Understanding hadronization through measurements of light-flavor hadron production with ALICE

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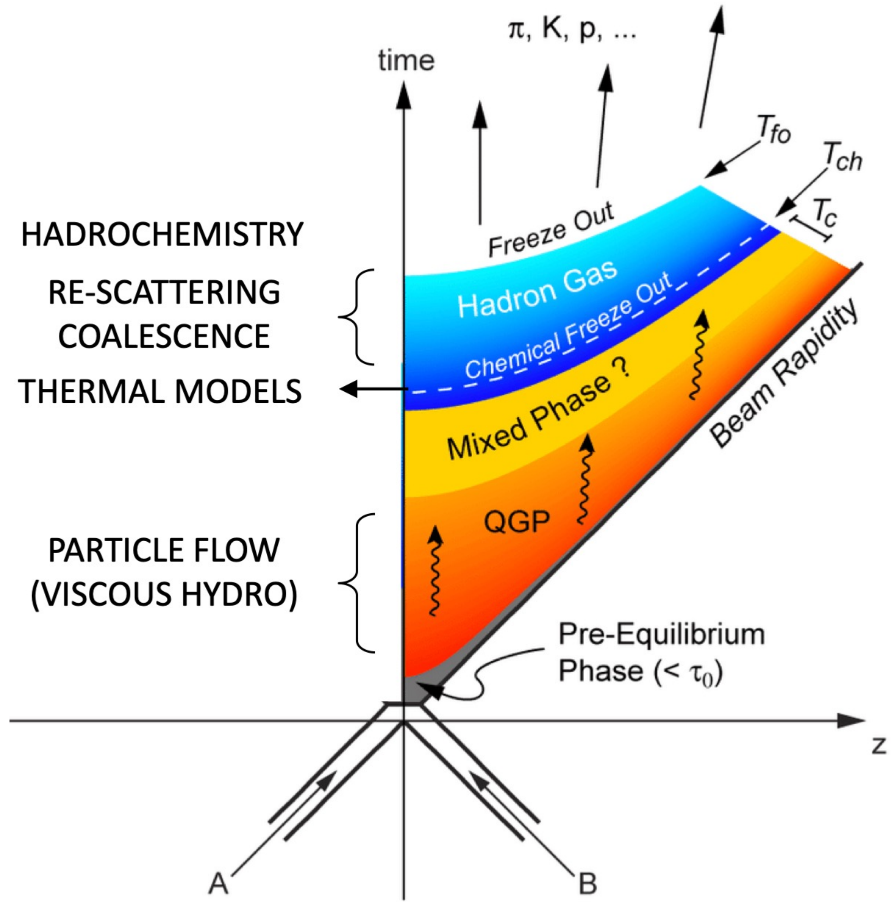
Technische Universität München

Excited QCD, Giardini Naxos – 24 Oct. 2022

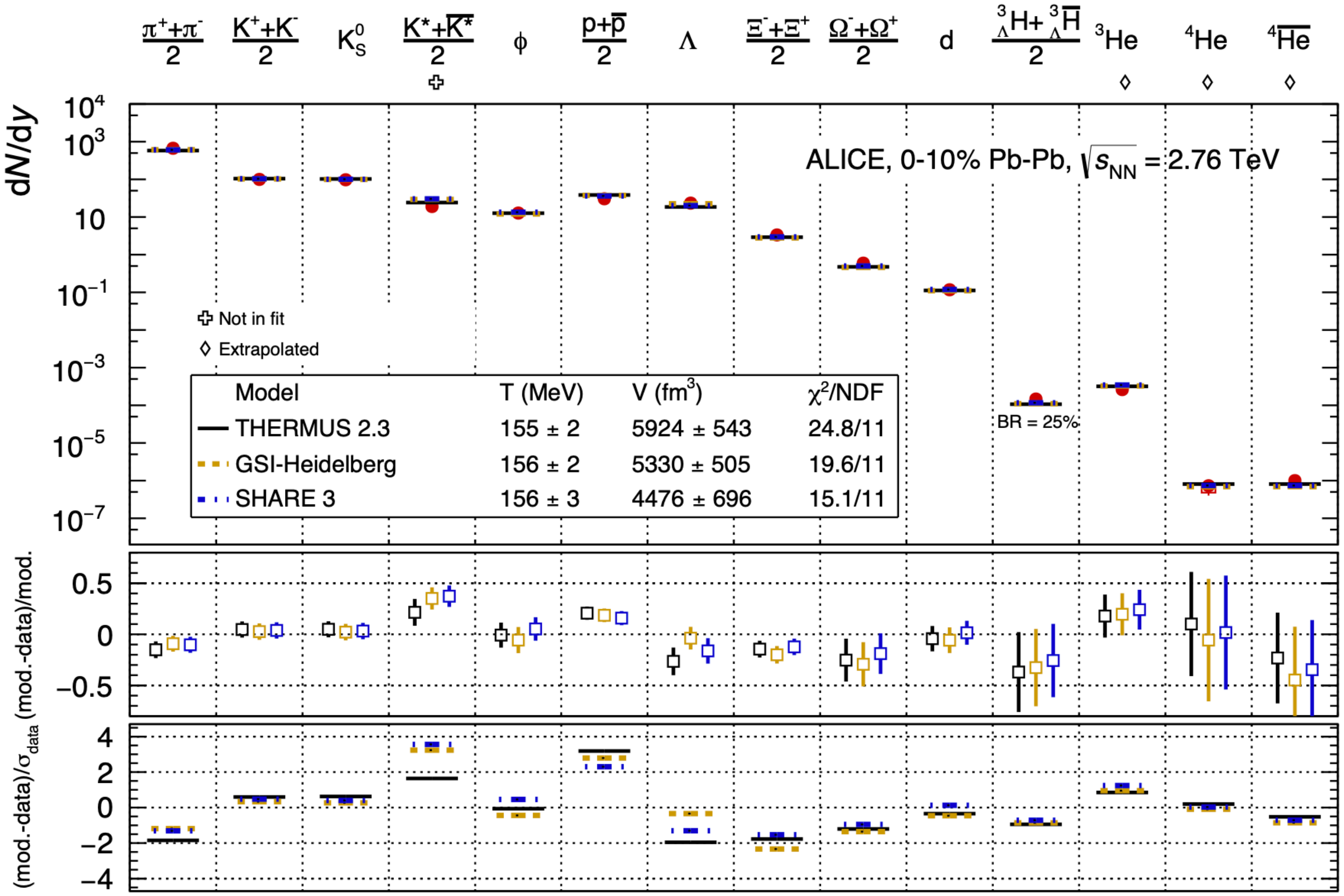
Motivation



- At LHC energies same amount of matter and antimatter is measured ($\mu_B \sim 0$)
- Light-flavor hadrons are the bulk of particle production at the LHC
- (Anti)(hyper)nuclei are also produced
- Results on LF production fundamental to:
  - study collectivity → heavy-ion collisions
  - investigate microscopic production models → large + small collision systems
- Production mechanism usually described with several phenomenological models
  - Statistical hadronization, coalescence, string fragmentation, core-corona, ropes hadronization, …

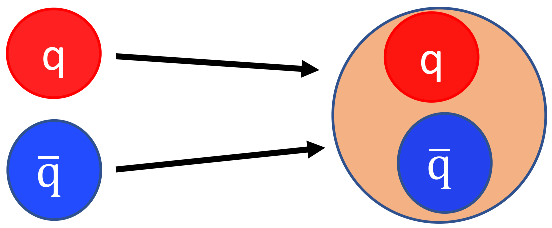
Statistical hadronisation model (SHM)

- Hadrons emitted during phase transition from a system in statistical and chemical equilibrium
- dN/dy ∝ exp(-m/T_{chem})
  - nuclei (large m): large sensitivity to T_{chem}
- In Pb—Pb collisions works very well for all LF species
  - including nuclei and hypernuclei, loosely bound states (typical binding energy of nuclei ~ few MeV)



Andronic et al., Nature 561 (2018) 321–330
NPA 971 (2018) 1-20

Hadron coalescence models



PRC 68 (2003) 034904
PRL 90 (2003) 202302
PLB 792 (2019) 132-137

- Hadrons are formed by coalescence of quarks close in phase space

- Yields of hadrons are given by:

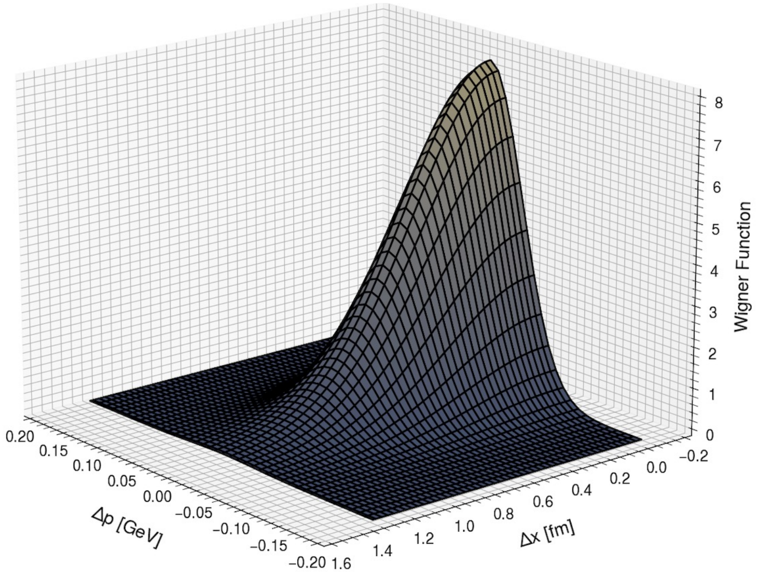
$$N_h^{\text{coal}} = g_h \int \left[\prod_{i=1}^{n} \frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{\mathrm{d}^3\mathbf{p}_i}{E_i} f(x_i, p_i) \right] \times f^W(x_1, \ldots, x_n : p_1, \ldots, p_n)$$

(iso)spin degeneracy factor

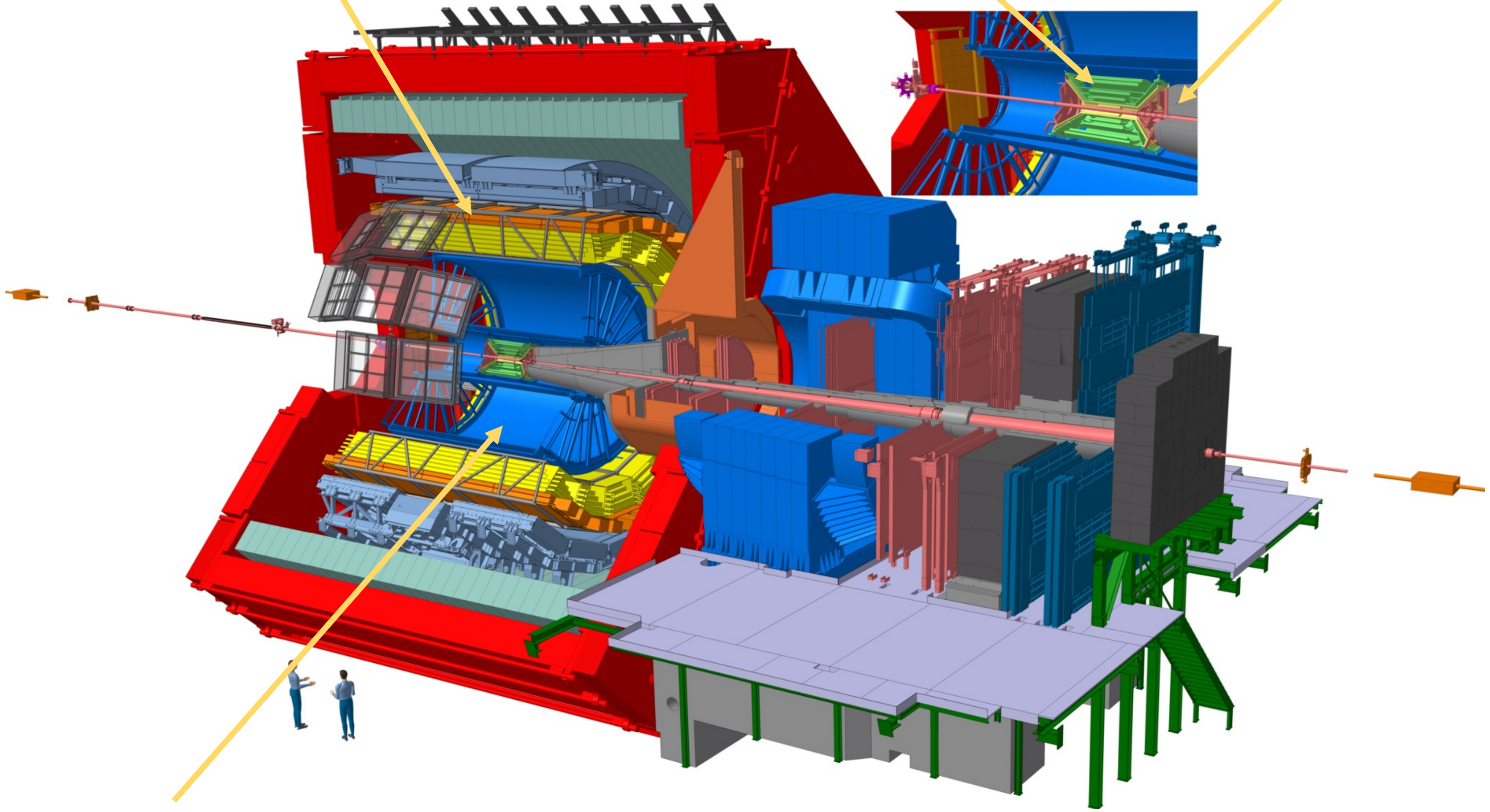
phase-space covariant distribution functions of quarks

Wigner density of the bound state

- Bound state wave function usually approximated by a Gaussian (also other WF available)



The ALICE detector



- pp, p—Pb, Pb—Pb collisions at various centre-of-mass energies
- excellent tracking and PID capabilities over a broad momentum range
  - TPC: $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim 5.5\%$ for pp
    $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim 7\%$ for Pb—Pb
  - TOF: $\sigma_{\mathrm{PID}} \sim 70$ ps for pp
    $\sigma_{\mathrm{PID}} \sim 60$ ps for Pb–Pb
- low material budget

Light-flavor particle production with ALICE

- precise p_{T} and centrality differential measurements of various light-flavour particle species in Pb—Pb collisions
- complemented by a large number of multiplicity dependent measurements in pp and p–Pb

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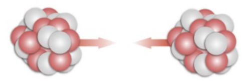
LARGE SYSTEMS



