Unveiling the strong interaction between stable and unstable baryons with ALICE at the LHC

Jacek Otwinowski (IFJ PAN)
On behalf of the ALICE Collaboration

Outline

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

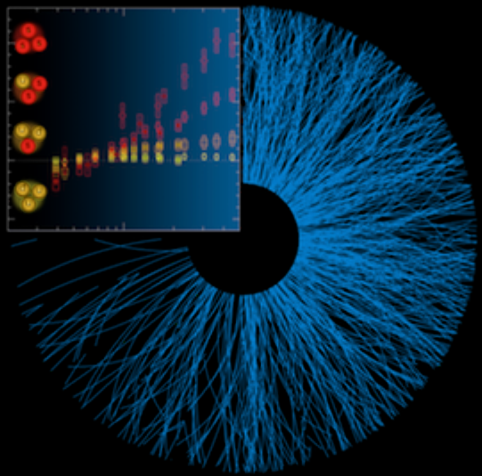
- Introduction
- ALICE measurements
- Summary and Outlook

Outline

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

- Introduction
- ALICE measurements
- Summary and Outlook

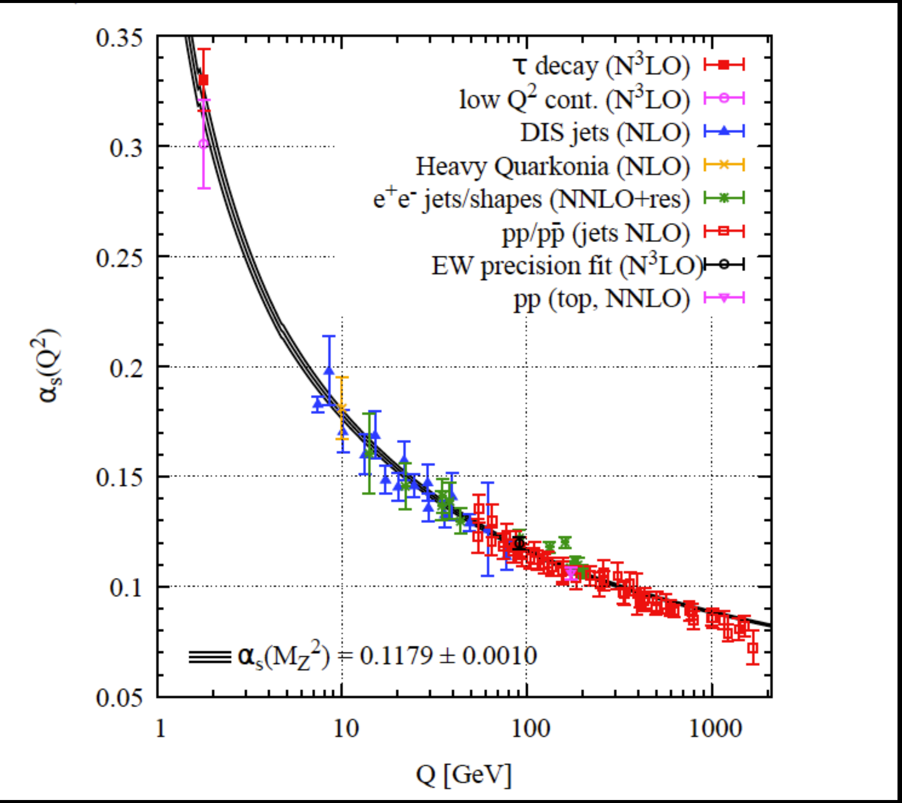
Focus on p-Ξ(dss) and p-Ω(sss) correlation measurements in pp and p-Pb collisions!



INTRODUCTION

The strong interaction

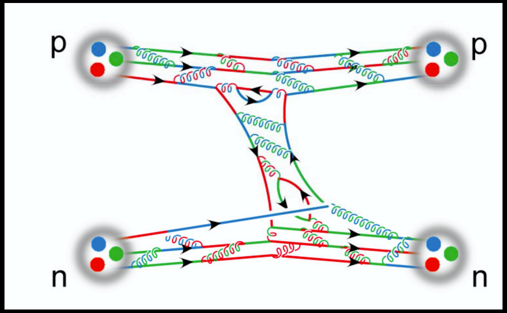
PDG 2020



$$\alpha_s(Q^2) \equiv \frac{g_s^2(Q^2)}{4\pi} = \frac{12\pi}{(33-2N_f)\ln(Q^2/\Lambda^2_{QCD})}$$

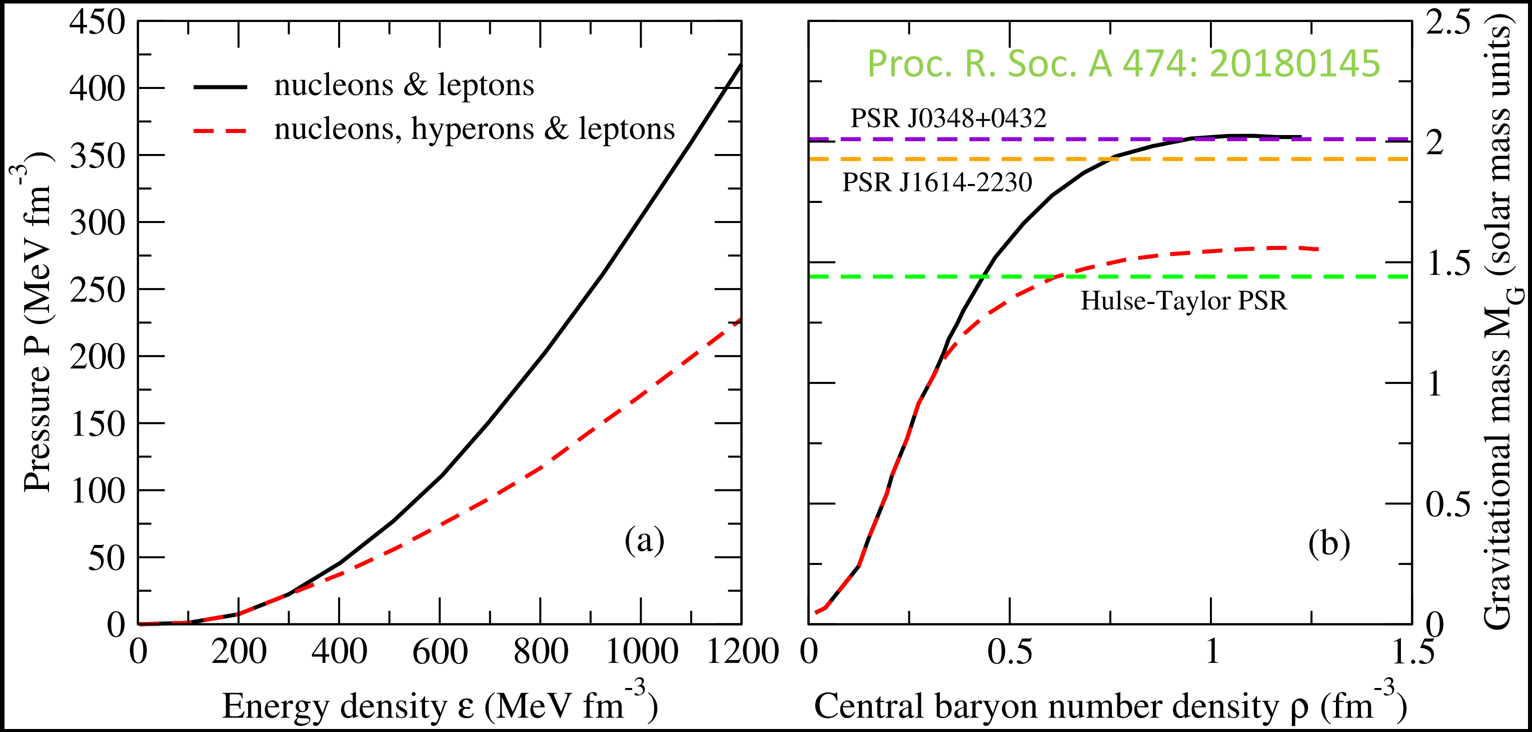
Running coupling constant α_s:

- Asymptotic freedom at small distance ($Q^2 >> \Lambda^2_{QCD}$)
- Confinement at large distance ($Q \lesssim 1$ GeV)
  - → Perturbative methods not applicable
  - → Effective theories with hadrons as degrees of freedom
  - → Lattice QCD calculations



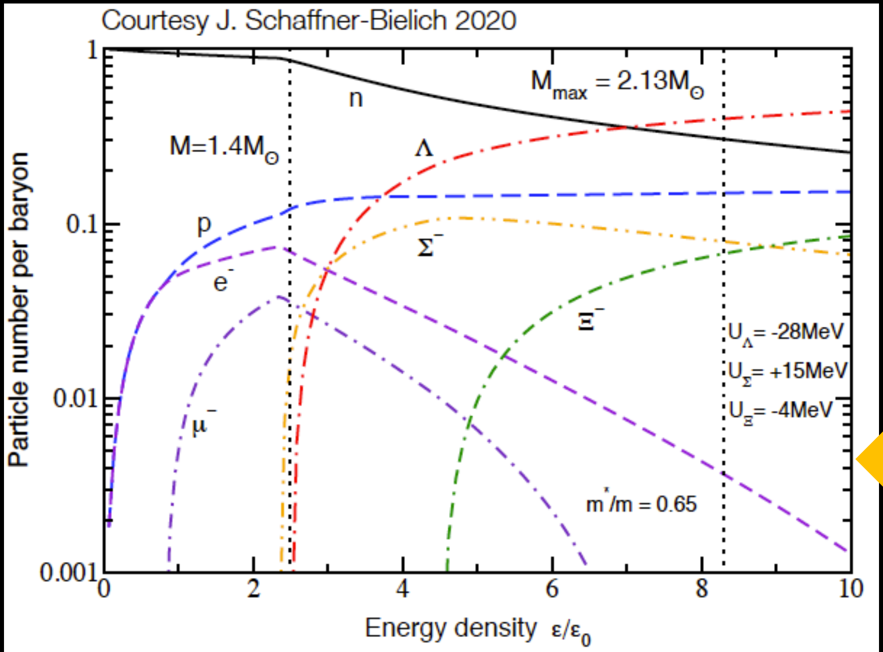
What is the strong interaction between different hadron species?

