Results on light (anti)nuclei production in Pb–Pb collisions with ALICE at the LHC

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FOR THE ALICE COLLABORATION

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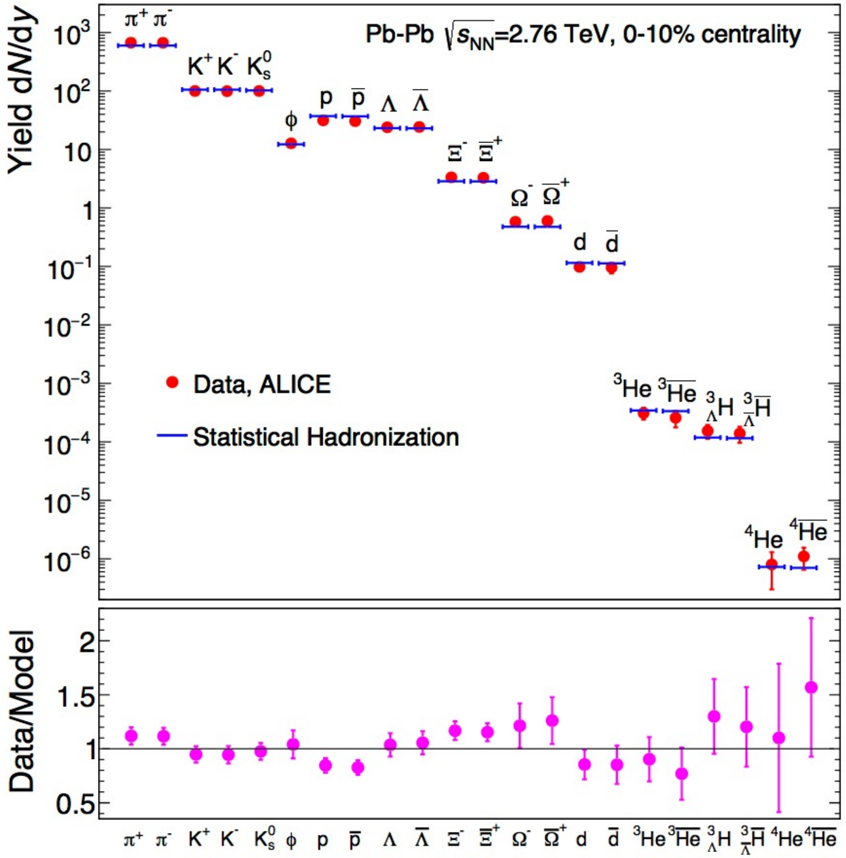
37TH WINTER WORKSHOP ON NUCLEAR DYNAMICS, PUERTO VALLARTA

Outline

- Introduction
- d, t, ^{3}He and ^{4}He production in Pb–Pb collisions
- Evolution of d/p, t/p, ^{3}He/p ratios with multiplicity
- Coalescence parameters B_2, B_3 and B_4
- Measurement of the $\overline{\mathrm{d}}$ and $^3\overline{\mathrm{He}}$ inelastic cross section

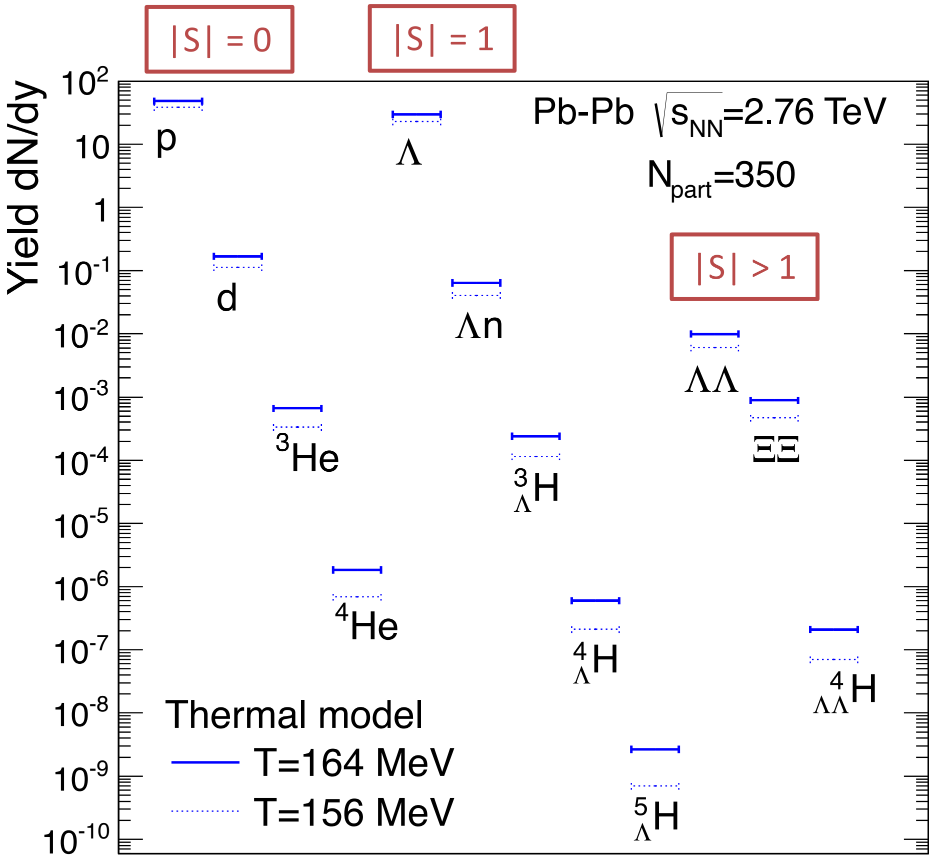
Introduction – statistical hadronization



A. Andronic, P. Braun-Munzinger,
K. Redlich, J.Stachel, Nature 561 (2018) 321

- In Pb–Pb collisions the system can be described by a grand canonical ensemble with the free parameters μ_B, V and T_{ch}
  → Quantum numbers are conserved on average
- Heavier particles are produced with lower probability
- ALICE Pb–Pb data compared to Statistical Hadronization Model predictions
  → Very good agreement
- Particles and antiparticles are produced equally at the LHC ($\mu_B \approx 0$)

Introduction – production of light nuclei

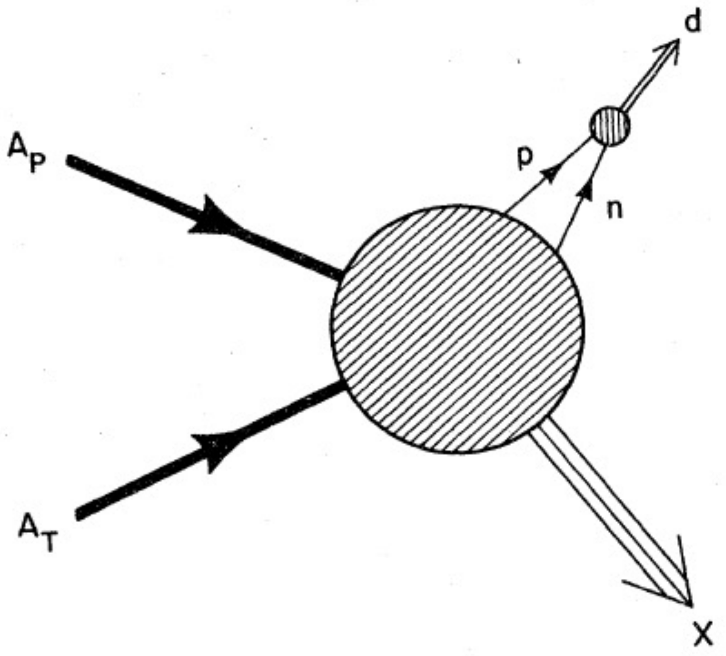


A. Andronic, private communication, model based on:
Phys. Lett. B 697 (2011) 203

- Abundance of nuclei strongly sensitive to chemical freeze-out temperature T_{ch}, due to
  - → Large mass
  - → Exponential dependence of the yield ~ $e^{(-m/T_{ch})}$

- Note: Binding energy of nuclei (few MeV) small compared to T_{ch}

Introduction – coalescence model



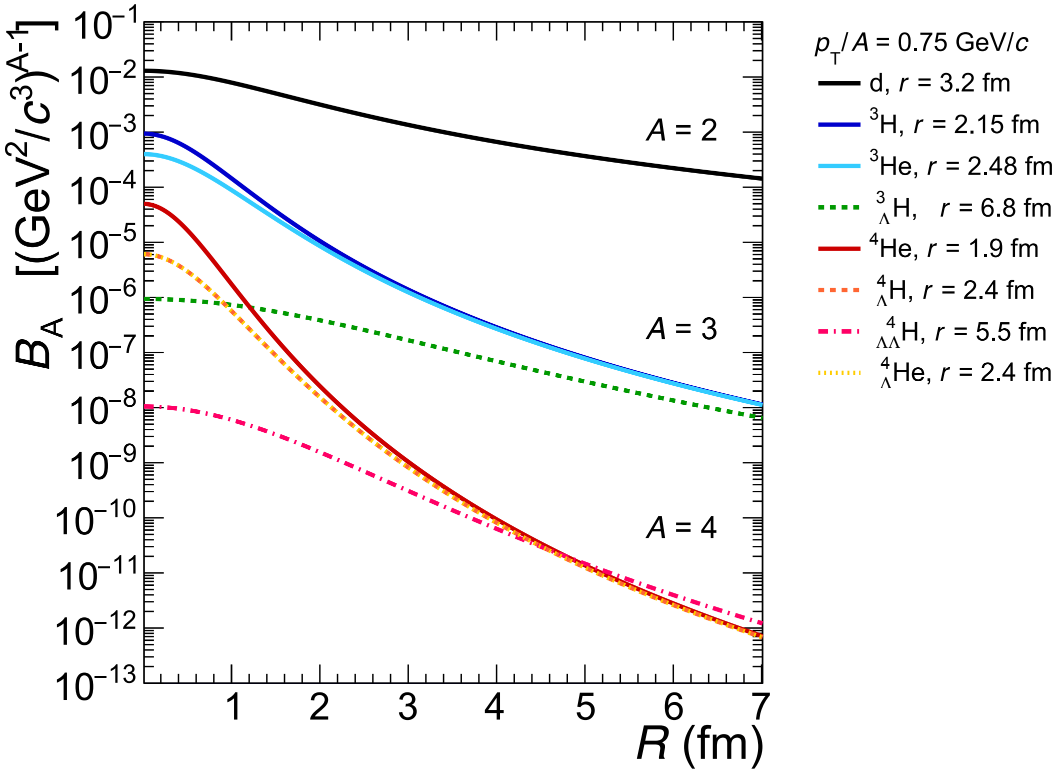
J. I. Kapusta, Phys. Rev. C 21 (1980) 1301

- Nuclei are formed after kinetic freeze-out by protons and neutrons which are nearby in space and have similar velocities

  → Production rate is connected to the size of the bound state

- Nuclei can break apart and be recreated by final-state coalescence

Introduction – coalescence model



F. Bellini, A. Kalweit, Acta Phys. Pol. B, 50(6):991

- Main parameter of the coalescence model B_A:

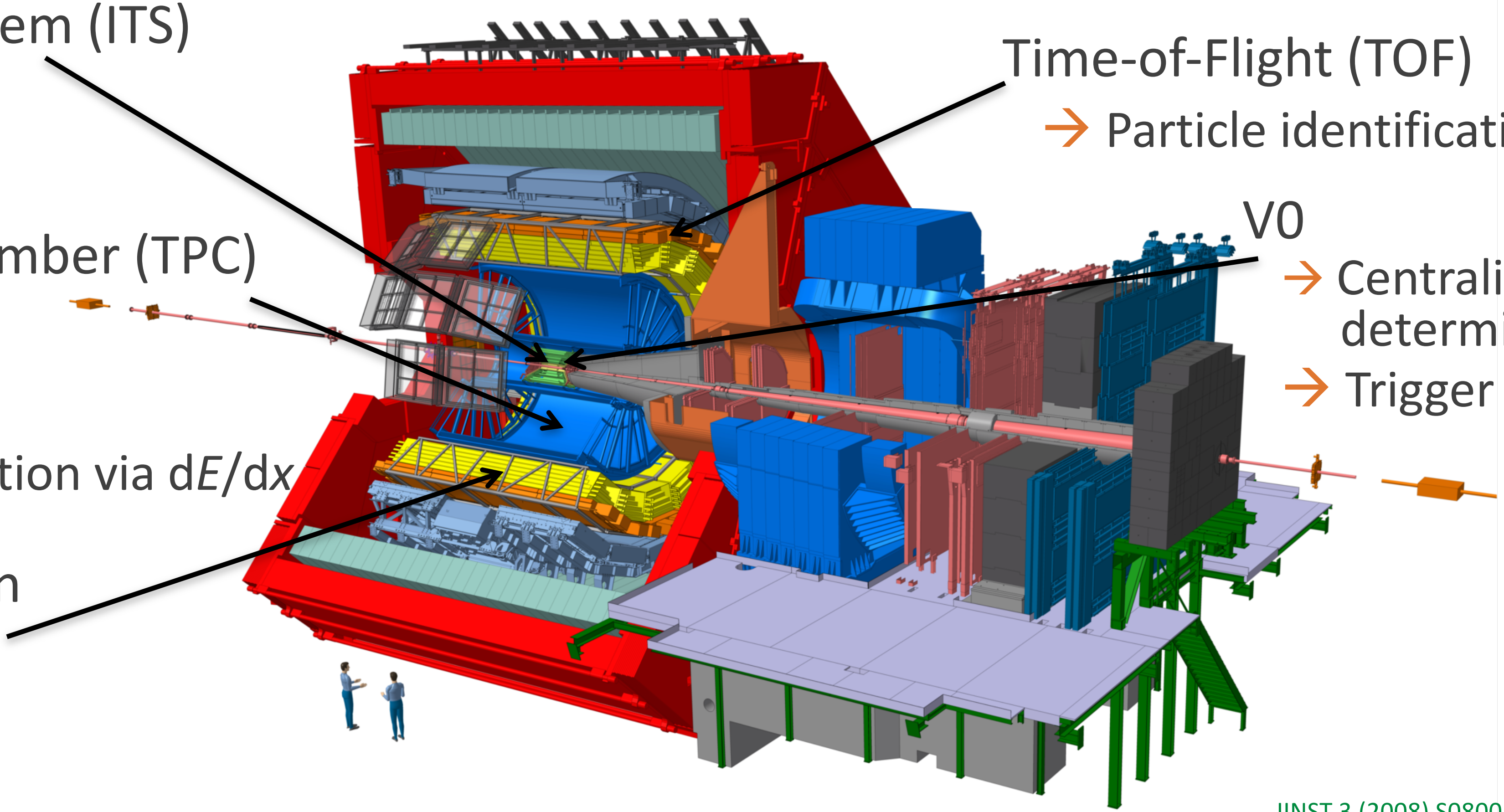
$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

A: mass number of nucleus

$p_p = p_A/A$

- B_A is related to the probability to form a nucleus via coalescence
- Advanced models use quantum mechanics
  - → Wave functions of the constituents have to overlap with the nucleus' wave function
  - → Typically, Wigner formalism is used

ALICE detector setup



Inner Tracking System (ITS)
- → Vertexing
- → Tracking

Time Projection Chamber (TPC)
- → Tracking
- → Vertexing
- → Particle identification via d*E*/dx

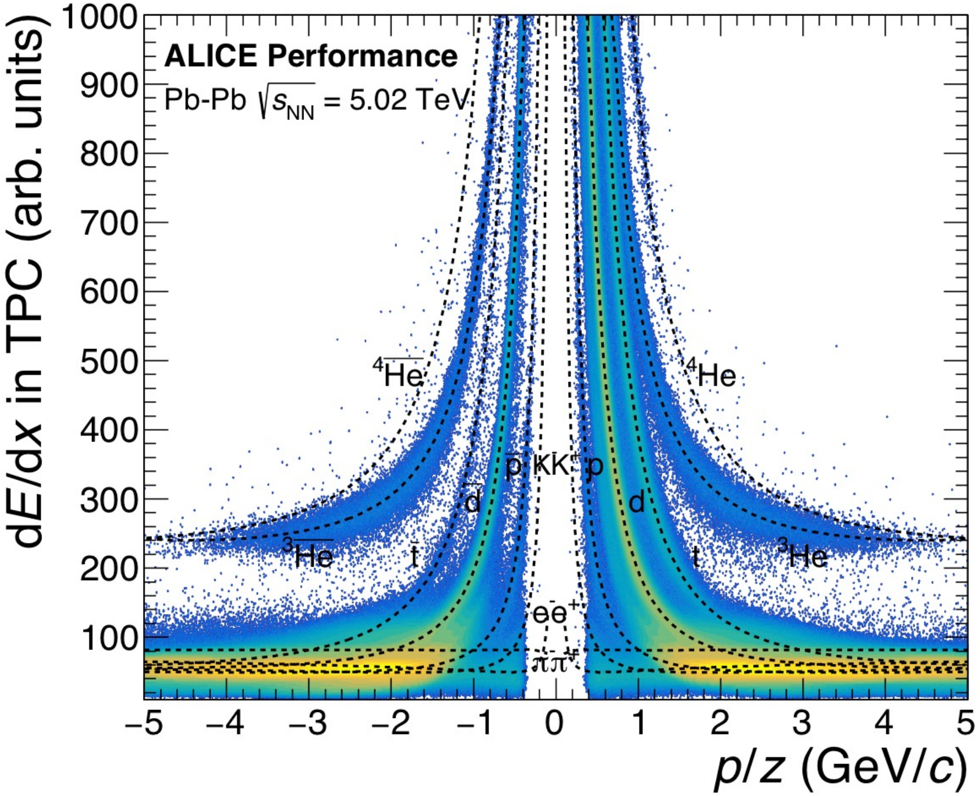
Transition Radiation Detector (TRD)
- → Tracking

