Probes of hadronization (resonances, (hyper)nuclei, charm baryons, coalescence)

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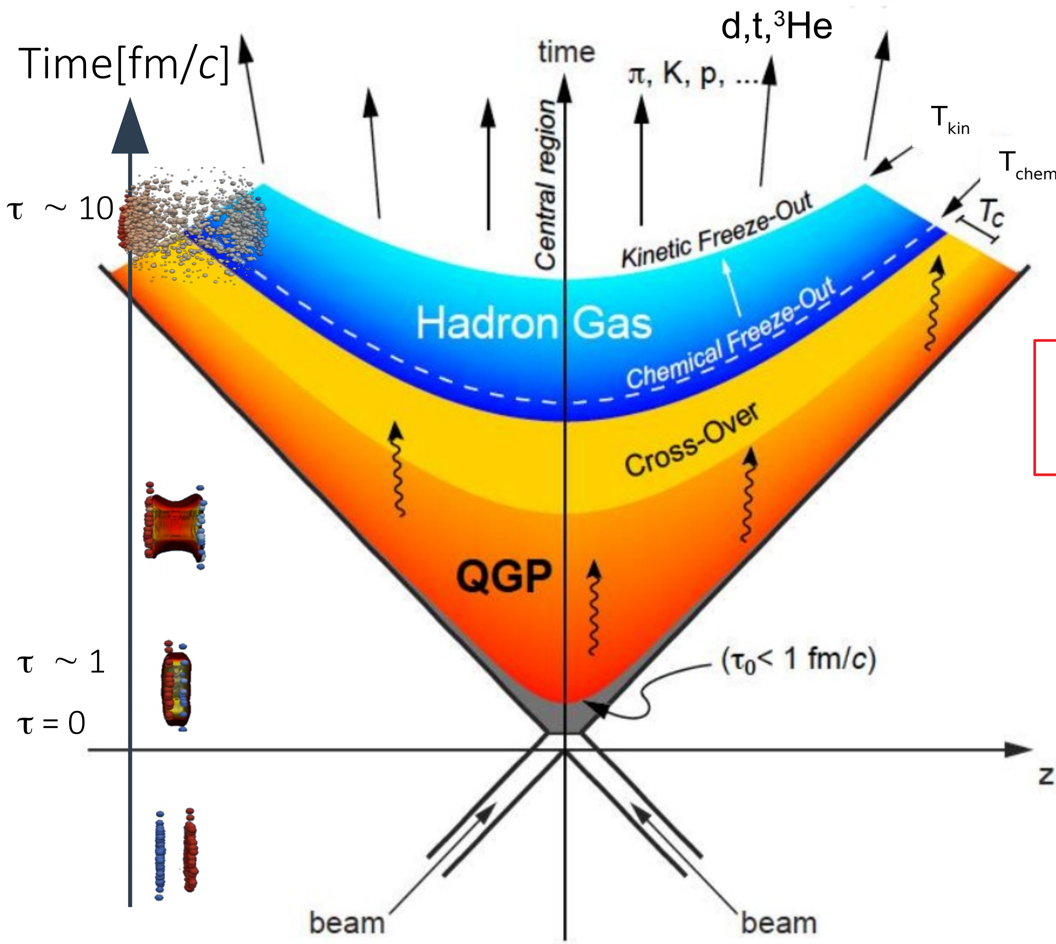
Physics Department, University and INFN Trieste

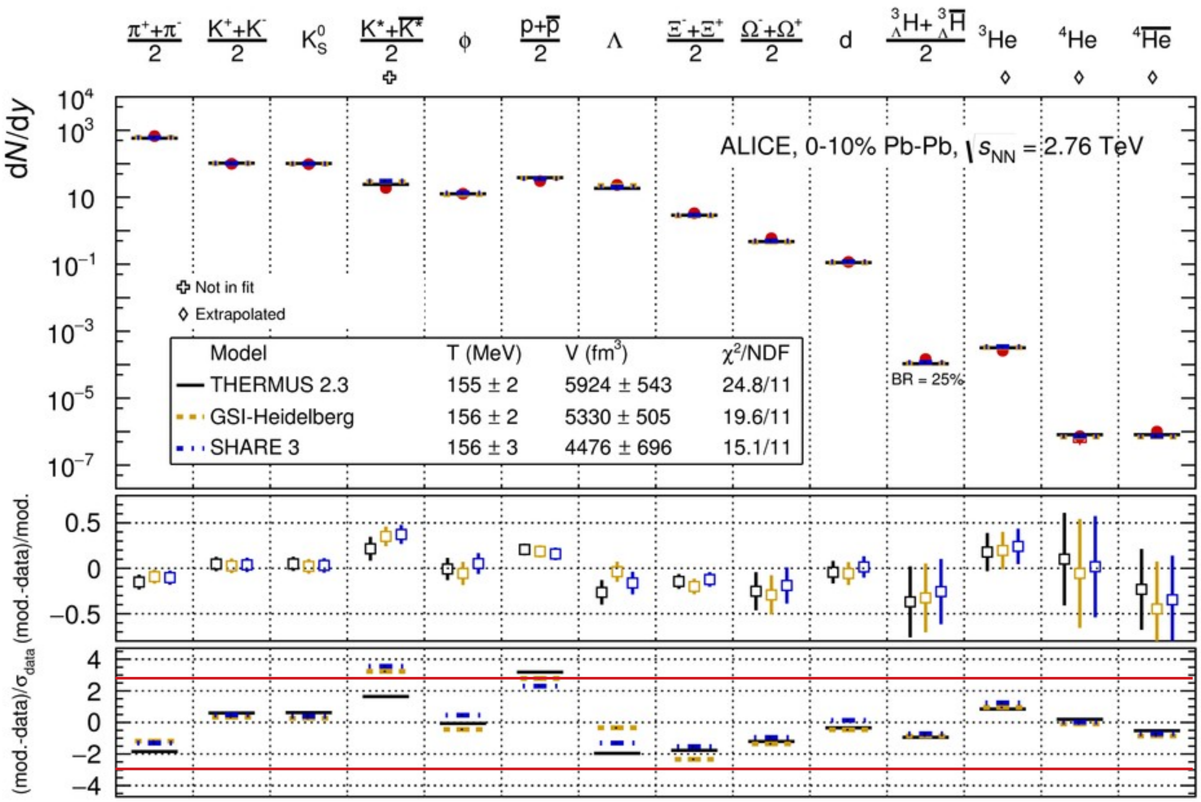
7th Edition of the Large Hadron Collider Physics Conference

Evolution of a heavy ion collision



- Two Lorentz contracted nuclei approach and collide
- "Pre-equilibrium"
- Formation of Quark-Gluon Plasma phase (if $T > T_c$)
- Phase transition from QGP to hadron gas ($T_C \approx 160$ MeV)
- Chemical freeze-out (T_{chem}~156 MeV):
  - inelastic reactions cease: the chemical composition of the system is fixed (particle yields and fluctuations)
- Kinetic freeze-out (T_{kin} ~ 100 MeV)
  - elastic reactions cease: spectra and correlations are frozen (free streaming of hadrons)

Thermal model fit to LHC data



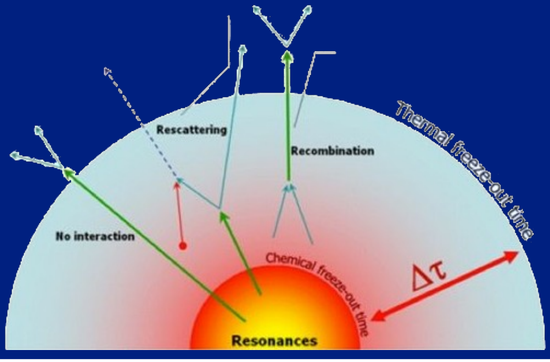
THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

K* not included in the fit

- Hadron abundances in HI (yields and ratios) can be successfully interpreted in terms of production at chemical equilibrium
- Statistical (thermal) models predict the yields of any particle at chemical freeze-out once that T_{ch} and μ_B are known
- At the LHC (μ_B = 0) particle yields of light flavor hadrons (including nuclei) are described within the thermal model with a common chemical freeze-out temperature (T_{chem} = 156 ± 2 MeV)

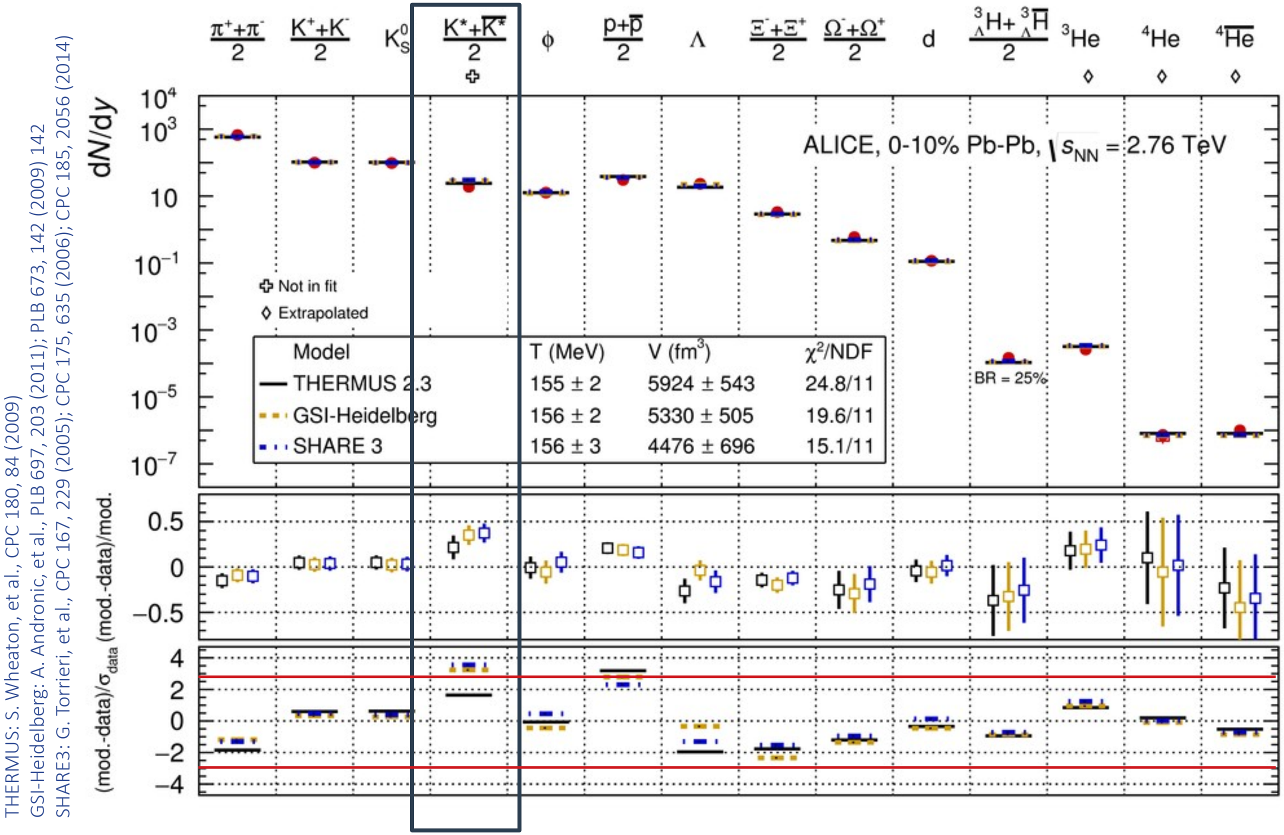
ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

Resonances



Rescattering
Recombination
Thermal freeze-out time
No interaction
Chemical freeze-out time
Δτ
Resonances

