Synthesis of light nuclei in hadronic collisions

Harald Appelshäuser

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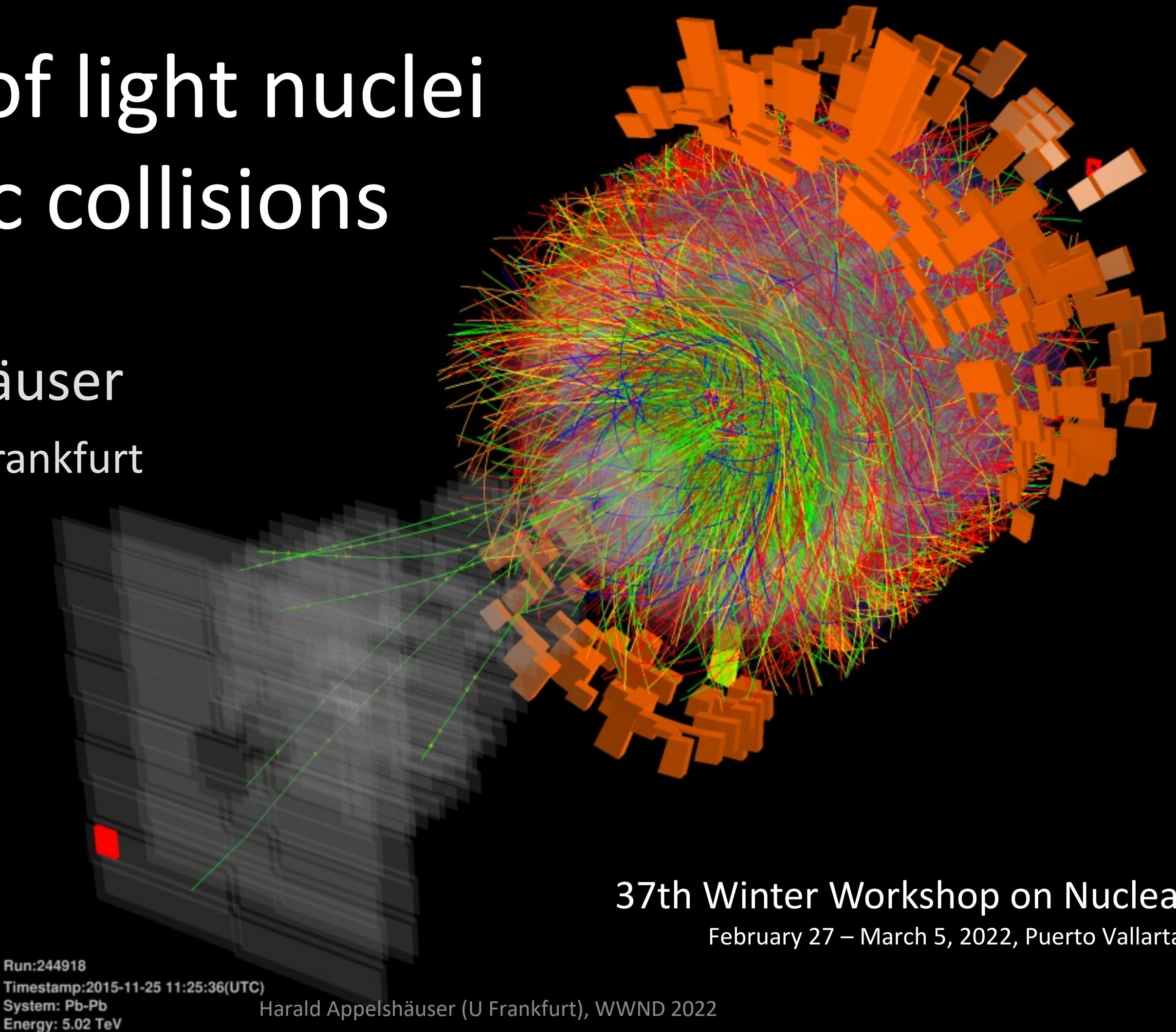


37th Winter Workshop on Nuclear Dynamics

February 27 – March 5, 2022, Puerto Vallarta, Mexico

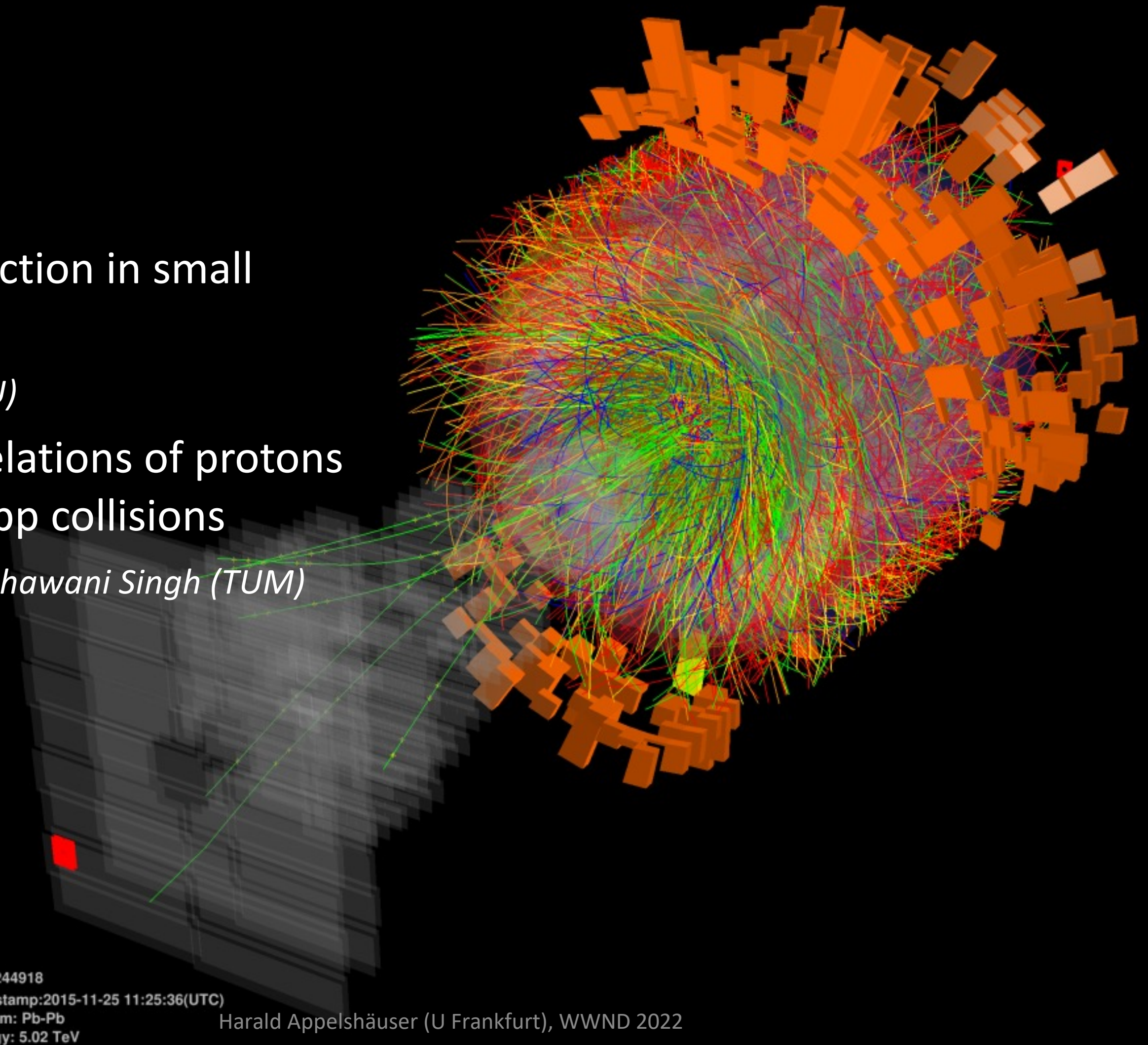
Outline

- Light nuclei production in small collision systems

  Michael Hartung (GU)

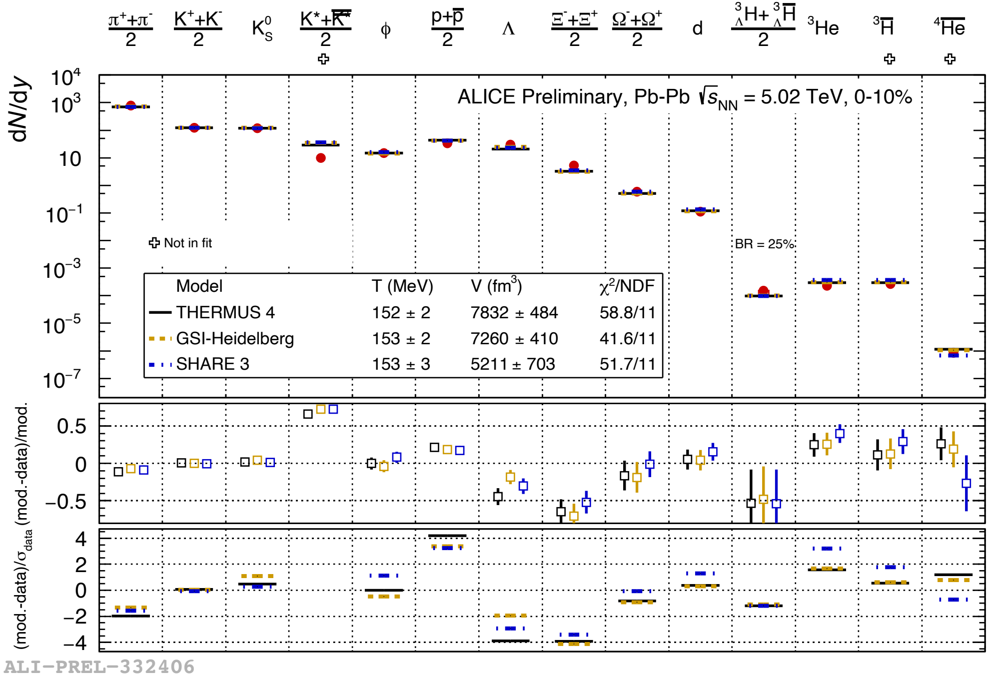
- Femtoscopic correlations of protons and deuterons in pp collisions

  Michael Jung (GU), Bhawani Singh (TUM)



Statistical hadronization

Statistical hadronization models (SHM) provide very good description of hadron production in central Pb-Pb collisions.

