(Anti-)Nuclei production at the LHC with ALICE

Ramona Lea

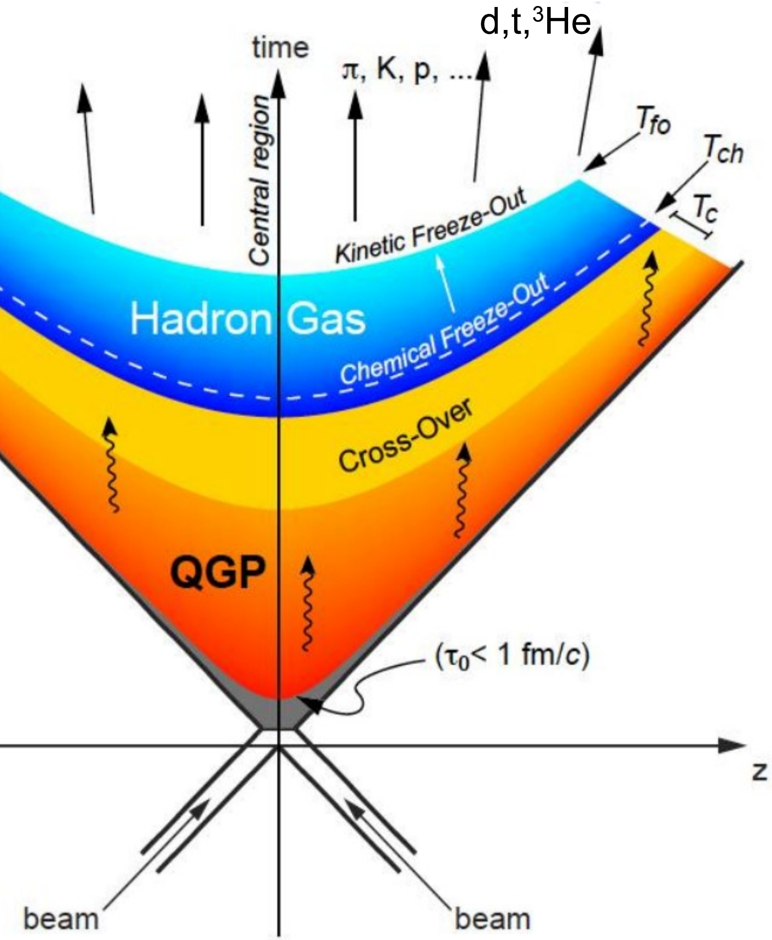
Physics Department, University and INFN Trieste

For the ALICE Collaboration

d19

2nd Cosmic-ray Antideuteron Workshop

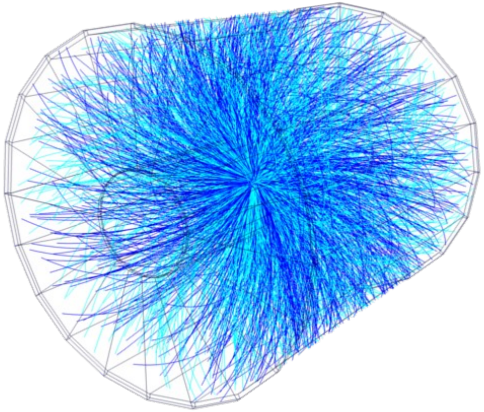
Light nuclei in heavy-ion collisions



- The study of the production of light (anti-)nuclei in high energy collisions is very important:
  - The production mechanism is not well understood
    - How/when do they form?
      - "early" at chemical freeze-out (thermal production)
      - or "late" at kinetic freeze-out (coalescence)?
    - Do they suffer for dissociation by rescattering?
  - Low binding energy (few MeV) "Snowballs in hell": nuclei formation is very sensitive to chemical freeze-out conditions and to the dynamics of the emitting source
  - Baseline for searches for exotic bound states
  - Light nuclei measurements in high energy physics can be used to estimate the background of secondary anti-nuclei in dark matter searches

Particle production at LHC

- Particle production in pp, p-Pb, and Pb-Pb collisions shows an **equal abundance** of matter and anti-matter in the central rapidity region
- A large number of particles is produced: $dN_{ch}/d\eta \approx 2000$ (central Pb-Pb collisions)



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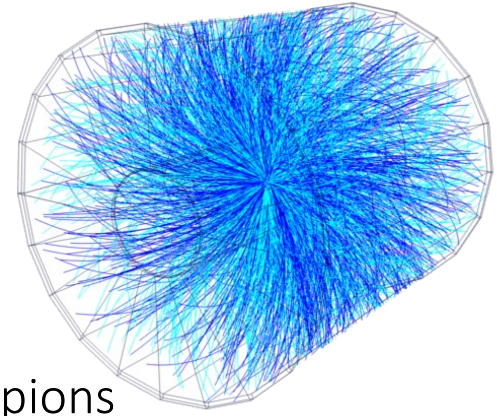

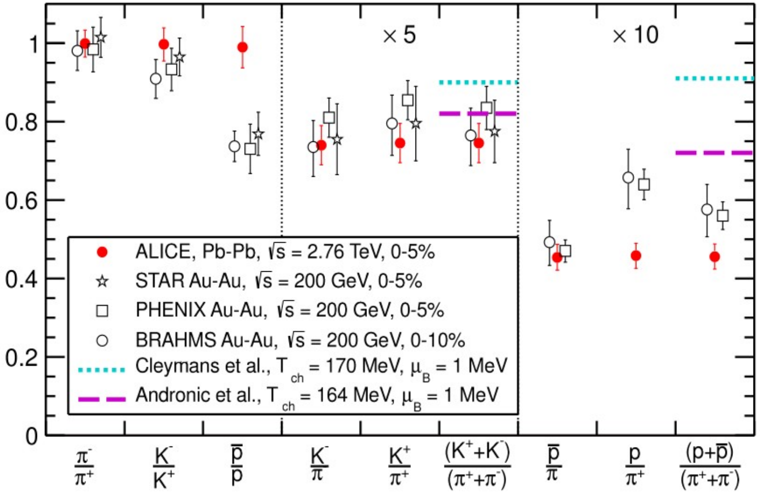

≈ 80% of all charged particles are pions
≈ 5% of all charged particles are protons

Phys. Rev. Lett.109, 252301

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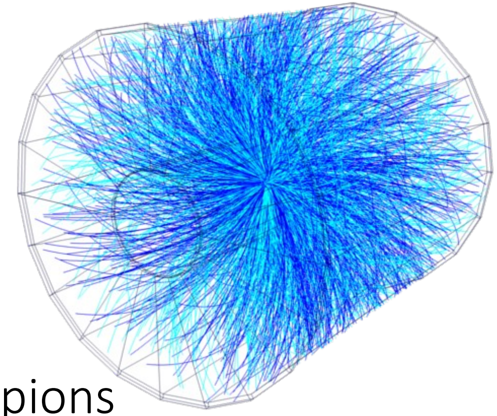

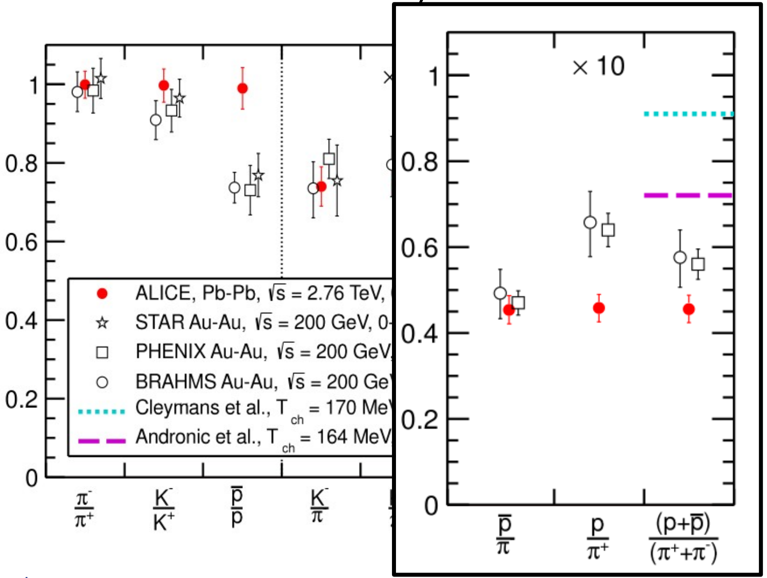

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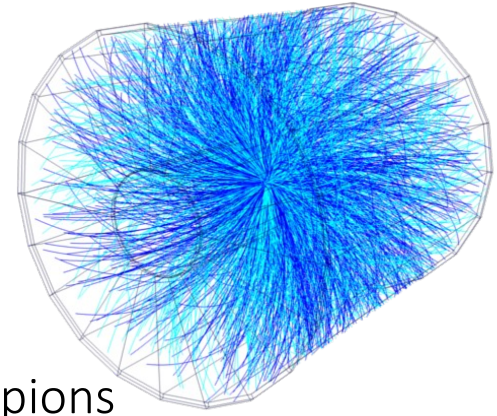

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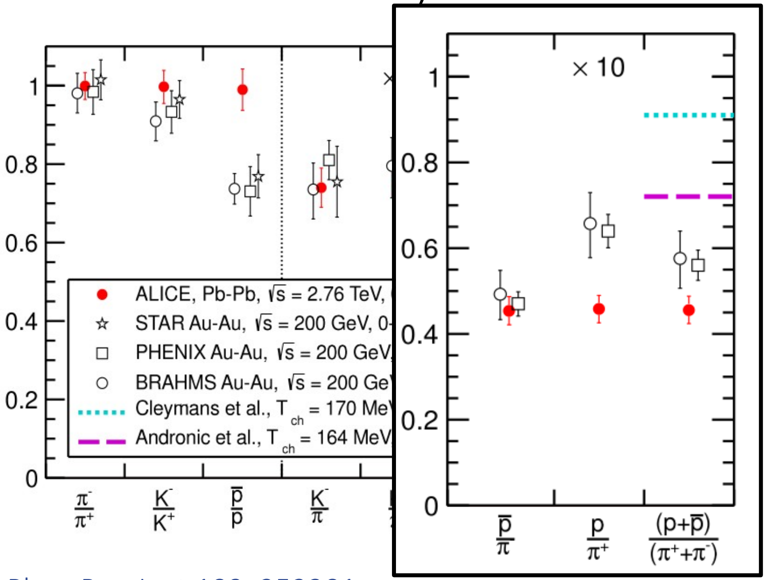

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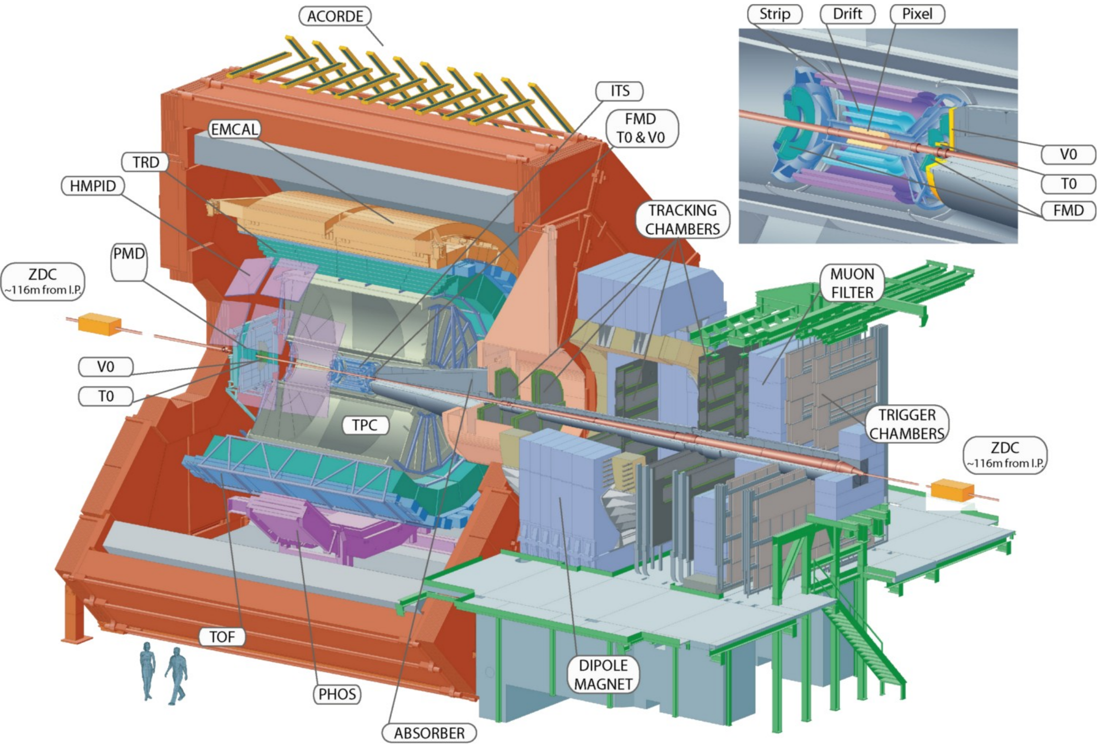
- Even in heavy ion collisions, light (anti-)nuclei are rarely produced:
  - ➢ (Anti-)nuclei up to A = 4 are within reach
  - ➢ For each additional nucleon the production yield at LHC decreases by a factor of about 350!

Experimental apparatus

A Large Ion Collider Experiment

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: specific energy loss (dE/dx), time of flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V^0, cascade).



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

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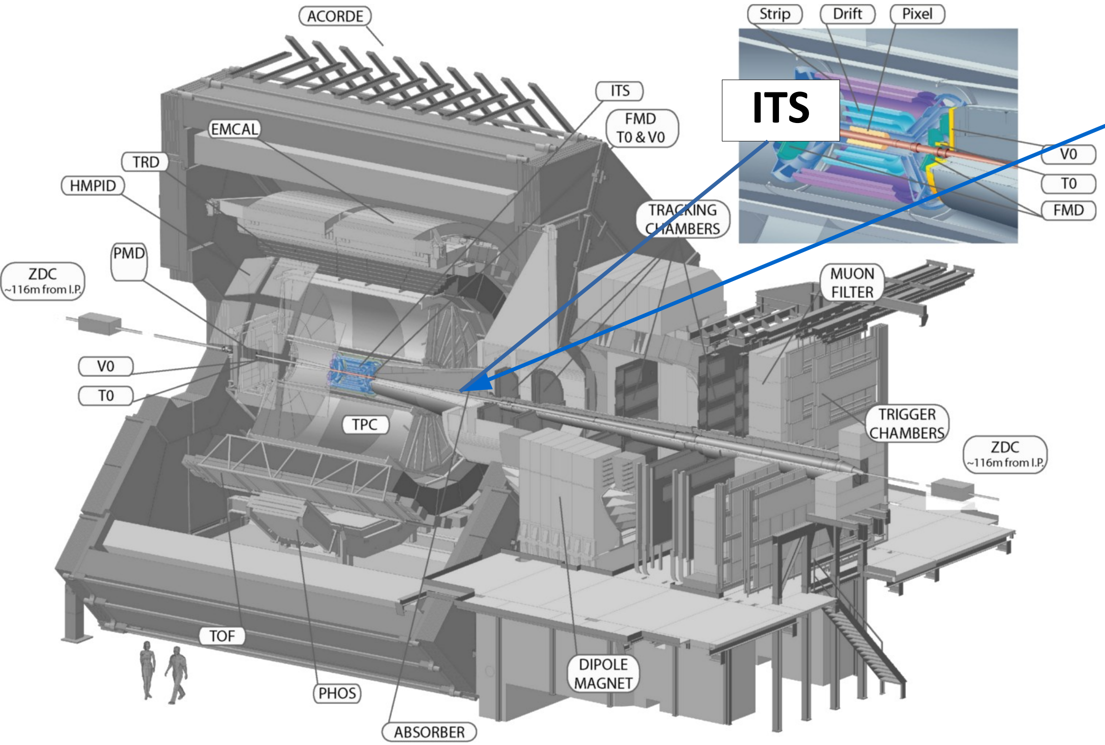

