TECHNISCHE UNIVERSITÄT MÜNCHEN

ALICE

Investigating the strong interaction between hadrons and light nuclei with femtoscopy and hypernuclei measurements with ALICE

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On behalf of the ALICE Collaboration

LHCPhysics

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Many-body systems in nuclear physics

- Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only
  L.E. Marcucci et al., Front. Phys. 8:69 (2020)

- NNN interaction contributes ~10% to the binding energies of ^{3}H and ^{4}He

- Many-body scattering requires three-body calculations (e.g. **neutron-deuteron**)
  L. Girlanda et al., PRC 102, 064003 (2020)

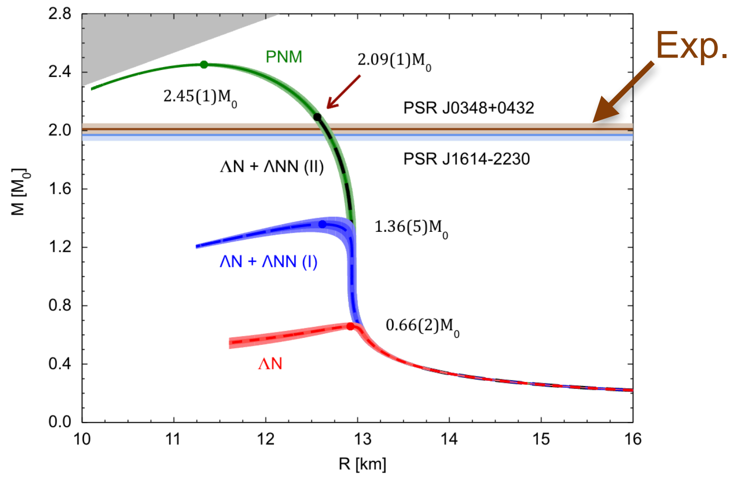
^{3}H and ^{4}He binding energies and n-d scattering length

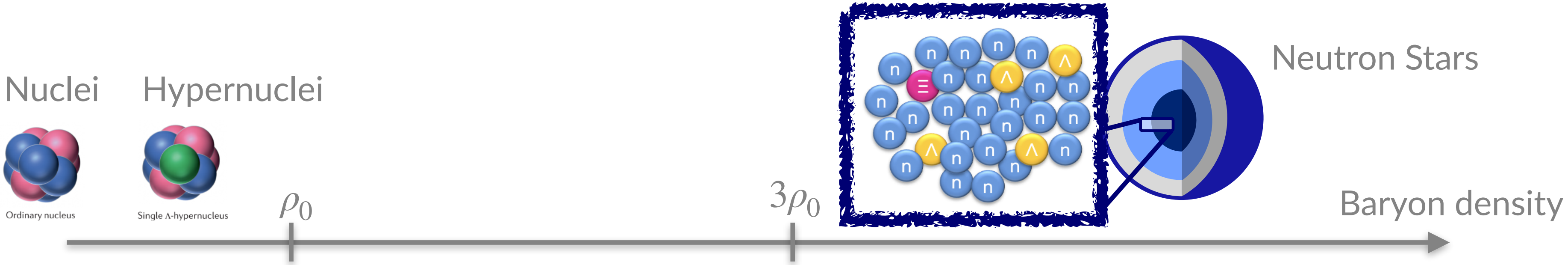
Potential(NN)	^{3}H[MeV]	^{4}He[MeV]	$^2a_{nd}$[fm]
AV18	7.624	24.22	1.258
CDBonn	7.998	26.13	
N3LO-Idaho	7.854	25.38	1.100
Potential(NN+NNN)			
AV18/UIX	8.479	28.47	0.590
CDBonn/TM	8.474	29.00	
N3LO-Idaho/N2LO	8.474	28.37	0.675
Exp.	8.48	28.30	0.645±0.010

Many-body systems in astrophysics

- Production of hyperons energetically favourable in neutron stars (NS) around 2-3 ρ_0
- Only two-body ΛN
  → Too soft EoS, incompatible with measured heavy NS
  → Large improvement in 2-body YN with femtoscopy
  ALICE Coll., PLB 833 (2022), ALICE Coll., Nature 588 (2020), L. Fabbietti et al., Ann.Rev.Nucl.Part.Sci. 71 (2021)
- Introduction of three-body ΛNN forces
  → Stiffens EoS, model-dependent
  → Need for additional experimental constraints

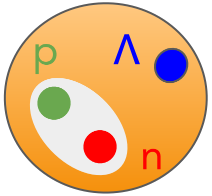
D. Lonardoni et al., PRL 114 (2019)





$^{3}_{\Lambda}$H lifetime and Λ separation energy

- Hypertriton ($^{3}_{\Lambda}$H): Λpn bound state
  - ➡ powerful probe for investigating the ΛN interaction



- Weakly bound state
  - ➡ ALICE measured with unprecedented precision the $^{3}_{\Lambda}$H lifetime and the energy (B_{Λ}) required to separate the Λ from the deuteron

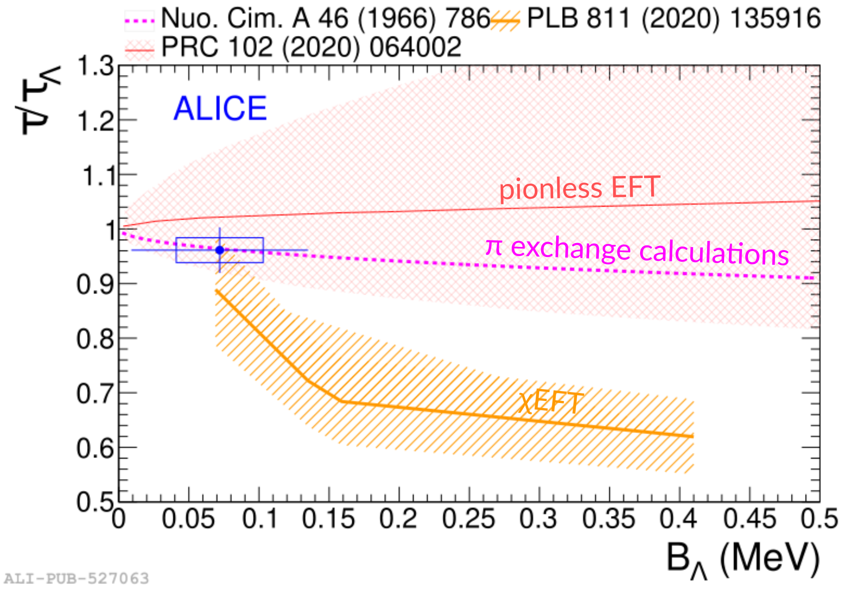
ALICE Coll., arXiv:2209.07360

B_{Λ}=[72±63 (stat.)±36 (syst.)] keV

  - ➡ the very low B_{Λ} of ~ 100 keV corresponds to a large radius of ~ 5 fm

Hildenbrand et al., Phys. Rev. C, 100(3), 034002 (2019)

How does this reflect on its production?



${}^{3}_{\Lambda}H$ production yield in Pb–Pb

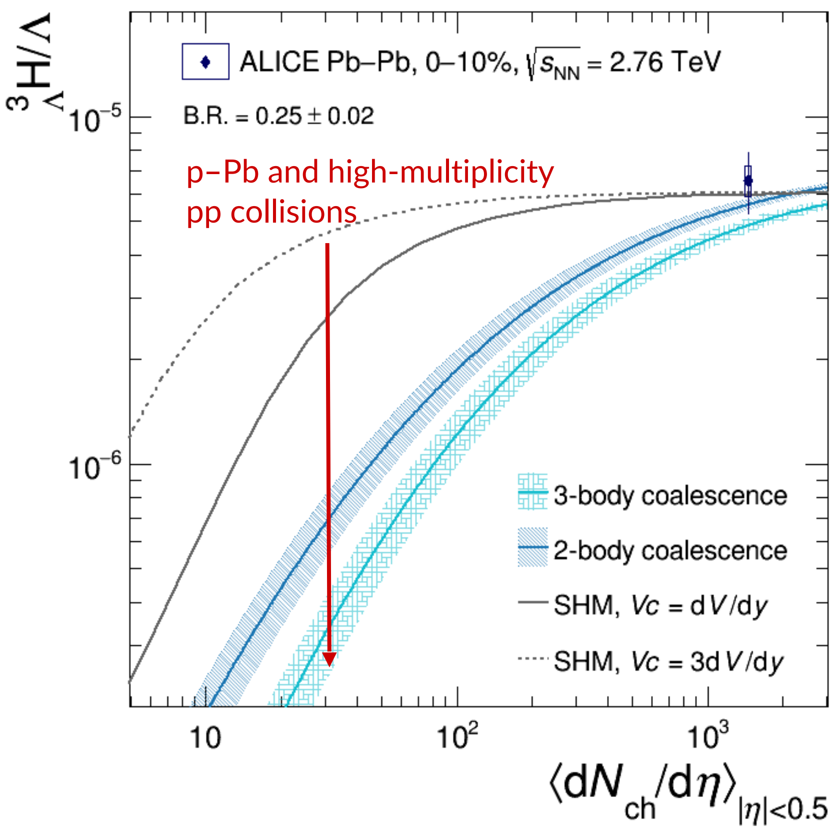
- Weakly bound state (B_{Λ} ~ 100 keV)
  - ➡ ${}^{3}_{\Lambda}H$ / Λ: large separation between statistical hadronization model (SHM) and coalescence predictions at low charged-particle multiplicity density

    Vovchenko et al., Phys. Lett., B 785, 171–174, (2018)
    Sun et al., Phys. Lett. B 792, 132–137, (2019)

  - ➡ coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function

- ${}^{3}_{\Lambda}H$ production in pp and p–Pb:
  a key to understand the nuclear production mechanism at the LHC

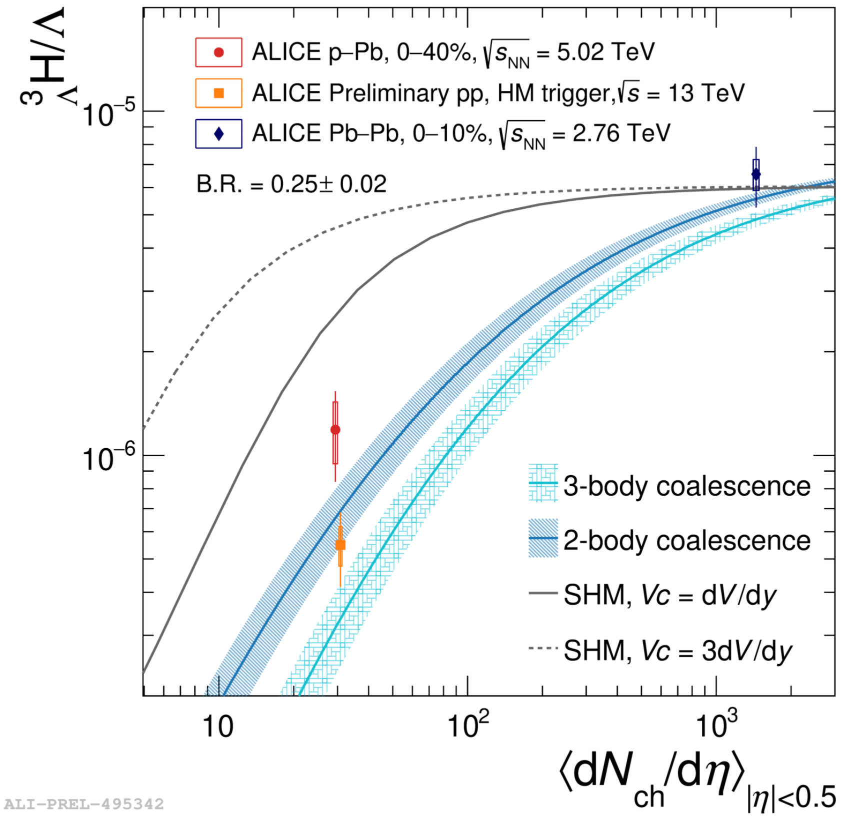
  ALICE Coll., Phys. Lett. B 754, 360–372, (2016)