Time-of-Flight (TOF)
- → Particle identification

V0
- → Centrality/multiplicity determination
- → Trigger

JINST 3 (2008) S08002

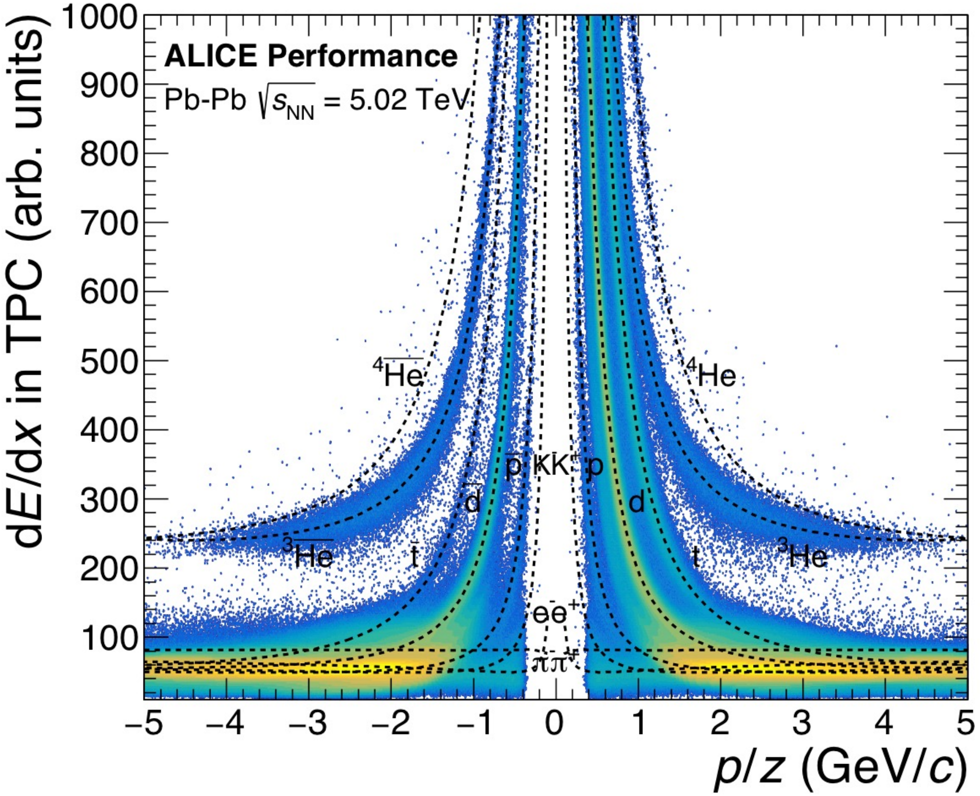
Particle identification



- Low momenta: TPC
  → Nuclei identified using the energy loss measurement

Int. J. Mod. Phys. A 29 (2014) 1430044

Particle identification

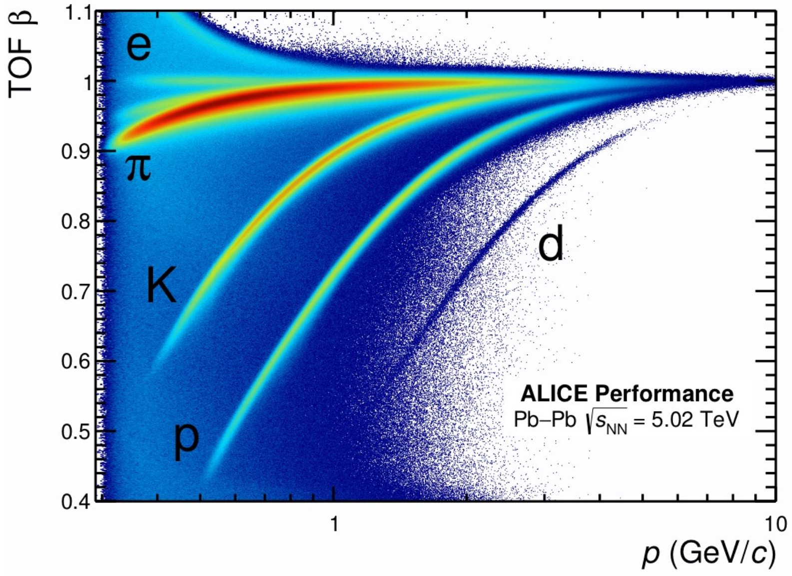


- Low momenta: TPC
  → Nuclei identified using the energy loss measurement
- Momentum determined from track curvature

$$\frac{p}{z} = r\,B$$

- High momenta: TOF

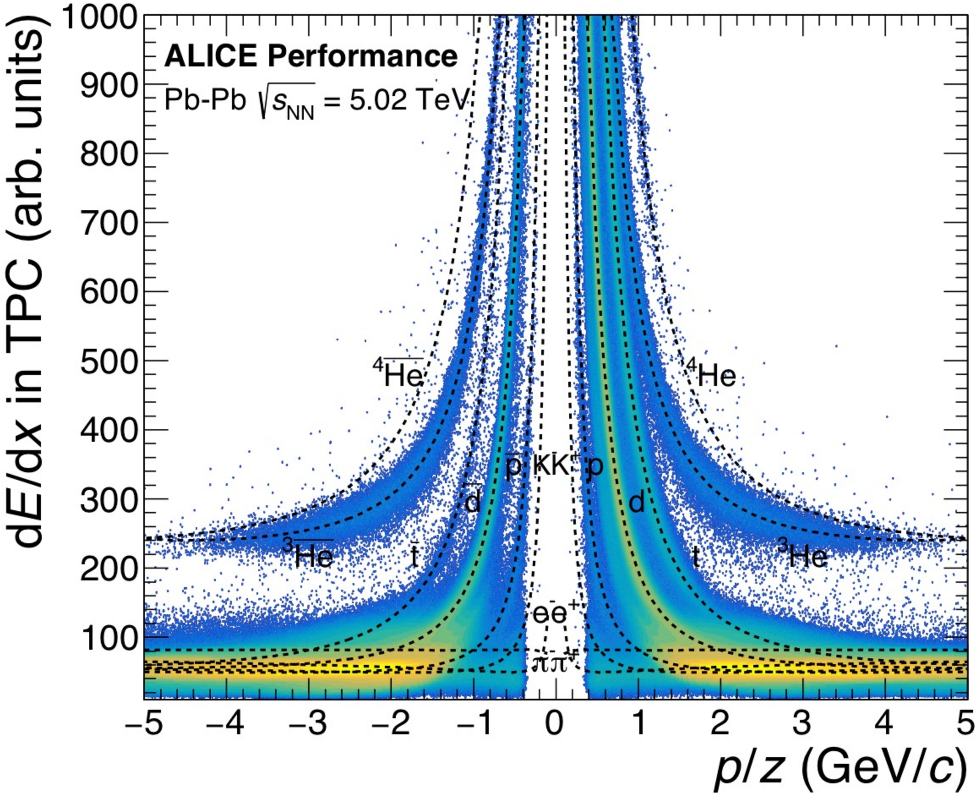
$$\beta = \frac{L}{t_{TOF}\,c}$$



-PERF-106336

Int. J. Mod. Phys. A 29 (2014) 1430044

Particle identification



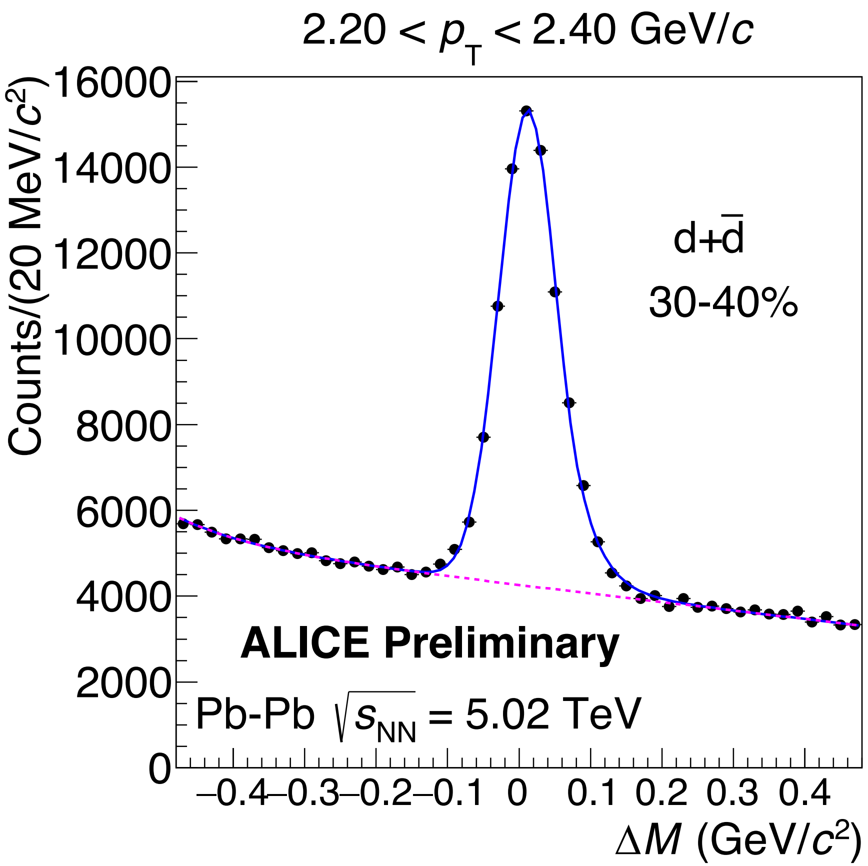
- Low momenta: TPC
  → Nuclei identified using the energy loss measurement

- Momentum determined from track curvature

$$\frac{p}{z} = r\,B$$

- High momenta: TOF
  → m^2 distribution is calculated from the time-of-flight measurement

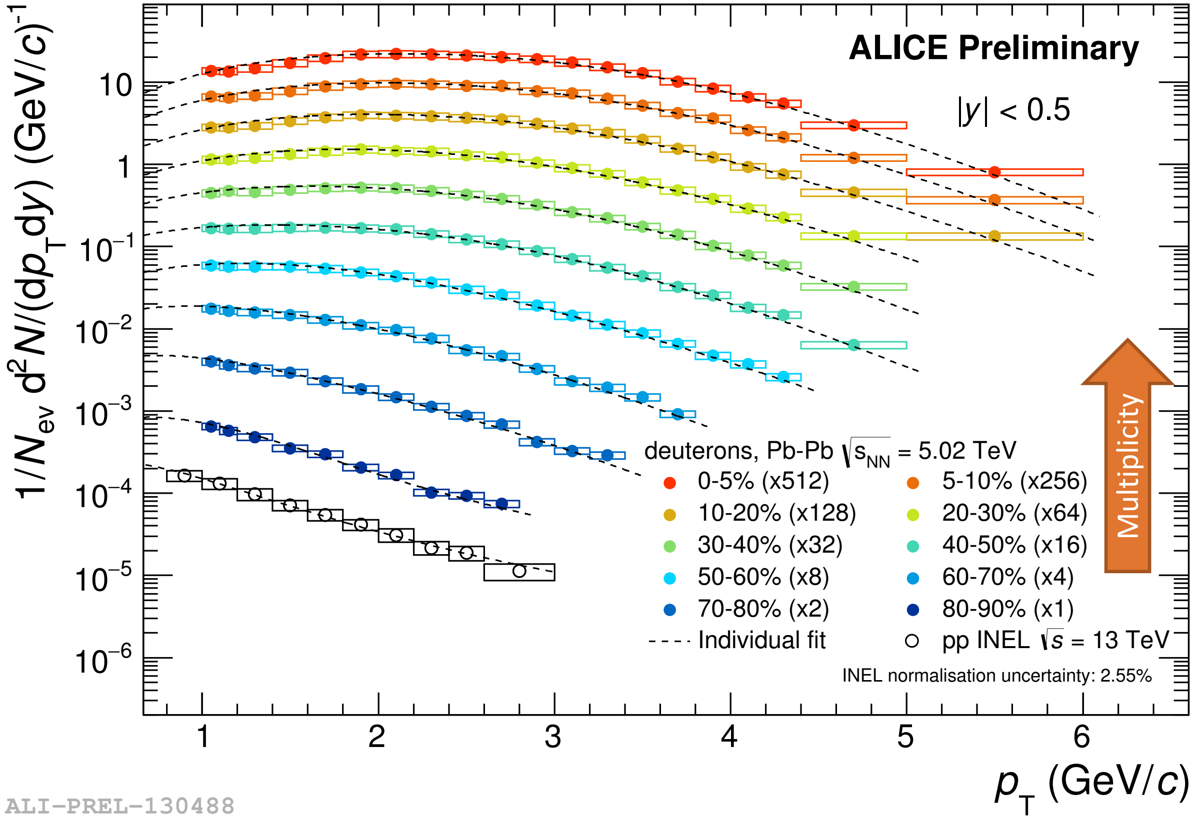
$$m^2 = \frac{(1-\beta^2)}{\beta^2}p^2$$



Int. J. Mod. Phys. A 29 (2014) 1430044

Deuteron spectra

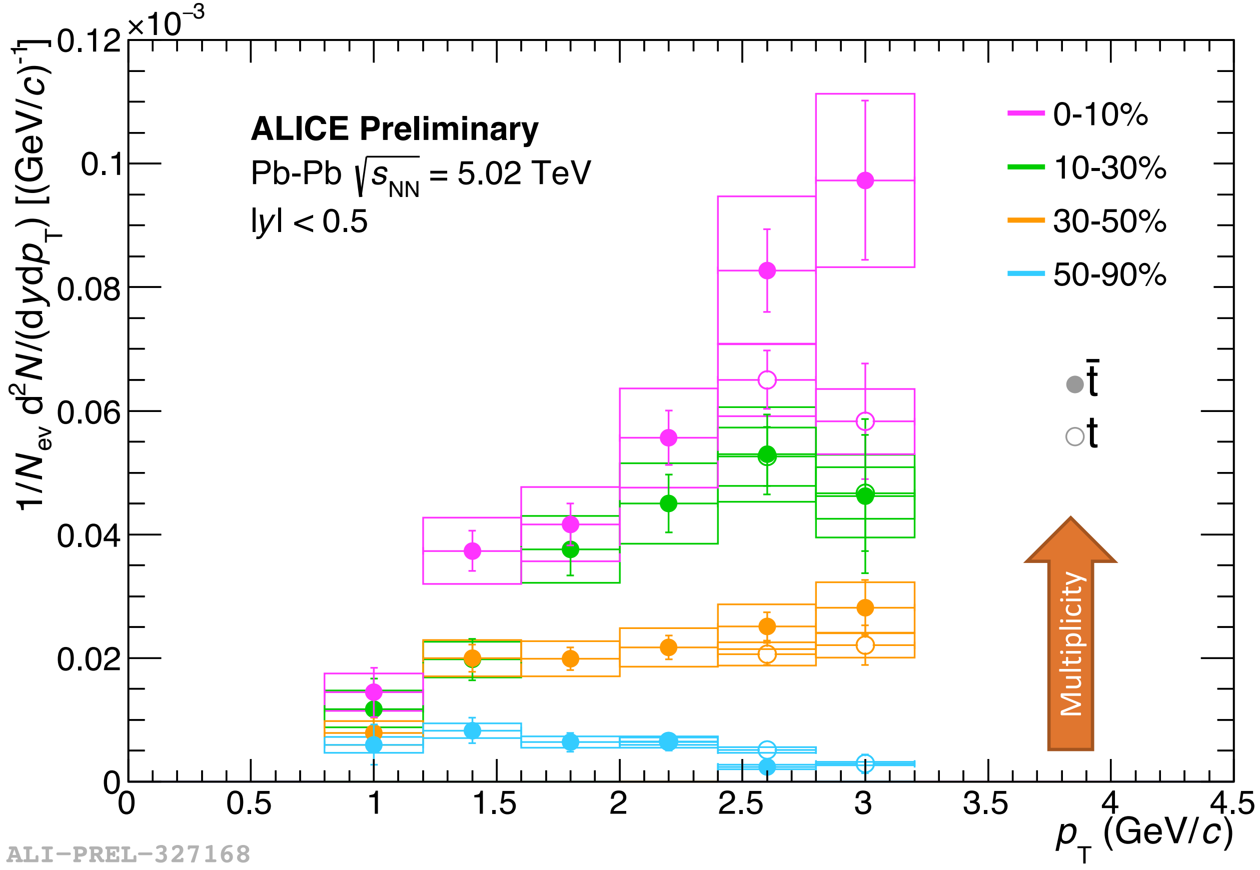
- d measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV
- d transverse momentum spectra measured in 10 centrality intervals
- Expected ordering of centralities
- Hardening of the spectra with increasing centrality
- Integrated production yield (dN/dy) extracted from Blast-Wave fits



