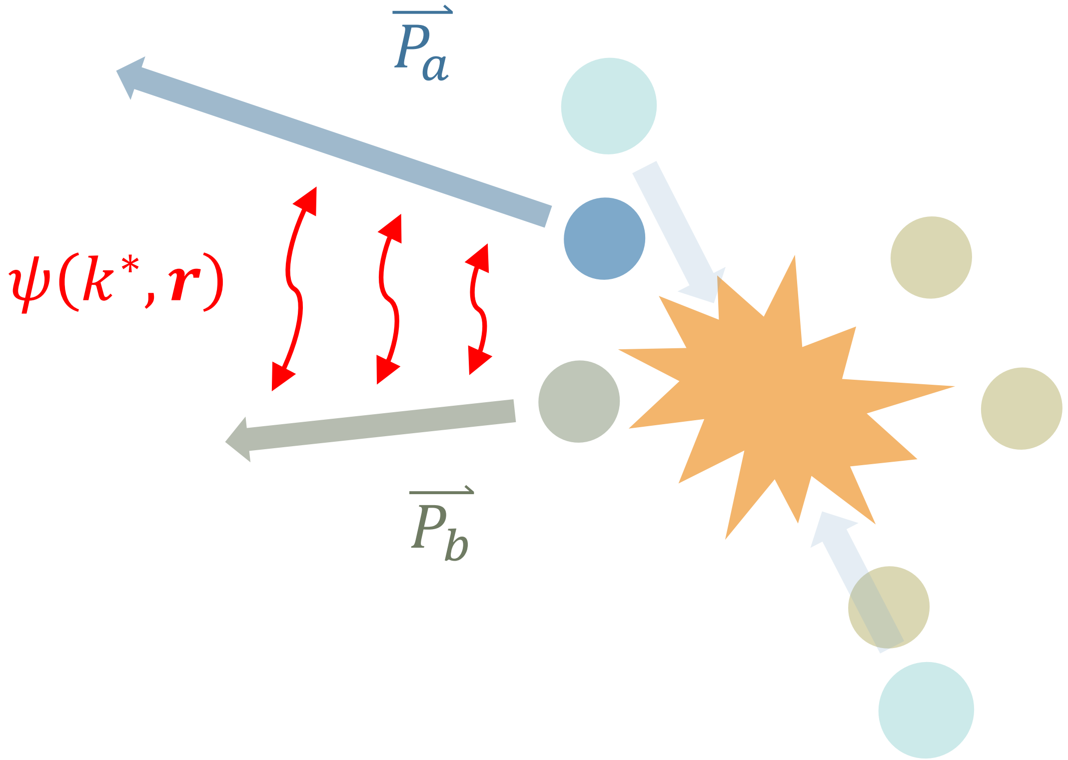
Two particle correlation function

- Study of correlations in the relative momentum k^* distribution of particle pairs



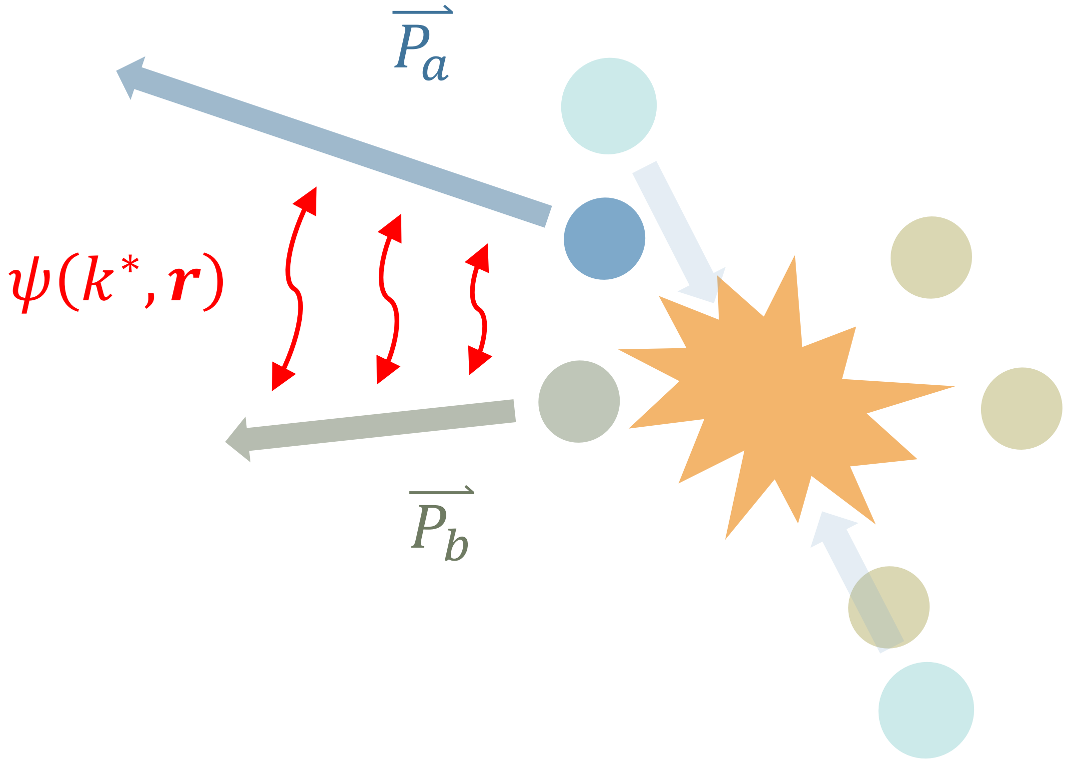
Two particle correlation function

- Study of correlations in the relative momentum k^*distribution of particle pairs



Two particle correlation function

- Study of correlations in the relative momentum k^* distribution of particle pairs
  - Attractive interaction → $C(k^*) > 1$
  - Repulsive interaction → $C(k^*) < 1$

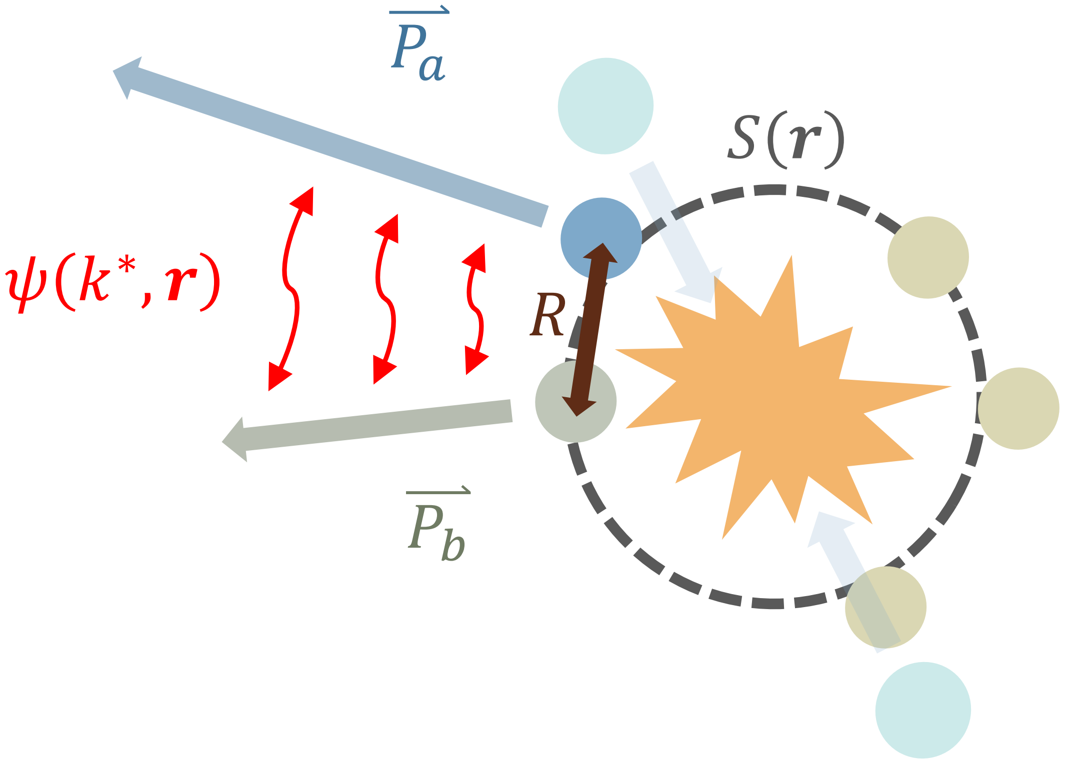


$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$k^* = \frac{1}{2}|p_a^* - p_b^*|$ and $p_a^* + p_b^* = 0$

Two particle correlation function

- Study of correlations in the relative momentum k^* distribution of particle pairs
- Correlation function linked to the source and two-particle wave function
  - Correlation Analysis Tool using the Schrödinger Equation
    D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394



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

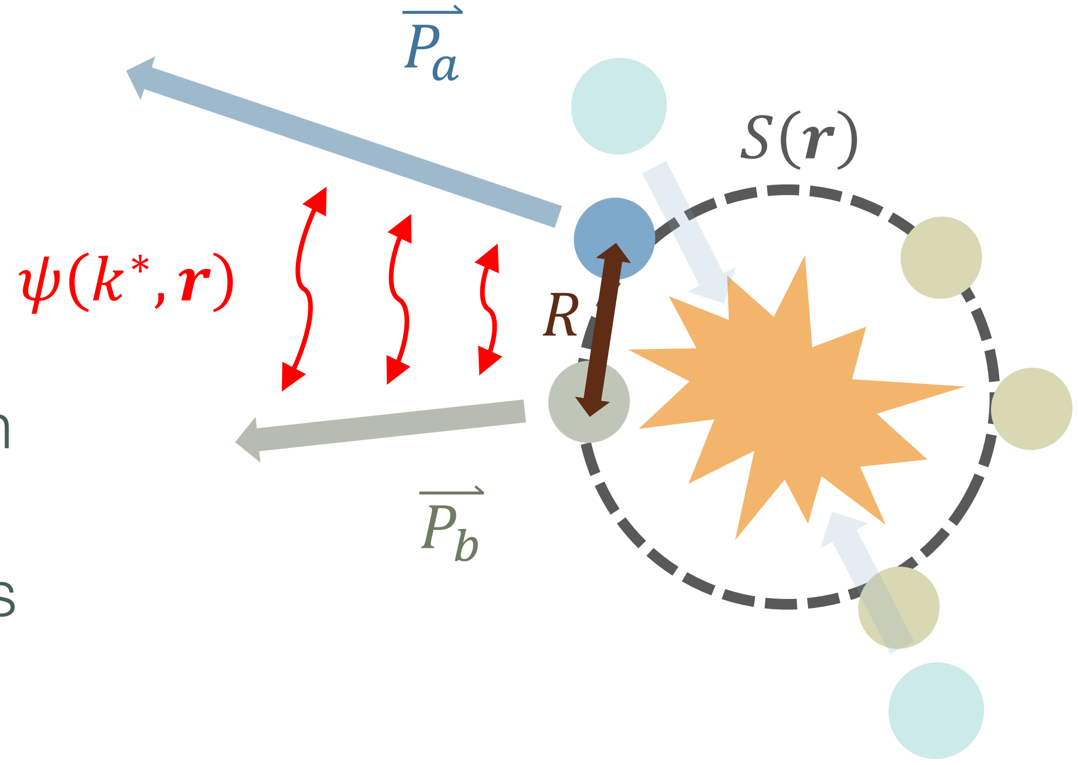
$k^* = \frac{1}{2}|p_a^* - p_b^*|$ and $p_a^* + p_b^* = 0$

Two particle correlation function

- Study of correlations in the relative momentum k^*distribution of particle pairs
- Correlation function linked to the source and two-particle wave function

➢ Constraint the emission of particles

➢ Study the interaction of selected pairs

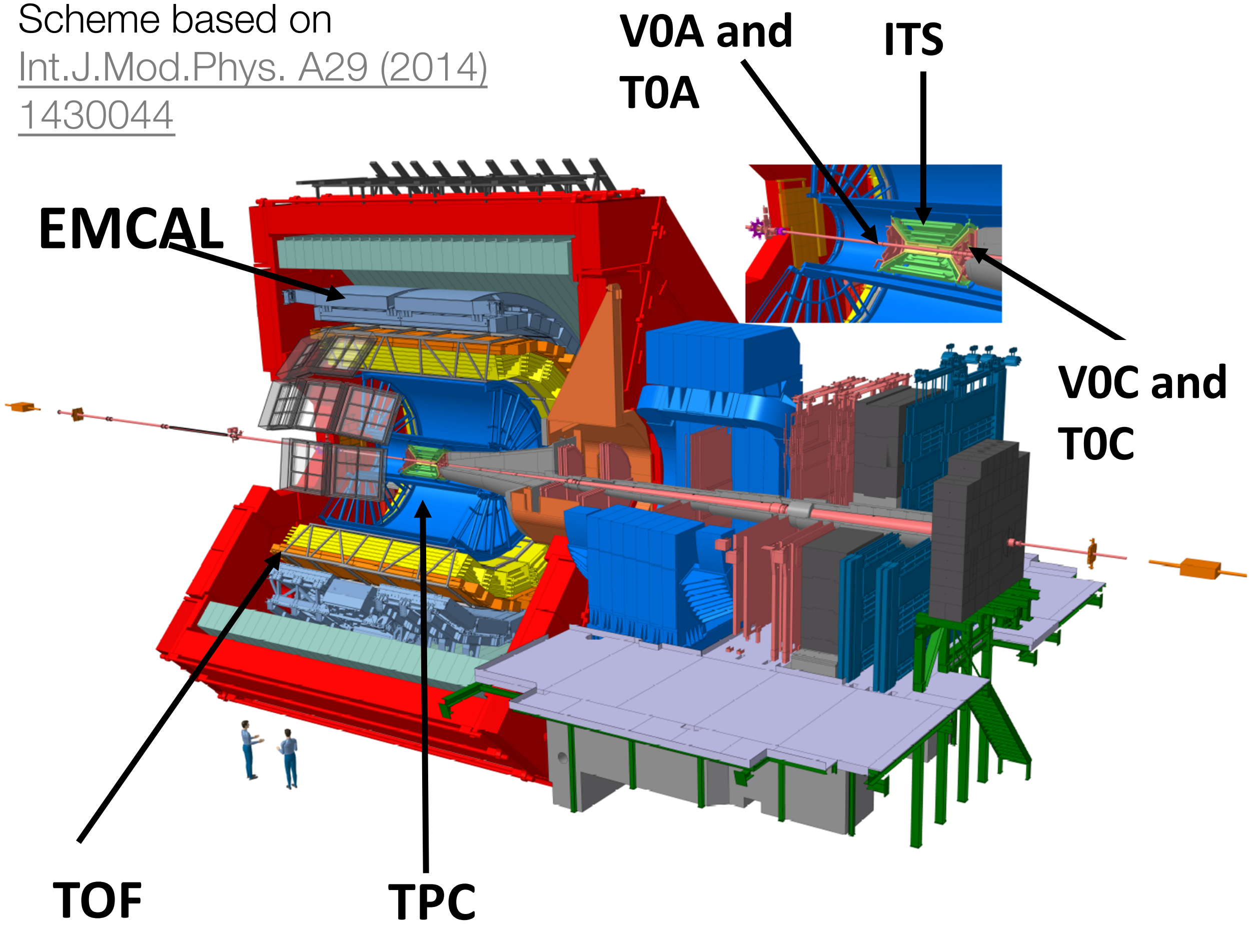


$$C(k^*) = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\boldsymbol{r}) |\psi(k^*, \boldsymbol{r})|^2 d^3 r$$

$k^* = \frac{1}{2} |p_a^* - p_b^*|$ and $p_a^* + p_b^* = 0$

The detector: ALICE

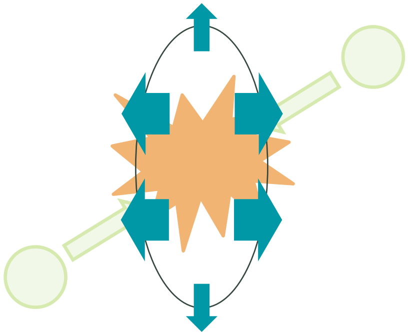
Scheme based on Int.J.Mod.Phys. A29 (2014) 1430044

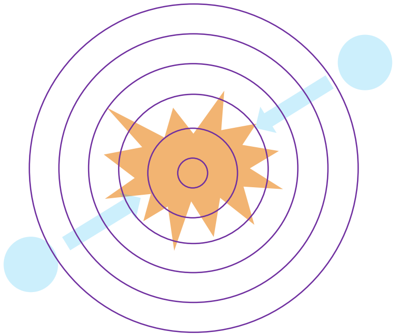


- Data set: pp 13 TeV High Multiplicity trigger (1000 M events)
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:

$$\Lambda \rightarrow p\pi^-$$
$$\Sigma^0 \rightarrow \Lambda\gamma$$
$$\Xi^- \rightarrow \Lambda\pi^-$$
$$\Omega^- \rightarrow \Lambda K^-$$

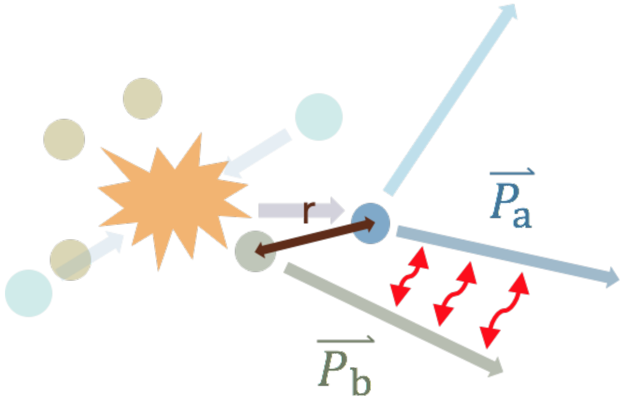
Collective Effects and Strong Resonances





Anisotropic + pressure gradients Radial

Different effect on different masses



Resonances with cτ ~ r_0 ~ 1fm (Δ^{++}, N^*, Σ^*)

Particle	Primordial fraction	Resonances <cτ>
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

U. Wiedemann U. Heinz (PRC56 R610, 1997)

$$S(r) = G(r, r_{core}(m_T)) = \frac{2\sqrt{\pi}r^2}{r_{core}^3}\exp\left(\frac{r^2}{4r_{core}^2}\right)$$