Inner Tracking System (ITS) :

- Primary vertex
- Tracking
- Particle identification via dE/dx

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

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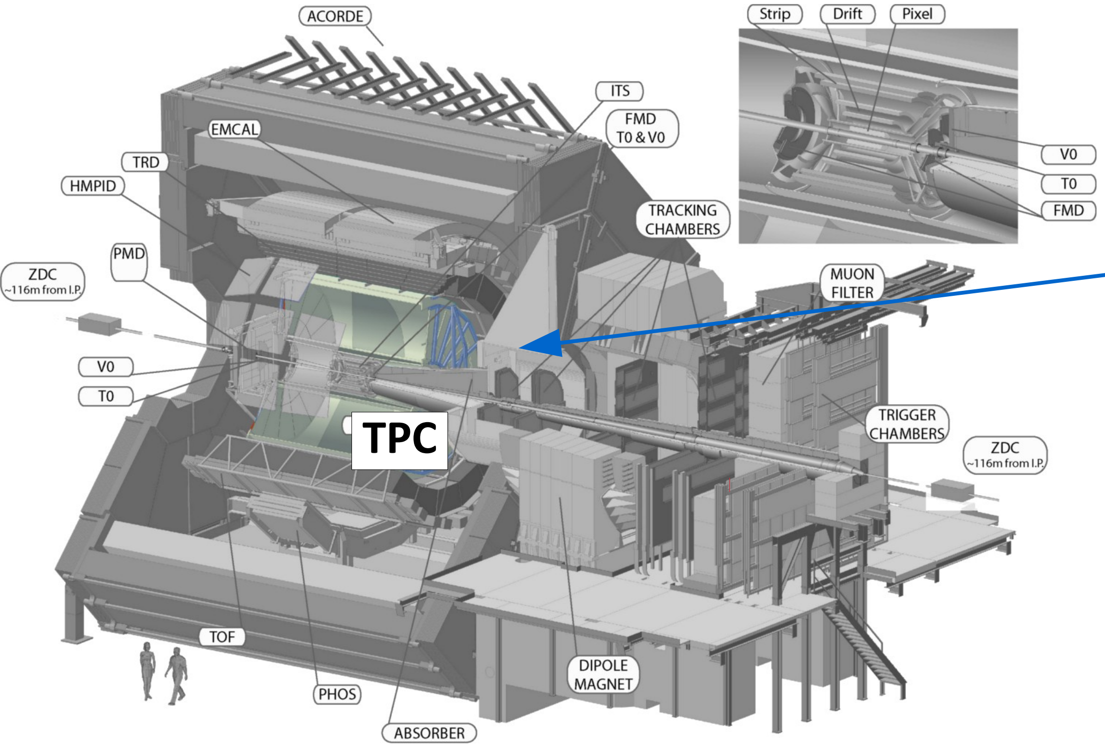

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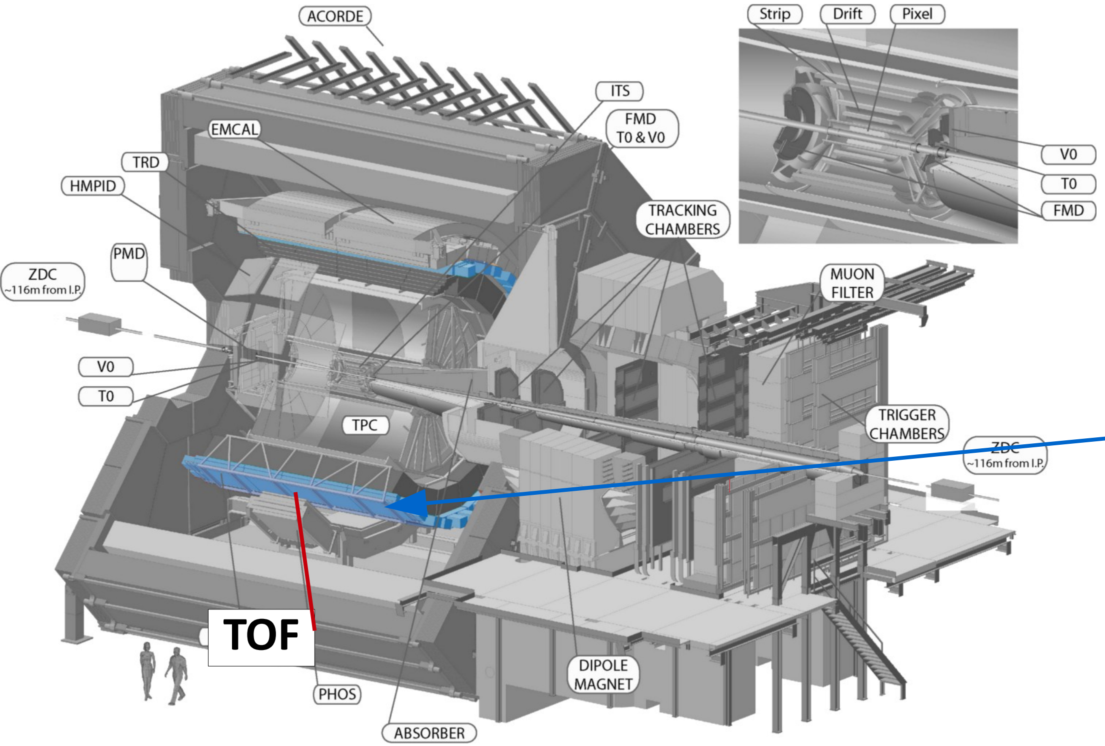

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Time Of Flight (TOF):
- Particle identification via velocity measurement

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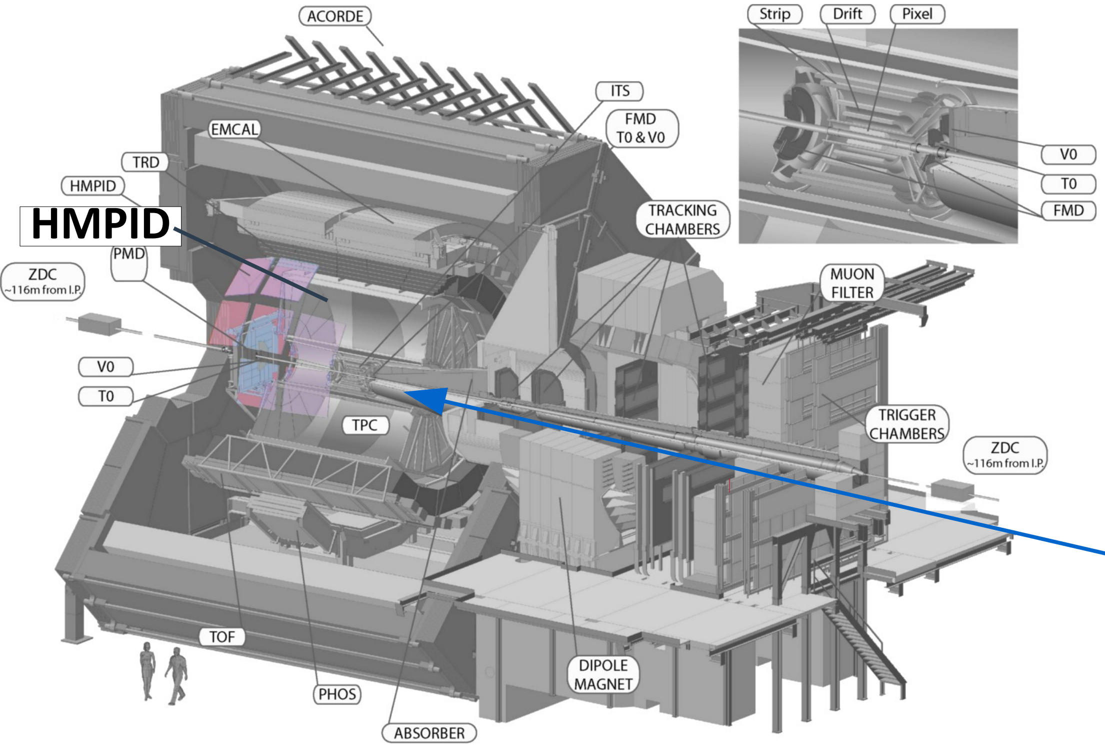

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High Momentum PID (HMPID):
- particle identification via ring imaging Cherenkov

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

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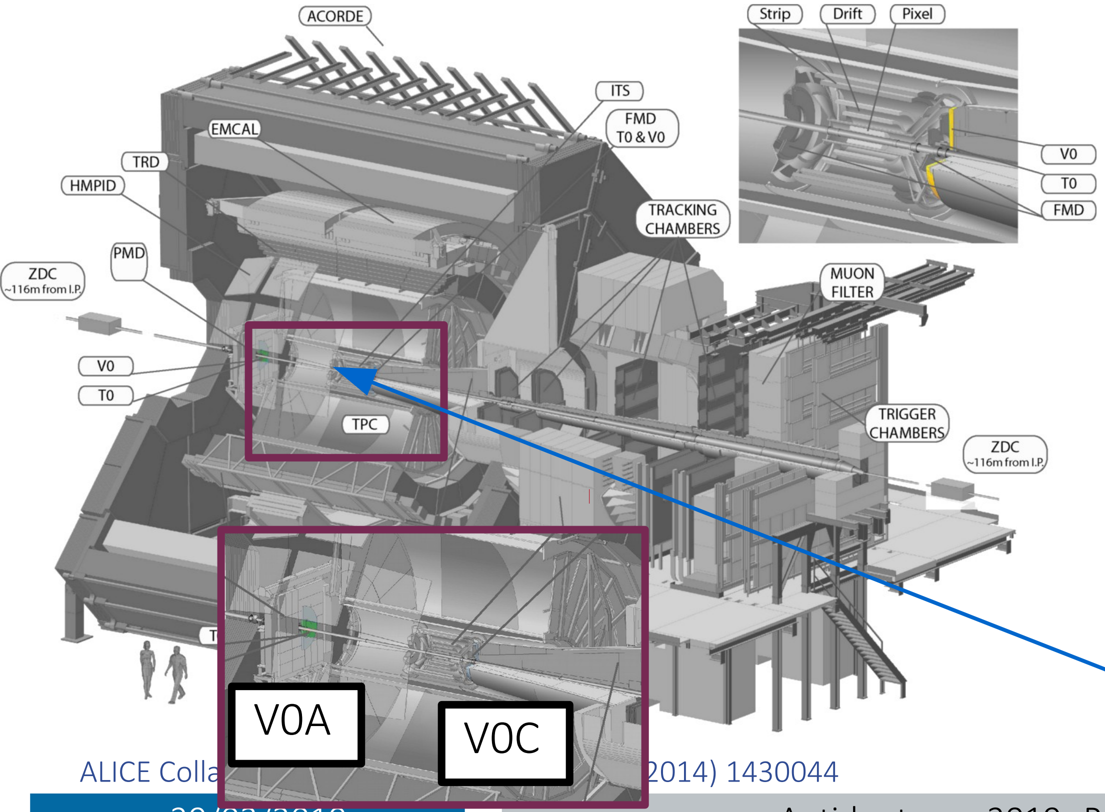

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V0 (A-C): Trigger, beam-gas event rejection, centrality, multiplicity classes

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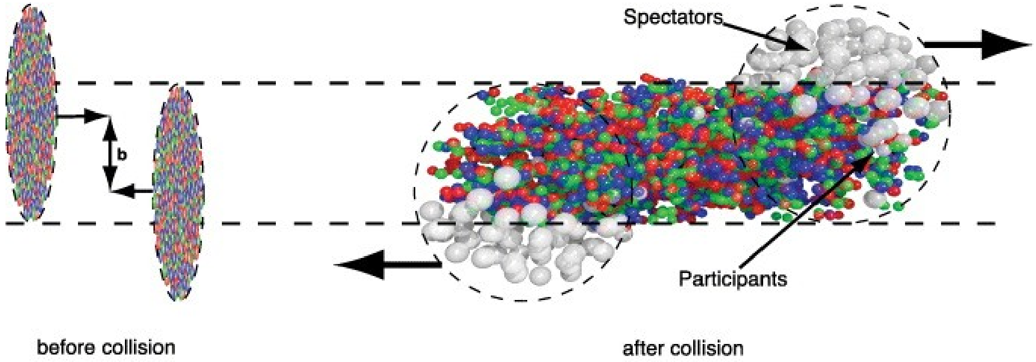
Centrality of the collisions

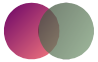


Centrality = degree of overlap of the 2 colliding nuclei

Central collisions:

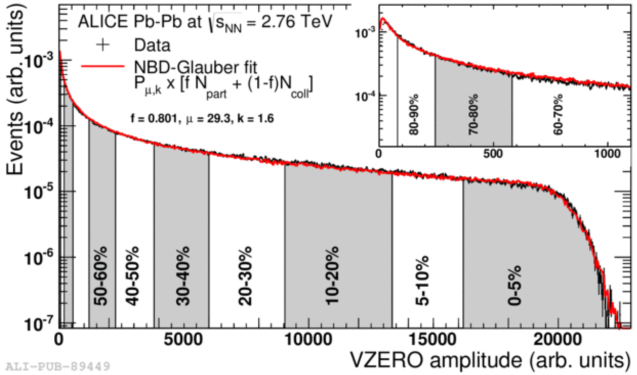
- small impact parameter *b*
- high number of participant nucleons → high multiplicity

Peripheral collisions:

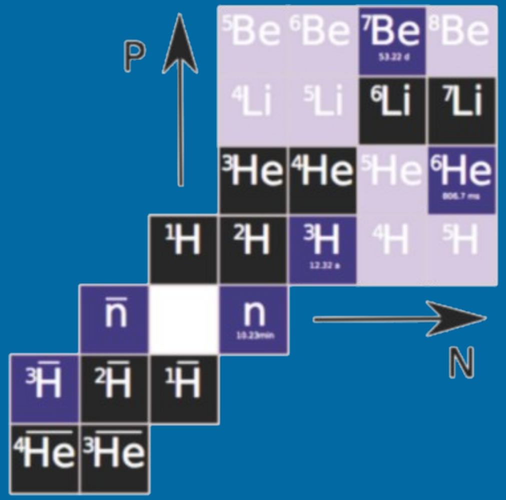


- large impact parameter *b*
- low number of participant nucleons → low multiplicity

Centrality connected to observables via Glauber model



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

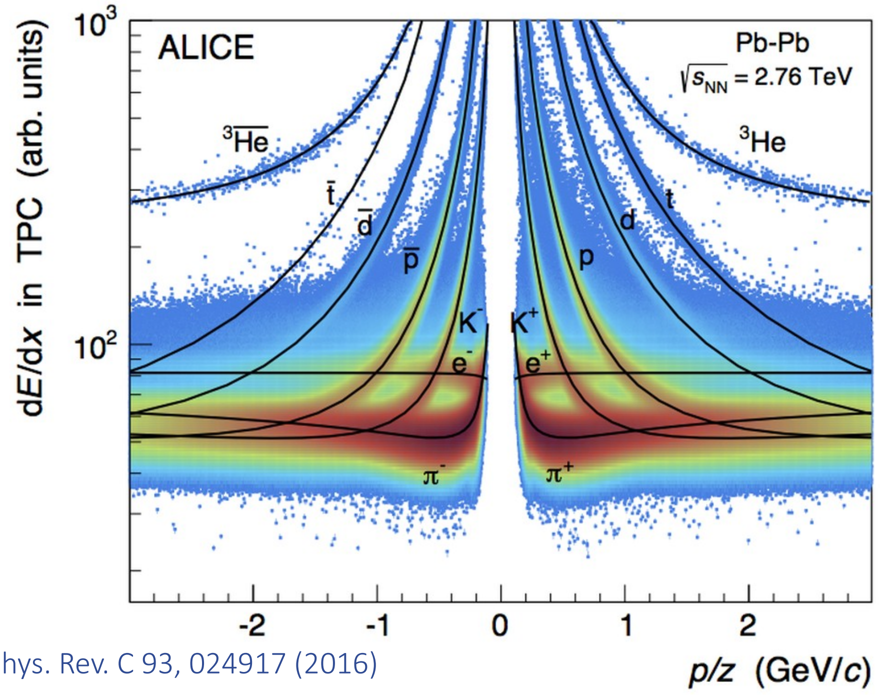


Production of light (anti-)nuclei

Identification of nuclei

Low momenta: specific energy loss in the TPC

- Nuclei identification via dE/dx measurement in the TPC:
  - dE/dx resolution in central Pb-Pb collisions: around 6.5%
  - Excellent separation of (anti-)nuclei from other particles over a wide range of momenta