Thermal model fit to ALICE data



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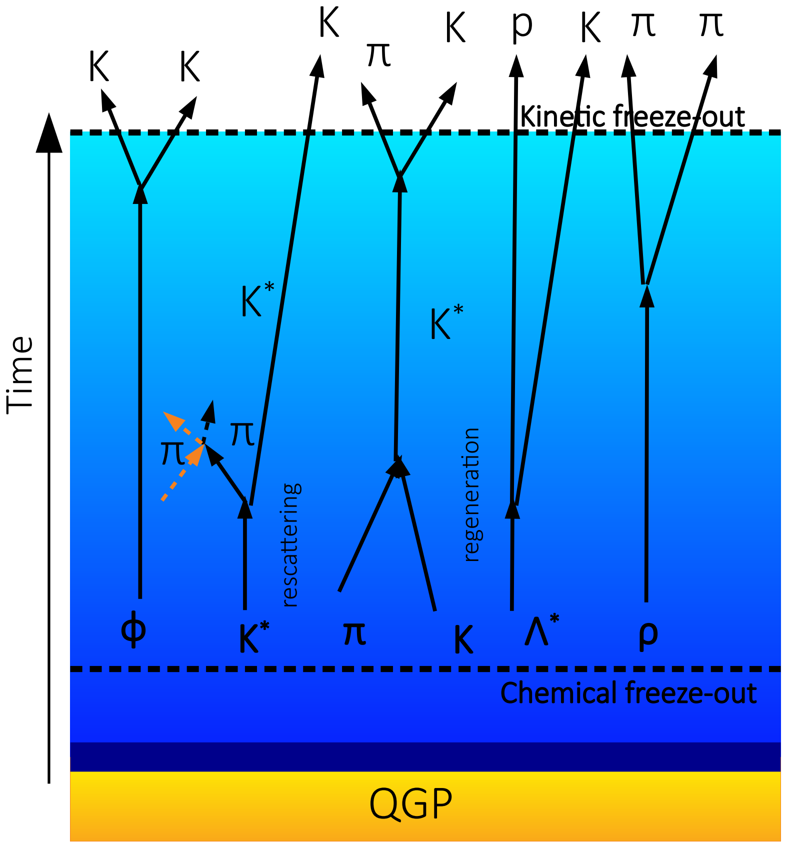
- Statistical (thermal) models predict the yields of any particle at chemical freeze-out once that T_{ch} and μ_B are known
- At the LHC ($\mu_B = 0$) particle yields of light flavor hadrons (including nuclei) are described within the thermal model with a common chemical freeze-out temperature ($T_{chem} = 156 \pm 2$ MeV)
- K*(892) production not described (yield suppressed)

ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

Hadronic phase



- The yield of resonances produced in heavy ion collisions is expected to be in agreement with T_{ch} chemical freeze-out equilibrium
- Although, can be altered by hadronic interactions between chemical and kinetic freezeouts:
  - **rescattering**: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal
  - **regeneration**: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$, etc.) → increased yields

- Effect of hadronic processes depends on:
  - lifetime and density of <u>hadronic phase</u>
  - <u>resonance</u> lifetime and scattering cross sections

Light flavoured hadronic resonances

	$\rho(770)^0$	$K^*(892)^0$	$\Lambda(1520)$	$\phi(1020)$
cτ(fm/c)	1.3	4.2	12.6	46.2
	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	uds	$s\bar{s}$

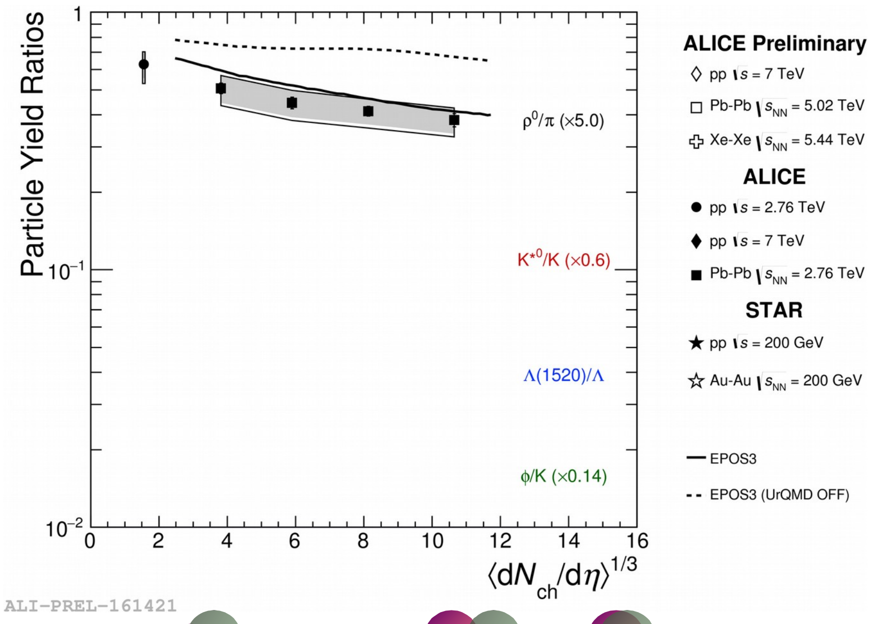
- Resonances have lifetimes comparable to that of the fireball produced in heavy-ion collisions:
  - can be used to study **properties** and **lifetime** of the late **hadronic phase**
- Resonances differ by mass and quark content:
  - **insights** on the multiplicity-dependent **enhancement** of **strangeness** production
  - **anomalous** baryon-to-meson **ratios** at **intermediate transverse momentum** parton energy loss

Suppression of hadronic resonances

ALICE Collaboration, arXiv:1805.04365

	ρ(770)⁰	K*(892)⁰	Λ(1520)	ϕ(1020)
cτ(fm/c)	1.3	4.2	12.6	46.2

- $\rho(770)^0/\pi^\pm$
  - The ratio of p_T integrated yields divided by particle with similar quark content ρ/π shows clear suppression going from pp and peripheral Pb-Pb collisions to central Pb-Pb

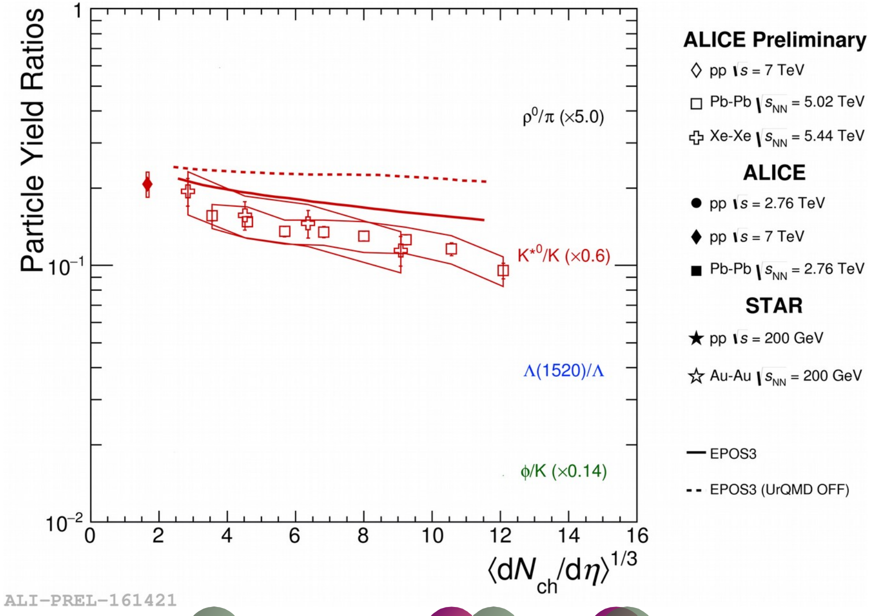


Suppression of hadronic resonances

ALICE Collaboration,
Phys. Rev. C 91 (2015) 024609

	$\rho(770)^0$	$K^*(892)^0$	$\Lambda(1520)$	$\phi(1020)$
$c\tau$(fm/c)	1.3	4.2	12.6	46.2

- $K^*(892)^0/K^\pm$
  - $K^*(892)/K$ ratio decreases as function of multiplicity
  - Suggests that re-scattering is dominant over regeneration



Suppression of hadronic resonances

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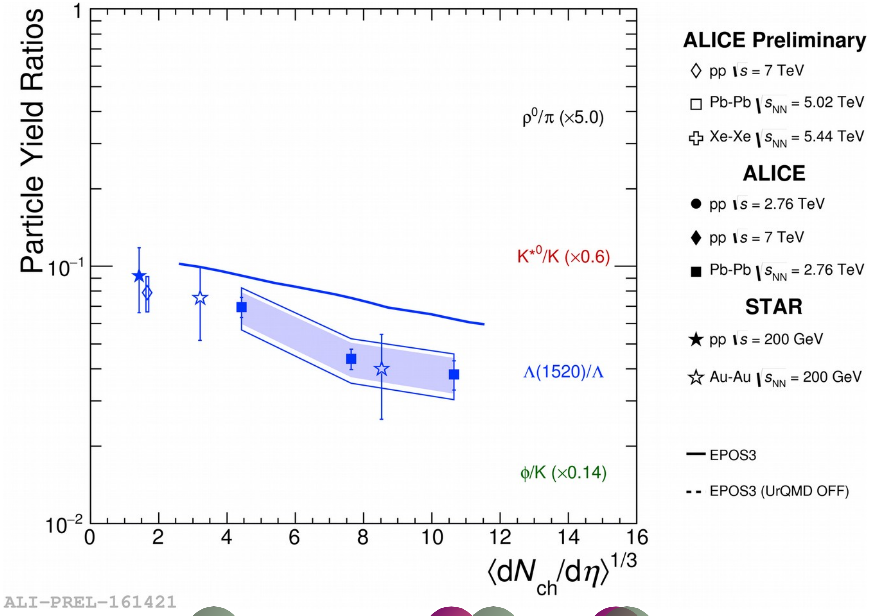
ALICE Collaboration, Phys.Rev. C99 (2019) 024905

STAR Collaboration, Phys.Rev.C78 (2008) 044906
STAR Collaboration, Phys. Rev. Lett. 97 (2006) 132301

- Λ(1520)/Λ
  - Λ(1520)/Λ ratio clearly decreases as function of multiplicity in Pb-Pb
  - Clear suppression compared to the thermal model predictions



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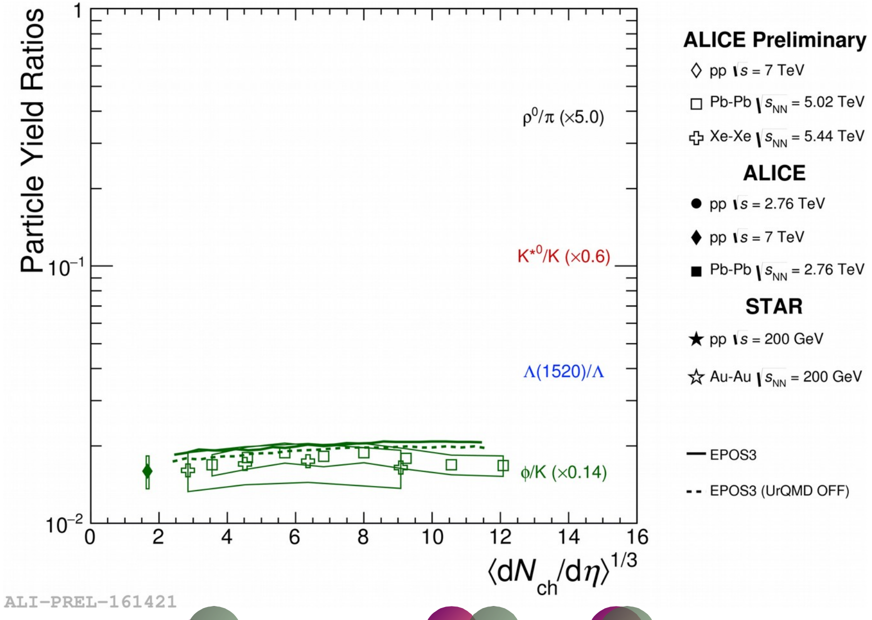
	$\rho(770)^0$	$K^*(892)^0$	$\Lambda(1520)$	$\phi(1020)$
$c\tau$(fm/c)	1.3	4.2	12.6	46.2

- $\phi(1020)/K^{\pm}$
  - $\phi(1020)/K$ ratio independent of collision system (energy)
  - The ratio $\phi(1020)/K$ increases at large $\langle dN_{ch}/d\eta \rangle$ because of strangeness enhancement