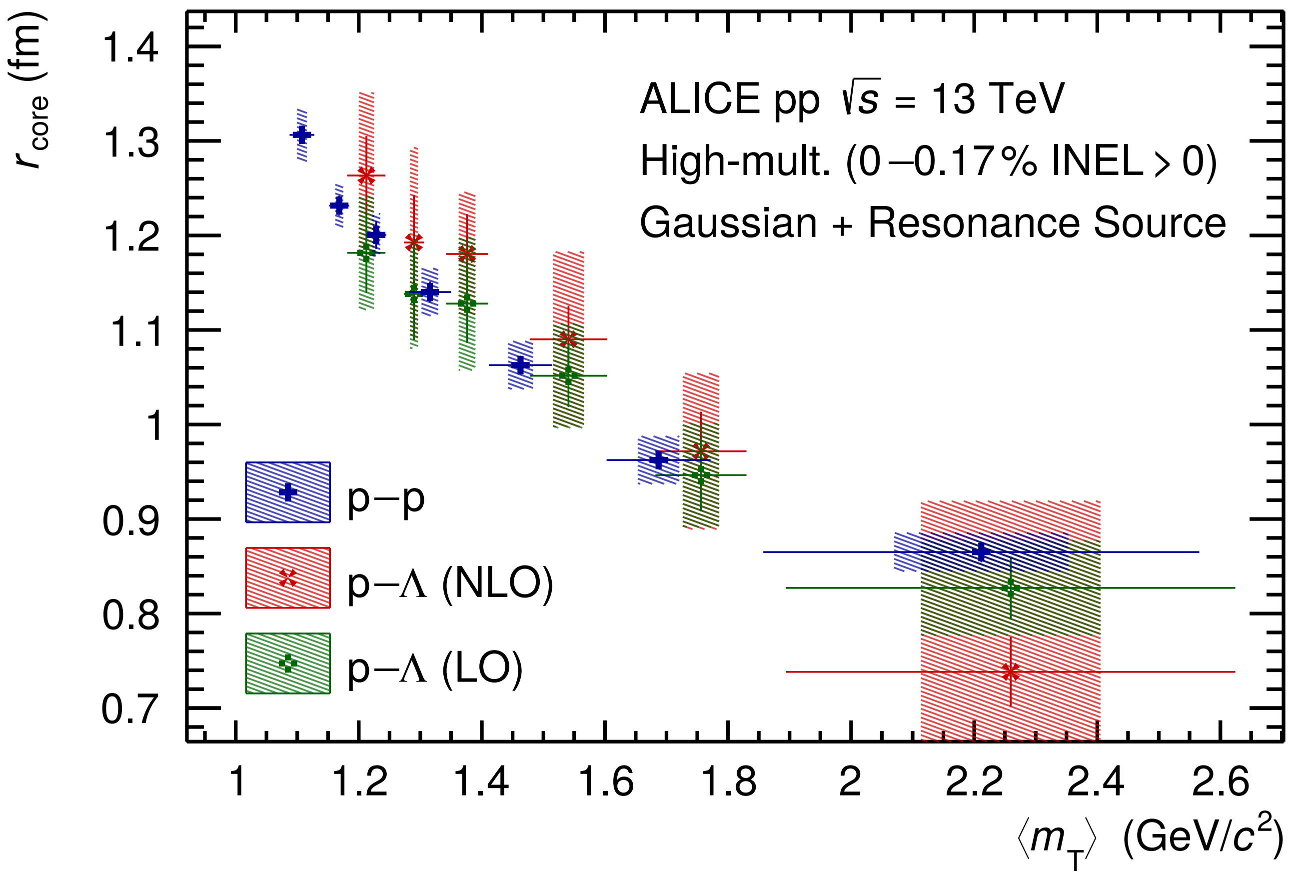
$\otimes$ Folded

$$E(r, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s}\exp(-\frac{r}{s})$$

$$s = \beta\gamma\tau_{res} = \frac{p_{res}}{M_{res}}\tau_{res}$$

A Gaussian source with resonances

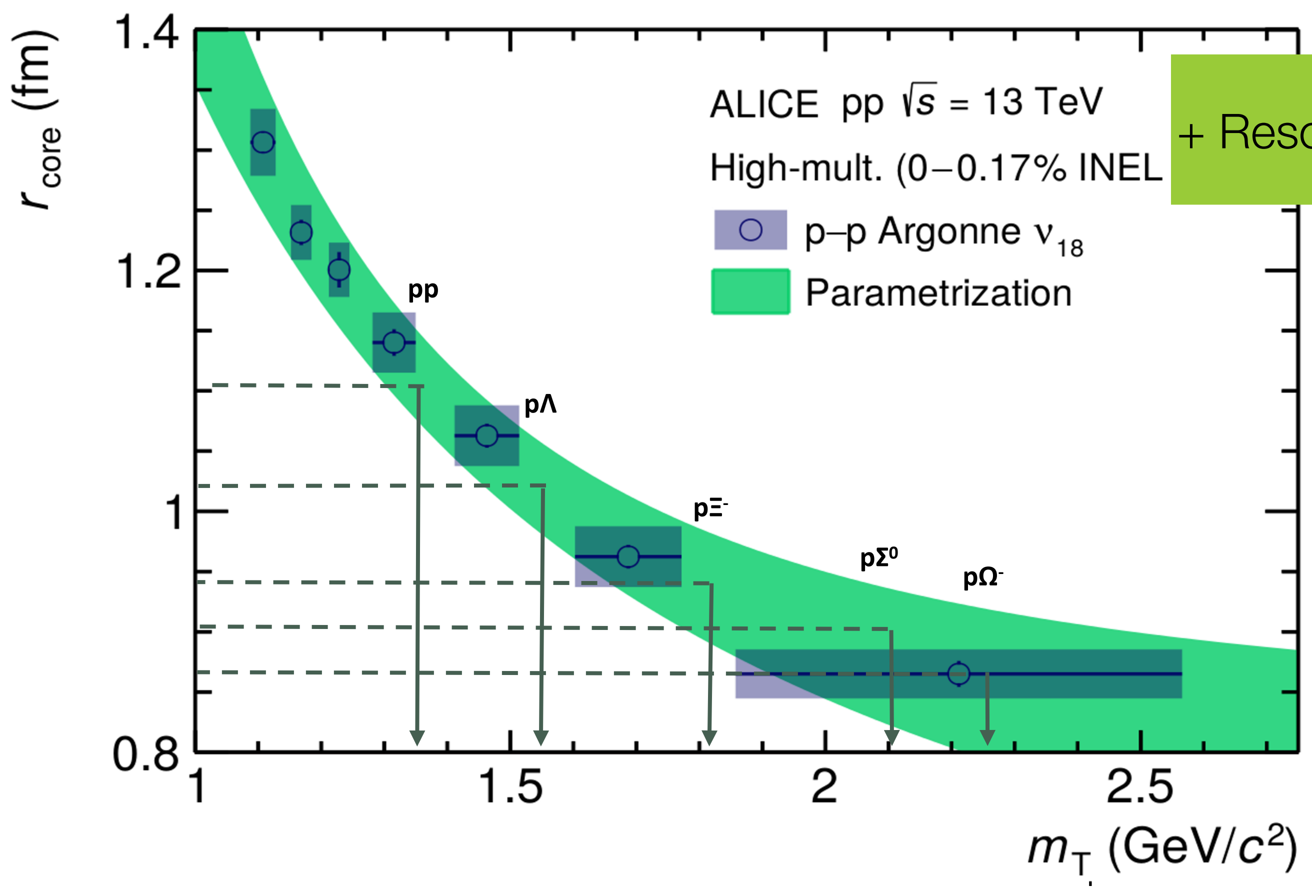
ALICE Collaboration, Physics Lett. B, 811, 135849



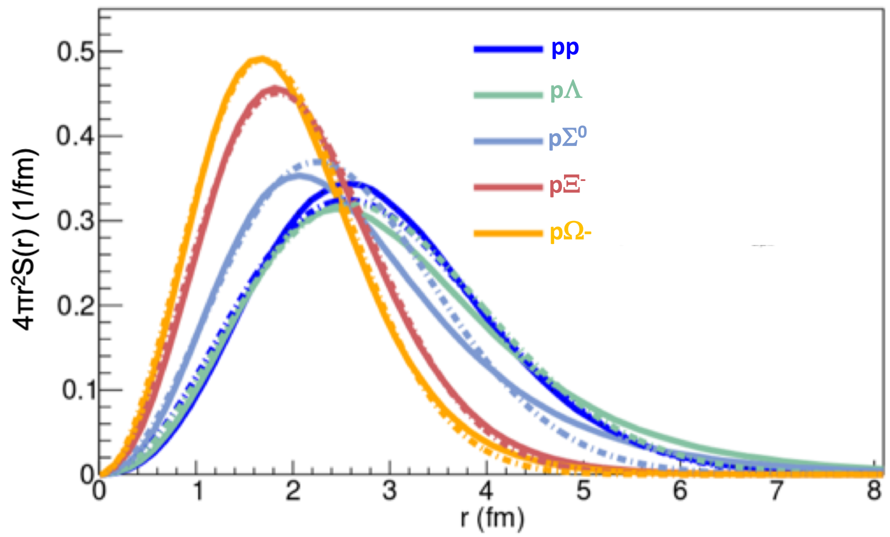
- Radii measured from the p-p and p-Λ correlation function
  - Input: Production fraction/life-times (SHM) and angular distributions (EPOS)
- Observation of a common m_T scaling of the core radius
  - Evidence of a universal emission source of baryons

A Gaussian source with resonances

ALICE Collaboration, Physics Lett. B, 811, 135849

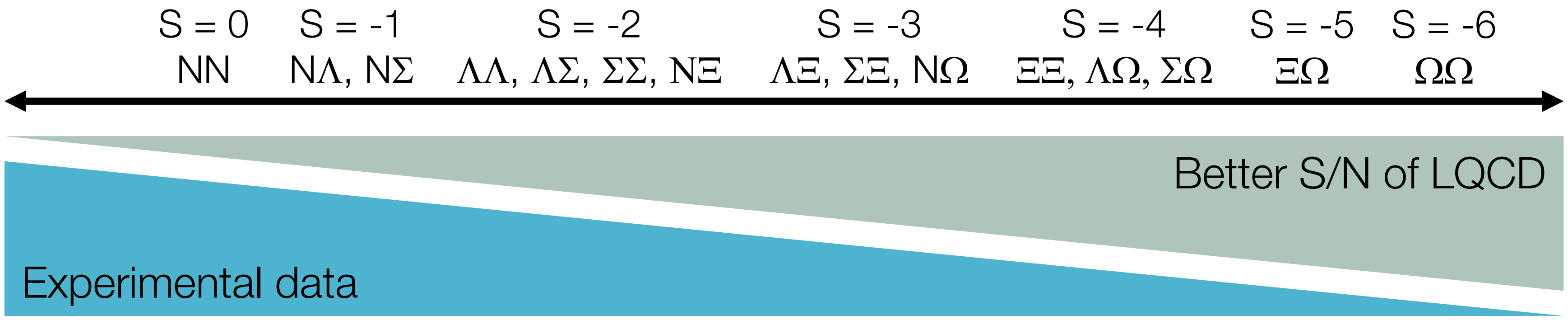


+ Resonances

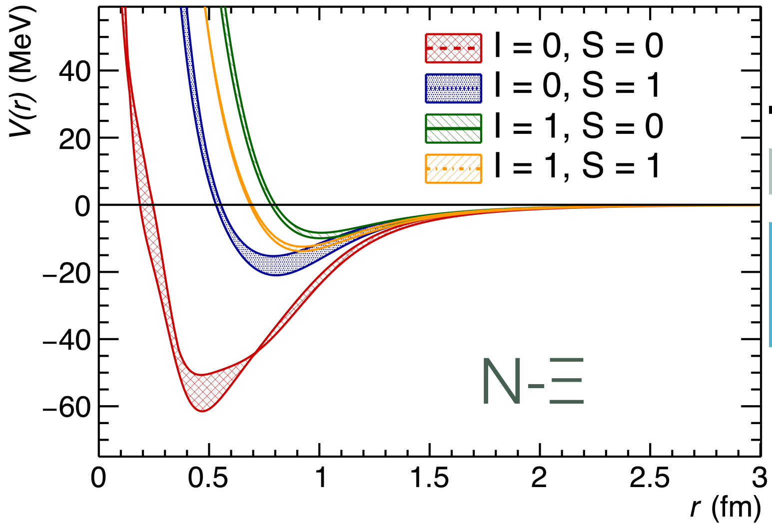


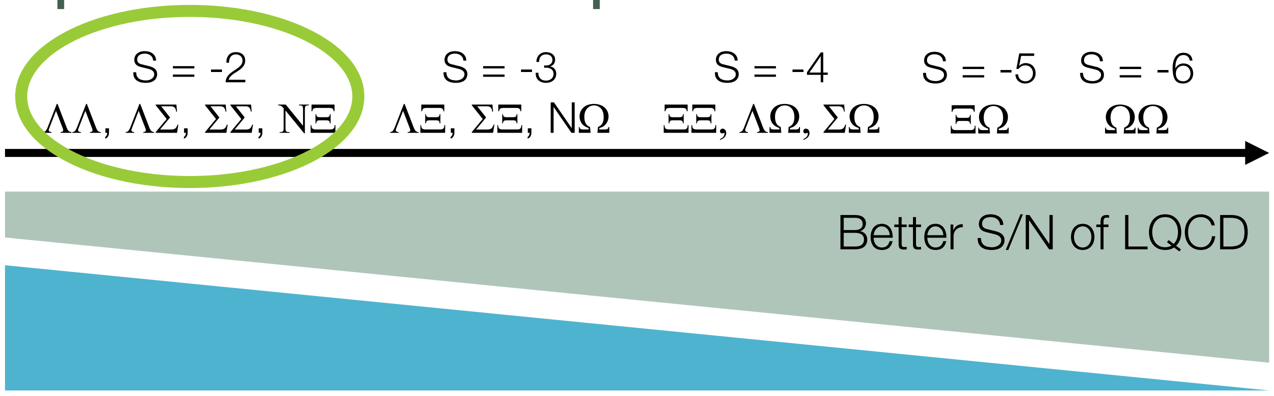
Pair	r_{Core} [fm]	r_{Eff} [fm]
p-p	1.1	1.2
p-Λ	1.0	1.3
p-Σ^0	0.87	1.02
p-Ξ^-	0.93	1.02
p-Ω^-	0.86	0.95

QCD p-Ξ^- and p-Ω^- lattice potentials



QCD p-Ξ^- and p-Ω^- lattice potentials

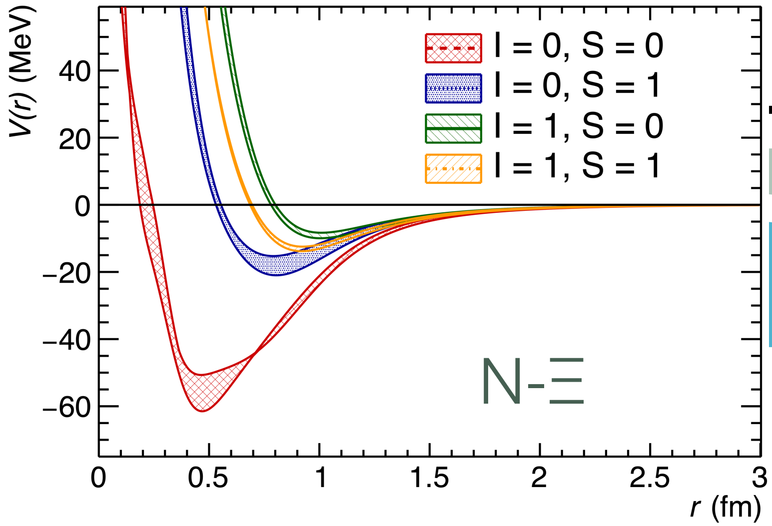


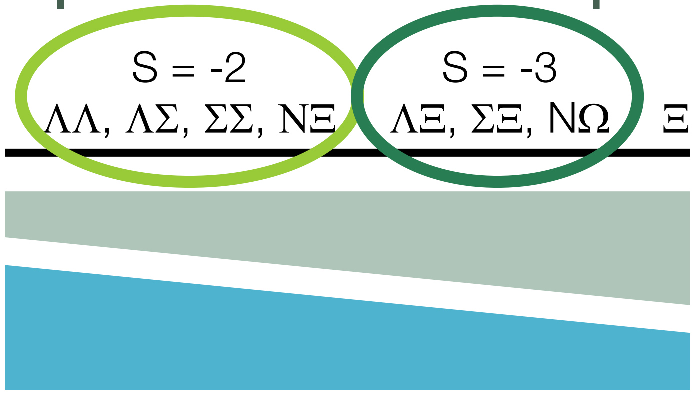


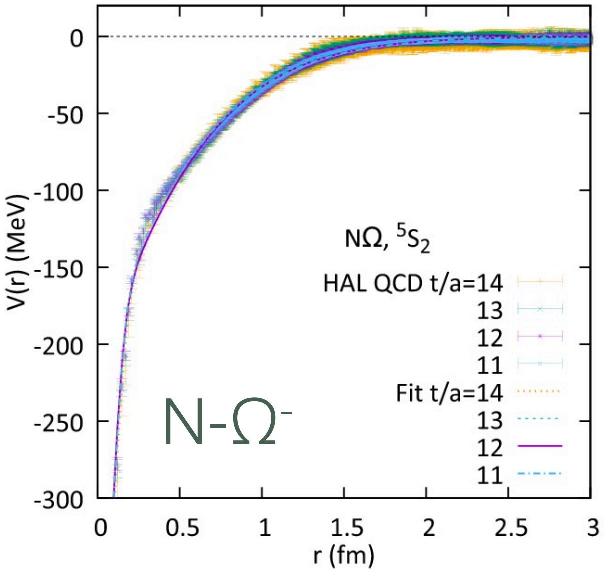
- Interaction of p–Ξ^- pairs in four Isospin (I = 0,1) and Spin (S=0,1) states

Nucl.Phys.A 998 (2020) 121737

QCD p-Ξ^- and p-Ω^- lattice potentials



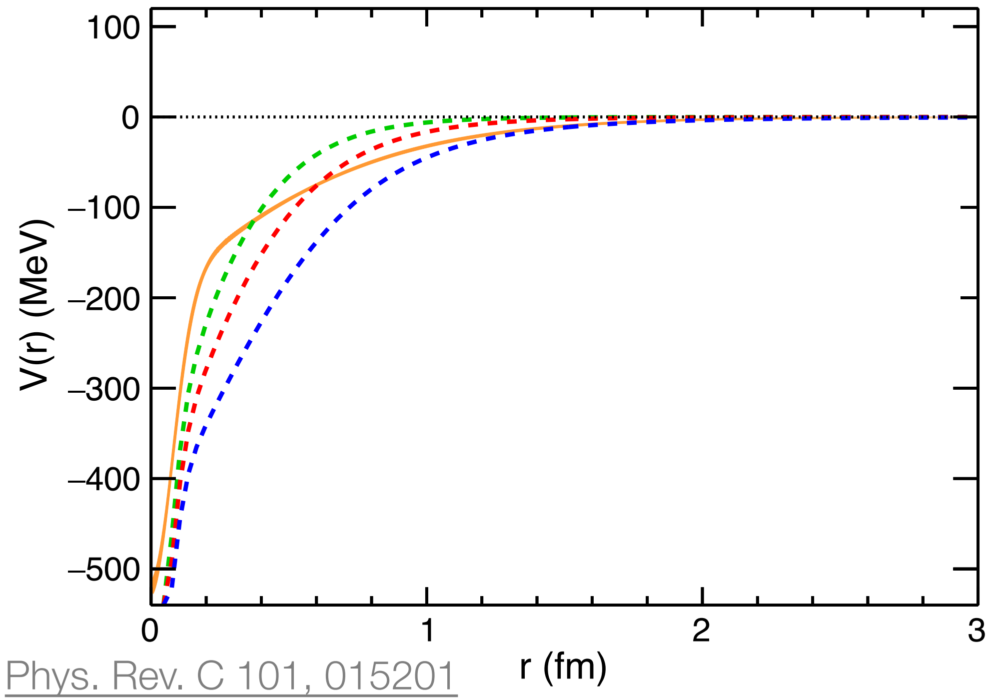




- Interaction of p–Ξ^- pairs in four Isospin (I = 0,1) and Spin (S=0,1) states
- Interaction of p–Ω^- pairs in $^3S_1$ +$^5S_2$ (S=1, 2) states
  - Inelastic channels (e.g. pΩ^- →$\Lambda\Xi^-$) in $^3S_1$not yet calculated on the lattice
  - Attraction in $^5S_2$ results in a bound state (B.E. = 1.54 MeV)