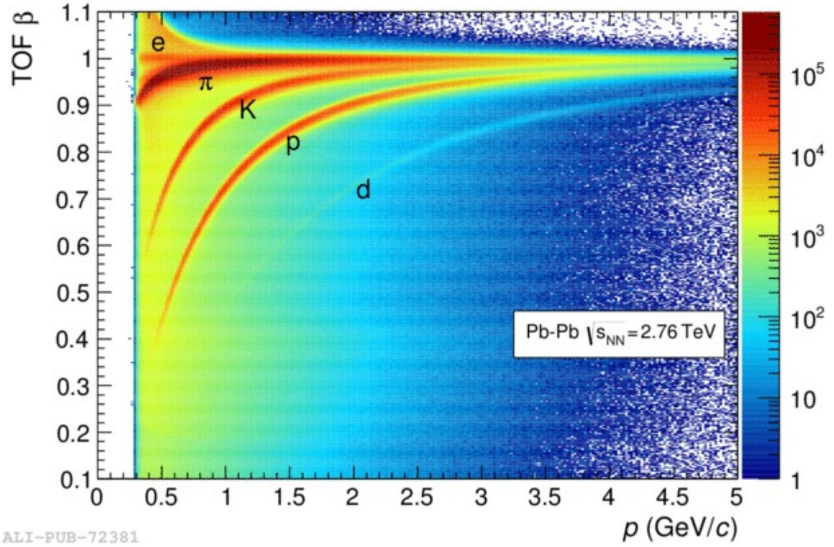
– Bethe-Bloch curves

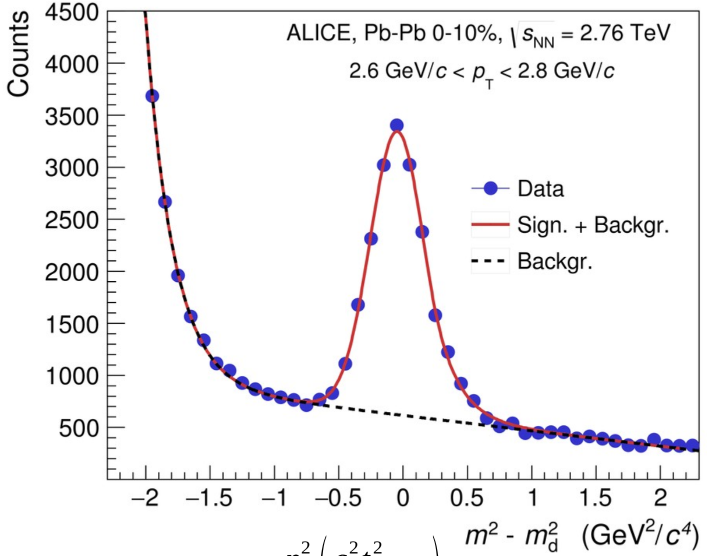
(rigidity)

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





$$m^2 = \frac{p^2}{c^2}\left(\frac{c^2 t^2}{L^2} - 1\right)$$

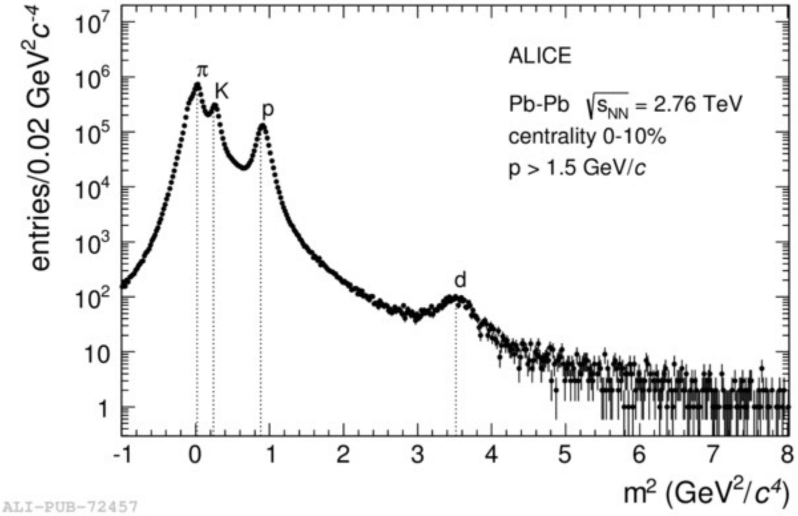
ALICE Collaboration, Int. J. Mod. Phys. A 29 (2014) 1430044

Identification of nuclei

Higher momenta: Cherenkov angle determination in the HMPID

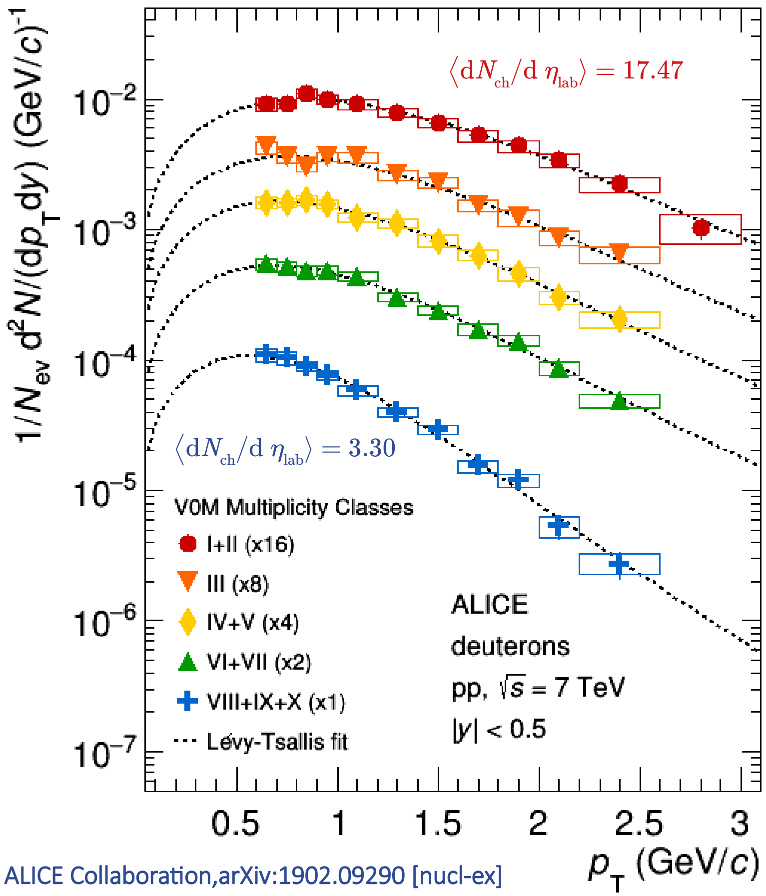
- The particle identification in the HMPID detector is based on the measurement of the Cherenkov radiation ($\theta_{Cherenkov}$) which allows us to determine the square mass of the particle by the following formula:

$$m^2 = p^2 \left(n^2 \cos^2\theta_{Cherenkov} - 1\right) \qquad \cos\theta_{Cherenkov} = \frac{1}{n\beta}$$

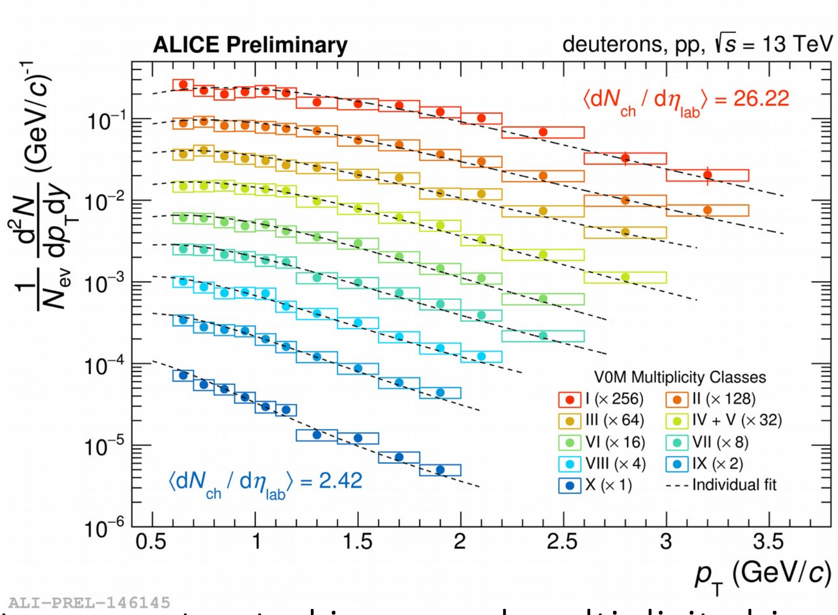


ALICE Collaboration, Int. J. Mod. Phys. A 29 (2014) 1430044

Deuteron p_T spectra in pp collisions



ALICE Collaboration,arXiv:1902.09290 [nucl-ex]

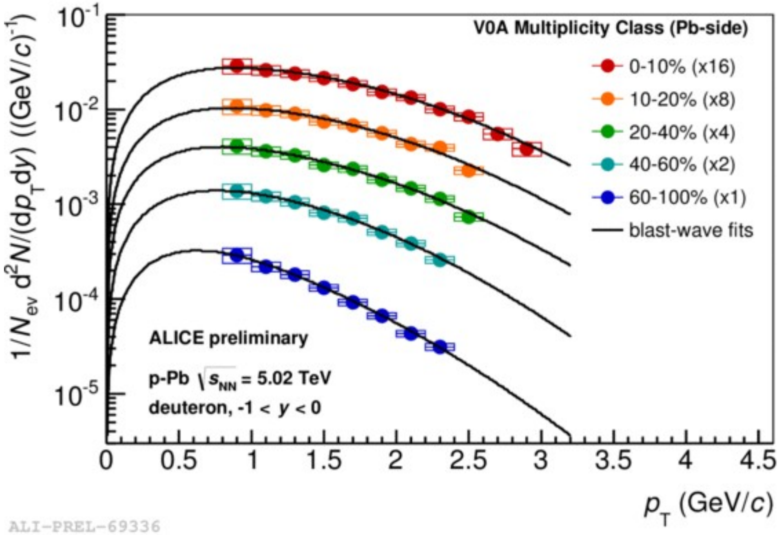


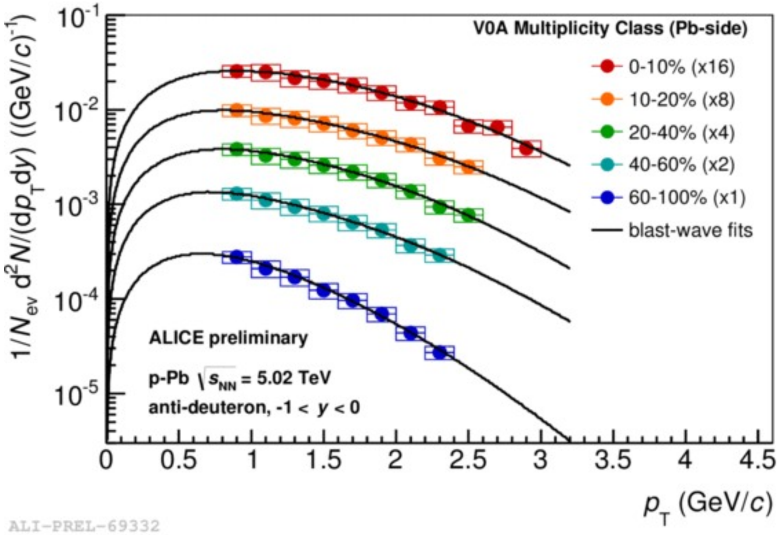
Spectra are extracted in several multiplicity bins and fitted with Lévy-Tsallis function for the extraction of yields

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = \frac{dN}{dy}\frac{(n-1)(n-2)}{2\pi nC[nC+m_0(n-2)]}\left(1+\frac{m_T-m_0}{nC}\right)^{-n}$$

C. Tsallis, J. Stat. Phys. 52 , 479 (1988) 980
STAR Collaboration, Phys. Rev. C75, 064901 981 (2007)

Deuteron p_T spectra in p-Pb collisions





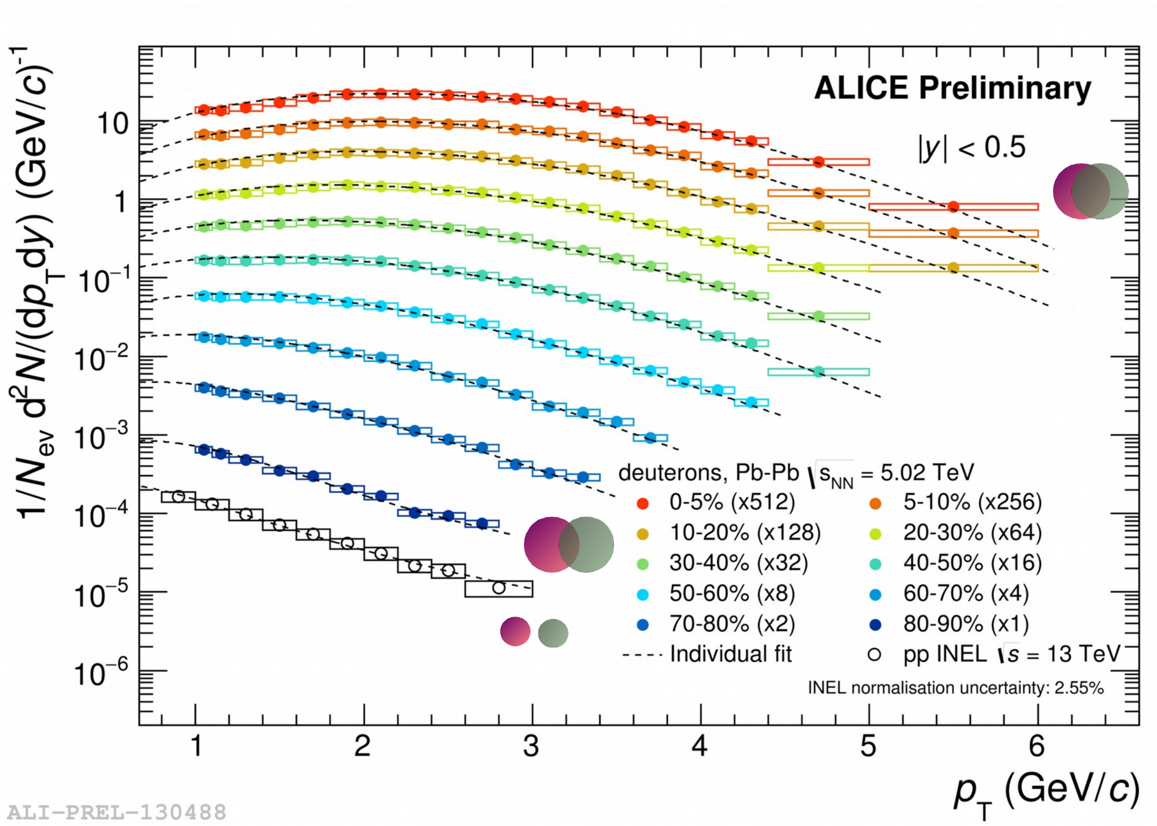
Spectra are extracted in several multiplicity bins and fitted with blast-wave function for the extraction of yields