ALICE-PUBLIC-2017-006

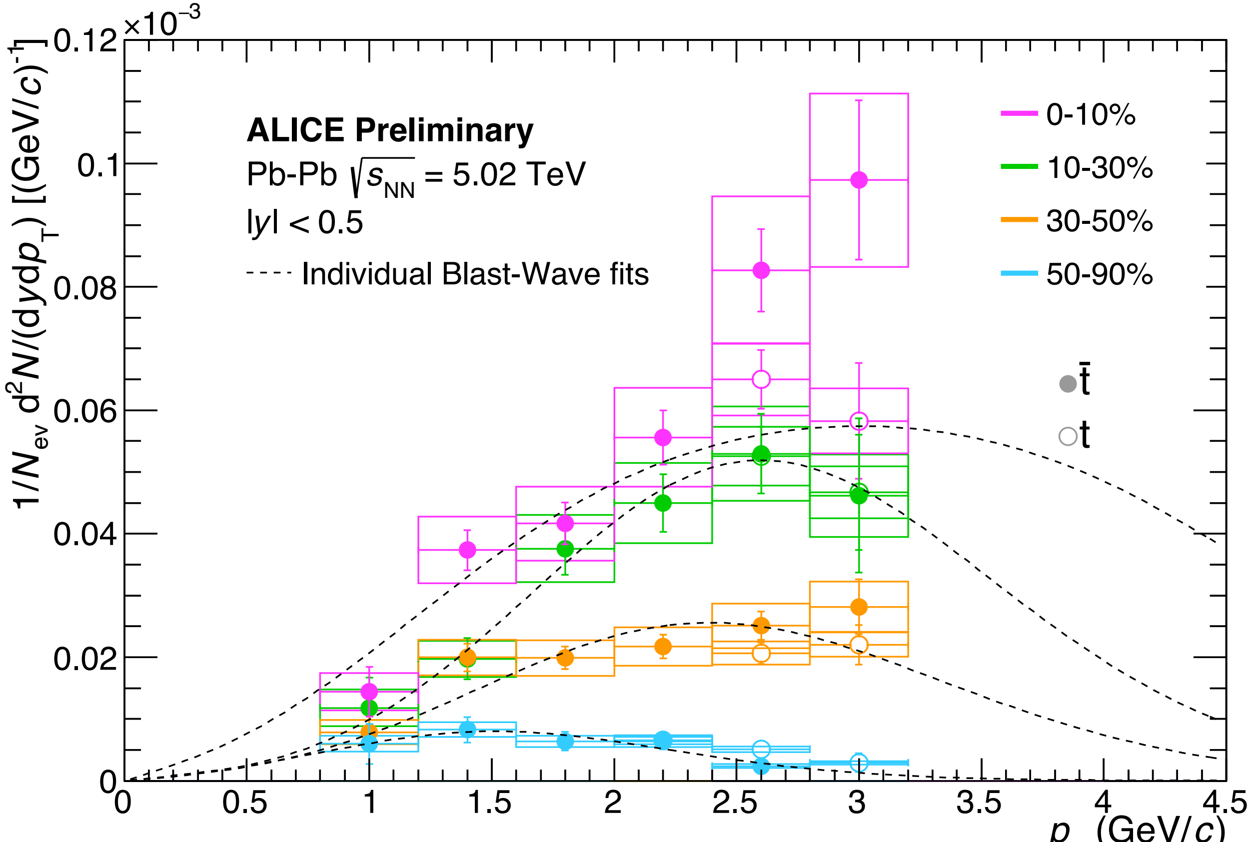
(Anti)triton spectra

- First $\bar{t}$ and t spectra in Pb–Pb collisions at the LHC
- $\bar{t}$ and t transverse momentum spectra measured in 4 centrality intervals
- Expected ordering of centralities
- Hardening of the spectra with increasing centrality
- $\bar{t}$ and t are compatible



(Anti)triton spectra

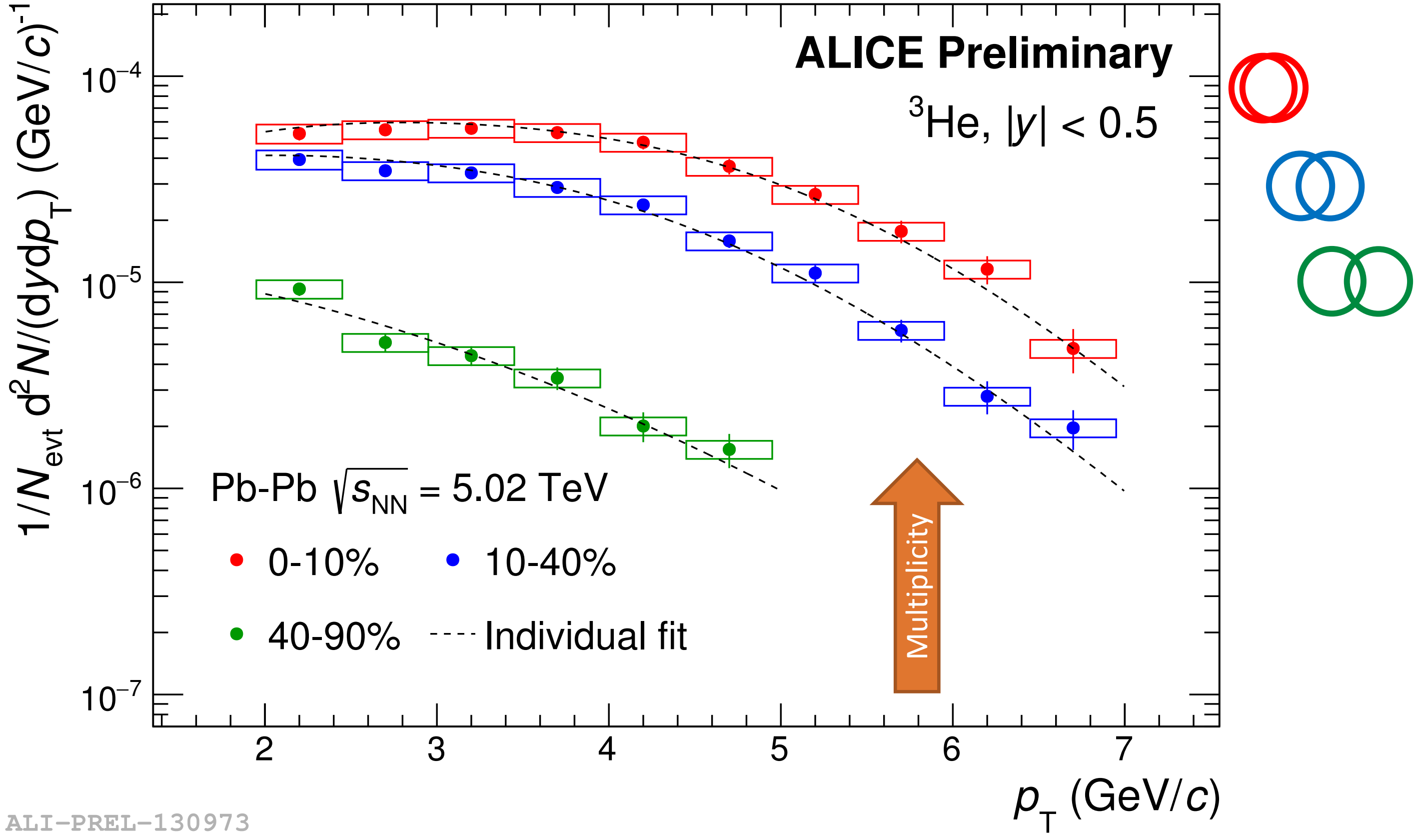
- First t̄ and t spectra in Pb–Pb collisions at the LHC
- t̄ and t transverse momentum spectra measured in 4 centrality intervals
- Expected ordering of centralities
- Hardening of the spectra with increasing centrality
- t̄ and t are compatible
- Integrated production yield (d*N*/d*y*) extracted from Blast-Wave fits



ALI-PREL-329128

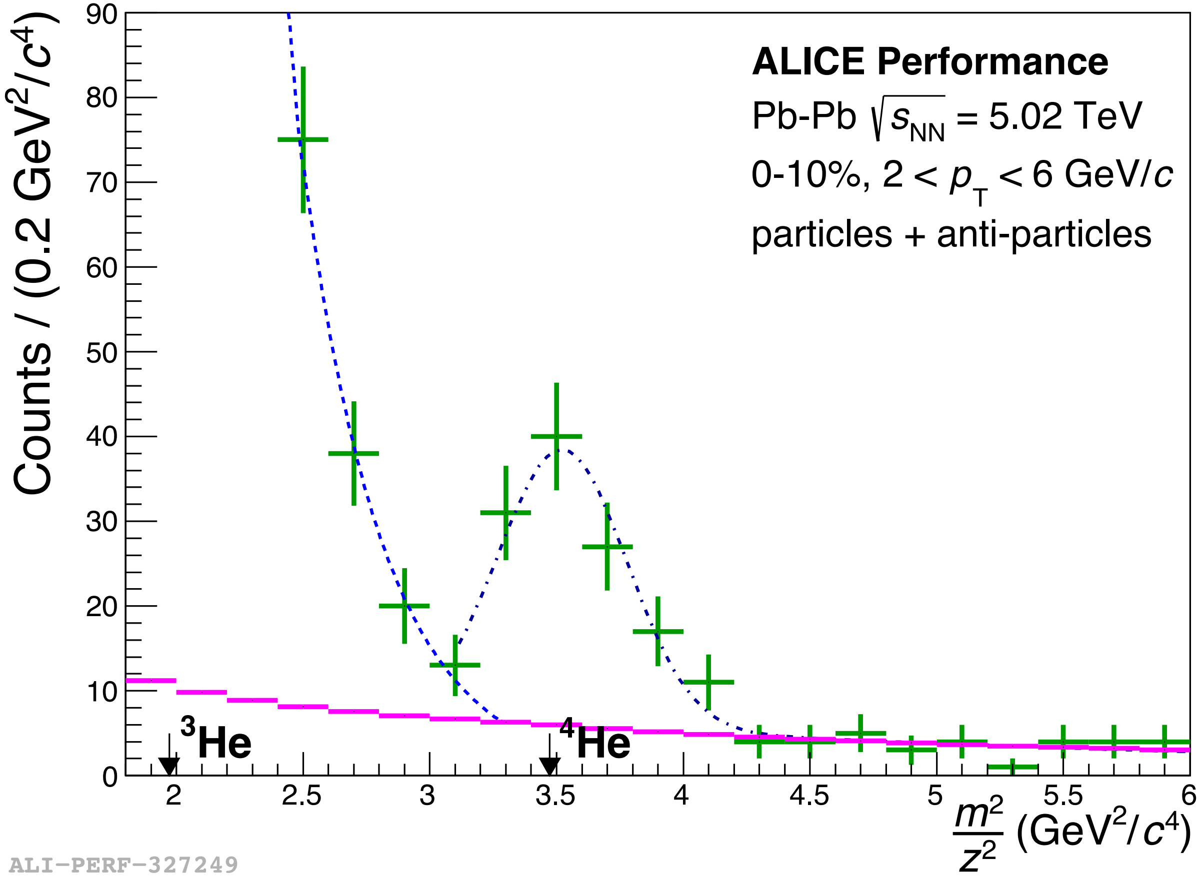
(Anti)^{3}He spectra

- $^3\overline{\text{He}}$ and ^{3}He measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}}$ = 5 TeV
- $^3\overline{\text{He}}$ and ^{3}He transverse momentum spectra measured in 3 centrality intervals
- Expected ordering of centralities
- Hardening of the spectra with increasing centrality
- Integrated production yield (dN/dy) extracted from Blast-Wave fits



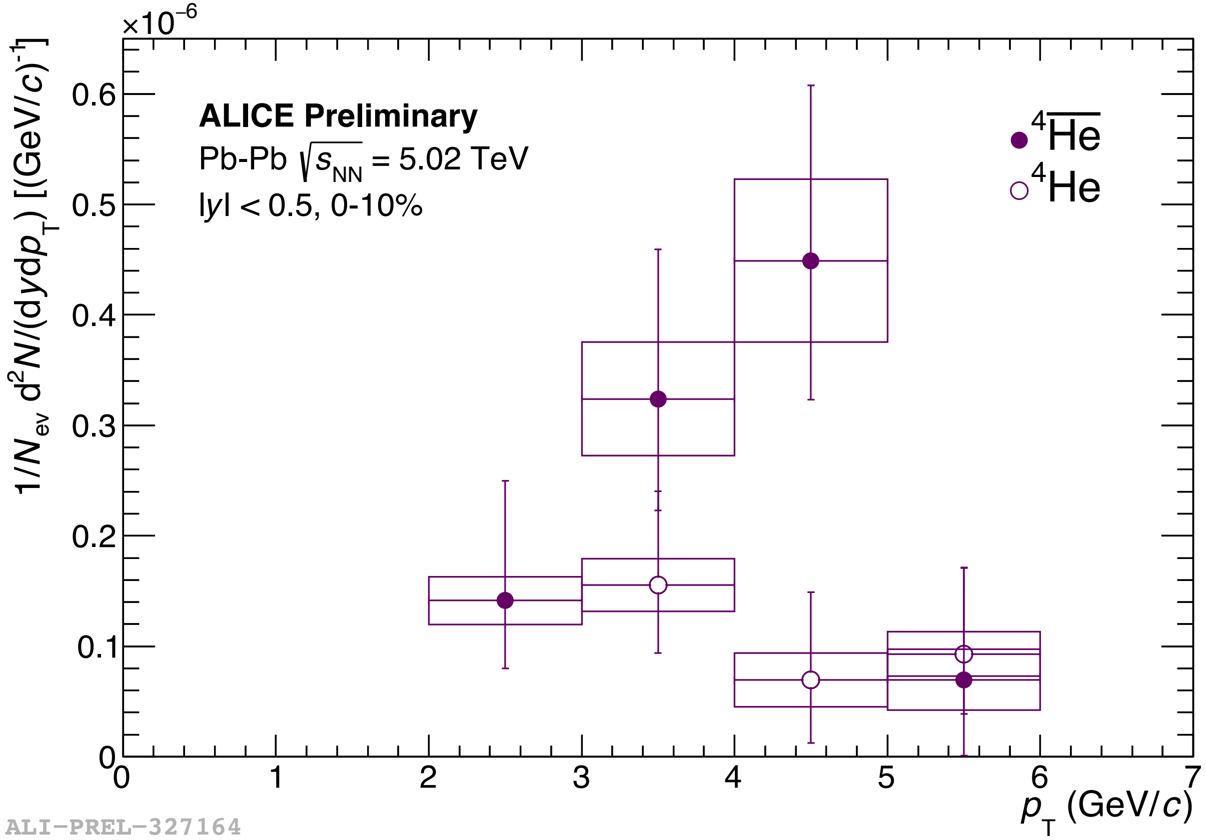
(Anti)^{4}He signal extraction

- $^4\overline{\mathrm{He}}$ and ^{4}He measured in the 0-10 % most central collisions
- ^{3}He and ^{4}He clearly separated in TOF mass (m^2/z^2 (^{4}He)= 3.475 GeV$^2/c^4$)
- Background from mismatches (magenta) and contribution from ^{3}He (dashed line) are subtracted from the ^{4}He yield



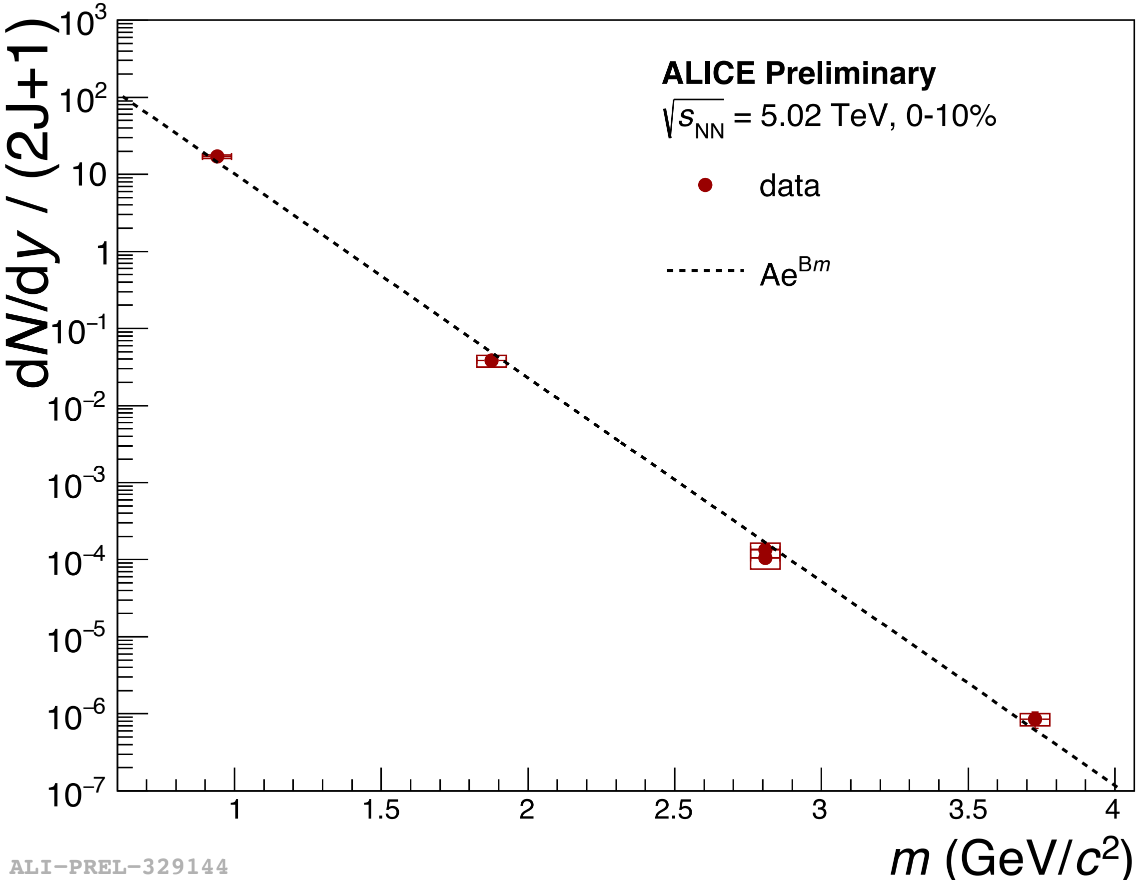
(Anti)^{4}He

- First $^4\overline{\text{He}}$ and ^{4}He transverse momentum spectra measured at the LHC
- Yield extracted in the 0-10 % most central collisions in 4 p_T bins from 2 to 6 GeV/c