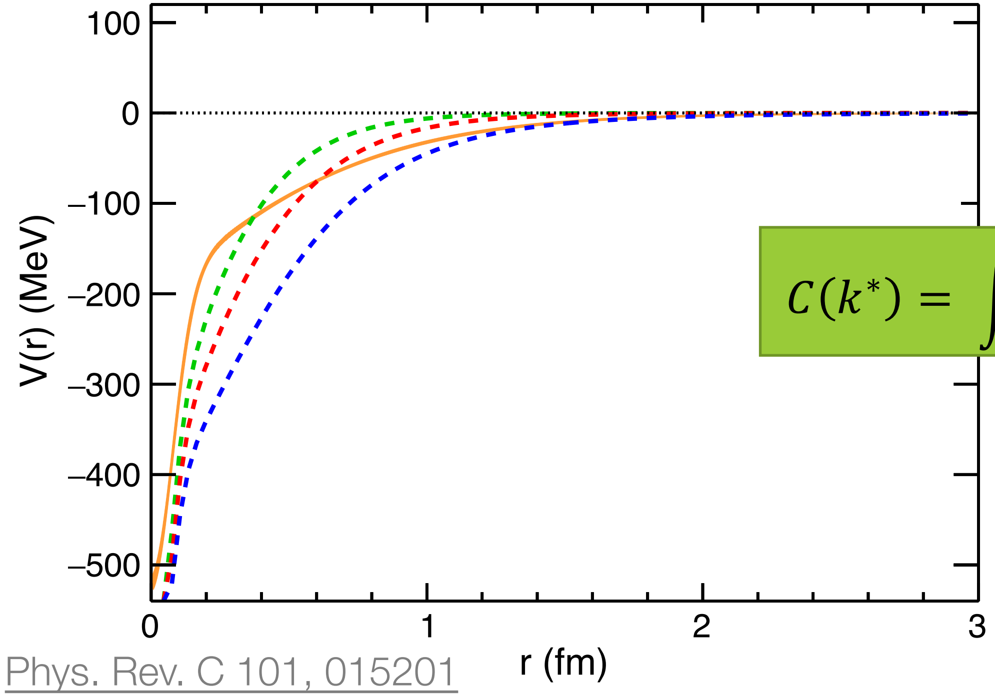
Nucl.Phys.A 998 (2020) 121737
Phys. Rev. C 101, 015201

One Femtoscopy to Bound (State) them all!



Phys. Rev. C 101, 015201

One Femtoscopy to Bound (State) them all!



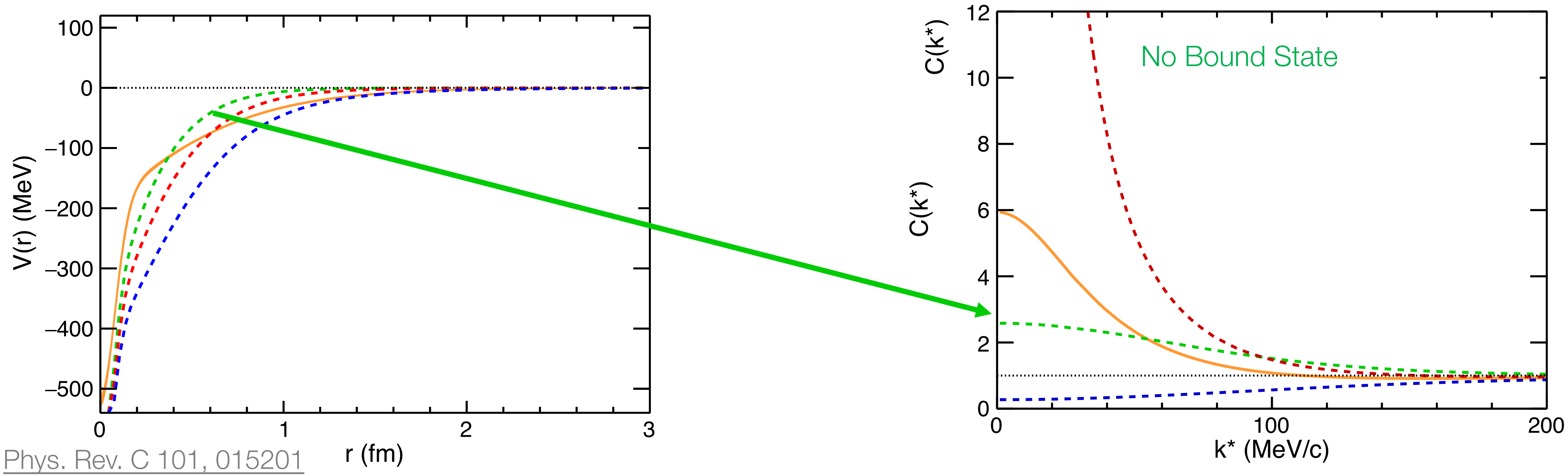
Phys. Rev. C 101, 015201

r_{eff}=0.95fm

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

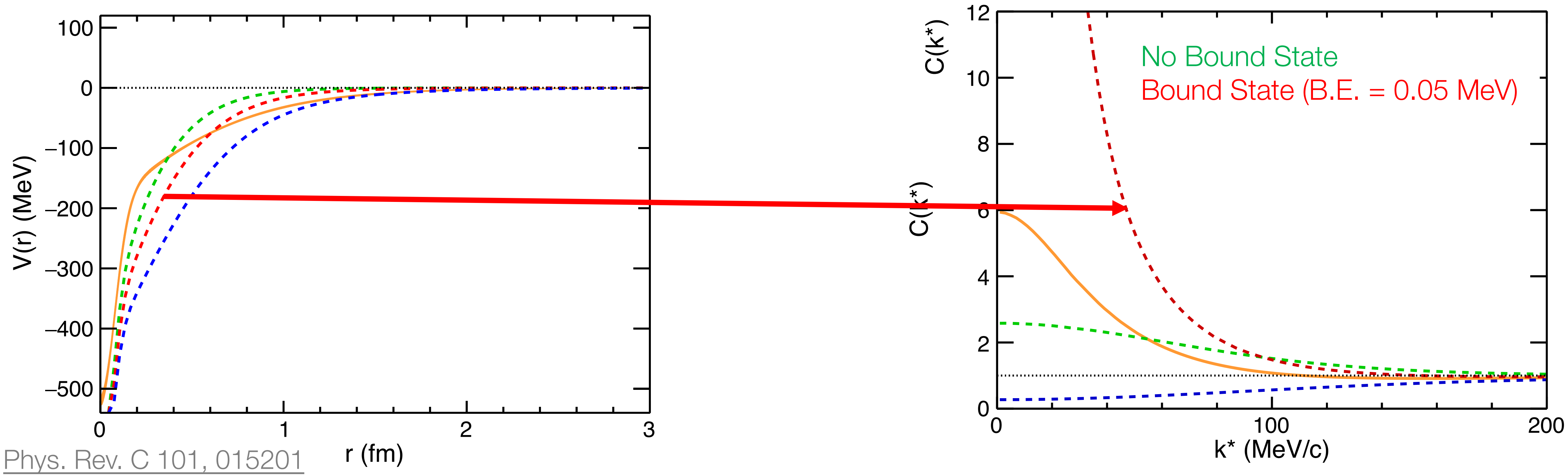
$$\widehat{\mathcal{H}} \cdot \psi(k^*,\boldsymbol{r}) = \mathrm{E} \cdot \psi(k^*,\boldsymbol{r})$$

One Femtoscopy to Bound (State) them all!



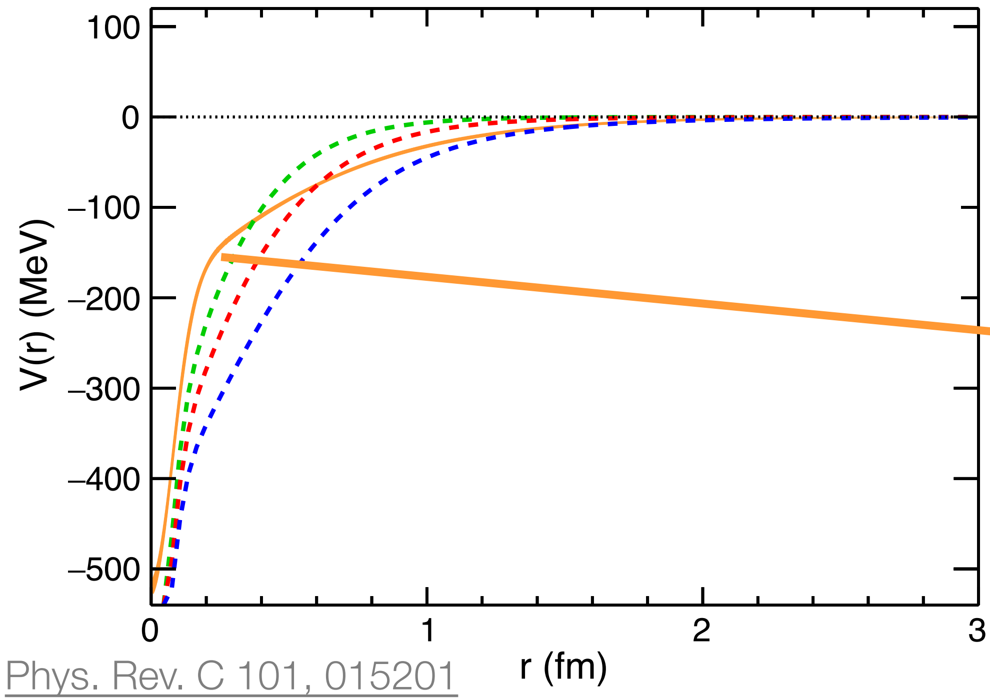
Phys. Rev. C 101, 015201

One Femtoscopy to Bound (State) them all!

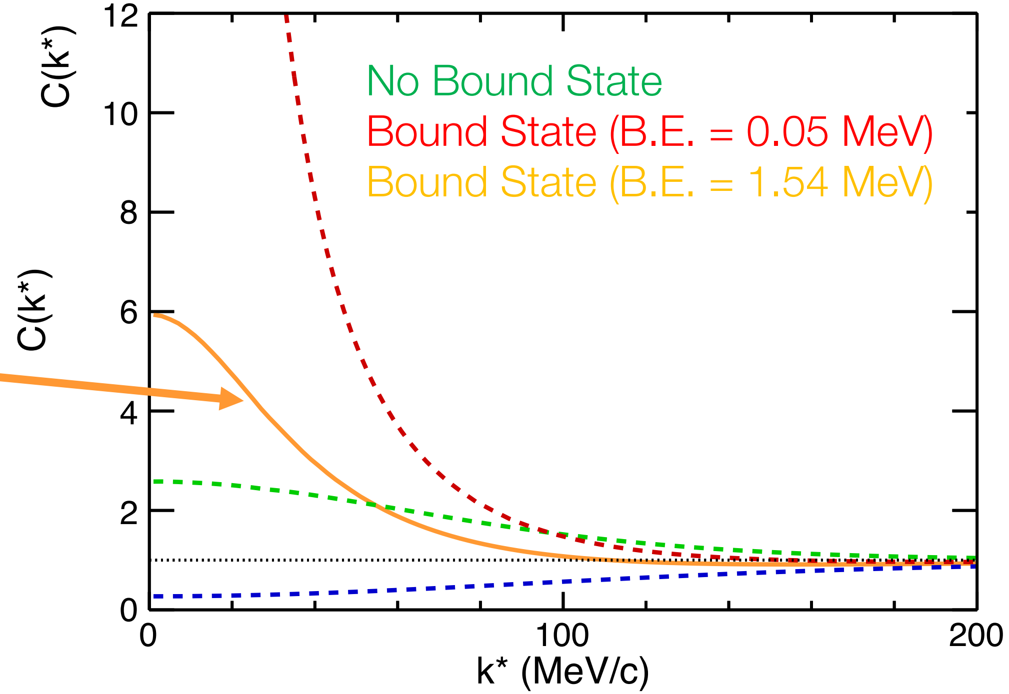


Phys. Rev. C 101, 015201

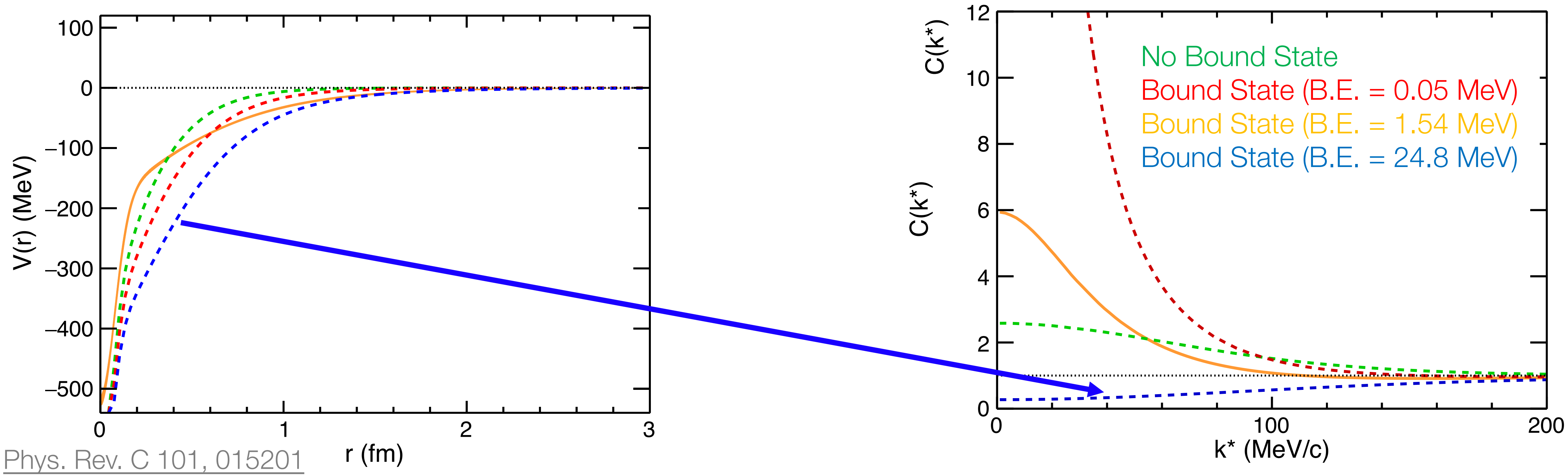
One Femtoscopy to Bound (State) them all!



Phys. Rev. C 101, 015201



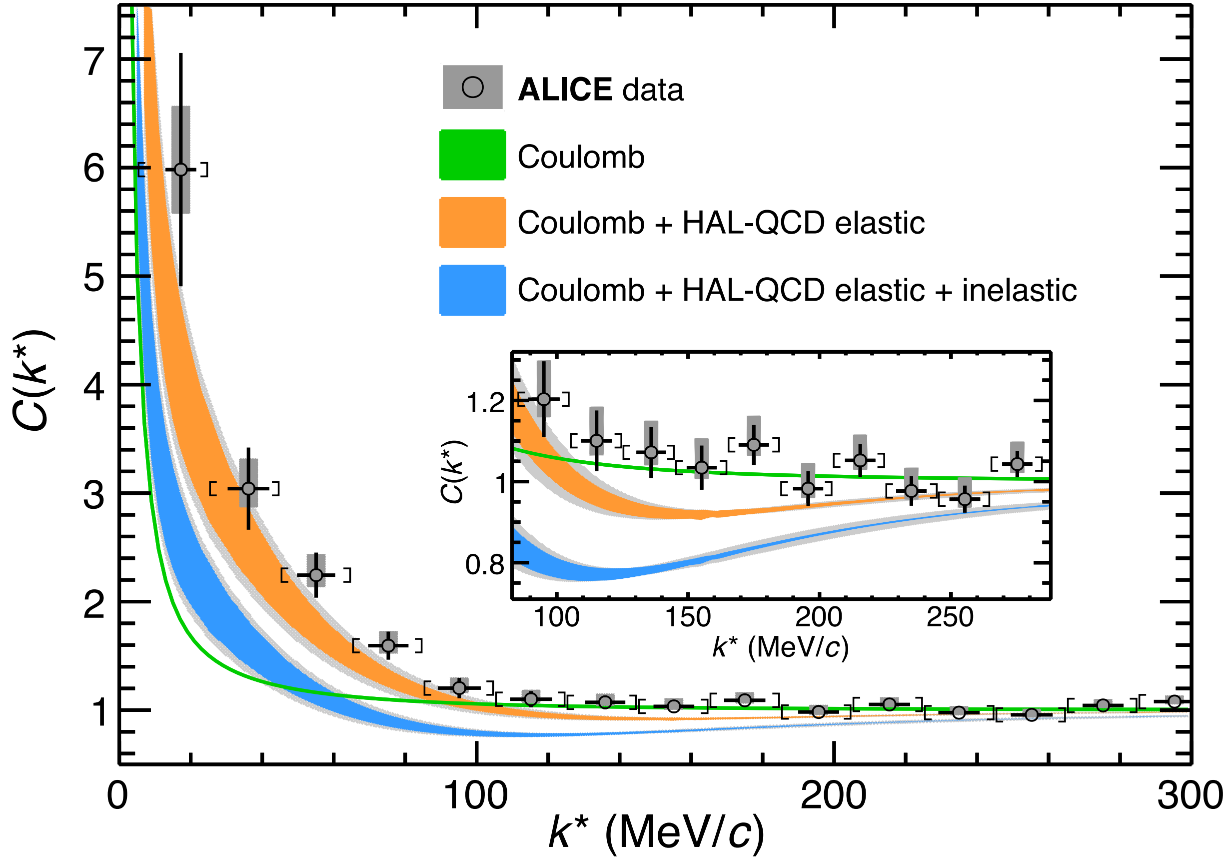
One Femtoscopy to Bound (State) them all!