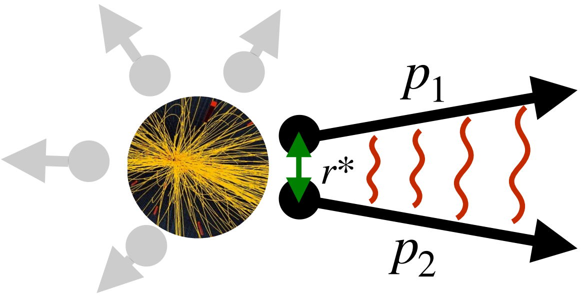
${}^{3}_{\Lambda}H$ production yield in pp and p–Pb

- First measurements of ${}^{3}_{\Lambda}H$ production in pp and p−Pb collisions
  - ➡ good agreement with 2-body coalescence
  - ➡ tension with SHM at low charged-particle multiplicity density
    - ‣ First significant constraint to SHM possible configurations
- Coalescence quantitatively describes the ${}^{3}_{\Lambda}H$ suppression in small systems
  - ➡ the nuclear size matters at low charged-particle multiplicity

ALICE Coll., Phys. Rev. Lett. 128, (2022) 252003



Two-body femtoscopy



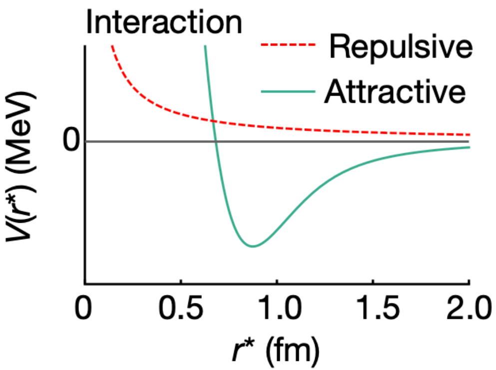
Emission source $S(r^*)$
ALICE Coll. PLB 811 (2020) 135849

ALICE Collaboration
pΛ: *PLB 833 (2022) 137272*
pΣ⁰: *PLB 805 (2020) 135419*
pΞ/pΩ: *Nature 588 (2020) 232-238*
pφ: *PRL 127 (2021) 172301*
Kp: *PRL 124 (2020) 09230*
PLB 822 (2021) 136708
arXiv 2205.15176
pp, pΛ, ΛΛ: *PRC 99 (2019) 2, 024001*
ΛΛ: *PLB 797 (2019) 134822*
pΞ: *PRL 123 (2019) 112002*
ΛK: *PRC 103 (2021) 5, 055201*
pD: *PRD 106 (2022) 052010*
ΛΞ: *arXiv 2204.10258*

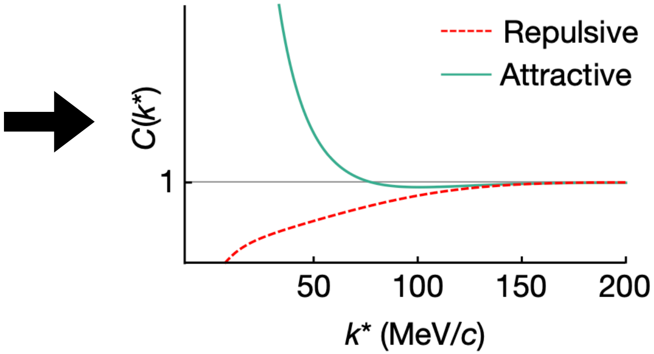
- Two-particle correlation function:

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

- Measurements in small colliding systems (~1-2 fm)
→ Access to the strong interaction and short-range dynamics



Schrödinger equation
Two-particle wave function
$\psi(\mathbf{k}^*, \mathbf{r}^*)$



Correlation function $C(k^*)$

Proton-deuteron correlations

Point-like particle models anchored to scattering experiments

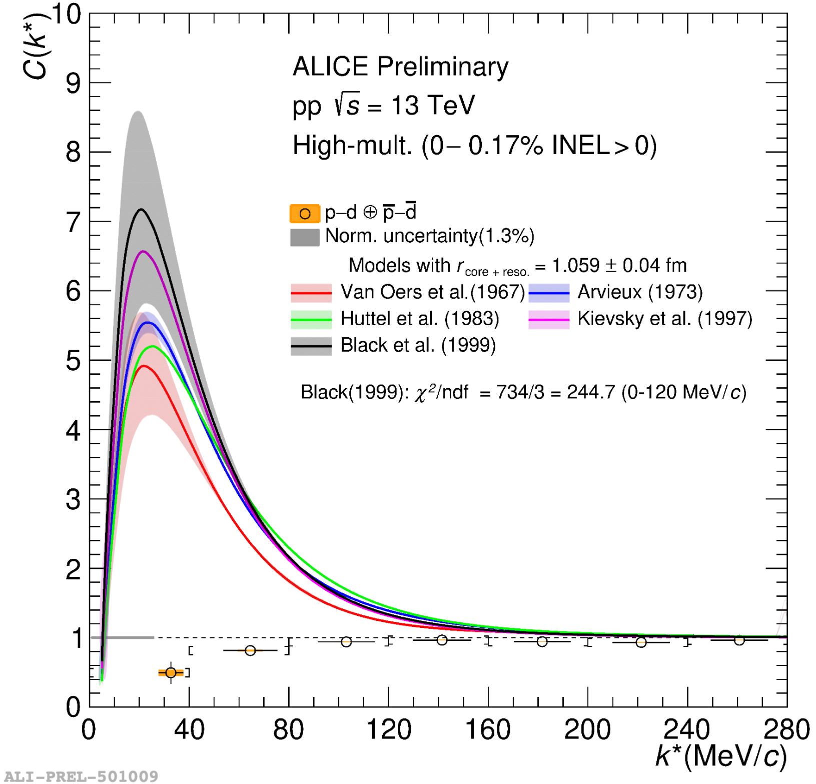
	S = 1/2		S = 3/2	
	f_0(fm)	d_0(fm)	f_0(fm)	d_0(fm)
Van Oers et al. (1967)	$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.20}_{-1.80}$	$2.05^{+0.25}_{-0.25}$
Arvieux (1973)	$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.10}_{-0.40}$	$2.63^{+0.01}_{-0.02}$
Huttel et al. (1983)	-4.0	—	-11.1	—
Kievsky et al. (1997)	-0.024	—	-13.7	—
Black et al. (1999)	$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—

W. T. H. Van Oers, & K. W. Brockman Jr, NPA 561 (1967);
J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);

- Coulomb + strong interaction using the Lednický model

Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)

- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal m_T scaling

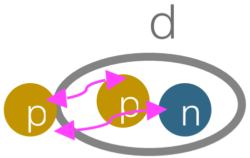


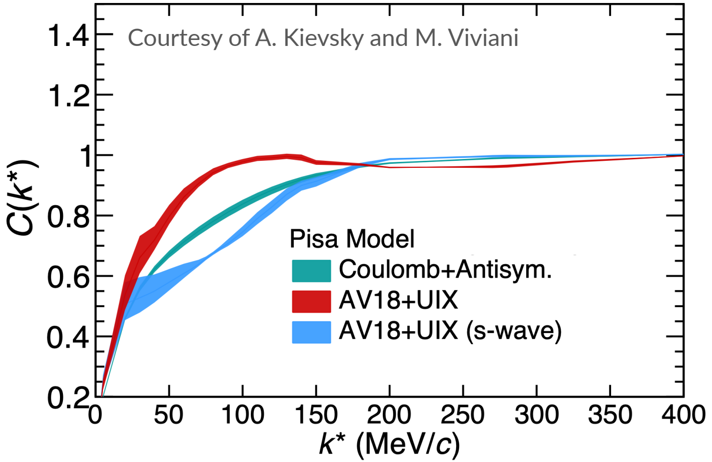
Point-like particle description doesn't work for p-d

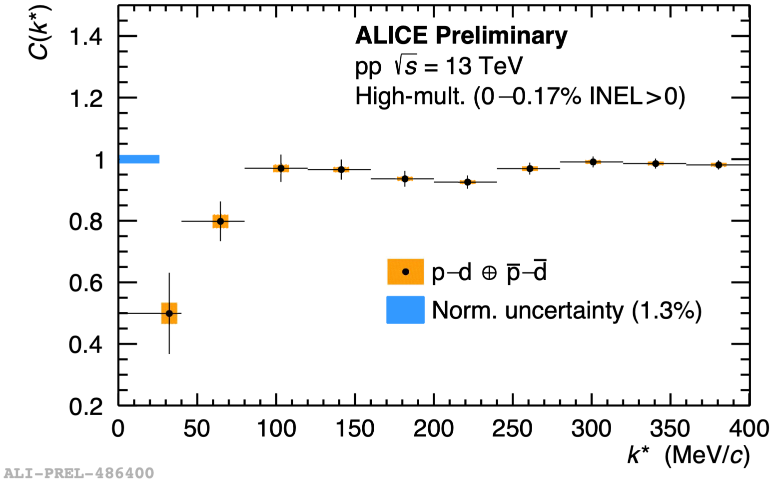
Proton-deuteron correlations

Deuteron treated as a composite object:

- Coulomb + strong interaction (NN and NNN) + Quantum Statistics





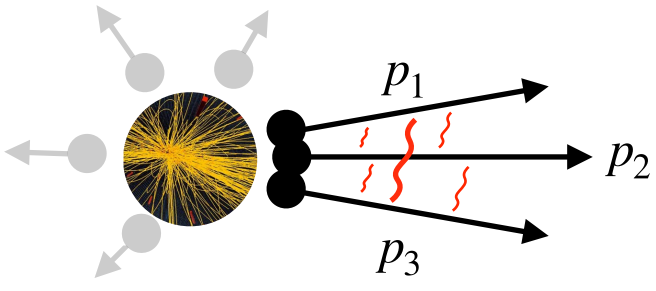


The measured p-d correlation function reflects the full three-nucleon dynamics (not the p-d int.)