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\, dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

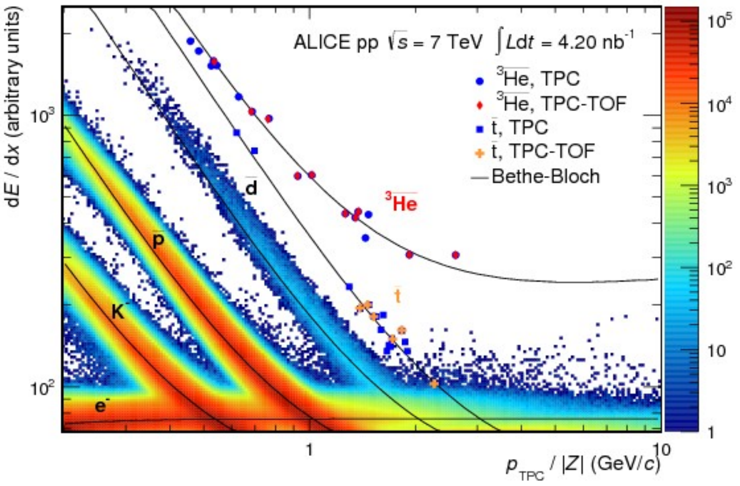
E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)

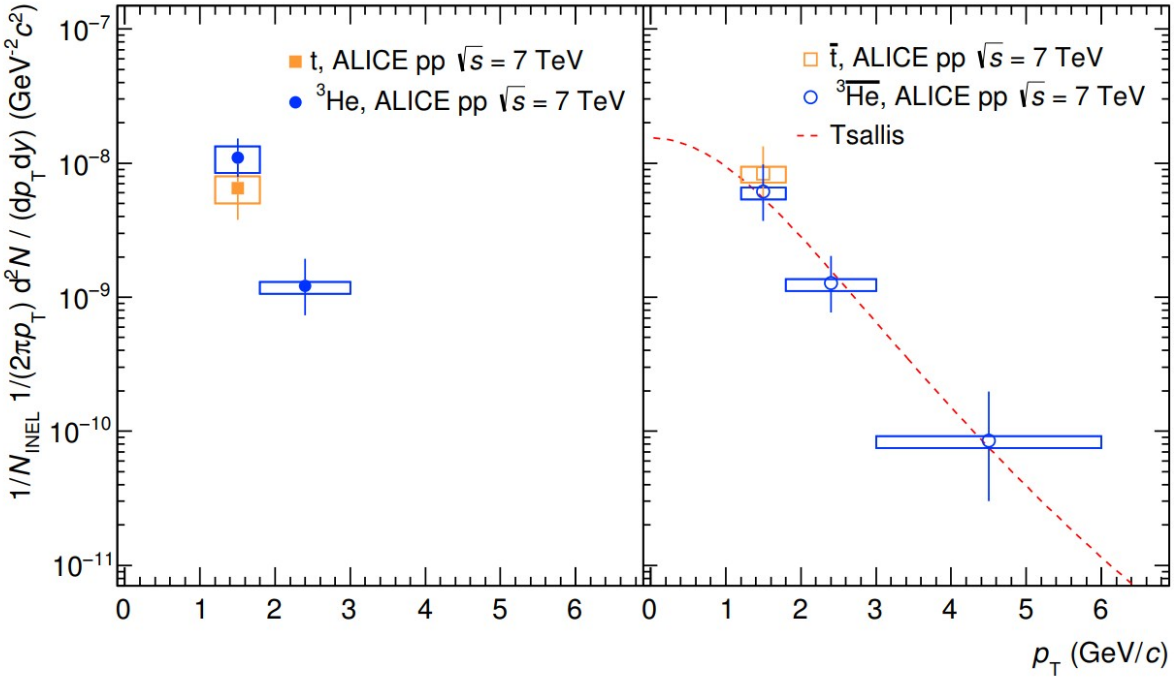
Deuteron p_T spectra in Pb-Pb collisions

ALICE-PUBLIC-2017-006



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

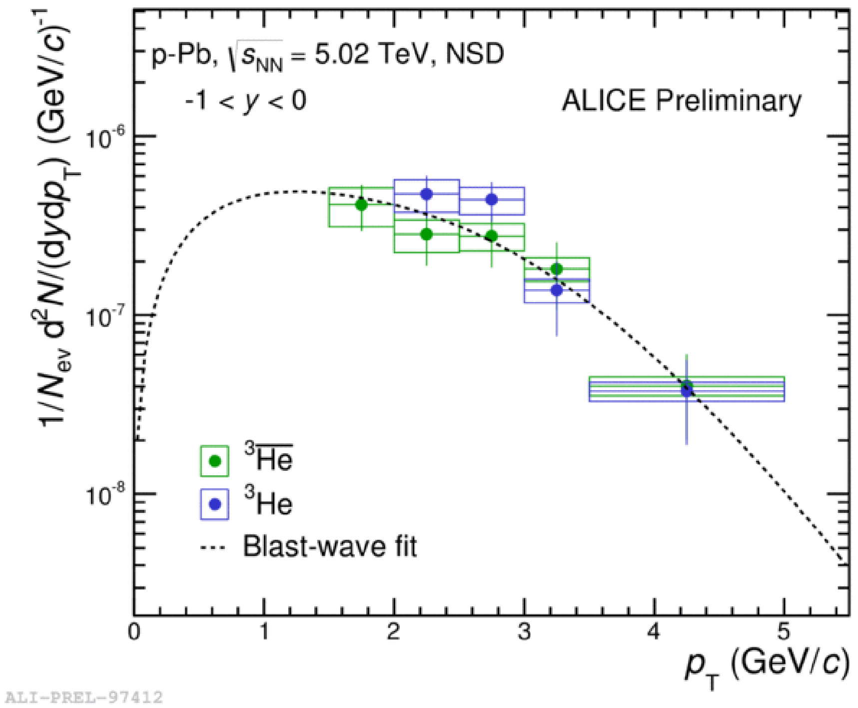


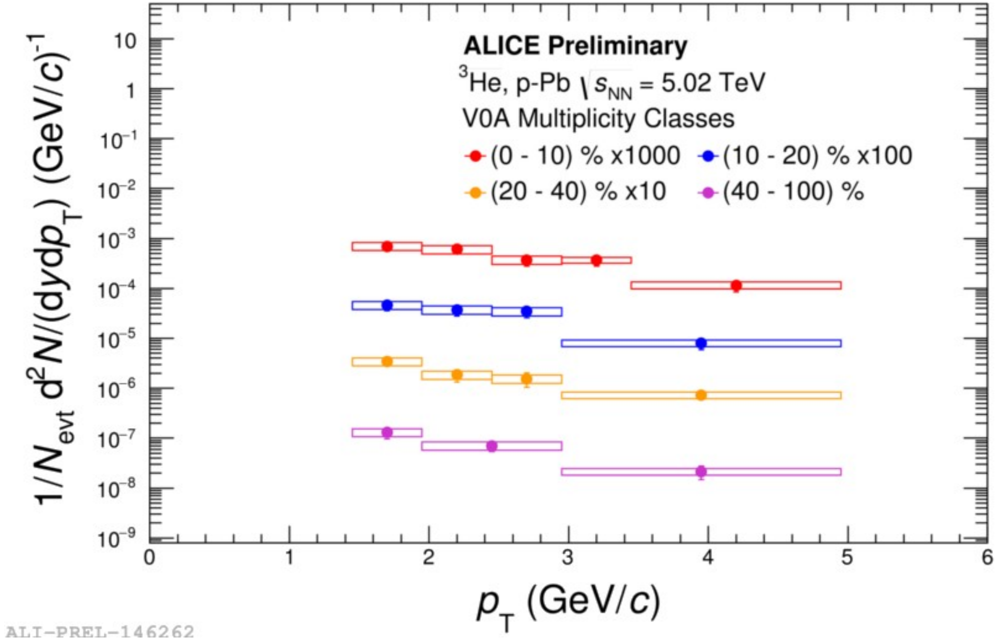


<u>First ever measurements</u> of $\bar{\text{t}}$ and $^3\overline{\text{He}}$ nuclei in pp collisions

ALICE Collaboration, Phys. Rev. C **97**, no.2, 024615 (2018)

^{3}He p_T spectra in p-Pb collisions

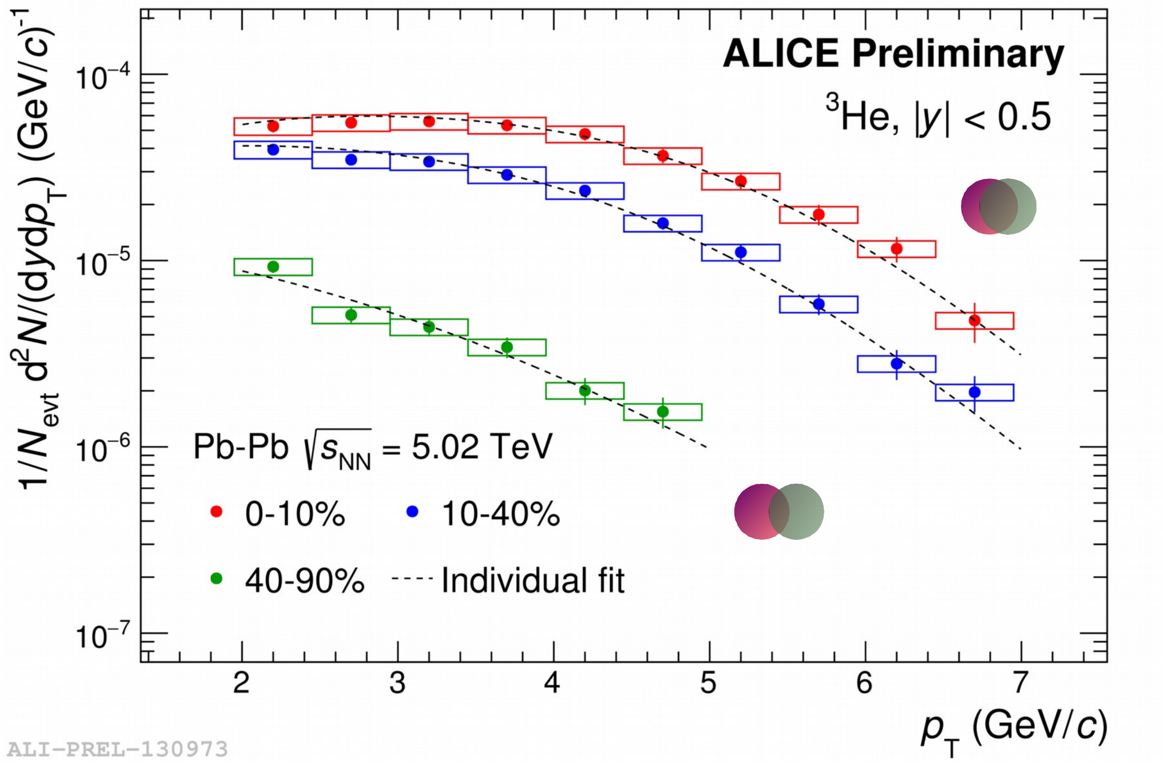




Spectra are extracted in several multiplicity bins and and fitted with blast-wave function for the extraction of yields