Phys. Rev. C 101, 015201

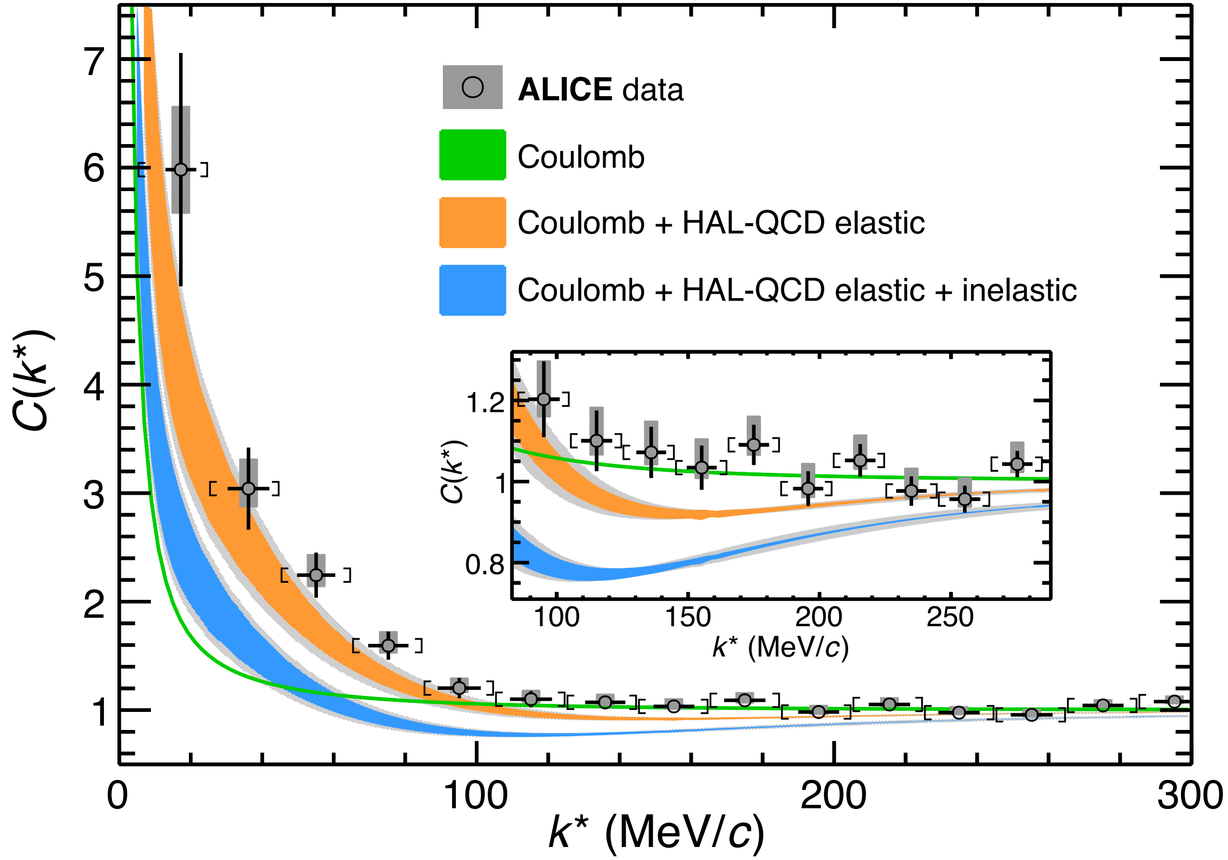
- Prediction sensitive to changes of the B.E.
- Femtoscopy in small systems sensitive to small system sensitive to minor differences in the interaction potentials

p–Ω⁻ correlation function in pp at 13 TeV

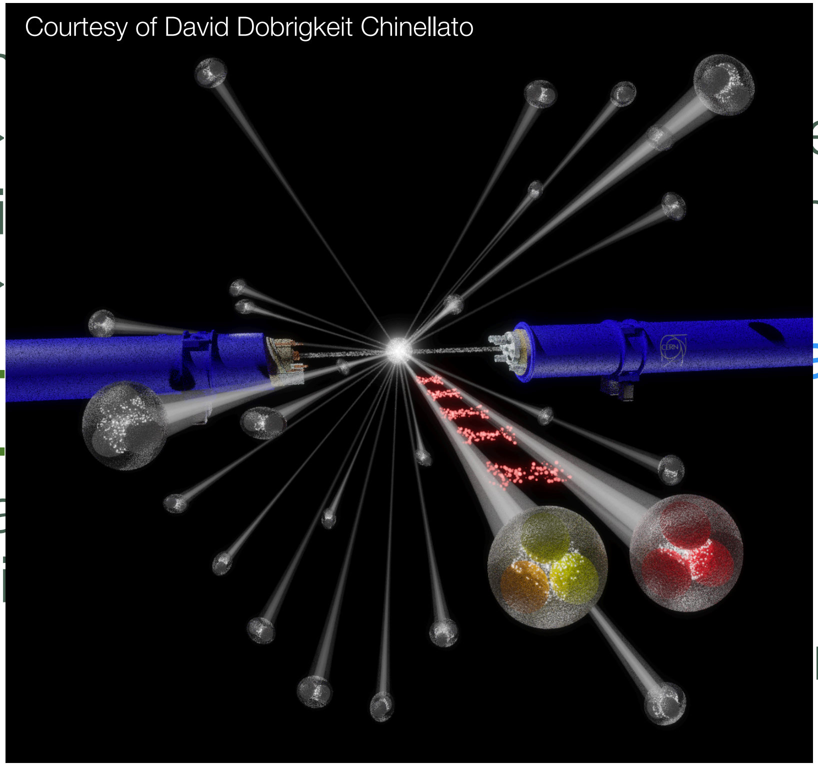


- Enhancement above Coulomb
  → Observation of the strong interaction
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  1. Total Absorption by inel. channels
  2. Neglecting inel. channels
- Data more precise than the first principle calculations
  - So far, no indication for a bound state
- Unveiling the strong interaction among stable and unstable hadrons at the LHC – accepted by Nature

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



- En… → …eraction
- Mi…nnel → …
  1. …annels
  2. …
- Da… pri…
  - …nd



- Unveiling the strong interaction among stable and unstable hadrons at the LHC – accepted by Nature

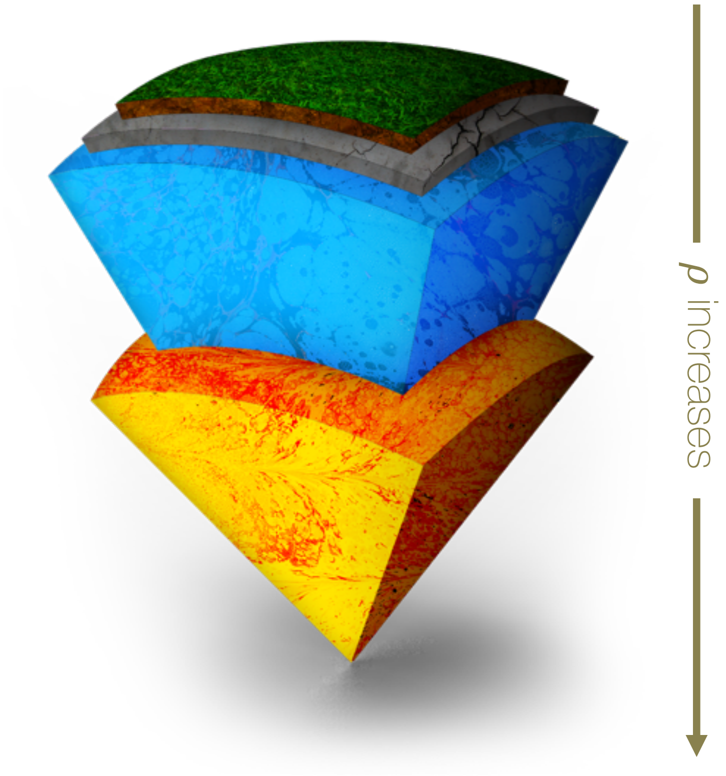
Excursion to neutron stars

Neutron Stars

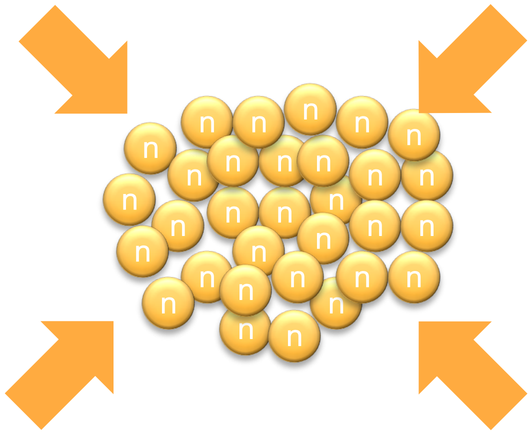
Dimensions
R ~ 10 – 15 km
M ~ 1.5 – 2 $M_{\odot}$

Outer Crust
Ions, electron Gas,
Neutrons

Inner Core
Neutrons?
Protons?
Hyperons?
Quark Matter?



- **Neutron Stars:** very dense, compact objects

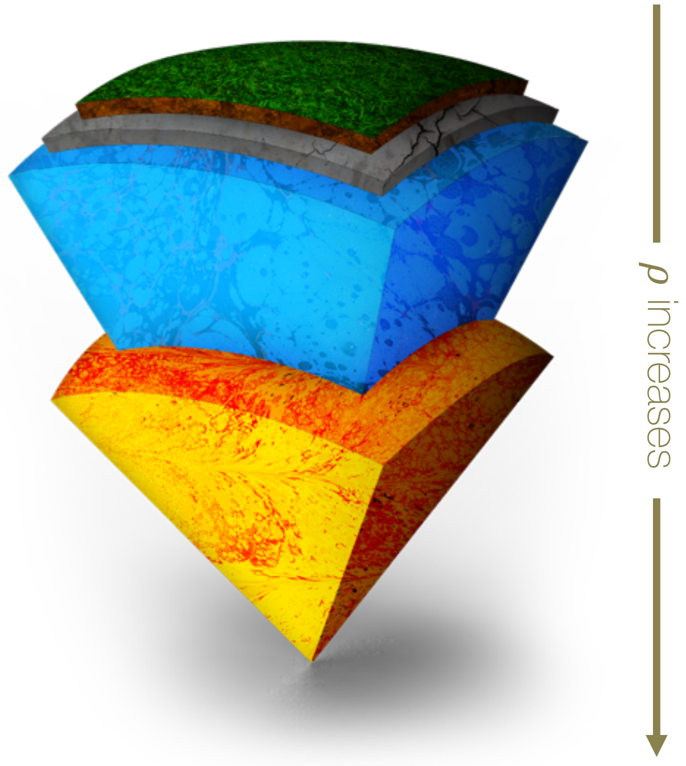


Neutron Stars

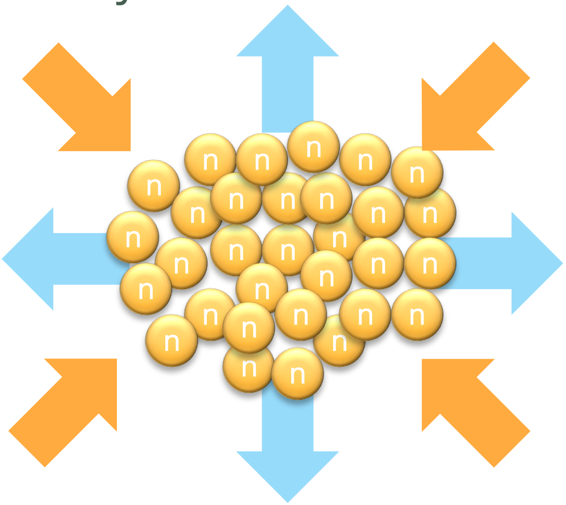
Dimensions
R ~ 10 – 15 km
M ~ 1.5 – 2 $M_\odot$

Outer Crust
Ions, electron Gas,
Neutrons

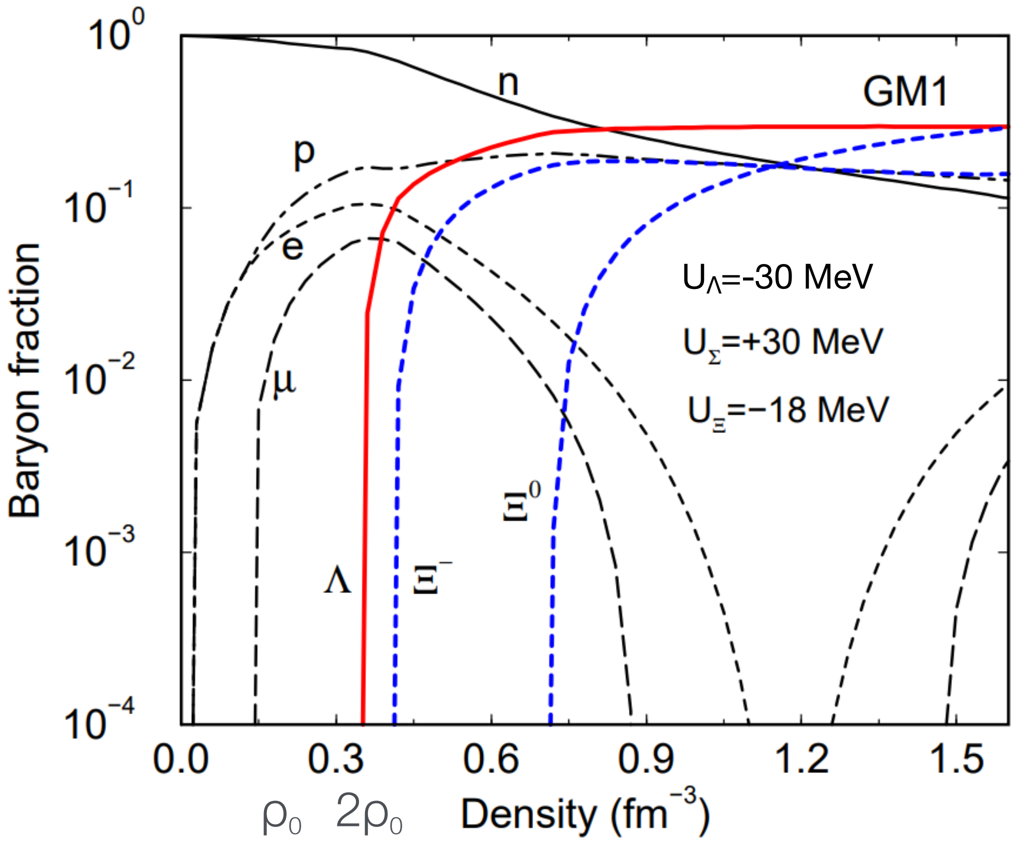
Inner Core
Neutrons?
Protons?
Hyperons?
Quark Matter?



- **Neutron Stars:** very dense, compact objects
- What is the EoS?
  - What are the constituents to consider?
  - How do they interact?

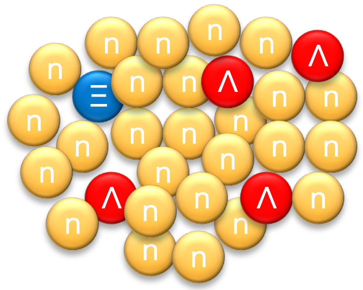


Hyperons in Neutron Stars?

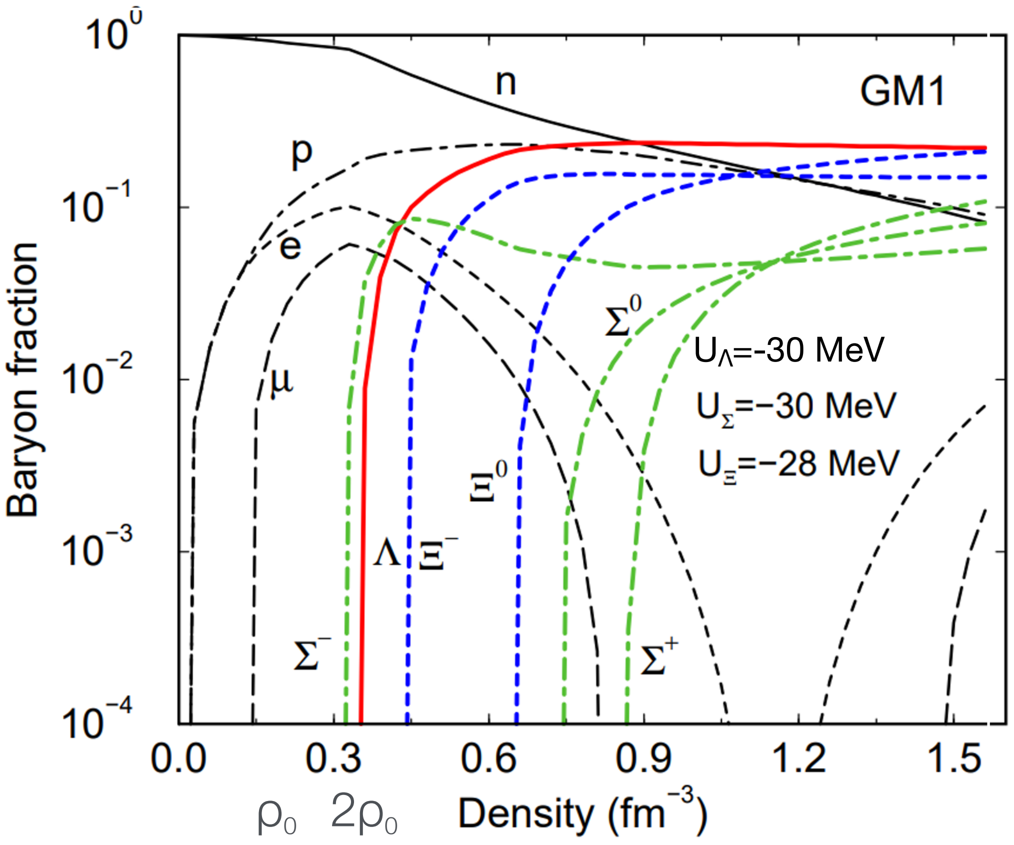


J. Schaffner-Bielich, Nucl. Phys. A 804 (2008), 309-321

- At finite densities **hyperon** production becomes energetically favorable

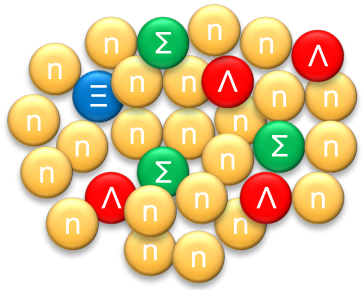


Hyperons in Neutron Stars?