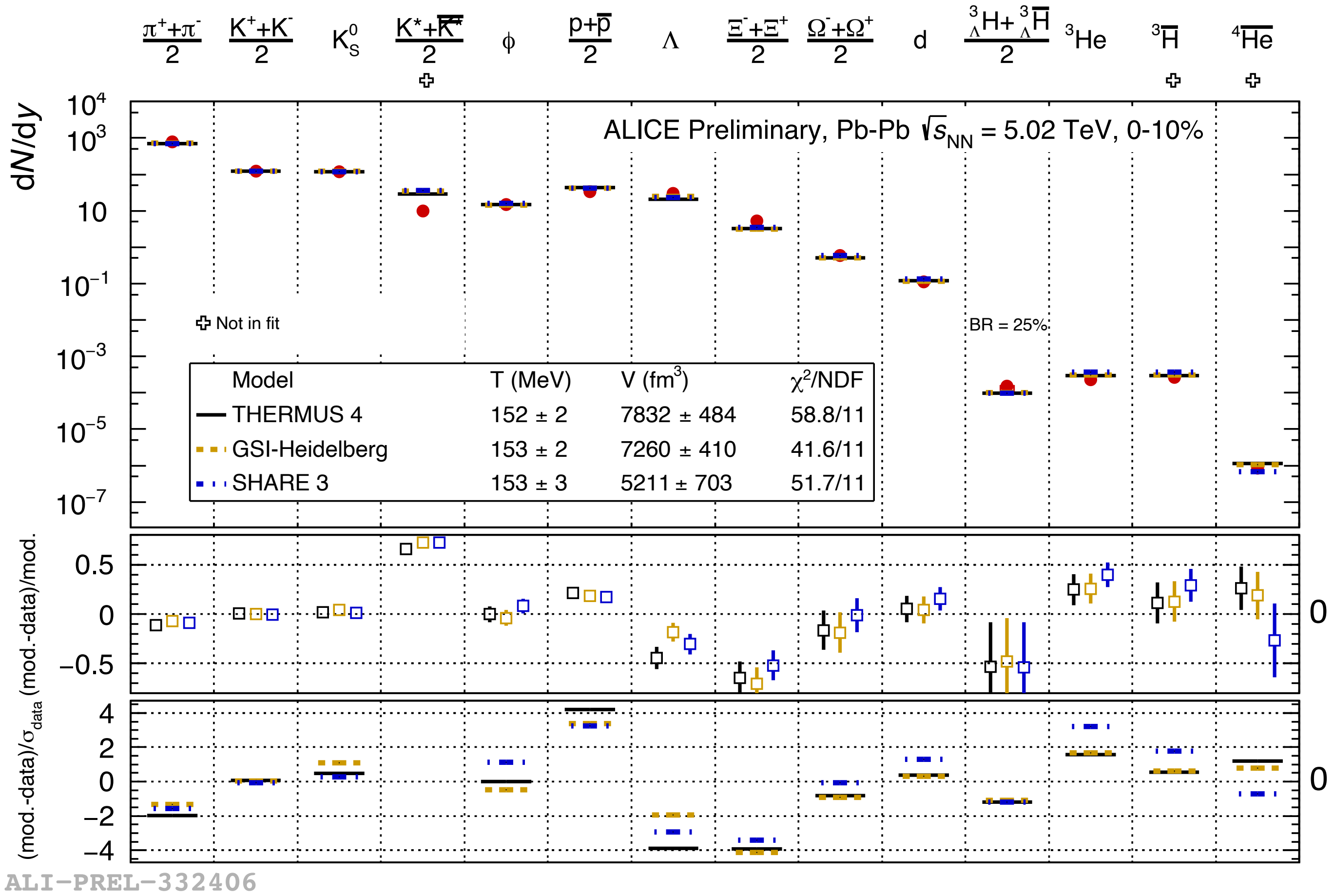


Mass ordering of the yield

- Exponential decrease of the yield of light nuclei with the mass visible
- In Pb–Pb collisions a penalty factor of about 300 for adding additional nucleons is observed



Thermal model fits

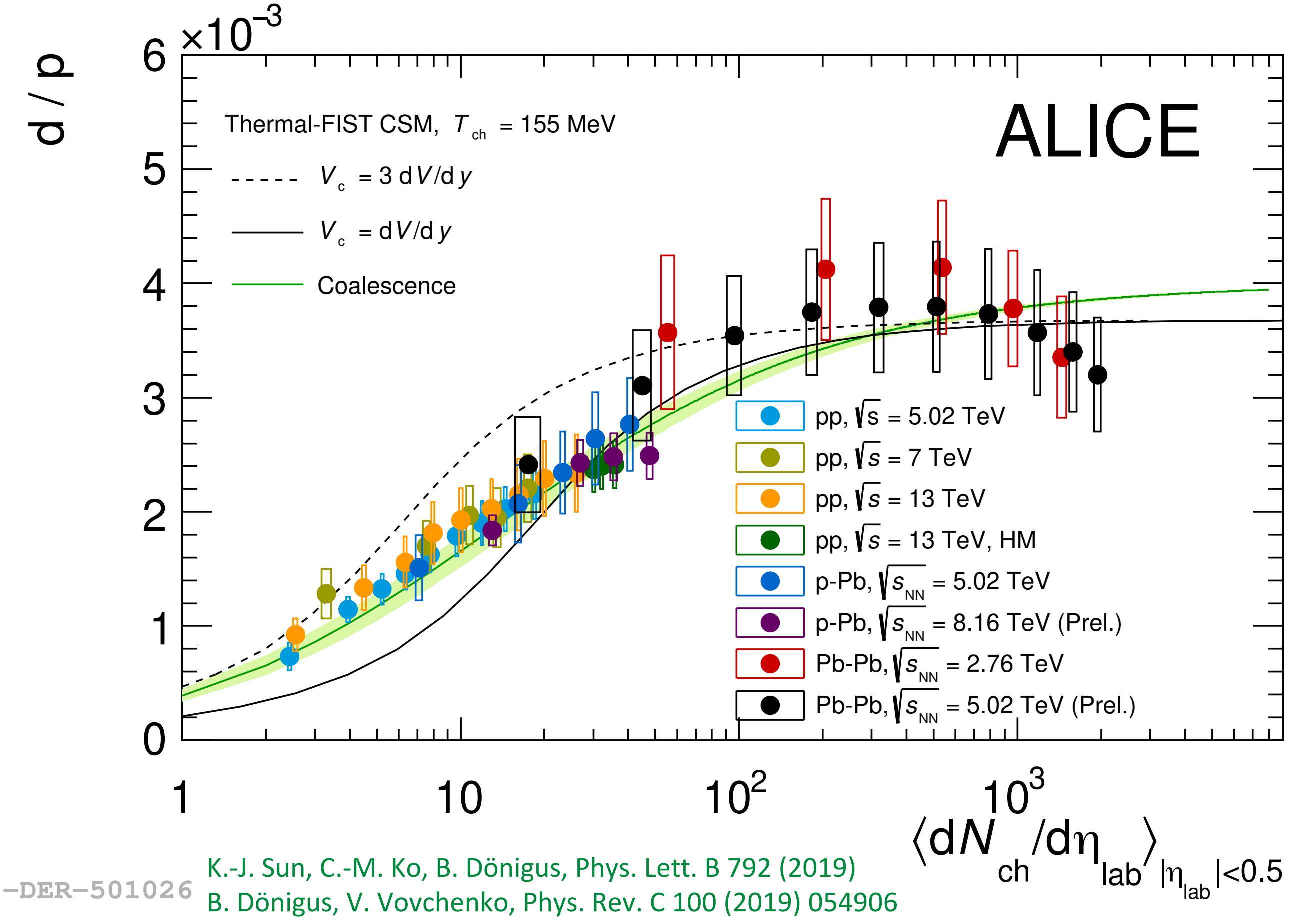


Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.8/11
GSI-Heidelberg	153 ± 2	7260 ± 410	41.6/11
SHARE 3	153 ± 3	5211 ± 703	51.7/11

- Different model variants describe particle yields including light (hyper-)nuclei well with T_{ch} of about 153 MeV

Deuteron over proton ratio versus multiplicity

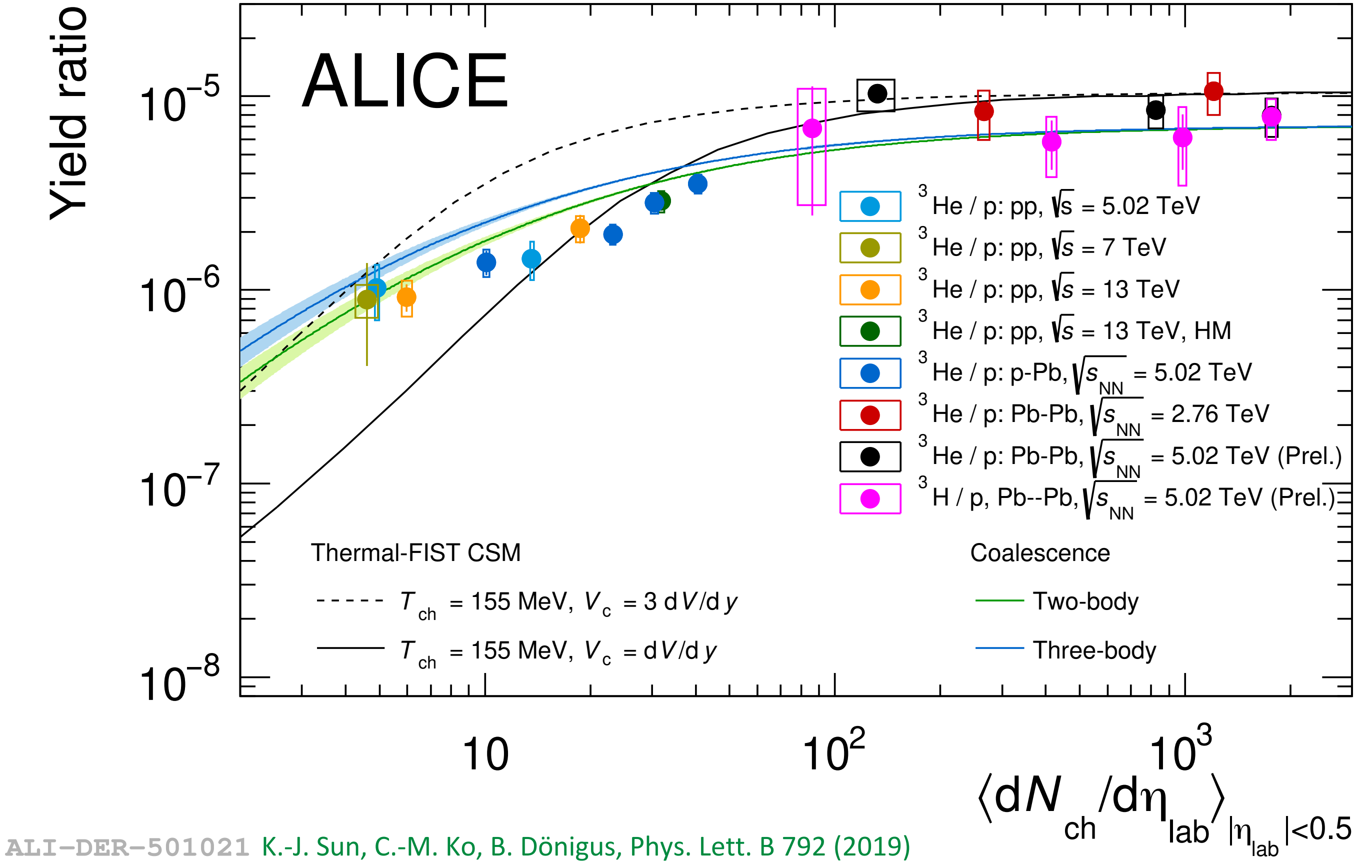
- Ratio of integrated yield of A=2 nuclei (deuterons) over integrated proton yield shows a clear trend as function of multiplicity measured in different collision systems
- Increasing trend from pp to p–Pb and saturation in Pb–Pb rather well described by SHM and coalescence models
- In small systems a canonical ensemble has to be applied (free parameters N, V, T_{ch})
  → Quantum numbers are conserved explicitly



K.-J. Sun, C.-M. Ko, B. Dönigus, Phys. Lett. B 792 (2019)
B. Dönigus, V. Vovchenko, Phys. Rev. C 100 (2019) 054906
Phys. Lett. B 785 (2018) 171

^{3}He and triton over proton versus multiplicity

- Ratio of integrated yield of A=3 nuclei over integrated proton yield shows a clear trend as function of multiplicity measured in different collision systems
- Increasing trend from pp to p–Pb and saturation in Pb–Pb
- Both models have problems in describing the shape at low and intermediate multiplicities



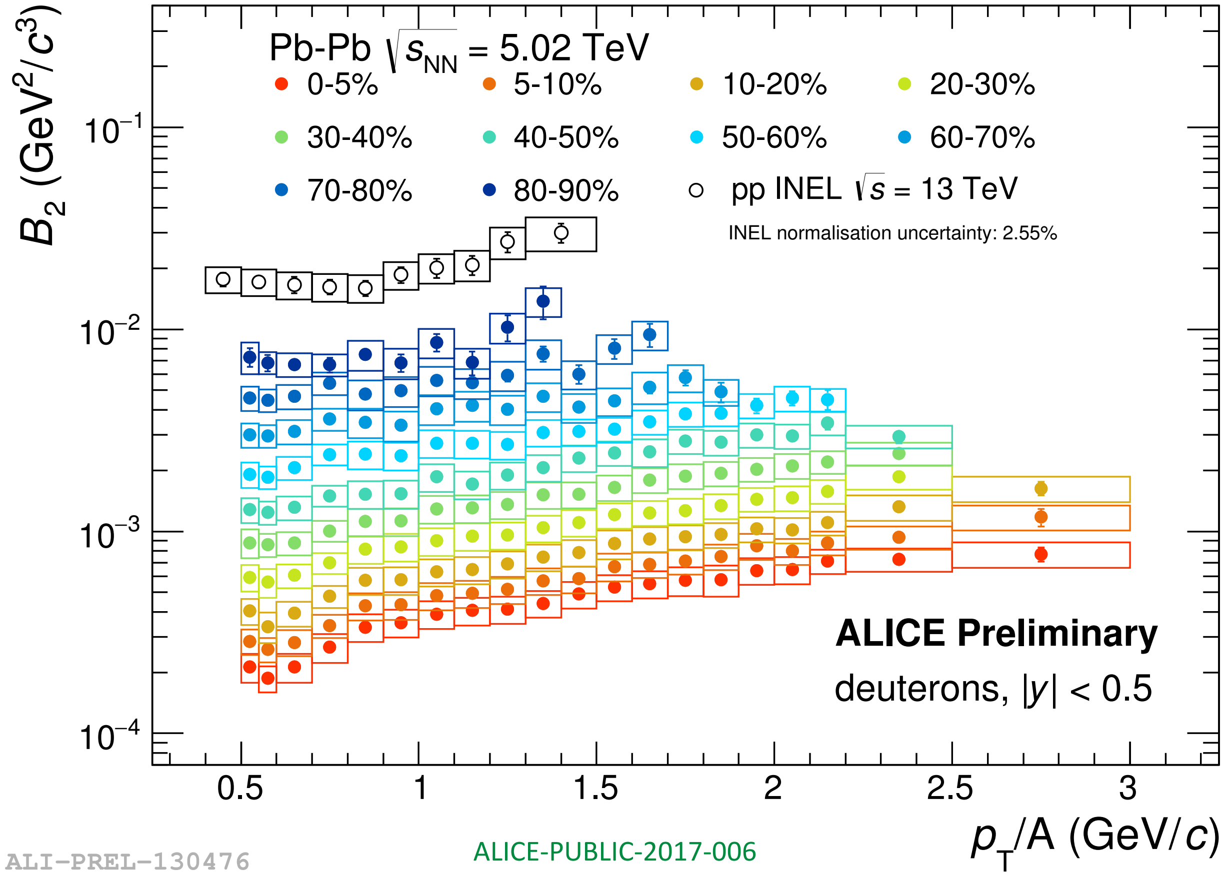
ALI-DER-501021 K.-J. Sun, C.-M. Ko, B. Dönigus, Phys. Lett. B 792 (2019)
B. Dönigus, V. Vovchenko, Phys. Rev. C 100 (2019) 054906
Phys. Lett. B 785 (2018) 171