Hyperon puzzle

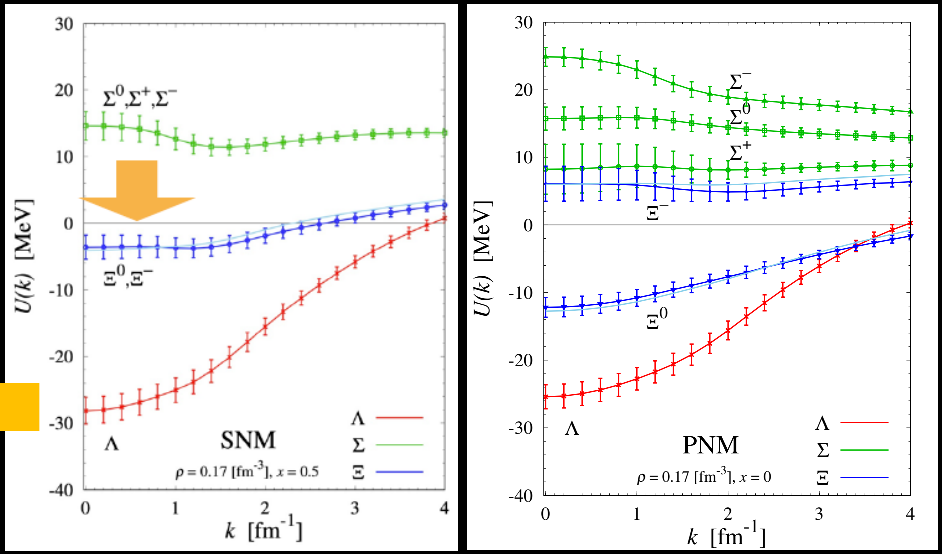


- Hyperons may appear in the inner core of neutron stars at densities of about 2–3ρ_0
- Their presence in the neutron star interior leads to a softening of the EoS and consequently to a reduction of the maximum mass (current predictions 1.4-1.8 $M_\odot$)
- Astrophysical observations of pulsars rule out almost all currently proposed EoS with hyperons…?
- Additional repulsion: Y-Y repulsive potential, hyperonic three-body forces (e.g. NNY, NYY, YYY), quark-gluon plasma below the hyperon threshold (hybrid neutron stars)…?

Hyperon puzzle and lattice QCD



HAL QCD, T. Ionue et al.AIP Conf.Proc. 2130 (2019) 1, 020002



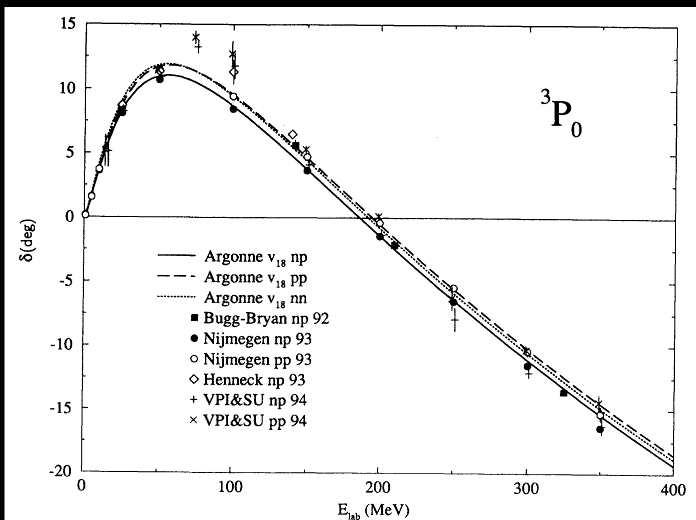
Hyperon single-particle potential

- Ξ^- attractive single-particle potential in symmetric nuclear matter (SNM) and repulsive in pure neutron matter (PNM)
- Ξ^- appears at larger densities in neutron stars

→ Resulting EoS of neutron stars is stiffer and matches astrophysical observation…

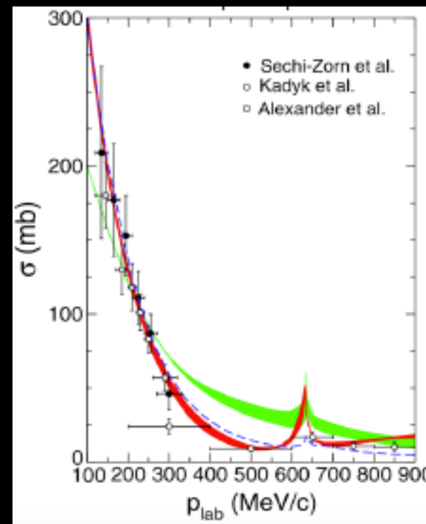
Experimental data to constrain the strong interaction

N+N → N+N



R. B. Wiringa et al., PRC 51 (1995) 38

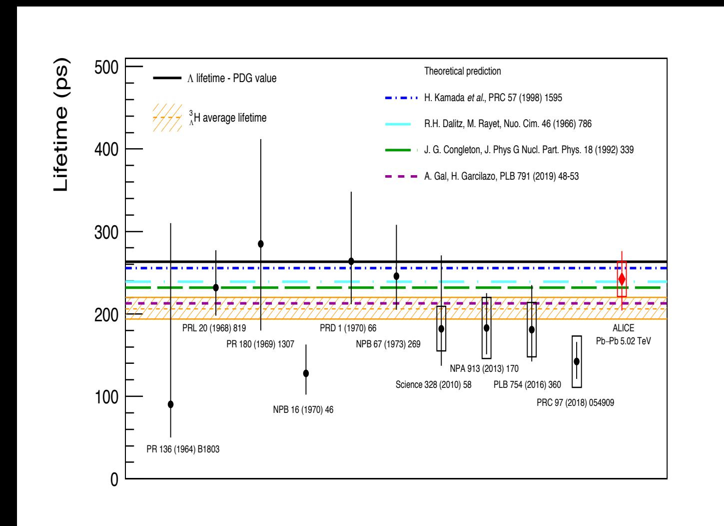
N + Λ → N + Λ



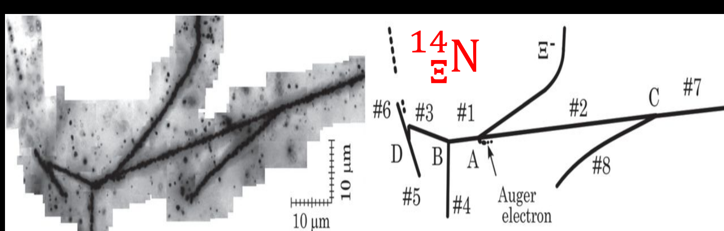
LO: H. Poinder et al. NPA 779 (2006) 244

NLO: J. Haindenbauer et al. NPA 915 (2013) 24

Hypertriton lifetime



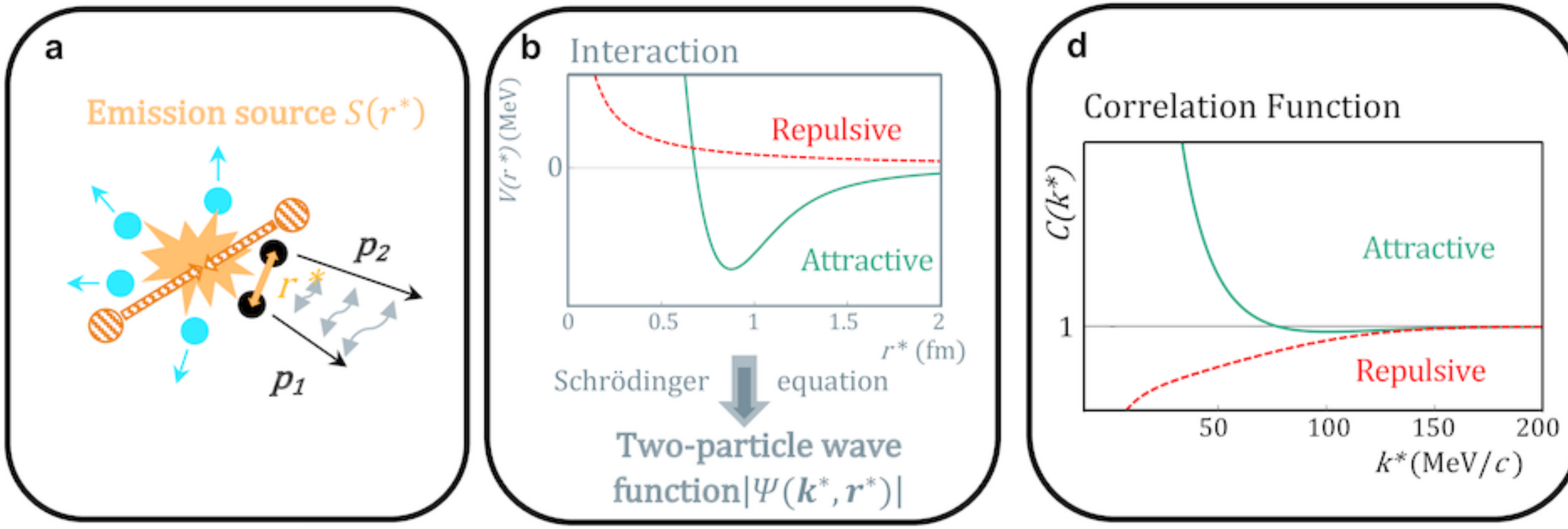
ALICE PLB797 (2019) 134905



K. Nakazawa, PTEP 2015 (2015) 033D02

- Good constraints for NN interaction
- Small statistics of scattering data for hyperons
- ~1000 Λ-hypernuclei and one $^{14}_{\Xi}$N discovered by now

Femtoscopy correlations to study hadron interactions



$k^* = \frac{|\boldsymbol{p}_1 - \boldsymbol{p}_2|}{2}$
(pair cms frame)