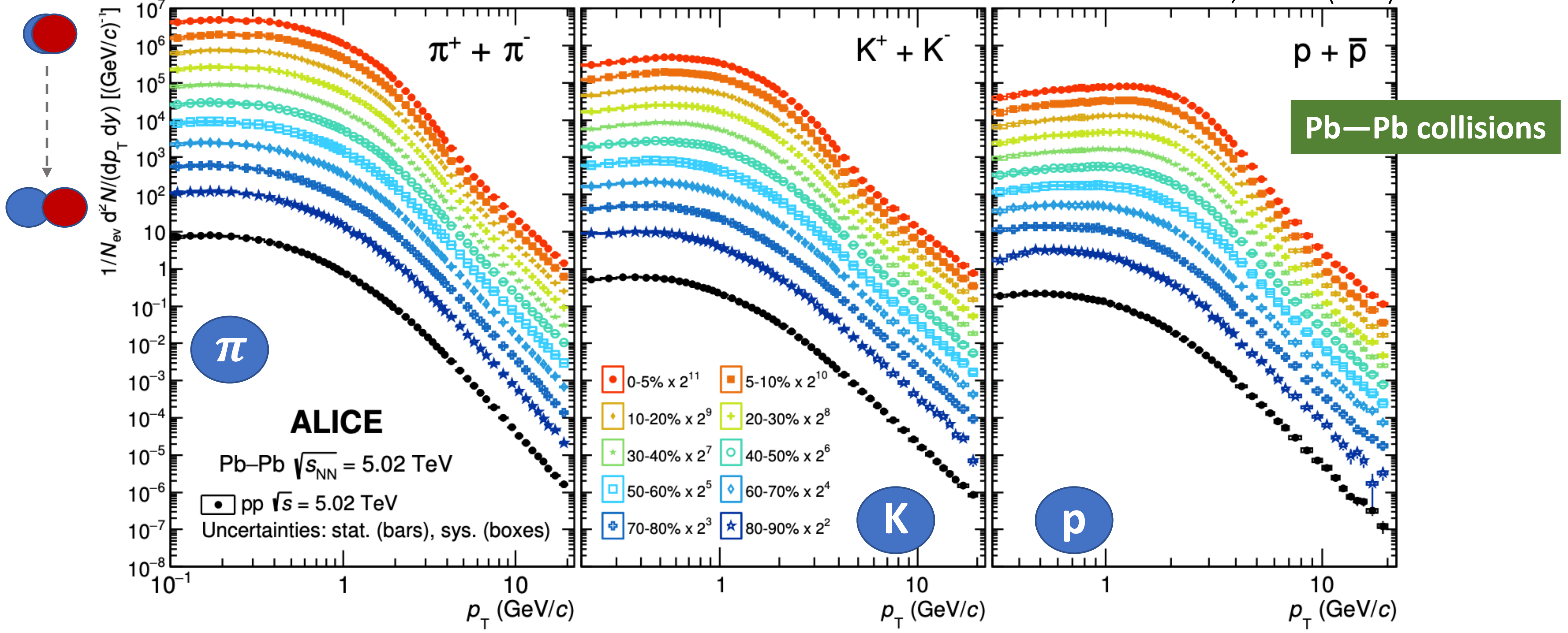
- allows for the study of collective motion for non-central collisions (flow coefficients)

SMALL SYSTEMS

- allows for the study of hadronisation mechanisms
- hypernuclei production is a key tool to distinguish among model predictions

Particle production in Pb–Pb collisions

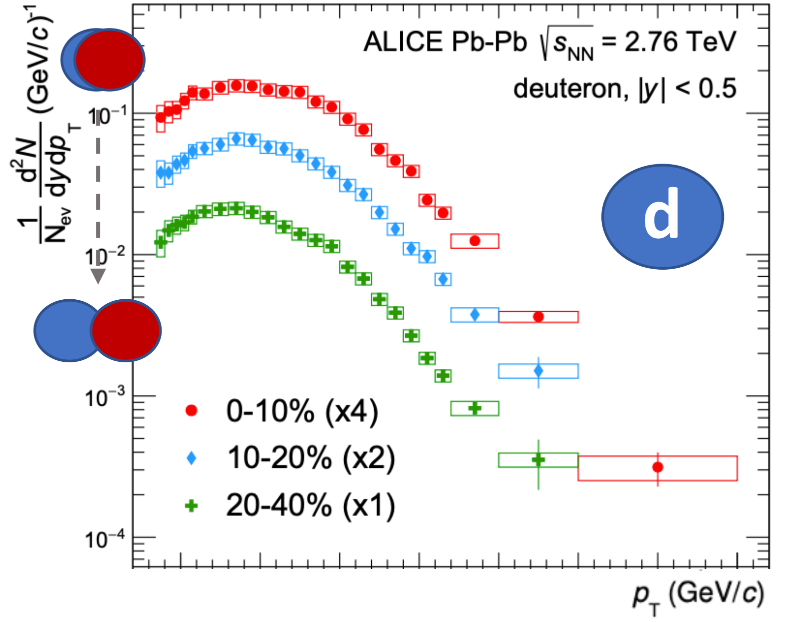
PRC 101, 044907 (2020)

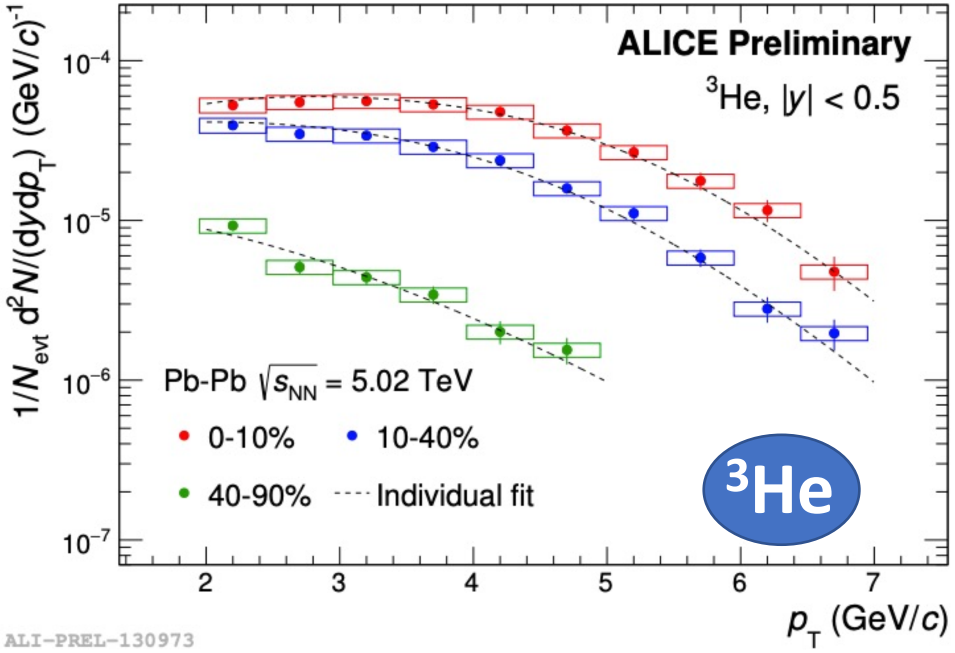


- Flattening of spectral shape at low p_T more pronounced for heavier particles → **hint for collective motion (radial flow)**

(Anti)(hyper)nuclei production in Pb–Pb collisions

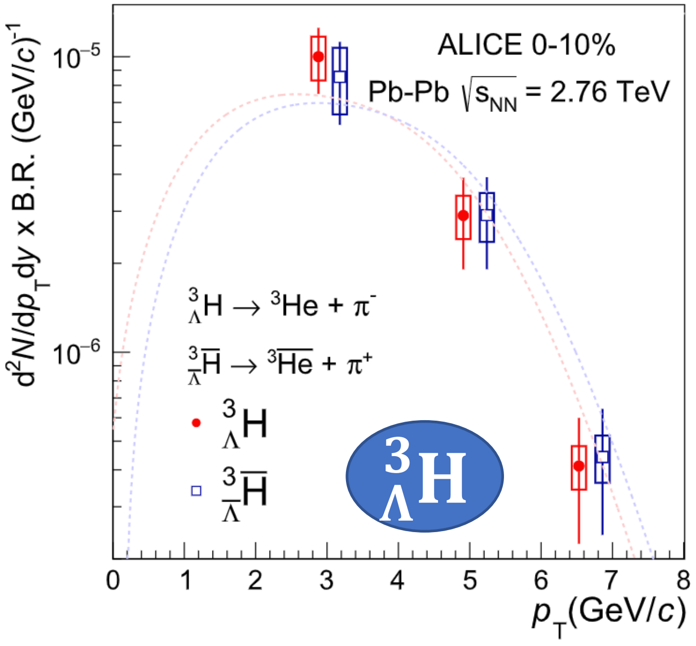
EPJC (2017) 77 :658

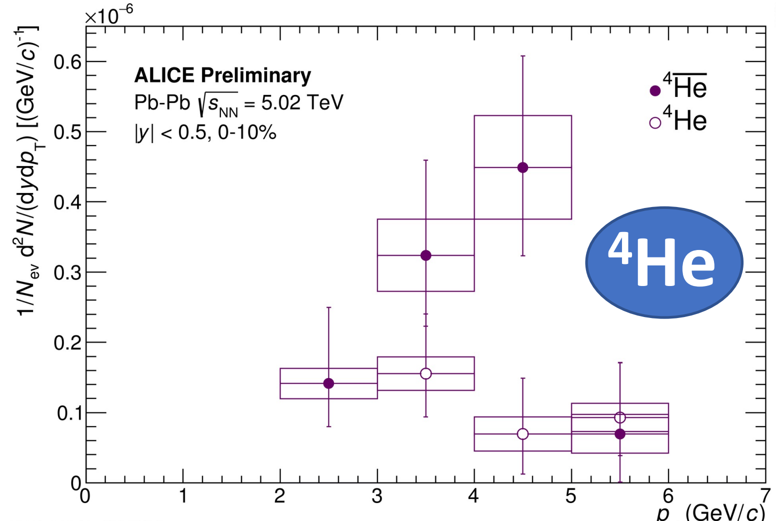




ALI-PREL-130973

PLB 754 (2016) 360–372





ALI-PREL-327164

- Light (anti)(hyper)nuclei measured up to A=4, also in different multiplicity classes
- Hardening with increasing centrality – as seen for other light-flavor hadrons → **hint for collective motion (radial flow)**

Pb—Pb collisions

(Anti)(hyper)nuclei production in Pb–Pb collisions

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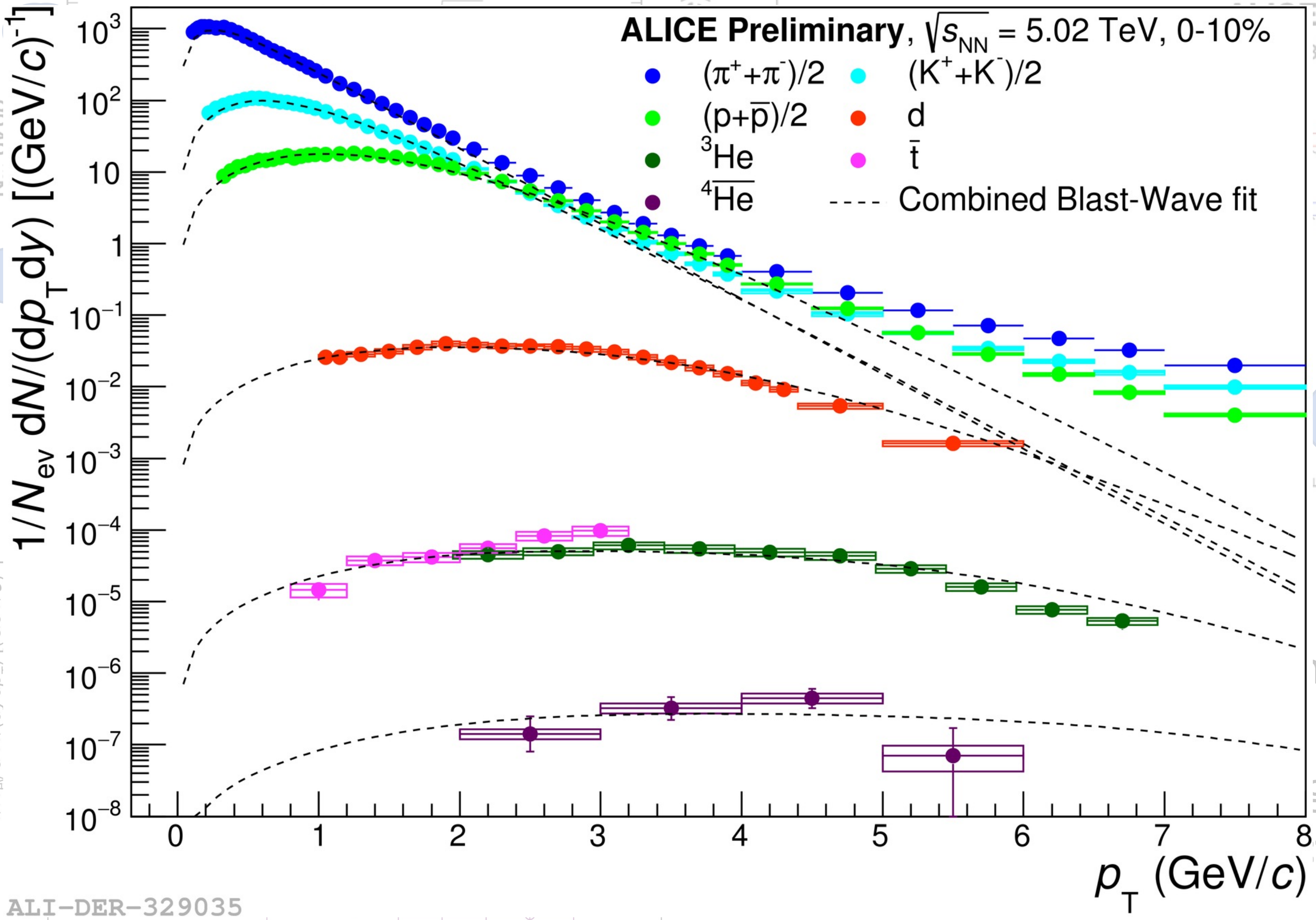
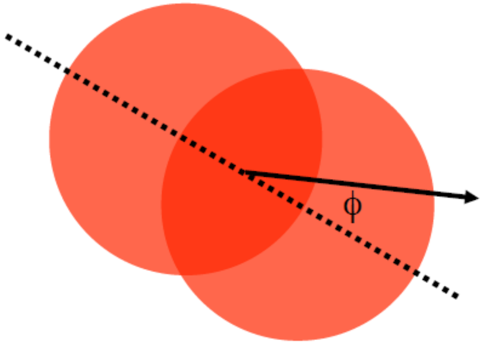


Blast-Wave fit of all light-flavor hadrons shows a common behavior for all particles, from π to α

Pb—Pb collisions

Collectivity in Pb–Pb collisions



Initial space anisotropy in non-central AA collisions

- azimuthal anisotropy of particle emission wrt symmetry plane

Particle azimuthal distribution can be espressed as a Fourier series

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n\geq 1} v_n \cos\left(n\left(\varphi - \Psi_n\right)\right)$$

$$\begin{cases} \Psi_n = n^{th} \text{ symmetry plane} \\ \varphi = \text{azimuthal angle} \\ v_n = \text{flow coefficients} \end{cases}$$

v_2: elliptic flow
v_3: triangular flow

Flow reflects conversion of initial state spatial anisotropy into final state anisotropies in momentum space

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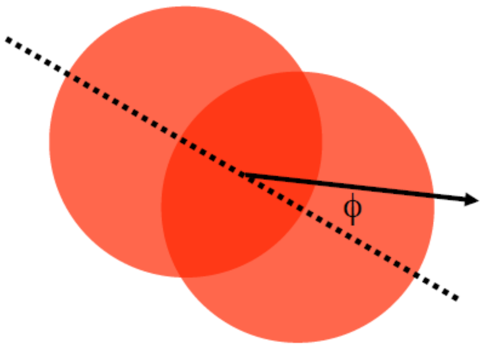