The coalescence parameter B_2

- The probability to form a nucleus can be quantified by the coalescence parameter B_A

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

- According to simple coalescence predictions B_A is flat in p_T

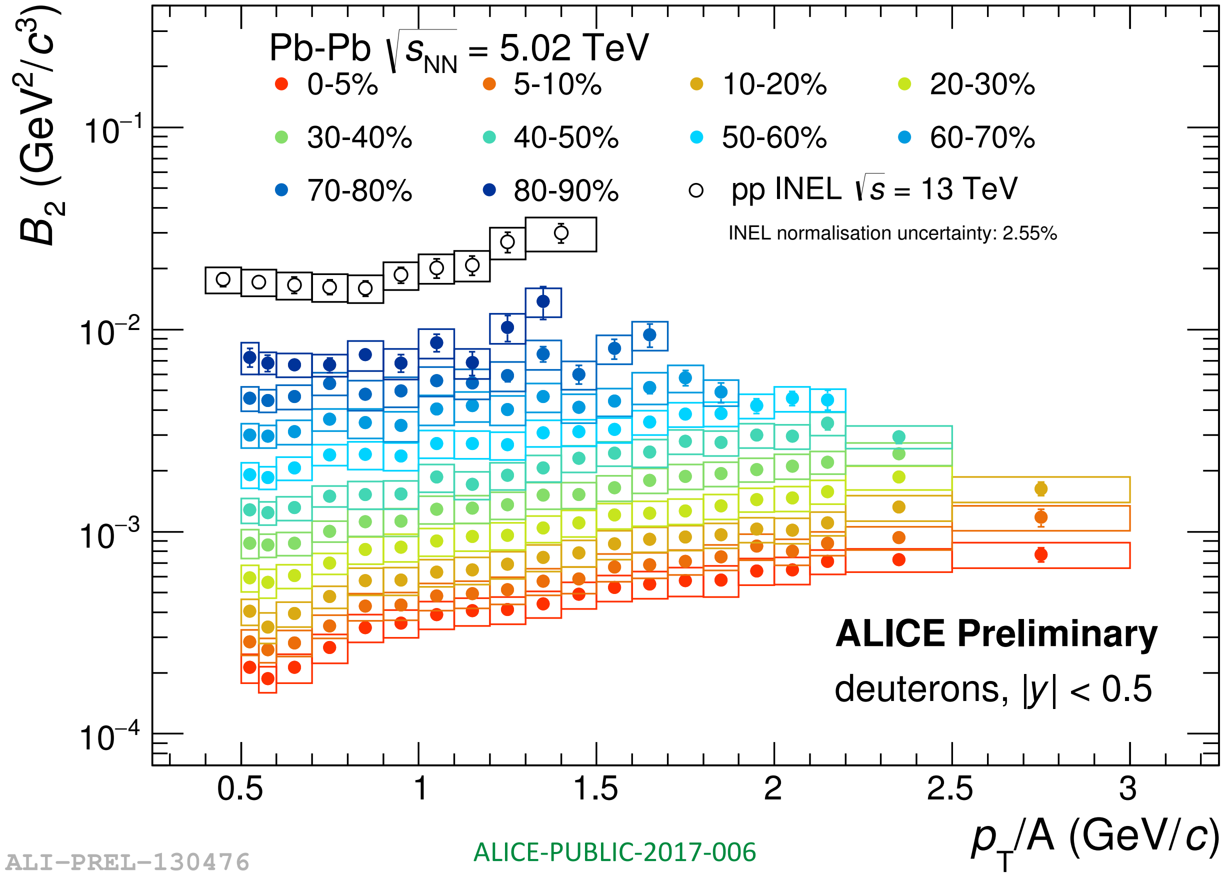


ALI-PREL-130476

ALICE-PUBLIC-2017-006

The coalescence parameter B_2

- In Pb–Pb collisions a rise of B_A with p_T is observed
- Can be explained by a smaller region of the source homogeneity that high p_T particle are originating from
- Moving from central to more peripheral collisions (i.e. towards lower multiplicities) the rise in p_T becomes milder



ALICE-PUBLIC-2017-006

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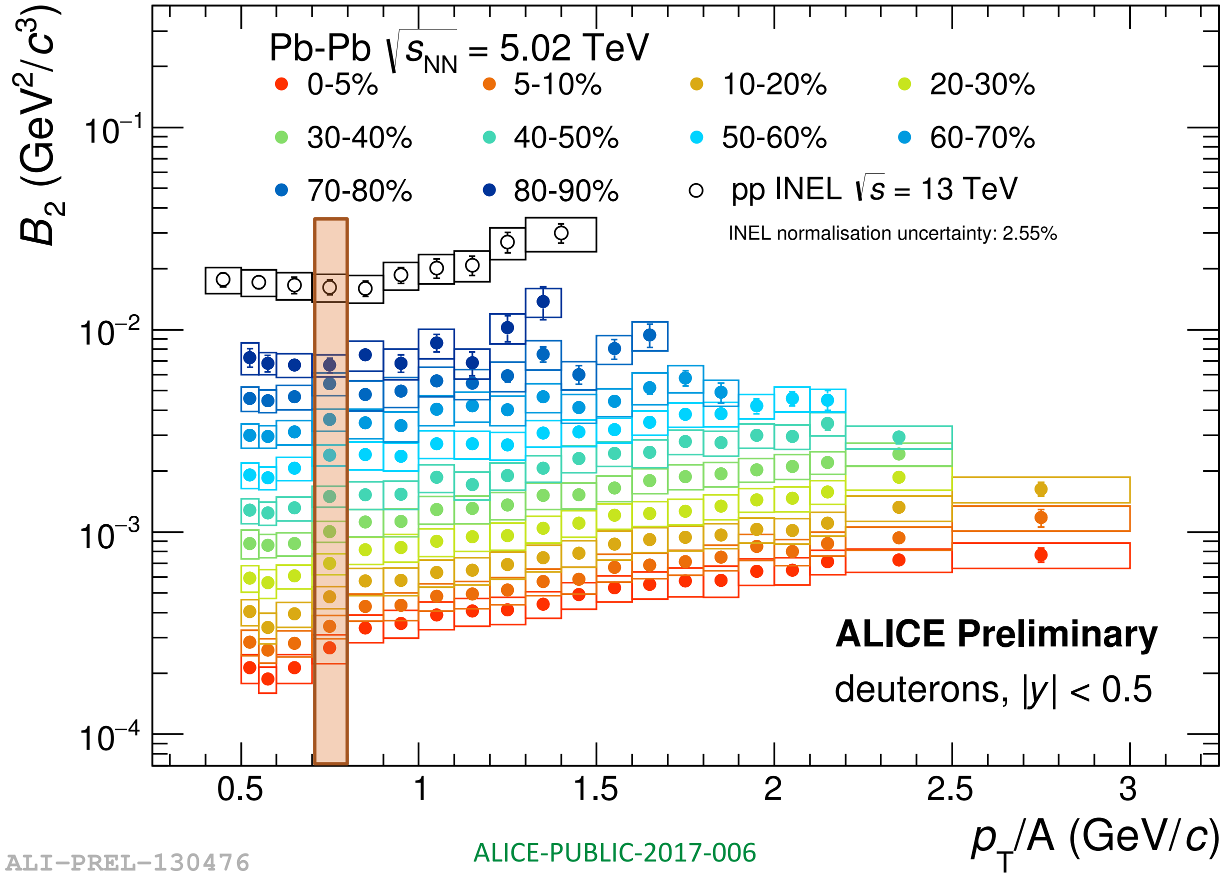
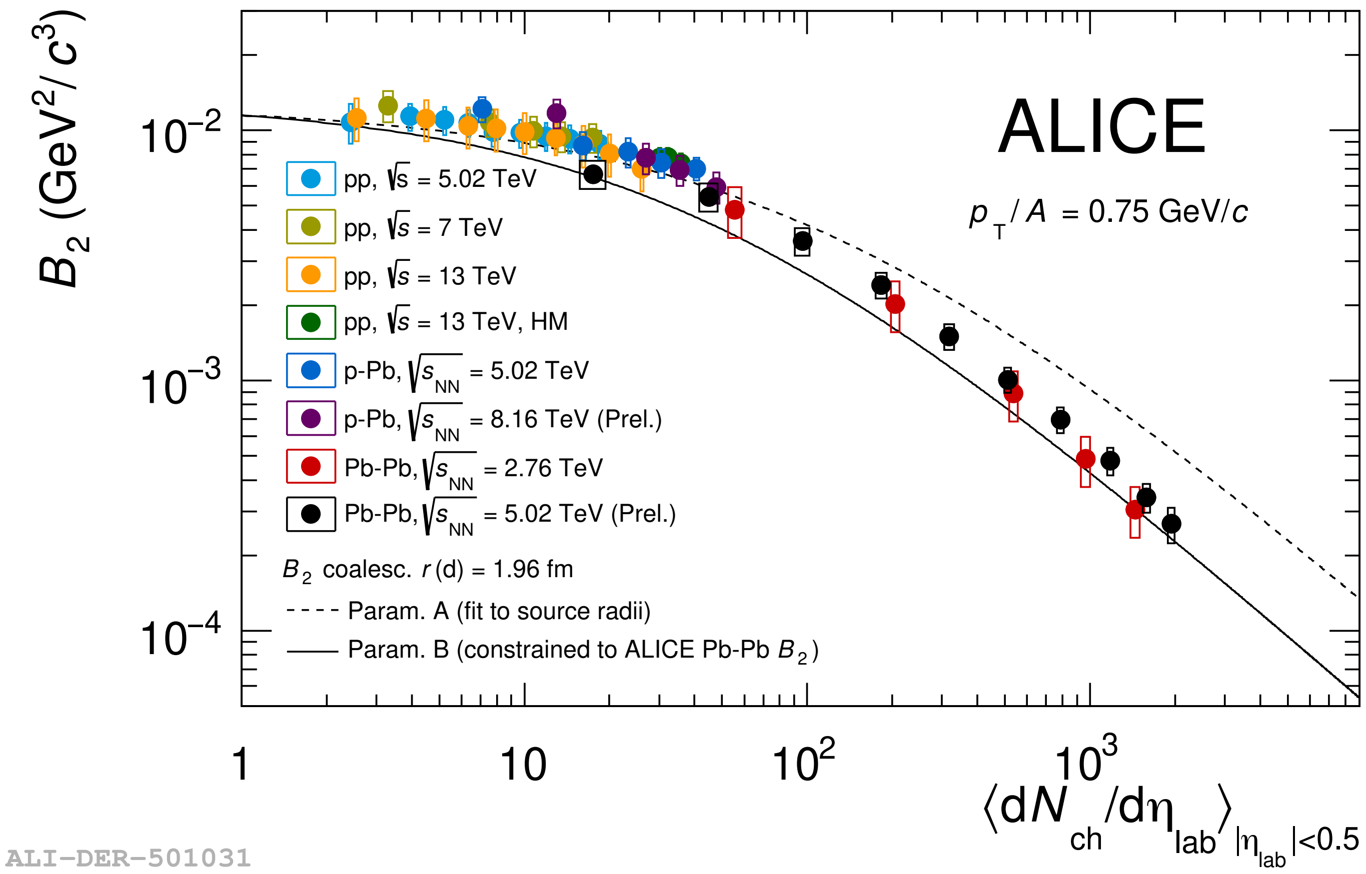


ALICE-PUBLIC-2017-006

Multiplicity dependence of B_2

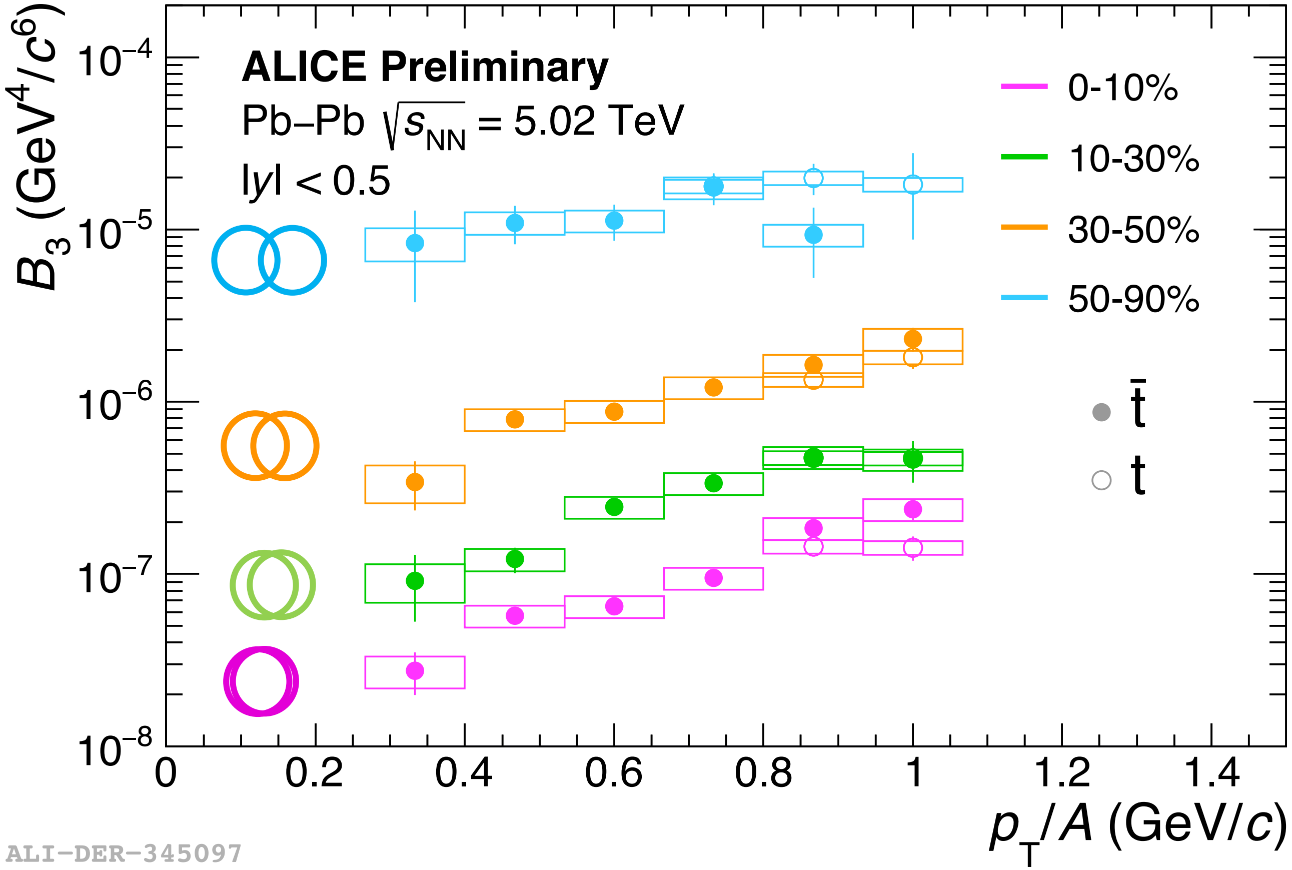
- B_2 shows an evolution with multiplicity, regardless of the collision system
  → Production mechanism depends only on the system size
- At lower multiplicities a flat behavior is observed
  → System size smaller than deuteron
- At higher multiplicities a decreasing trend is observed
  → System size larger than deuteron



ALI-DER-501031

The coalescence parameter B_3 of anti(t)