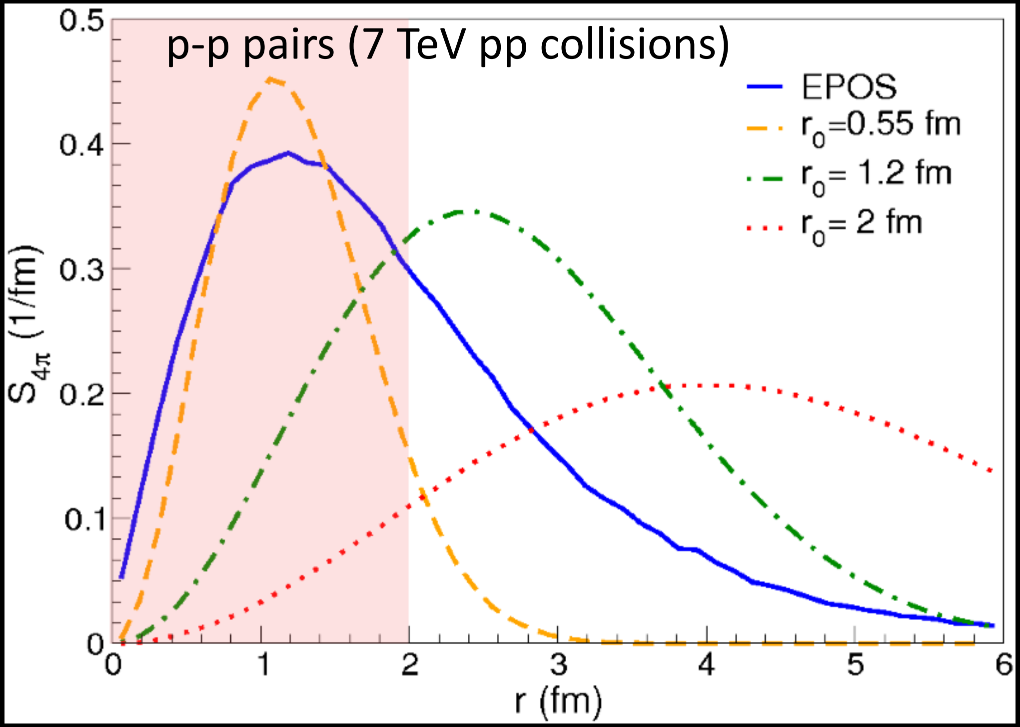
Correlation function

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

- Origin of correlations: quantum interference, resonances, conservation laws or final-state interactions
- Final-state interactions dominate at small *k**

Femtoscopy in small systems

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



Gaussian emission source:

$$S(r^*) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_0^2}\right)$$

Pair emission probability:

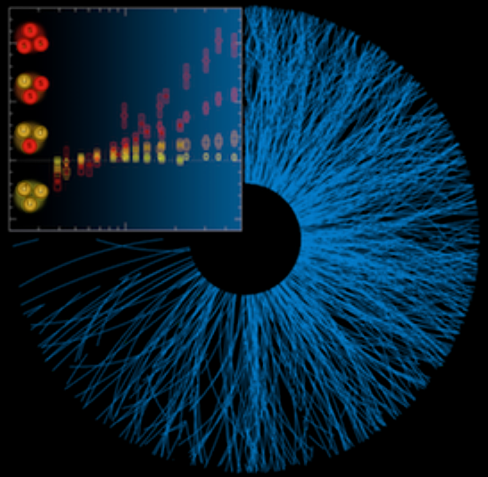
$$S_{4\pi}(r^*) = 4\pi r^2 S(r^*)$$

EPOS model predicts non-Gaussian emission source

T. Pierog et al. PRC 92 (2015) 034906

- A lot of pairs is emitted from the source at distance below ~2 fm (typical range of strong interaction)

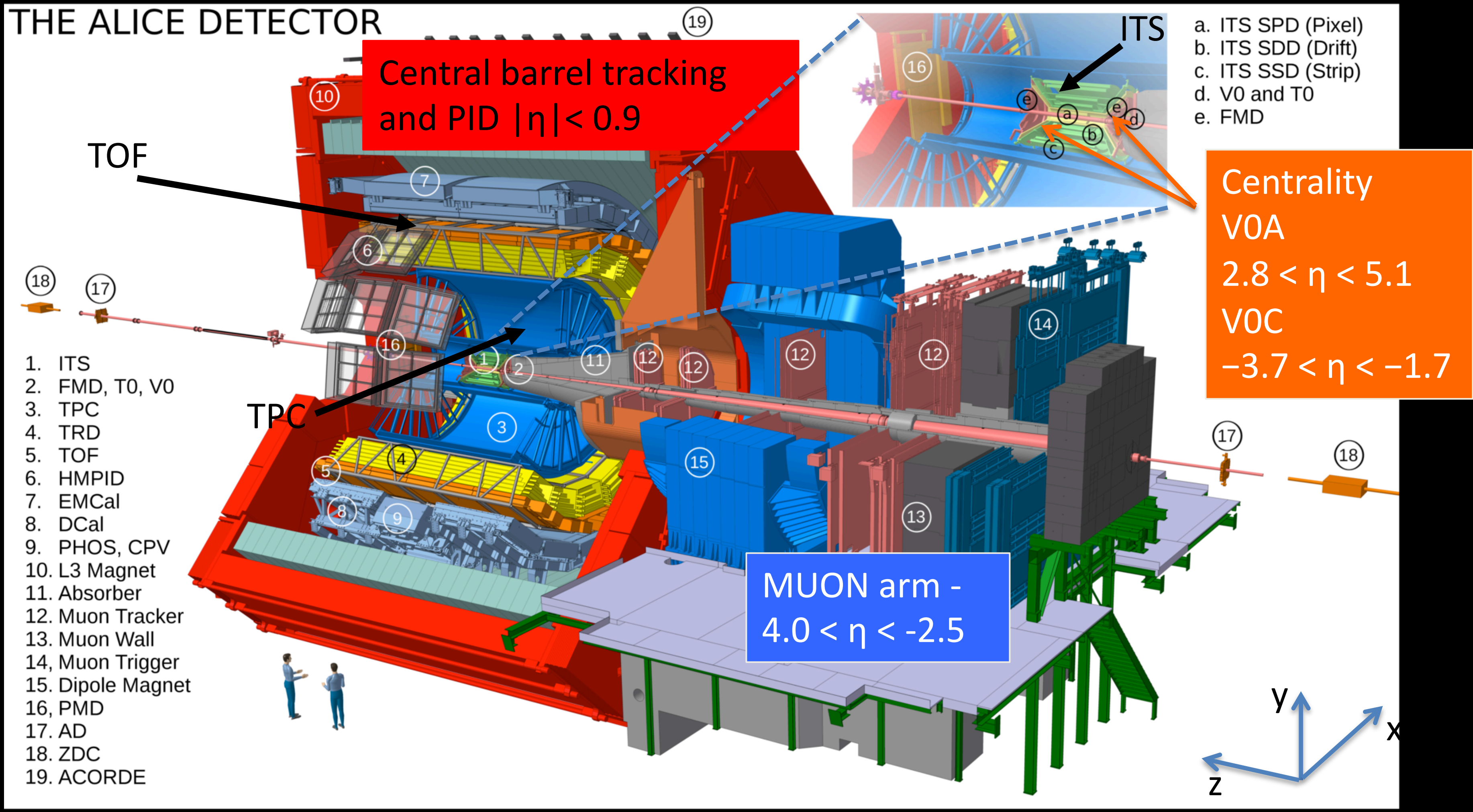
→ Small particle emission source in pp and p-Pb collisions is essential to study the strong interaction!



ALICE MEASUREMENTS

A Large Ion Collider Experiment

- Excellent particle identification capabilities over a wide p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% for p_T = 0.1-50 GeV/c

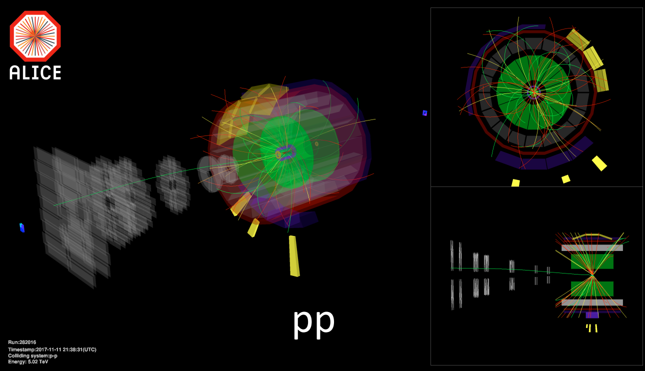


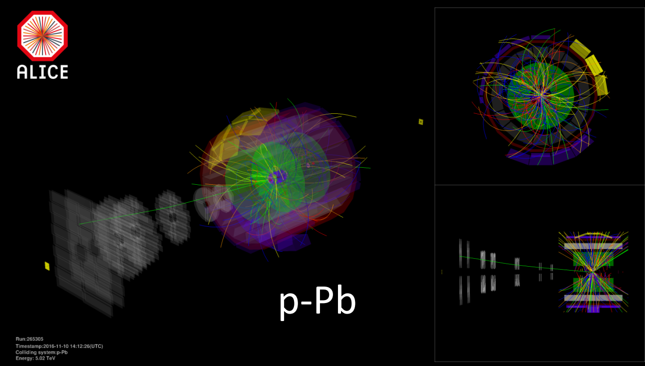
ALICE at work since 2009

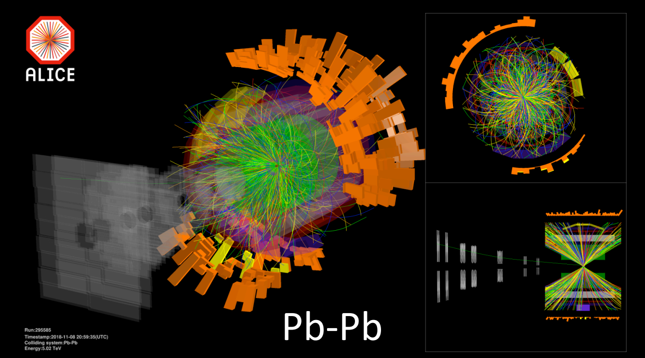
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1}, ~59 pb^{-1}

- Energy and system dependence studies of particle production are possible
- Large statistics of pp, p-Pb and Pb-Pb collisions at the same $\sqrt{s_{NN}}$

- pp at 13 TeV (high multiplicity) and p-Pb at 5 TeV used for p-Ξ and p-Ω correlation measurements