➡ Sensitivity to the short inter-particle distances

➡ Sensitivity to the details of the wave function

Three-body femtoscopy



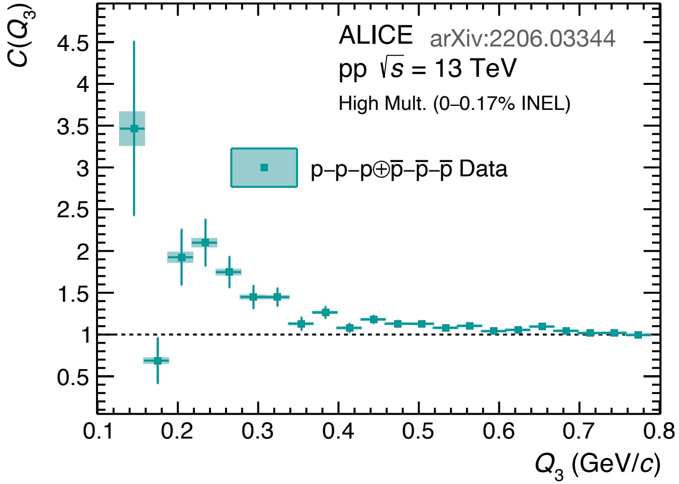
- Three-particle correlation function:

$$C(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) = \iiint S_3(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)\left|\psi_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)\right|^2 d^3x_1 d^3x_2 d^3x_3 = \mathcal{N}\cdot\frac{N_{\mathrm{same}}(Q_3)}{N_{\mathrm{mixed}}(Q_3)}$$

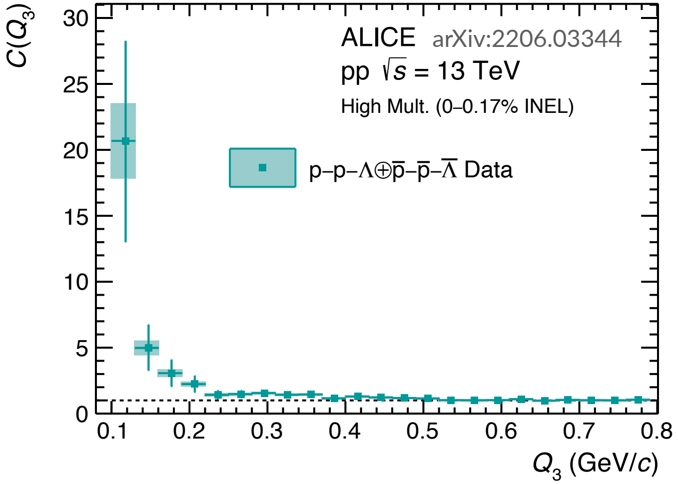
- Lorentz-invariant Q_3 is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2} \qquad q_{ij}^{\mu} = 2\left(\frac{m_j E_i}{m_i+m_j} - \frac{m_i E_j}{m_i+m_j}, \frac{m_j}{m_i+m_j}\mathbf{p}_i - \frac{m_i}{m_i+m_j}\mathbf{p}_j\right)$$

p-p-p

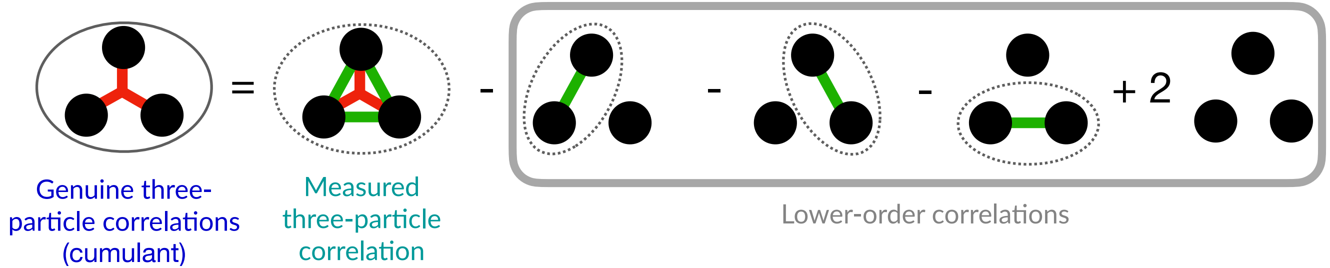


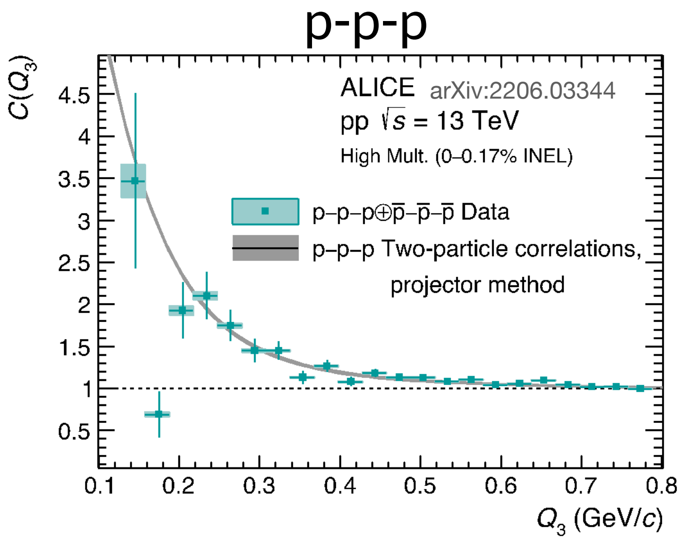
p-p-Λ

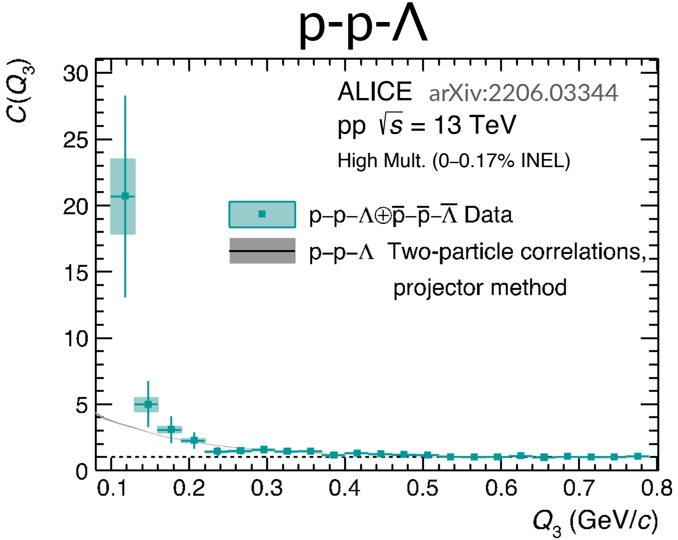


Cumulants in femtoscopy

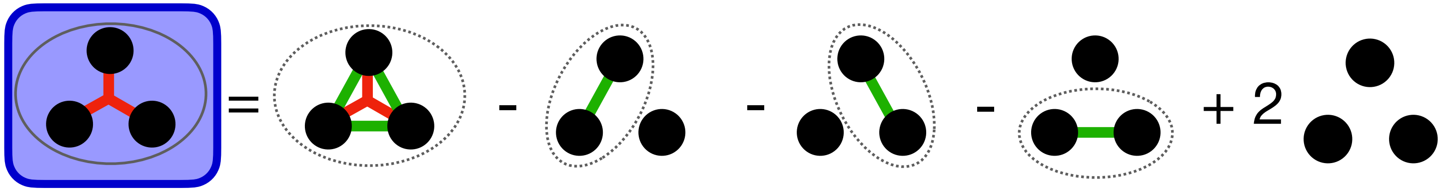
R. Kubo, J. Phys. Soc. Jpn. 17, pp. 1100-1120 (1962)







p-p-p cumulant



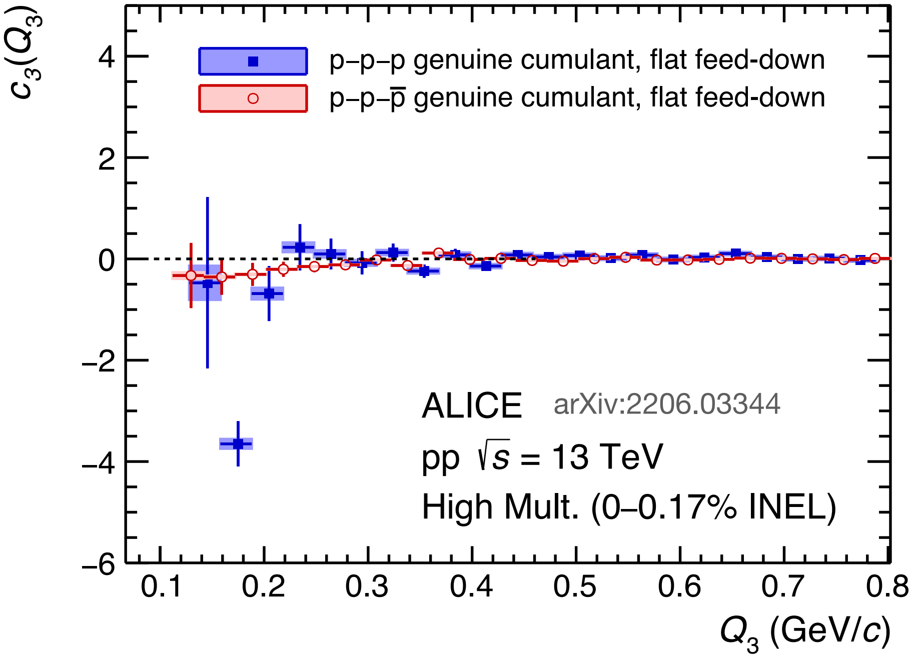
Negative cumulant for p-p-p

Possible effects at play:

- Pauli blocking at the three-particle level
- three-body strong interaction

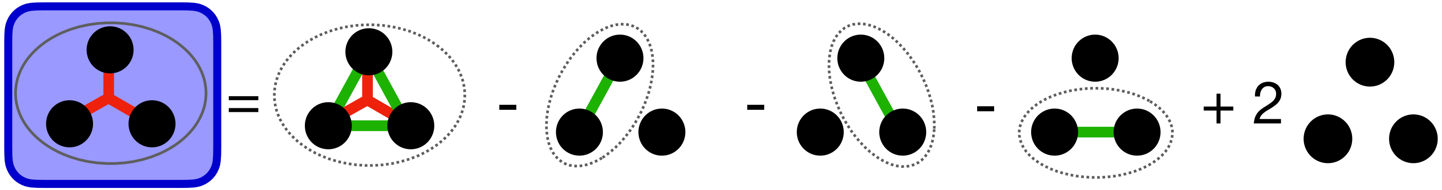
Statistical significance:

n_σ= 6.7 for Q_3 < 0.4 GeV/c



Test with mixed-charge particles, cumulant negligible.