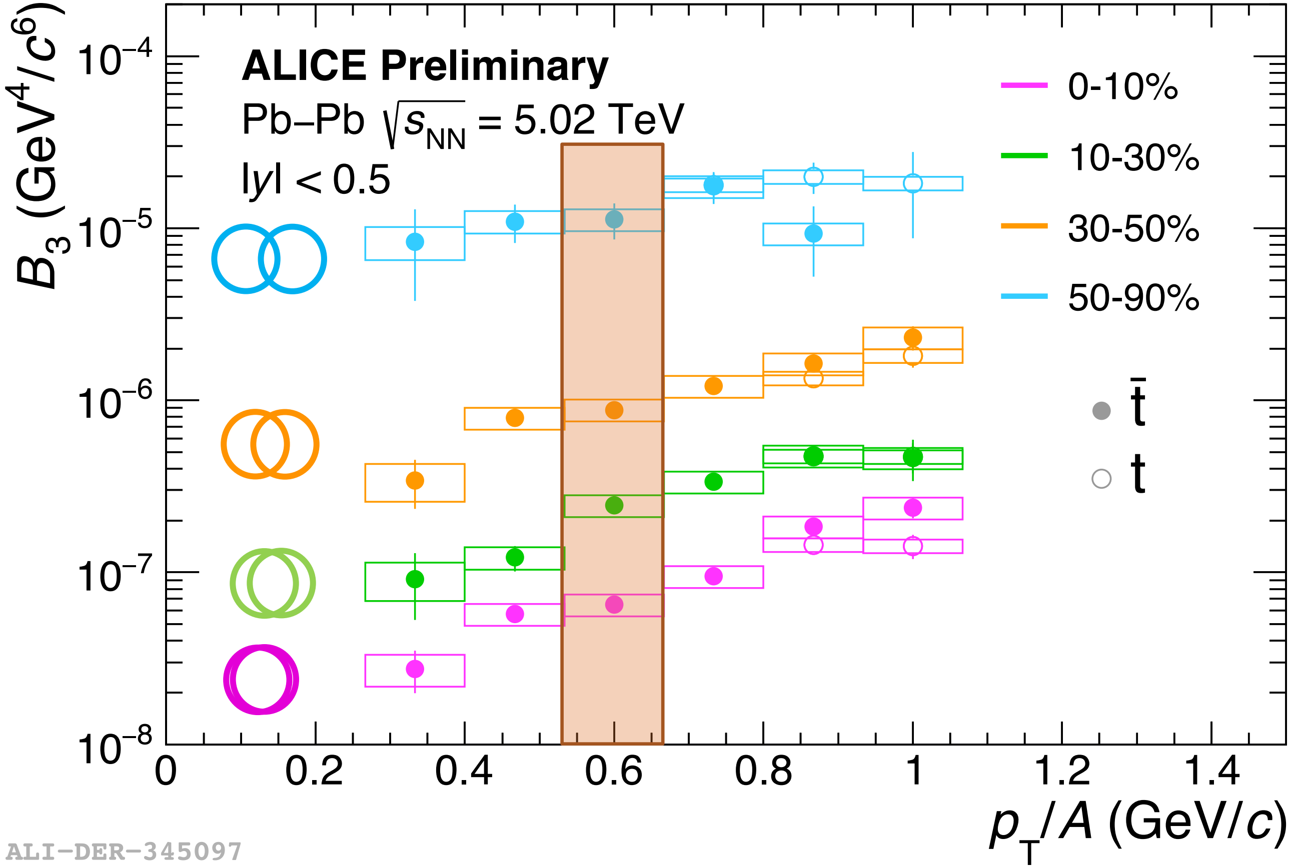
- In Pb–Pb collisions rise in p_T is observed
- B_3 is larger for peripheral collisions where the system size and thus the configuration space is smaller



ALI-DER-345097

The coalescence parameter B_3 of anti(t)

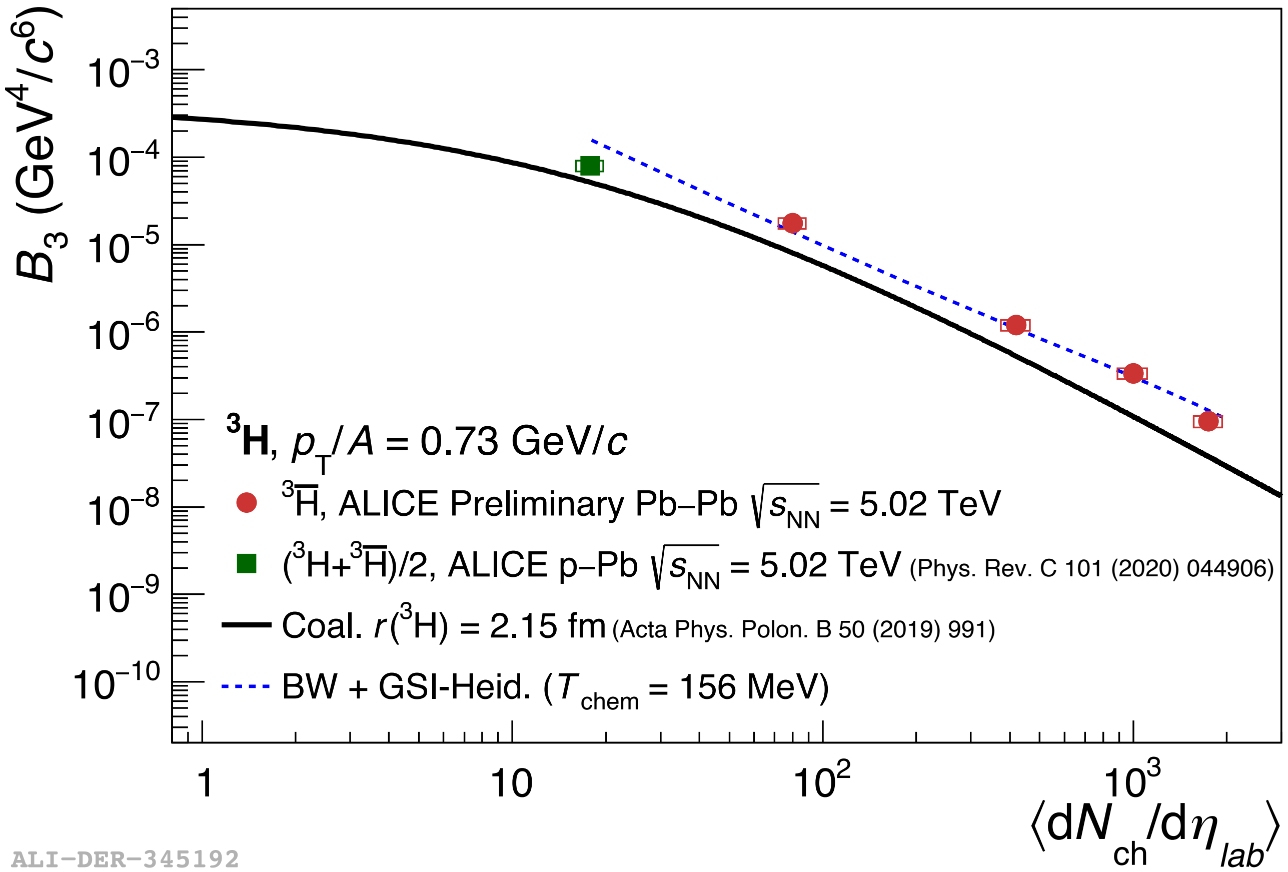
- In Pb–Pb collisions rise in p_T is observed
- B_3 is larger for peripheral collisions where the system size and thus the configuration space is smaller
- B_3 can also be plotted versus multiplicity for certain p_T/A
  → Dependence of coalescence production on the system size



ALI-DER-345097

Multiplicity dependence of B_3 of (anti)t

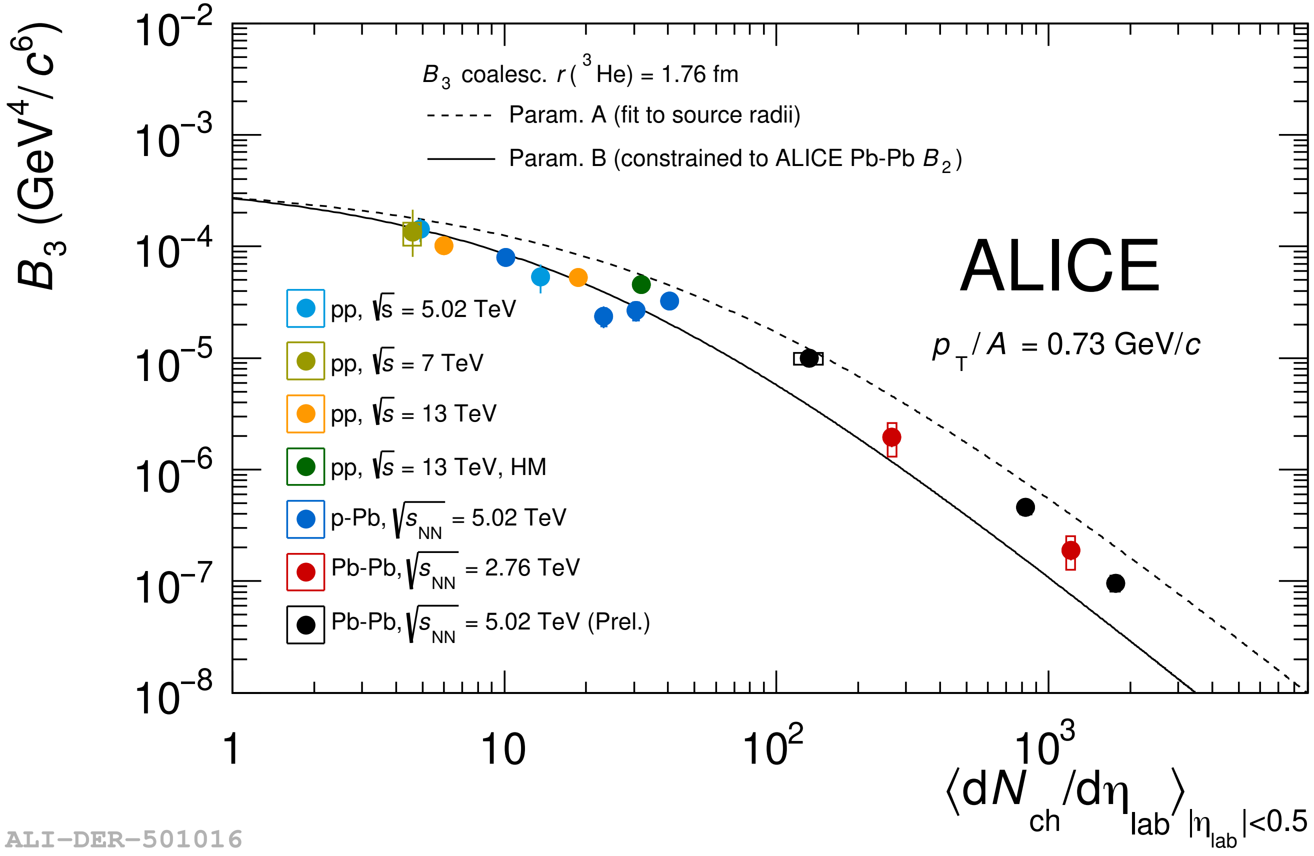
- B_3 versus multiplicity shown at $p_T/A = 0.73$ GeV/c
- B_3 shows an evolution with multiplicity
  → Production mechanism depends on the system size
- Comparison to coalescence and statistical hadronization + Blast-Wave models
  → Trend described by both models, data a bit closer to stat. hadronization model



ALI-DER-345192

Multiplicity dependence of B_3 of (anti)^{3}He

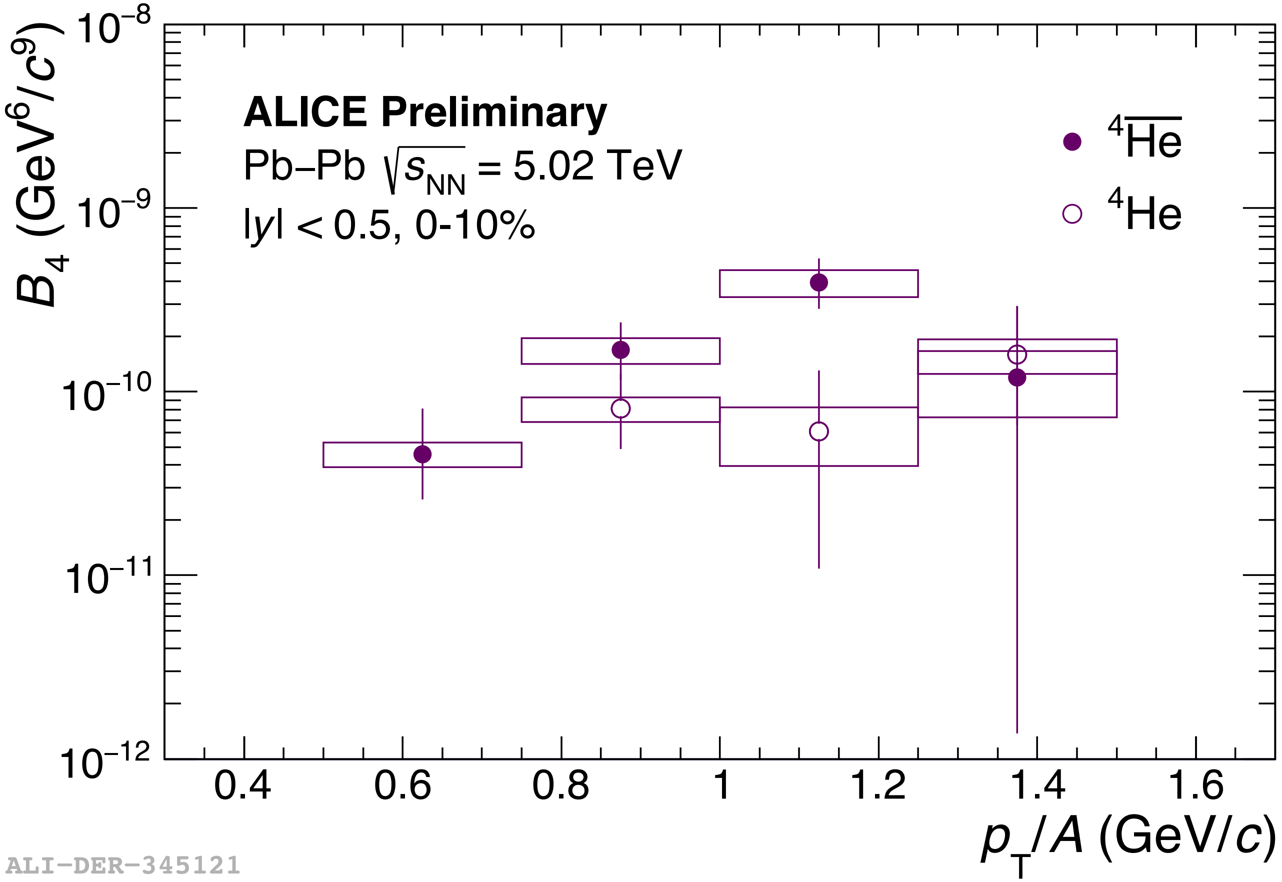
- B_3 shows an evolution with multiplicity, regardless of the collision system
  → Production mechanism depends only on the system size
- At lower multiplicities a flat behavior is observed
  → System size smaller than nucleus
- At higher multiplicities a decreasing trend is observed
  → System size larger than nucleus



ALI-DER-501016

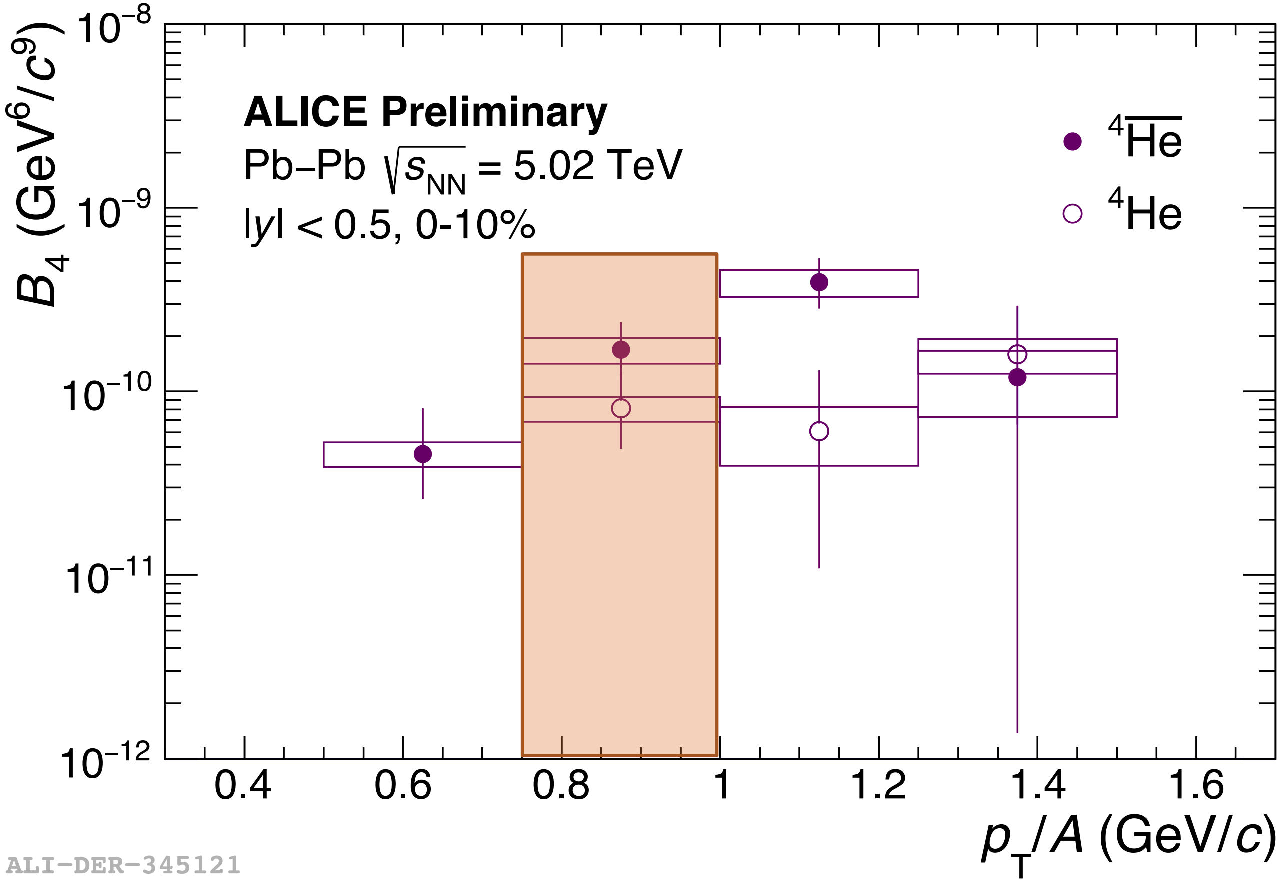
The coalescence parameter B_4 of anti(^{4}He)