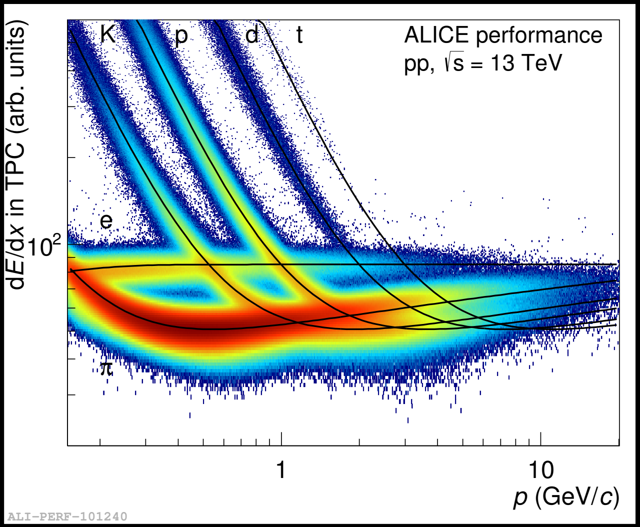


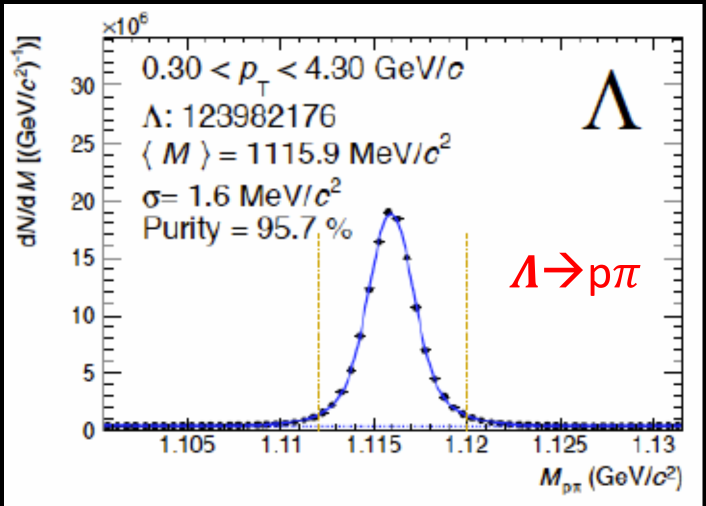


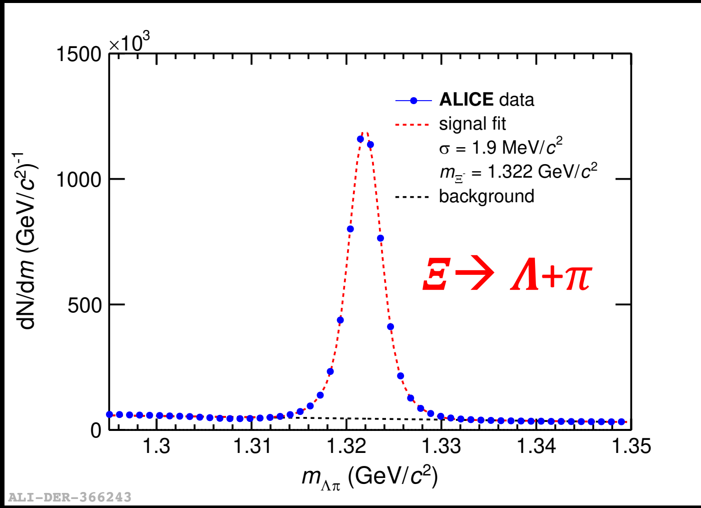


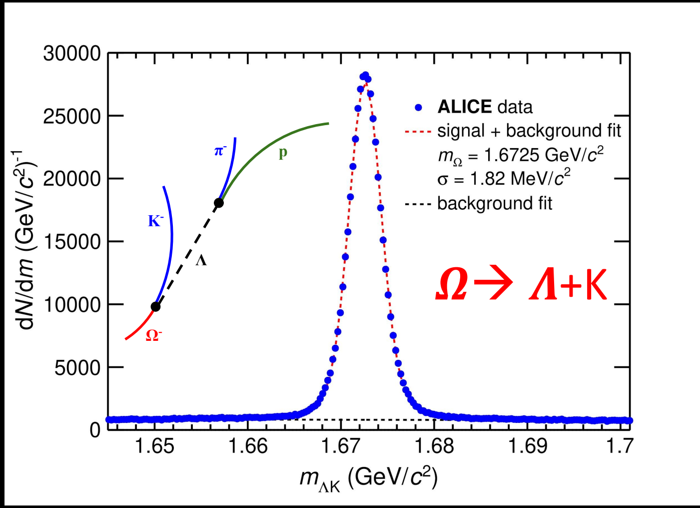
Particle identification in ALICE

- Pion, kaon and proton identification via dE/dx and TOF
- Hyperon identification with decay topology and invariant mass analysis





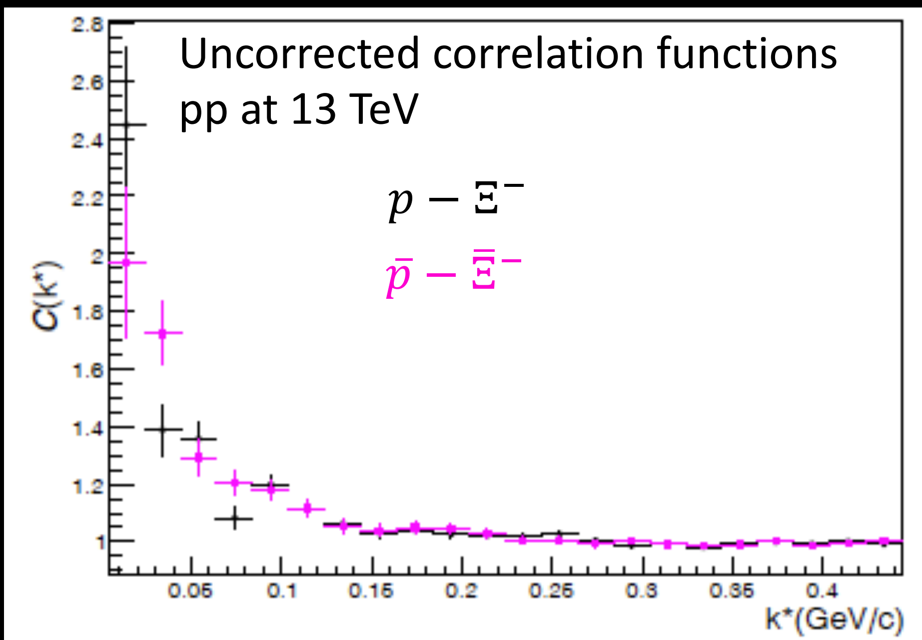




Measured correlation function

Correlation function:

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



Corrections $\varsigma(k^*)$:

- Detector effects
- Misidentified baryons
- Proton or hyperon yields from resonances (feed-down)
- Non-femtoscopic background (energy-momentum conservation, mini-jets,…)

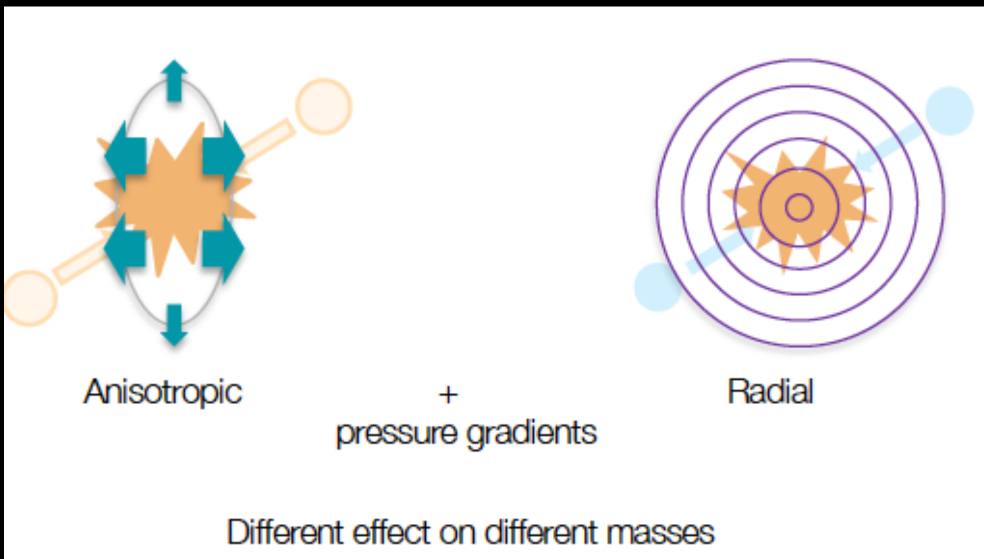
Feed-down to p–Ξ

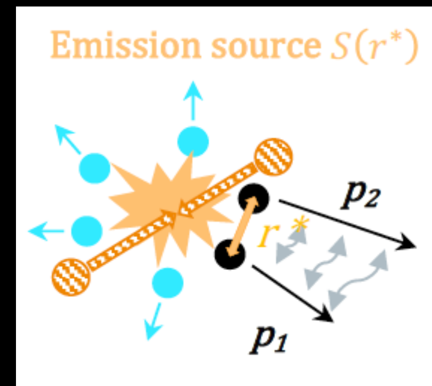
p–Ξ^-

Pair	λ [%]	Pair	λ [%]	Pair	λ [%]
p–Ξ^-	58.3	p_Λ–Ξ^-_Ω	0.08	$\tilde{p}$–$\Xi^-_{\Xi^0(1530)}$	0.09
p–$\Xi^-_{\Xi^-(1530)}$	6.5	p_{Σ^+}–Ξ^-	1.1	$\tilde{p}$–Ξ^-_Ω	0.00
p–$\Xi^-_{\Xi^0(1530)}$	12.9	p_{Σ^+}–$\Xi^-_{\Xi^-(1530)}$	0.12	p–$\tilde{\Xi}^-$	7.3
p–Ξ^-_Ω	0.6	p_{Σ^+}–$\Xi^-_{\Xi^0(1530)}$	0.24	p_Λ–$\tilde{\Xi}^-$	1.0
p_Λ–Ξ^-	8.4	p_{Σ^+}–Ξ^-_Ω	0.01	p_{Σ^+}–$\tilde{\Xi}^-$	0.14
p_Λ–$\Xi^-_{\Xi^-(1530)}$	0.93	$\tilde{p}$–Ξ^-	0.39	$\tilde{p}$–$\tilde{\Xi}^-$	0.05
p_Λ–$\Xi^-_{\Xi^0(1530)}$	1.87	$\tilde{p}$–$\Xi^-_{\Xi^-(1530)}$	0.04		