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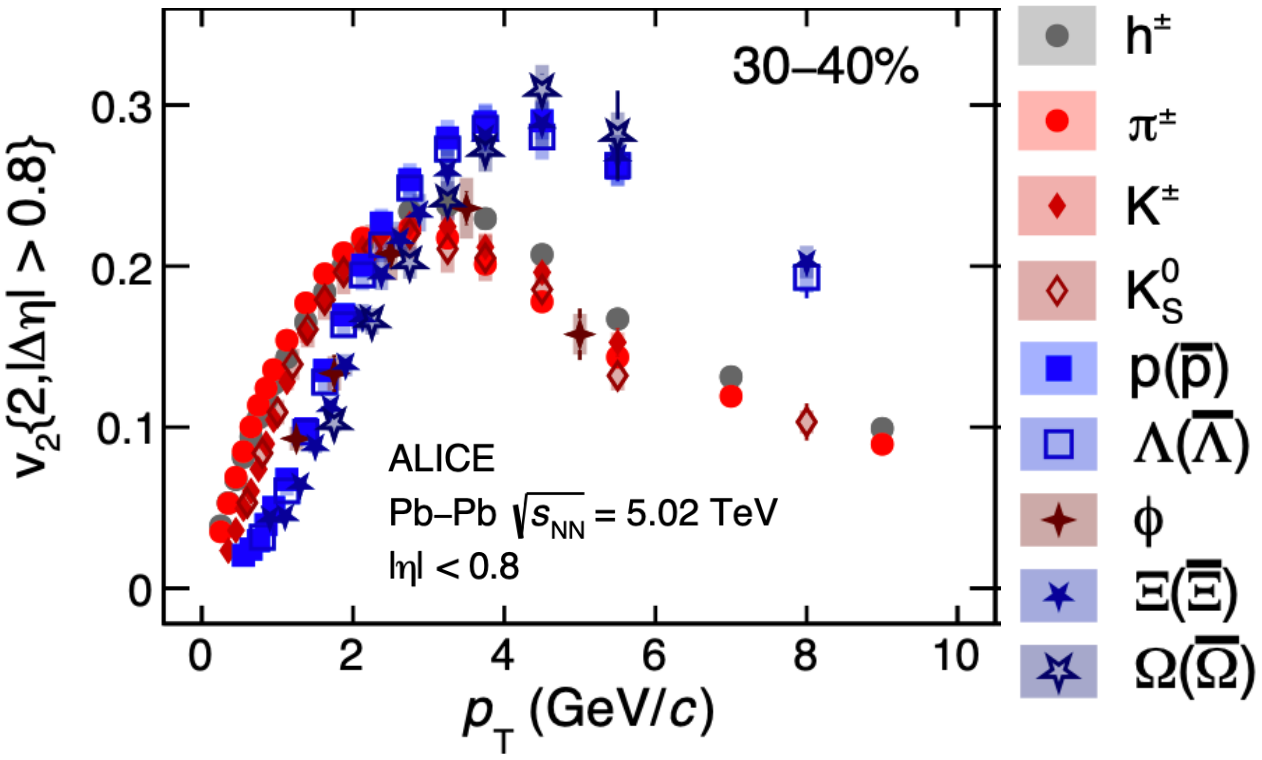
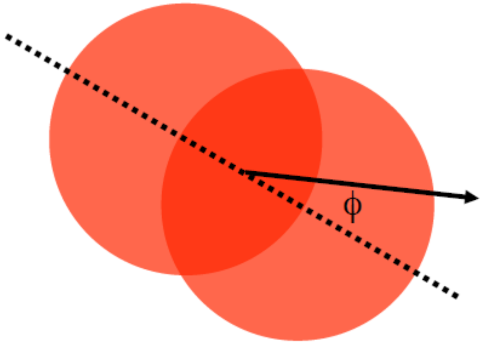
arXiv:2206.04587



- Mass ordering at low p_T → interplay between radial flow and anisotropic expansion of the system
- Intermediate p_T : baryon-meson grouping → hadron formation via quark coalescence in this range

Collectivity in Pb–Pb collisions



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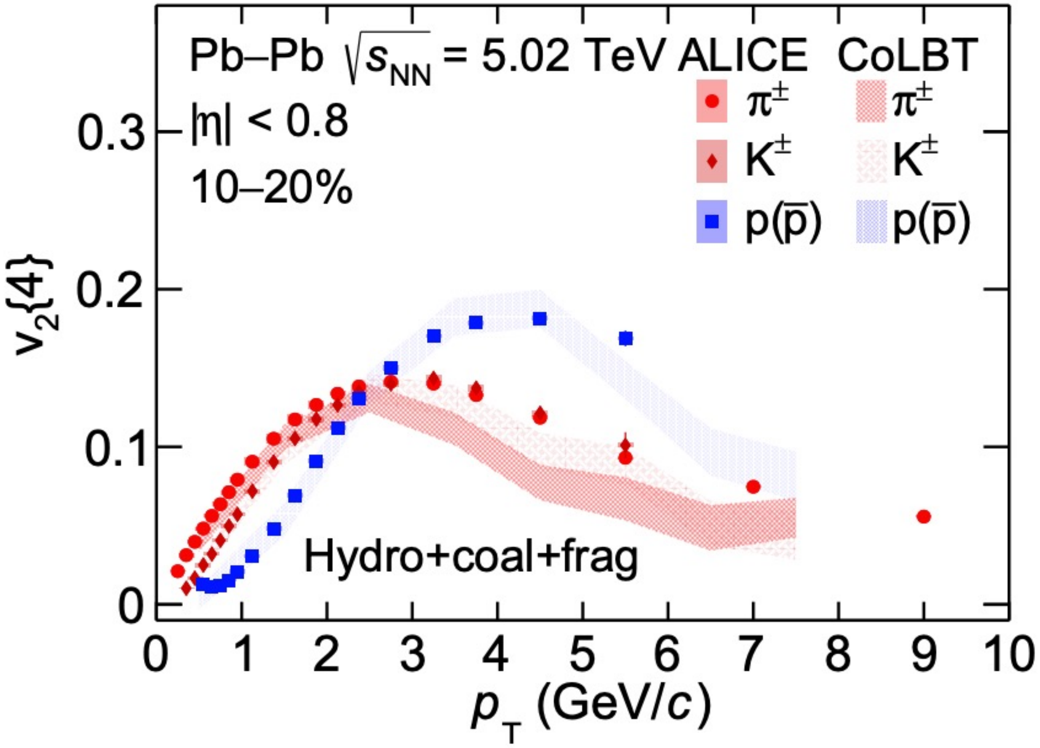

- Mass ordering at low p_T → interplay between radial flow and anisotropic expansion of the system
- Intermediate p_T : baryon-meson grouping → hadron formation via quark coalescence in this range
- Expectations from relativistic hydrodynamics are fulfilled

Light-flavor particle production with ALICE

- precise p_T and centrality differential measurements of various light-flavour particle species in Pb—Pb collisions
- complemented by a large number of multiplicity dependent measurements in pp and p–Pb

LARGE SYSTEMS

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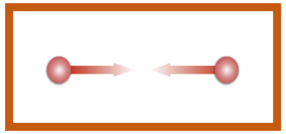

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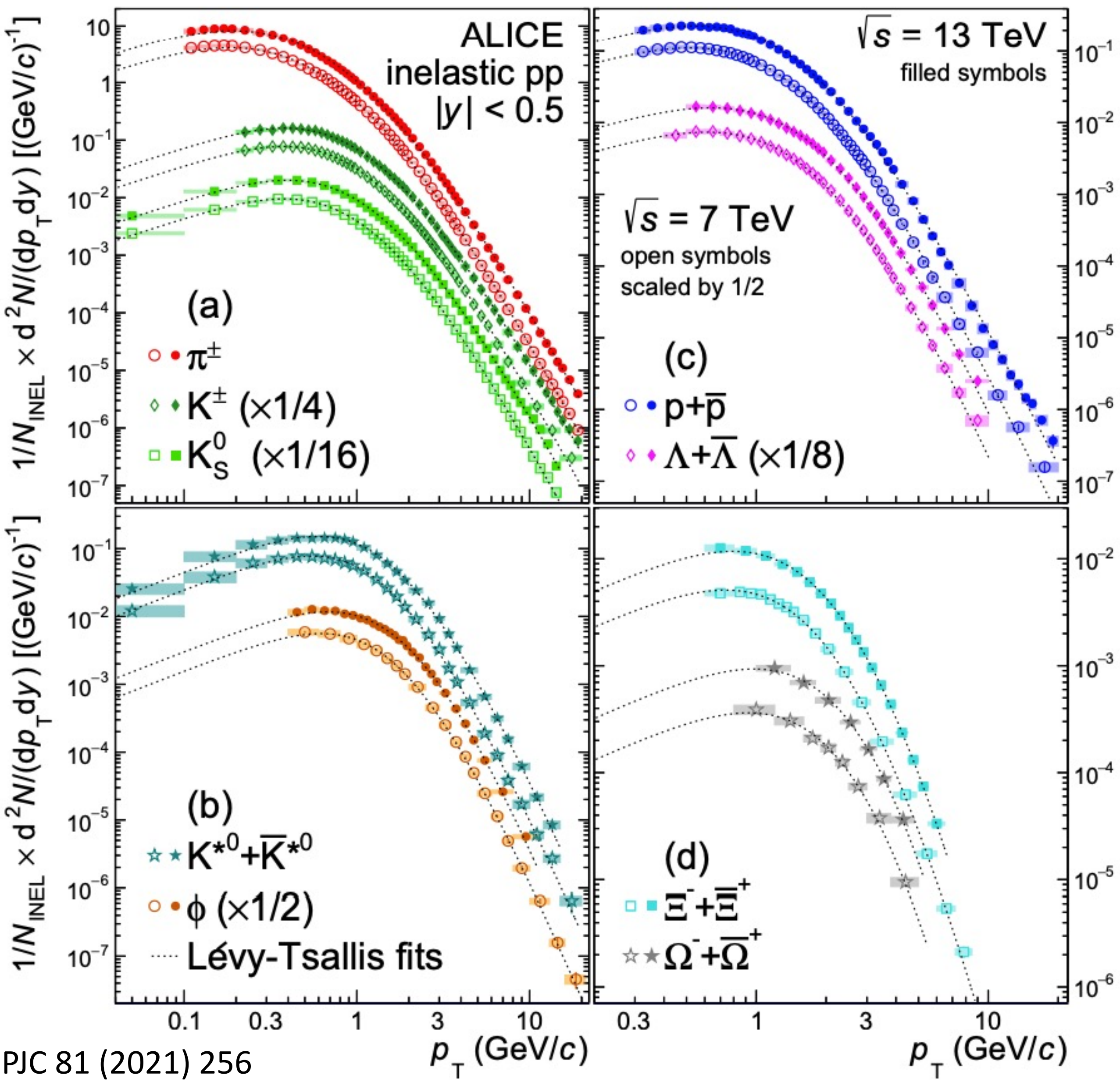
- hypernuclei production is a key tool to distinguish among model predictions

Light-flavor particle production in small systems



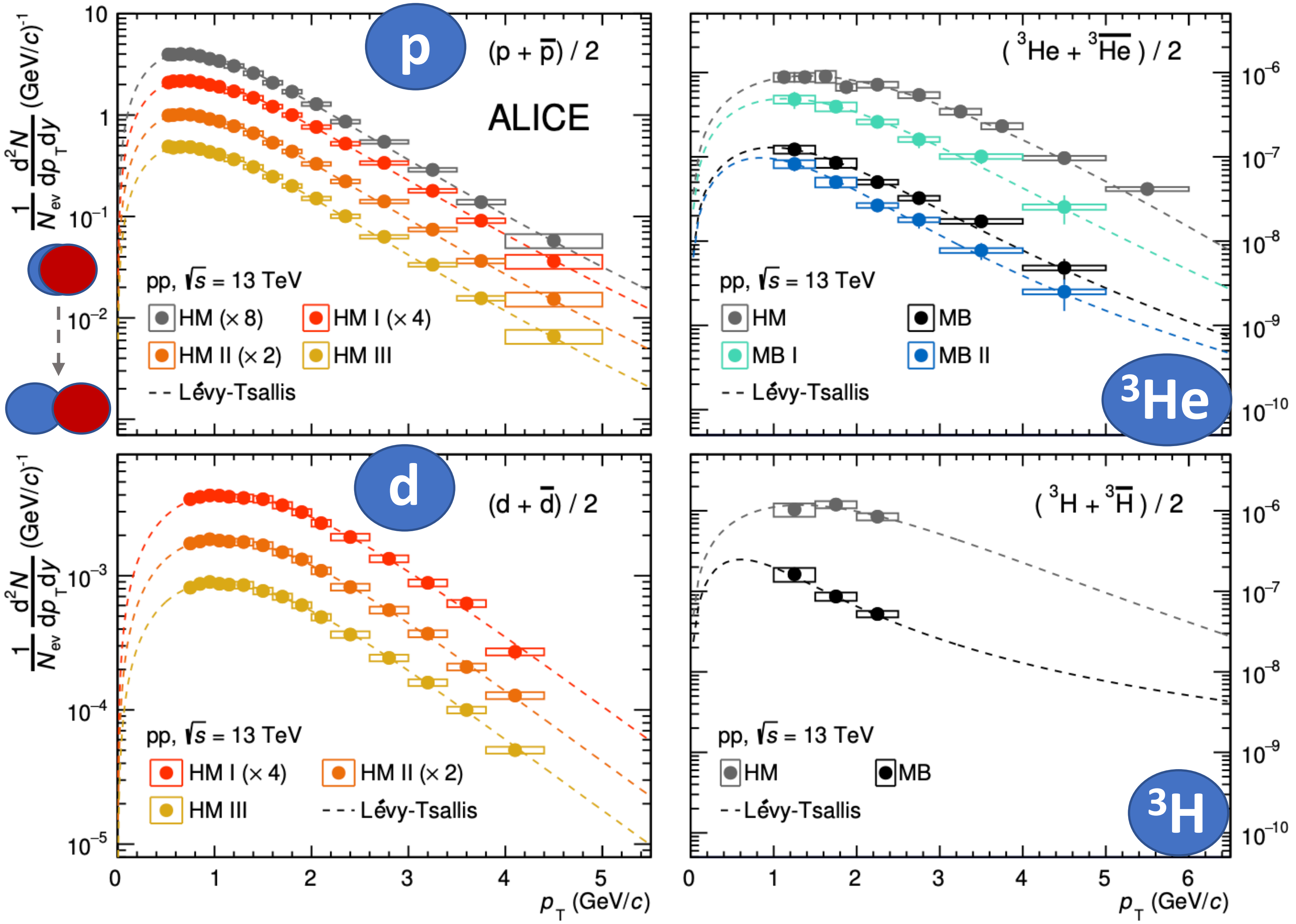
EPJC 81 (2021) 256

- Progressive evolution of spectral shape at high p_T with increasing collision energy
- Hard processes become dominant in the production of high-p_T particles