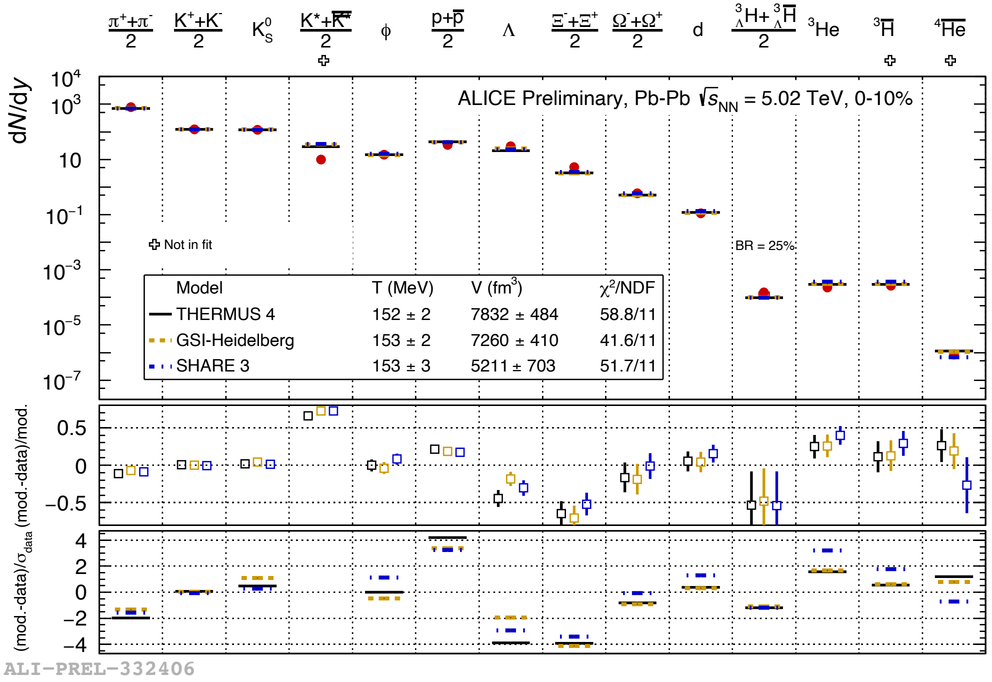


Statistical hadronization

Statistical hadronization models (SHM) provide very good description of hadron production in central Pb-Pb collisions.

Description almost too good:

- Vacuum masses at T_c
- Loosely bound states

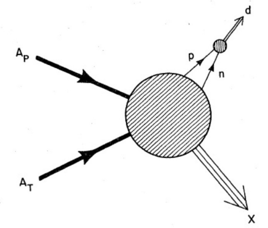


Coalescence

Nuclear clusters are formed after kinetic freeze-out if nucleons are close in phase space.

Coalescence into cluster A is determined by the momentum space density of n, p:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Big|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$



J. Kapusta, Phys. Rev. C 21 (1980) 1301

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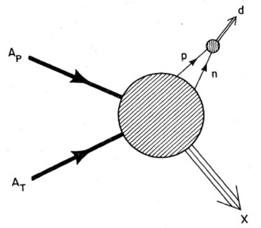
State-of-the-art approaches include source size R and finite size r_A of the cluster, e.g. for deuterons:

$$B_2 \approx \frac{3\pi^{3/2} \langle C_d \rangle}{2 m_T R^3(m_T)}$$

with

$$\langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)} \right)^2 \right]^{-3/2}$$

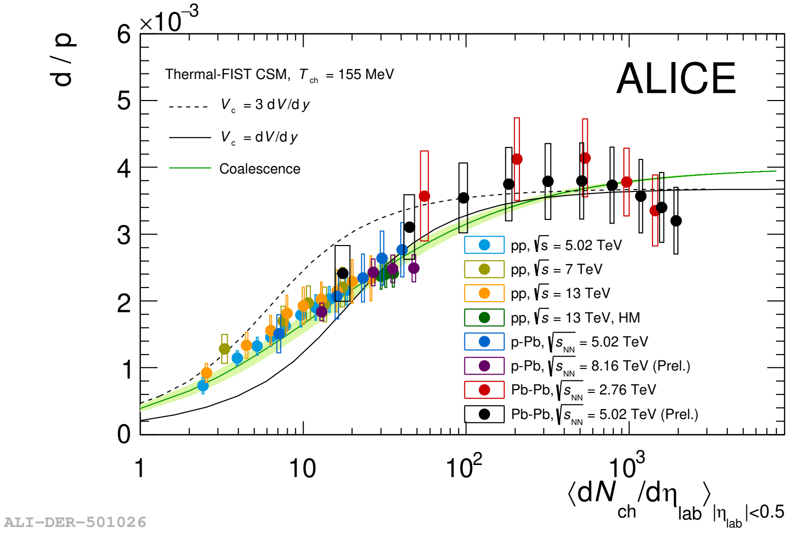


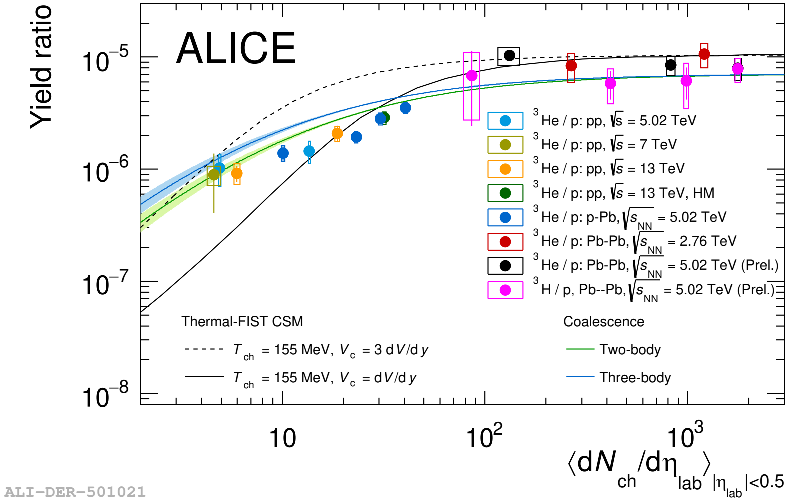
J. Kapusta, Phys. Rev. C 21 (1980) 1301

F. Bellini, A. Kalweit, Phys. Rev. C99 (2019) 5, 054905
K.-J. Sun, C.M. Ko, B. Doenigus, PLB792 (2019)

Light nuclei production in small systems

Comprehensive ALICE data on d and ^{3}He production in different collision systems exist:





- Suppression at small system sizes observed
- Compatible with coalescence calculations
- SHM with canonical suppression can explain data as well

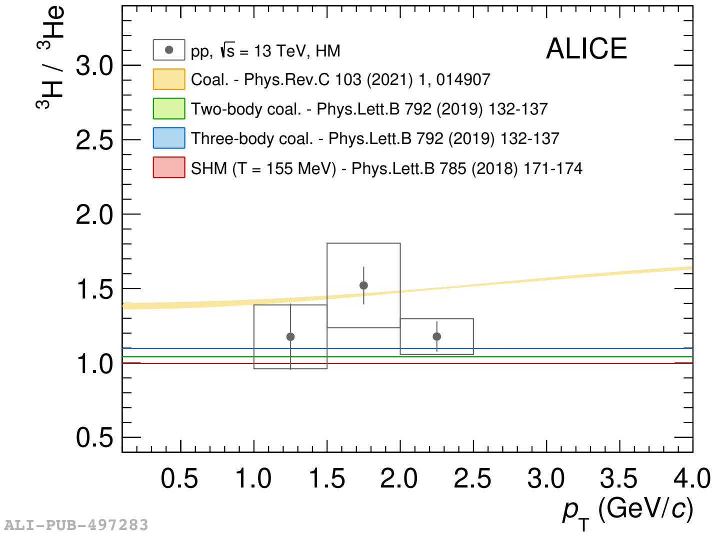
$^3H/^3He$ ratio

Coalescence predicts $^3H/^3He > 1$ in small systems due to different nuclear radii:

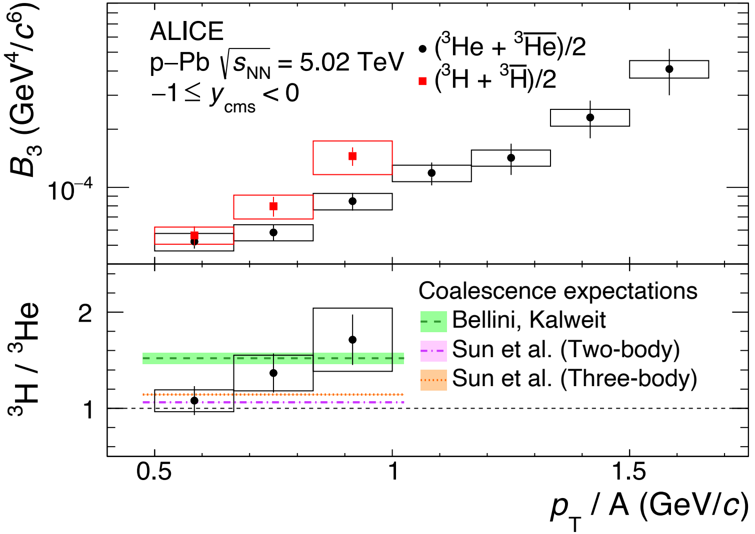
$$r_{^3H}/r_{^3He} \approx 0.9$$

while $^3H/^3He = 1$ in SHM

ALICE, JHEP 01 (2022) 106

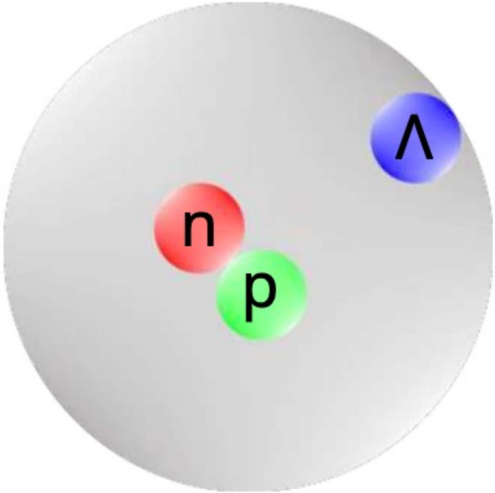


ALICE, Phys.Rev.C 101 (2020) 4, 044906



Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus



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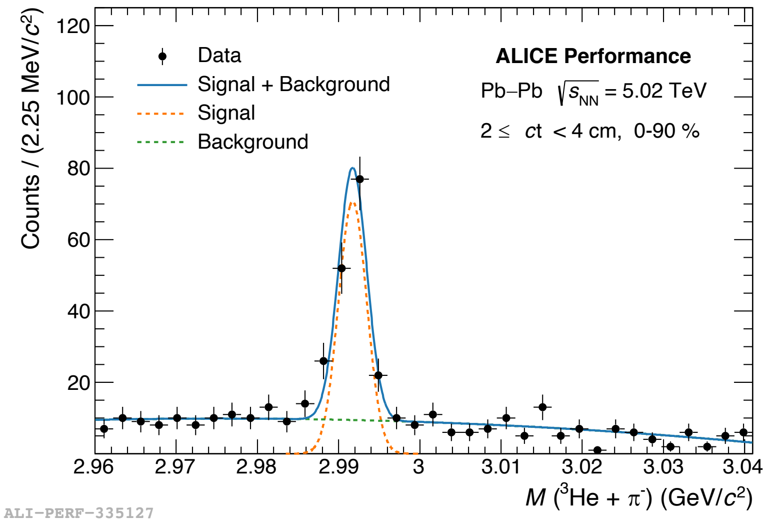
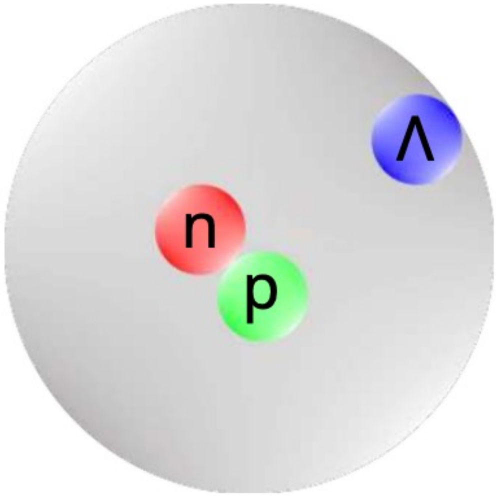
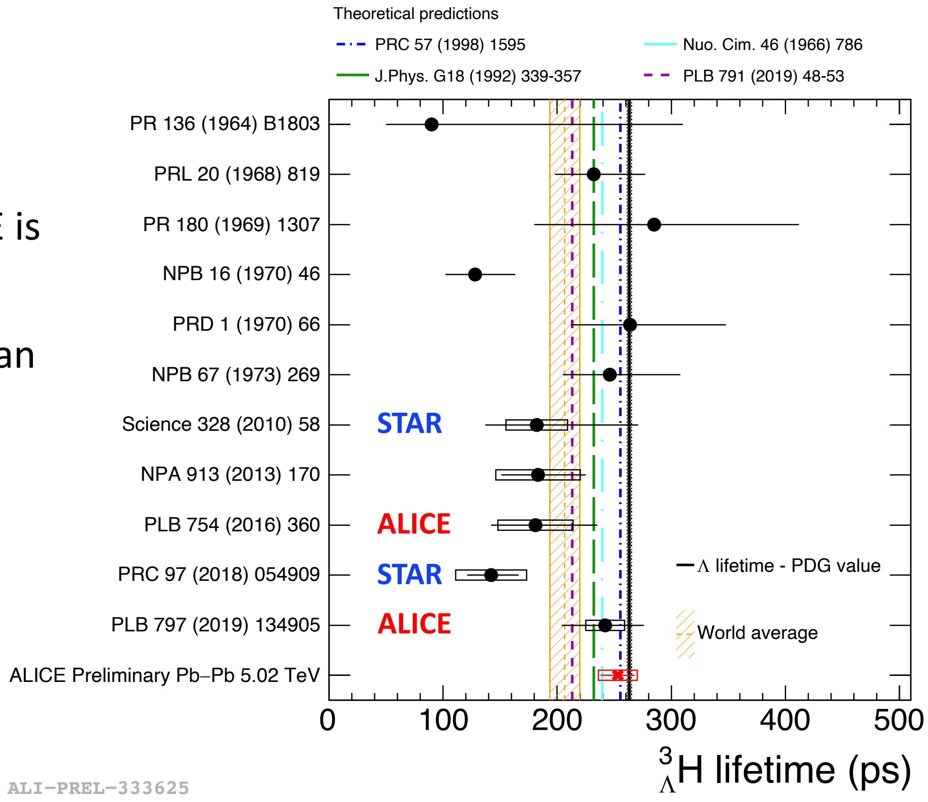




Hypertriton lifetime

- Hypertriton lifetime measured by ALICE is compatible with the free-Λ lifetime
- Preliminary ALICE data more precise than previous world average
- No more lifetime puzzle



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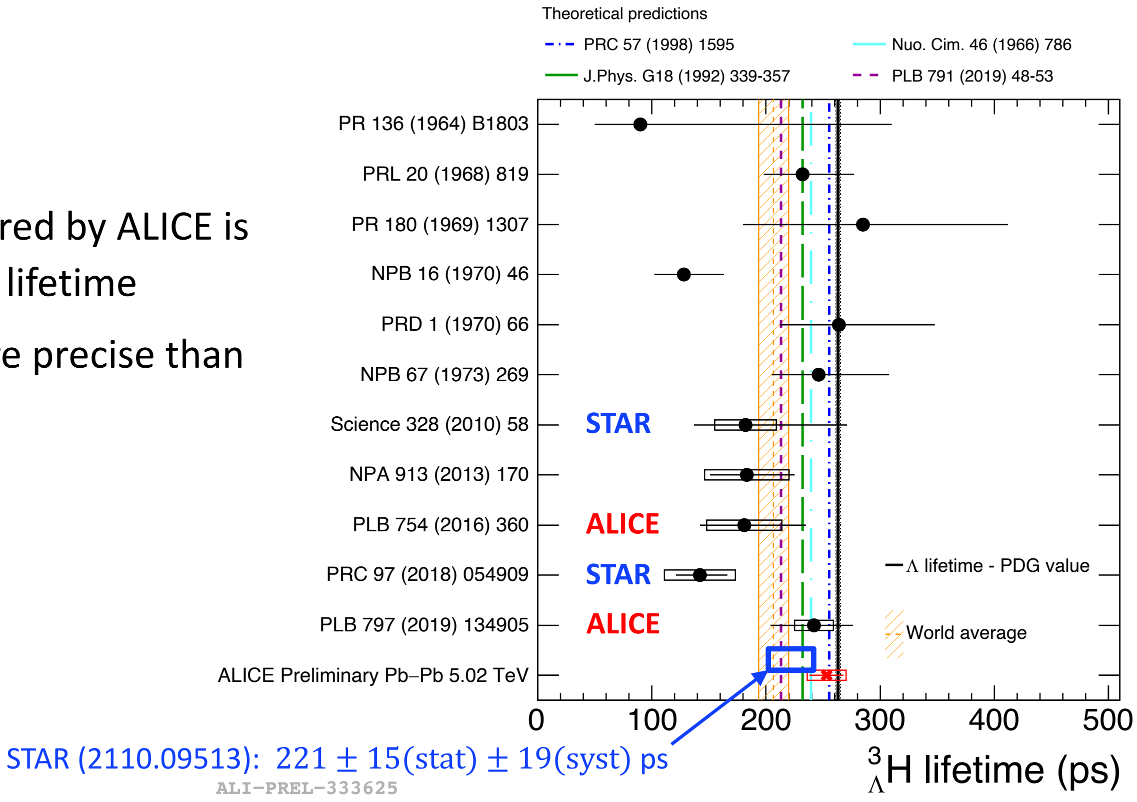
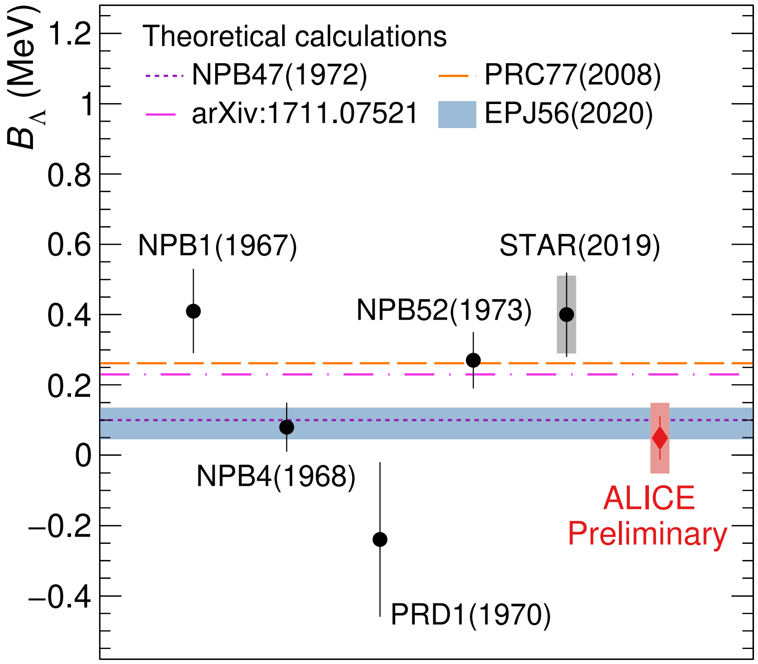