Common baryon source

Collective flow and feed-down from short lived resonances modify source size





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

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

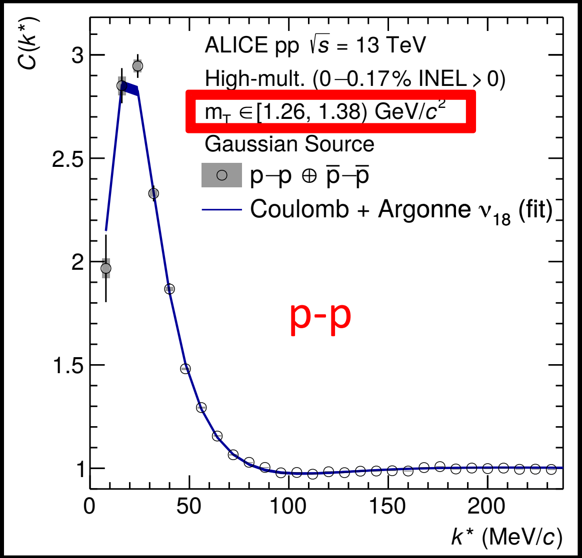
U. Wiedemann U. Heinz (PRC56 R610, 1997)

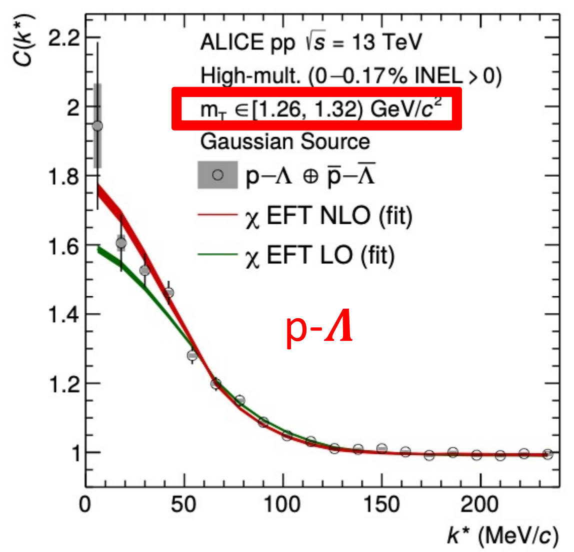
$$m_T = \sqrt{k_T^2 + m^2},\ k_T = \frac{1}{2}|p_{T1} + p_{T2}|$$

$$S(r^*) = G(r^*, r_{core}(m_T)) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_{core}^2}\right) \otimes E(r^*, M_{res}, \tau_{res}, p_{res})$$

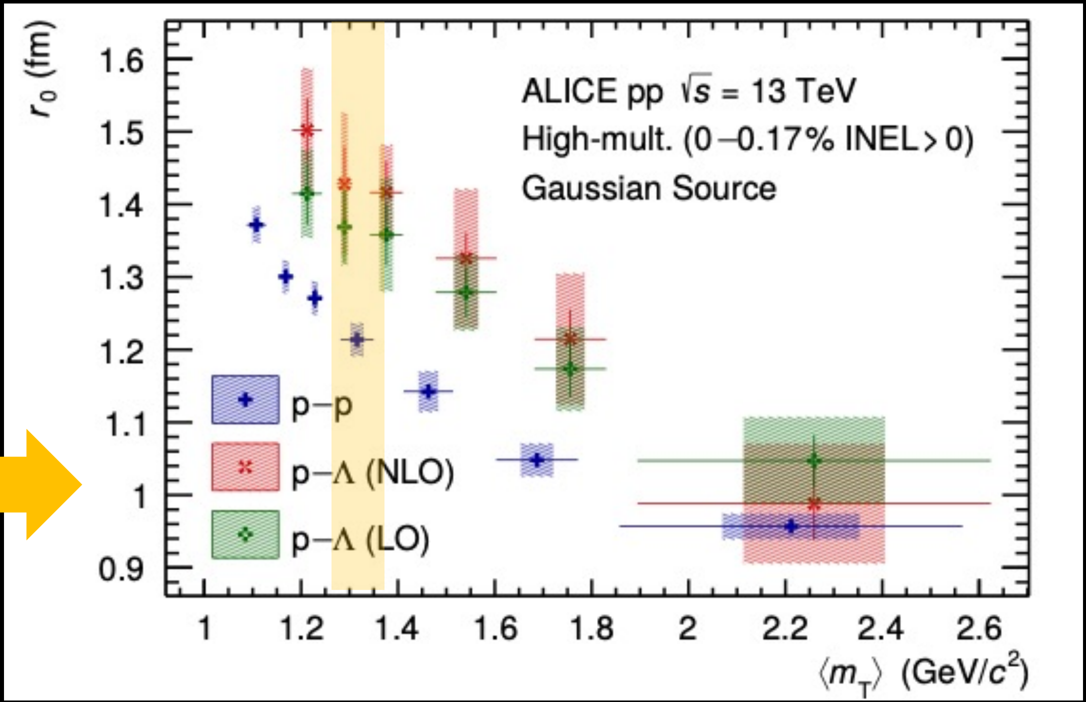
$$E(r^*, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s} \exp\left(-\frac{1}{s}\right),\ s = \beta\gamma\tau_{res} = \frac{p_{res}}{M_{res}}\tau_{res}$$

Common baryon source





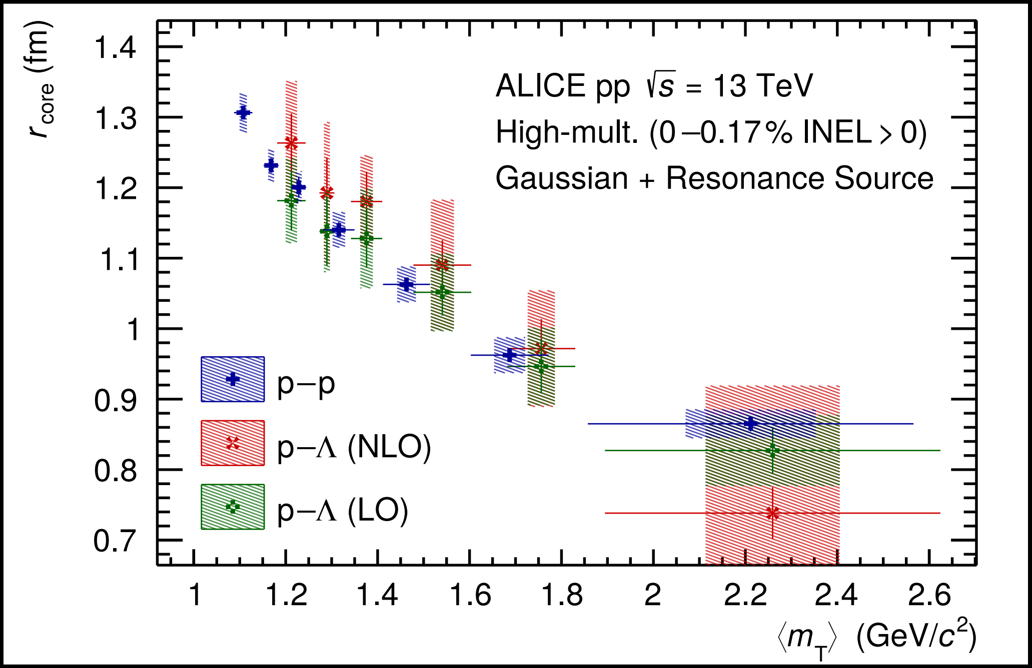
ALICE PLB 811 (2020) 135849

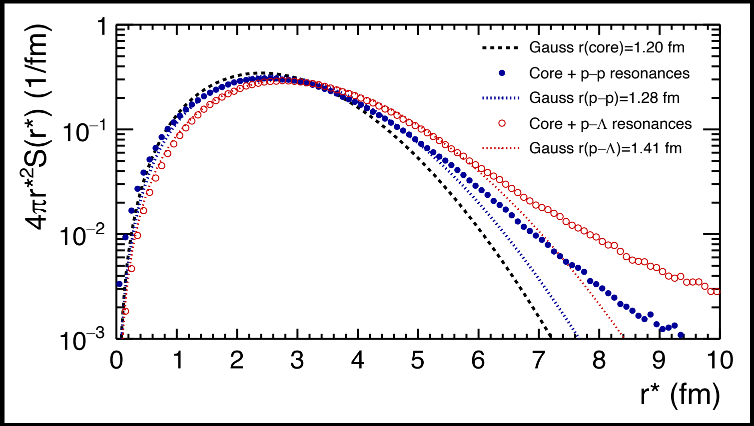


- Different source size depending on the baryon pair
- Gaussian source scales with m_T

Common baryon source

ALICE PLB 811 (2020) 135849





- Relative particle abundances from Statistical Hadronization Model *
- Kinematic distributions from EPOS **