pp collisions

Light (anti)nuclei in small systems

JHEP 01 (2022) 106

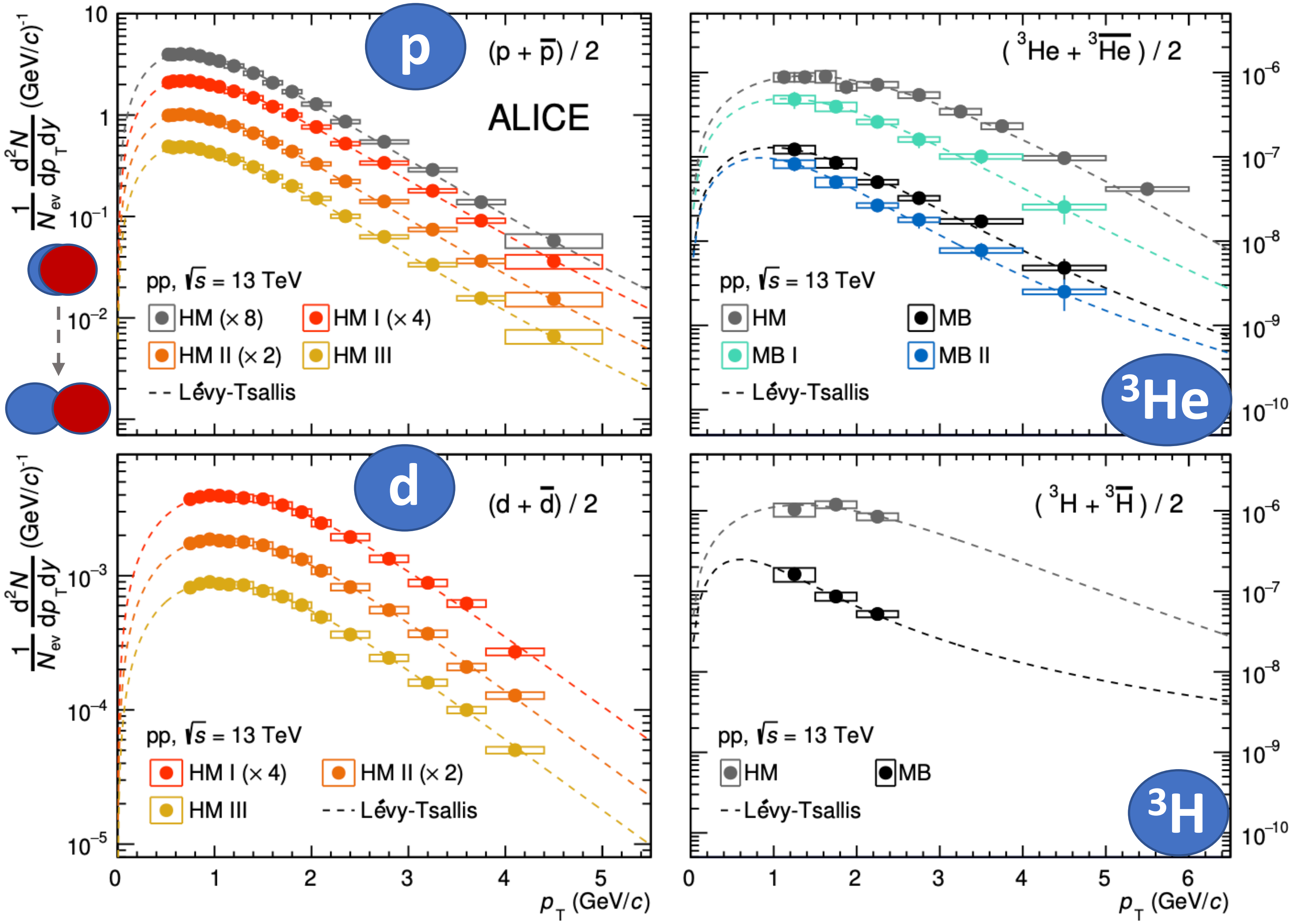


HM pp @ 13 TeV

- Focus on the HM data sample → narrow multiplicity interval covered

Light (anti)nuclei in small systems

JHEP 01 (2022) 106



HM pp @ 13 TeV

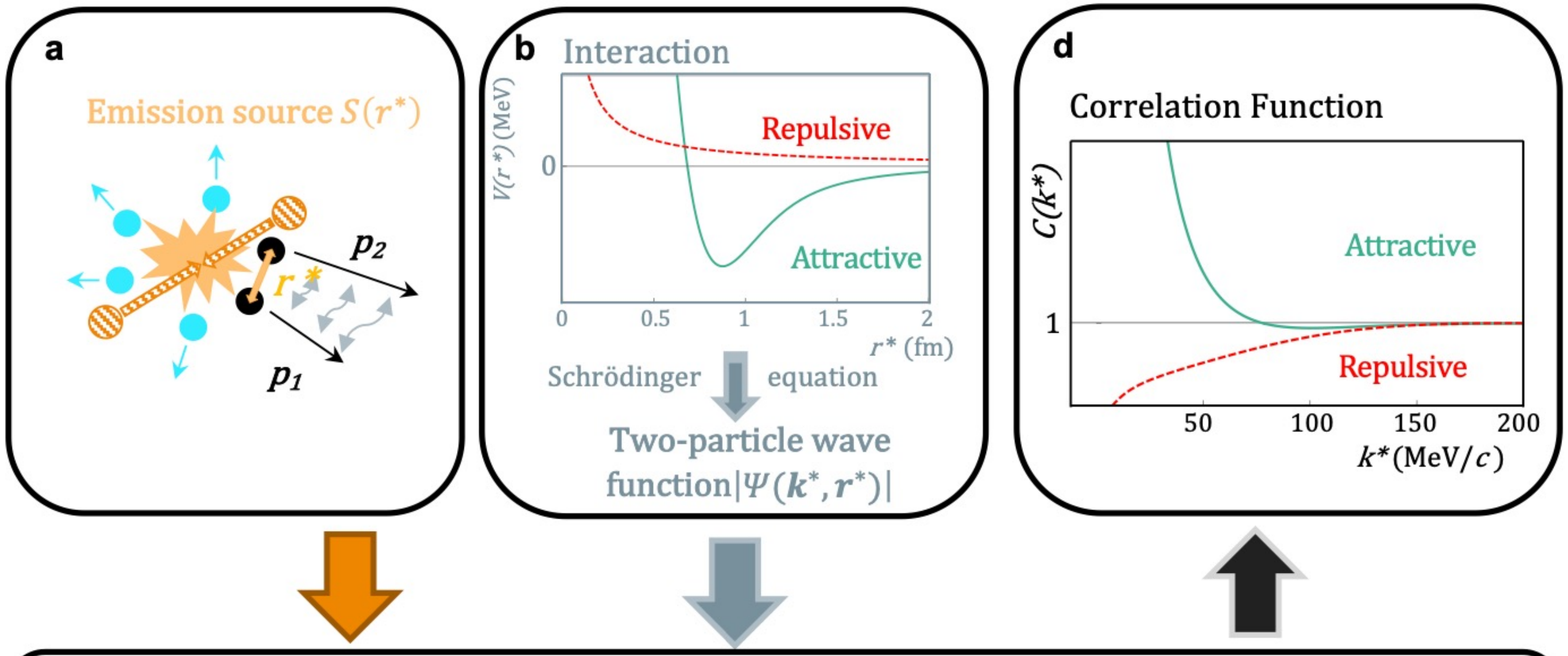
- Focus on the HM data sample → narrow multiplicity interval covered
- Precise measurement of the emission source size r_{core} using femtoscopy is available

→ **crucial to test the coalescence model**

Hadron-hadron correlation

Nature 588 (2020) 232-238

- ALICE is pioneering the study of strong interactions using femtoscopic correlations
- Momentum correlations can be employed to explore two-particle dynamics
- **Correlation function** depends on two ingredients:
  - emission source function (pp collisions: $r_{\mathrm{eff}} \sim 1$ fm, Gaussian profile)
  - two-particle relative wave function (quantum statistics + Coulomb + strong interactions)



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

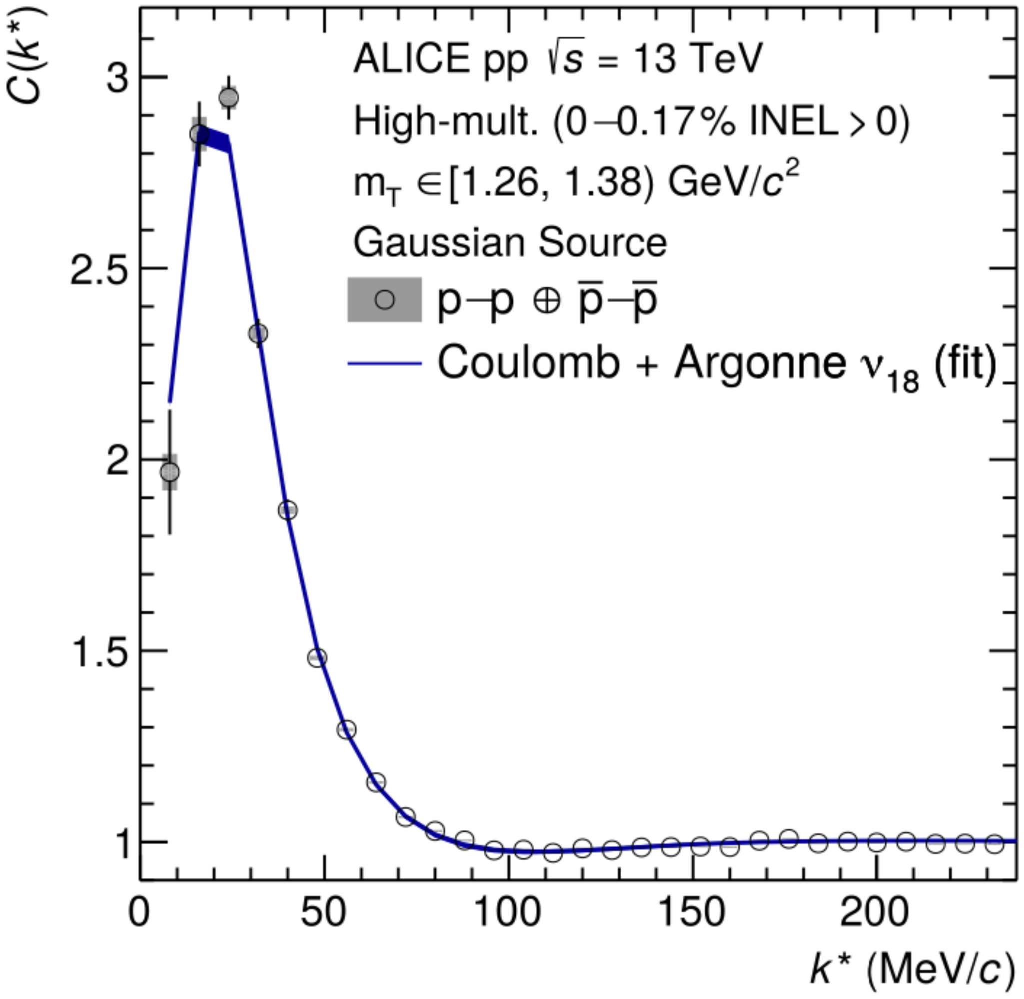
Measuring $C(k^*)$, fixing the source $S(r^*)$, study the interaction

relative momentum: $k^* = \frac{1}{2}\, |\vec{p_1} - \vec{p_2}|$

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

proton-proton correlation

PLB 811 (2020) 1358249

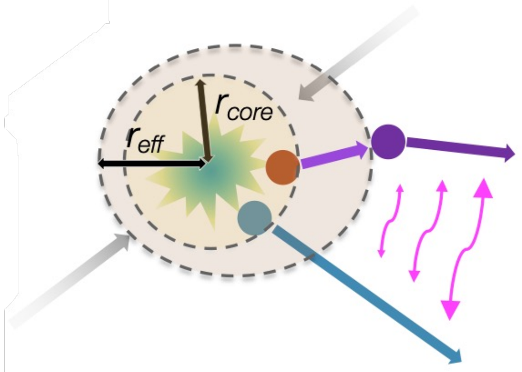


HM pp @ 13 TeV

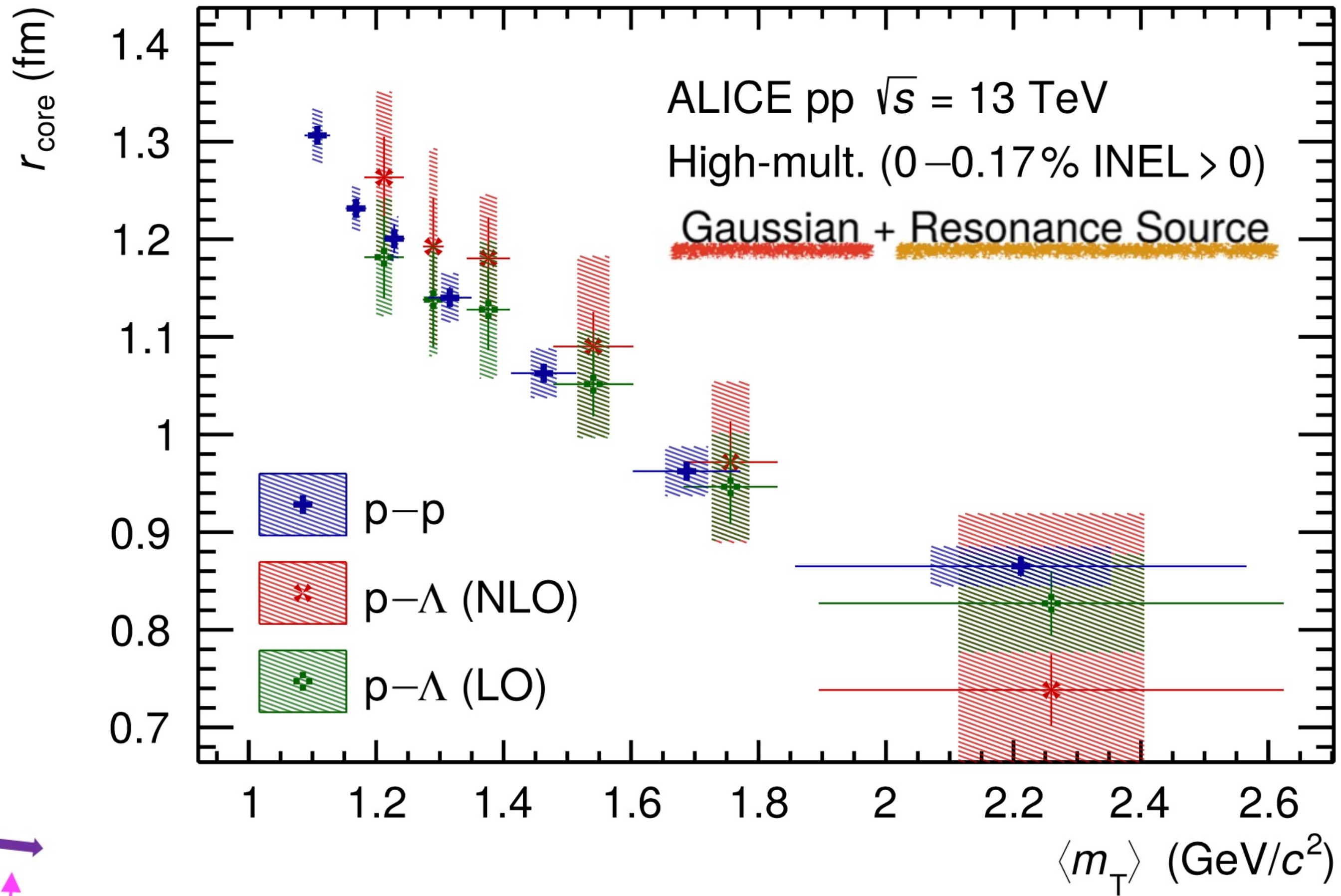
- proton-proton (p-p) correlation is well known
- p-p correlation function properly described by using:
  - Fermi-Dirac wave function
  - Coulomb interaction
  - strong interaction
- Measurement of correlation function done for several m_T intervals
- If the interaction is well known, hadron-hadron correlation can be used to measure the radius of the emitting source

Characterization of the emission source size

- Assumption: particle emission from a **gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \lesssim 10$ fm) also taken into account: mainly Δ (Σ*) resonances for protons (Λ)
- Same m_T scaling obtained from both p-p and p-Λ correlations → hint for universal emission source of baryons