Hypertriton binding energy

- High-resolution mass spectroscopy allows measurement of the Λ binding energy
- B_Λ is compatible with zero
- Loosely-bound nature confirmed



ALI−PREL−486370

Hypertriton

- Λ, p, n bound state
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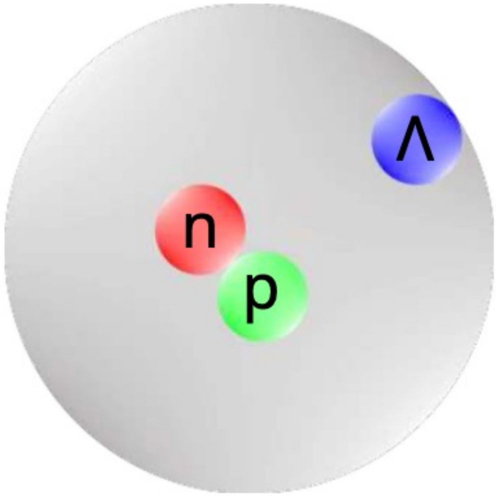
- Loosely bound

- Large radius:

$$r_{^3_\Lambda H}/r_{^3He} \approx 3-5$$



Hypertriton coalescence

- Λ, p, n bound state
- Lightest known hypernucleus
- Loosely bound

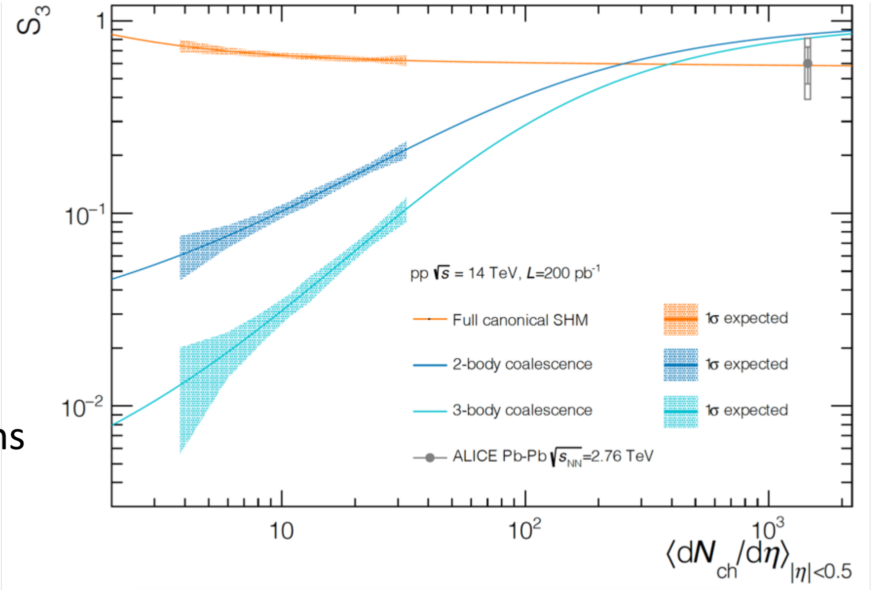
- Large radius:

$$r_{^3_\Lambda H}/r_{^3He} \approx 3-5$$

- Large discriminating power between SHM and coalescence expected in small systems in

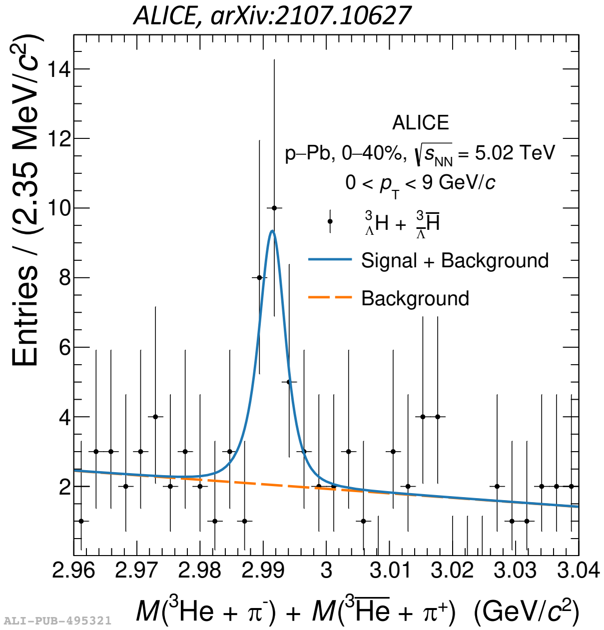
$$S_3 = \frac{^3_\Lambda H/\,^3He}{\Lambda/p}$$

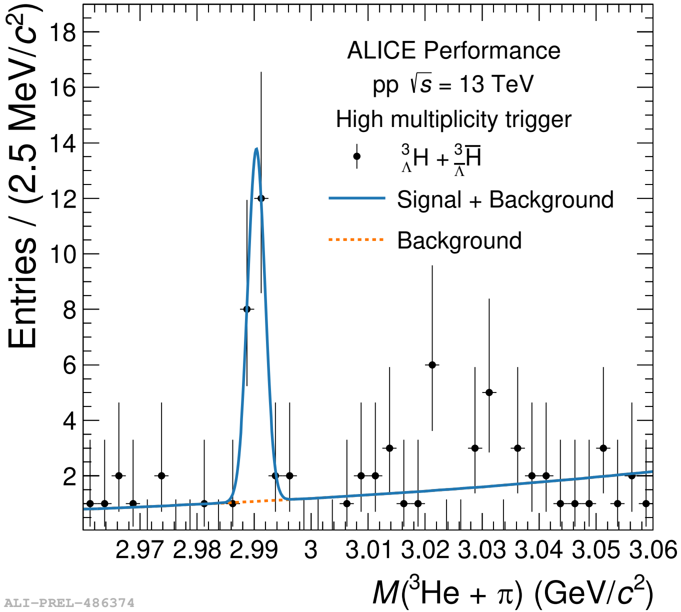
CM: K.-J. Sun, C.M. Ko, B. Dönigus, PLB792 (2019) 132
SHM: V. Vovchenko, B. Dönigus, and H. Stoecker, PLB785 (2018) 171

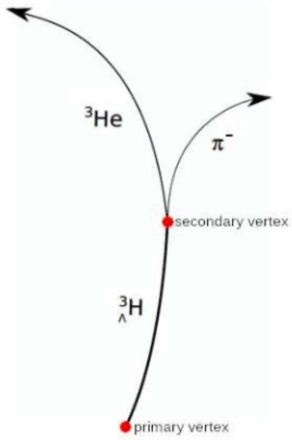


Hypertritons in pp and p-Pb

- First data available on hypertriton production in p-Pb and high-multiplicity pp collisions from ALICE:







$$^3_\Lambda H \rightarrow {}^3He + \pi^-$$
$$B.R. = 0.25$$

Hypertritons in pp and p-Pb

- First S_3 measurements in p-Pb and pp are compatible with coalescence models and disfavor SHM predictions