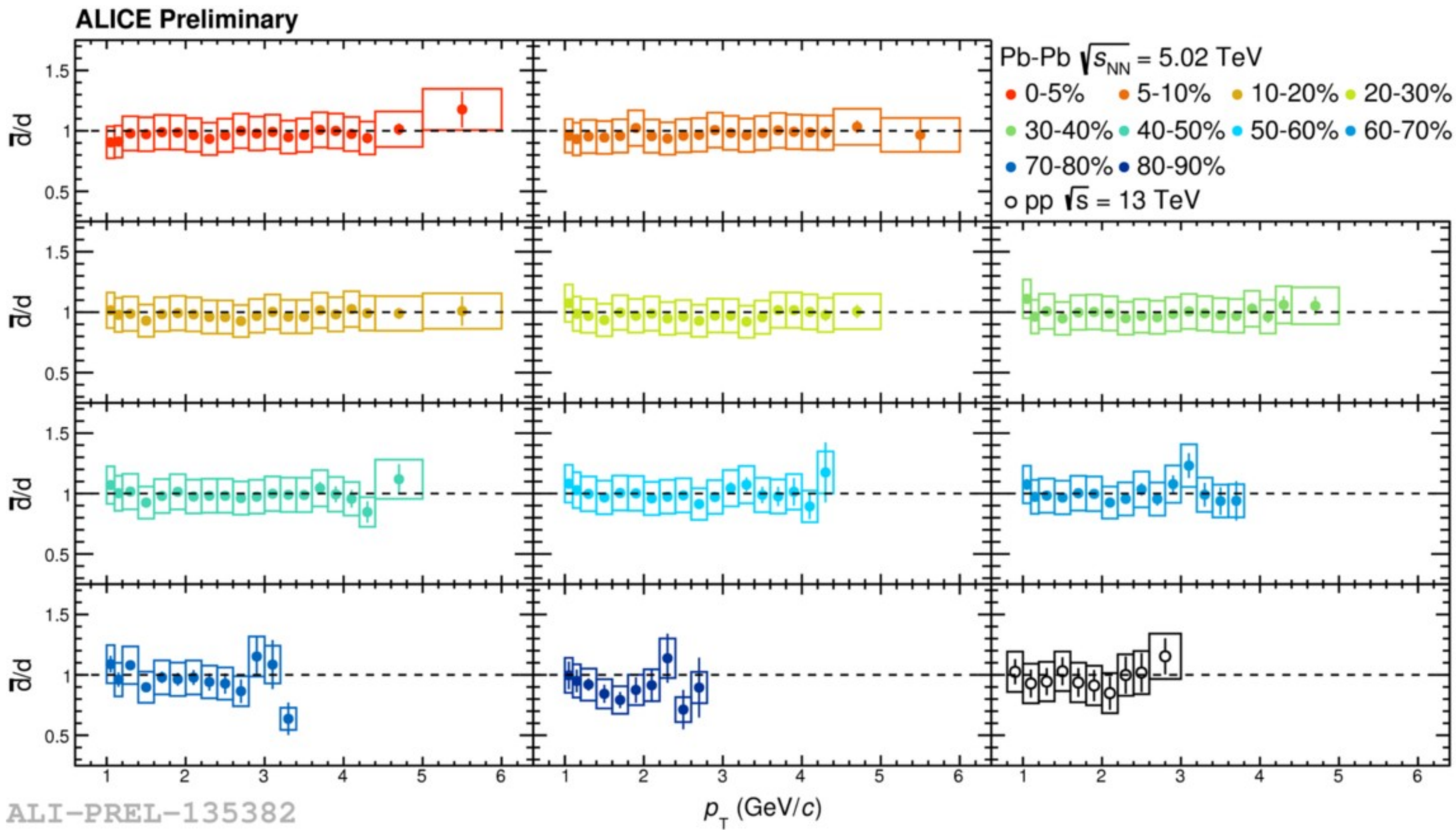
^{3}He p_T spectra in Pb-Pb collisions

ALICE-PUBLIC-2017-006



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

Anti-Matter production



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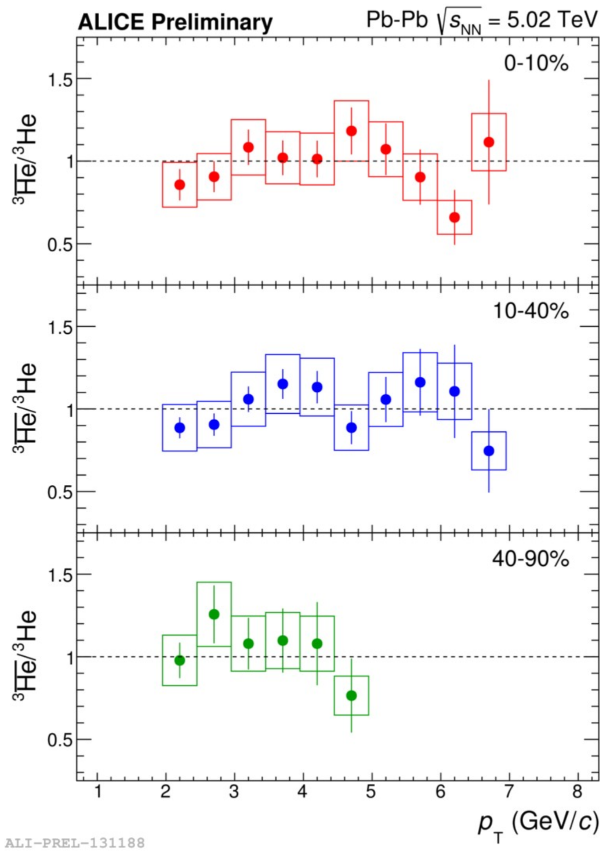
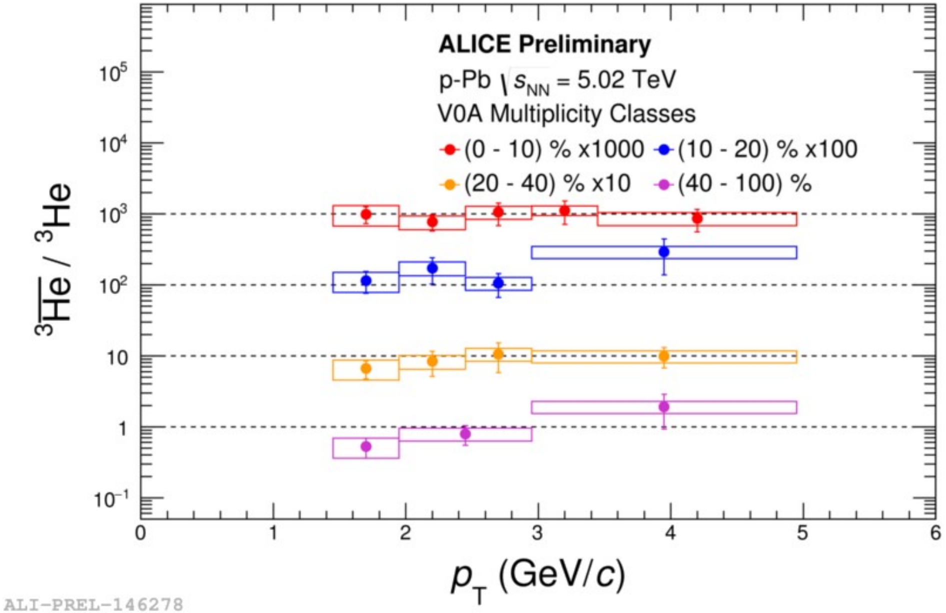
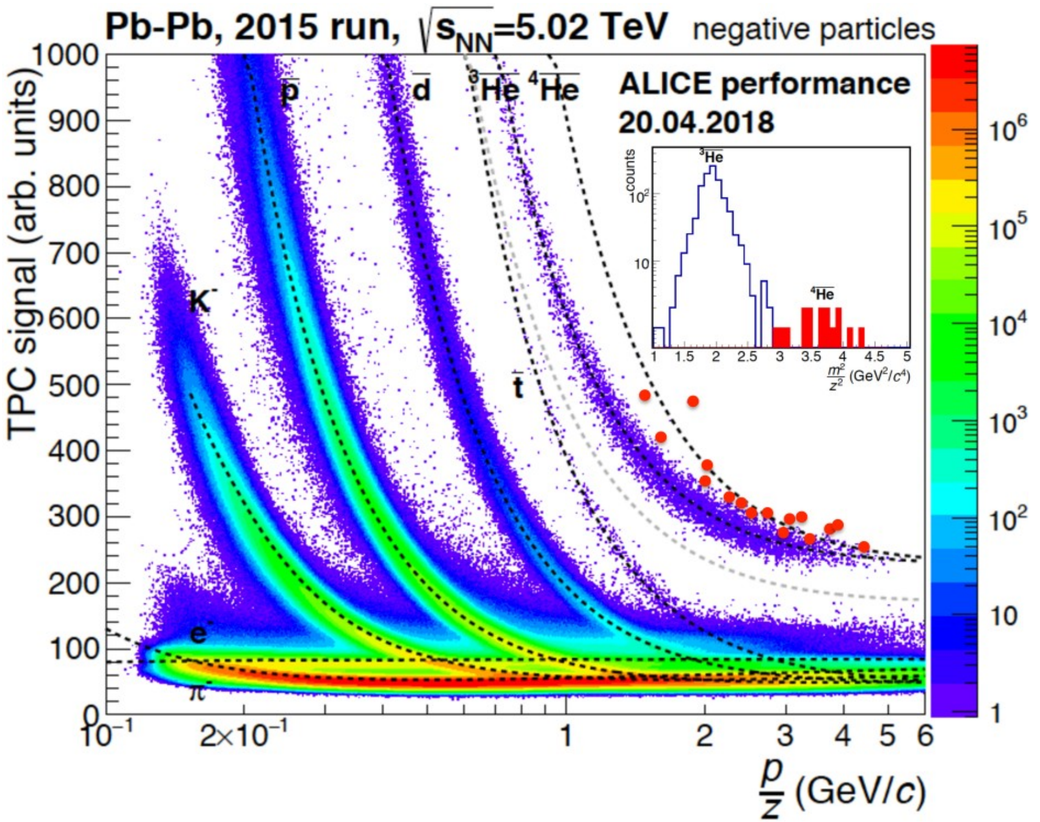




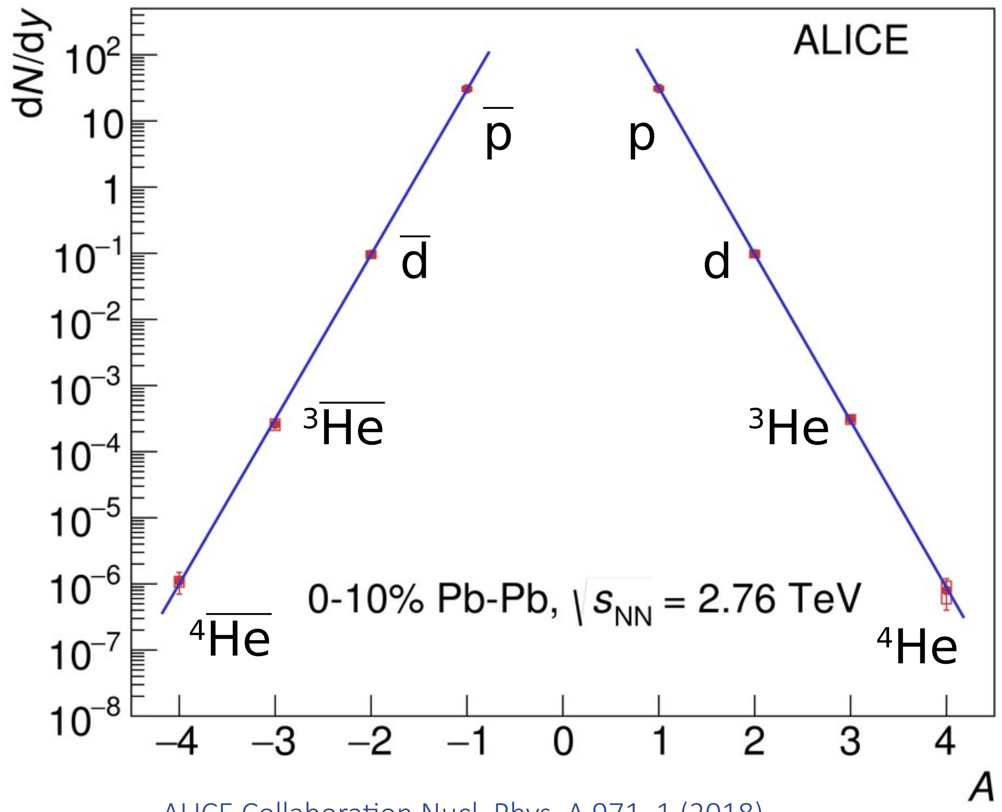
- Anti-nuclei/nuclei ratios are consistent with unity (similar to other light particle species) in the measured p_T-interval
- Ratios are constant as a function of p_T and centrality

$^4\overline{He}$ 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
- ±3σ from the expected value for ^{4}He
- Signal extraction from mass squared distribution obtained using TOF

Nuclei production yield



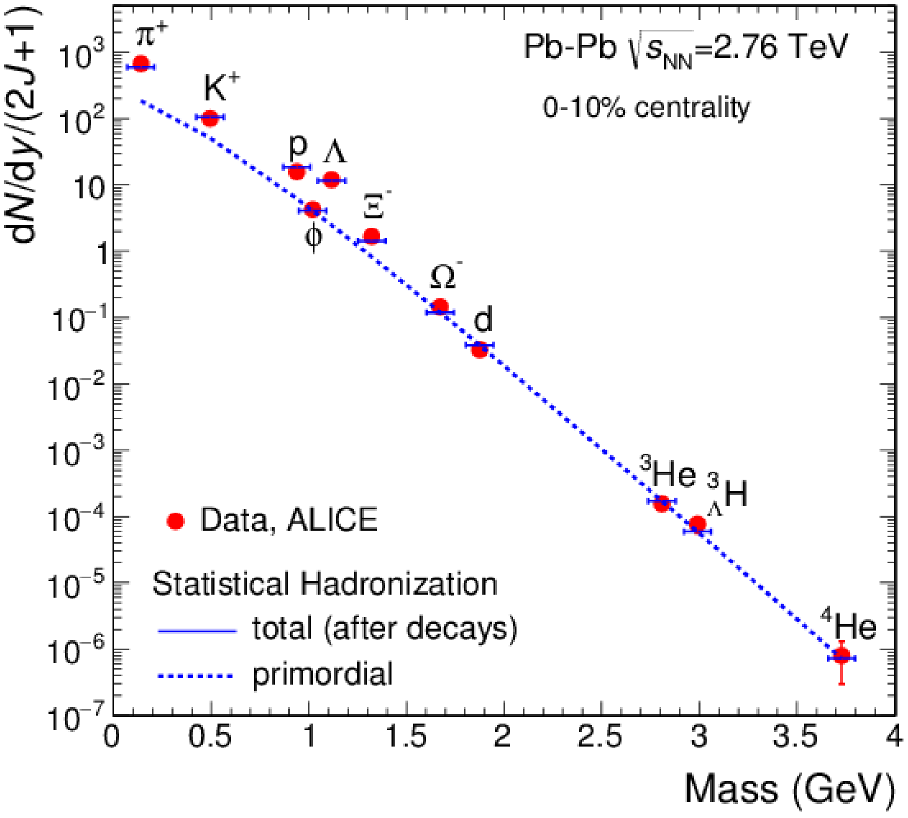
ALICE Collaboration Nucl. Phys. A 971, 1 (2018)

Exponential decrease of the nuclei yield with the mass number

Penalty factor for adding one baryon:

- ~350 in Pb-Pb collisions
- ~600 in p-Pb collisions
- ~1000 in pp collisions

Thermal model



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

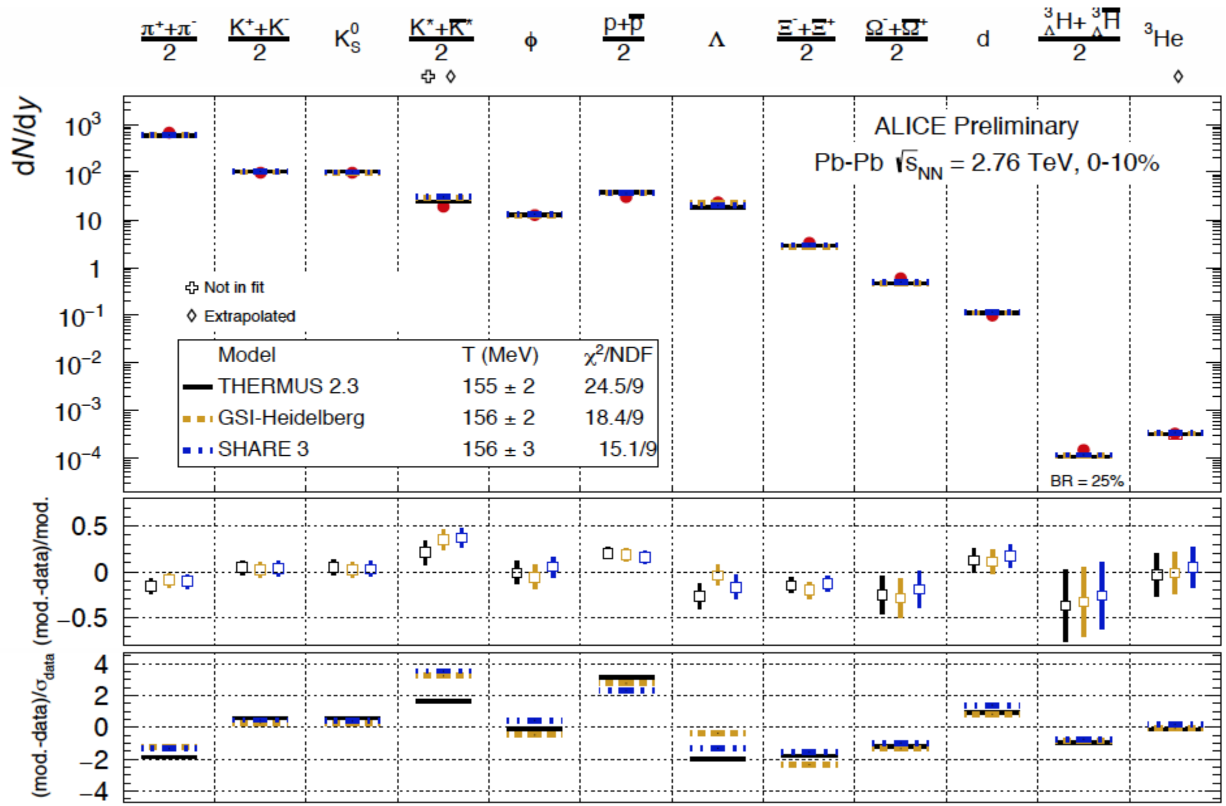
Statistical hadronization model: thermal emission from equilibrated source

Particle abundances fixed at chemical freeze-out

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

- 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

Thermal model fit to ALICE 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

- The p_T-integrated yields and ratios can be interpreted in terms of statistical (thermal) models
- Particle yields of light flavor hadrons (including nuclei) are described with a common chemical freeze-out temperature (T_{chem} = 156 ± 2 MeV)

Coalescence model

- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed

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- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

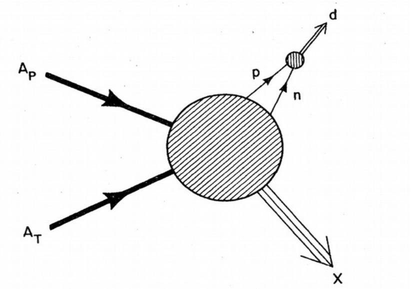

FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.