- All baryon pairs with included resonances show common m_T scaling

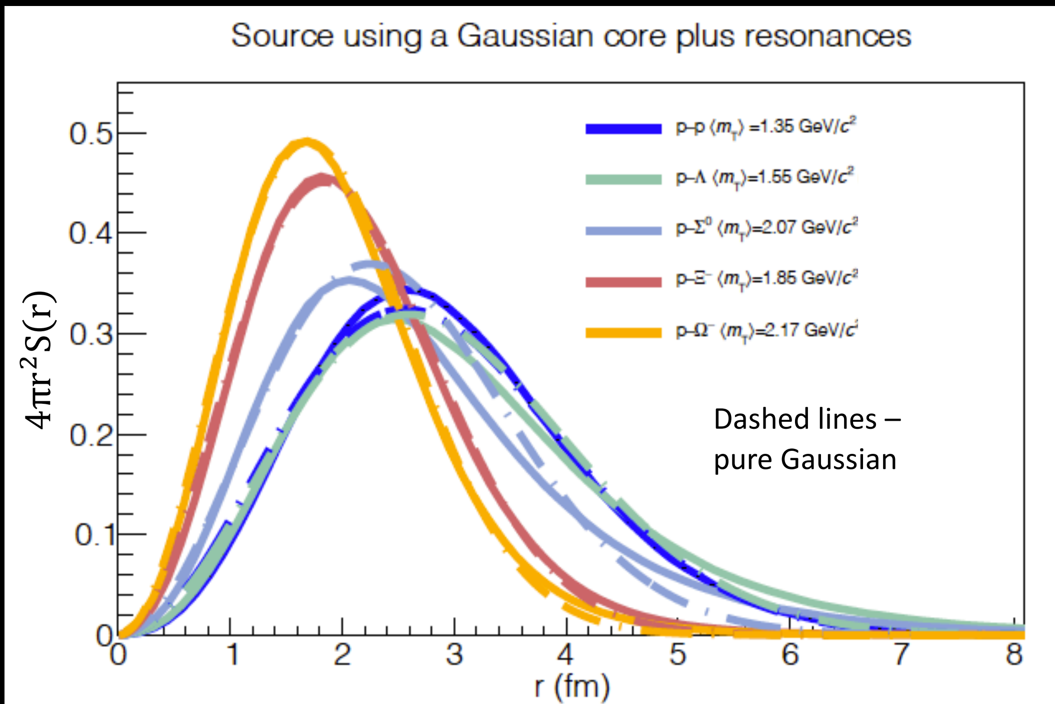
→ Indication of common baryon source

→ One can use p-p correlation to fix source size for other baryon pairs

* F. Becattini et al. J. Phys. G: Nucl. Part. Phys. **38** 025002

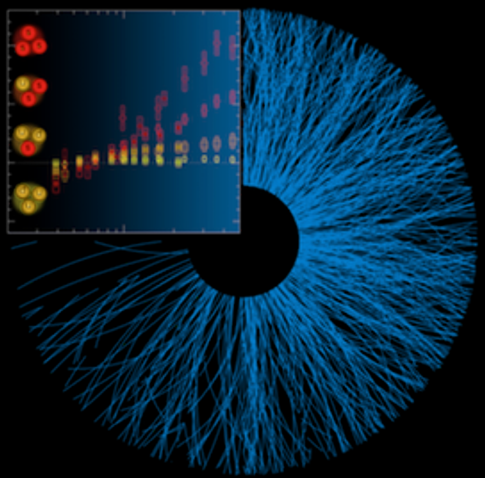
** T. Pierog et al. PRC 92 (2015) 034906

Common baryon source



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

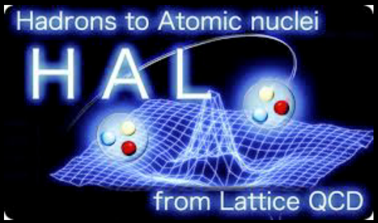
- Emission source for heavier pairs using p-p correlation function plus resonances
- Gaussian source with r_{eff} = 1.02±0.05 (0.95±0.06) fm used for the p-Ξ (p-Ω) emission

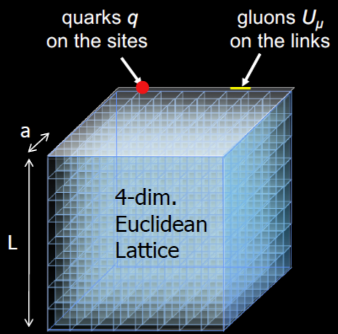


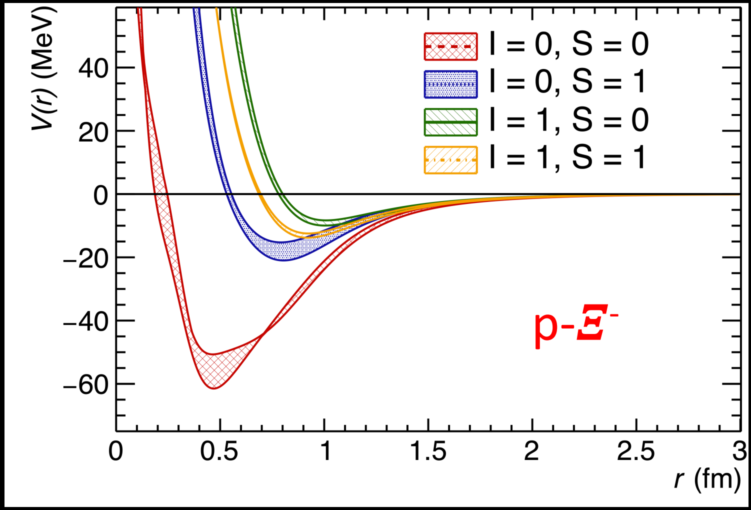
RESULTS

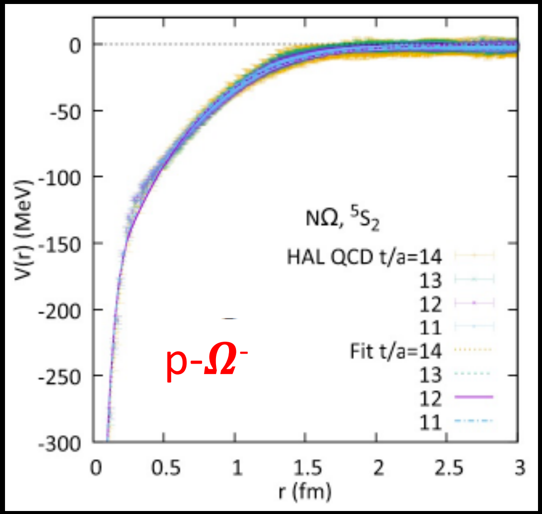
The strong interaction for p-Ξ and p-Ω on lattice

HAL QCD Coll., NPA 998 (2020) 121737, PLB 792 (2019) 284







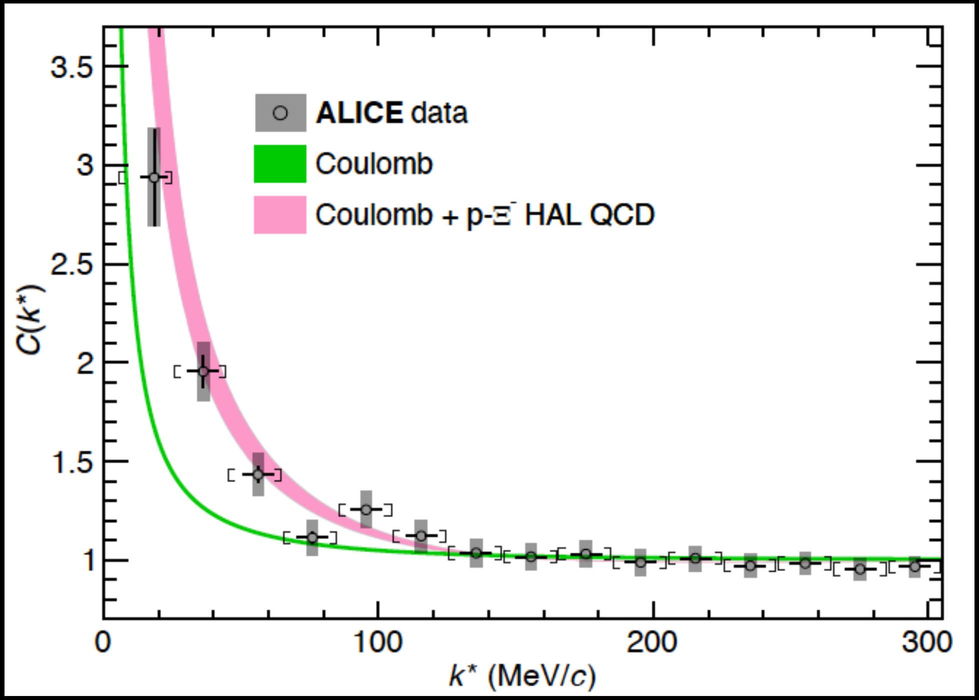


- a = 0.085 fm
- L = 8.1 fm
- m_π = 146 MeV/c²
- m_K = 525 MeV/c²

- p-Ξ interaction in four channels: isospin (I = 0,1) and spin (S=0,1)
  - Attractive with repulsive core at small distances
- p-Ω interaction in $^5S_2$ (I=1/2, S=2) channel
  - Attractive in the whole range
  - After inclusion Coulomb interaction prediction of bound state with binding energy ~ 2.5 MeV
- p-Ω interaction in $^3S_1$ state does not include yet inelastic channels (e.g. pΩ → $\Lambda\Xi$)

p-Ξ correlation function in pp at 13 TeV

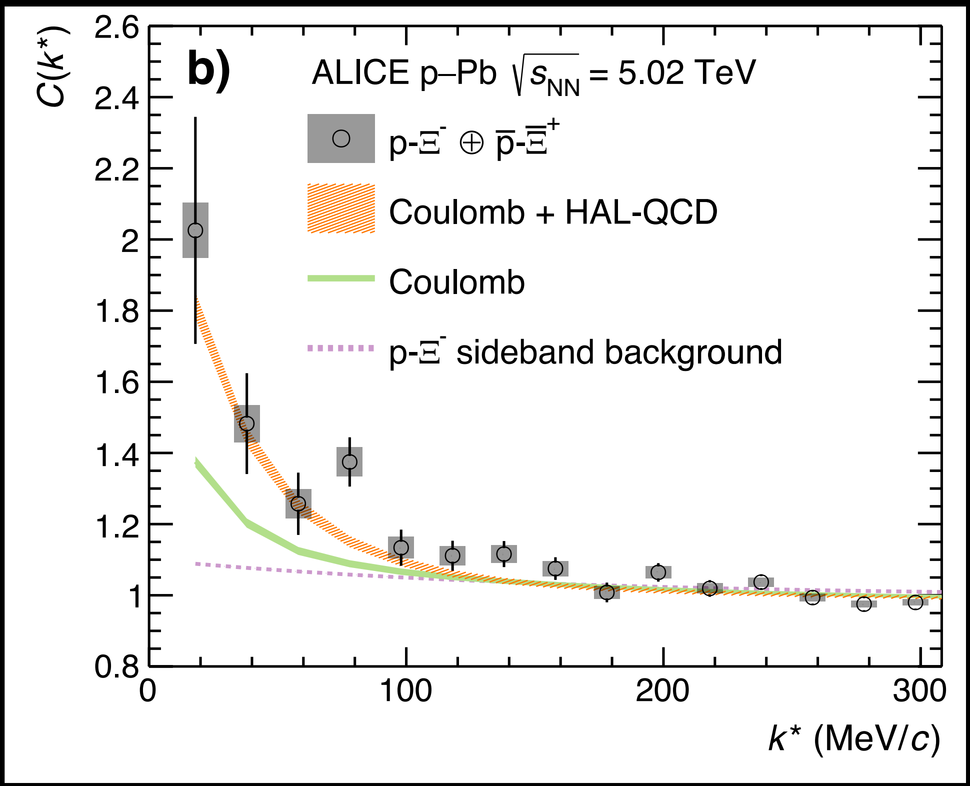
ALICE Nature 588, (2020) 232



- p-Ξ interaction is attractive
- No indication of bound state in data
- p-Ξ interaction stronger than Coulomb → observation of strong interaction
- Coulomb + HAL QCD in agreement with p-Ξ measurements