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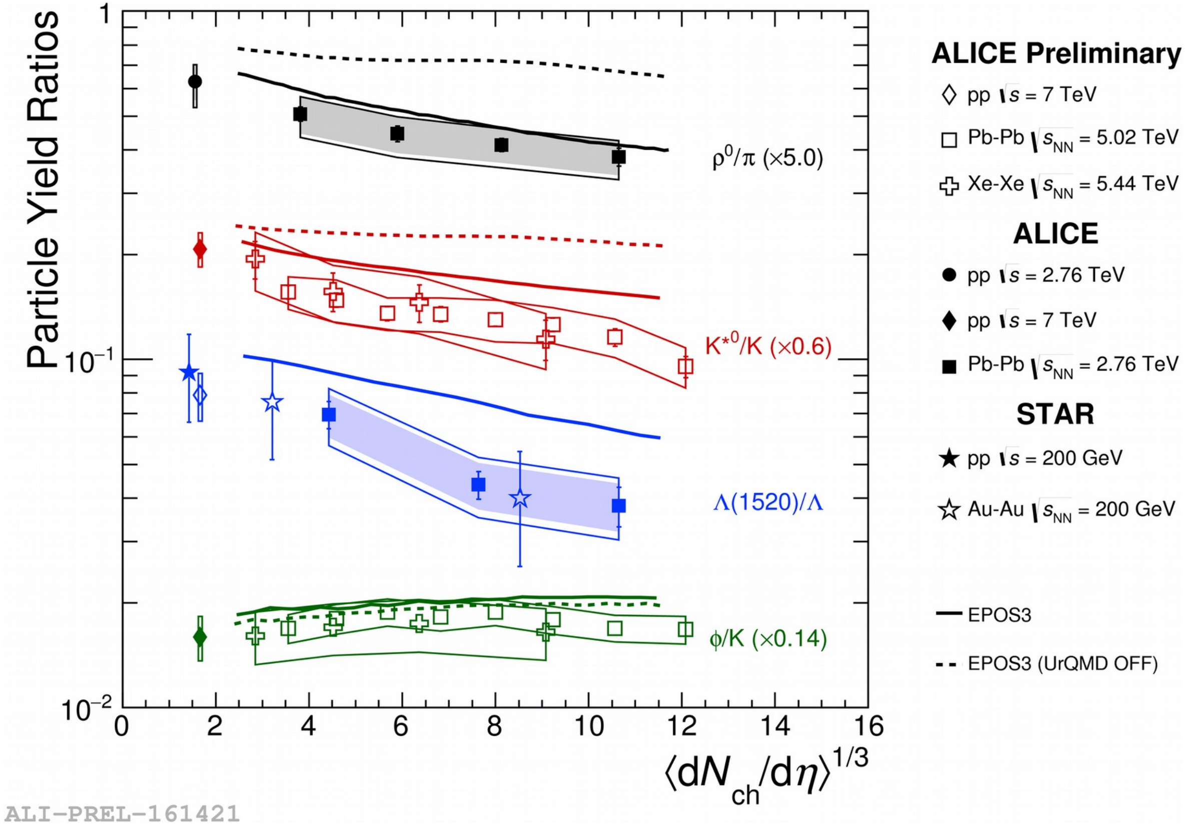
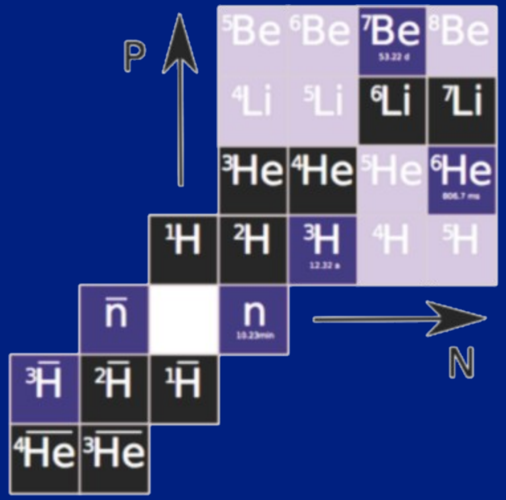


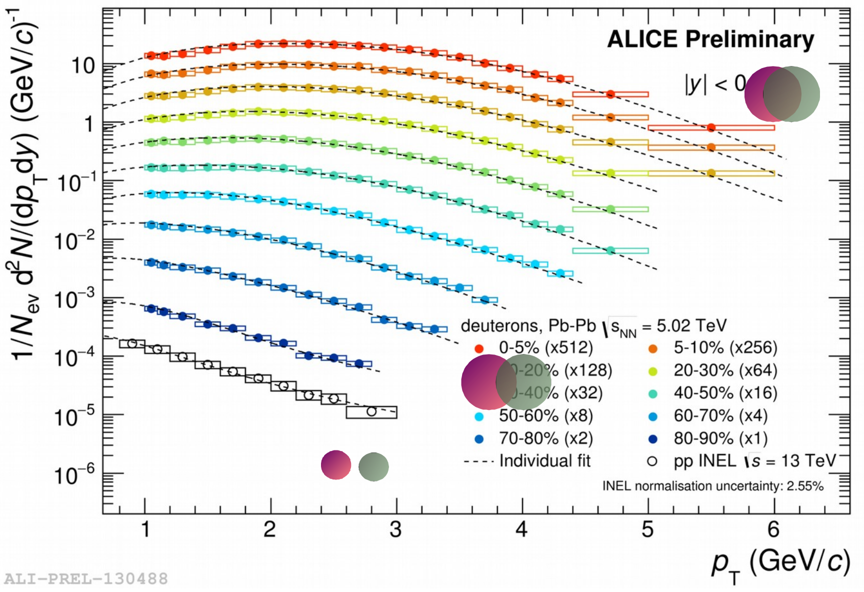
- Hadronic Resonances:
  - Suppression of ρ^0, K^{*0}, $\Lambda(1520)$, while ϕ not suppressed
  - Qualitative description is obtained with EPOS+UrQMD
    - Hadronic phase (UrQMD) important in EPOS to describe data
  - Consistent results for Xe-Xe and Pb-Pb at similar multiplicity
  - → **Indication of the existence of a hadronic phase**

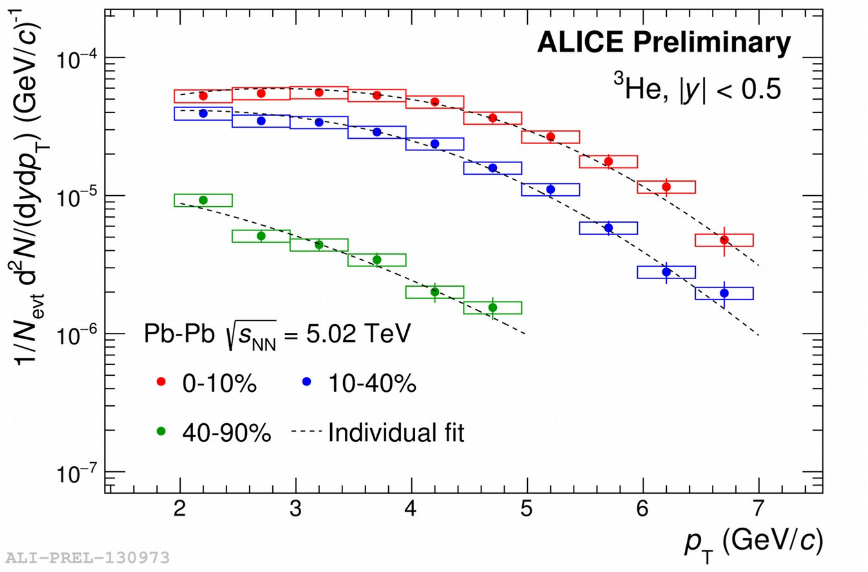


Light (hyper-)nuclei

Deuteron p_T spectra in Pb-Pb collisions

ALICE-PUBLIC-2017-006

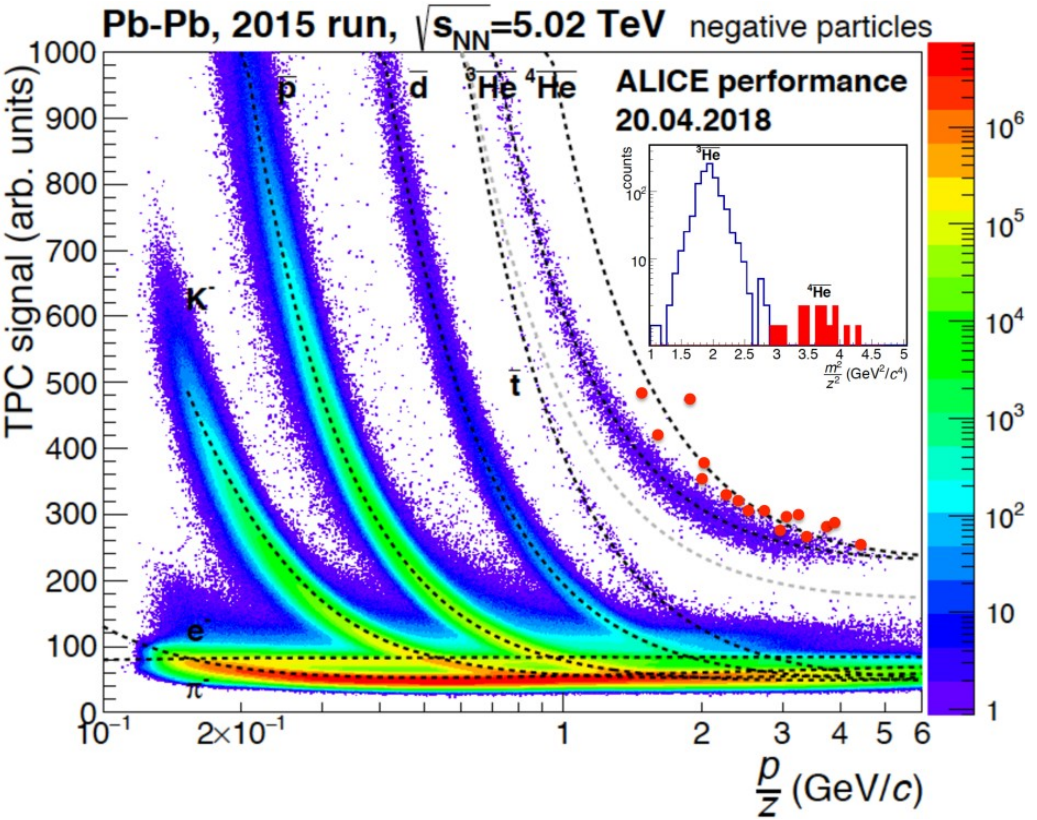




Spectra are extracted in several centrality bins and fitted with blast-wave function for the extraction of yields

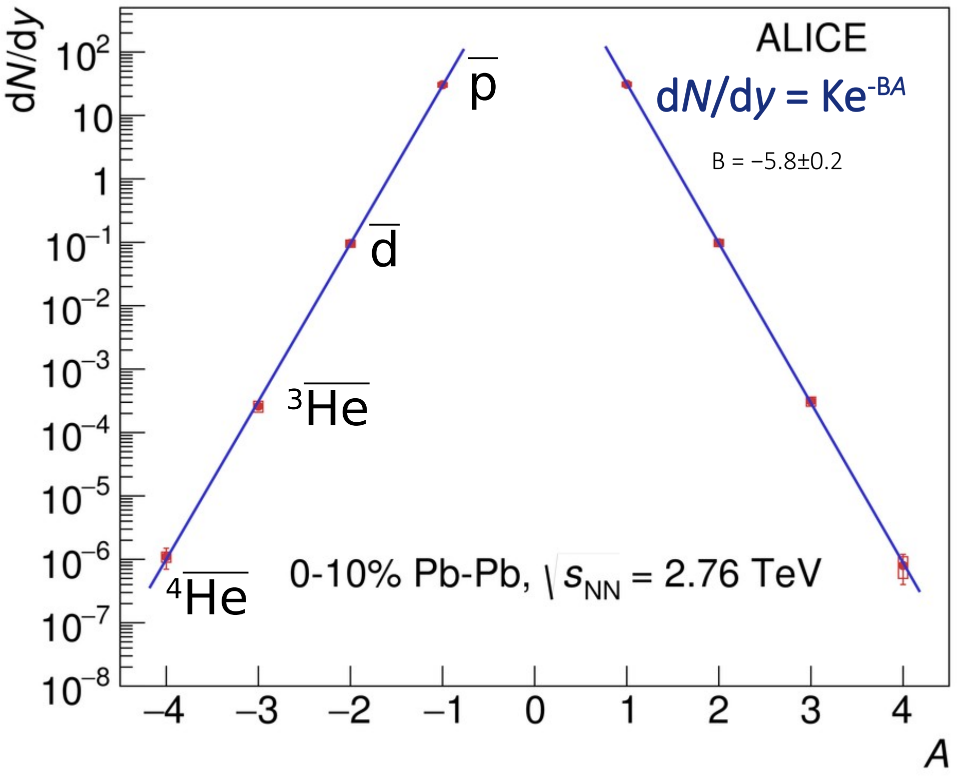
E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)

$^{4}\overline{\text{He}}$ production in Pb-Pb collisions



- Heaviest anti-nucleus observed : 16 candidates in Pb-Pb at 5.02 TeV
- Pre-selection using dE/dx measured in TPC
- Selection: ±3σ from the expected value for ^{4}He
- Signal extraction from mass squared distribution obtained using TOF

Nuclei production in Pb – Pb collisions



ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

- Thermal model prediction: exponential dependence of the yield

$$\frac{dN}{dy} \propto \exp\left(-\frac{m}{T_{chem}}\right)$$

- The density ratio of a particle with the next heavier one:

$$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T_{chem}}\right)$$

$(m_p – m_d)$ ~ 938 MeV
p/d ~ exp(938/160) ~ 350

Thermal model expectation

p/d ~ exp(-B) ~ 330^{+70}_{-61}

Experimental result

Hypernuclei

- A hypernucleus is a nucleus which contains at least one hyperon (a baryon containing one or more strange quarks) in addition to nucleons
- **Main goals of hypernuclear physics:**
  - Extension of nuclear chart
  - Understand the baryon-baryon interaction in strangeness sector
  - Study the structure of multi-strange systems

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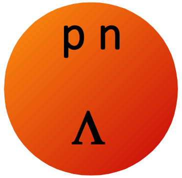