- Also B_4 shows a rise in p_T
- About 3 orders of magnitude smaller than B_3 due to one additional nucleon



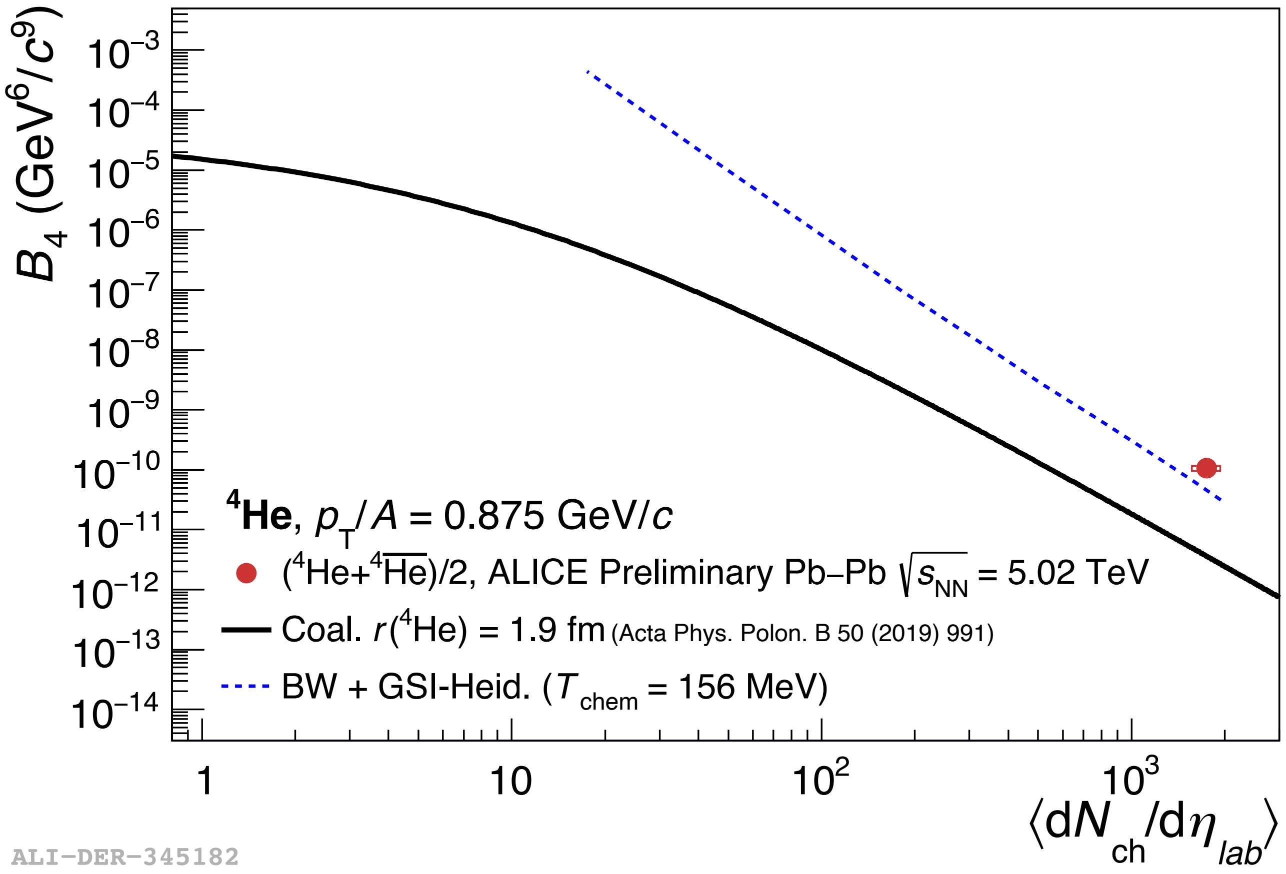
The coalescence parameter B_4 of anti(^{4}He)

- Also B_4 shows a rise in p_T
- About 3 orders of magnitude smaller than B_3 due to one additional nucleon
- B_4 can also be compared to models for certain p_T/A



B_4 of (anti)^{4}He compared to models

- Averaged B_4 of ^{4}He and $^4\overline{\text{He}}$ shown at p_T/A = 0.875 GeV/c
- Comparison to coalescence and statistical hadronization + Blast-Wave models
  → Data closer to statistical hadronization model

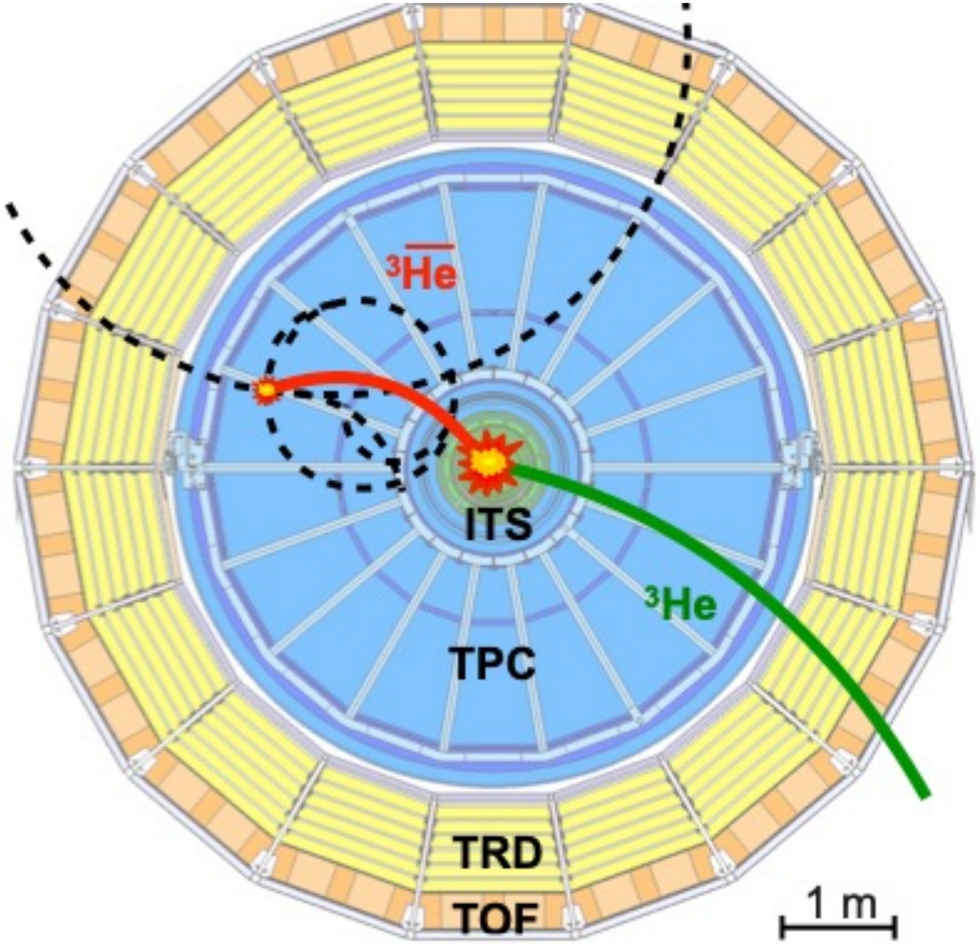


Measurement of $\overline{\mathrm{d}}$ and $^{3}\overline{\mathrm{He}}$ σ_{inel}

- No previous measurement is available
  → Creating $\overline{\mathrm{d}}$/$^{3}\overline{\mathrm{He}}$ beam impossible

- Idea:
  → Use LHC as an antimatter factory
  → Use ALICE detector material as target

- Average mass ⟨A⟩ and charge ⟨Z⟩ number of ALICE is determined by weighting the contribution of different materials with their density times the length crossed by particles



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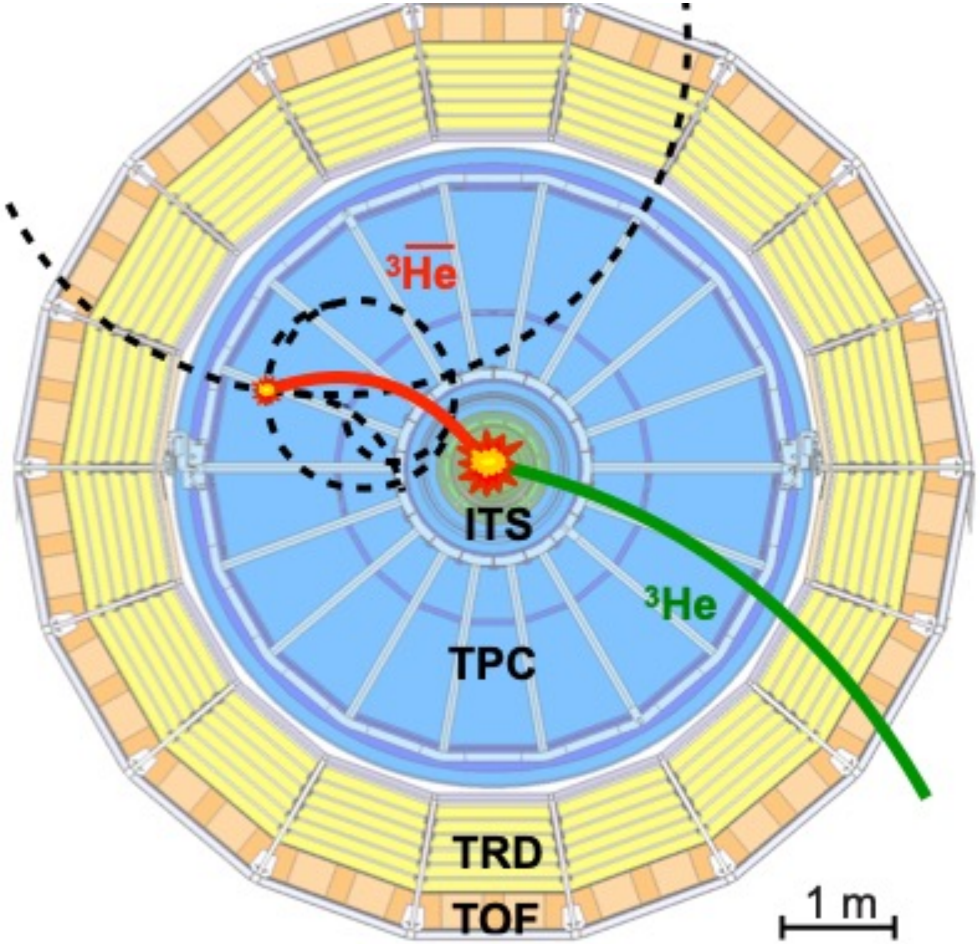
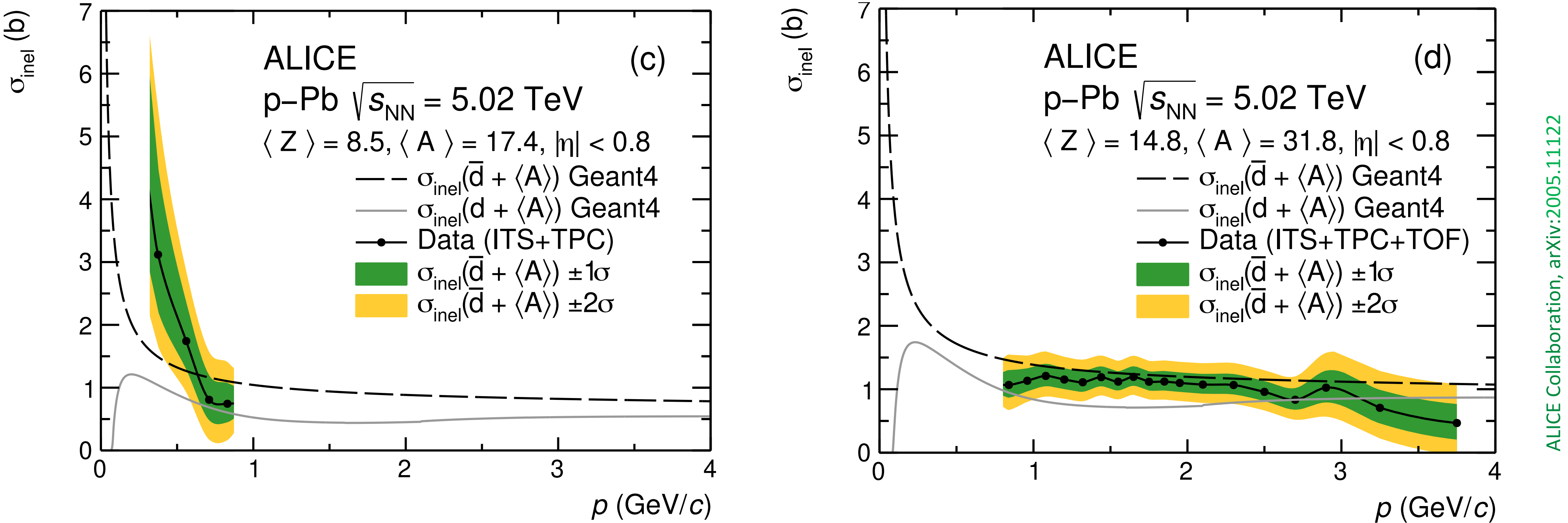
- No previous measurement is available
  → Creating $\bar{\mathrm{d}}/^{3}\overline{\mathrm{He}}$ beam impossible

- Idea:
  → Use LHC as an antimatter factory
  → Use ALICE detector material as target

- Two alternative methods employed
  → Comparison of $\bar{\mathrm{d}}$ ($^{3}\overline{\mathrm{He}}$) to d (^{3}He) yields → applied in p–Pb (pp) dataset at 5 TeV (13 TeV)
  → Comparison of $^{3}\overline{\mathrm{He}}$ reaching TOF to all reconstracted $^{3}\overline{\mathrm{He}}$→ applied in Pb–Pb at 5 TeV



Measured $\sigma_{\text{inel}}(\bar{\text{d}})$ in p–Pb collisions



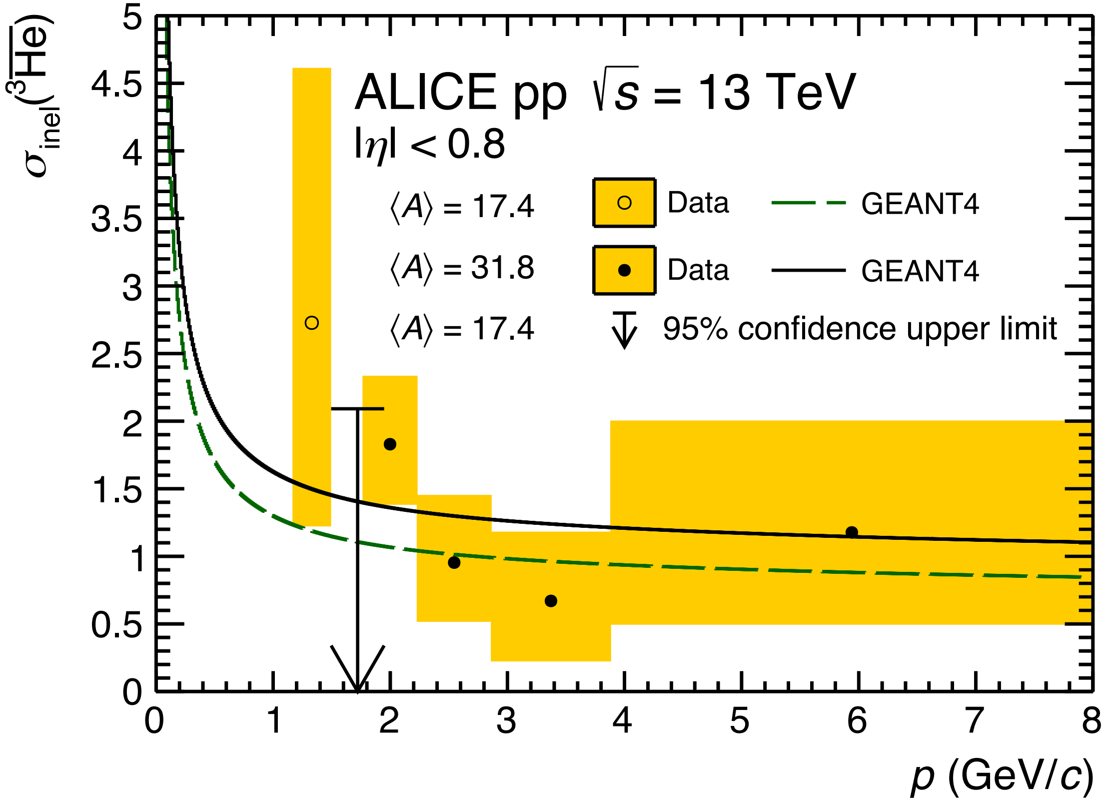
ALI-PUB-490977

ALI-PUB-490982

- Absorption cross section of $\bar{\text{d}}$ versus momentum for ⟨A⟩ = 17.4 (ITS+TPC system) at low momenta and ⟨A⟩ = 31.8 (ITS+TPC+TOF system) at higher momenta
- In agreement with the cross section used in GEANT4 within 2 σ (except first point)