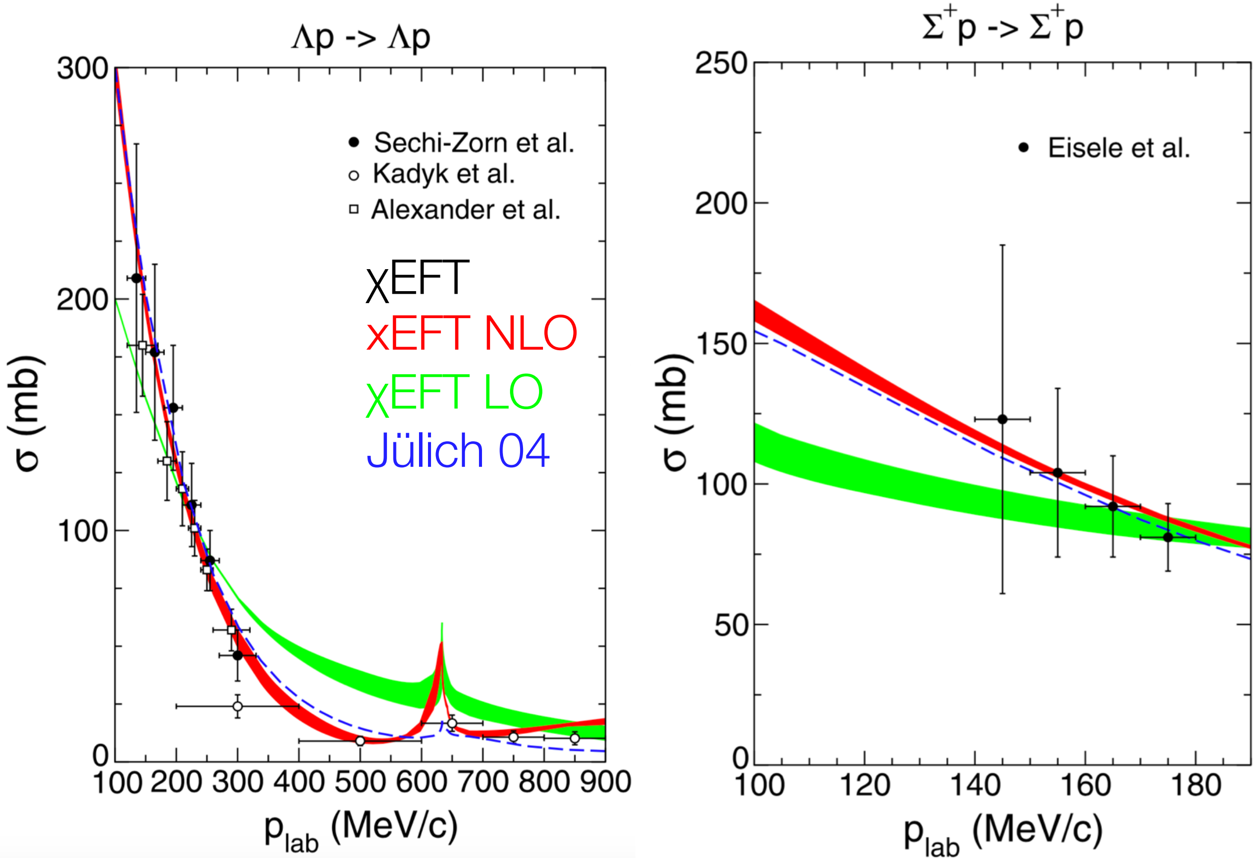
J. Schaffner-Bielich, Nucl. Phys. A 804 (2008), 309-321

- At finite densities **hyperon** production becomes energetically favorable
- Exact composition strongly depends on constituent interactions and couplings!



|S| = 1 sector – Λ and Σ baryons

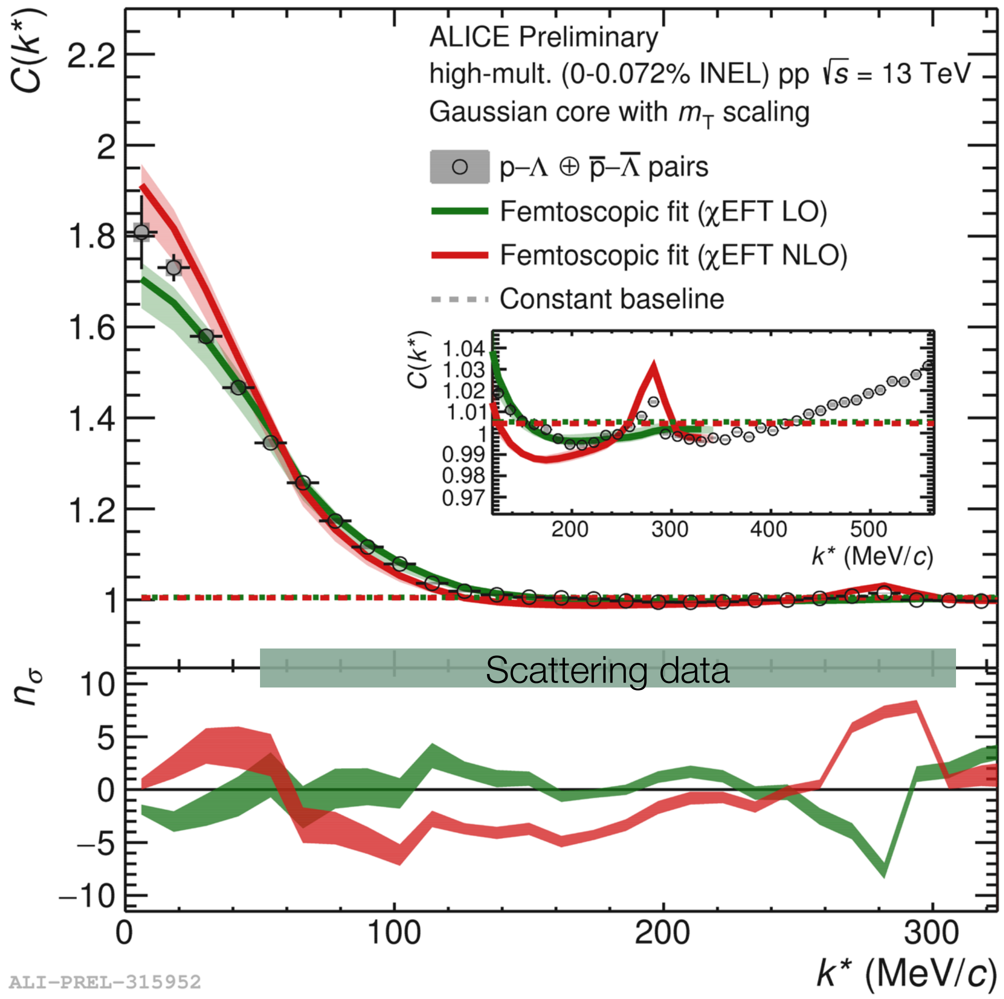
- Scarce experimental data
  - No constraints at lab momenta below 100 MeV/*c*
- Theoretical predictions for cusp: Coupling of Σ–N - Λ–N
  - Coupling introduces a repulsive short-range component in the p–Λ interaction
  - **Not experimentally confirmed so far**



J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24.

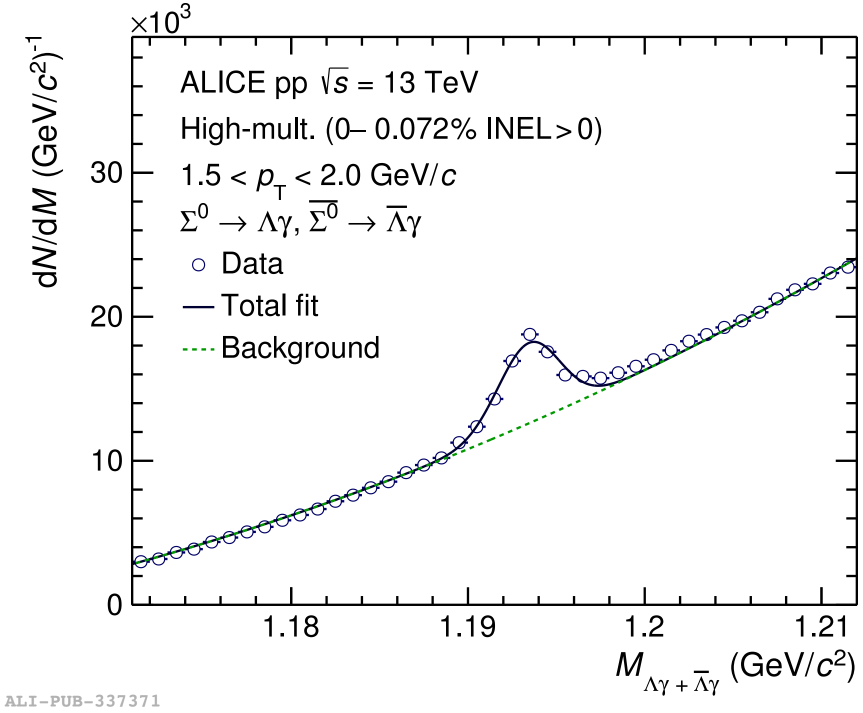
Measurement of the p–Λ interaction

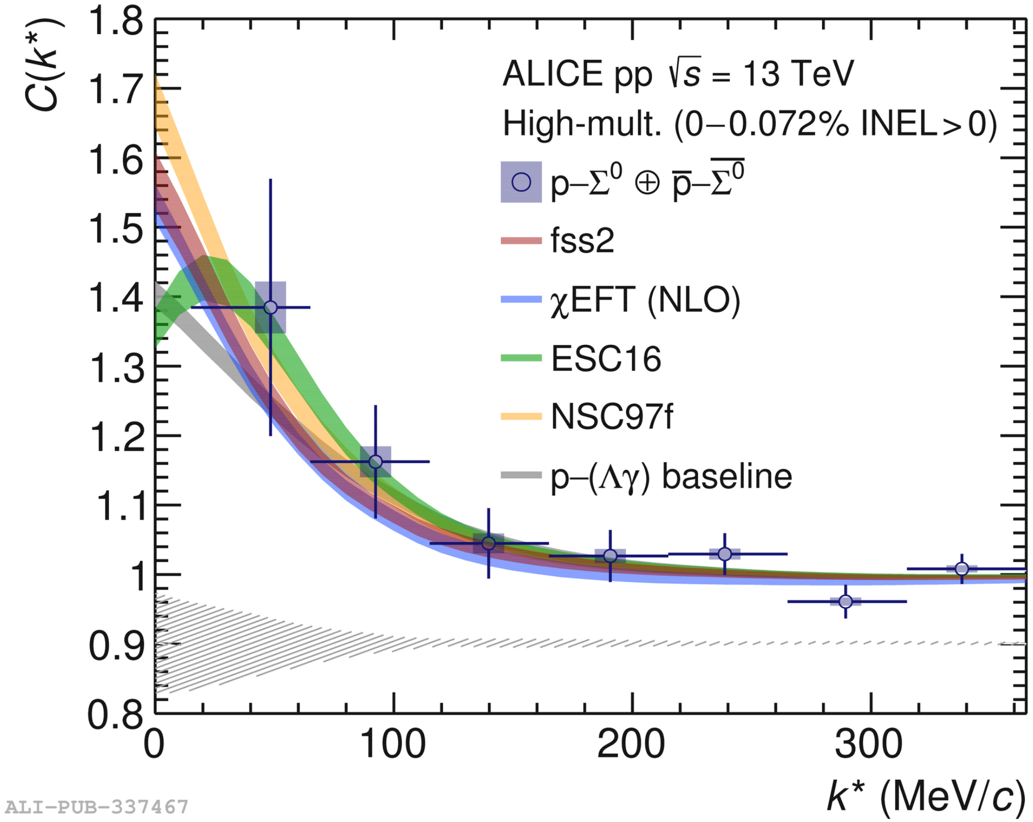
- Significant extension of the kinematic range
- Clear experimental evidence for the cusp of NΛ⇔NΣ^0 coupling
- Discrimination power between calculations at LO and NLO
  - Updated predictions → Agreement improves significantly for NLO
  - In the future: Use the data to fine tune theory
- Paper currently in collaboration review



Measurement of the p–Σ^0 interaction

- $\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)
  - Identification of the photon via conversions
  - Significant contribution from correlated p–($\Lambda\gamma$) background due to low purity
    ALICE collaboration, Phys. Lett. B 805 (2020) 135419

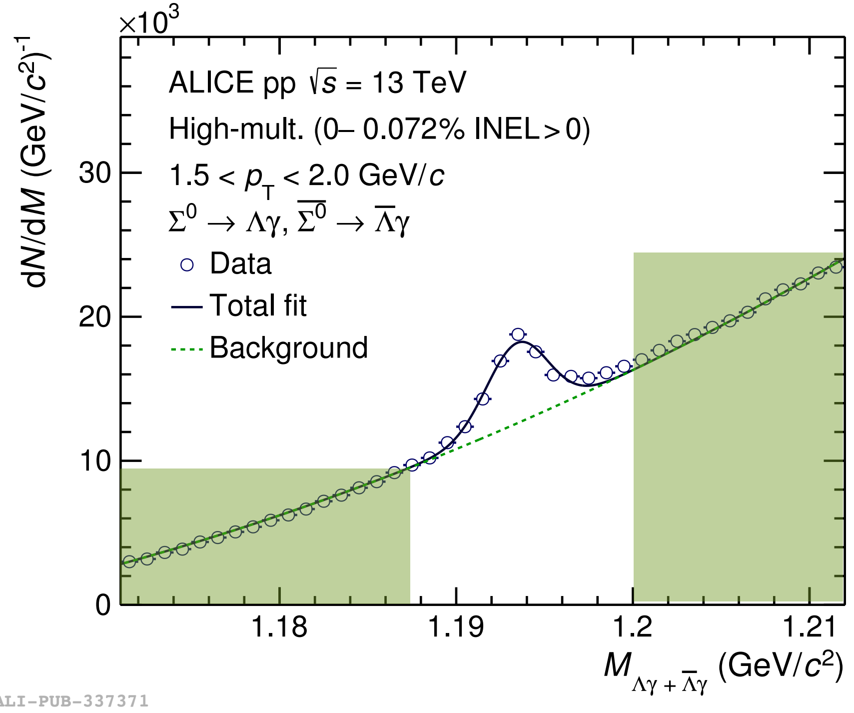


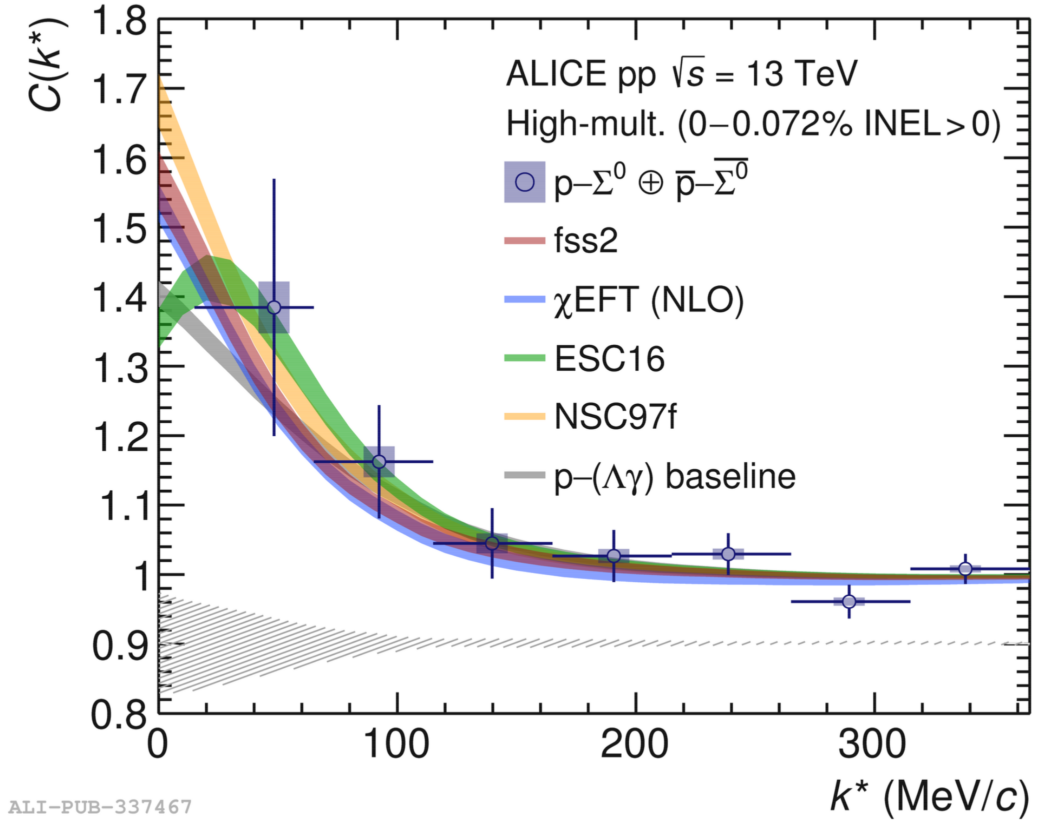


χEFT: J. Haidenbauer et. al, Nucl. Phys. A915 (2013) 24–58.
NSC97f: T. A. Rijken et. al, Phys. Rev. C59 (1999) 21–40
ESC16: M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003
fss2: Y. Fujiwara et al., Prog. Part. Nucl. Phys. 58, 439–520 (2007)

Measurement of the p–Σ^0 interaction

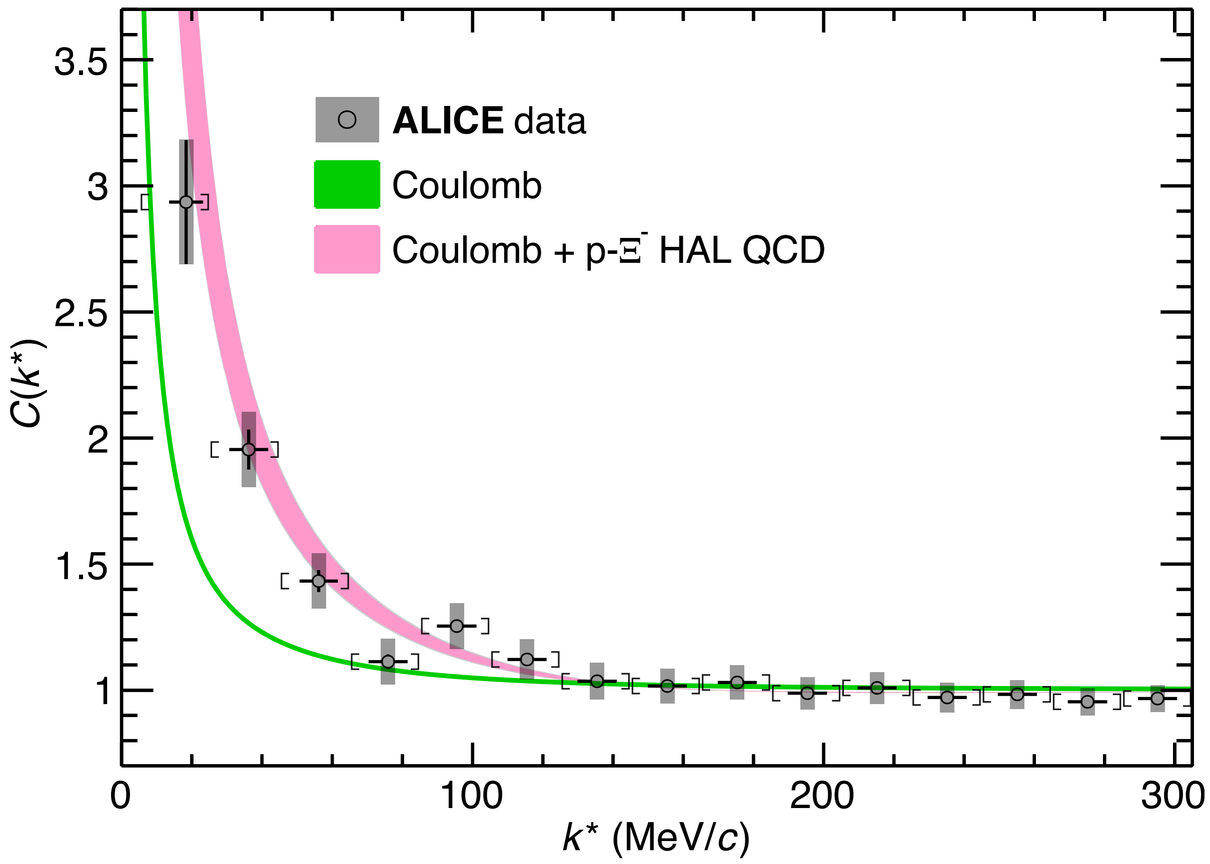
- $\Sigma^0 \rightarrow \Lambda\,\gamma$ (BR: almost 100 %)
  - Identification of the photon via conversions
  - Significant contribution from correlated p–($\Lambda\gamma$) background due to low purity
    ALICE collaboration, Phys. Lett. B 805 (2020) 135419