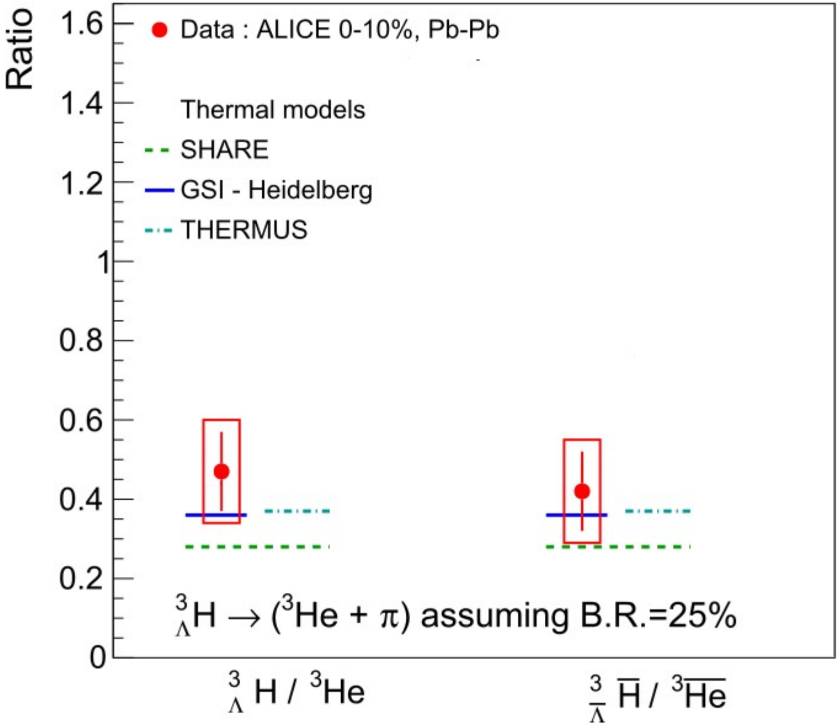
$^{3}_{\Lambda}H$ is the lightest known hypernucleus and is formed by (p,n,Λ).

- Mass = 2.991 GeV/c^2
- **B_Λ = 0.13 ± 0.05 MeV** (B_d = 2.2 MeV, B_t = 8.5 MeV, B_{3He} = 7.7 MeV)

($^{3}_{\Lambda}\overline{H}$) $^{3}_{\Lambda}H$ is unstable under weak decay and branching ratios are not well known → Only few theoretical calculations available [1]

[1]Kamada et al., Phys. Rev. C57(1998)4

Thermal model comparison



- $^{3}_{\Lambda}H/^{3}He$ ratio compared with different thermal models:
  - Extracted yield is in good agreement with equilibrium thermal model prediction for T_{chem} = 156 MeV, such as GSI-Heidelberg model [1] even if B_{Λ} is << T_{ch}

ALICE Collaboration Phys. Lett. B 754 (2016) 360-372

[1]A. Andronic et al., Phys. Lett. B 697, 203 (2011)

Thermal model fit

THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
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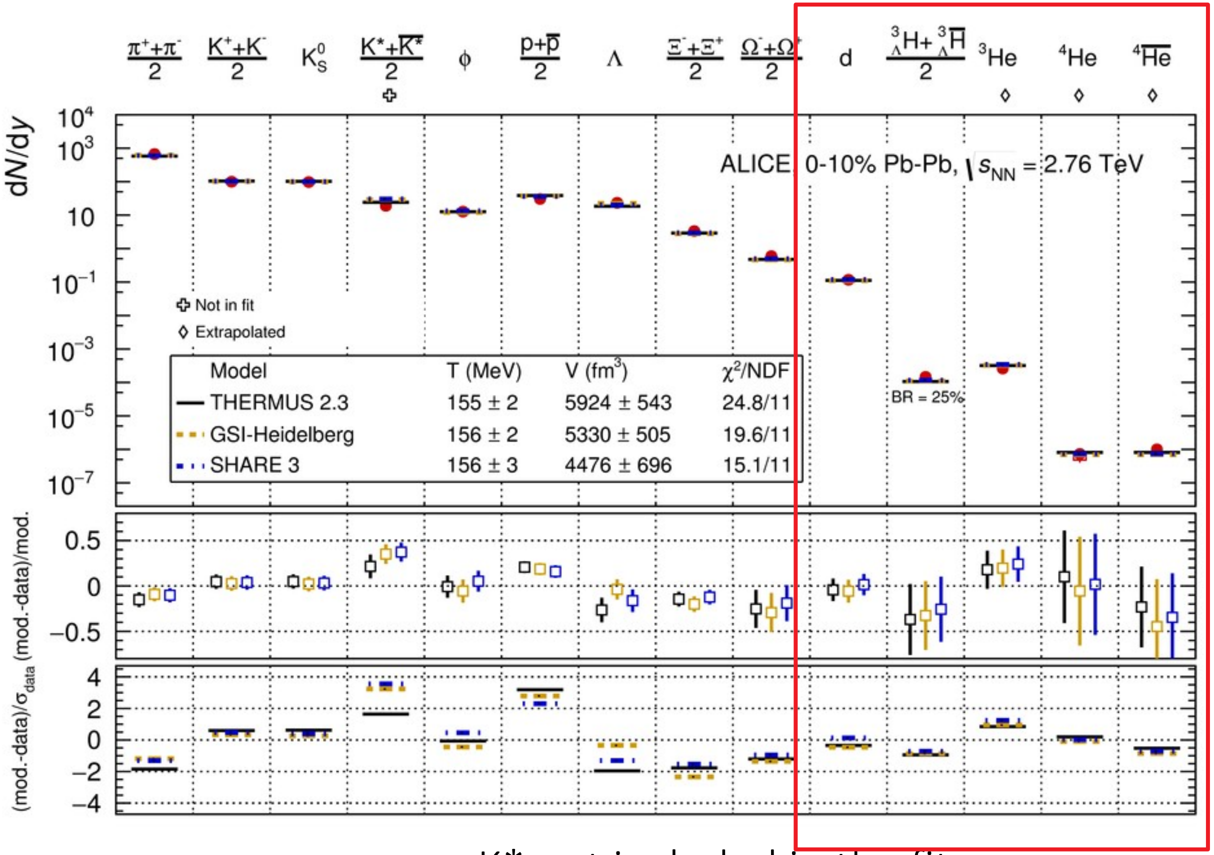

K* not included in the fit

- Opposite to resonances, yields of (hyper)nuclei are described by the common chemical freeze-out temperature (T_{chem} = 156 ± 2 MeV)
- The binding energy of (hyper)nuclei is very small and it is surprising that they do not immediately dissociate in the hadronic phase
  - T_{ch} (160 MeV) < $T_{hadronic}$ < T_{kin} (100 MeV)

ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

Coalescence Model

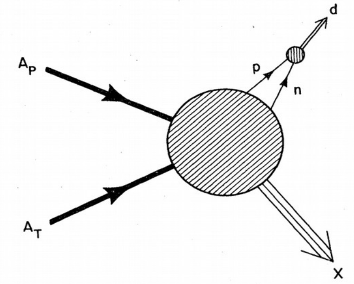

FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.

Coalescence model

- Model originally developed to describe light-nuclei production (deuteron, triton…)
  - If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
  - Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
  - Assuming that p an n have the same mass and have the same p_T spectra, the yield of any nucleus can be determined as

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

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A!} \frac{M}{m^A}$$

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Measured nucleus p_T-spectra

Measured proton p_T-spectra

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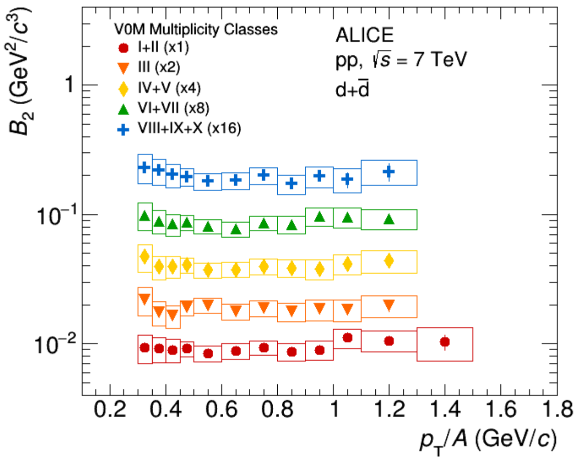
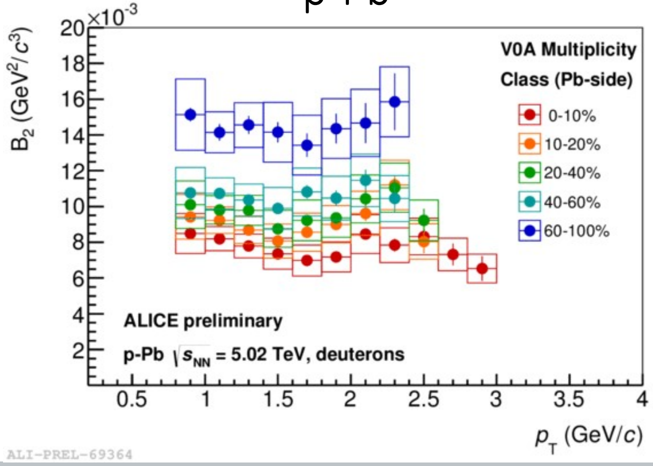
ALICE Collaboration,arXiv:1902.09290 [nucl-ex]

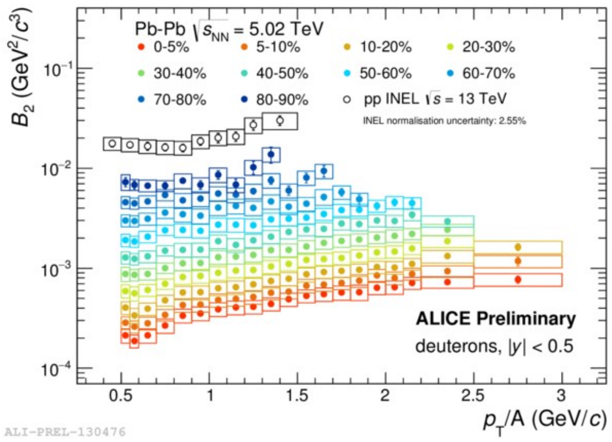
pp



p-Pb



Pb-Pb



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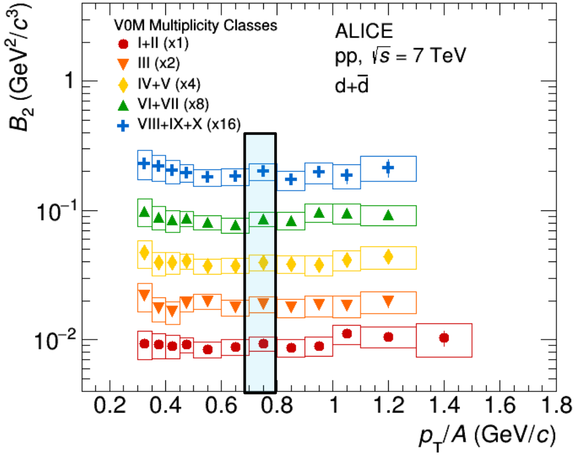
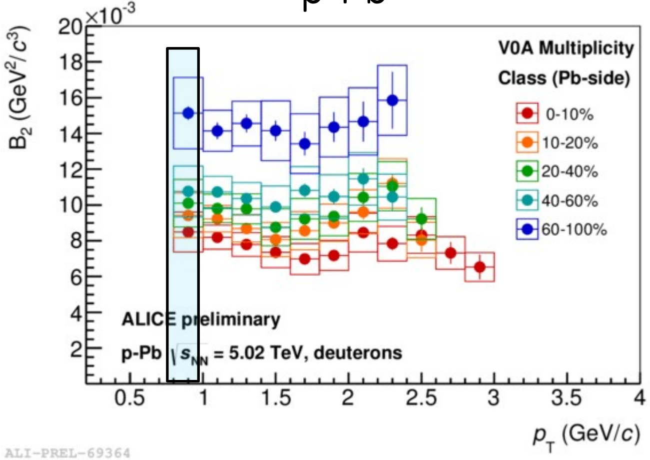
$p_T/A = 0.75$ GeV/c