p-p-Λ cumulant



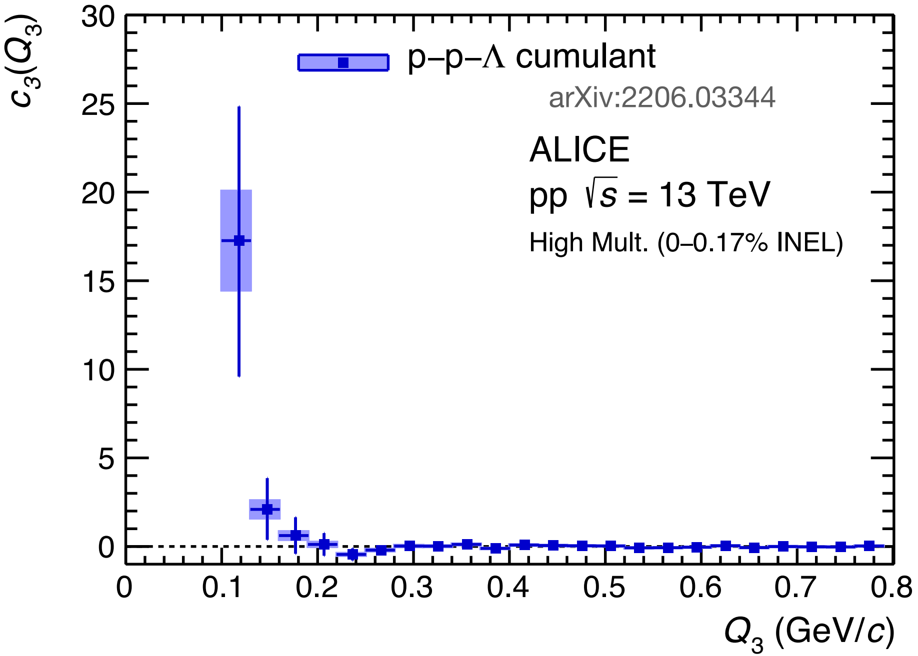
Positive cumulant for p-p-Λ

- Only two identical and charged particles
  - ✓ Main expected contribution from three-body strong interaction
- Relevant measurement for equation of state of neutron stars

Statistical significance:

n_σ= 0.8 for Q_3 < 0.4 GeV/c

In Run 3, two orders of magnitude gain in statistics expected!



Conclusions

- New precise measurements of the lifetime, Λ separation energy and production yields of the hypertriton ($3_{\Lambda}H$):
  - **Weakly bound state B_{Λ} ~ 100 keV** corresponds to large radii ~ 5 fm
  - $^{3}_{\Lambda}H$ / Λ ratio in pp and p–Pb favours coalescence expectation
    - **nuclear size matters at low-charged particle multiplicity**

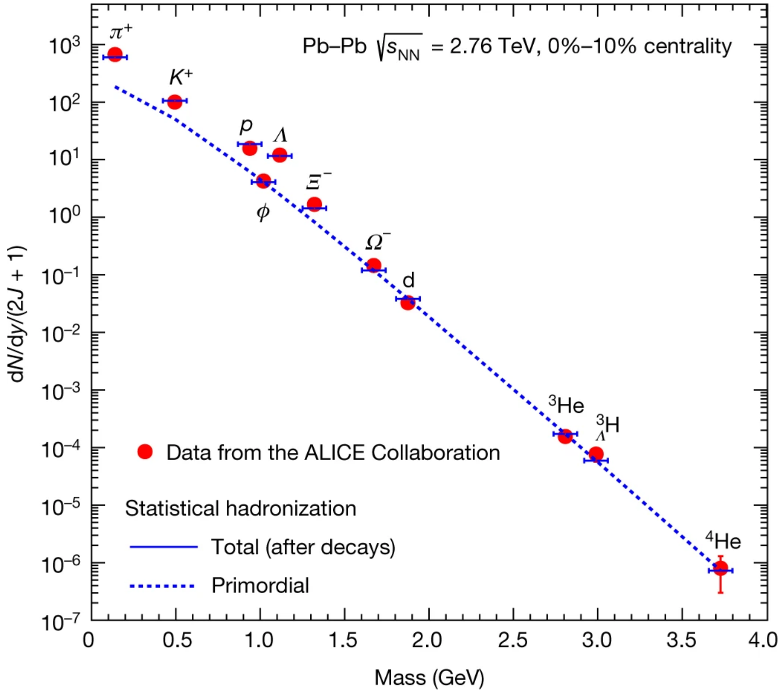
- Femtoscopic correlations to probe many-body dynamics
  - **p-d** correlation can not be described without including the **full three-nucleon dynamics**
  - **p-p-p** correlation function shows a **significant deviation** from the simple description in terms of mutual two-body interactions
  - **p-p-Λ** correlation exhibits **no significant deviation**
    - Precision measurements to come in LHC Run 3 and Run 4!

Backup slides

Nucleosynthesis at the LHC

- (Hyper)Nuclei: unique probes to study the interactions between hadrons
  - at the LHC (hyper)nuclei formation occurs at extremely high temperatures (T ~ 100 MeV)

- Two theoretical models available to describe nuclear production
  - Statistical Hadronisation Models (SHM) [1, 2]: yields described by filling the available phase-space after the collision
    - No microscopic description of nuclei formation



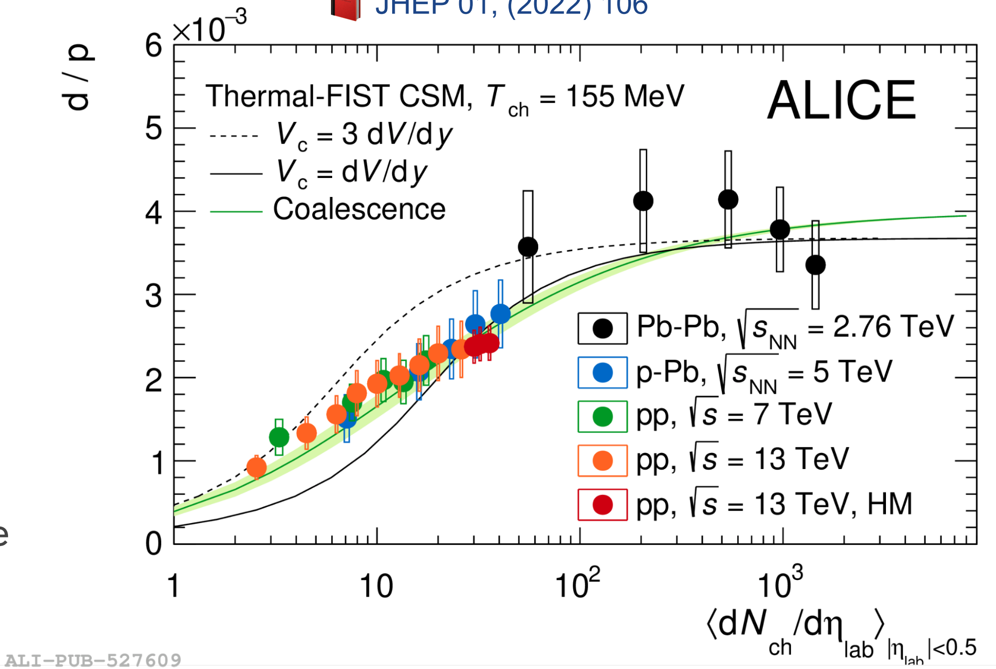
2 A. Andronic et al., Nature 561, (2018) 3210

1 *Vovchenko et al.*, Phys. Lett. B 785, (2018) 171

Nucleosynthesis at the LHC

- (Hyper)Nuclei: unique probes to study the interactions between hadrons
  - at the LHC (hyper)nuclei formation occurs at extremely high temperatures (T ~ 100 MeV)
- Two theoretical models available to describe nuclear production
  - SHM [1]
  - Coalescence [2]: nuclei arise from the overlap of the nucleons in the phase space
    - microscopic description
    - yield predictions only relative to the nucleon ones

JHEP 01, (2022) 106



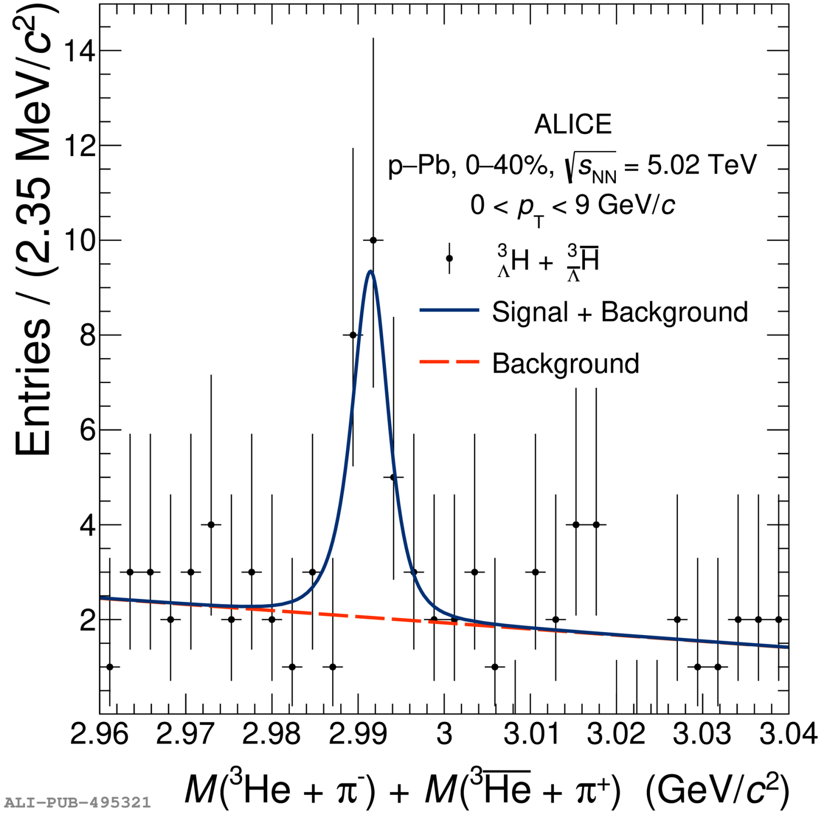
[1] *Vovchenko et al.*, Phys. Lett. B 785, (2018) 171