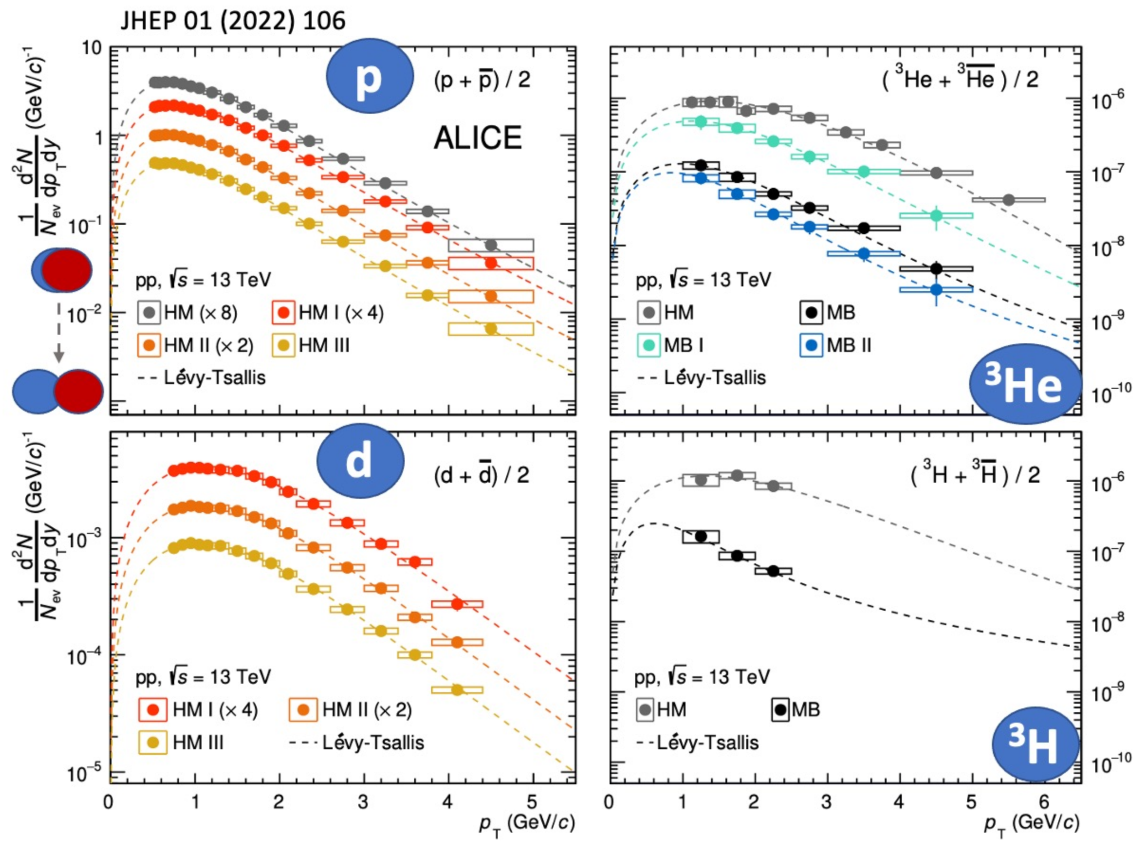
PLB 811 (2020) 135849

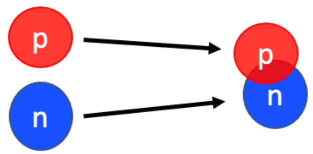


$\propto p_T$

HM pp @ 13 TeV

…putting pieces together

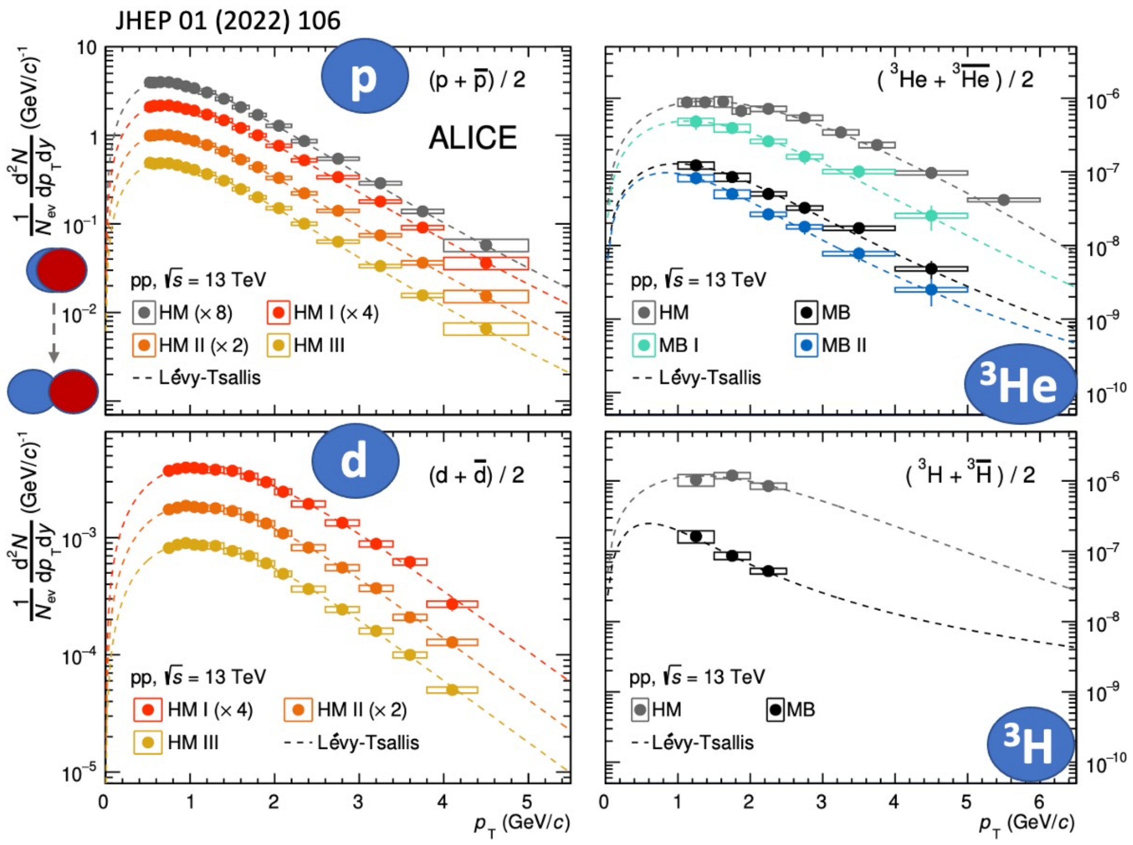


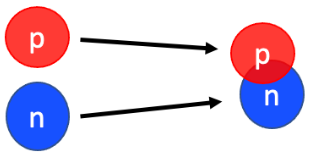


Compute coalescence probability using:

$$B_A(p_T^p) = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}\, p_A^3} \Big/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}\, p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

…putting pieces together





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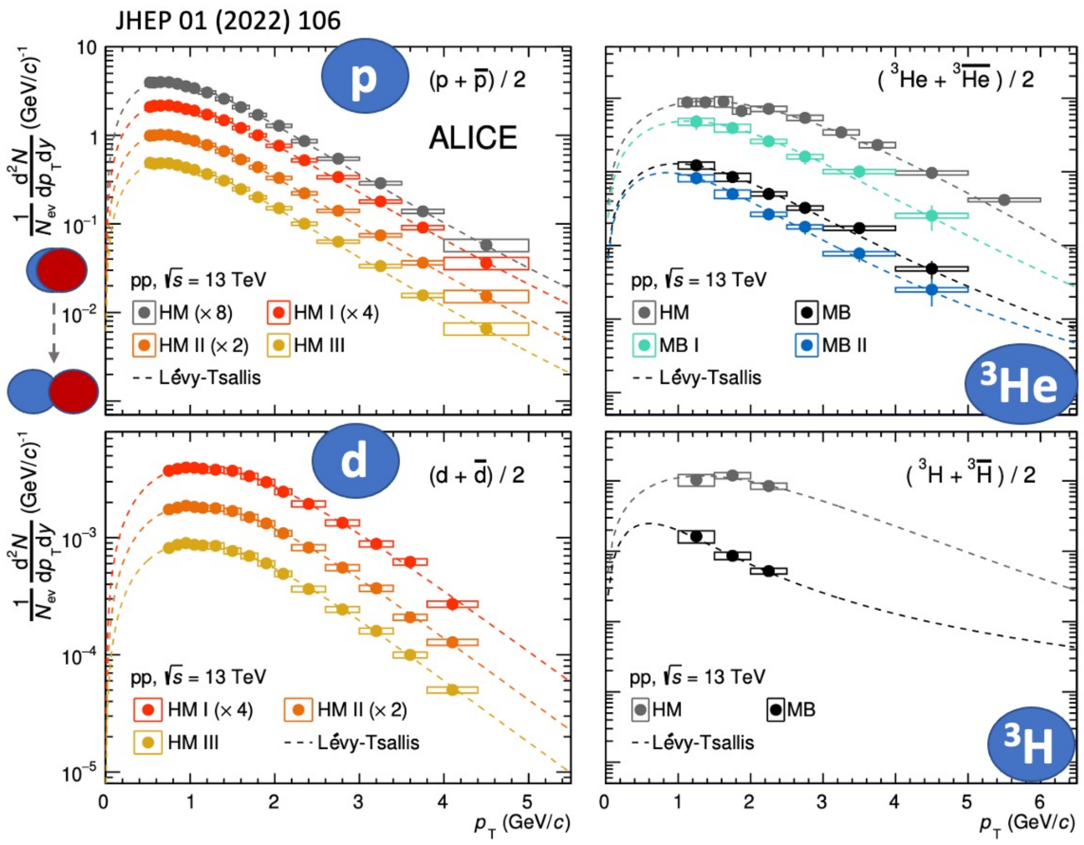
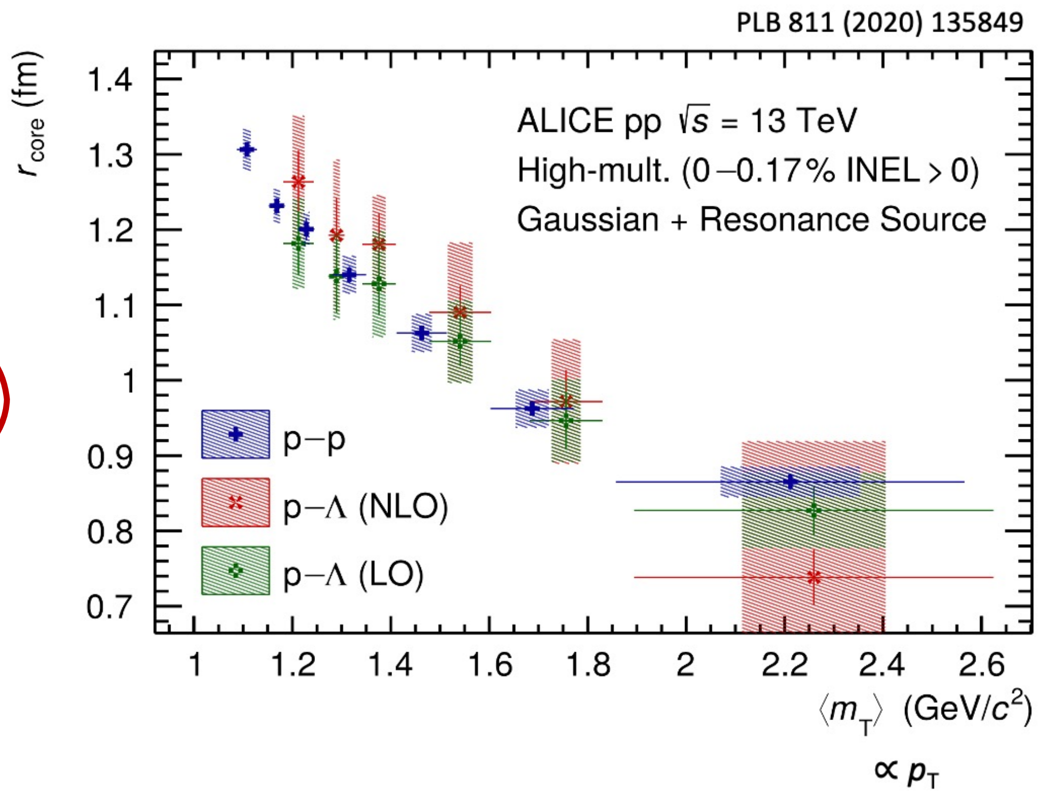
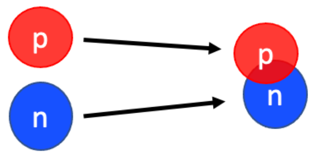
Compare with predictions of coalescence model

…putting pieces together







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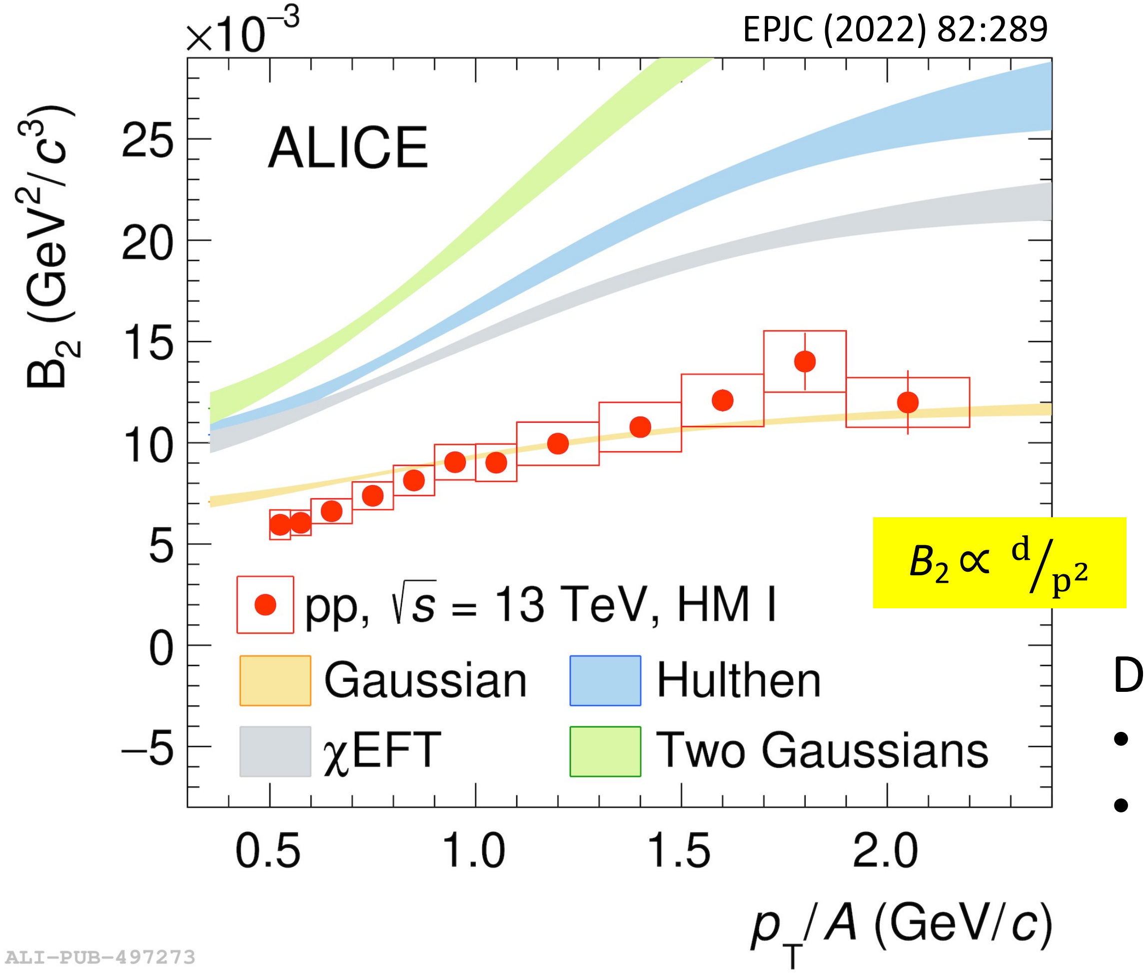
Compare with predictions of coalescence model

Testing coalescence model

HM pp @ 13 TeV

B_A measurements sensitive to the nuclear wave function

- HM data sample also used for the precise measurement of the source radii



emission source size

$$B_2(p_T) \approx \frac{3}{2m} \int d^3q D(q) e^{-R^2(p_T)\, q^2}$$

$$D(q) = \int d^3r |\phi_d(r)|^2 e^{-iq\cdot r}$$

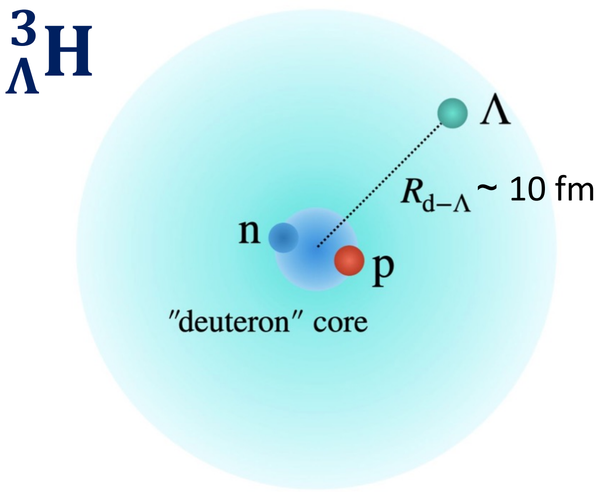
deuteron wave function (*size d = 3.2* fm)

Different wave functions are tested:

- **Hulthen**: favoured by low-energy scattering experiments
- **Gaussian**: best description of currently available ALICE data

Blum, Takimoto, PRC 99 (2019) 044913
Scheibl, Heinz, PRC 59 (1999) 1585-1602
Kachelrieß et al., EPJA 1 (2020) 4