pp



p-Pb



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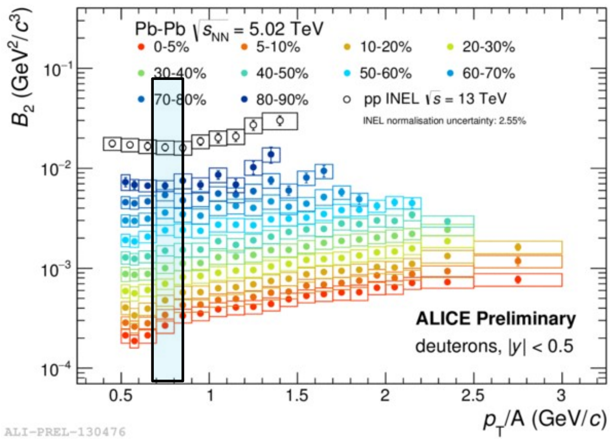
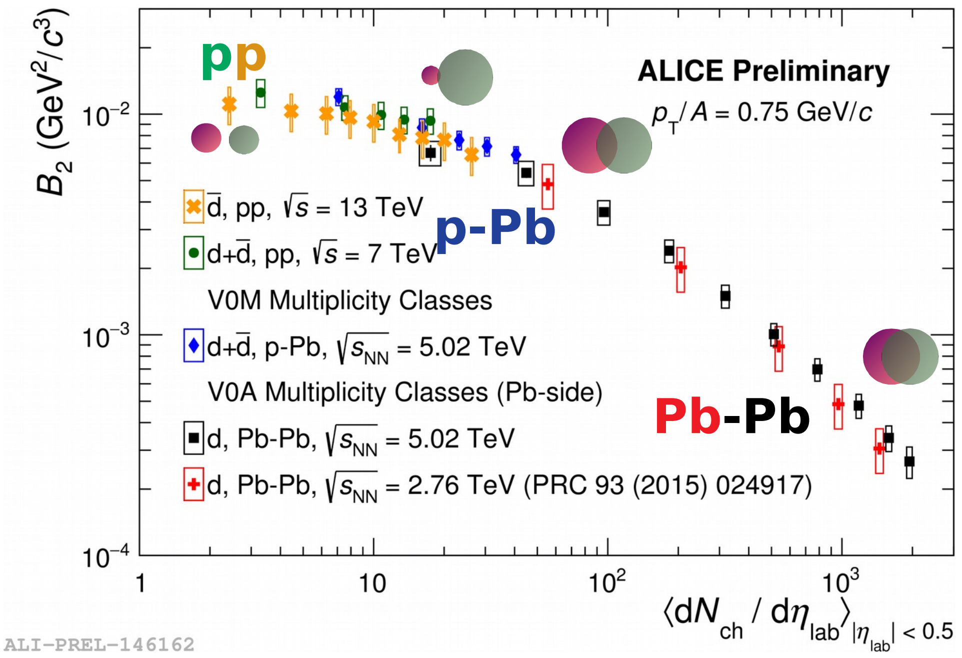


Coalescence parameter B_2



Simple coalescence model

- Flat B_2 vs p_T and no dependence on multiplicity/centrality
  - ✔ Approximately observed in "small systems": pp, p-Pb and peripheral Pb-Pb

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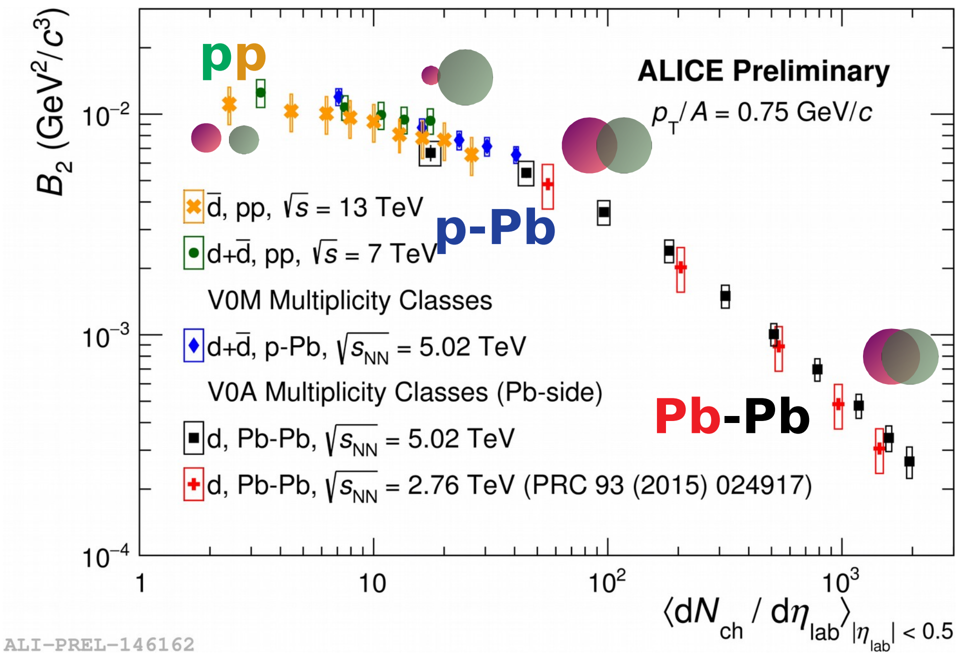

F.Bellini and A. P.Kalweit, arXiv:1807.05894 [hep-ph].
R. Scheibl, U. Heinz, PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

Simple coalescence model

- Flat B_2 vs p_T and no dependence on multiplicity/centrality
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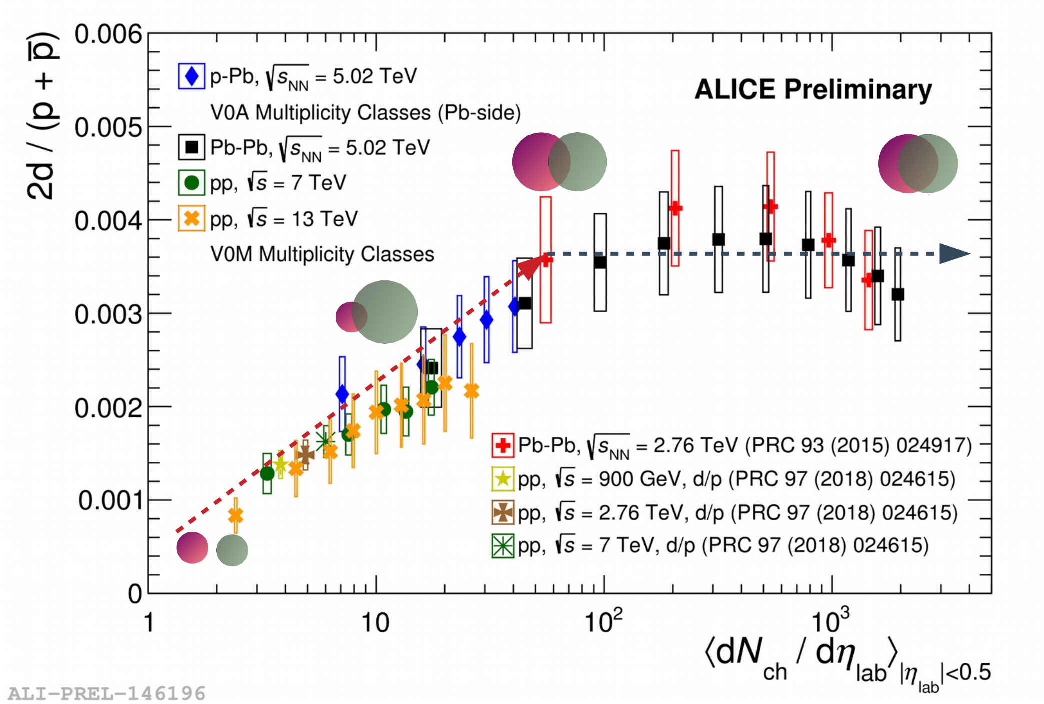
More elaborate coalescence model takes into account the volume of the source:

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

- B_2 scales like HBT radii (R)
  - ➢ decrease with centrality in Pb-Pb is explained as an increase in the source volume
  - ➢ increase with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume (i.e. volume with similar flow properties) in HBT
  - ✔ Qualitative agreement in central Pb-Pb collisions

Light nuclei production: Deuteron to proton ratio



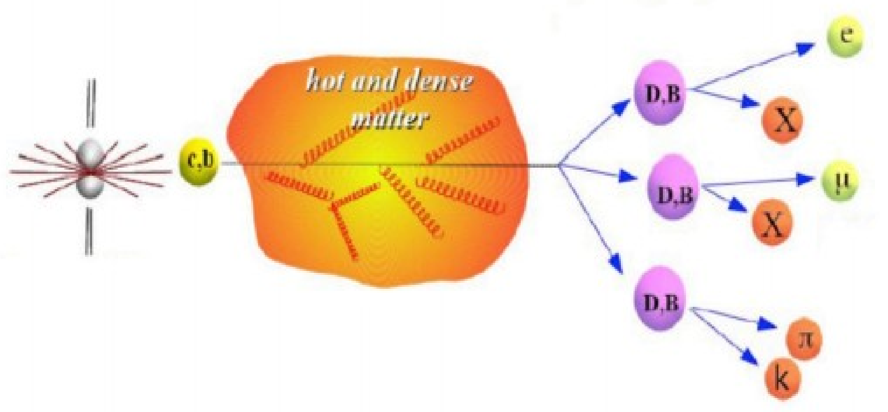
- d/p increases with multiplicity going from pp to peripheral Pb-Pb : consistent with simple coalescence (d ∝ p^2)
- No significant centrality dependence in Pb-Pb : consistent with thermal model (yield fixed by T_{chem})
- How the two models are connected is not yet fully understood
  - **Is there a single particle production mechanism?**

Charm Baryon

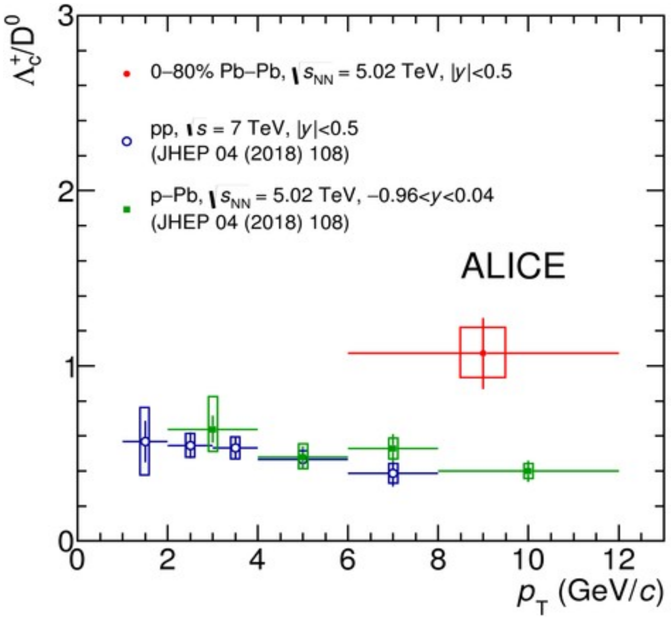
Heavy quarks in heavy ion collisions

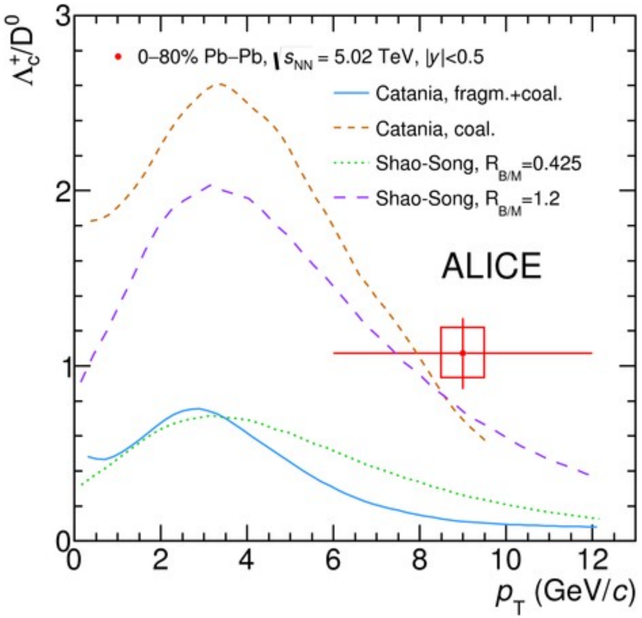
- Charm and beauty quarks are produced in parton hard scatterings in the initial phase of the heavy-ion collision (production time of $c\bar{c}$($b\bar{b}$) pair at rest
- Flavour is conserved in strong interactions → Transported through the full system evolution

- What can be tested?
  - In-medium energy loss: colour-charge and quark-mass dependence
  - Heavy quark participation in the collective expansion, thermalisation in the medium
  - **Modification of the hadronization mechanisms in the medium**