CM: K.-J. Sun, C.M. Ko, B. Dönigus, PLB792 (2019) 132
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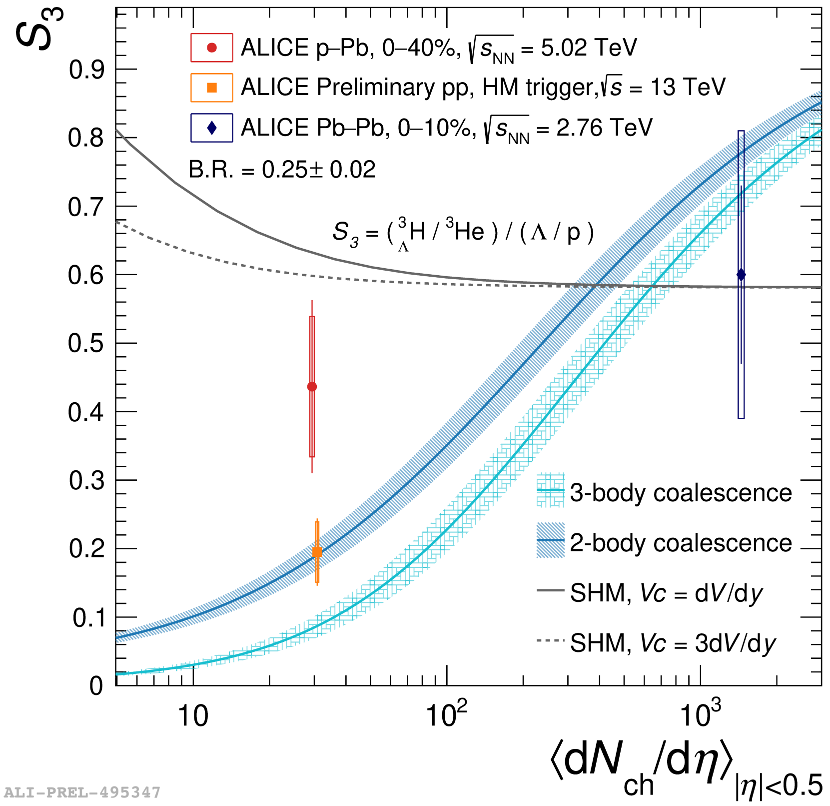

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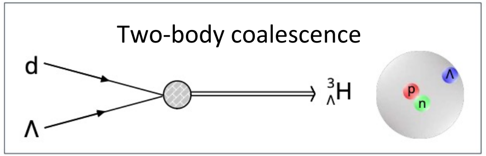
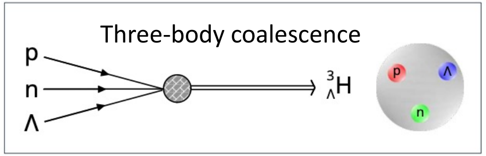
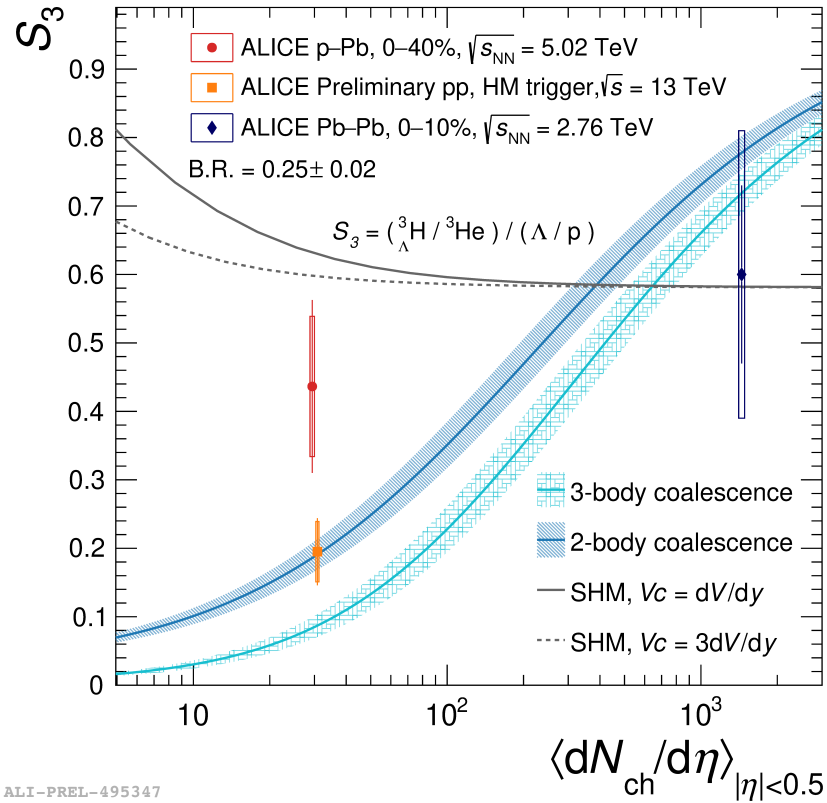




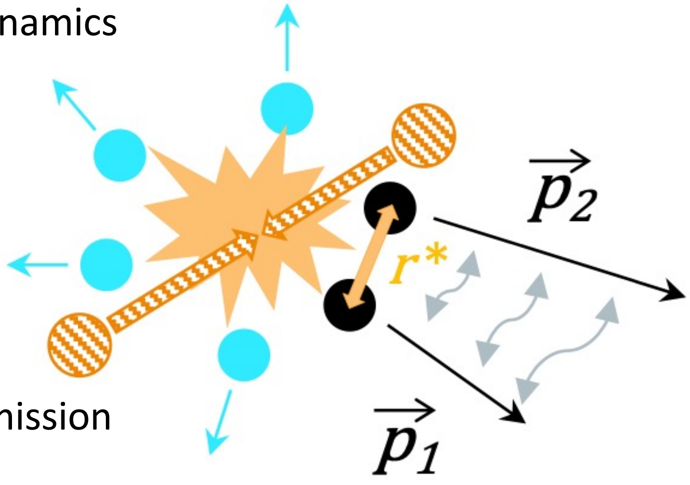
- Present data slightly favor two-body over three-body coalescence

CM: K.-J. Sun, C.M. Ko, B. Dönigus, PLB792 (2019) 132
SHM: V. Vovchenko, B. Dönigus, and H. Stoecker, PLB785 (2018) 171



Femtoscopy

Employ final-state correlations to unravel two-particle dynamics



Experimental correlation function:

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

Koonin-Pratt formalism connects characteristics of the emission source with two-particle dynamics:

$$C(k^*) = \int S(r^*)|\Psi(k^*,r^*)|^2 d^3r^*$$

$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$

$S(r^*)$: source function

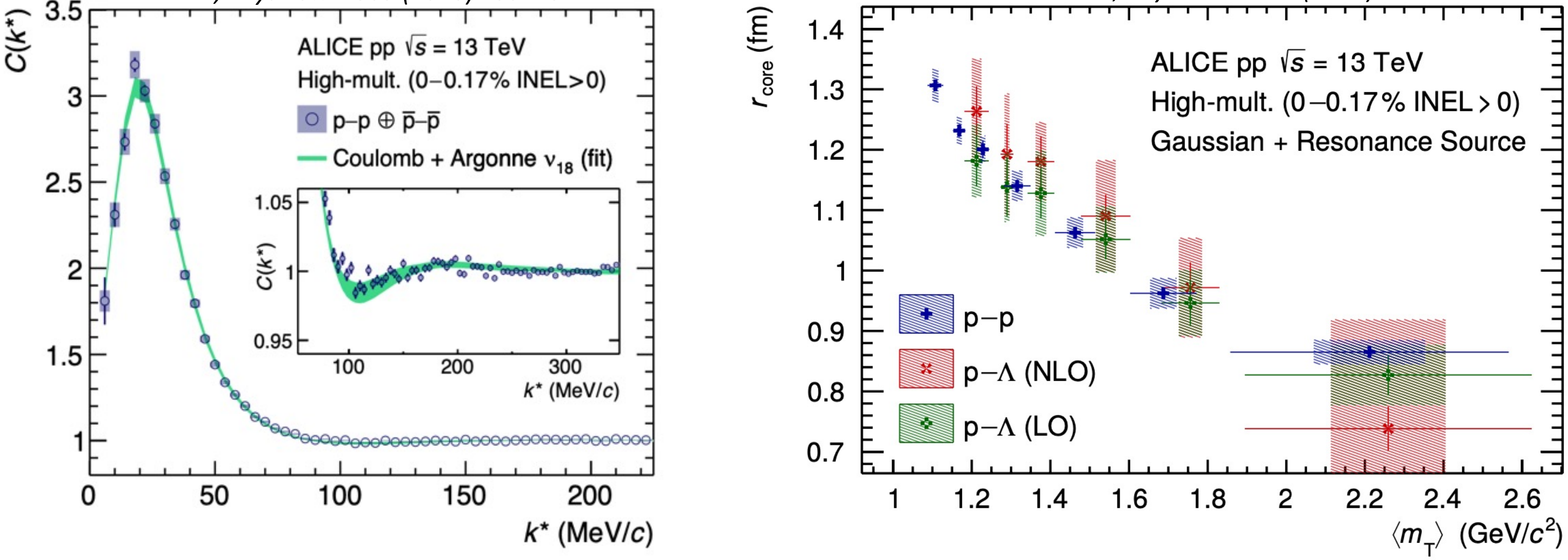
$\Psi(k^*,r^*)$: quantum statistics, final-state interactions (strong, EM)

Femtoscopy 1: Source size

If $\Psi(k^*, r^*)$ is well known, study of $C(k^*)$ allows characterization of the particle source $S(k^*)$:

ALICE, Phys.Lett.B 805 (2020) 135419

ALICE, Phys.Lett.B 811 (2020) 135849



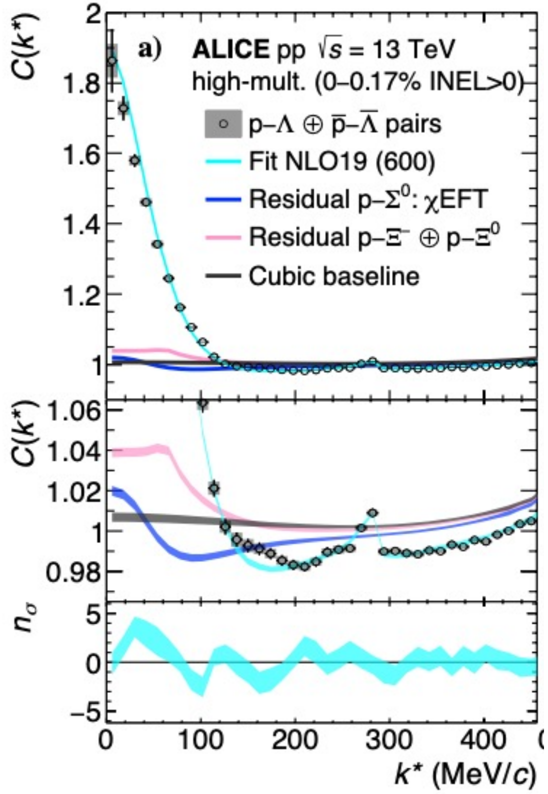
- Excellent description of the **p-p** correlation function using known interaction and quantum statistics
- Common baryon source in pp collisions observed

Femtoscopy 2: Interactions

If $S(k^*)$ is well known, study of $C(k^*)$ allows characterization of the particle dynamics in $\Psi(k^*, r^*)$:

- Cusp structure in **p-Λ** correlation function at 289 MeV/c is evidence for $N\Sigma \leftrightarrow N\Lambda$ coupling
- High-precision study constrains Λ in-medium properties relevant for hyperon puzzle in neutron stars

ALICE, arXiv:2104.04427

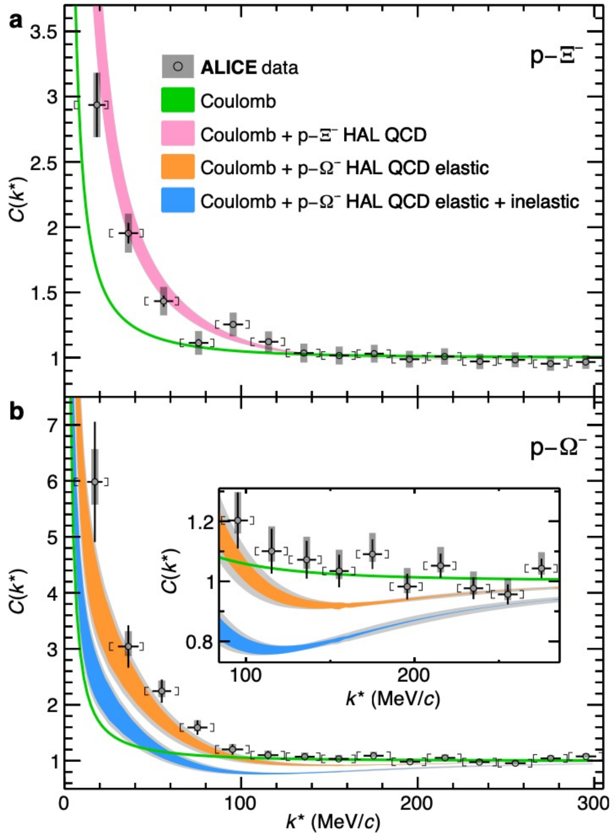


Femtoscopy 2: Interactions

If $S(k^*)$ is well known, study of $C(k^*)$ allows characterization of the particle dynamics in $\Psi(k^*, r^*)$:

- Precision study of **p-Ξ** and **p-Ω** interactions
- Allows direct comparison to lattice QCD
  - Good agreement for p-Ξ
  - Comparison to p-Ω requires better understanding of inelastic ΞΛ and ΞΣ interactions
  - Possible p-Ω bound state not observed

ALICE, Nature 588 (2020) 232



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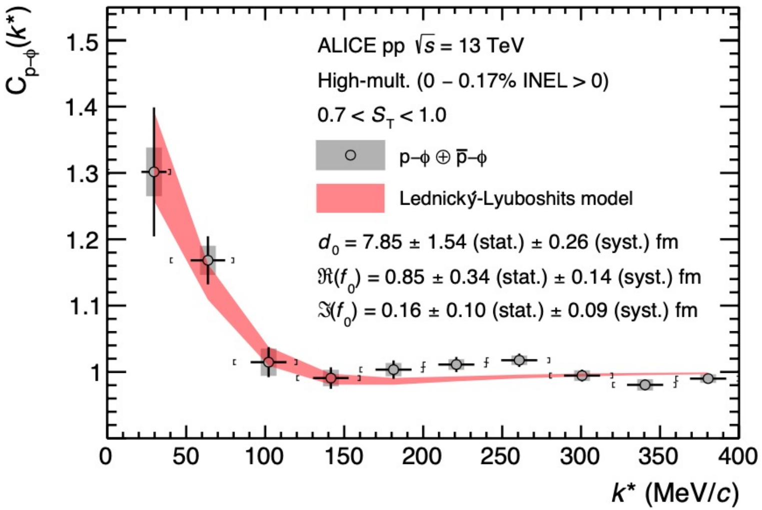
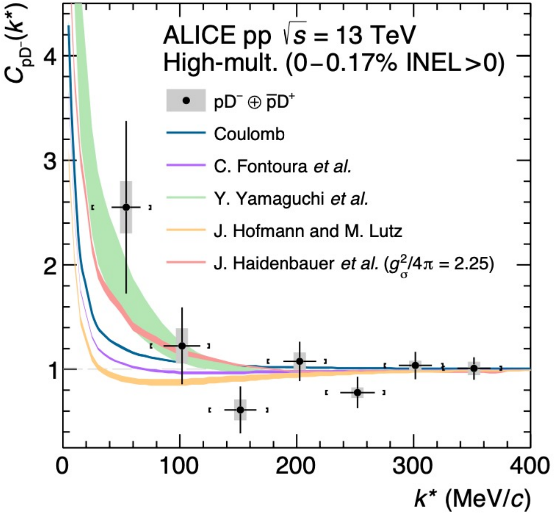
ALICE, Phys.Rev.Lett. 127 (2021) 17, 172301



ALICE, arXiv:2201.05352



First measurement of the **p-ϕ** interaction:

- Attractive, dominantly elastic
- Important to constrain broadening and absorption of ϕ-mesons in nuclei

- Exploratory study of **p-D** correlations indicates attractive interaction
- Future precision measurements of the strong interactions among charmed hadrons can shed light on nature of exotic states with charm

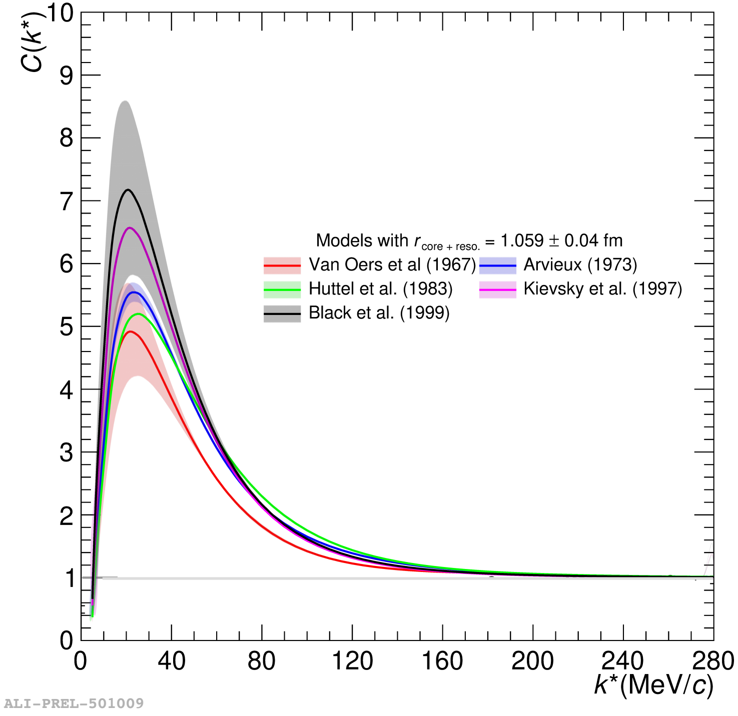
Femtoscopy of the Third Kind

In the case of **p-d**, both $S(k^*)$ and $\psi(k^*, r^*)$ are well constrained:

Measured p-d scattering parameters allow prediction of p-d correlation functions

- Coulomb + strong interaction from Lednicky-Lyuboshits approach
- $r_{core+reso.} = 1.06 \pm 0.04$ fm
- Scattering parameters from experiments ($S = 3/2$ and $S = 1/2$)