Coalescence model

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- 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

$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A$$

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

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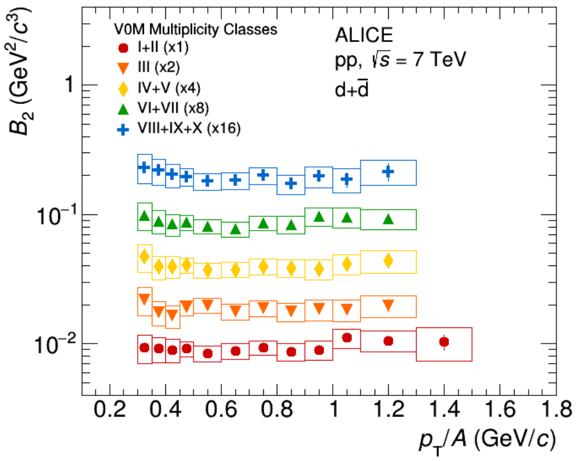
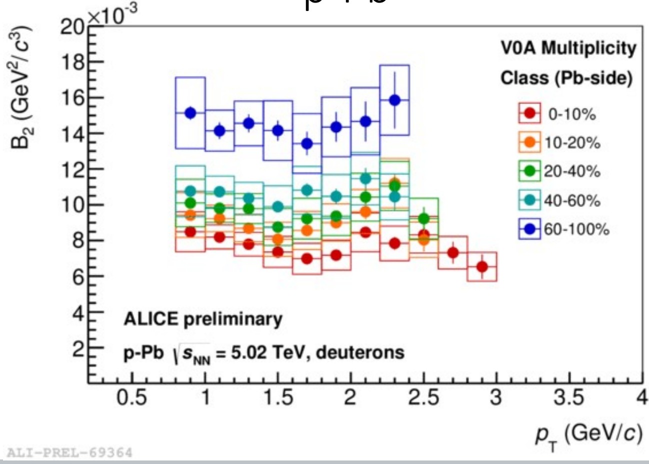
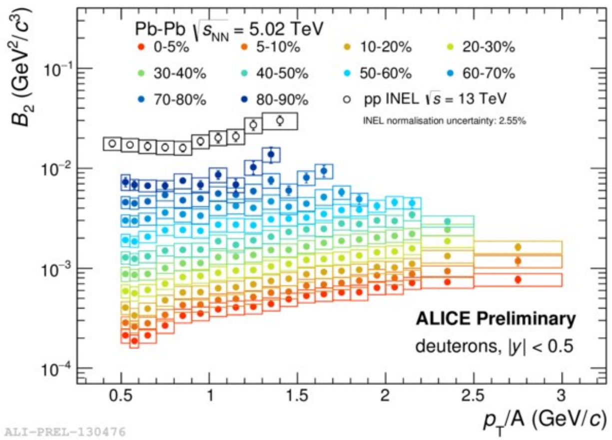
pp



p-Pb



Pb-Pb



Coalescence model

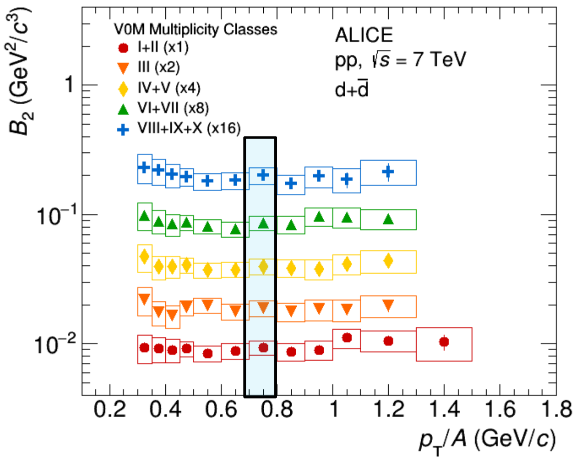
- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that p an n have the same mass and have the same p_T spectra, the yield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

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

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

$p_T/A = 0.75$ GeV/c

pp



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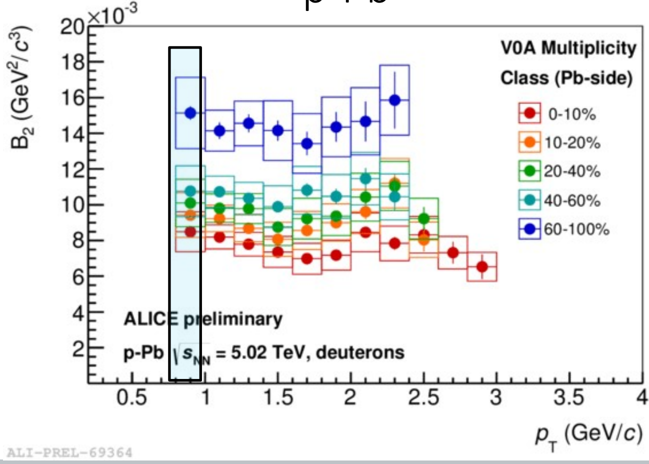

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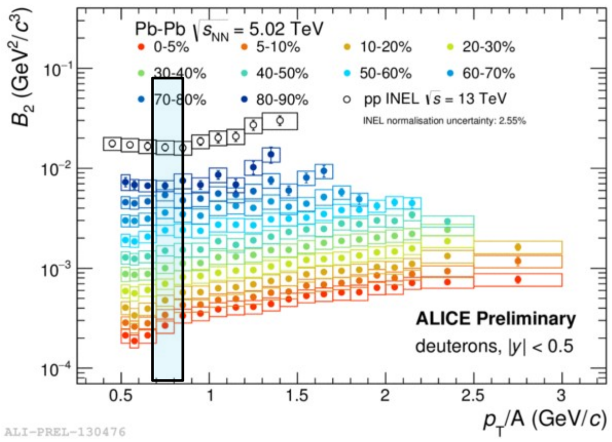
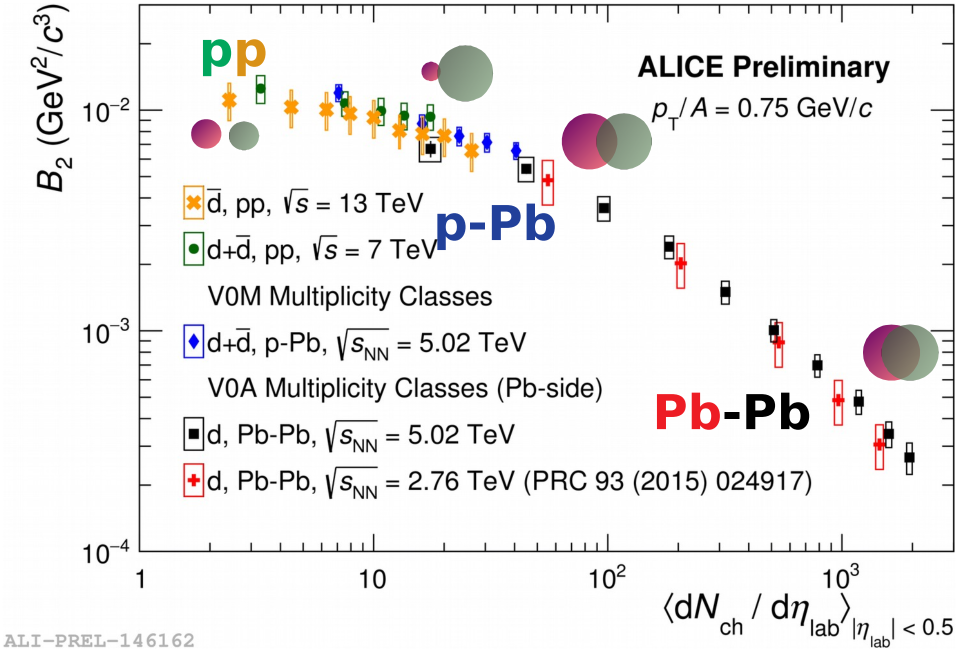


Coalescence parameter B_2



Simple coalescence model

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

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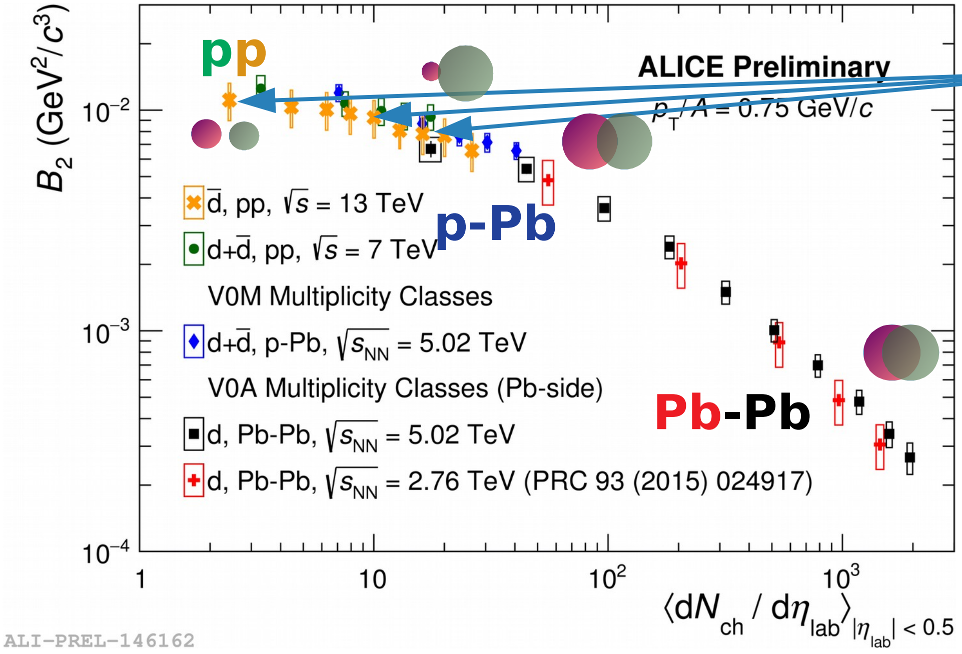

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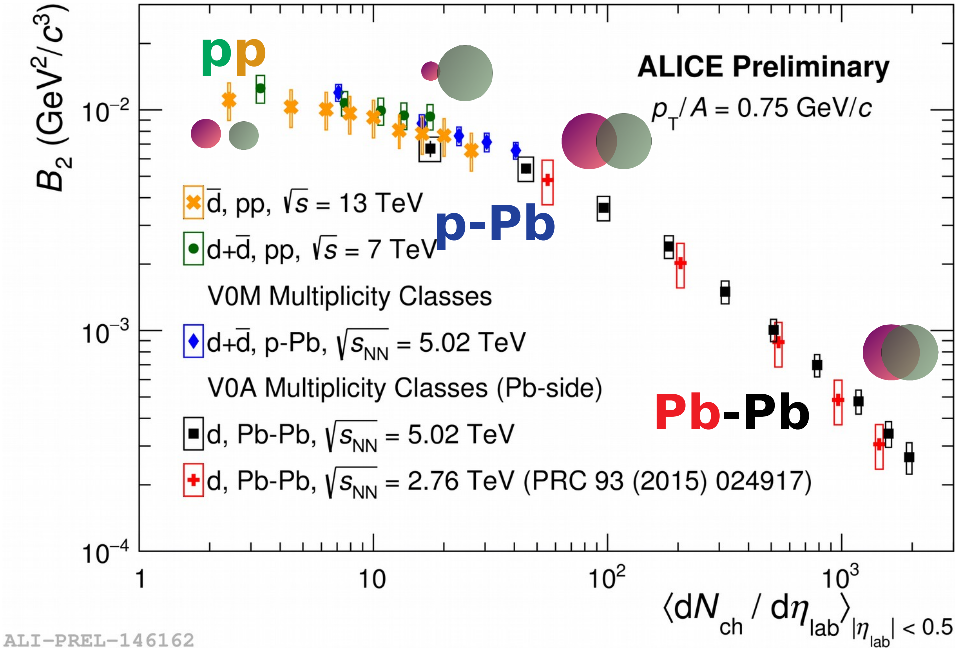

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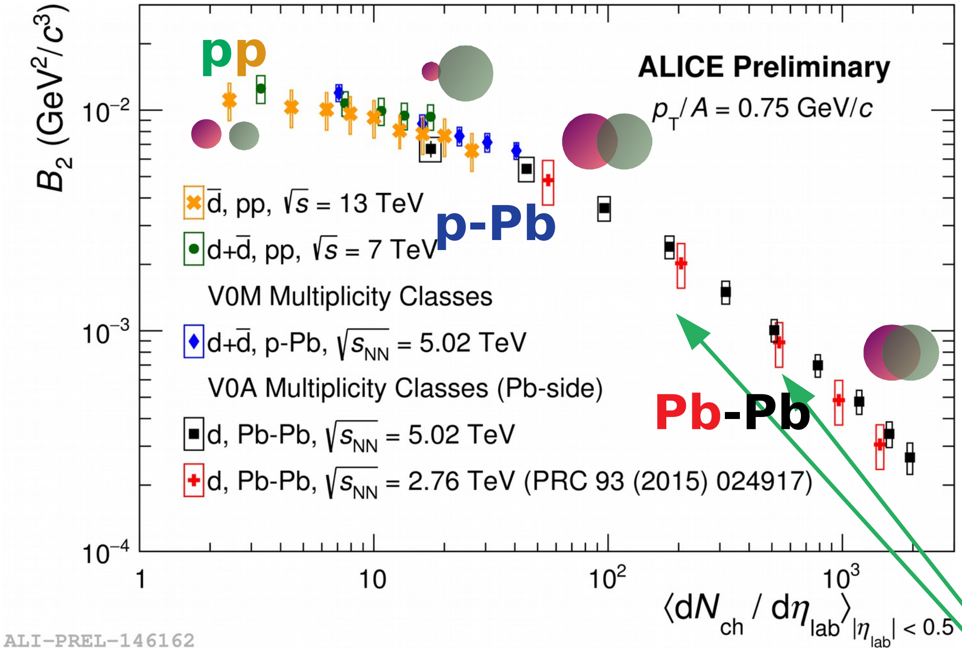
More elaborate coalescence model takes into account the volume of the source:

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

- 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

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

Coalescence parameter B_2



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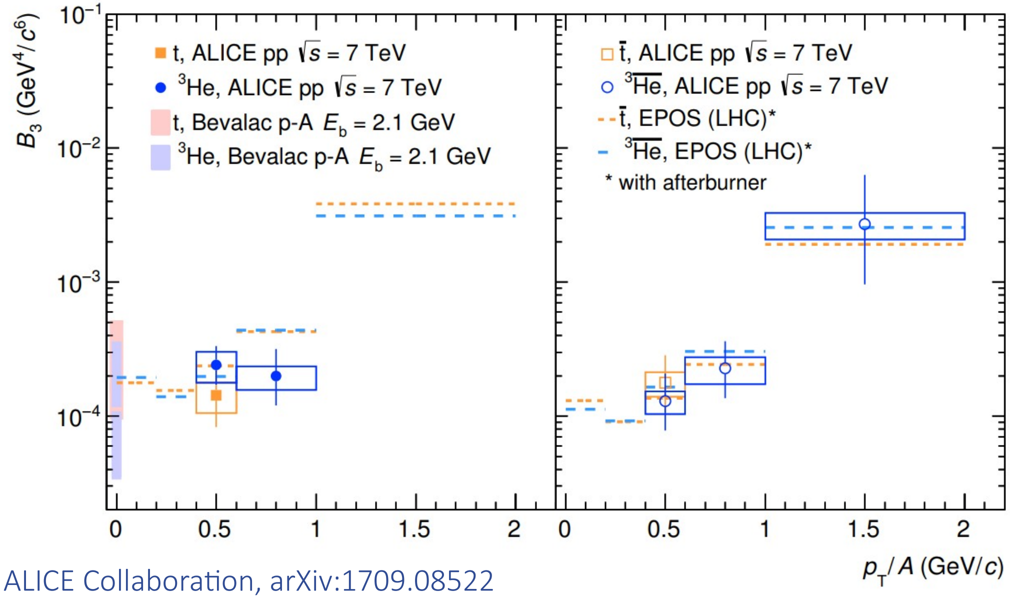
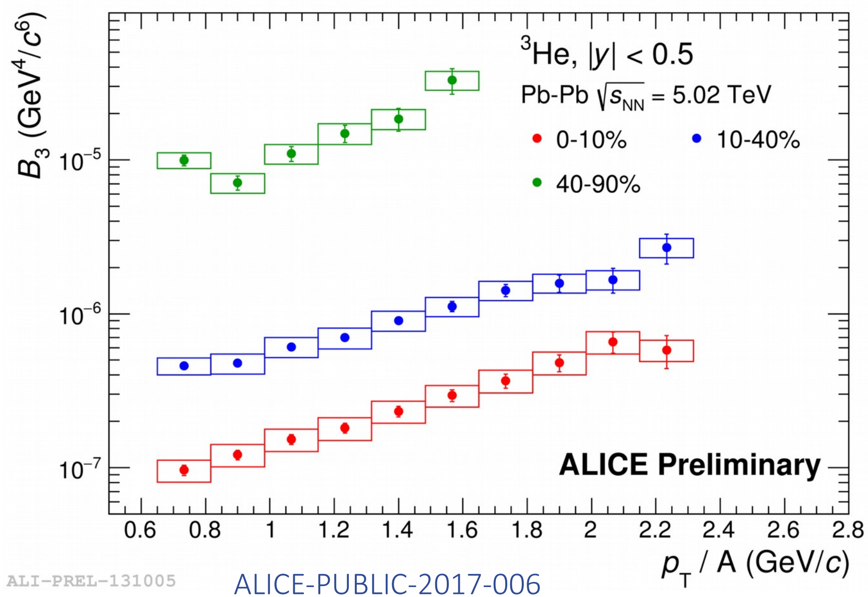
Coalescence parameter B_3

pp



ALICE Collaboration, arXiv:1709.08522

Pb-Pb



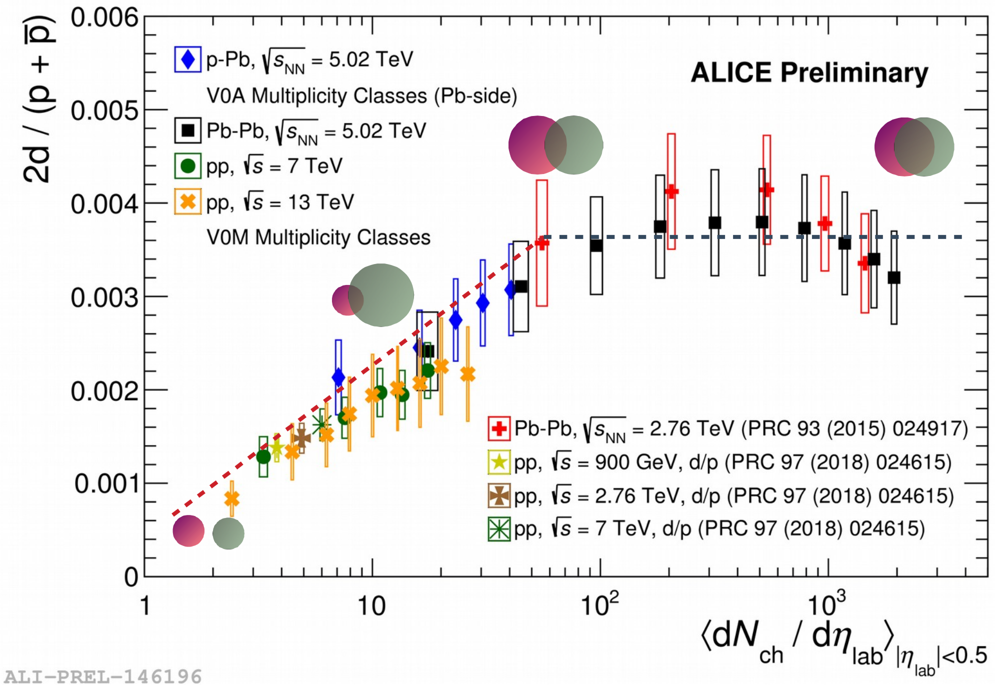
ALICE-PUBLIC-2017-006

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

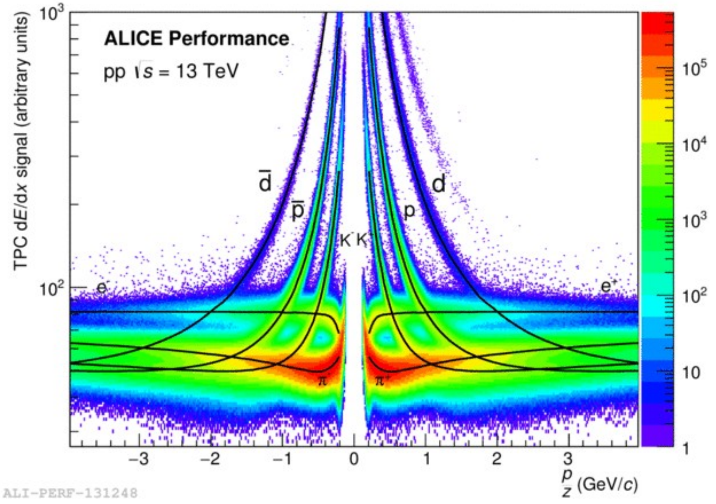
First ever measurements of the B_3 of $\bar{t}$ and $^3\overline{He}$ in pp collisions

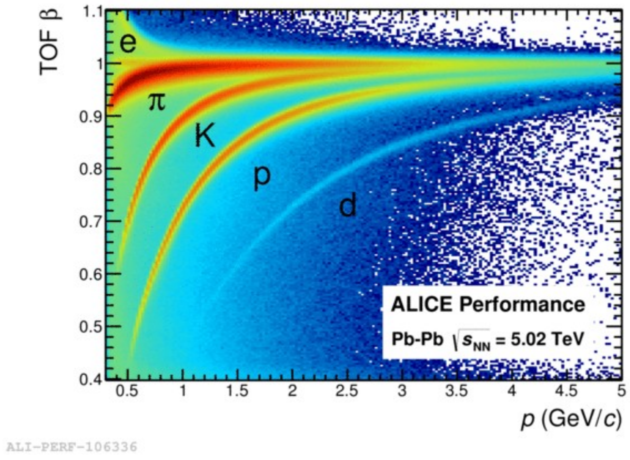
Increasing trend with p_T and centrality observed in Pb-Pb collision

Light nuclei production: Deuteron to proton ratio



- d/p increases with multiplicity going from pp to peripheral Pb-Pb : consistent with simple coalescence ($d \propto p^2$)
- No significant centrality dependence in Pb-Pb : consistent with thermal model (yield fixed by T_{chem})
  - Smooth transition: is there a single particle production mechanism?



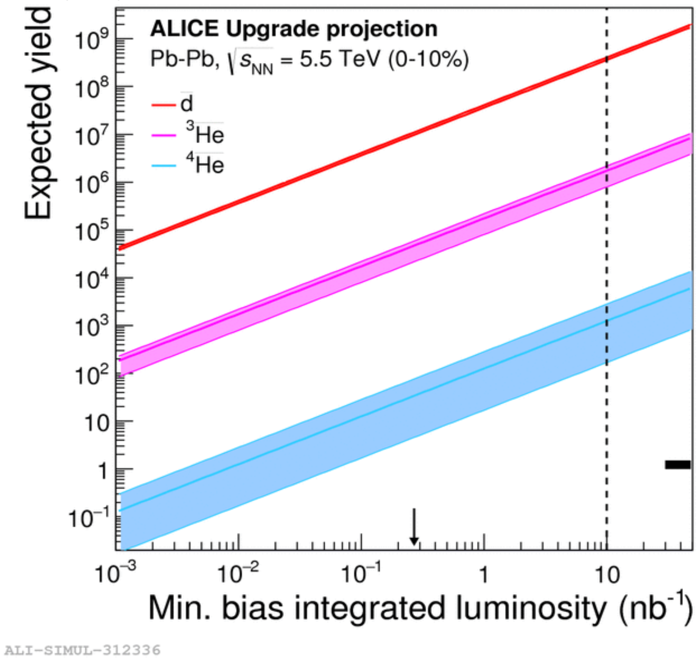


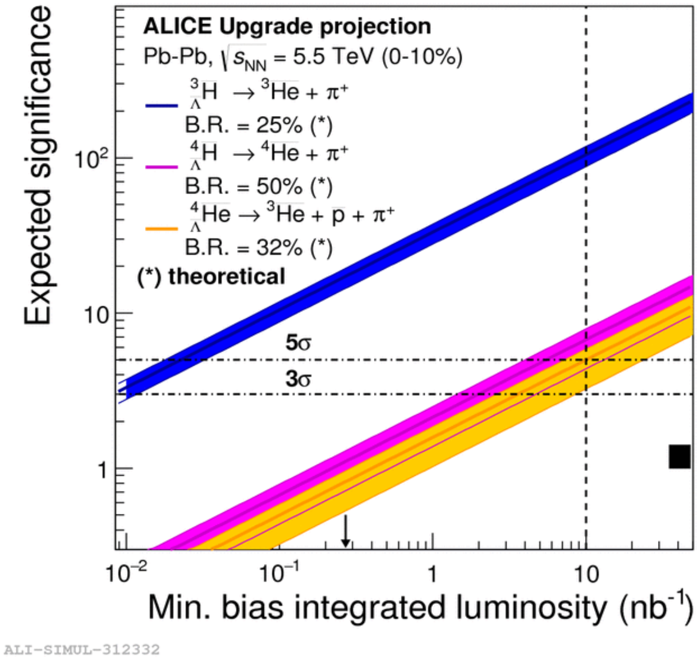
- pp collisions at $\sqrt{s}$ = 13 TeV: new results are expected soon for light (anti-)nuclei production
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 8 TeV collected at the end of 2016 → will provide new and more precise measurements
- Pb-Pb run at the end of 2018: expected a significant increase of statistics → more precise measurements

Outlook – ALICE upgrade

After the Long Shutdown 2 ALICE will be able to collect data with better performance at higher luminosity

- Expected integrated luminosity: ~10 nb^{-1} (~ $8x10^{9}$ collisions in the 0-10% centrality class)
- New ITS: less material budget and more precise tracking for the identification of hyper-nuclei
- All the physics done for A = 2 and A = 3 (hyper-)nuclei will be possible also for A = 4





Conclusions

- Study of (anti-) nuclei is an important tool to study hadronization for multi-baryon systems
- Thermal model successfully describes nuclei yields
  - Survival of loosely bound states at T_{chem}>> binding energy is not understood yet
- B_A reveals system size dependence of hadronization
- d/p ratio:
  - Increasing trend (qualitatively) described by coalescence
  - Plateau consistent with thermal model value
- New and more precise data are expected from the LHC on the presented topics in the next years. These will provide stricter constraints to the theoretical models

Backup

“More elaborate” coalescence model

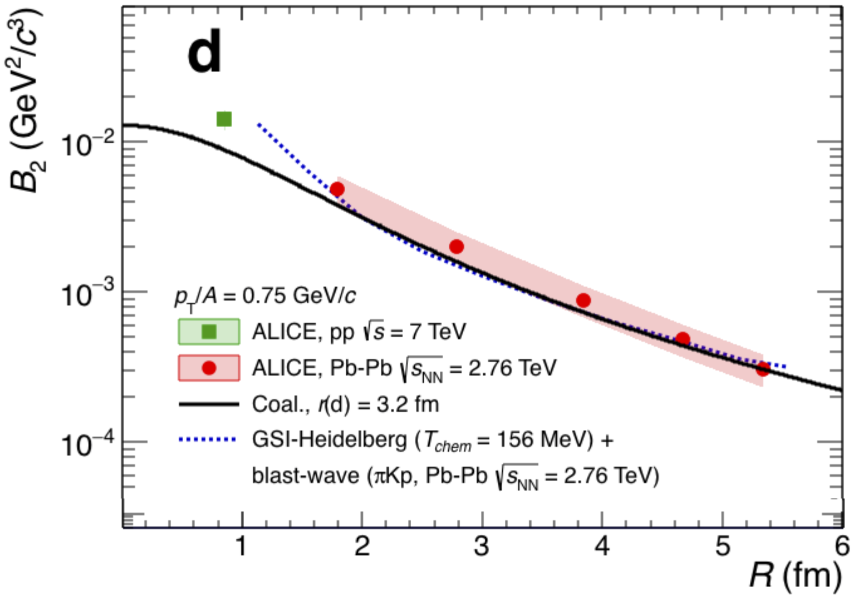
ALICE

- 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, …)

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

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

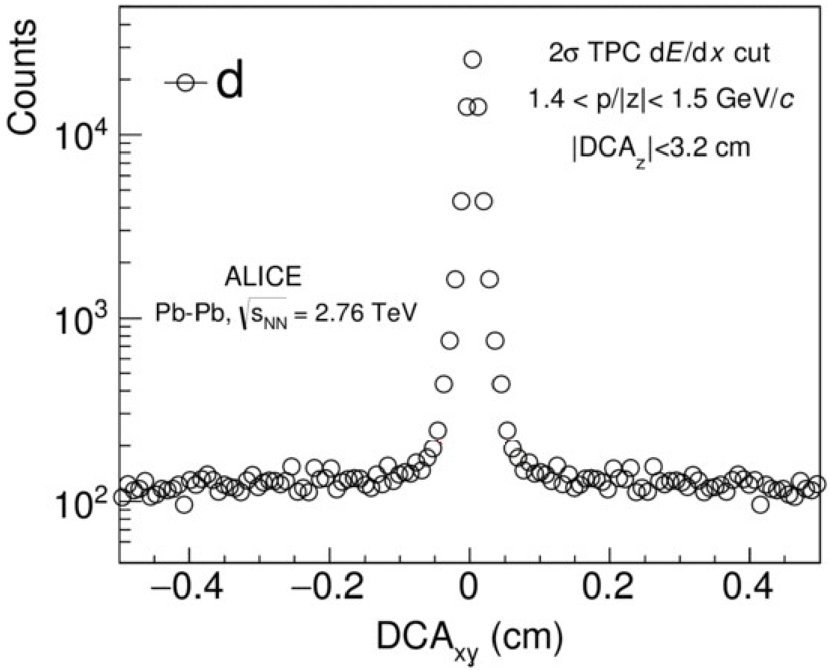
F.Bellini and A. P.Kalweit, arXiv:1807.05894 [hep-ph].