The hypertriton



- Lightest known hypernucleus
- Bound state of p + n + Λ
- Discovered in early 50s by M. Danysz and J. Pniewski [1]

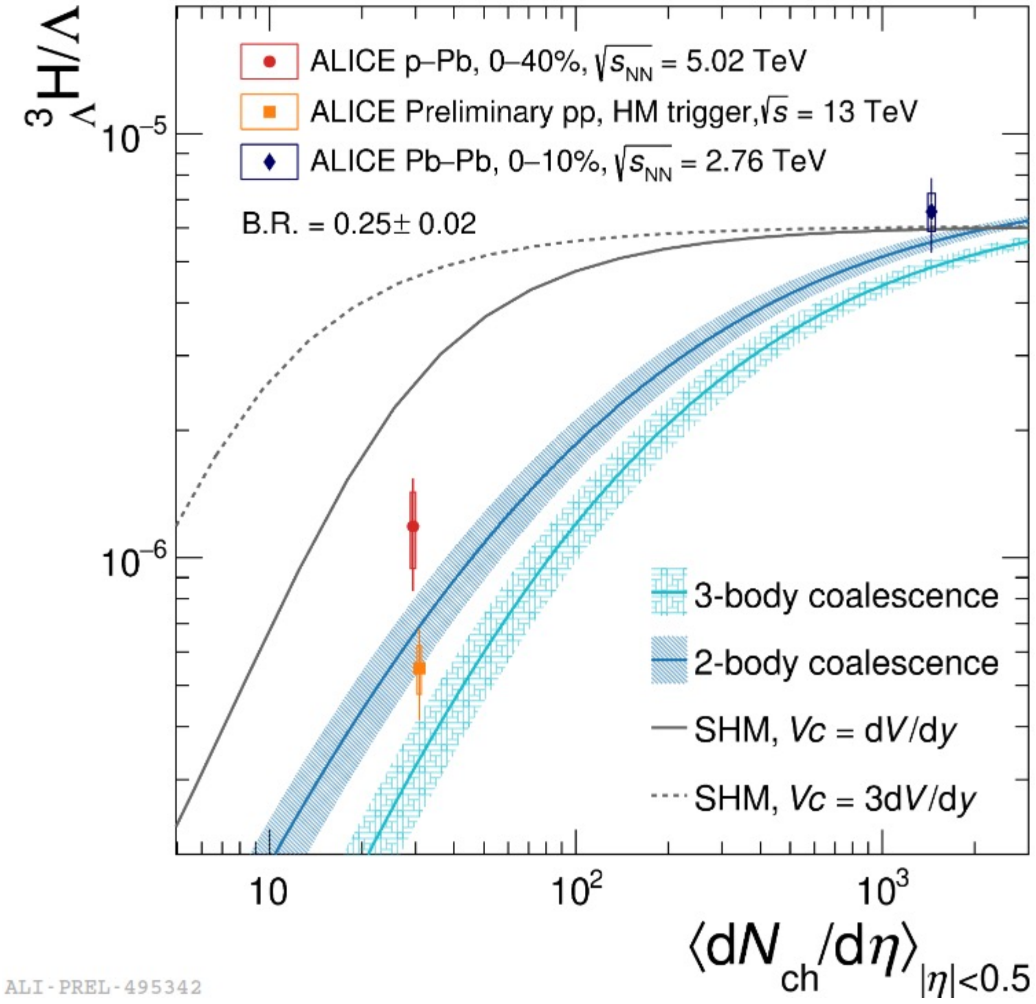
- Two-body halo nucleus
- $^{3}_{\Lambda}\mathrm{H}$ approximated as a bound state of a deuteron and a Λ with an expected radius of ~ 10 fm [2]

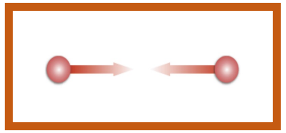
- $^{3}_{\Lambda}\mathrm{H}$ lifetime and B_{Λ} reflect its structure
- Weakly bound nature of $^{3}_{\Lambda}\mathrm{H}$ is confirmed by the latest ALICE measurement in Pb—Pb collisions [3]
  - $\tau = [253 \pm 11\ (\mathrm{stat.}) \pm 6\ (\mathrm{syst.})]\ \mathrm{ps}$
  - $B_{\Lambda} = [72 \pm 63\ (\mathrm{stat.}) \pm 36\ (\mathrm{syst.})]\ \mathrm{keV}$

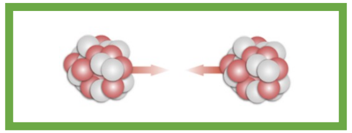
$r_{^{3}_{\Lambda}\mathrm{H}\ (np\Lambda)}$: 4.9 fm ($B_{\Lambda}$= 2.35 MeV)
$r_{^{3}_{\Lambda}\mathrm{H}\ (d\Lambda)}$: ~10 fm ($B_{\Lambda}$ ~ 0.13 MeV)

[1] M. Danysz, J. Pniewski, Philos. Mag. 44 348 (1953)
[2] Hildenbrand F. et al., PRC 100 (2019) 034002
[3] arXiv:2209.07360

Hypertriton production







- $^{3}_{\Lambda}$H/Λ ratio provides a powerful tool to investigate nuclear production mechanism

- **Pb—Pb collisions**:
  - small difference between SHM and coalescence predictions
- **pp and p—Pb collisions**:
  - large separation between production models
  - good agreement with 2-body coalescence
  - tension with SHM at low charged-particle multiplicity density
  - configuration with V_C = 3dV/dy is excluded by more than 6σ

p—Pb: PRL 128 (2022) 25, 252003
Pb—Pb: PLB 754 (2016) 360-372

Summary

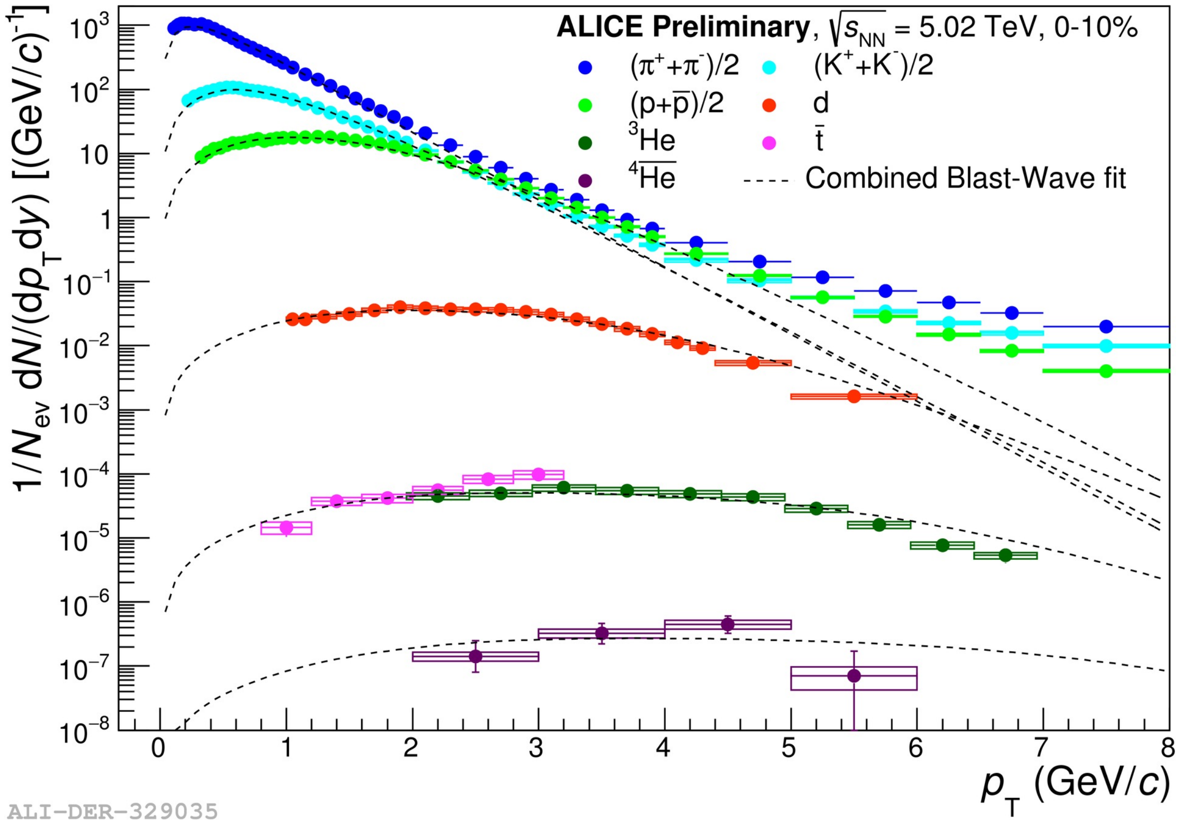
- Light-flavor particle production studied in all available collision systems and energies with ALICE

- **Small collision systems** (pp and p—Pb) are particularly interesting
  - test production models

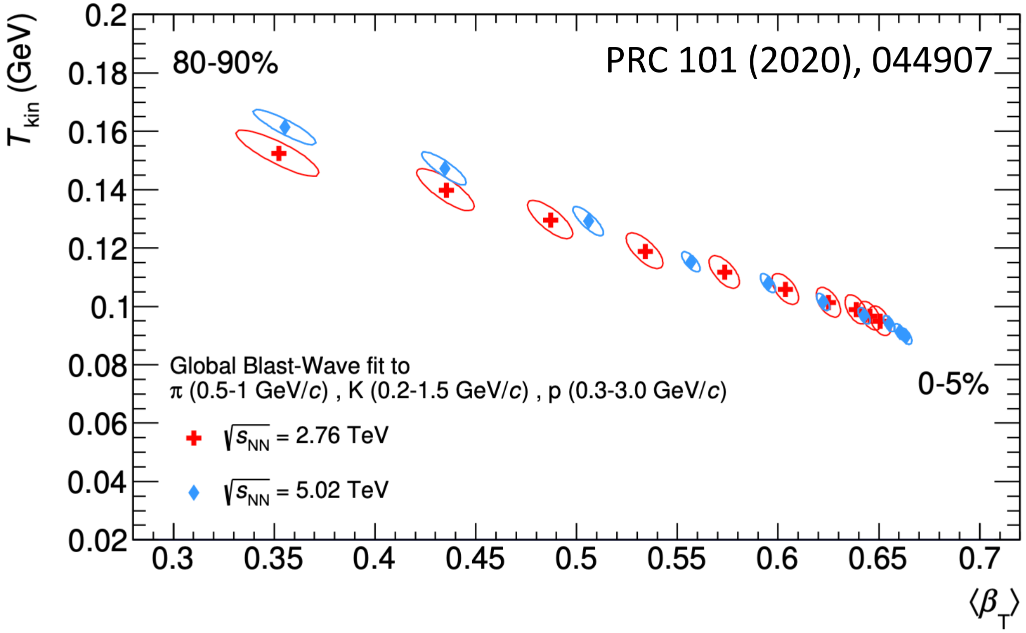
- **Large collision systems** (Pb—Pb) are useful
  - investigate collective motion

- **Production mechanism still not completely clear**
  - stay tuned for new results with the upcoming LHC Run 3!

(Anti)(hyper)nuclei production in Pb–Pb collisions



- Blast-Wave model describes the particle distribution at the kinetic freeze-out as a result of the expansion of a thermalized source
- The expanding source causes a mass dependent hardening
- The expansion velocity and decoupling temperature are free parameters of the model



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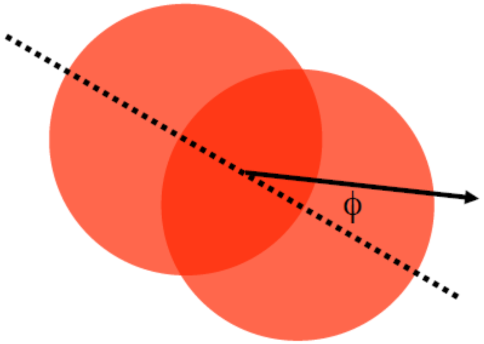
Pb—Pb collisions

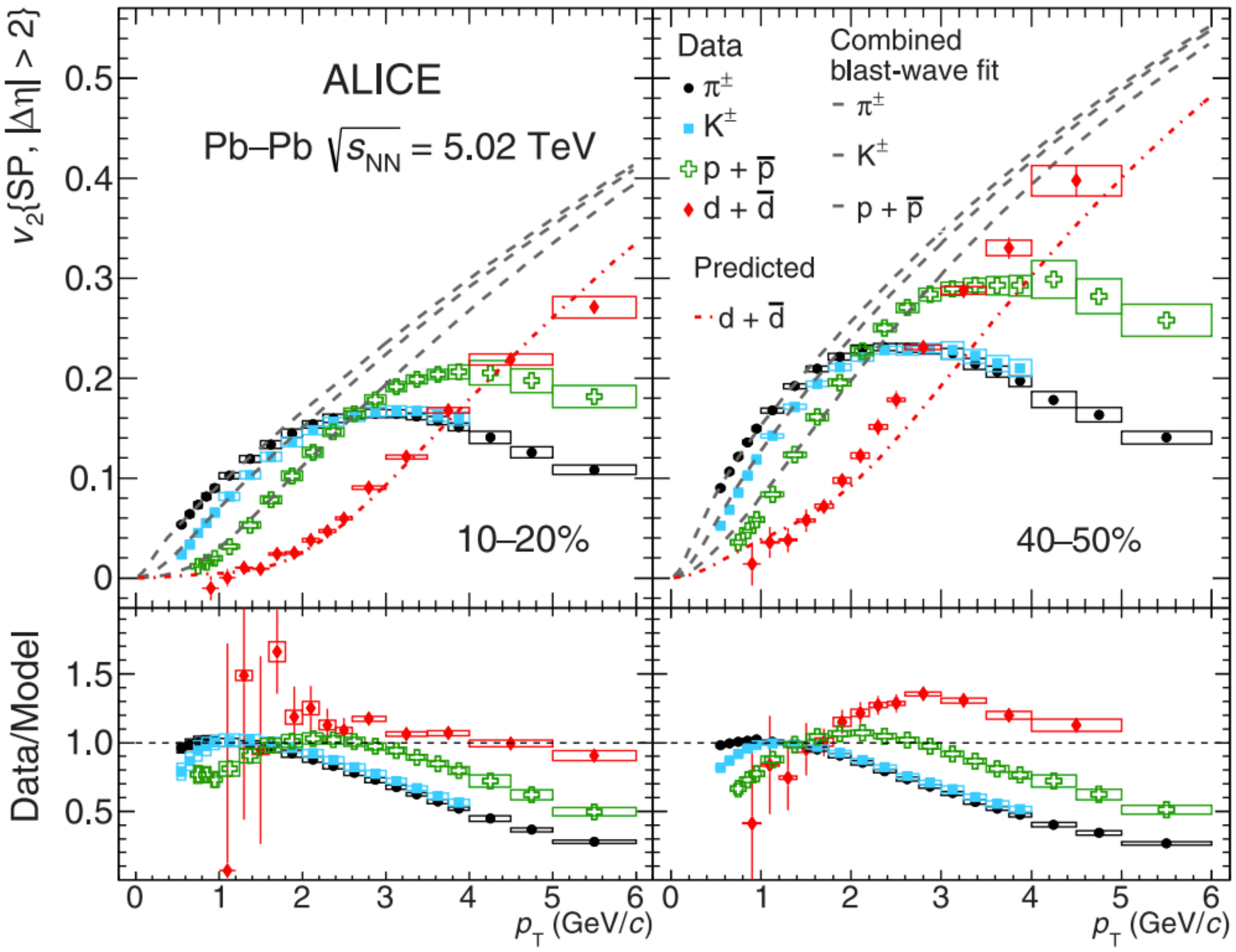
Collectivity in Pb–Pb collisions



Initial space anisotropy in non-central A-A collisions

- azimuthal anisotropy of particle emission wrt symmetry plane

PRC 102, 055203 (2020)