[2] *Sun et al.*, Phys. Lett. B 792, (2019) 132

$^{3}_{\Lambda}$H selection in pp and p–Pb collisions

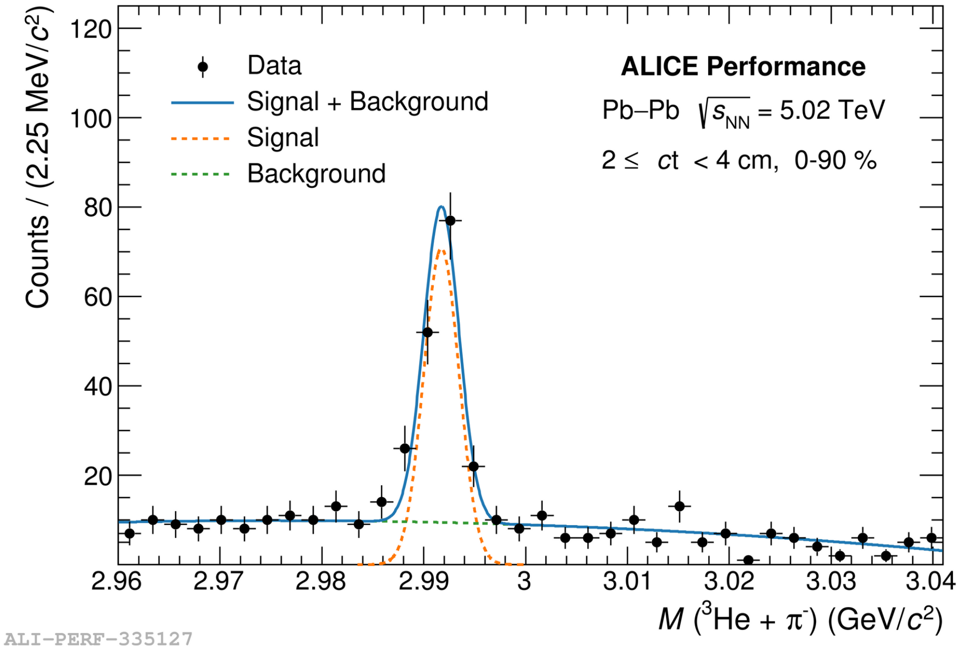
- Data samples:
  - pp collisions at $\sqrt{s}$ = 13 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected during Run 2
- $^{3}_{\Lambda}$H selection in pp: trigger on high multiplicity events using V0 detectors + topological selections on triggered events
- $^{3}_{\Lambda}$H selection in p–Pb: 40% most central collisions + BDT Classifier
- Significance > 4σ both in pp and p–Pb

Phys. Rev. Lett. 128, (2022), 252003



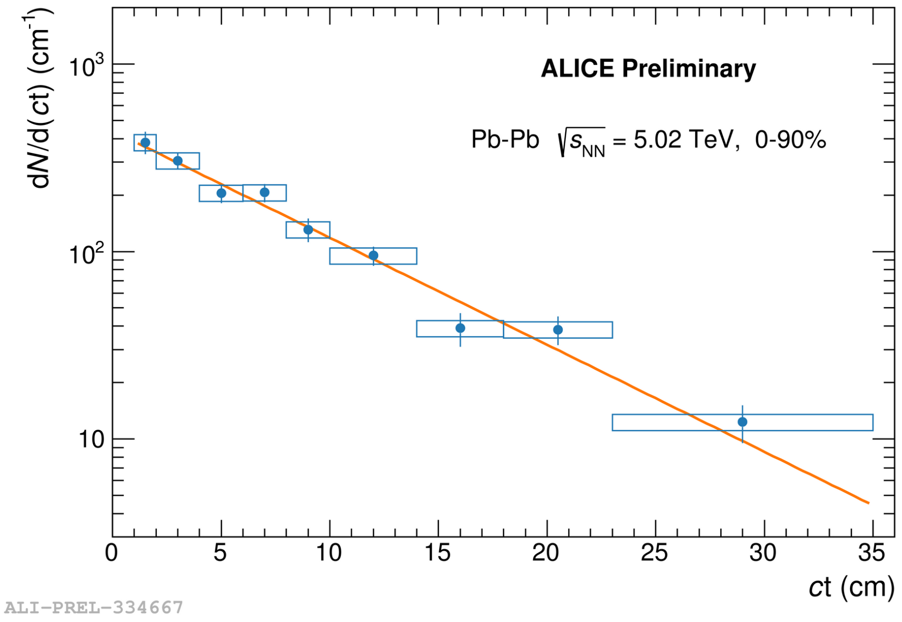
Signal extraction in Pb–Pb

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- high significance over a wide range
    - 9 ct bins from 1 to 35 cm



$^{3}_{\Lambda}H$ Lifetime

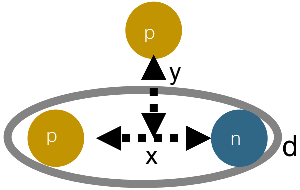
- Corrected ct spectrum fitted with an exponential function
- Lifetime value from the fit
    - Statistical uncertainty ~ 6%
    - Systematic uncertainty ~ 7%
- Most precise measurement of the lifetime ever done so far



Proton-deuteron wave function

The three body wave function with proper treatment of 2N and 3N interaction at very short distances goes to a p–d state.

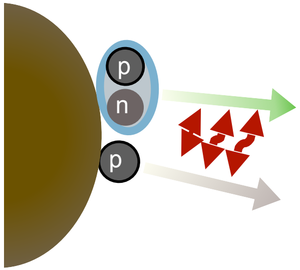
- Three–body wavefunction for p–d: $\Psi_{m_2,m_1}(x,y)$ describing three-body dynamics, anchored to p–d scattering observables.
  - x = distance of p-n system within the deuteron
  - y = p-d distance
  - m2 and m1 deuteron and proton spin



- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state:

$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \Psi^{(\text{free})}_{m_2,m_1} + \sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi}\, i^L \sqrt{2L+1}\, e^{i\sigma_L} (1m_2\tfrac{1}{2}m_1|SJ_z)(L0SJ_z|JJ_z)\widetilde{\Psi}_{LSJJ_z} .$$

Asymptotic form — Strong three-body interaction



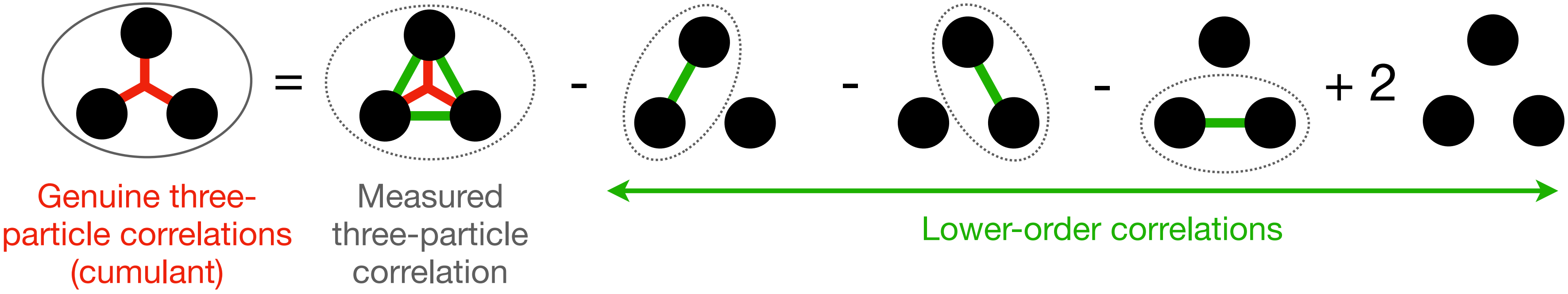
➡ $\widetilde{\Psi}_{LSJJ_Z}$ describe the configurations where the three particles are close to each other

➡ $\Psi^{(\text{free})}_{m_1,m_2}$ an asymptotic form of p-d wave function

Kievsky et al, Phys. Rev. C 64 (2001) 024002
Kievsky et al, Phys. Rev. C 69 (2004) 014002
Deltuva et al, Phys. Rev. C71 (2005) 064003

Cumulants in femtoscopy

Genuine three-particle correlations are obtained from the total three-particle correlations by subtracting the lower-order contribution [1]:



In terms of correlation functions:

$$c_3\left(Q_3\right) = C\left(Q_3\right) - \boxed{C_{12}\left(Q_3\right) - C_{23}\left(Q_3\right) - C_{31}\left(Q_3\right) + 2}$$

How to estimate lower-order contributions?

[1] R. Kubo, J. Phys. Soc. Jpn. 17, pp. 1100-1120 (1962)

Kubo's cumulant expansion method

- X_i denotes the general i-th stochastic variable
- The most general decomposition of 2-particle correlation is:

$$\langle X_1 X_2 \rangle = \langle X_1 \rangle \langle X_2 \rangle + \langle X_1 X_2 \rangle_c$$

- By definition, the 2nd term on the right is the 2-particle cumulant
- Cumulants cannot be measured directly, however:

$$\langle X_1 X_2 \rangle_c = \langle X_1 X_2 \rangle - \langle X_1 \rangle \langle X_2 \rangle$$

Kubo's cumulant expansion method

- The most general decomposition of 3-particle correlation is:

$$\begin{aligned}\langle X_1 X_2 X_3 \rangle &= \langle X_1 \rangle \langle X_2 \rangle \langle X_3 \rangle \\ &+ \langle X_1 X_2 \rangle_c \langle X_3 \rangle + \langle X_1 X_3 \rangle_c \langle X_2 \rangle + \langle X_2 X_3 \rangle_c \langle X_1 \rangle \\ &+ \langle X_1 X_2 X_3 \rangle_c\end{aligned}$$

- Using the 2-particle cumulant: $\langle X_1 X_2 \rangle_c = \langle X_1 X_2 \rangle - \langle X_1 \rangle \langle X_2 \rangle$

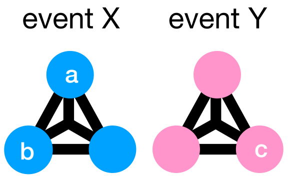
- Working recursively from higher to lower orders, we have 3-particle cumulant expressed in terms of the measured 3-, 2-, and 1-particle averages:

$$\begin{aligned}\langle X_1 X_2 X_3 \rangle_c &= \langle X_1 X_2 X_3 \rangle \\ &- \langle X_1 X_2 \rangle \langle X_3 \rangle - \langle X_1 X_3 \rangle \langle X_2 \rangle - \langle X_2 X_3 \rangle \langle X_1 \rangle \\ &+ 2 \langle X_1 \rangle \langle X_2 \rangle \langle X_3 \rangle\end{aligned}$$

Lower-order contributions

Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:



$$C_{ab,c}(Q_3) = \frac{N_2\left(\mathbf{p}_a\,,\mathbf{p}_b\right) N_1\left(\mathbf{p}_c\right)}{N_1\left(\mathbf{p}_a\right) N_1\left(\mathbf{p}_b\right) N_1\left(\mathbf{p}_c\right)}$$

- Lorentz-invariant scalar Q_3 calculated using the single particle momenta $\mathbf{p}_a, \mathbf{p}_b, \mathbf{p}_c$

Projector method

- Use two-particle measured or theoretical correlation function $C(k^*_{ab})$
- Perform kinematic transformation:

two-body CF projector

$$C_{ab,c}(Q_3) = \int \underbrace{C(k^*_{ab})}\underbrace{W_{ab}(k^*_{ab}, Q_3)}dk^*_{ab}$$

Measured/modeled 2-body correlation functions

Jacobian from 2-body to 3-body coordinates

R.D.G., L. Šerkšnytė et al. EPJC 82 (2022) 244

Projection onto Q_3

- The projection onto Q_3 is performed as follows

$$C_3(Q_3) = \iiint_{(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\in\mathcal{D}} C_3(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\,\mathcal{N}\,d^3\mathbf{p}_1\,d^3\mathbf{p}_2\,d^3\mathbf{p}_3$$

$$\mathcal{D} = \{(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)\in\mathcal{S}\mid Q_3 = \text{constant}\}$$

density of states in the phase space (uniform)