p-Ξ correlation function in p-Pb at 5 TeV

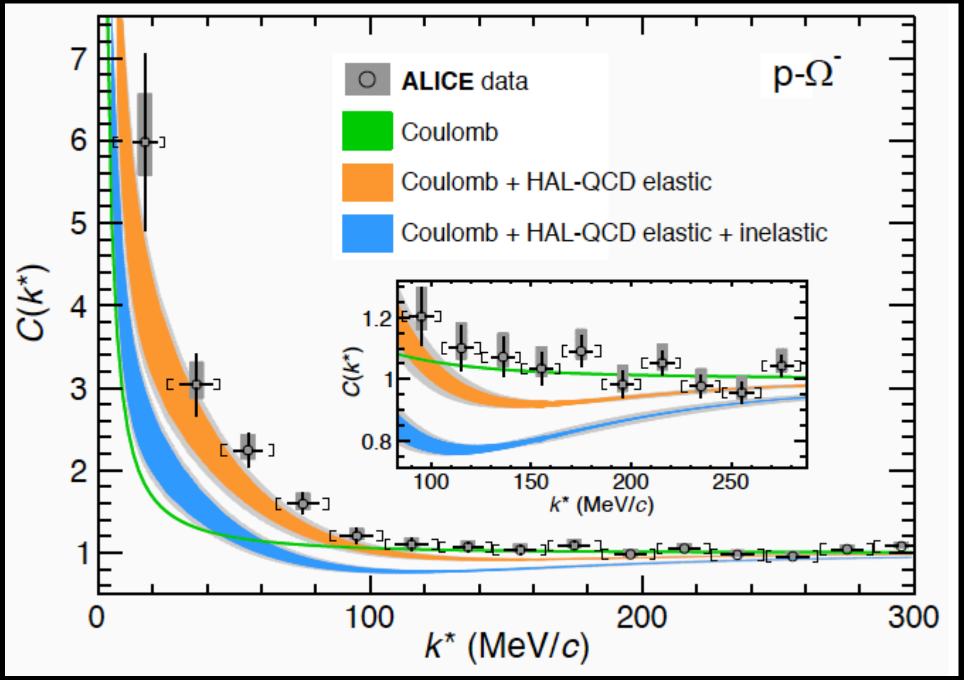
ALICE PRL 123, 112002 (2019)



- p-Ξ interaction is attractive
- No indication of bound state in data
- p-Ξ interaction stronger than Coulomb → observation of strong interaction
- Coulomb + HAL QCD in agreement with p-Ξ measurements

p-Ω correlation function in pp at 13 TeV

ALICE Nature 588, (2020) 232



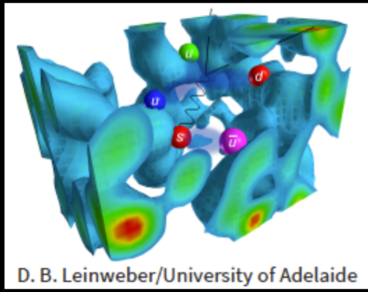
- p-Ω interaction is attractive
- No indication of bound state in data
- p-Ω interaction stronger than Coulomb → observation of strong interaction

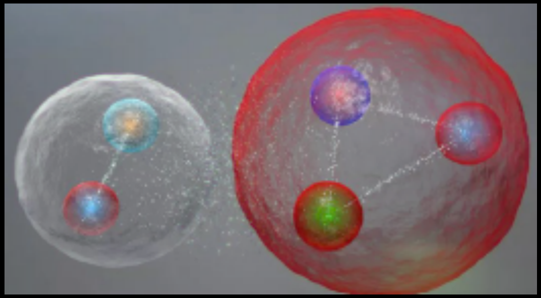
- Calculations underestimate p-Ω measurements for both cases tested for missing p-Ω inelastic channels in $^3S_1$ state
  - Inelastic channel dominated by absorption
  - Neglecting inelastic channel

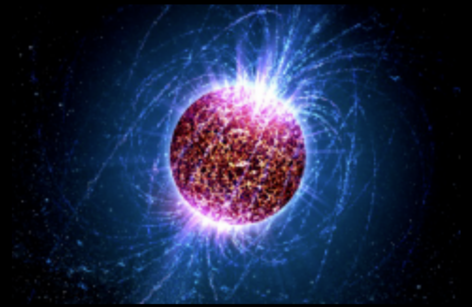
Summary

- ALICE unveils the strong interaction between stable and unstable baryons (p-Ξ and p-Ω) in pp and p-Pb collisions at the LHC
- The precisely measured p-Ξ and p-Ω correlation functions show attractive interaction for small relative momentum k^*< 100 MeV/c
- No indication of bound states

- Calculations including final-state Coulomb and strong (HAL QCD potential) interaction
  - Good agreement with p-Ξ results in both pp and p-Pb collisions
  - Underestimate p-Ω results (missing inelastic channels in $^3S_1$ state) for both limiting cases
  - Formation of bound p-Ω state (not seen in data at the moment)

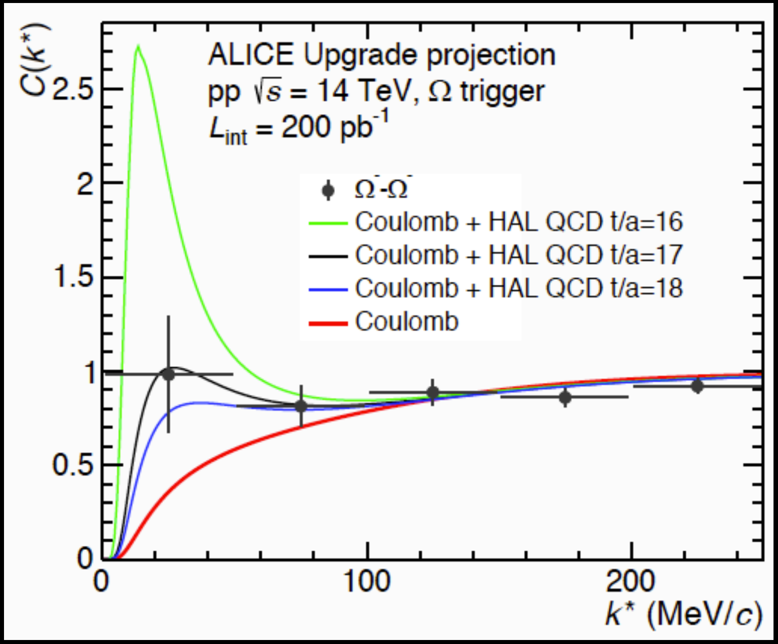


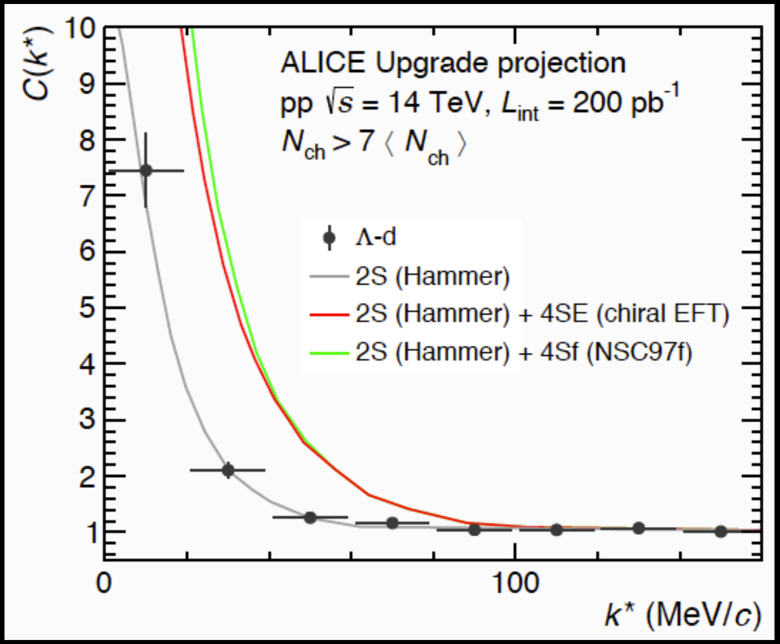




Outlook

- ALICE plans (anti)baryon-(anti)baryon correlation measurements in future LHC Run3 and Run4 including
  - pΩ correlations in p-Pb collisions
  - $\Lambda\Xi$ and $\Sigma\Xi$ (pΩ strangeness rearrangement channels) in pp and p-Pb collisions
  - and others...



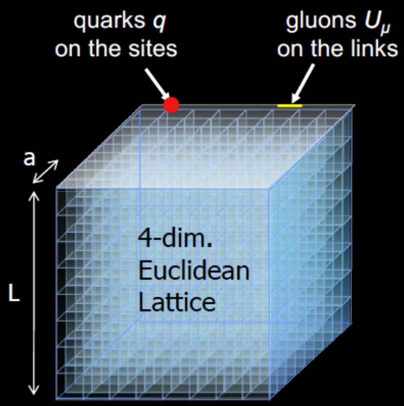


THANK YOU FOR YOUR ATTENTION!