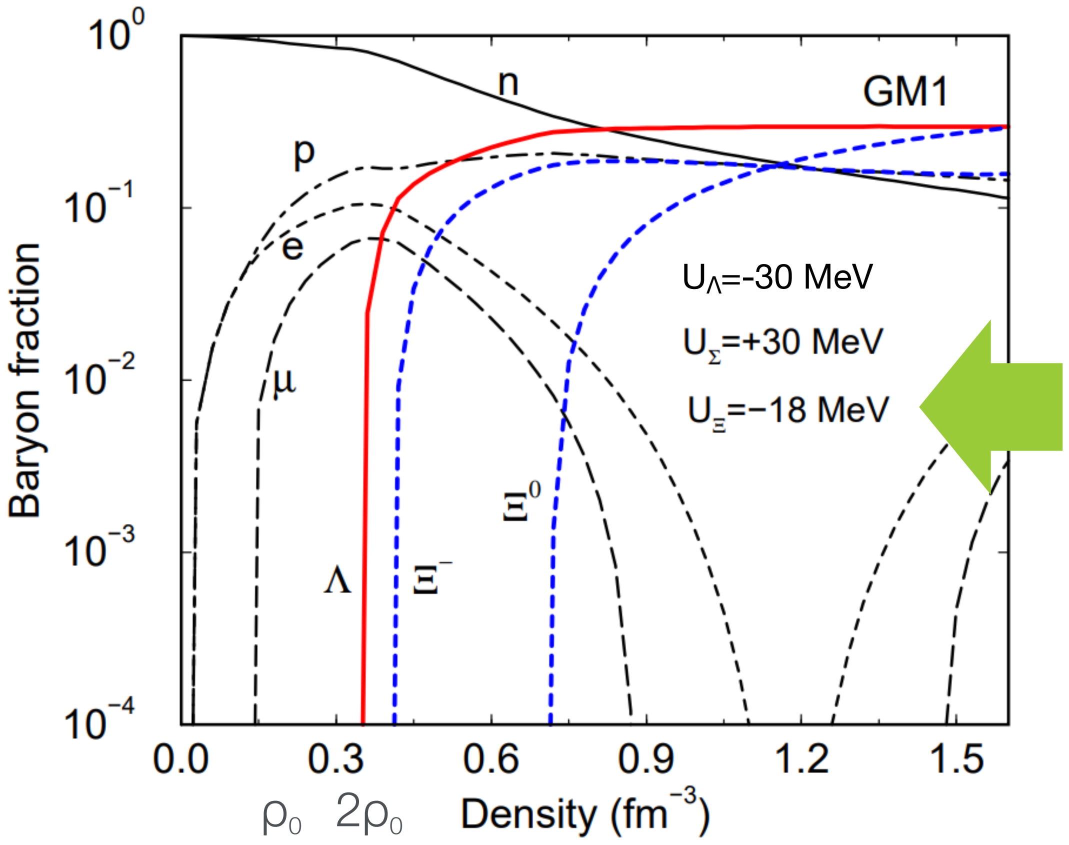
χEFT: J. Haidenbauer et. al, Nucl. Phys. A915 (2013) 24–58.
NSC97f: T. A. Rijken et. al, Phys. Rev. C59 (1999) 21–40
ESC16: M. M. Nagels et. al, Phys. Rev. C99 (2019) 044003
fss2: Y. Fujiwara et al., Prog. Part. Nucl. Phys. 58, 439–520 (2007)

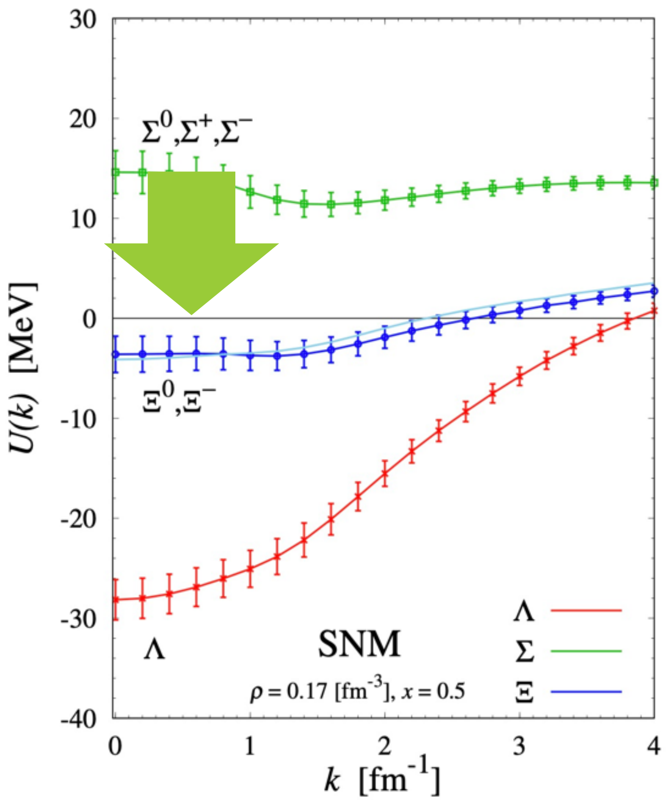
p–Ξ⁻ correlation function in pp at 13 TeV



- Enhancement above Coulomb → Observation of the strong interaction
- Measurement in different collision system retains excellent agreement with lattice predictions (HAL-QCD)
  - Continuation of the study in the p-Pb system Phys. Rev. Lett. 123, 112002
- Unveiling the strong interaction among stable and unstable hadrons at the LHC – accepted by Nature

Single particle potentials from lattice QCD

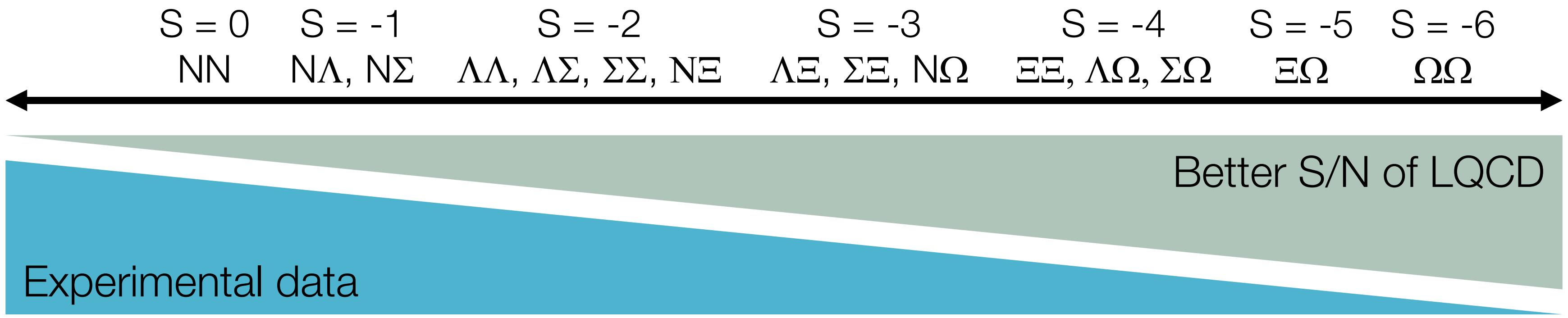




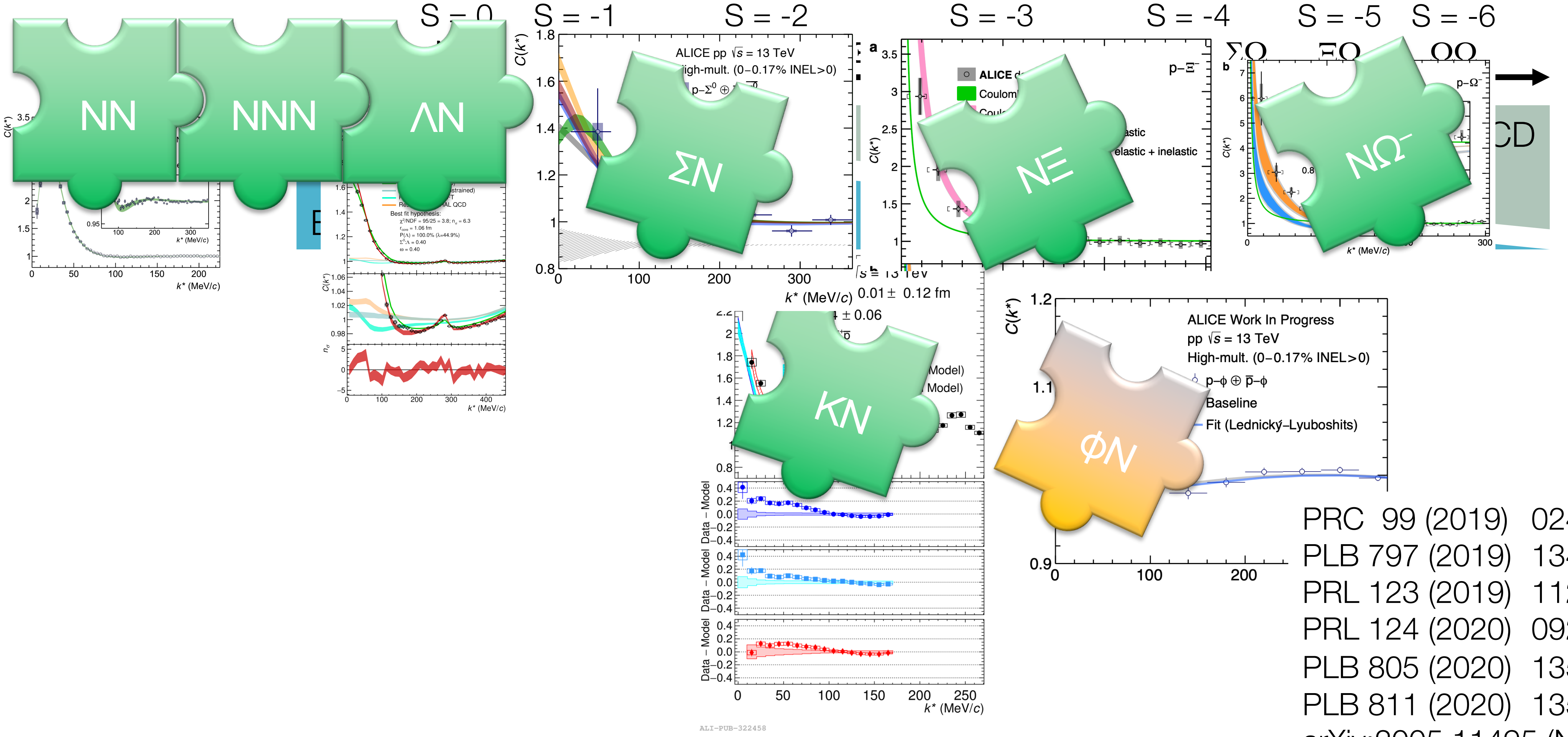
J. Schaffner-Bielich, Nucl. Phys. A 804 (2008), 309-321

Inoue, T. Strange nuclear physics from QCD on lattice. AIP Conference Proceedings 2130, 020002 (2019)

The Harvest of Run 2 and beyond

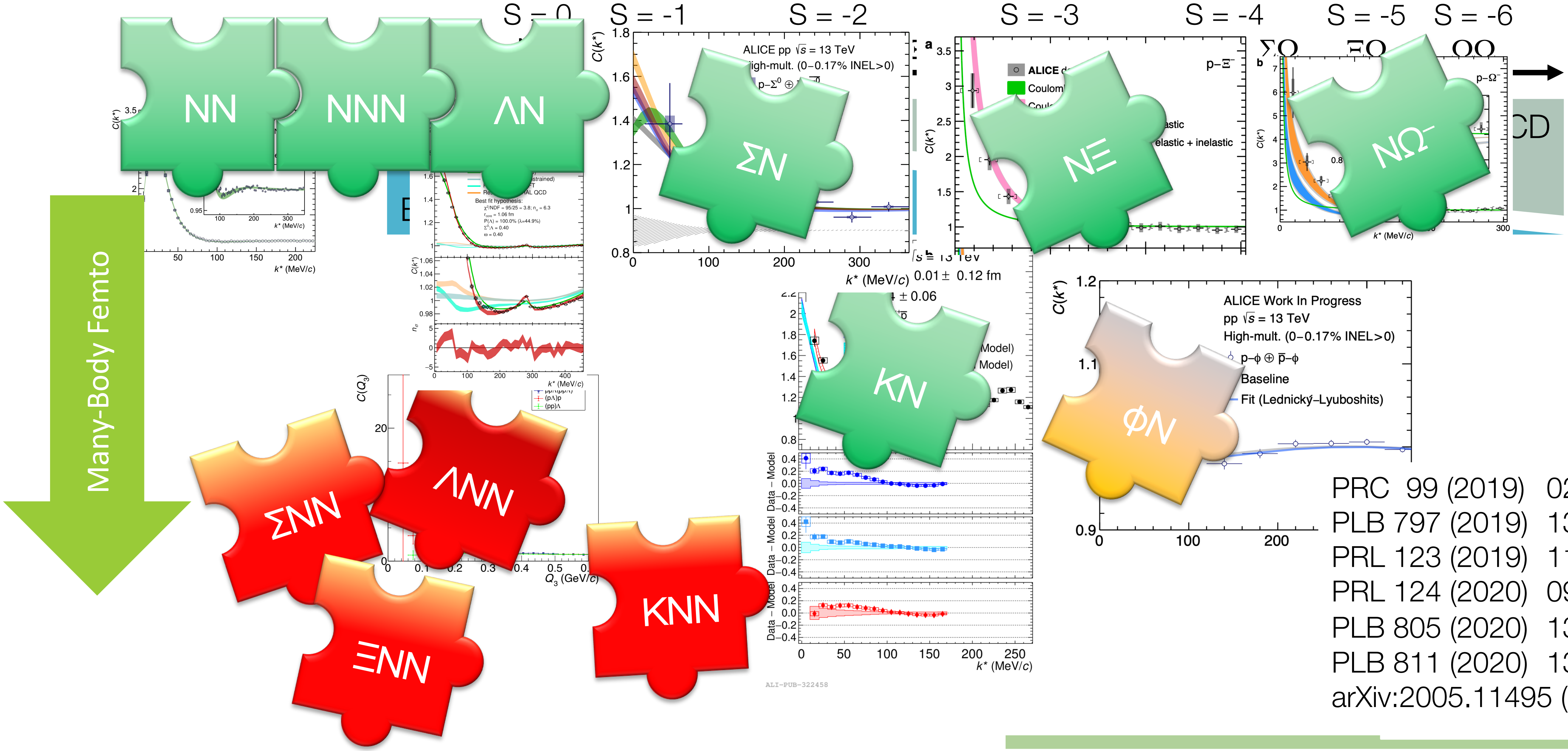


The Harvest of Run 2 and beyond



PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
arXiv:2005.11495 (Nature)

The Harvest of Run 2 and beyond



PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
arXiv:2005.11495 (Nature)

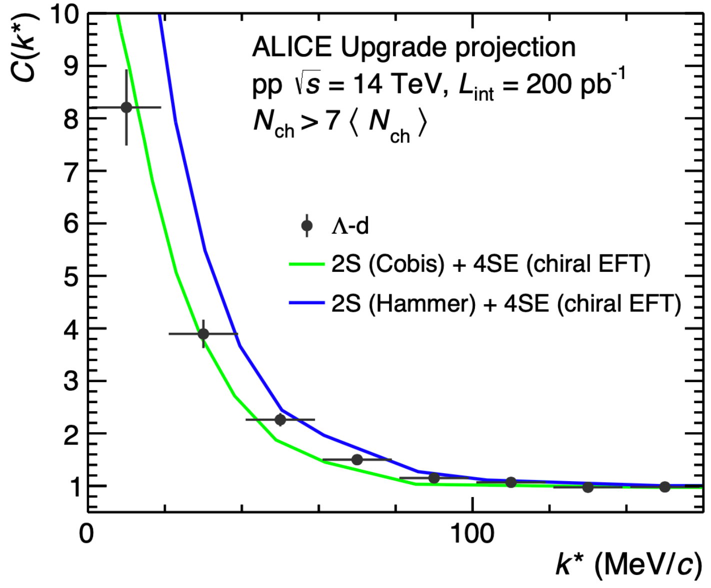
The future is soon: Run3 of the LHC

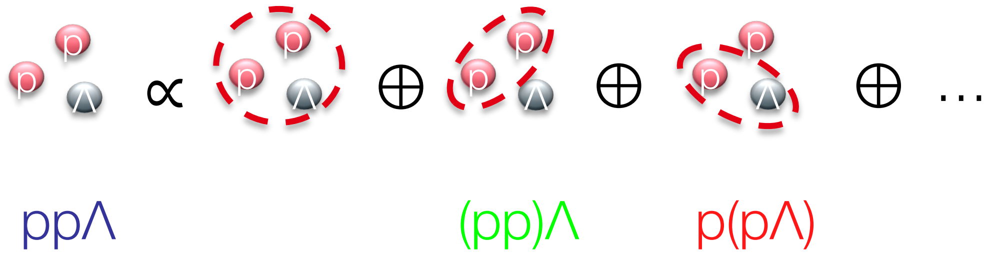
- Commissioning of upgrades of several ALICE detectors
  - e.g. New ITS, TPC read-out etc.
- Improved data taking conditions
  - Higher luminosities by the LHC
  - Continuous readout
- Good news for Femtoscopy studies!
  - ➢ O(100) larger event sample
  - ➢ Dedicated trigger to detect events with hyperons e.g. Ω^-