- In the case of two-body correlations, the projections turns to be

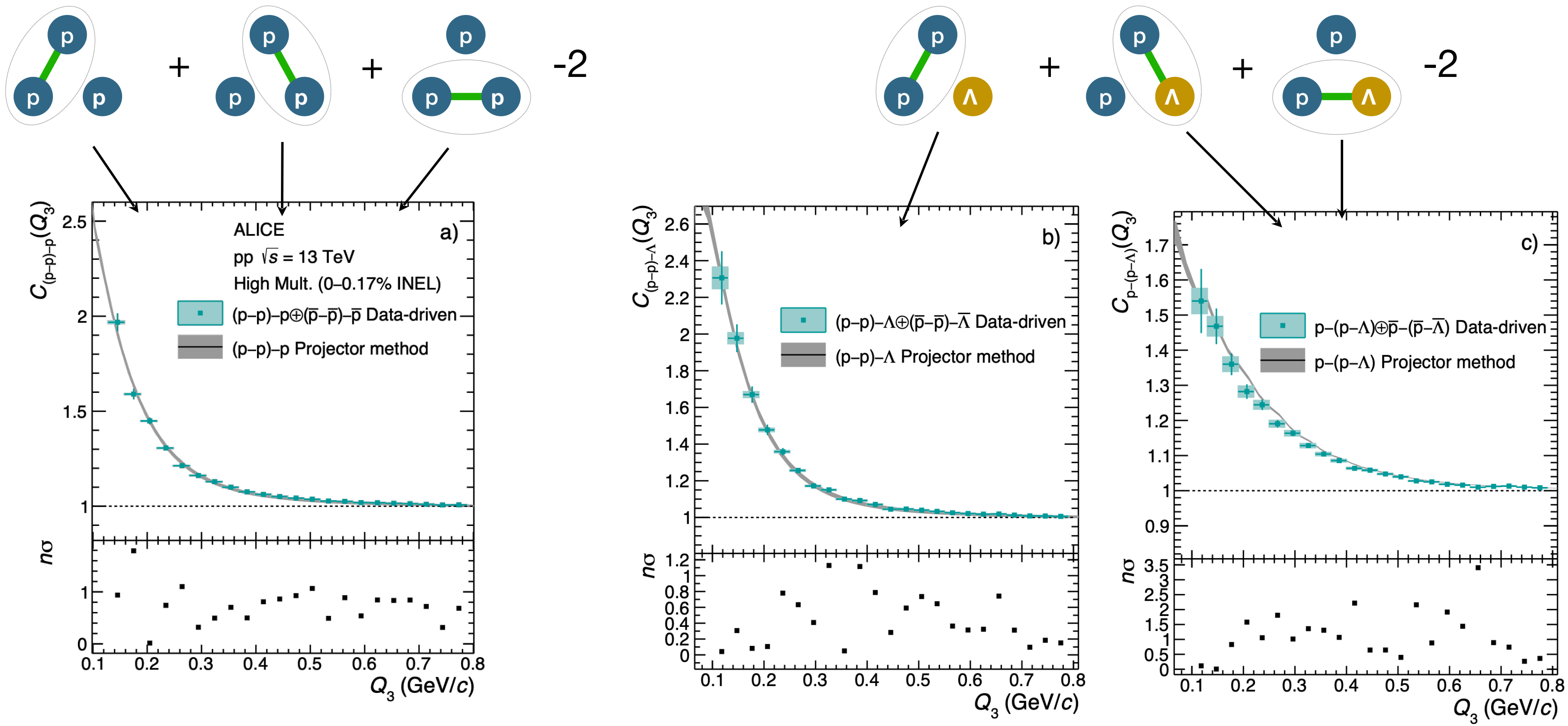
two-body correlation function

projector $W(k_1, Q_3)$ ----> phase space density at Q_3 = constant

$$C_3(Q_3) = \int_0^{\sqrt{\frac{\gamma}{\alpha\gamma-\beta^2}}Q_3} C_2(k_1)\left[\frac{16(\alpha\gamma-\beta^2)^{3/2}k_1^2}{\pi Q_3^4\gamma^2}\sqrt{\gamma Q_3^2-(\alpha\gamma-\beta^2)k_1^2}\right]dk_1$$

where α, β and γ are constants depending on the particles mass.

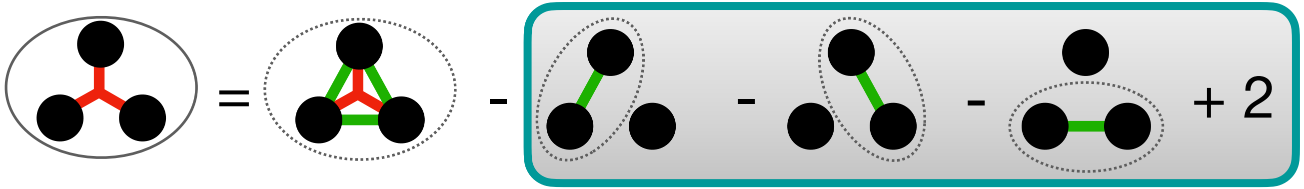
Lower-order contributions in p-p-p and p-p-Λ

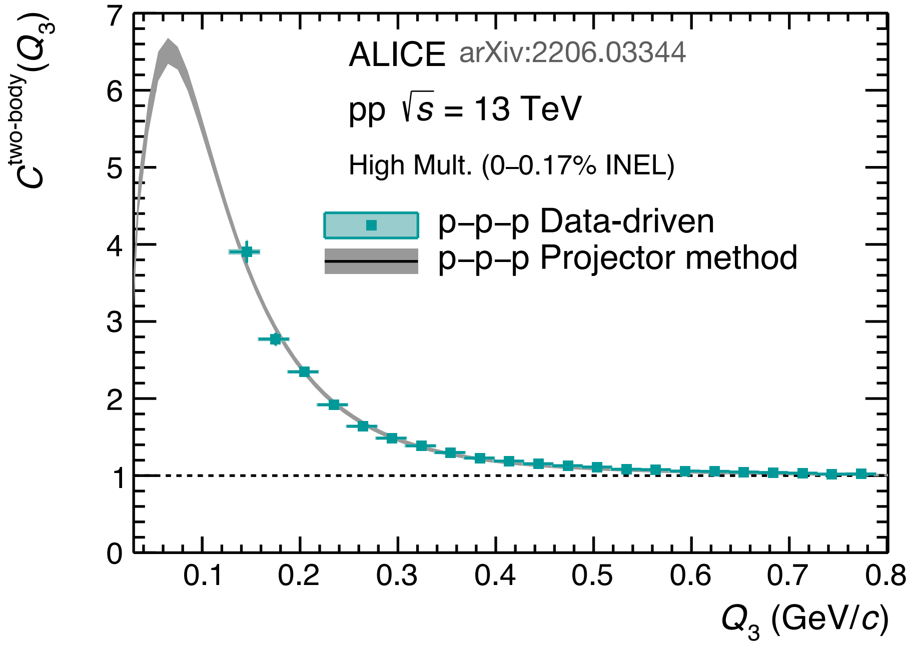


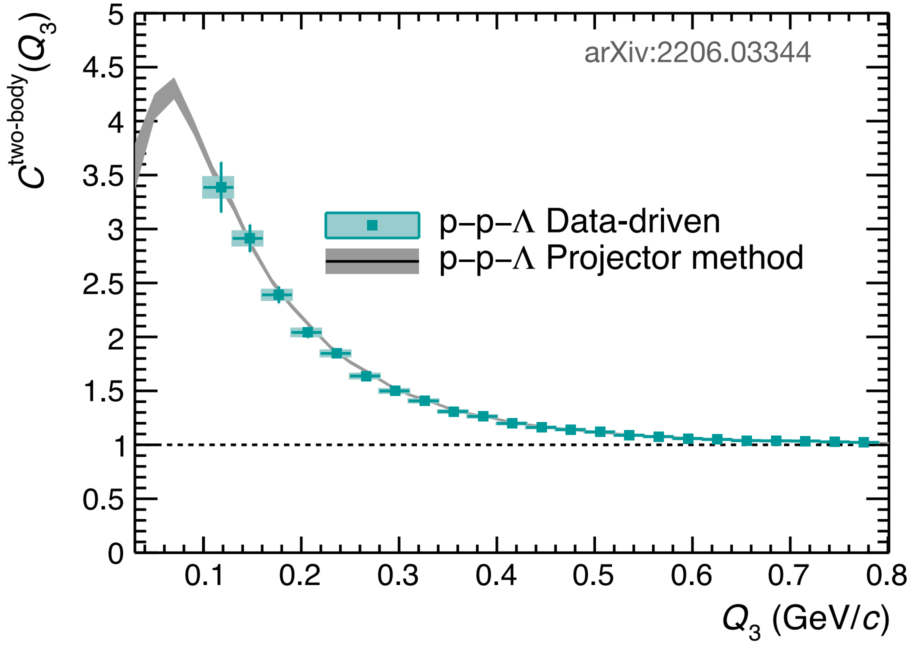
Measured p-p correlation *ALICE Coll. PLB 805 (2020) 135419*