BACKUP

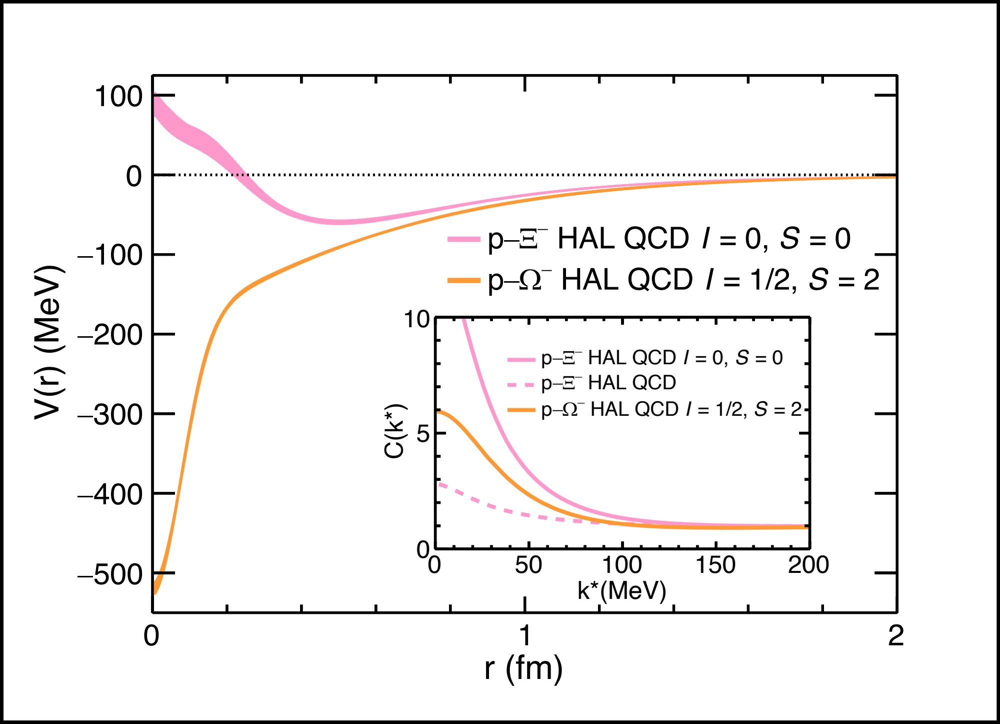
The strong interaction for p-Ξ and p-Ω on lattice

Hadrons to Atomic nuclei HAL from Lattice QCD



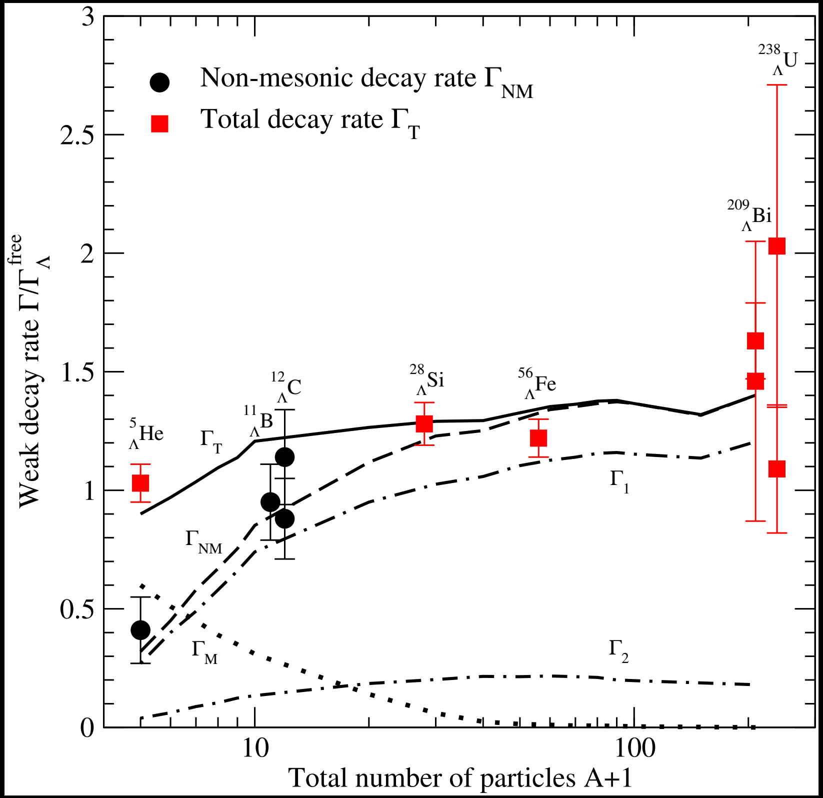
- a = 0.085 fm
- L = 8.1 fm
- m_π = 146 MeV/c^2
- m_K = 525 MeV/c^2

HAL QCD Coll., NPA 998 (2020) 121737



Hypernuclei weak decays

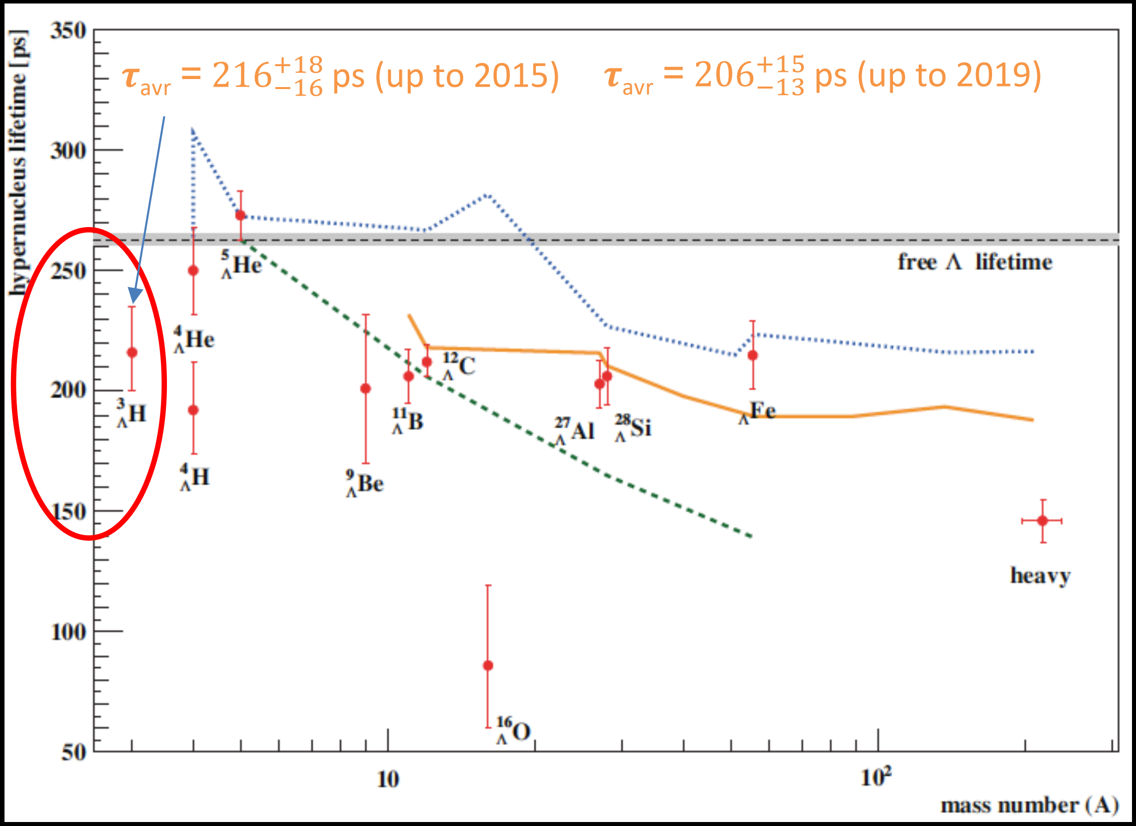
Proc. R. Soc. A 474: 20180145



- Free Λ baryon decays
  - $\Lambda \rightarrow N + \pi$
- Hypernuclei decay via mesonic and non-mesonic channels
- In large hypernuclei mesonic decays are strongly suppressed by the Pauli principle (p_N < Fermi momentum)
  - $\Lambda N \rightarrow N + N$
  - $\Lambda N N \rightarrow N + N + N$

Hypernuclei lifetimes

E. Botta et al. Nuovo Cimento 38 (2015) 387

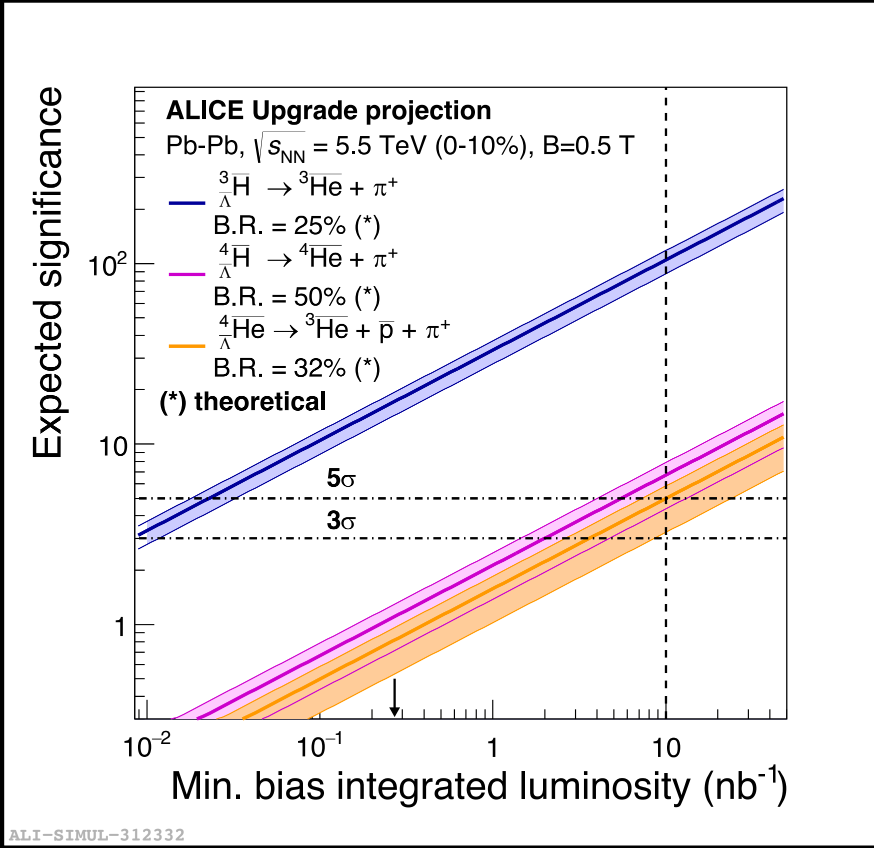


Models:

- K. Itonaga et al. Nucl. Phys. A, 639 (1998) 329c
    - One pion exchange approach
- E. Bauer et al. Phys. Rev. C 81 (2010) 064315
    - 2 nucleon non-mesonic weak decays
- K. Itonaga et al. Prog. Theor. Phys. Suppl., 185 (2010) 252
    - One-pion exchange with addition of many exchange terms

- A big decrease of (anti-)hypertriton lifetime as compared to 2015 value
- heavy = weighted average of lifetimes of nuclei with 180 < A < 238

Hypernuclei - future perspectives



- L = 10/nb Pb+Pb statistics is expected in ALICE during LHC Run-3 (2021-2023) and Run-4 (2024-2028)
  - Above 3$\boldsymbol{\sigma}$ significance for $^{4}_{\bar{\Lambda}}\overline{\mathbf{H}}$e
- Further experiments are planned in the future at BNL, KEK and J-PARC with K− beams, and at FAIR/GSI with protons and antiprotons