Λ_c production in heavy ion collisions

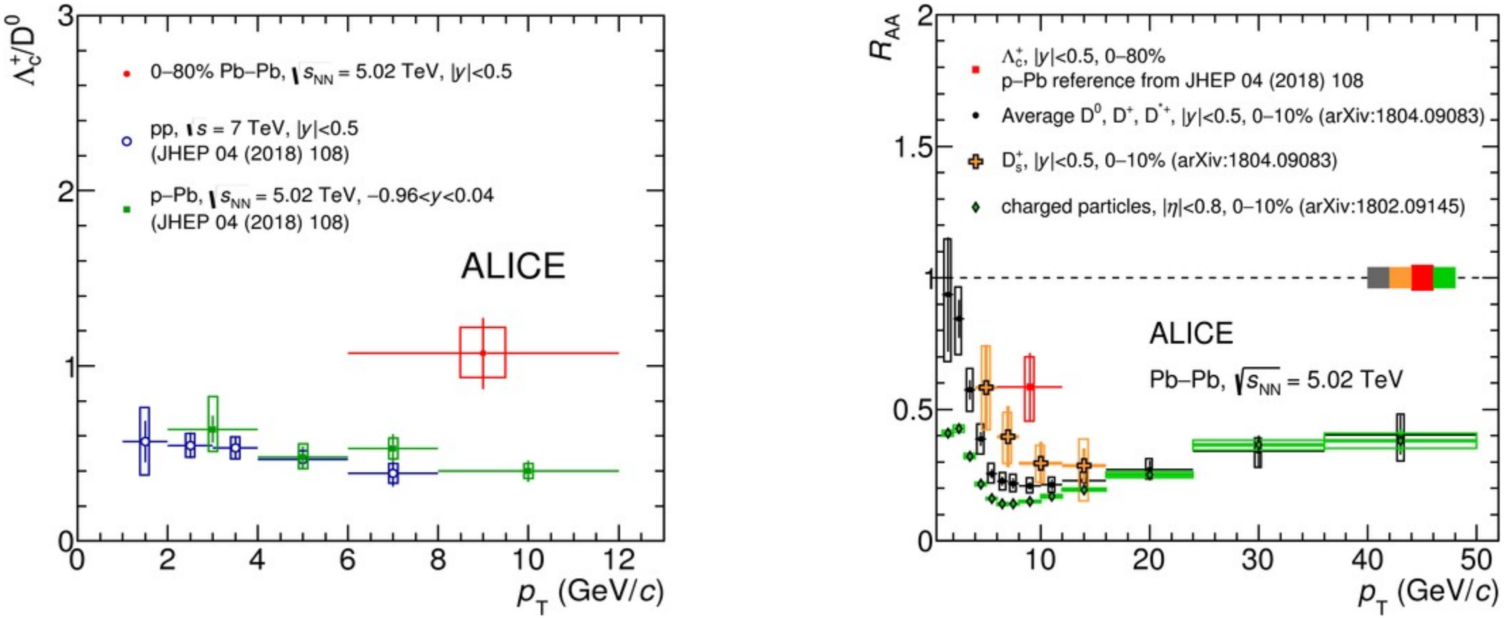




- ALICE measured Λ_c in Pb-Pb collisions at 5.02 TeV for 0-80% centrality class
  - 2.5σ hint of Λ_c / D^0 ratio enhanced in Pb-Pb collisions w.r.t. pp and p-Pb collisions
    - **Coalescence production** mechanism at play

ALICE Collaboration arXiv:1809.10922
DOI: 10.1016/j.physletb.2019.04.046

Λ_c production in heavy ion collisions



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  - ~2.5σ hint of Λ_c / D^0 ratio enhanced in Pb-Pb collisions w.r.t. pp and p-Pb collisions
  - ~2.0σ hint of larger R_{AA} of Λ_c than D mesons in 0-10% centrality class
    - Charm quark hadronization via **coalescence**:
      - hierarchy of the R_{AA} Λ_c > D_s > Non-strange D-meson > pions

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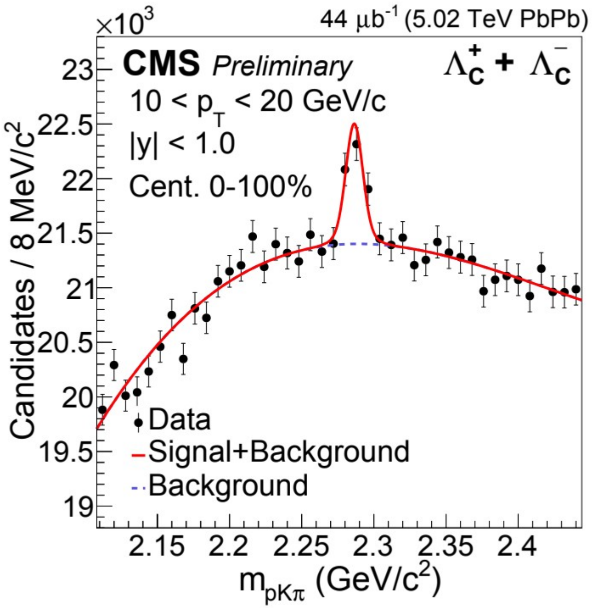
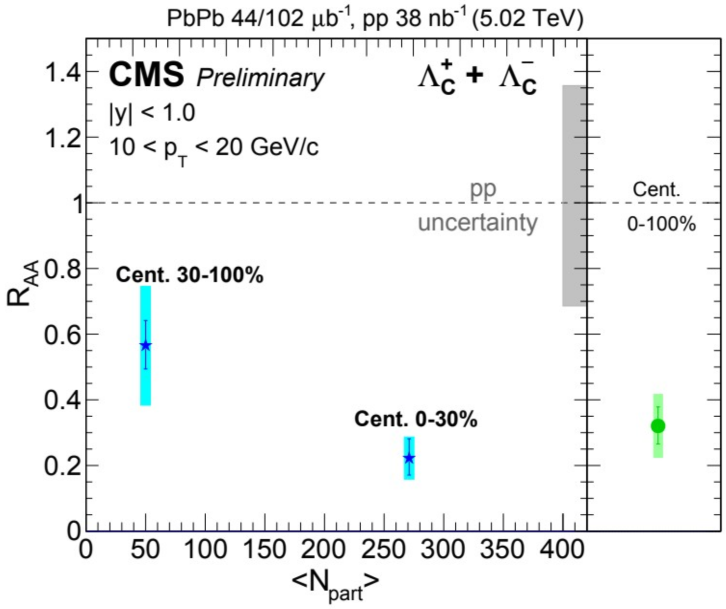
Λ_c production in heavy ion collisions

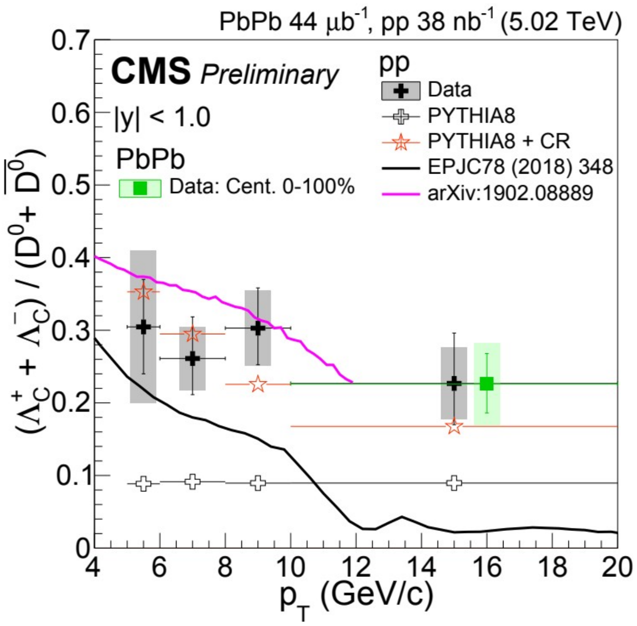


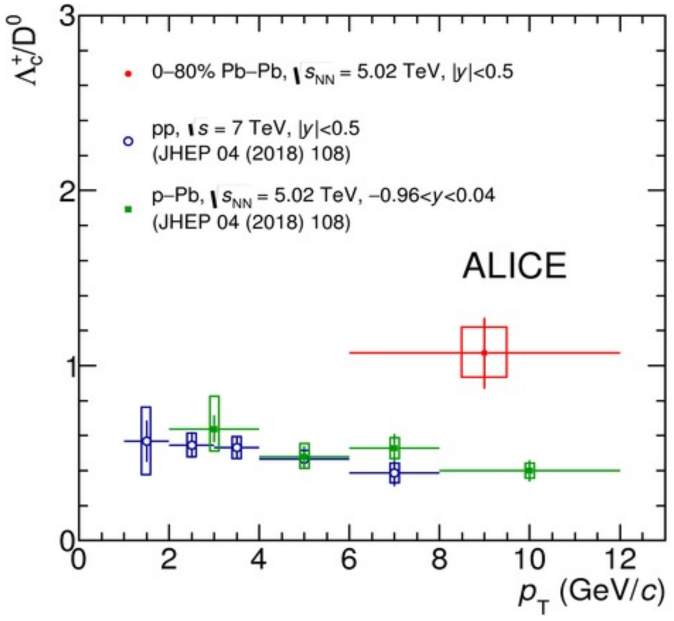


- CMS measured Λ_c^+ production in 2 centrality intervals (0-30%) and (30-50%) in the p_T interval 10-20 GeV/*c*:
  - The R_{AA} for Λ_c^+ show a hint of suppressed production of Λ_c^+ for p_T > 10 GeV/c (0-100%), but no conclusion can be drawn due to the large uncertainty in the pp differential cross section.

CMS Collaboration CMS PAS HIN-18-009

Λ_c production in heavy ion collisions





- The Λ_c / D^0 ratio in Pb-Pb collisions, is consistent with the result from pp collisions:
  - Result in contrast w.r.t ALICE observation of a large enhancement in the Λ_c / D^0 ratio in the p_T range of 6-12 GeV/*c*
    - ➢ may suggest that there is no significant contribution from the coalescence process for p_T > 10 GeV/*c* in Pb-Pb collisions

CMS Collaboration CMS PAS HIN-18-009

Conclusions

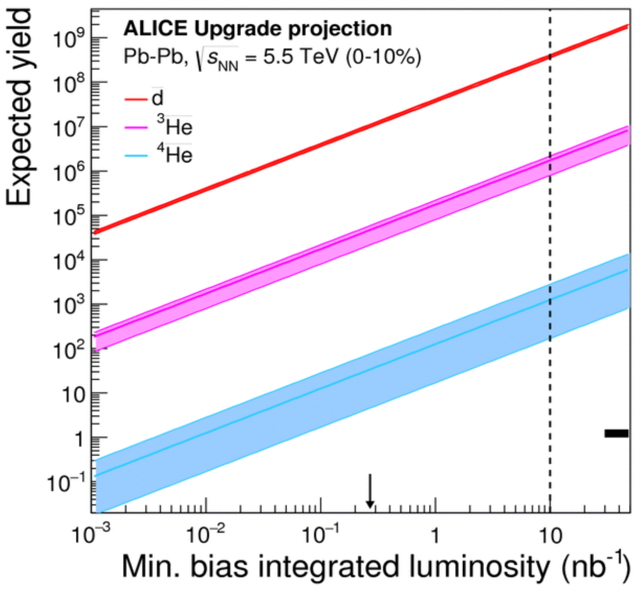
- **Thermal models** are able to describe the production yields of light flavor hadrons and (hyper)nuclei within a **common chemical freeze-out temperature**
- Resonance results support the **existence** of a **hadronic phase** in central heavy-ion collisions that lasts long enough to cause a significant reduction of the reconstructed yields of short lived resonances: surprisingly **nuclei** seem to **survive** thru this phase
- Light nuclei measurement reveals **system size dependence** of **hadronization**:
  - Evolution of B_A and d/p ratio vs multiplicity: is there a **single** particle production **mechanism**?
- Charmed-baryon Λ_c is less suppressed than D mesons: favored production mechanism is quark **coalescence** for p_T < 10 GeV/c, for higher momenta this has not been observed
- **Beautiful picture, but there is still a lot to do and to understand!**
  - ➢ New and more precise data can be expected from the LHC on the presented topics in the next years