Particle azimuthal distribution can be espressed as a Fourier series

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n\geq 1} v_n \cos\left(n\left(\varphi - \Psi_n\right)\right)$$

$$\begin{cases} \Psi_n = n^{th} \text{ symmetry plane} \\ \varphi = \text{azimuthal angle} \\ v_n = \text{flow coefficients} \end{cases}$$

v_2: elliptic flow

v_3: triangular flow

- Mass ordering at low p_T, increasing trend with p_T and centrality
  - Expectations from relativistic hydrodynamics are fulfilled

Underlying event activity

- Production in small collision systems can also be explored using the underlying event (UE) activity

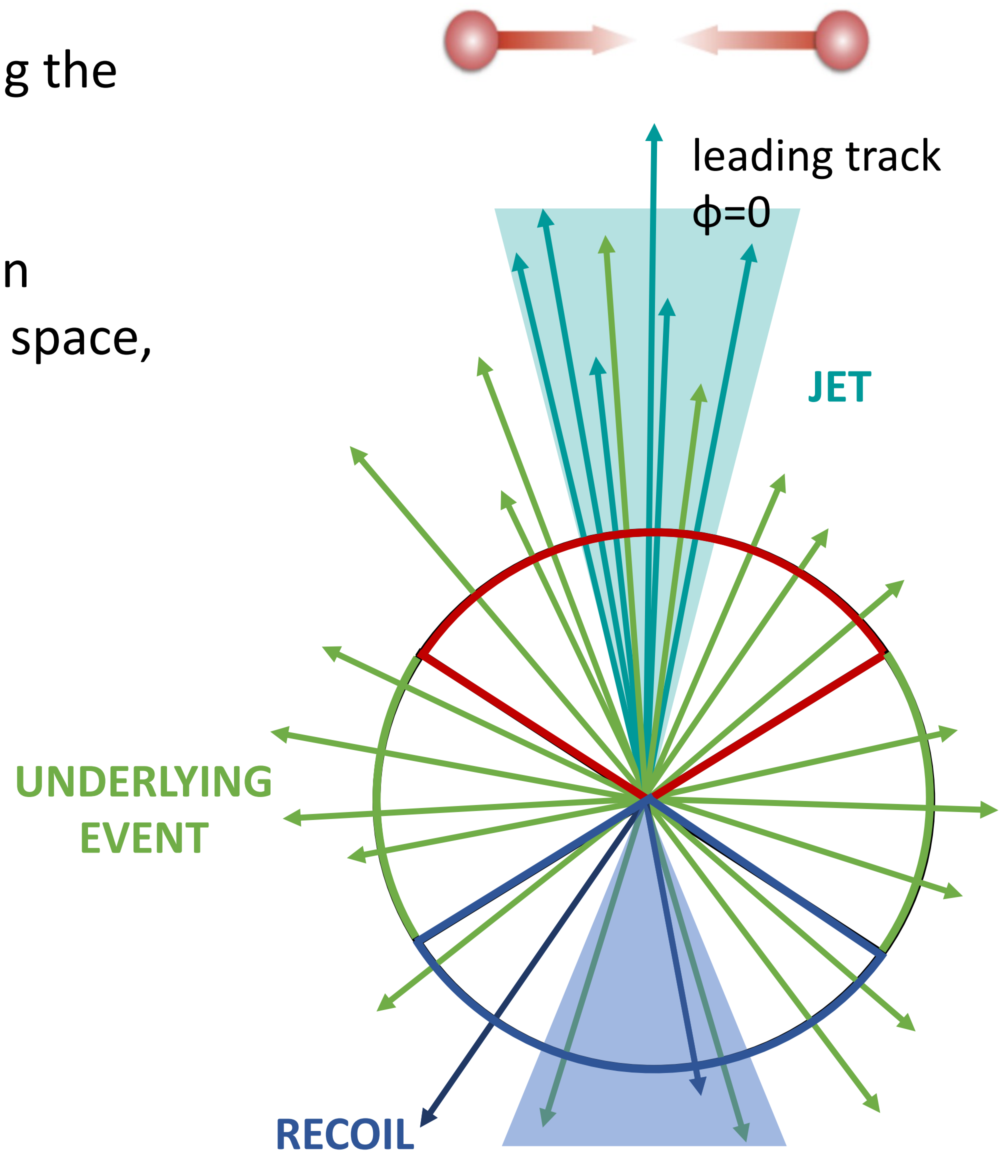
- Coalescence mechanism can be tested comparing the deuteron production in jets, where nucleons are already closer in phase space, with that in the underlying event

- Highest p_T particle (p_T^{lead} > 5 GeV/c) used as jet proxy

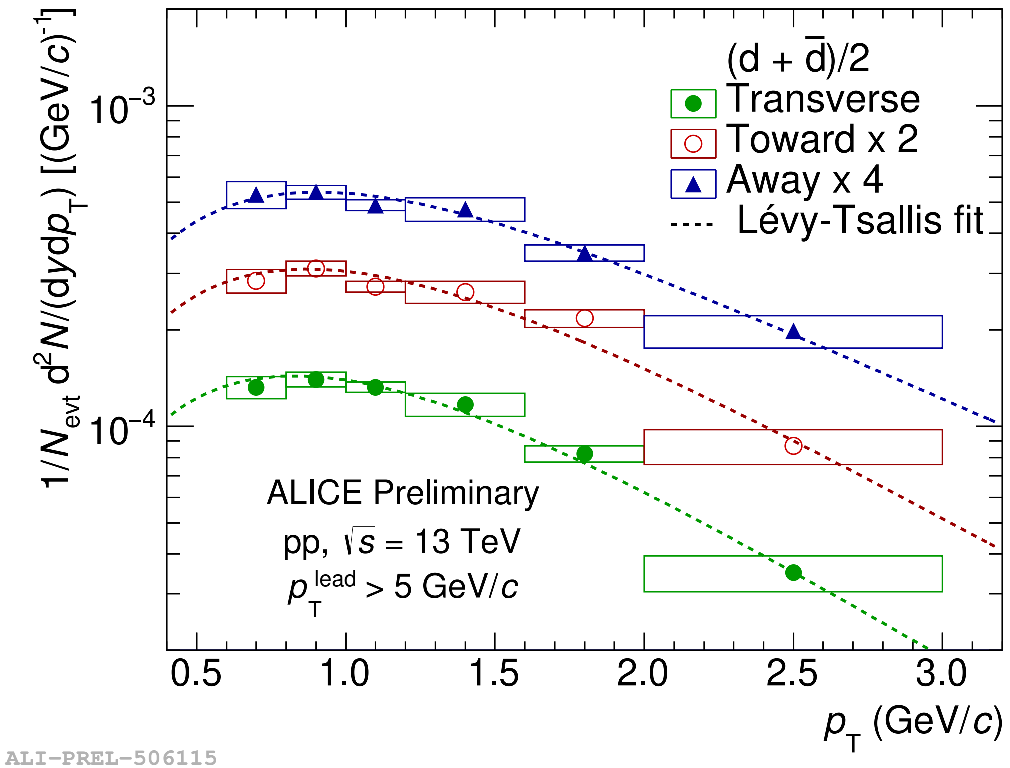
- 3 regions in the transverse plane wrt leading track:
  - Toward: |Δϕ| < 60° (Jet + UE)
  - Transverse: 60° < |Δϕ| < 120° (UE)
  - Away: |Δϕ| > 120° (Recoil jet + UE)

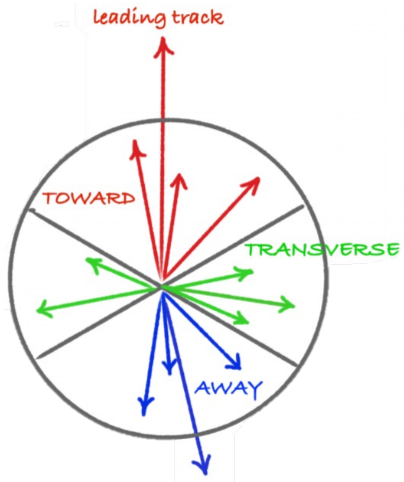
→ Jet = Toward – Transverse

Martin et al., EPJC (2016) 76: 299



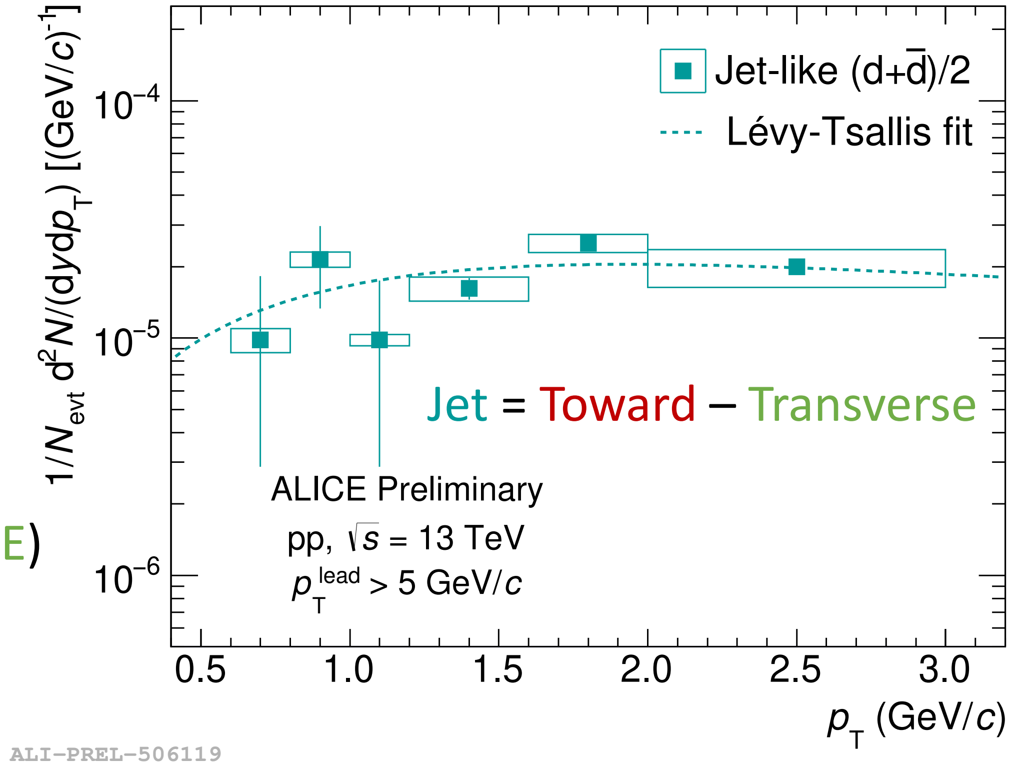
Underlying event activity





Toward region (Jet + UE)

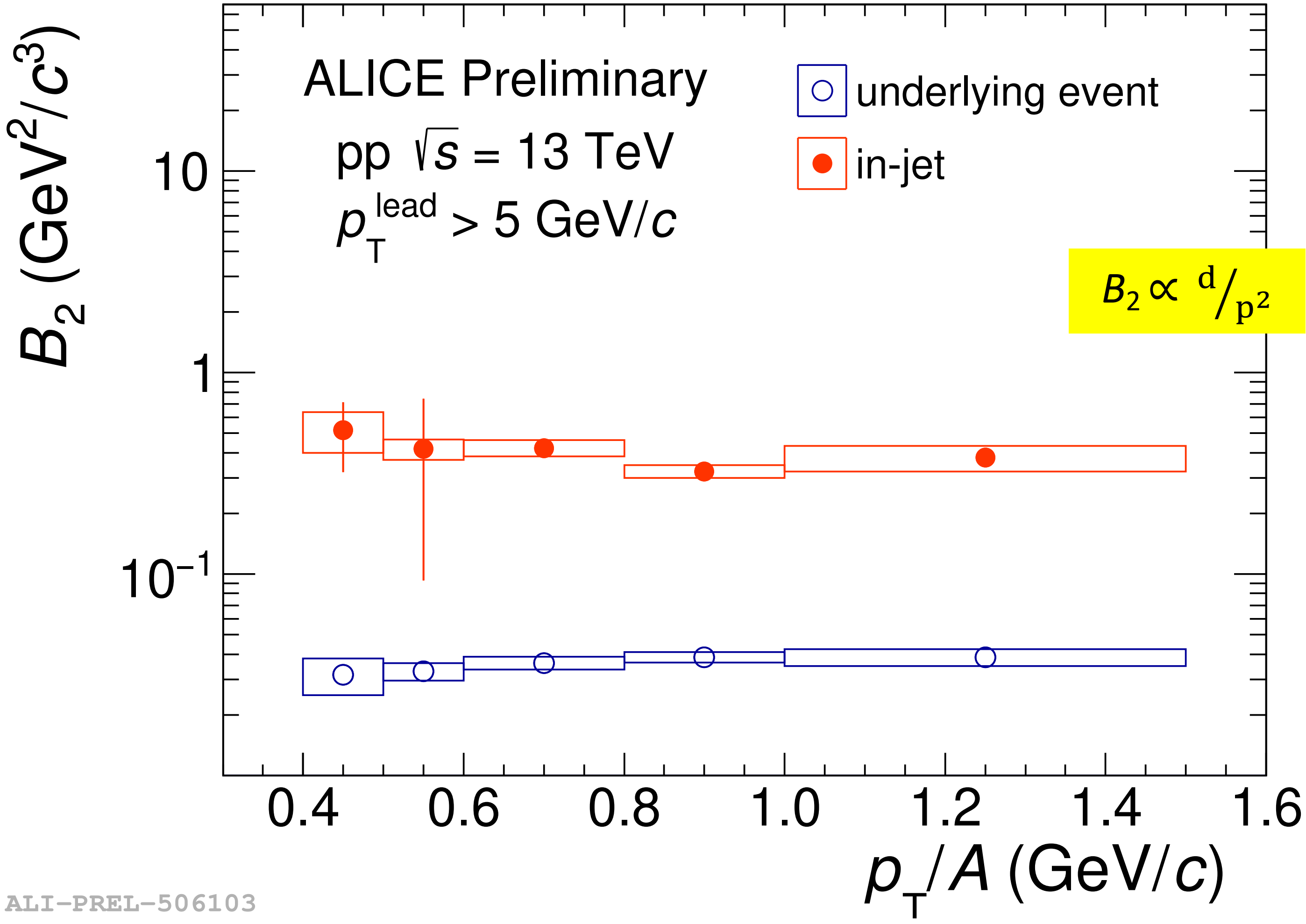
Transverse region (UE)



- Deuteron production from events with a jet: $p_T^{lead} > 5$ GeV/c
- Jet: ~10% of total production

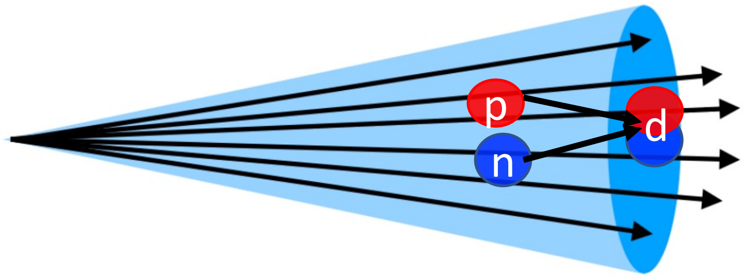
→ The majority of deuterons is produced in the underlying event