Reaction	Energy	Total Statistics RUN3 (evts)
pp	5.5 TeV 14 TeV	4×10^{11} 2.4×10^{11}
pp	14 TeV	2×10^{9}
p-Pb	8.8 TeV	6×10^{11}

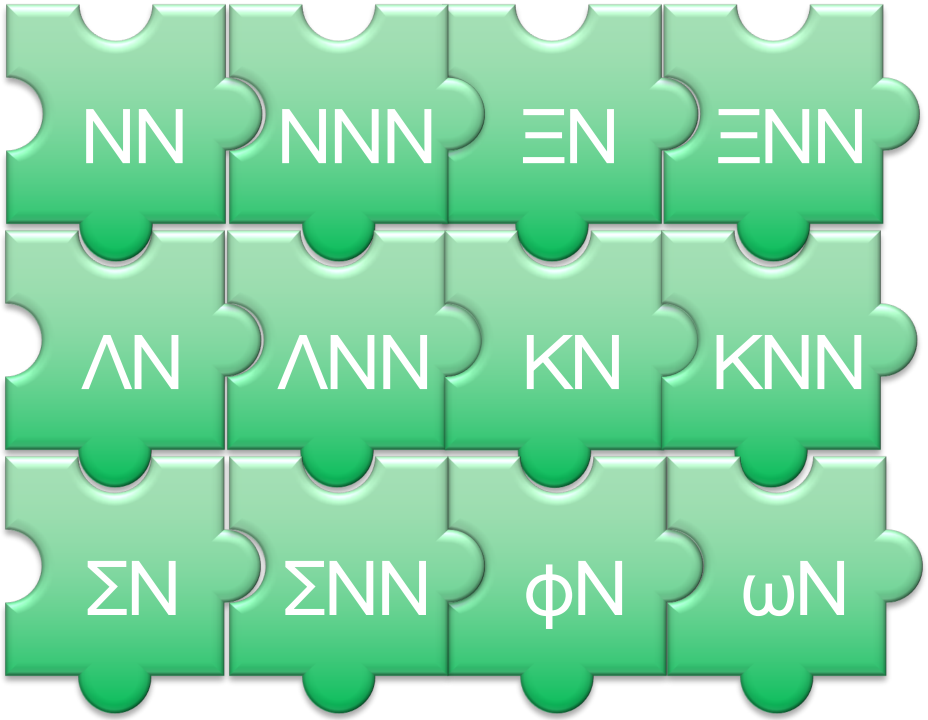
Measurements of the 3-body Forces

- Indirect: Λ-d correlations
  - Hypertriton $^{3}_{\Lambda}\mathrm{H}$ binding energy ⇔ Scattering parameters of the doublet ^{2}S state
  - Spin triplet $^{3}S_{1}$ Λ–N interaction ⇔ ^{4}S state
- Direct: Extraction of the genuine ppΛ three-body force via cumulants
  - Following the methods described in PRC 89 (2014) 024911
- The Run 3 & 4 data samples will provide a high-precision measurement





… towards the solution of the puzzle



Thanks for your attention

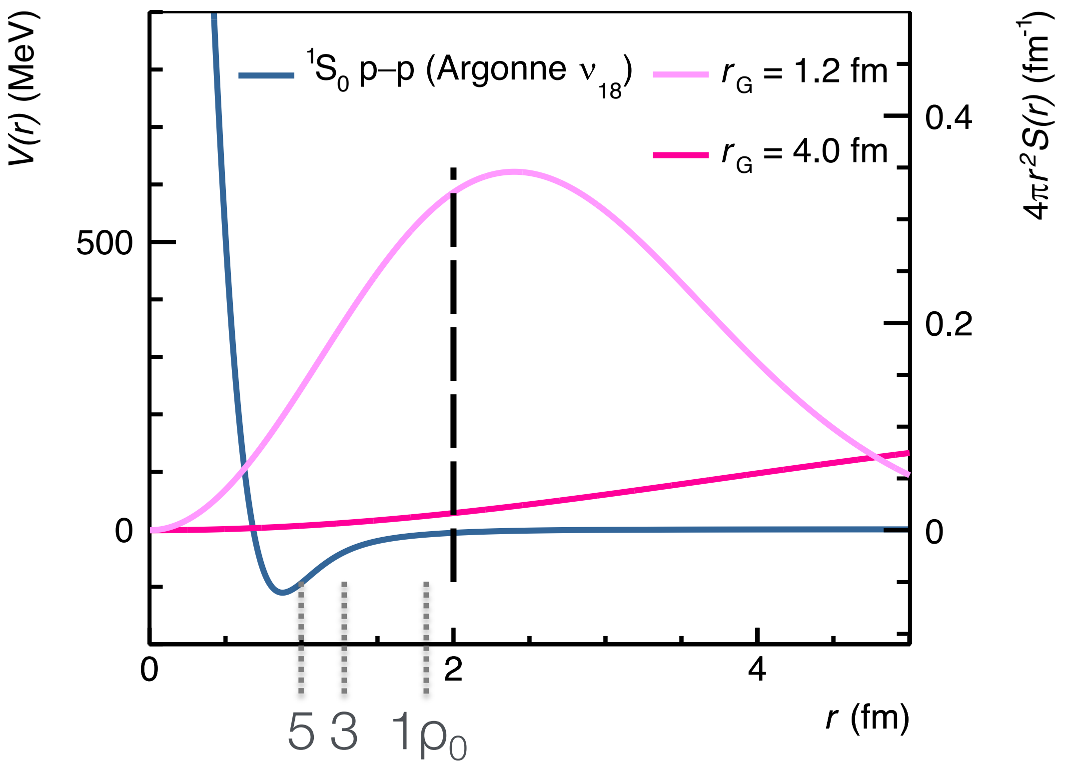
Backup

Strong interaction among (strange) baryons

	Effective Theories		First principles calculations
	Meson exchange models	Chiral Effective field theory	Lattice QCD calculations
General properties	• Hadronic degrees of freedom • Coupling constants fitted to scattering data and Hypernucleii data		• Quarkonic and gluonic degrees of freedom • Lattice calculations with almost physical Pion (146 MeV) and Kaon (525 MeV) masses
NN	✓	✓ (N^3LO)	✗
NΛ	✓	✓ (NLO)	✗
NΣ	✓	✓ (NLO)	✗
ΛΛ	✓	✓ (NLO)	✓
NΞ	✓	✓ (NLO)	✓
NΩ	✓	✗	✓

Two-particle correlation function

- Study of correlations in the relative momentum k^* distribution of particle pairs
- Linked to the source and two-particle wave function
- In elementary collisions: small source sizes
  - ➢ Doorway to study large densities



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

Residual and non-femtoscopic correlations

$$C_{tot}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down misidentifications

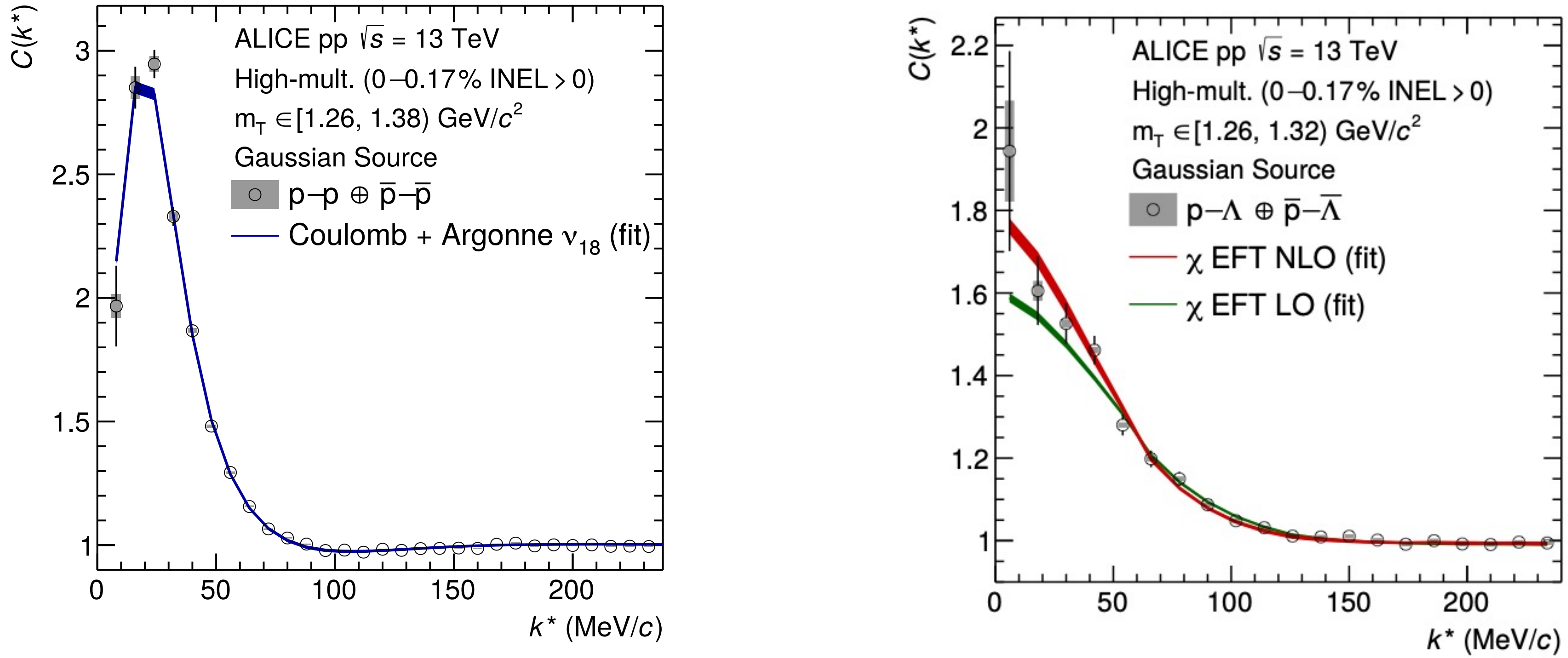
- Pair contributions quantified by purity ($\mathcal{P}_i$) and feed-down fractions (f_i)

$$\lambda_{ij} = \mathcal{P}_1 \cdot f_{i_1} \cdot \mathcal{P}_2 \cdot f_{j_2}$$

- Finite momentum resolution of the detector
- Non flat baseline

(Details see Phys. Rev. C 99 (2019), 024001)

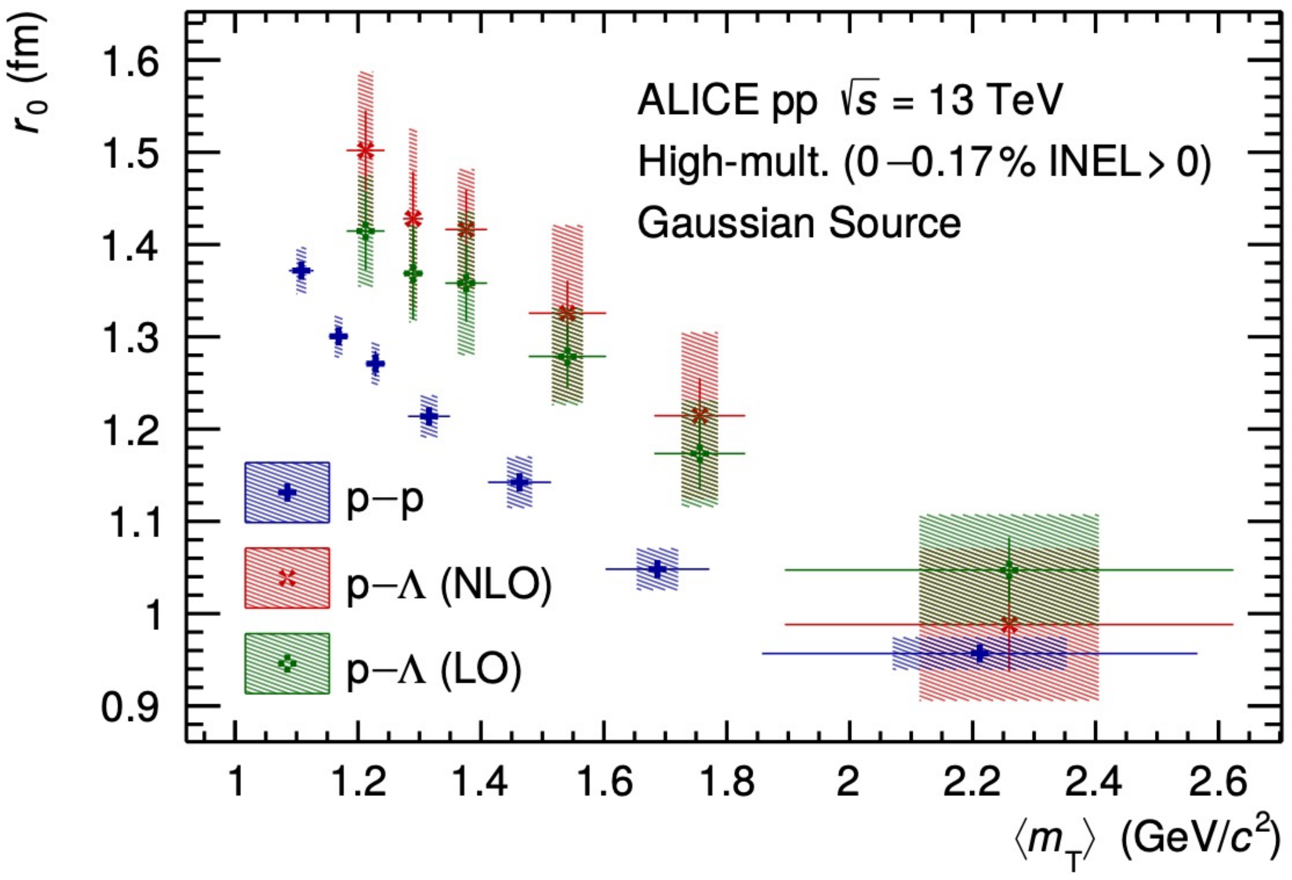
A Gaussian source with resonances



- Each <m_T> bin fitted independently with the two source models
- Our Ansatz: The scaling should be the same
    - The results are compared for p-p and p-Λ correlation

Paper in press at PLB

A Gaussian source with resonances



Paper in press at PLB

Coupled channel wave functions

- Pairs close in mass with the same quantum numbers: e.g. p–Ξ^- and Λ–Λ
- Schrödinger equation of one pair → Equation system of all 1, … , N pairs

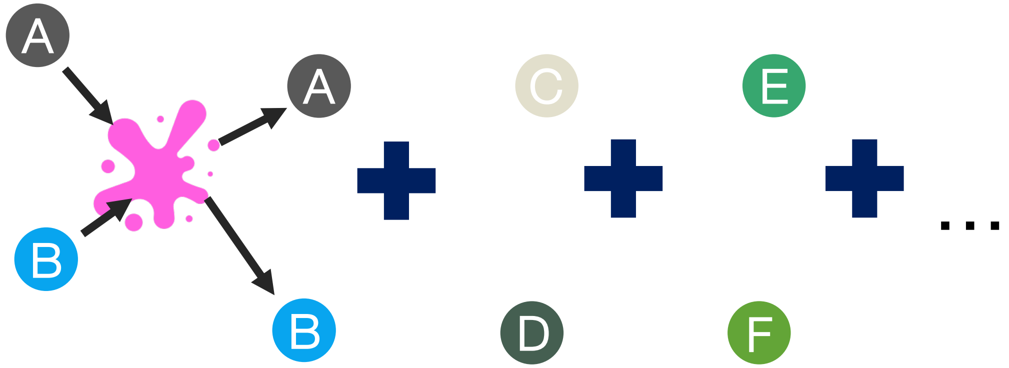
$$\hat{\mathcal{H}} \cdot \psi = \mathrm{E} \cdot \psi \mapsto \begin{pmatrix} \hat{\mathcal{H}}_{11} & \cdots & \hat{\mathcal{H}}_{1\mathrm{N}} \\ \vdots & \ddots & \vdots \\ \hat{\mathcal{H}}_{\mathrm{N}1} & \cdots & \hat{\mathcal{H}}_{NN} \end{pmatrix} \cdot \begin{pmatrix} \psi_1 \\ \vdots \\ \psi_N \end{pmatrix} = E \cdot \begin{pmatrix} \psi_1 \\ \vdots \\ \psi_N \end{pmatrix}$$

1) Coupled channels influence the elastic channels of the two-particle wave function ψ_j

Observation of coupled channels

Scattering experiments: Boundary condition given by the initial state

- e.g. beam + target of particle pair of interest
- Coupled channels measured in the final state



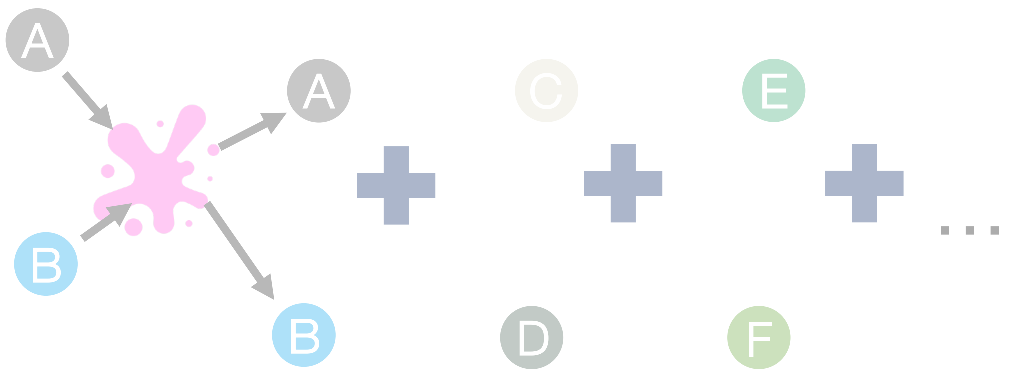
Observation of coupled channels

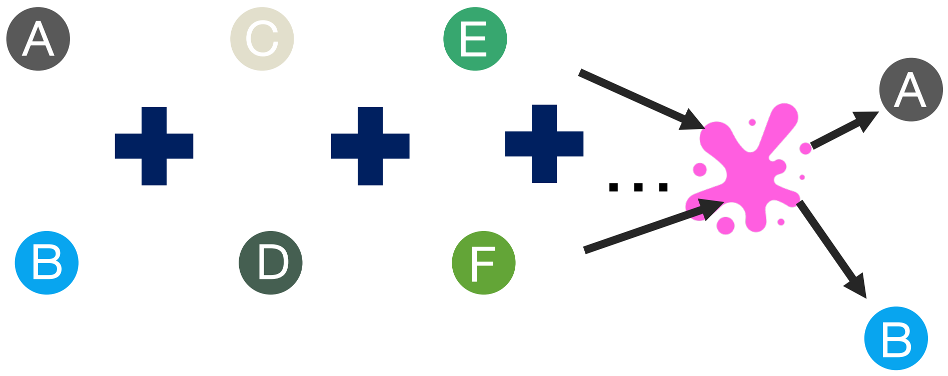
Scattering experiments: Boundary condition given by the initial state

- e.g. beam + target of particle pair of interest
- Coupled channels measured in the final state