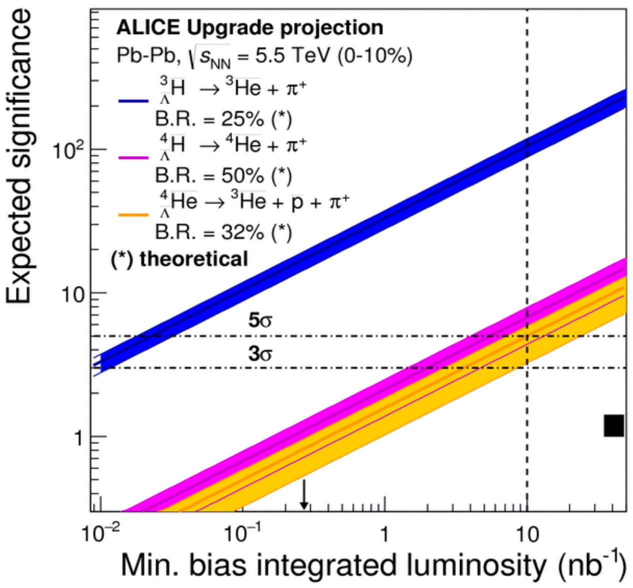
Extra Material

Production of light (anti-)(hyper)nuclei

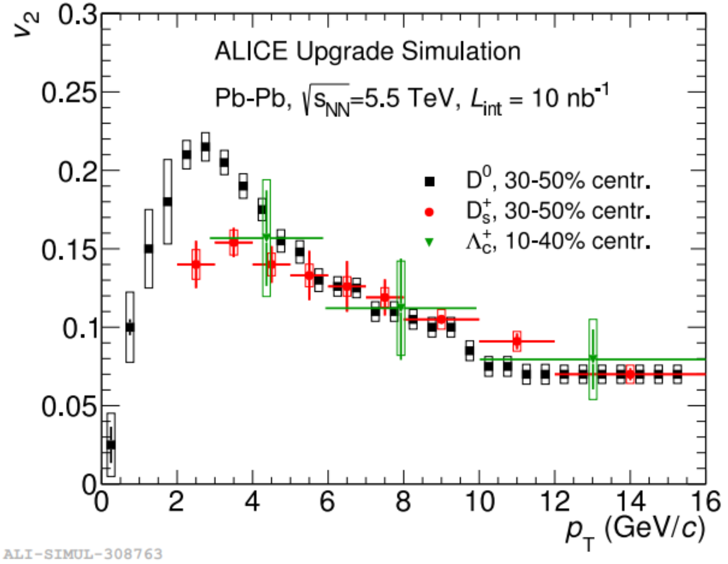
After the Long Shutdown 2 data will be collected with better performance at higher luminosity

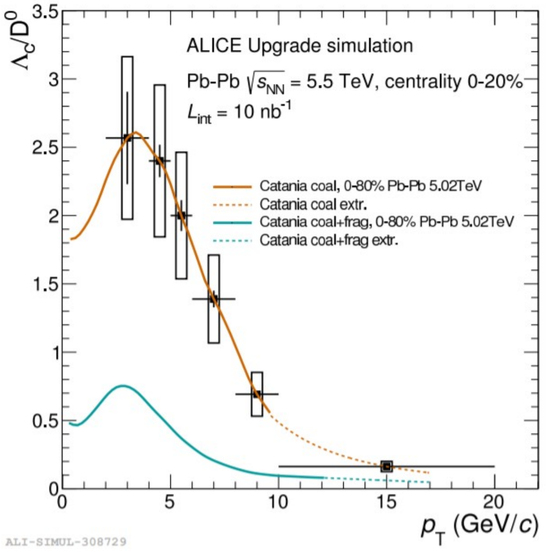
- Expected integrated luminosity: ~10 nb^{-1} (~ $8x10^{9}$ collisions in the 0-10% centrality class)
  - Precision test of coalescence / thermal production models
    - Sensitive to size ratio of the object and the source
  - Search for rarely produced anti- and hypermatter: Insights on the strength of the hyperon-nucleon interaction, relevant for nuclear physics and neutron stars.





Hadronization of Heavy Quark



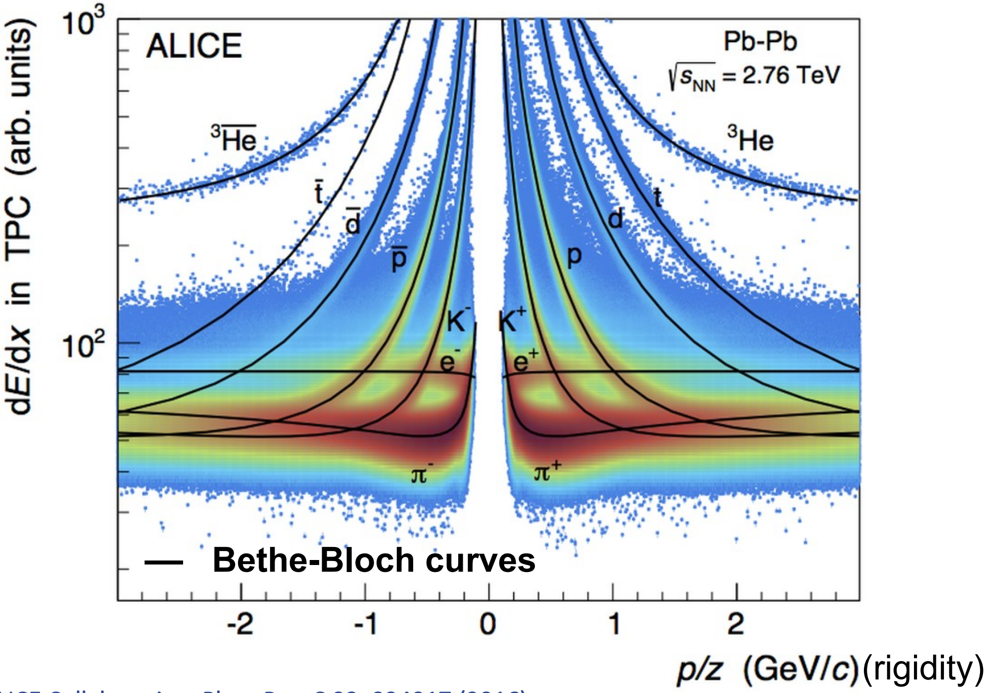


- Charm quark number is conserved in strong interaction
- Hadronization chemistry: crucial for the interpretation of the heavy flavor hadron spectra
- Run 3+4 data will allow the first comprehensive survey of this effect
- D_s , B_s and Λ_c spectra from low to high p_T in Pb-Pb collisions
- Provide the necessary statistical accuracy to see the emergence of the effect at low p_T

Identification of nuclei

Low momenta: specific energy loss in the TPC

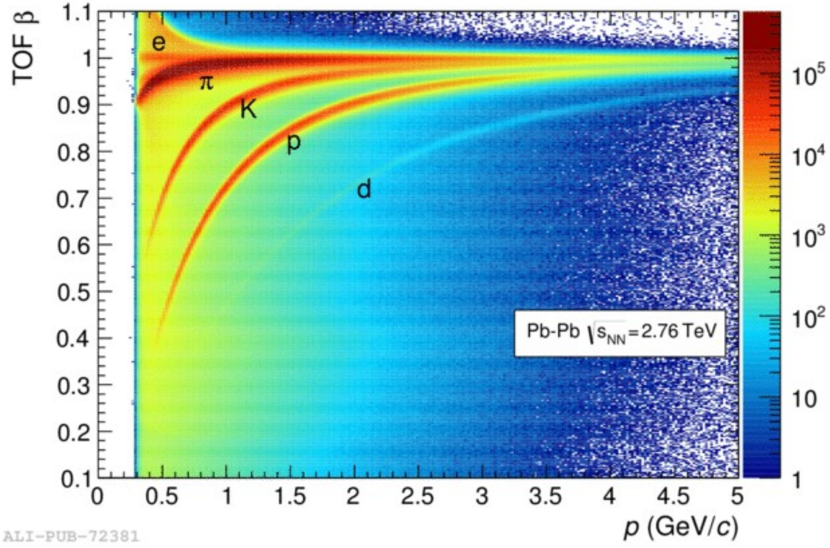
- Nuclei identification via dE/dx measurement in the TPC:
  - Excellent separation of (anti-)nuclei from other particles over a wide range of momenta



ALICE Collaboration, Phys. Rev. C 93, 024917 (2016)

Higher momenta: time-of-flight measurement in the TOF

- Velocity measurement with the Time Of Flight detector is used to evaluate the m^2 distribution
- Excellent TOF performance: $\sigma_{TOF} \approx$ 85 ps in Pb-Pb collisions



ALICE Collaboration, Int. J. Mod. Phys. A 29 (2014) 1430044

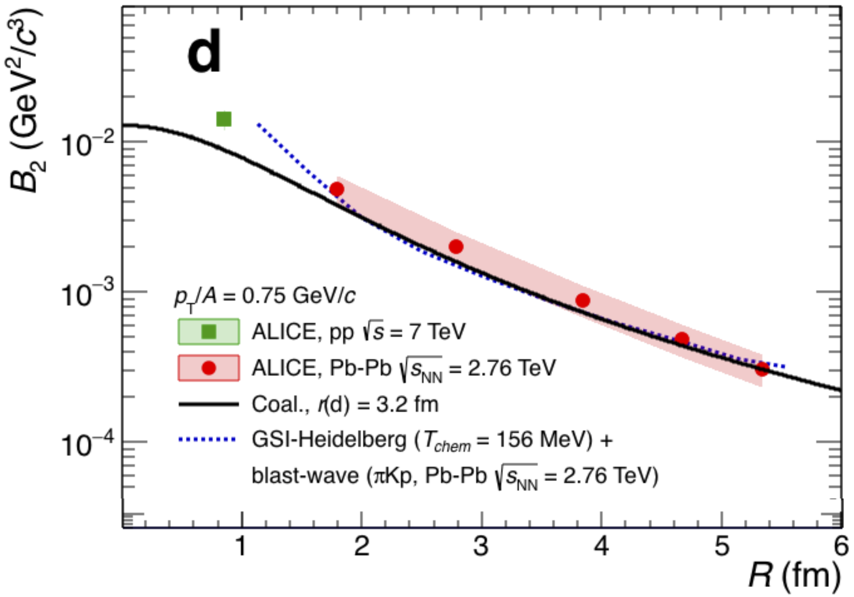
“More elaborate” coalescence model

- For “large” systems, the size of the emitting volume (V_{eff}) has to be taken into account:
  - the larger the distance between the protons and neutrons which are created in the collision, the less likely it is that they coalesce
- The source can be parameterized as rapidly expanding under radial flow (hydro)
- The coalescence process is governed by the same correlation volume (“length of homogeneity”) which can be extracted from HBT interferometry
- The source radius enters in the B_A and in the quantum-mechanical correction $\langle C_A \rangle$ factor that accounts for the size of the object being produced (d, ^{3}He, …)

$$B_A = \frac{2J_A+1}{2^A} A \langle \mathcal{C}_A \rangle \frac{V_{\rm eff}(A, M_t)}{V_{\rm eff}(1, m_t)} \left(\frac{(2\pi)^3}{m_t V_{\rm eff}(1, m_t)} \right)^{A-1}$$

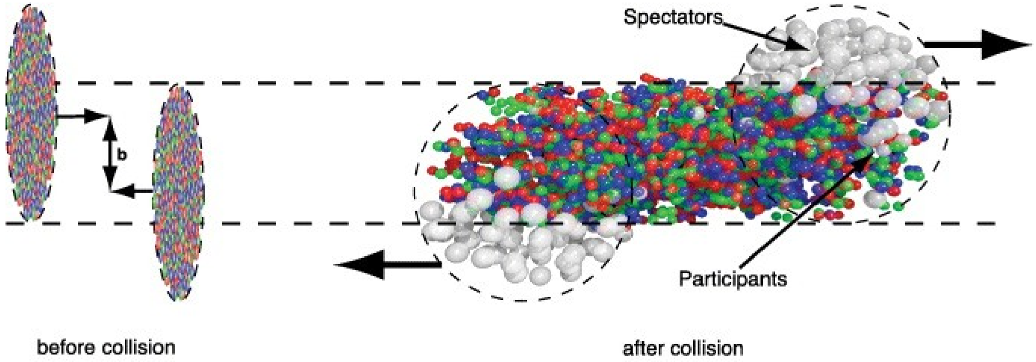
R. Scheibl, U. Heinz, PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

F.Bellini and A. P.Kalweit, arXiv:1807.05894 [hep-ph].