Measured $\sigma_{\mathrm{inel}}(^3\overline{\mathrm{He}})$ in pp collisions

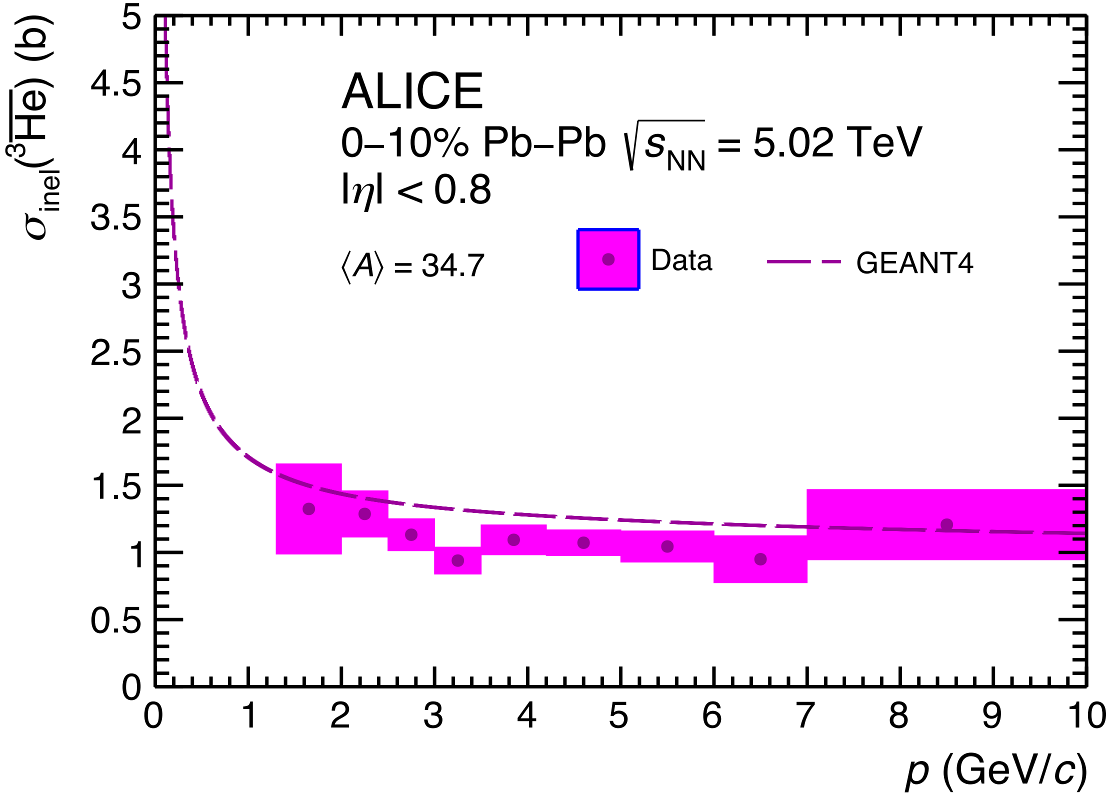
- Absorption cross section of $^3\overline{\mathrm{He}}$ versus momentum for ⟨A⟩ = 17.4 (ITS+TPC system) at low momenta and ⟨A⟩ = 31.8 (ITS+TPC+TRD system) at higher momenta
- In agreement with the cross section used in GEANT4 for both values of ⟨A⟩ within 2 σ in the studied momentum range



ALICE Collaboration, arXiv:2202.01549

Measured $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ in Pb–Pb collisons

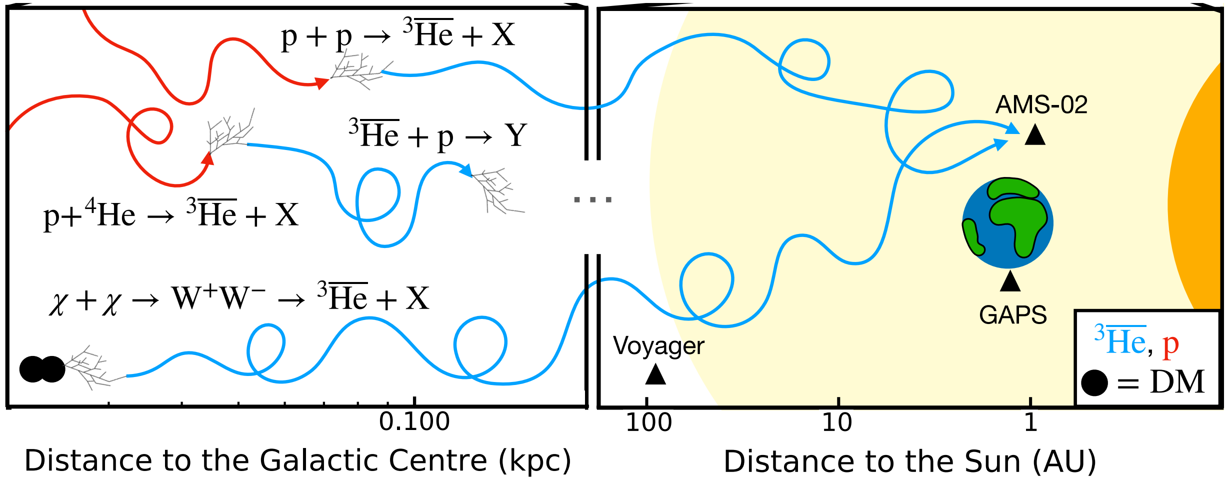
- Absorption cross section of $^{3}\overline{\mathrm{He}}$ versus momentum for ⟨A⟩ = 34.7 (TRD system)
- In agreement with the cross section used in GEANT4 within 2 σ in the studied momentum range
- In all measurements, GEANT4 describes the momentum dependence well, the scale can be calibrated using the data
- $^{3}\overline{\mathrm{He}}$ is promising source to discover dark matter particles



ALICE Collaboration, arXiv:2202.01549

$^{3}\overline{\text{He}}$ propagating through space

- Measured $^{3}\overline{\text{He}}$ cross section can be used to determine $^{3}\overline{\text{He}}$ flux near earth
- Two possible $^{3}\overline{\text{He}}$ sources considered:
  - → Dark matter (WIMP) annihilation
    - → Distribution peaks at low $^{3}\overline{\text{He}}$ energies
  - → Cosmic ray interactions
    - → Distribution peaks at higher $^{3}\overline{\text{He}}$ energies

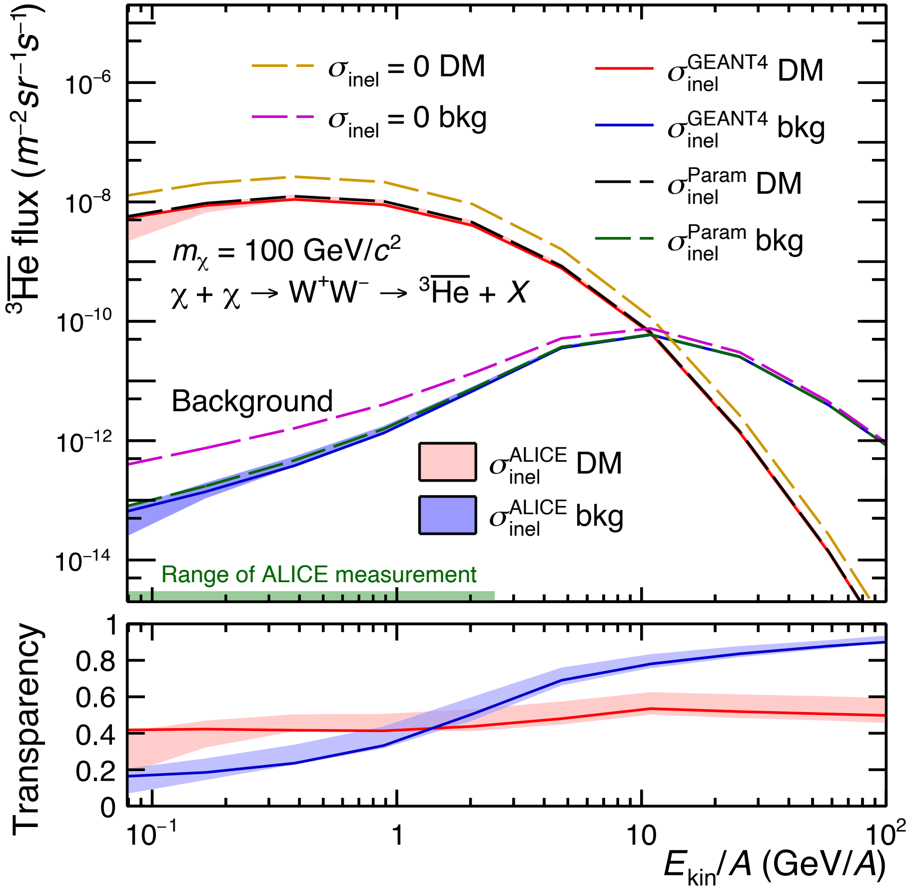


ALICE Collaboration, arXiv:2202.01549

- GALPROP code used to describe propagation of $^{3}\overline{\text{He}}$ through galaxy, includes source function, diffusion, convection, fragmentation, decays, inelastic interactions, …
- Measured ALICE absorption cross section implemented in GALPROP

$^{3}\overline{\text{He}}$ flux near earth

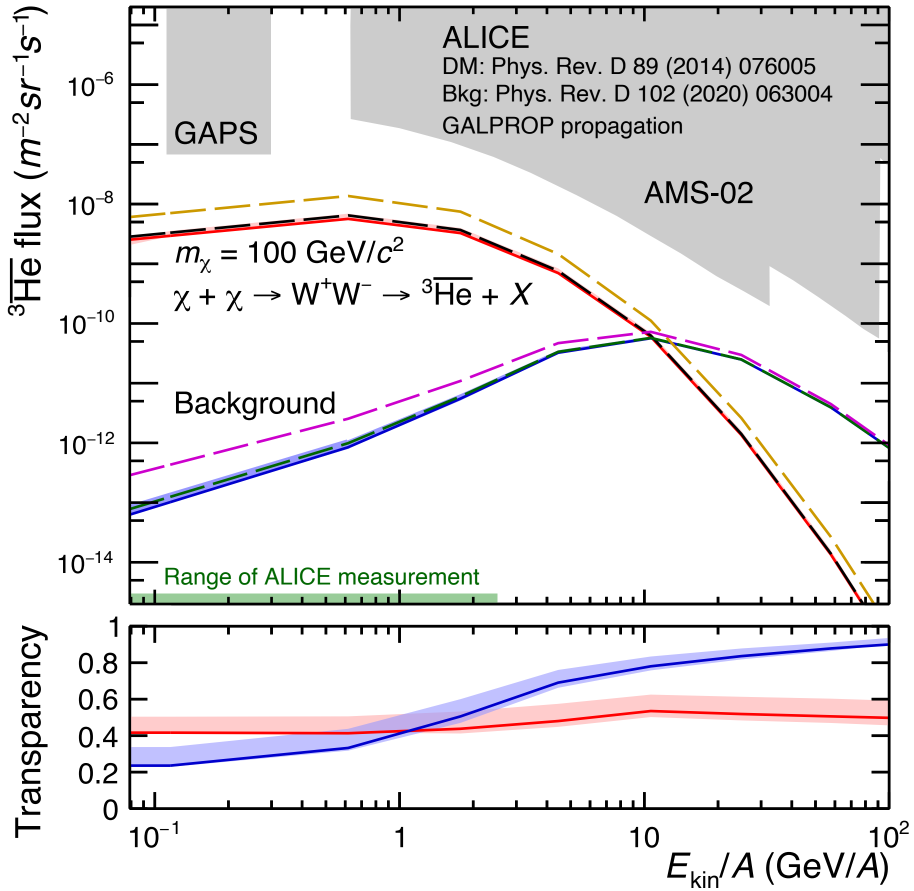
- $^{3}\overline{\text{He}}$ flux near earth coming from dark matter and cosmic rays (bkg) shown for various cases of inelastic cross section
- Low energy region almost free of background for dark matter searches
- Lower panel shows transparency of the galaxy (ratio of the flux with and without inelastic processes in GALPROP)



ALICE Collaboration, arXiv:2202.01549

$^{3}\overline{\text{He}}$ flux near earth with solar modulation

- Inside the solar system solar magnetic field taken into account (employing Force Field approximation)
  - → Several species of cosmic rays used and tuned to match measurements of protons and light nuclei outside and within the solar system
- High-momentum particles are shifted to lower energies by solar modulation
- Gray areas show expected sensitivity of the GAPS and AMS-02 experiments



ALICE Collaboration, arXiv:2202.01549

Summary

- Light nuclei production in Pb–Pb collisions has been presented
- Production yields in Pb–Pb collisions are well described by thermal models
- Coalescence parameters B_2, B_3, B_4 and particle yield ratios show common trend with multiplicity, well described by statistical and coalescence models
- First measurement of $\overline{\mathrm{d}}$ and $^3\overline{\mathrm{He}}$ inelastic cross section has been presented, in agreement within 2 σ with the one implemented in GEANT4

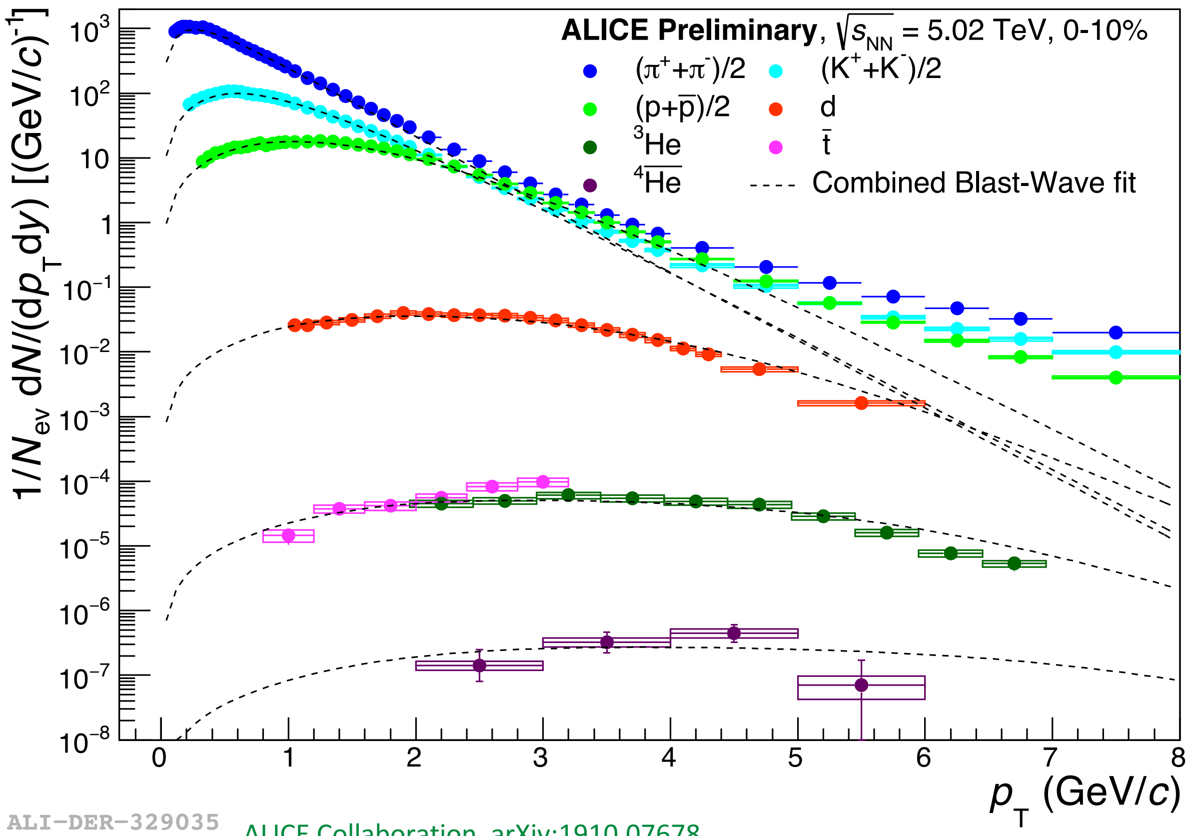
  → Used to determine $^3\overline{\mathrm{He}}$ flux from dark matter particles near earth

Backup

Combined Blast-Wave fits

- Simultaneous Blast-Wave fit of $\pi^{\pm}$, $K^{\pm}$, p, d, $\bar{t}$, ^{3}He and $^{4}\overline{\text{He}}$ spectra in central Pb-Pb collisions describes all particles quite well

- Spectra show clear radial flow
  → common flow velocity ⟨β⟩ and kinetic freeze-out temperature T_{kin}



ALI-DER-329035

ALICE Collaboration, arXiv:1910.07678