Femtoscopy: Boundary condition given by the final state

- All coupled pairs produced in the initial state contribute to the final state
- Measurement of one final state





Femtoscopy with coupled channels

2) Each <u>inelastic coupled channel</u> contributes to the correlation function

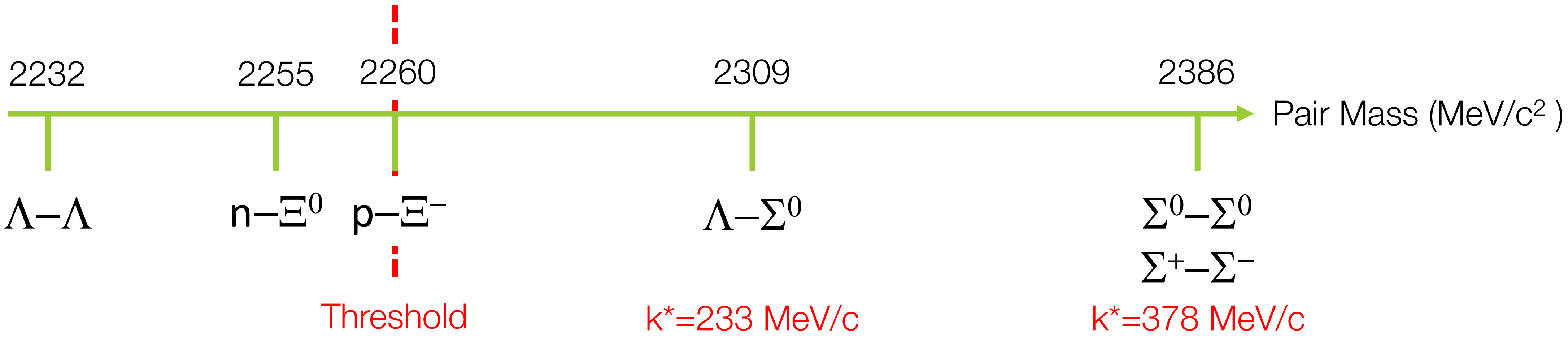
$$C(k^*) = \int S(\boldsymbol{r})|\psi(k^*,\boldsymbol{r})|d^3r \mapsto C(k^*) = \sum_j \int w_j \cdot S_j(\boldsymbol{r})\left|\psi_j(k^*,\boldsymbol{r})\right|d^3r$$

- Wave function $\psi_j(k^*,\boldsymbol{r})$ of each channel j contributes to $C(k^*)$
  - ➢ Obtained from the coupled channel Schrödinger equation
  - ➢ Shifted to fulfill the boundary condition given by the outgoing pair
- Weights w_j related to the prompt particle yield N(h):
  - ➢ $w_j = (N(h'_1)N(h'_2))_{coupled}/(N(h_1)N(h_2))_{outgoing}$
  - ➢ Estimated from e.g. Statistical Hadronization Model

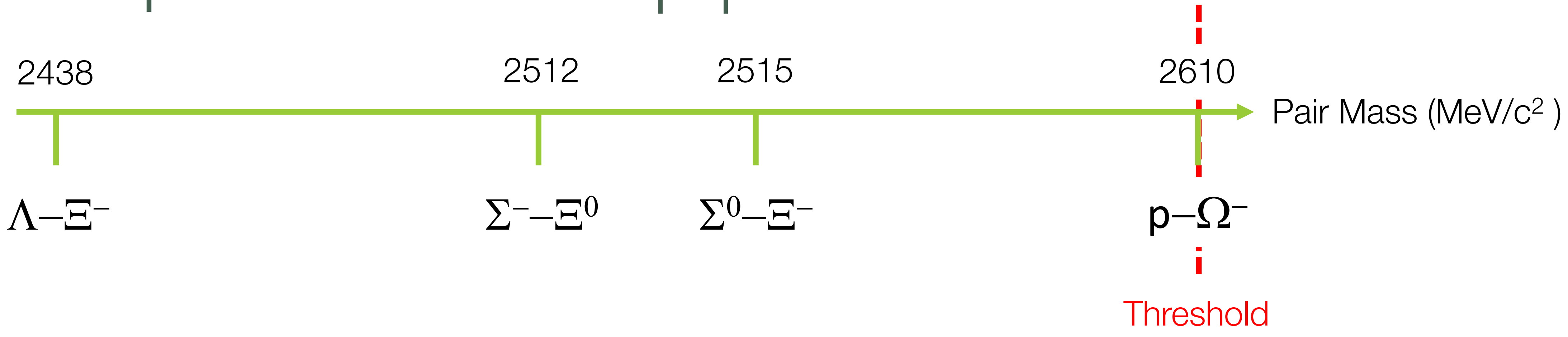
Coupled channels in |S| = 2

2) Each <u>inelastic coupled channel</u> contributes to the correlation function

$$C(k^*) = \sum_j \int w_j \cdot S_j(\boldsymbol{r}) \left|\psi_j(k^*, \boldsymbol{r})\right| d^3r$$



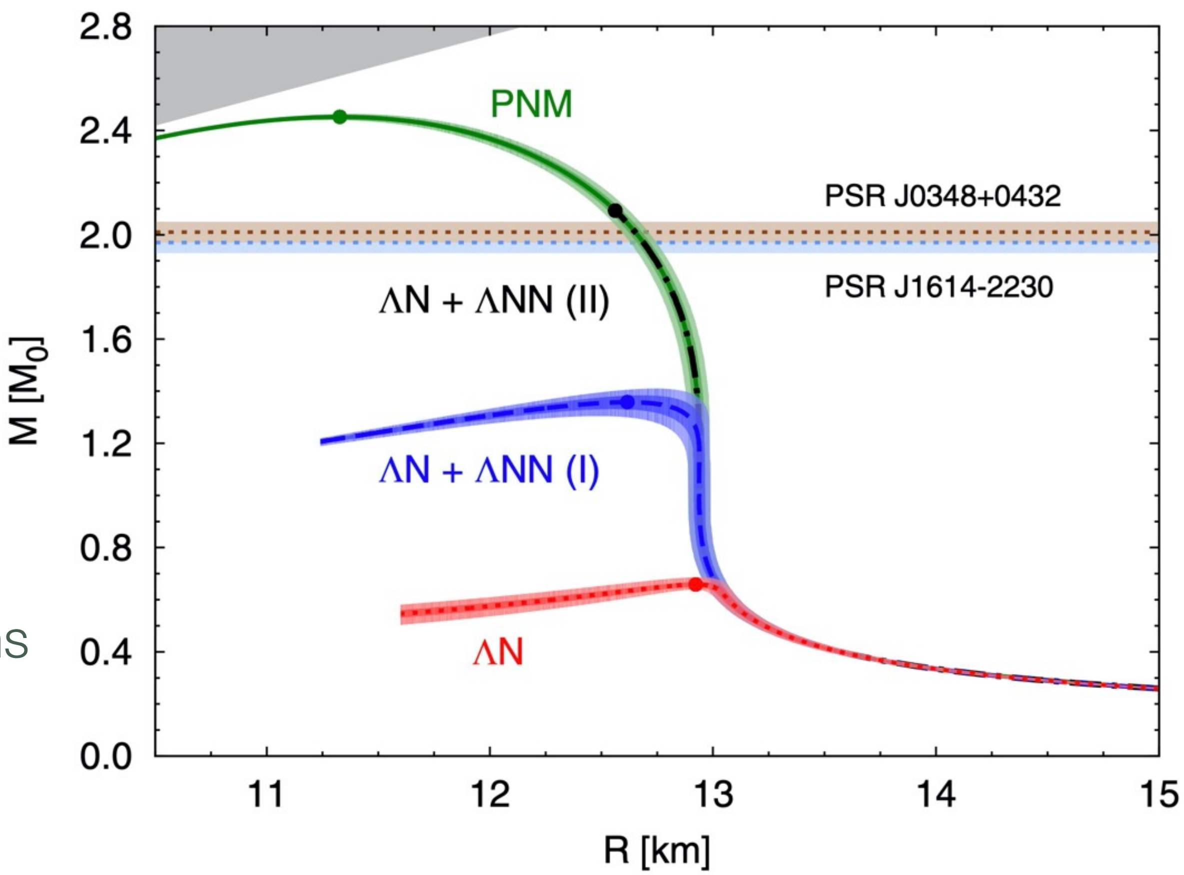
Couple channels in |S| = 3



- 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

EoS and three-body Forces

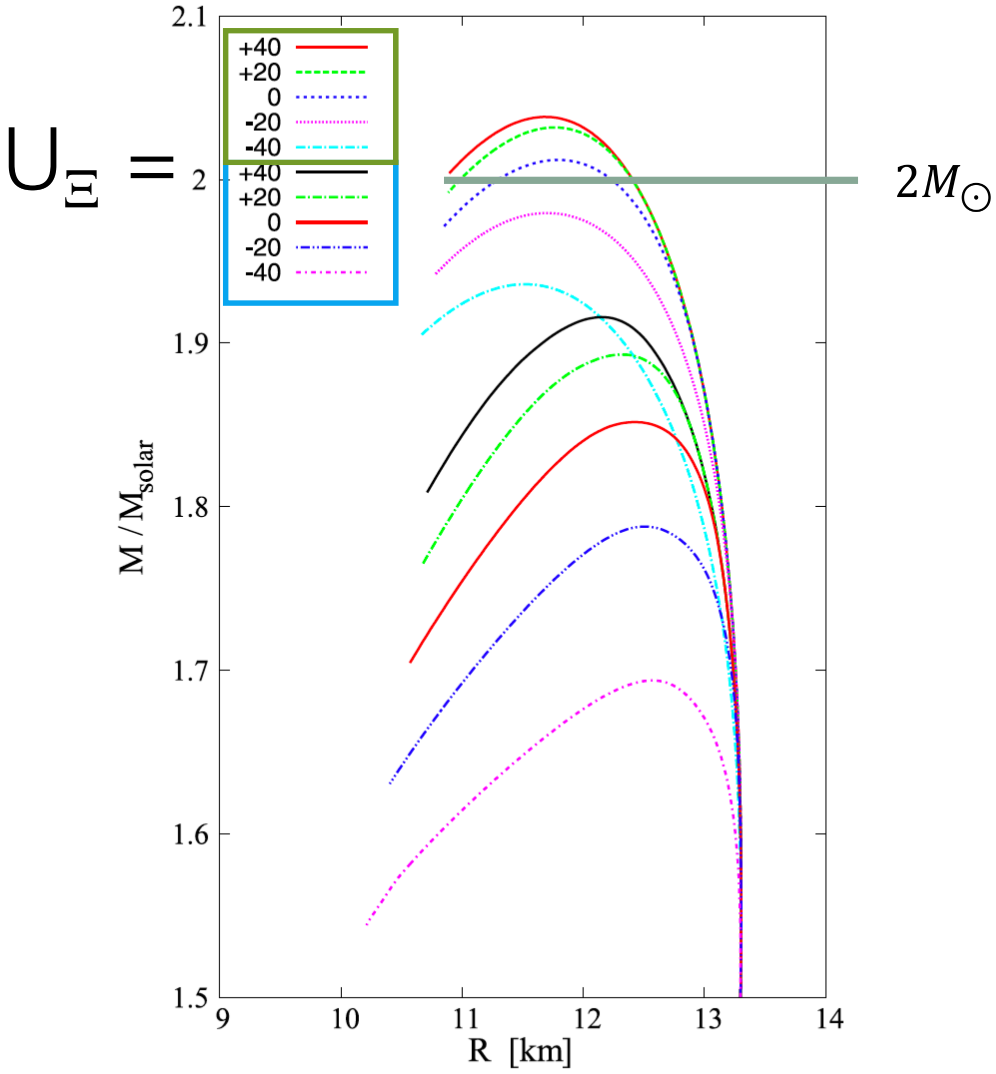
- Benchmark for EoS: Observation of neutron stars with $m=2M_{\odot}$
- Explore presence of nucleons + Λ's
  - 2-body ΛN interaction: $M_{max} << 2\ M_{\odot}$
    - ➢Hyperon Puzzle
  - Additional repulsive 3-body forces
    - Constraint by a fit to hypernucleii binding energies
    - In line with expectation by χEFT calculations
      e.g. https://doi.org/10.1140/epja/s10050-020-00180-2
- What about the other Hyperons?!



dx.doi.org/10.1103/PhysRevLett.114.092301

Exemplary EoS with Ξ Baryons

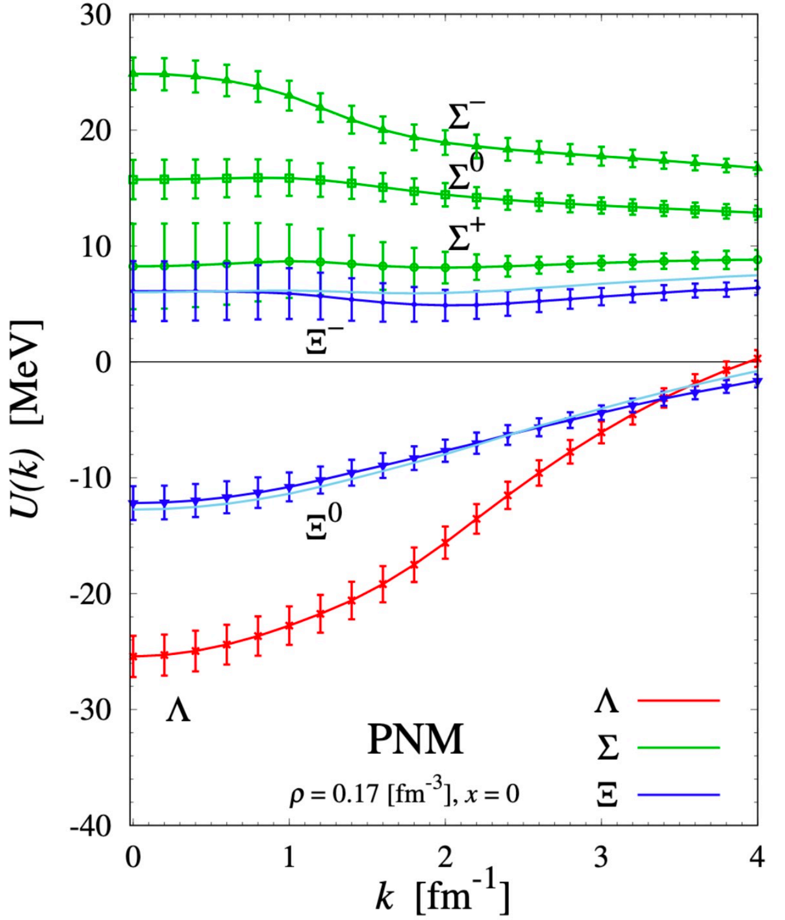
- Scan of different single particle potentials U_Ξ in pure neutron matter
- Ingredients:
  - Attractive U_Λ = - 30 MeV fitted to data from Hypernucleii
  - Assumes repulsive U_Σ = 30 MeV
  - With and without repulsive Hyperon Hyperon interaction



S. Weissborn et al., Nuclear Physics A 881 (2012) 62-77

Implications for neutron stars

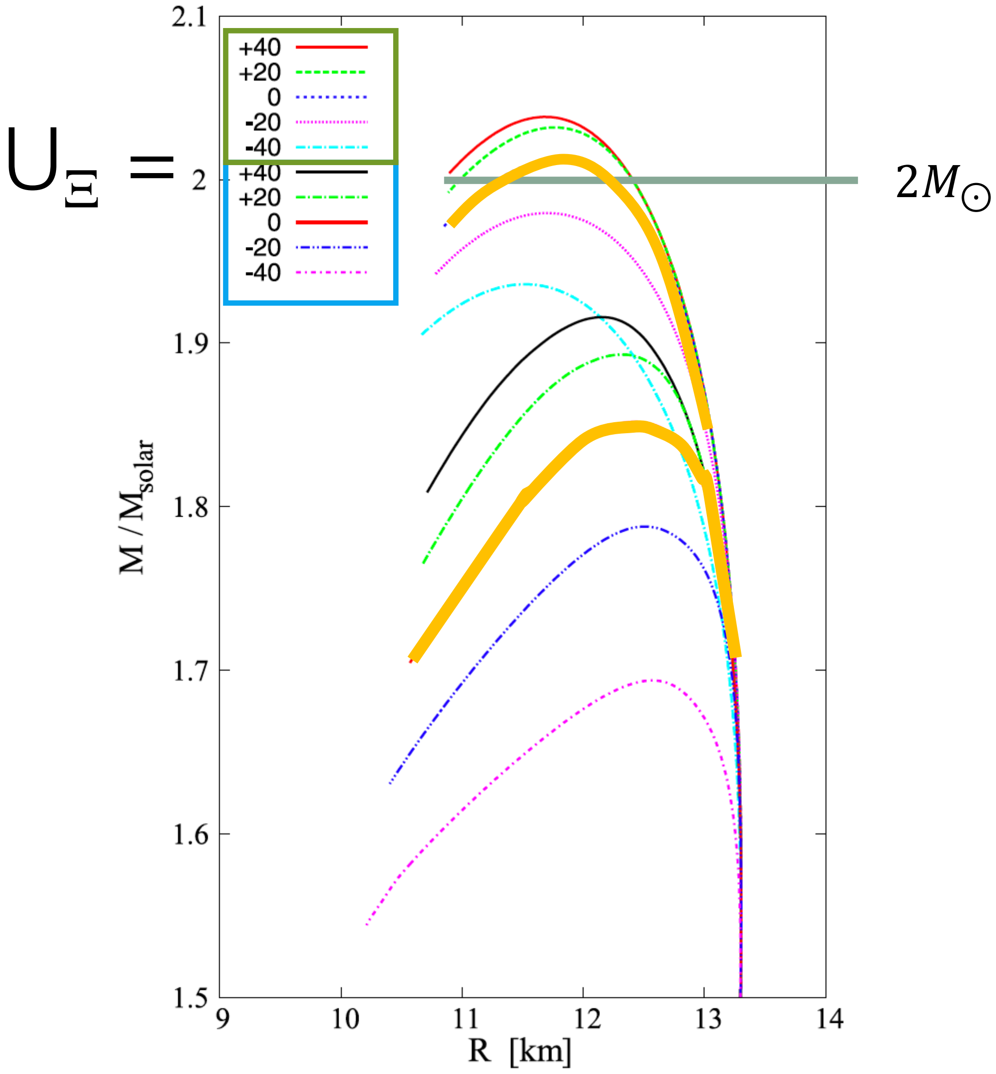
- In medium: Many body interaction – particle experiences an average potential
  - ➢ Single particle potential
- Neutron star: Pure neutron matter
  - Slightly repulsive U_{Ξ^-} ~ 6 MeV/c



HAL QCD Collaboration, arXiv:1809.08932

Implications for neutron stars

- In medium: Many body interaction – particle experiences an average potential
  - ➢ Single particle potential
- Neutron star: Pure neutron matter
  - **Slightly repulsive U_{Ξ^-} ~ 6 MeV/c**



S. Weissborn et al., Nuclear Physics A 881 (2012) 62-77