Good description of the data

Centrality of the collisions



Centrality = degree of overlap of the 2 colliding nuclei

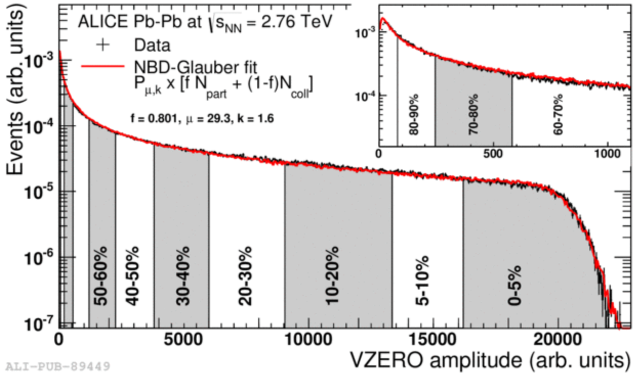
Central collisions:

- small impact parameter *b*
- high number of participant nucleons → high multiplicity

Peripheral collisions:

- large impact parameter *b*
- low number of participant nucleons → low multiplicity

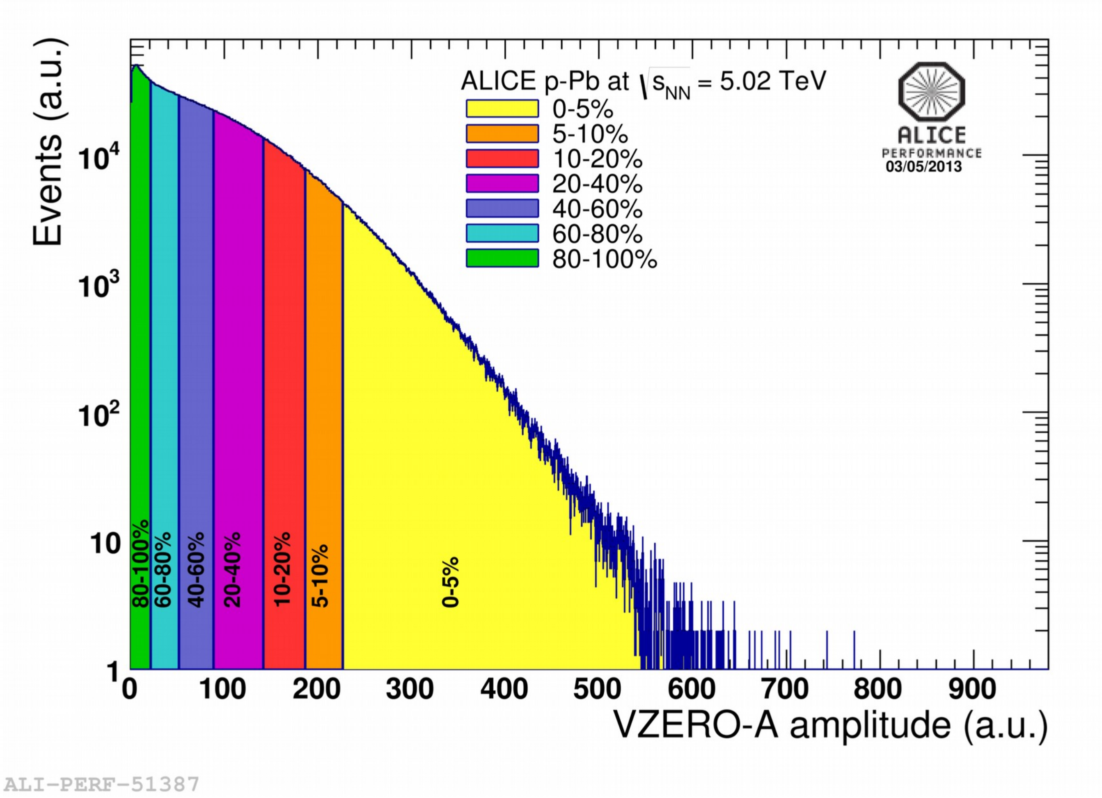
Centrality connected to observables via Glauber model



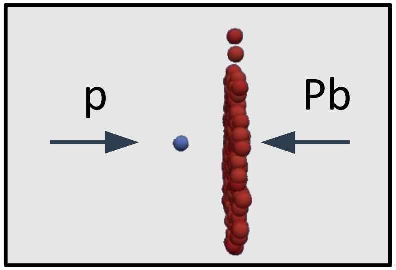
ALICE Collaboration, Phys. Rev. Lett. 106, 032301 (2011)

Centrality of the collisions: p-Pb and pp

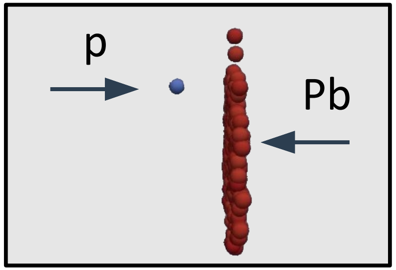
Multiplicity estimator: slices in VZERO-A (V0A) amplitude



Central collision



Peripheral collision

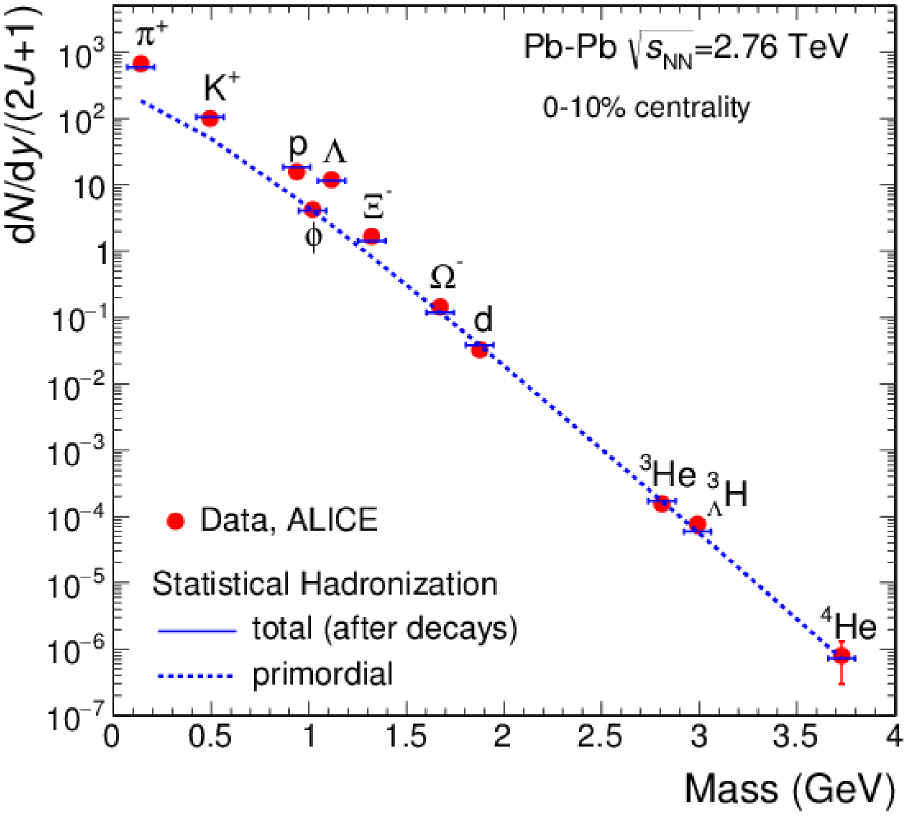


Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb

Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collision: all the particles are produced at chemical freeze-out
- Starting point: Grand Canonical partition function (Z) for a relativistic ideal quantum gas of hadrons of particle type i (i = pion, proton,... → full PDG)
- Thermal model can predict also the yields of any particle at chemical freeze-out
- Exponential dependence of the particle yield: $$\frac{dN}{dy} \propto e^{\left(-\frac{m}{T_{chem}}\right)}$$
- The thermal model predicts an exponential decrease of particle yields with increasing mass at a given temperature
- The density ratio of a particle with the next heavier one: $$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$$

Thermal model



Nature 561 (2018) no.7723, 321-330 arXiv:1710.09425 [nucl-th]

Statistical hadronization model: thermal emission from equilibrated source

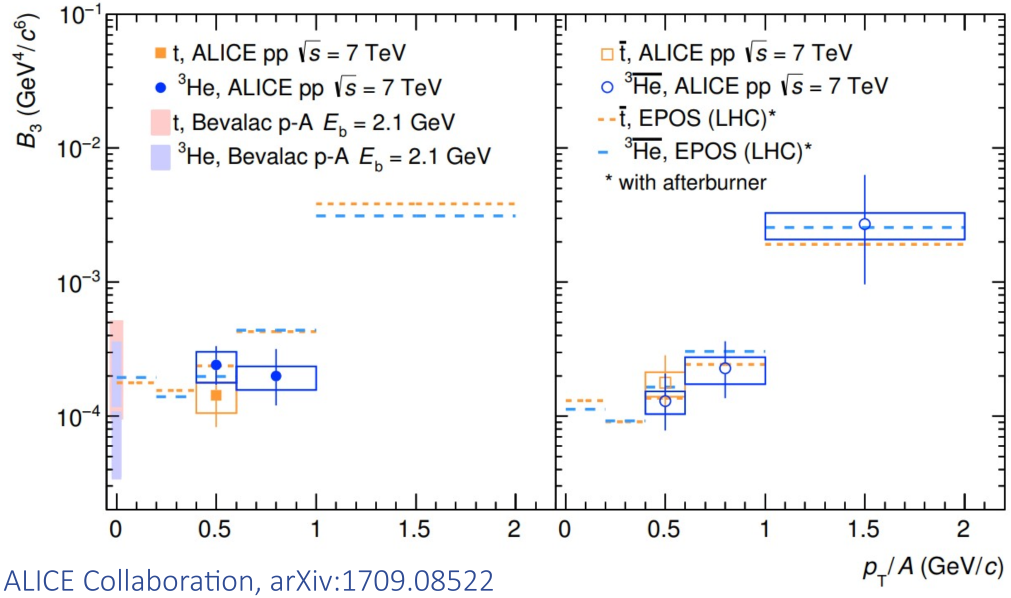
Particle abundances fixed at chemical freeze-out

$$N_i = \frac{g_i V}{2\pi^2} \int_0^{+\infty} \frac{p^2 dp}{\exp\left[-\left(\frac{E-\mu_B}{T_{\mathrm{chem}}}\right)\right] \pm 1}$$

- Primordial yields modified by hadron decays:
  - Contribution obtained from calculations based on known hadron spectrum
  - Excellent agreement with data with only 2 free parameters: T_{chem} , V

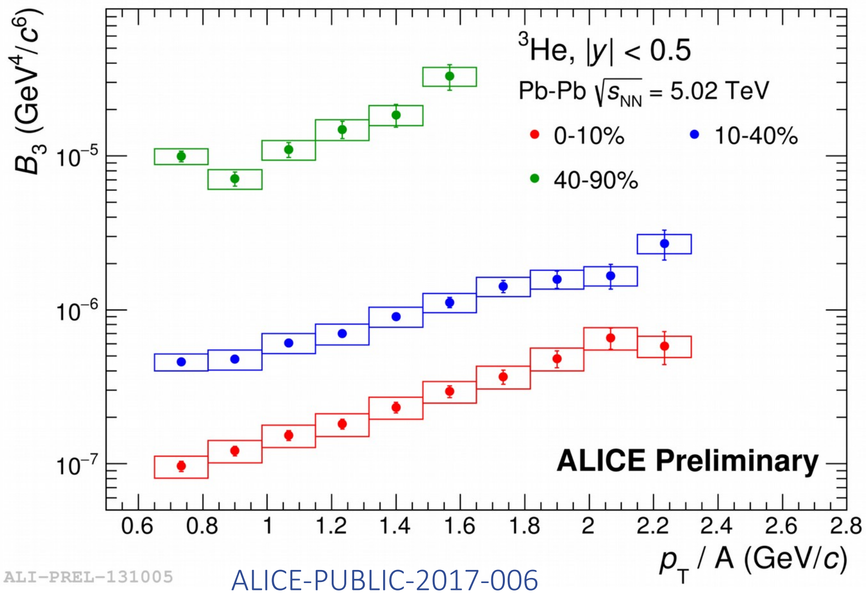
Coalescence parameter B_3

pp



ALICE Collaboration, arXiv:1709.08522

Pb-Pb



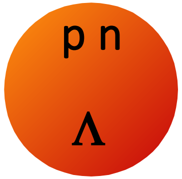
ALICE-PUBLIC-2017-006

B_3 of ($\bar{t}$)t and ($^3\overline{He}$)^{3}He measured in pp and Pb-Pb collisions

First ever measurements of the B_3 of $\bar{t}$ and $^3\overline{He}$ in pp collisions

Increasing trend with p_T and centrality observed in Pb-Pb collision

Hypertriton ($^{3}_{\Lambda}\mathrm{H}$)



$^{3}_{\Lambda}\mathrm{H}$ is the lightest known hypernucleus and is formed by (p,n,Λ).

- Mass = 2.991 GeV/c^2
- **B_{Λ} = 0.13 ± 0.05 MeV** (B_d = 2.2 MeV, B_t = 8.5 MeV, B_{3He} = 7.7 MeV)

($^{3}_{\overline{\Lambda}}\overline{\mathrm{H}}$) $^{3}_{\Lambda}\mathrm{H}$ is unstable under weak decay. Possible decay modes:

$$^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-} \quad (\sim 25\%)$$
$$^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{H} + \pi^{0} \quad (\sim 13\%)$$
$$^{3}_{\Lambda}\mathrm{H} \to d + p + \pi^{-} \quad (\sim 41\%)$$
$$^{3}_{\Lambda}\mathrm{H} \to d + n + \pi^{0} \quad (\sim 21\%)$$

$$^{3}_{\overline{\Lambda}}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{He}} + \pi^{+} \quad (\sim 25\%)$$
$$^{3}_{\overline{\Lambda}}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{H}} + \pi^{0} \quad (\sim 13\%)$$
$$^{3}_{\overline{\Lambda}}\overline{\mathrm{H}} \to \overline{d} + \overline{p} + \pi^{+} \quad (\sim 41\%)$$
$$^{3}_{\overline{\Lambda}}\overline{\mathrm{H}} \to \overline{d} + \overline{n} + \pi^{0} \quad (\sim 21\%)$$

- Branching ratios are not well known
  - Only few theoretical calculations[1] available

[1]Kamada et al., Phys. Rev. C57(1998)4