Underlying event activity



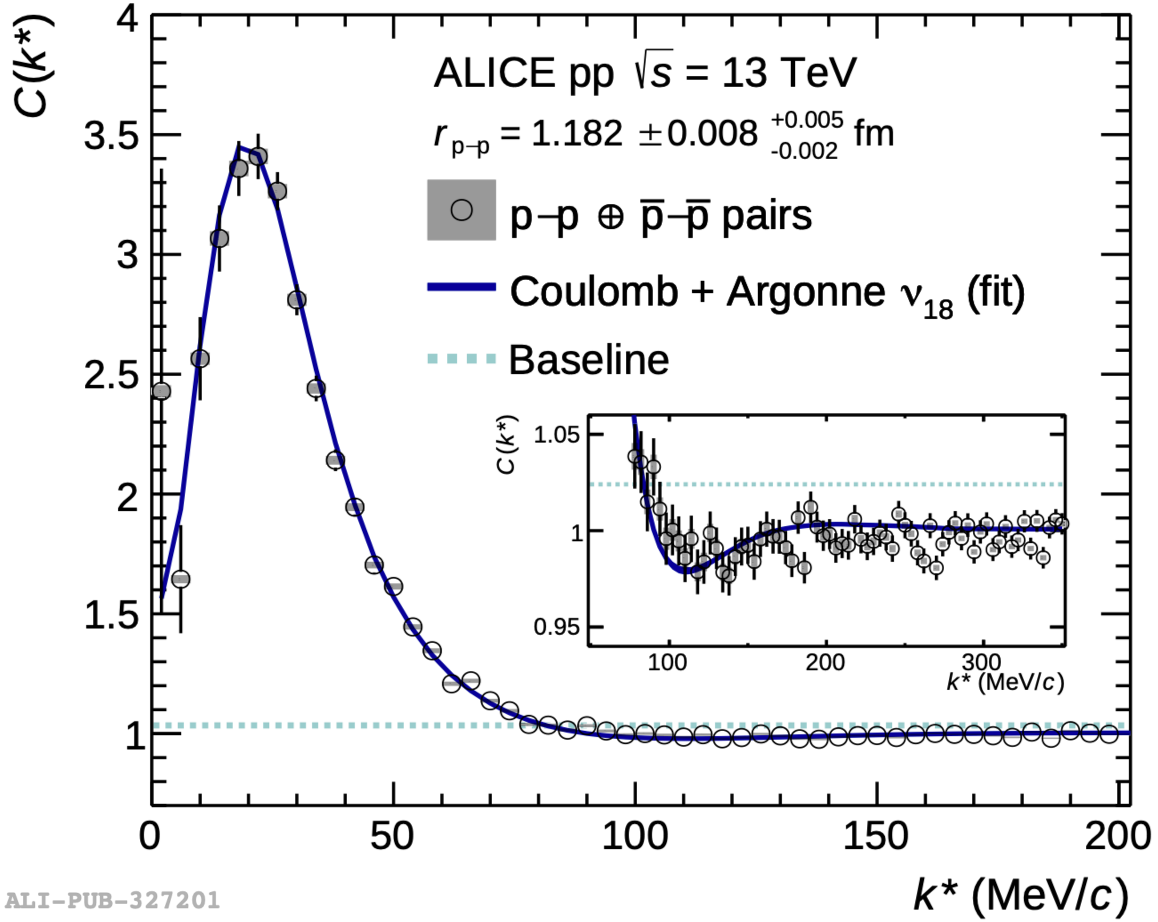
$B_2 \propto d/p^2$

- B_2 in-jet ~ 15 times larger than B_2 in UE
- *Enhanced deuteron coalescence probability in jets is observed for the first time!*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence

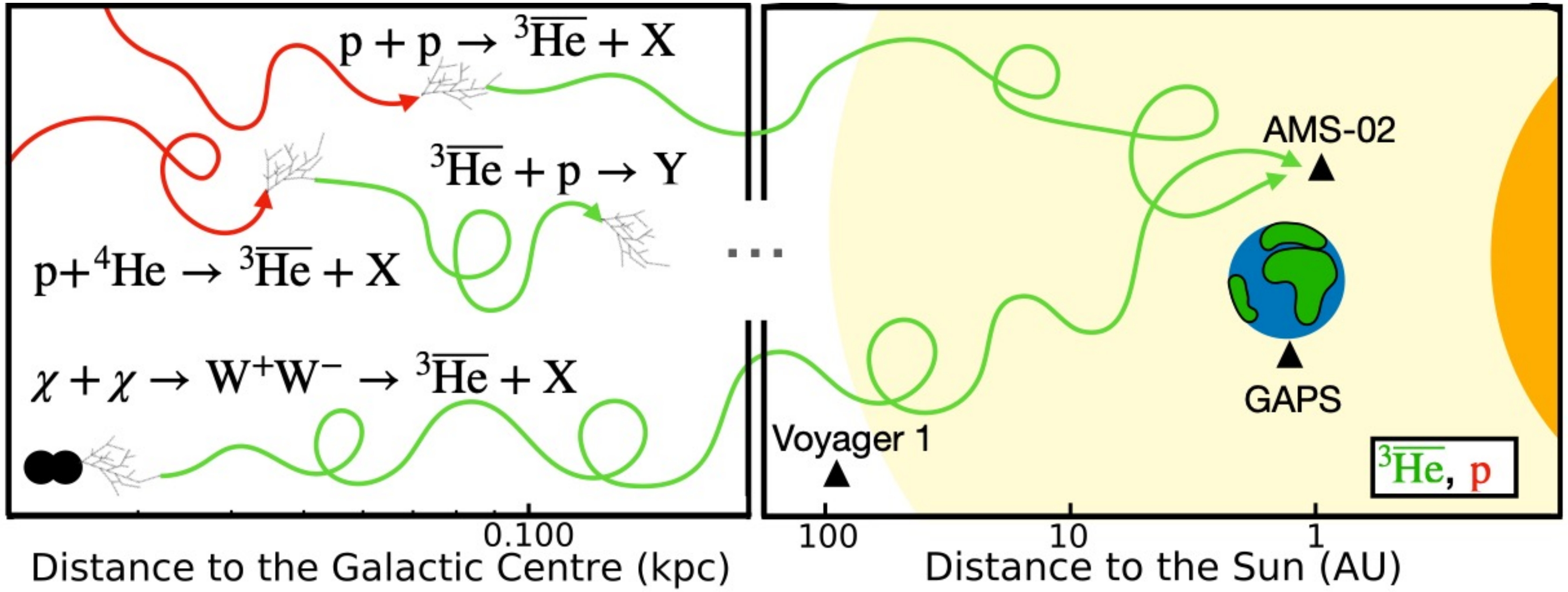


proton-proton correlation

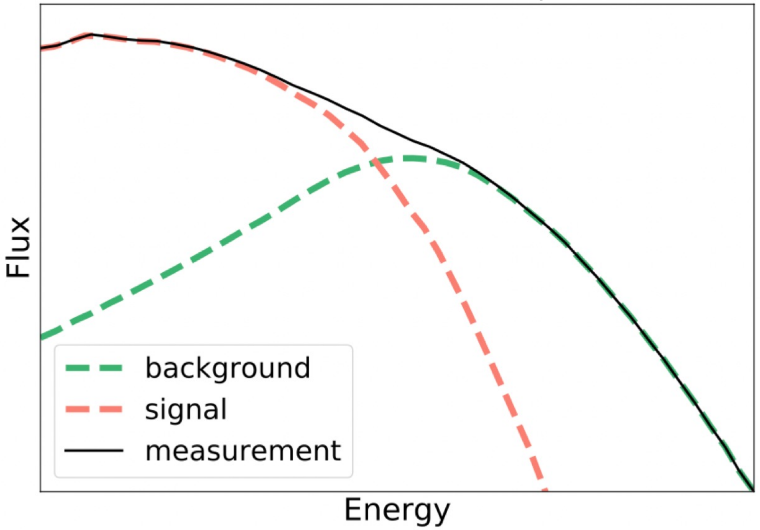
PLB 797 (2019) 134822



- proton-proton (p-p) correlation is well known
- p-p correlation function properly described by using:
  - Fermi-Dirac wave function
  - Coulomb interaction
  - strong interaction
- Source size can be extracted:
  - $r_{p-p} \sim 1.18$ fm
- If the interaction is well known, hadron-hadron correlation can be used to measure the radius of the emitting source



Antinuclei cosmic ray flux



Antinuclei production:

- pp, p–A and (few) A–A reactions between primary **cosmic rays** and the interstellar medium
- **dark-matter** annihilation processes

To determine exact primary and secondary fluxes → precise knowledge of antinuclei production, propagation and annihilation is needed

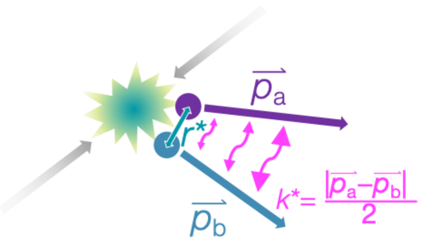
Hadron-hadron correlation

ALICE is pioneering the study of strong interactions using femtoscopic correlations

Momentum correlations can be employed to explore two-particle dynamics

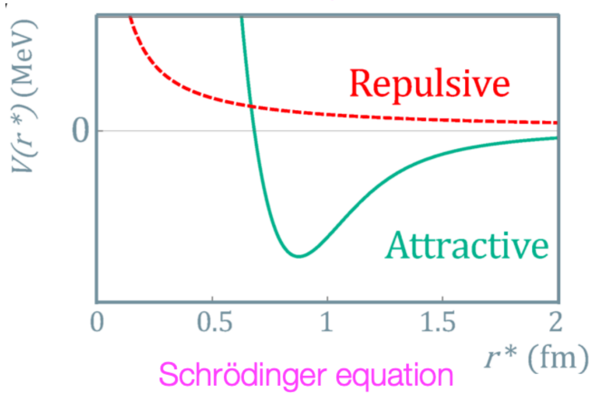
Correlation function depends on two ingredients:

- emission source function (pp collisions: $r_{eff} \sim 1$ fm, Gaussian profile [9])
- two-particle relative wave function (quantum statistics + Coulomb + strong interactions)

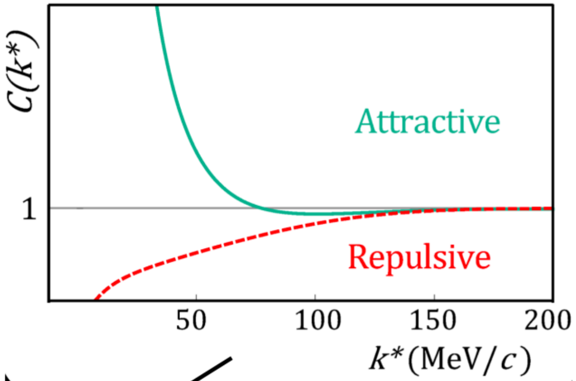


Emission source S(r*)

Interacting potential



Correlation function



Schrödinger equation

Two-particle wave function

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

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

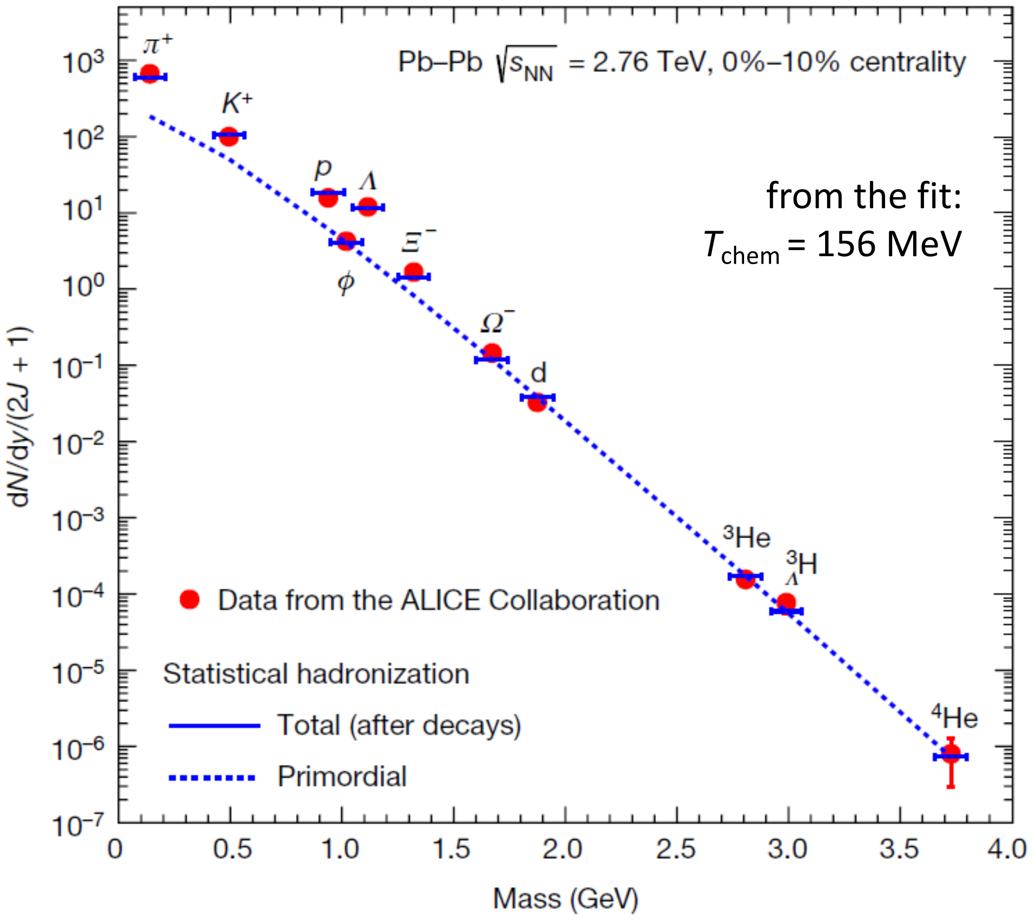
CATS Framework: D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

Statistical models

- Hadrons emitted from a system in statistical and chemical equilibrium
- $dN/dy \propto \exp(-m/T_{chem})$

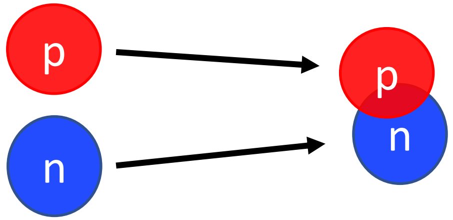
  $\Rightarrow$ Nuclei (large m): large sensitivity to T_{chem}
- Light hadrons are produced during phase transition
- Typical binding energy of nuclei ~ few MeV ($E_B \sim 2$ MeV for d)

  ⇒ how can they survive the hadronic phase environment?



Andronic et al., Nature 561, 321–330 (2018)

Coalescence models



[1]PRC 99 (2019) 024001
[2]PRL 123 (2019) 112002

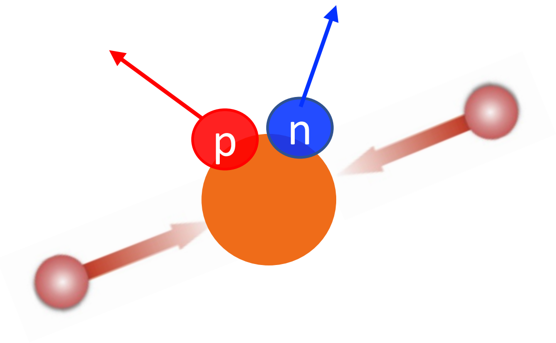
- If (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p_0}$) and match the spin state, they can form a (anti)nucleus
- Coalescence parameter B_A is the key observable

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\, p_A^3} \Bigg/ \left(E_p \frac{d^3 N_p}{d\, p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

- Experimental observable tightly connected to the coalescence probability

Larger $B_A \Leftrightarrow$ Larger coalescence probability

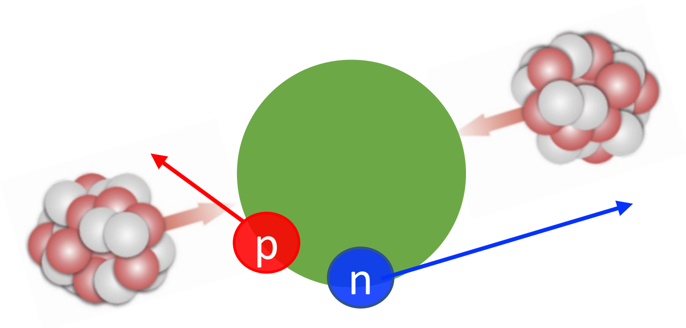
- Coalescence probability depends on the system size



pp[1], p—Pb[2]: r_0 = 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

$\Leftrightarrow$ large B_A



Pb—Pb[3]: r_0 = 3–6 fm

Large distance in space
(Both momentum and space correlations matter)

$\Leftrightarrow$ small B_A