Measured p-Λ correlation *ALICE Coll. PLB 833 (2022), 137272*

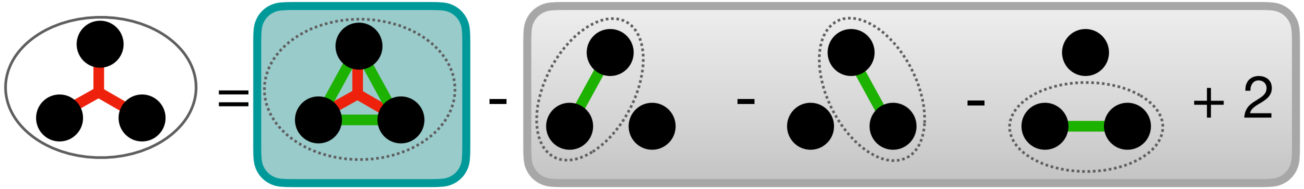
p-p-p and p-p-Λ correlation functions

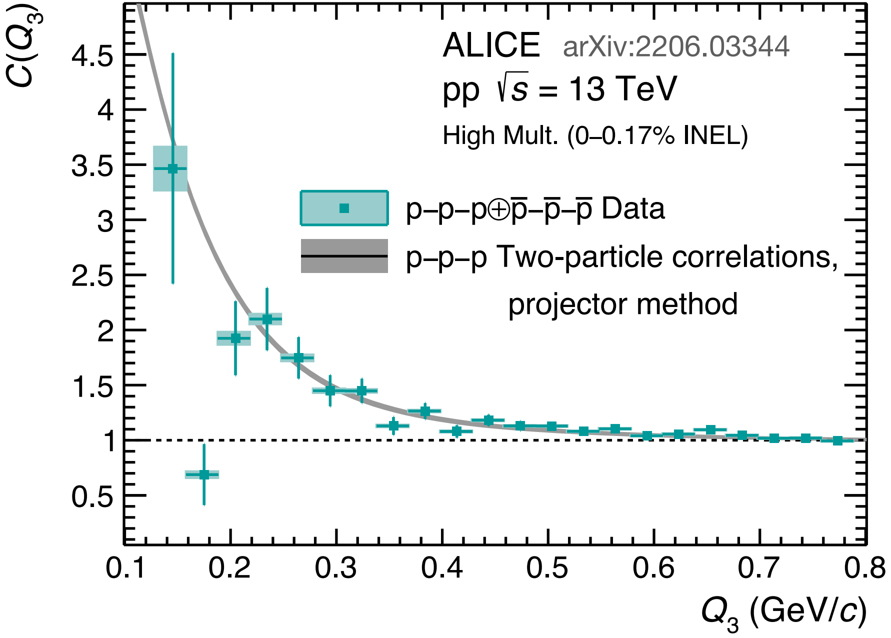


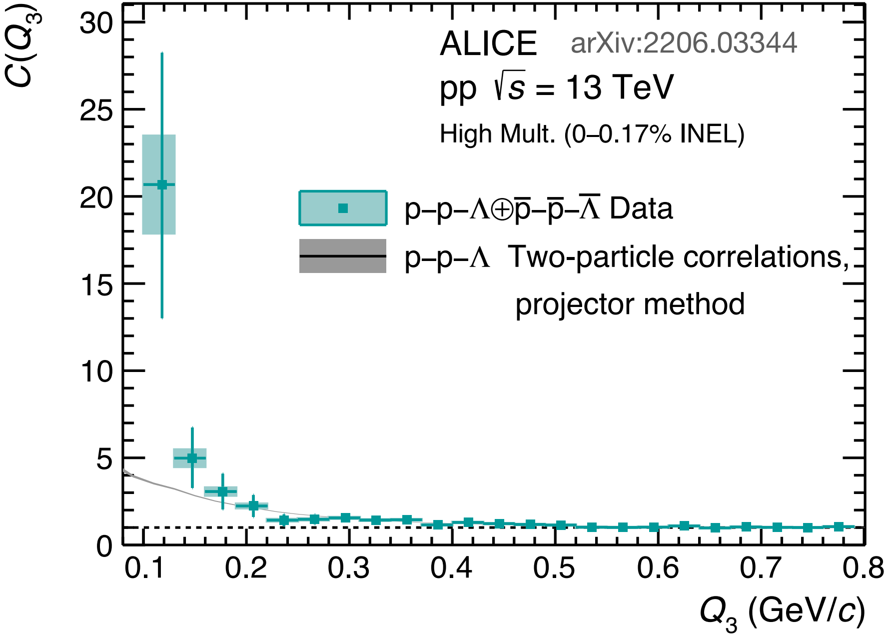




p-p-p and p-p-Λ correlation functions



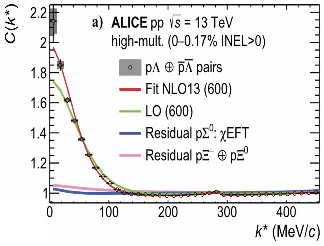




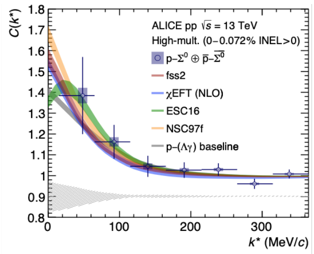
An example of Equation of State for NS

Correlation = two-body interaction

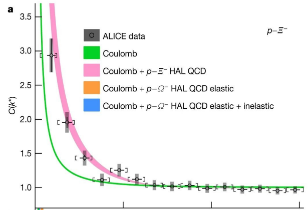
pΛ



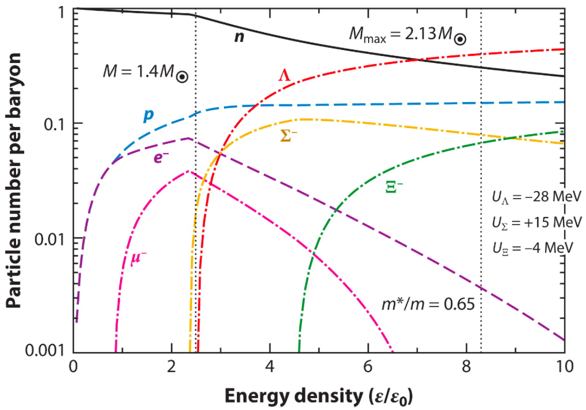
pΣ



pΞ

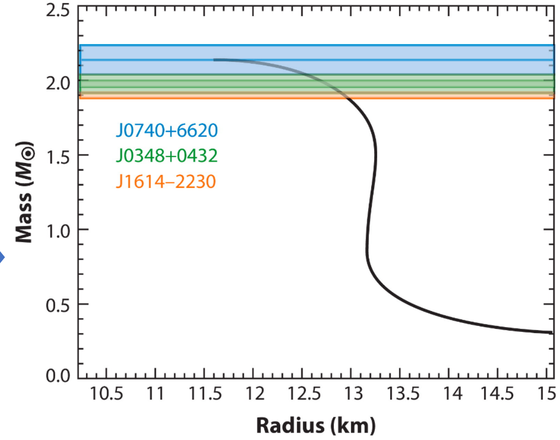


Single-particle potentials = Equation of State



Courtesy J. Schaffner-Bielich 2020

Mass-Radius diagram for hyperon stars



L. Fabbietti et al. Ann.Rev.Nucl.Part.Sci. 71 (2021)

What about the three-body strong interaction?

Source determination

The first step is "traditional" femtoscopy: known interaction → determine source size

- p–p interaction: Argonne v18 potential
- crosscheck with p–Λ (χEFT)

Determine **gaussian "core" radius**
- As a function of pair <m_T>
- **Common to all hadron-hadron pairs**

✖

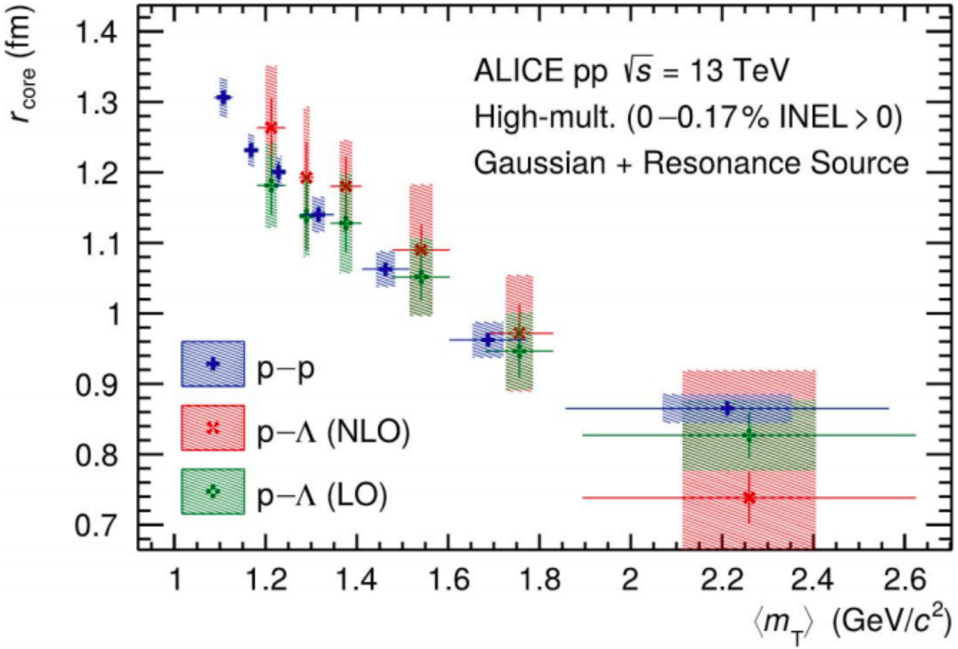
Effect of strong short-lived resonances
Adds **exponential tail** to the source profile
→ Angular distributions from EPOS

→ Production fraction from SHM

	Primordial	Resonances lifetime
p	35.8 %	1.65 fm
Λ	35.6 %	4.69 fm

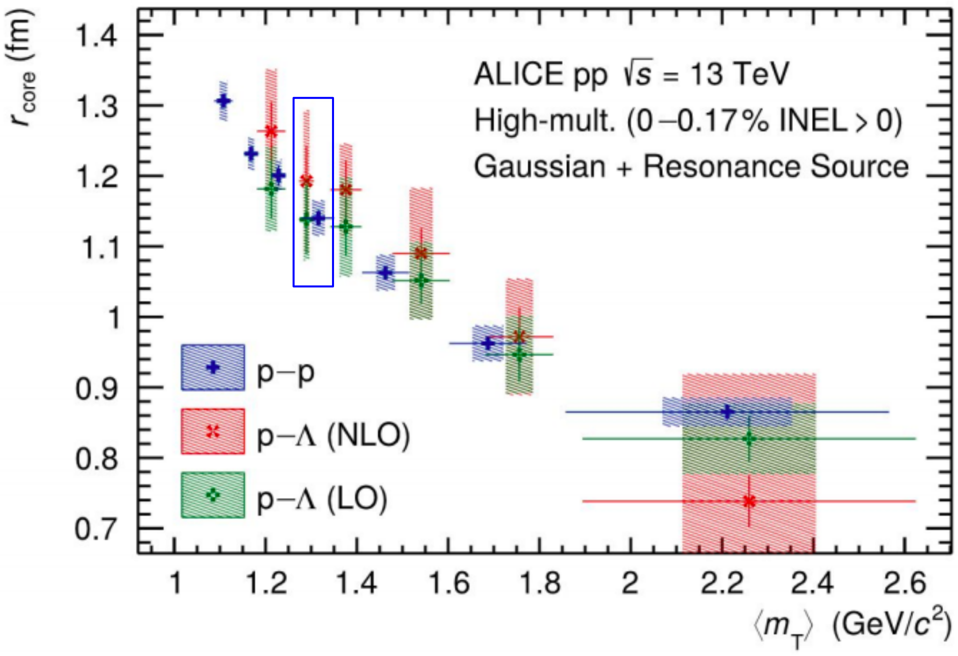
[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