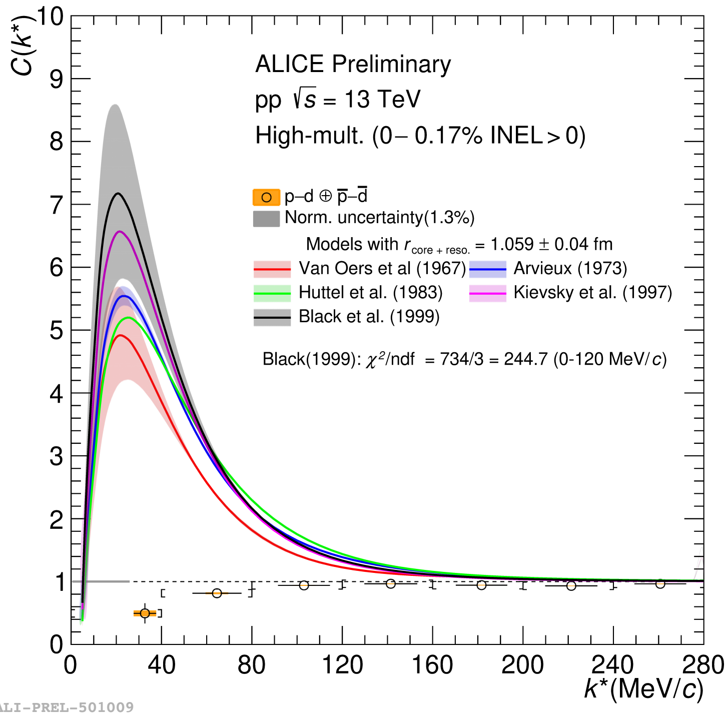
	Quartet $^4S_{3/2}$	Doublet $^2S_{1/2}$
Van Oers et al. (1967)	$11.4^{+1.8}_{-1.2}$	$1.2^{+0.2}_{-0.2}$
Arvieux et al. (1973)	$11.88^{+0.4}_{-0.1}$	$2.73^{+0.1}_{-0.1}$
Huttel et al. (1983)	11.1	4.0
Kievsky et al. (1997)	13.8	0.024
Black et al. (1999)	$14.7^{+2.3}_{-2.3}$	$-0.13^{+0.04}_{-0.04}$



Femtoscopy of the Third Kind

Preliminary p-d correlation data in significant disagreement with predictions based on scattering data and known source characteristics

- First occurence in ALICE femto analyses
- First time nuclei are involved: possible effects from formation time and coalescence



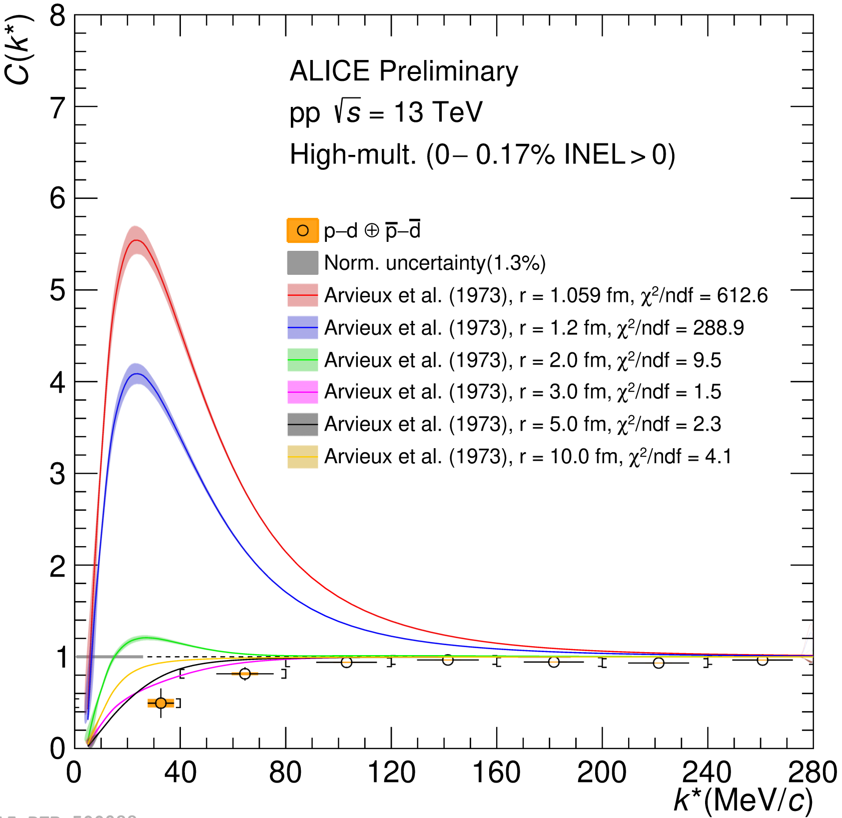
Femtoscopy of the Third Kind

Description improves with larger source size:

- Best agreement with $r \approx 3$ fm
- Effective source size can be increased due to coalescence and formation time of deuterons
- Depletion of correlation function at small k^* can be connected to ^{3}He formation
- Picture can be more complicated due to 3N interactions among preformed nucleons

Further constraints from Λ-d correlations expected:

- No Coulomb
- Coalescence to $^3_\Lambda$H suppressed



ALI-DER-500988

Summary

- Creation of nuclear clusters in high-energy heavy-ion collisions is still not fully understood
- Study of small collision systems puts additional constraints on particle production models
- Comprehensive data set on d, t, ^{3}He and $^{3}_{\Lambda}H$ production from ALICE exists, revealing patterns characteristic for coalescence
- Femtoscopic correlations provide a new handle to study deuteron and mass-3 nuclei production mechanisms

Thanks for making this workshop possible..

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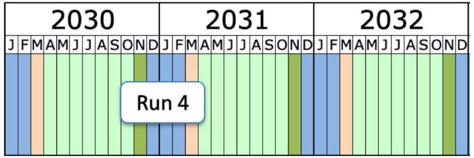
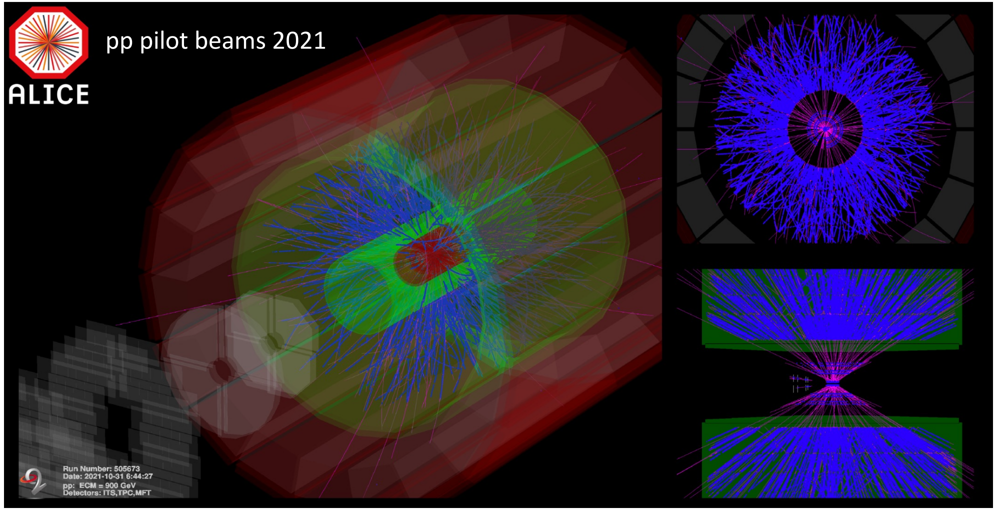
Outlook – Run 3 and Run 4



- ALICE Run 3 and 4 upgrades ready
- Factor 50-100 more data than in Runs 1 and 2 expected



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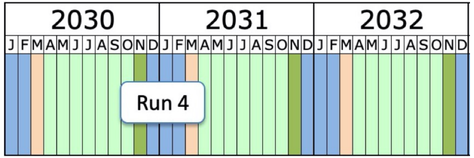
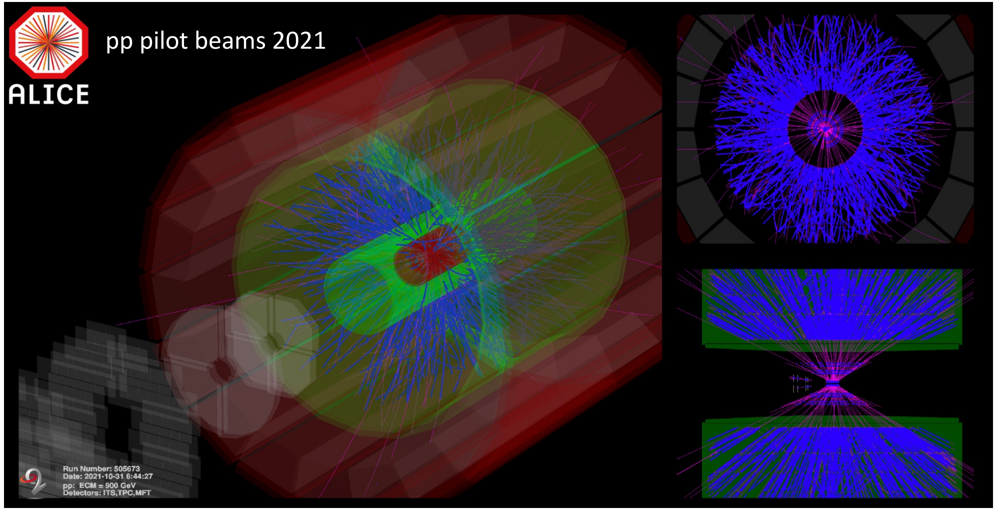
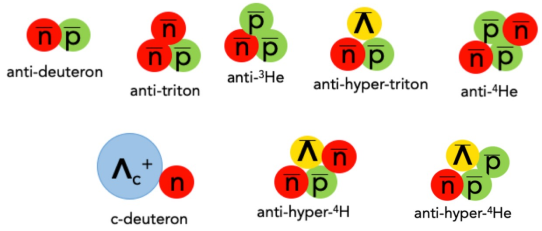