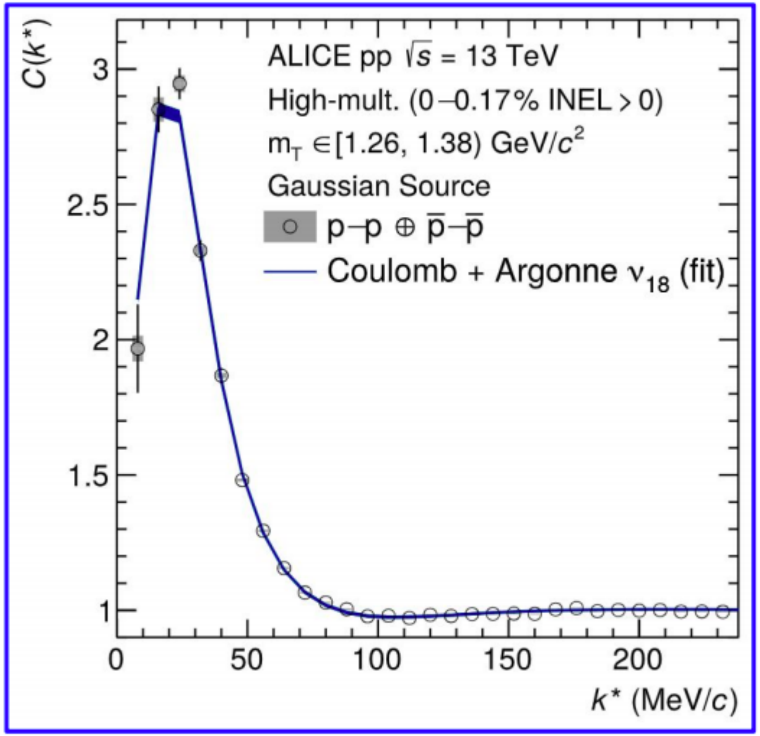
Source determination



[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

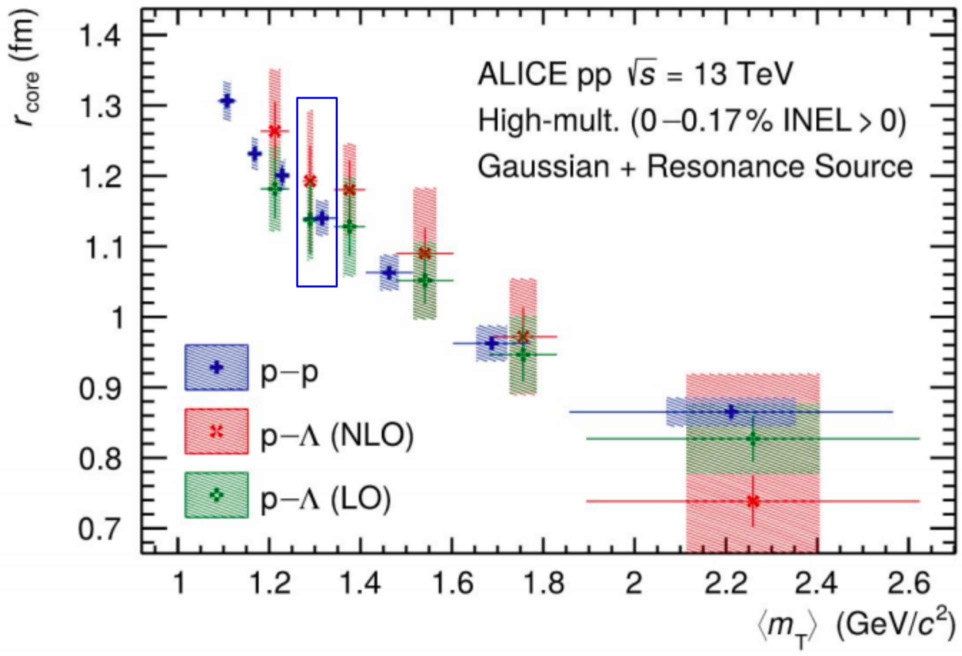
Source determination

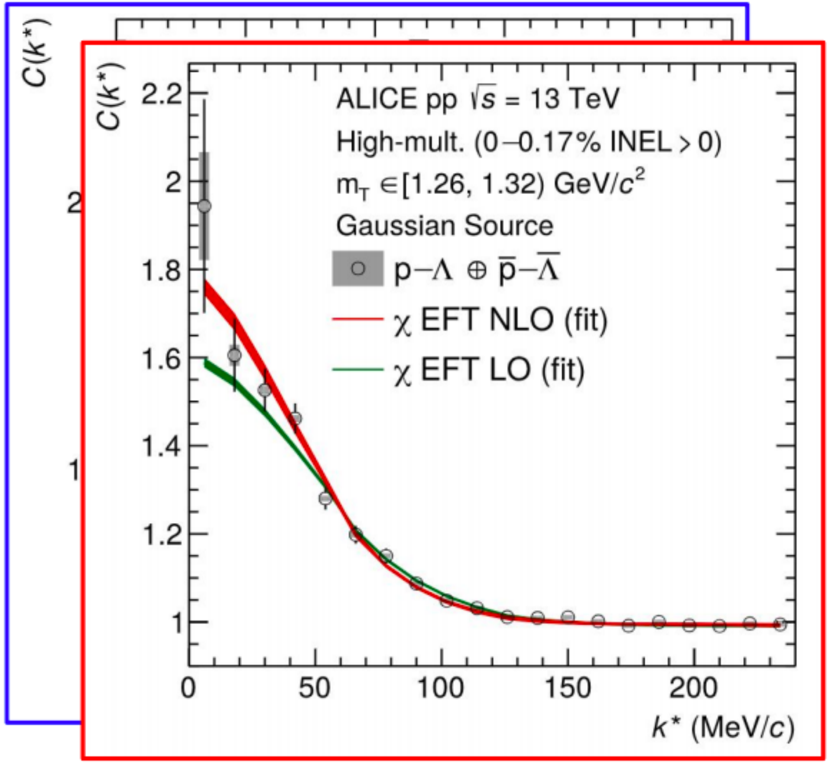




[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

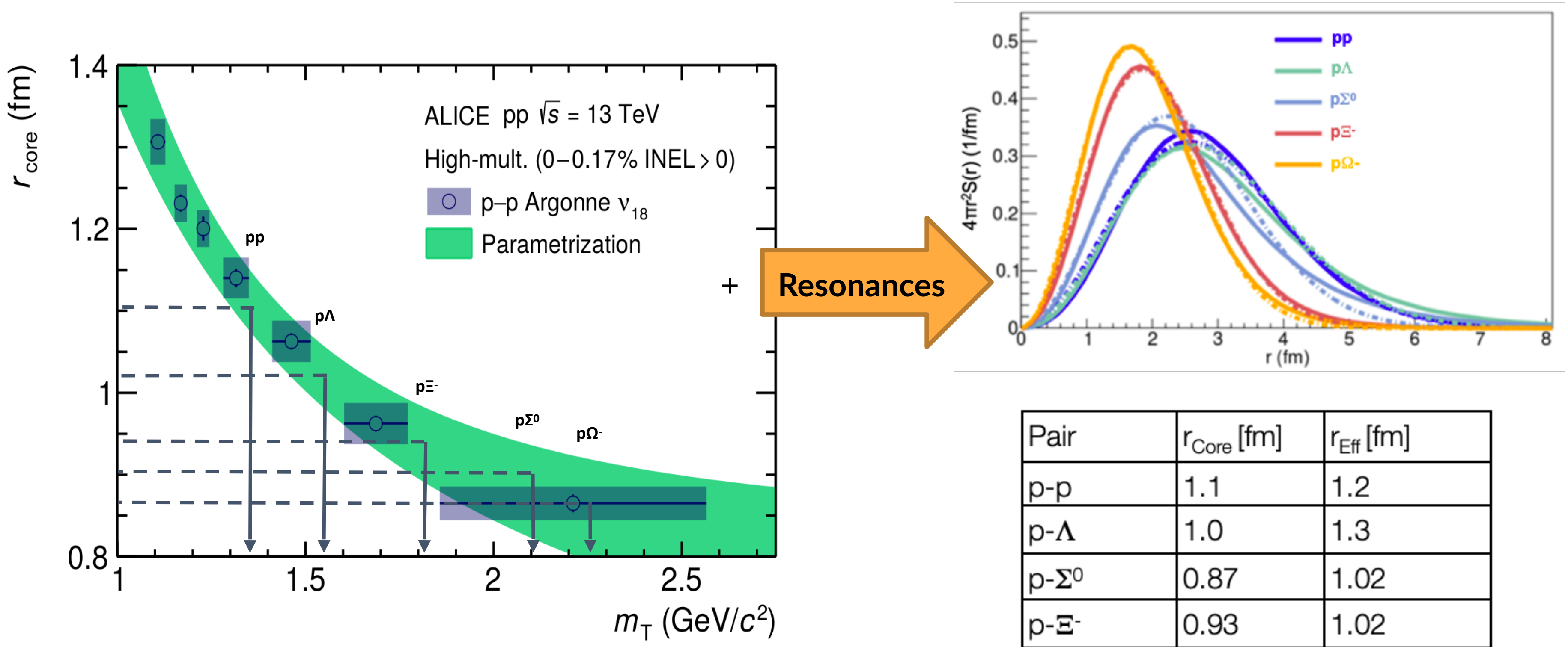
Source determination





[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

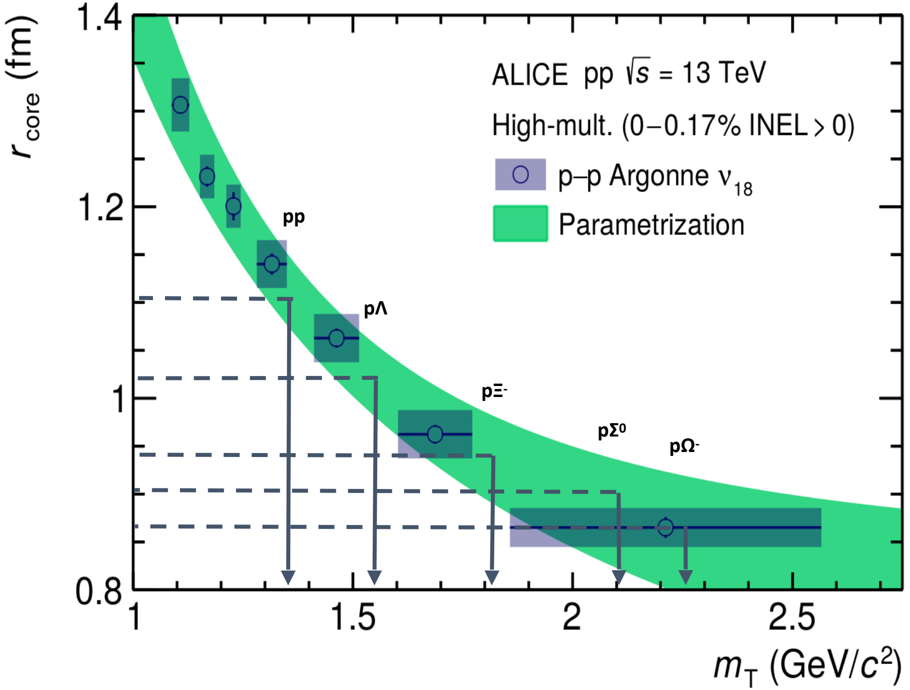
Gaussian source with resonances



ALICE Coll. PLB 811 (2020)

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

Small particle-emitting sources



ALICE Coll. PLB 811 (2020)

Small particle-emitting source created in pp and p−Pb collisions at the LHC.