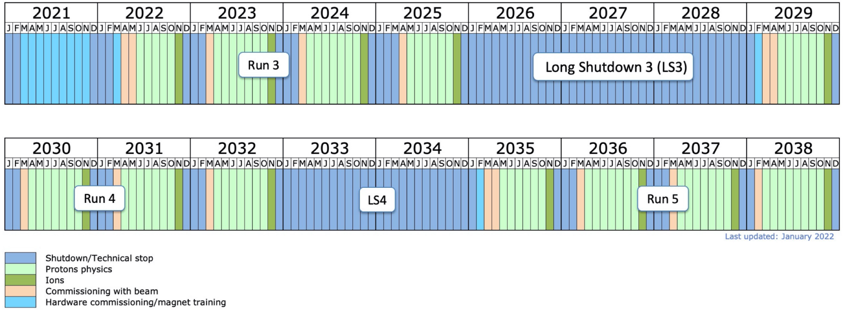
Runs 1+2

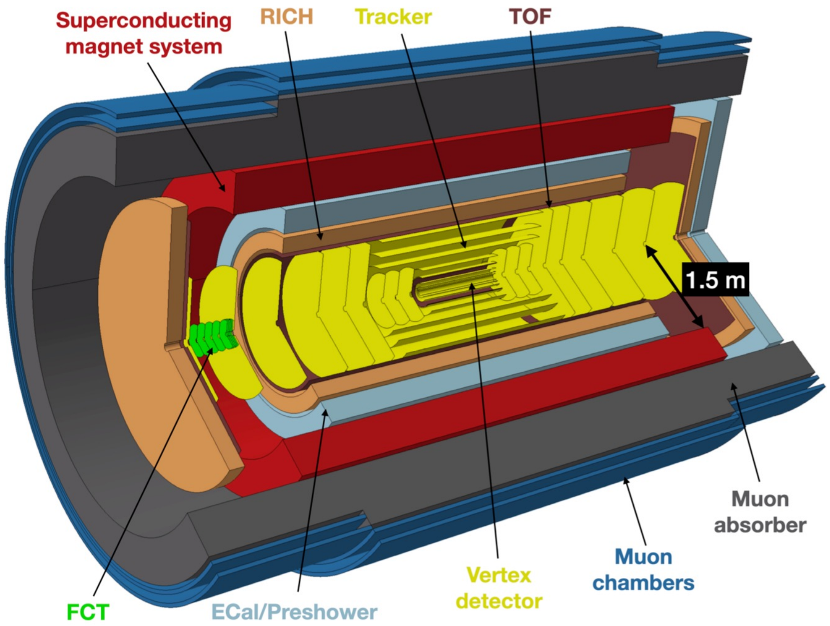
Runs 3+4



Outlook – ALICE 3

A next-generation heavy-ion experiment at the LHC:





- Letter of Intent under LHCC review

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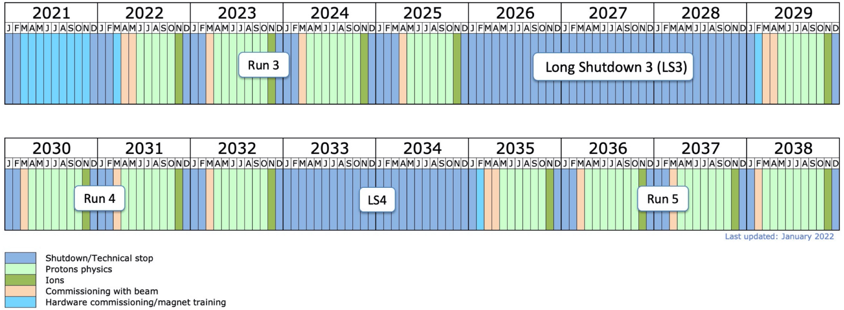

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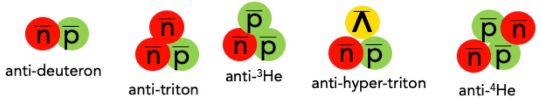
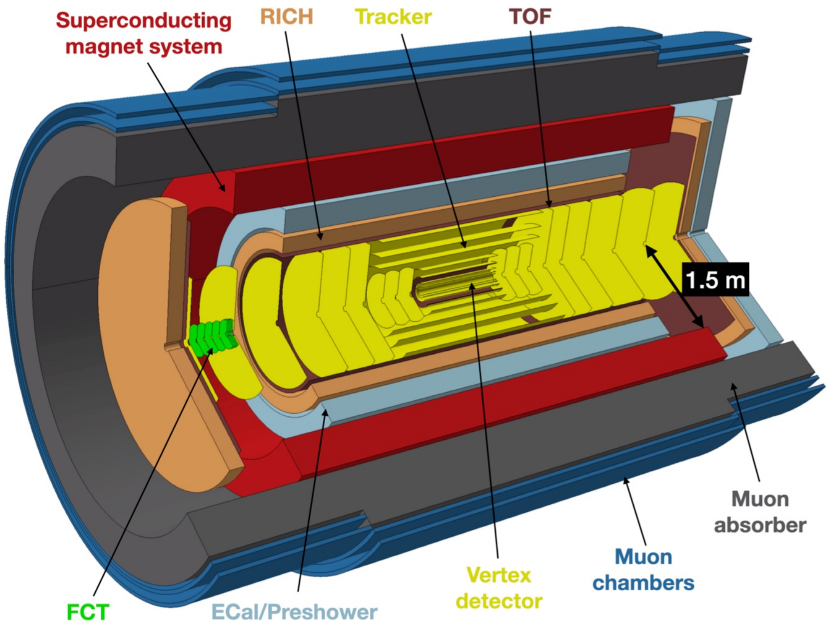


Runs 3+4

Runs 5+6



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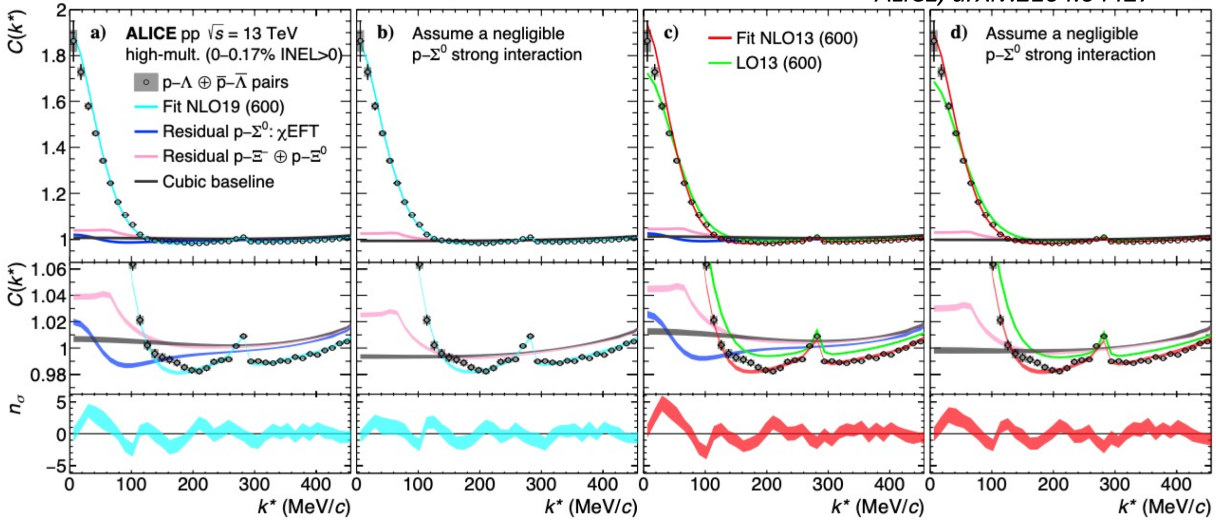
ALICE, arXiv:2104.04427



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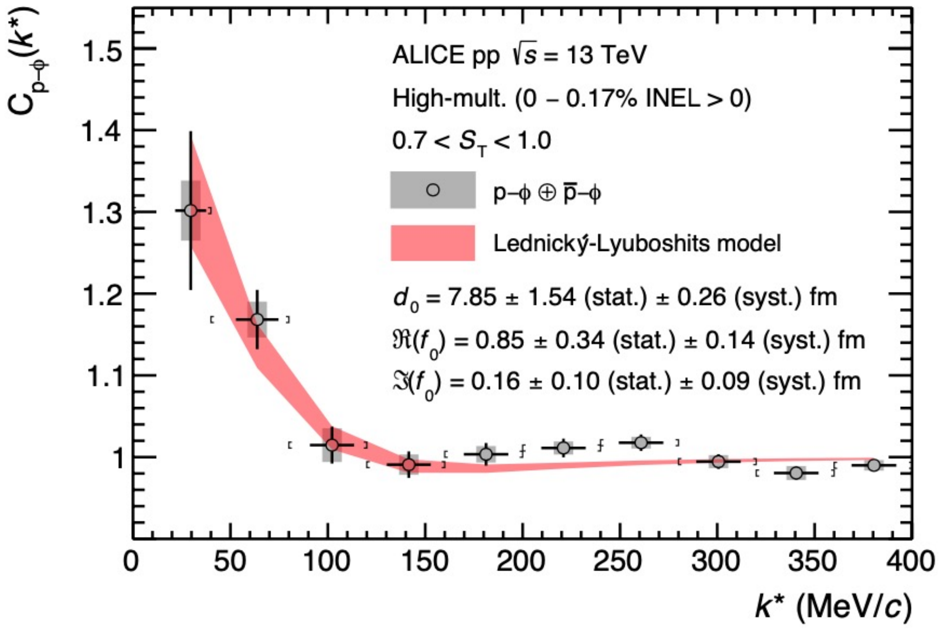

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ALICE, arXiv:2201.05352