Good description of the data

Identification of nuclei: secondaries

The measurement of nuclei is strongly affected by background from knock-out from material



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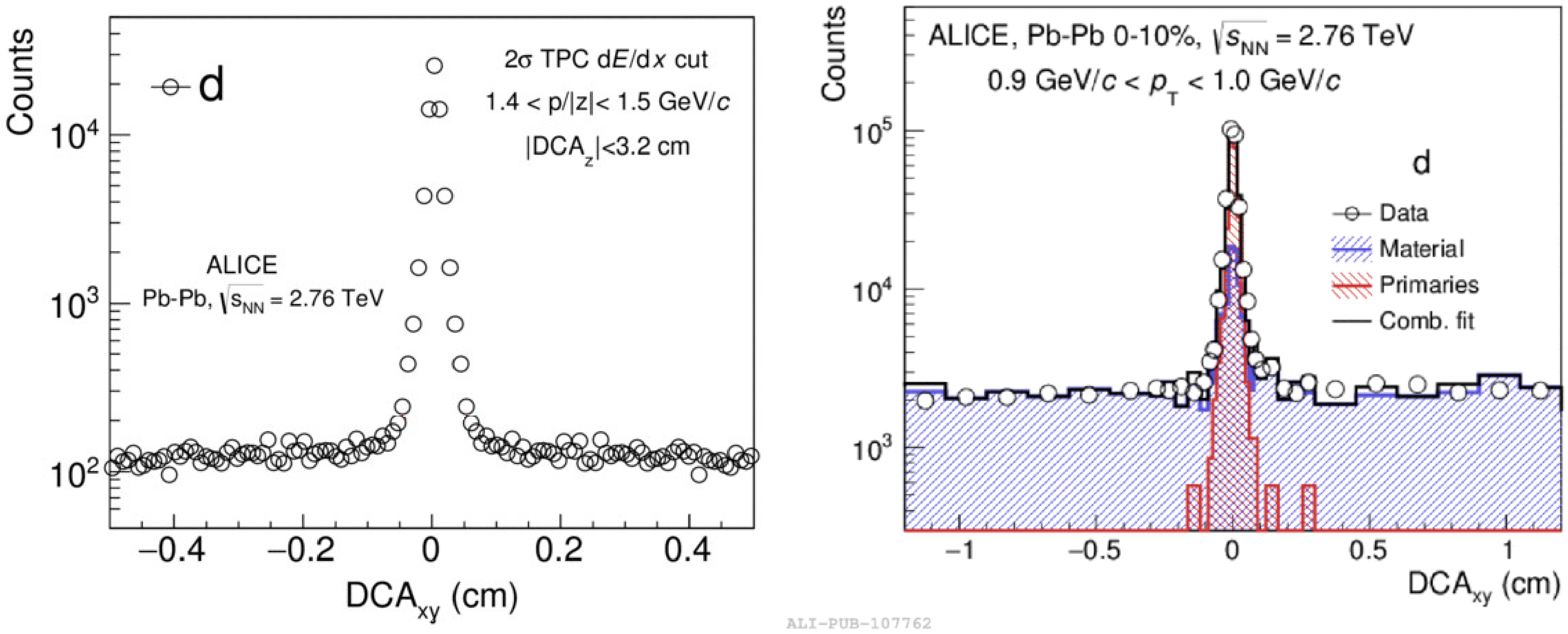
➔ Rejection is possible via fitting the DCA_{XY} distributions with templates



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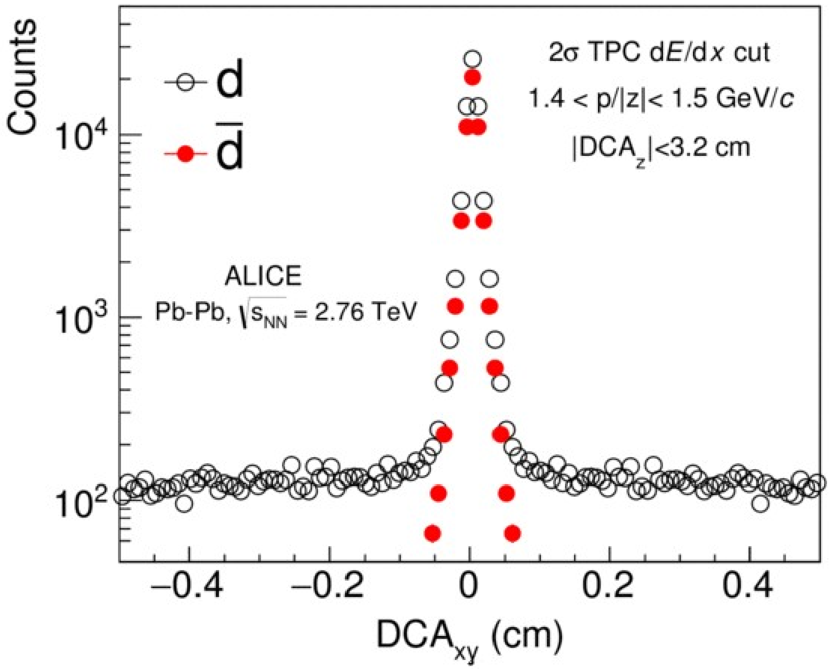
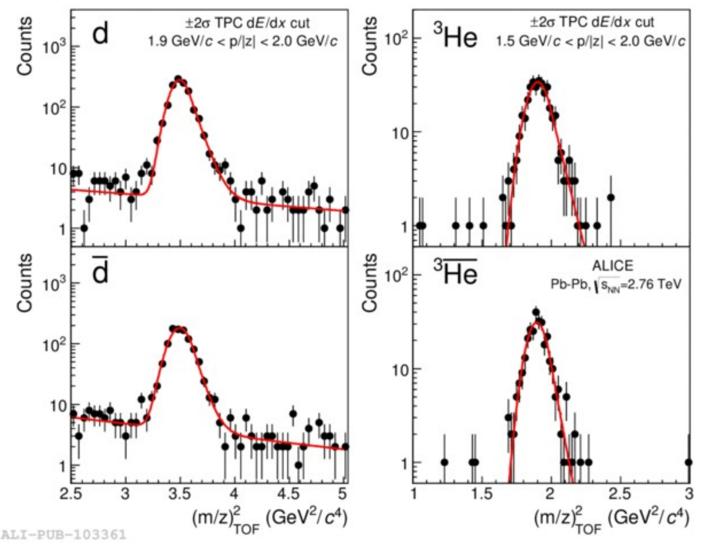


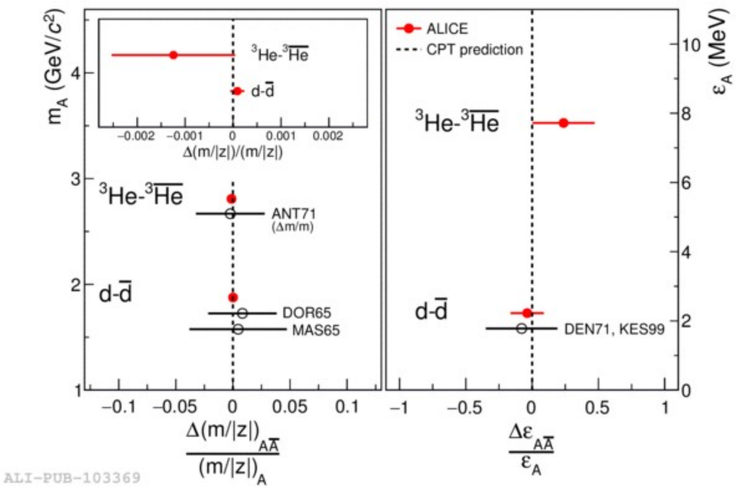
Not relevant for anti-nuclei.
However, larger systematic uncertainty from hadronic interaction cross section

Precise mass measurement

- The precise measurement of the mass difference between nuclei and their anti-counterparts allows to probe any difference in the interaction between nucleons and anti-nucleons.
- Looking at the mass difference between nuclei and their anti-nuclei it is possible to test the **CPT invariance** of the residual **QCD "nuclear force"**

ALICE Collaboration: Nature Phys. 11, 811 (2015)





- Masses and binding energies of nuclei and anti-nuclei are compatible within uncertainties
- **Measurement confirms the CPT invariance for light nuclei**

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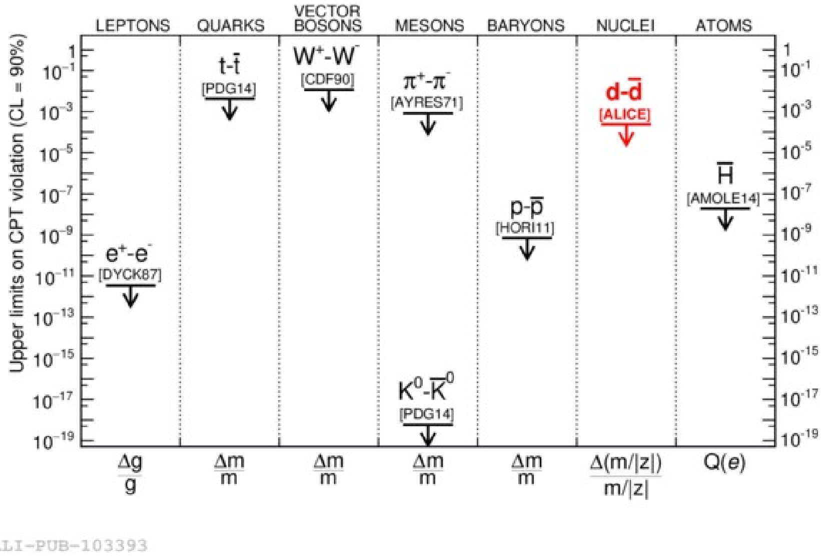
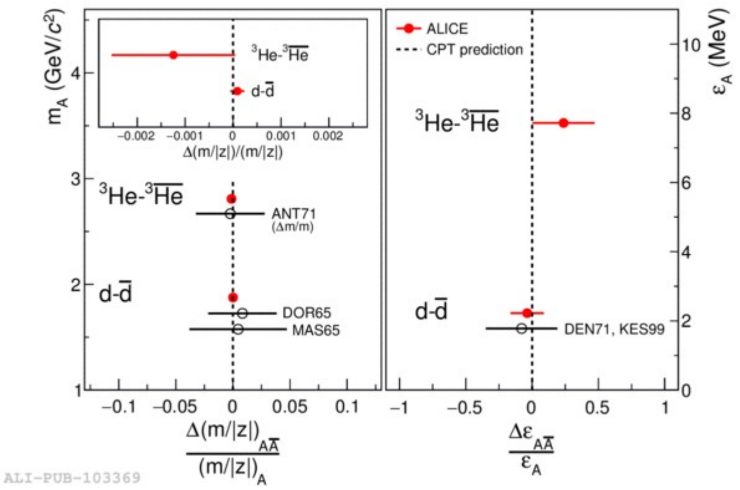


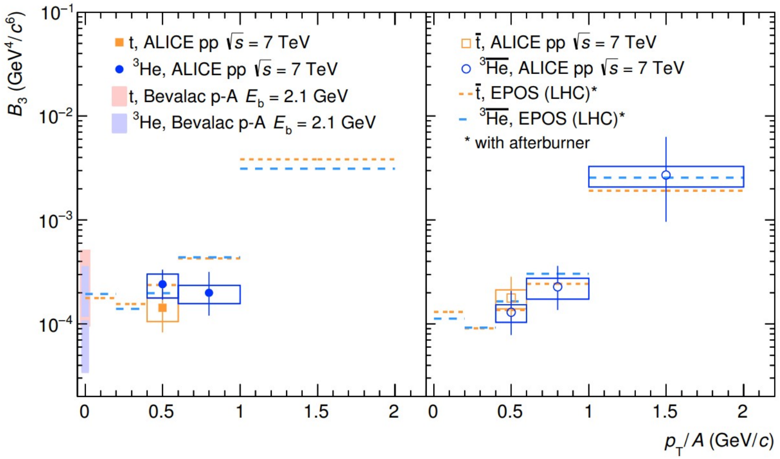


- Masses and binding energies of nuclei and anti-nuclei are compatible within uncertainties
- **Measurement confirms the CPT invariance for light nuclei**

Anti-nuclei in pp collisions

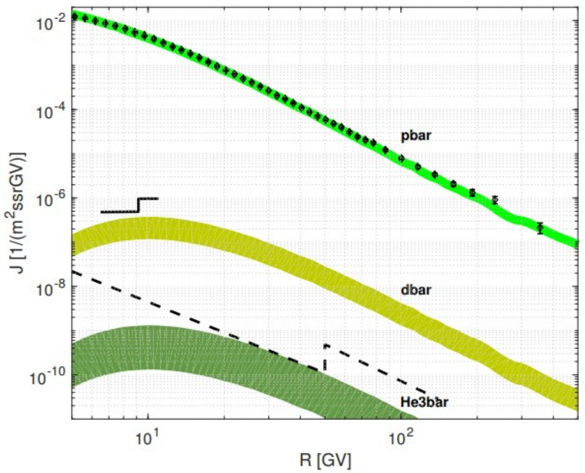
Searches for dark matter WIMP candidate decaying in $\overline{d}$ and $^{3}\overline{He}$ require estimate of expected secondary astrophysical background (secondary anti-nuclei produced in cosmic ray interactions)

Precise measurement of coalescence parameters at the LHC can provide constraints for models

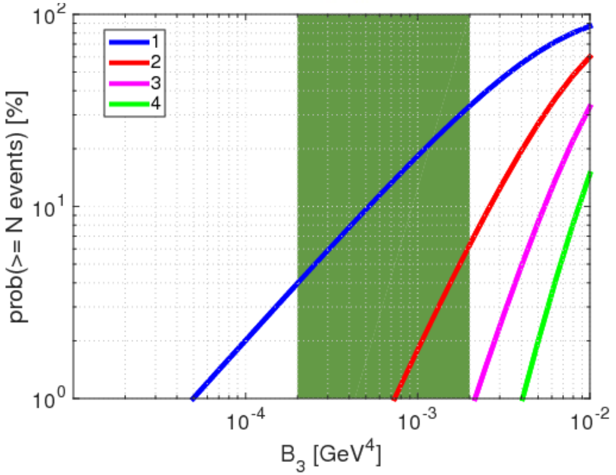


ALICE Collaboration, arXiv:1709.08522

Predicted flux of $\overline{p}$, $\overline{d}$, $^{3}\overline{He}$ in AMS (5-yr, 95%CL)



Poisson probability for detecting N≥1, 2, 3, 4 $^{3}\overline{He}$ events in a 5-yr analysis of AMS02



K. Blum et al., arXiv:1704.05431

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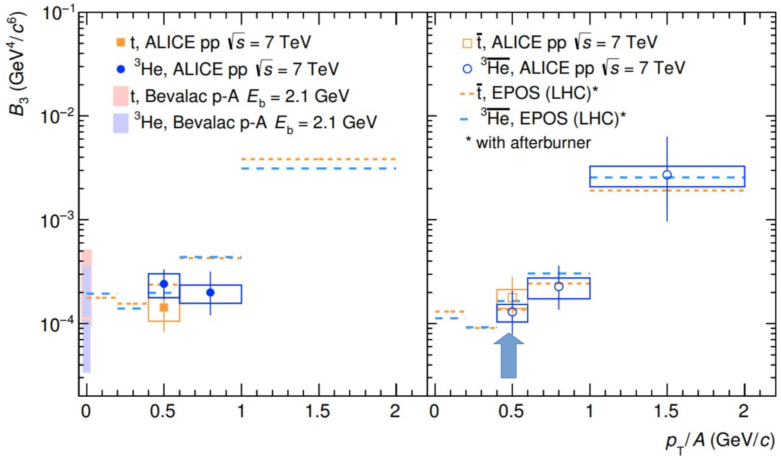

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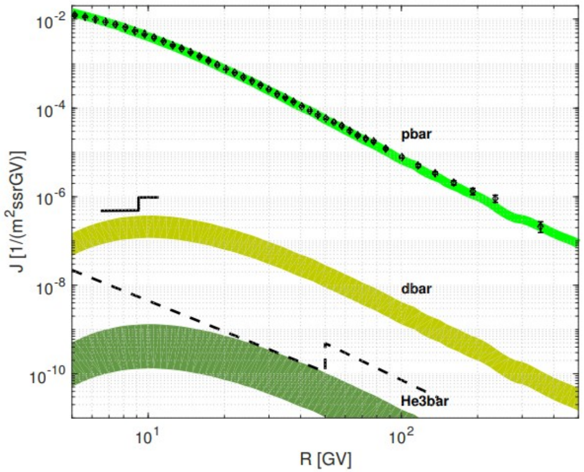

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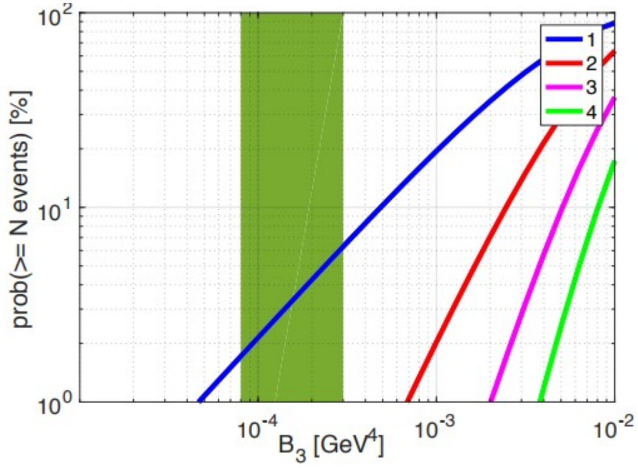
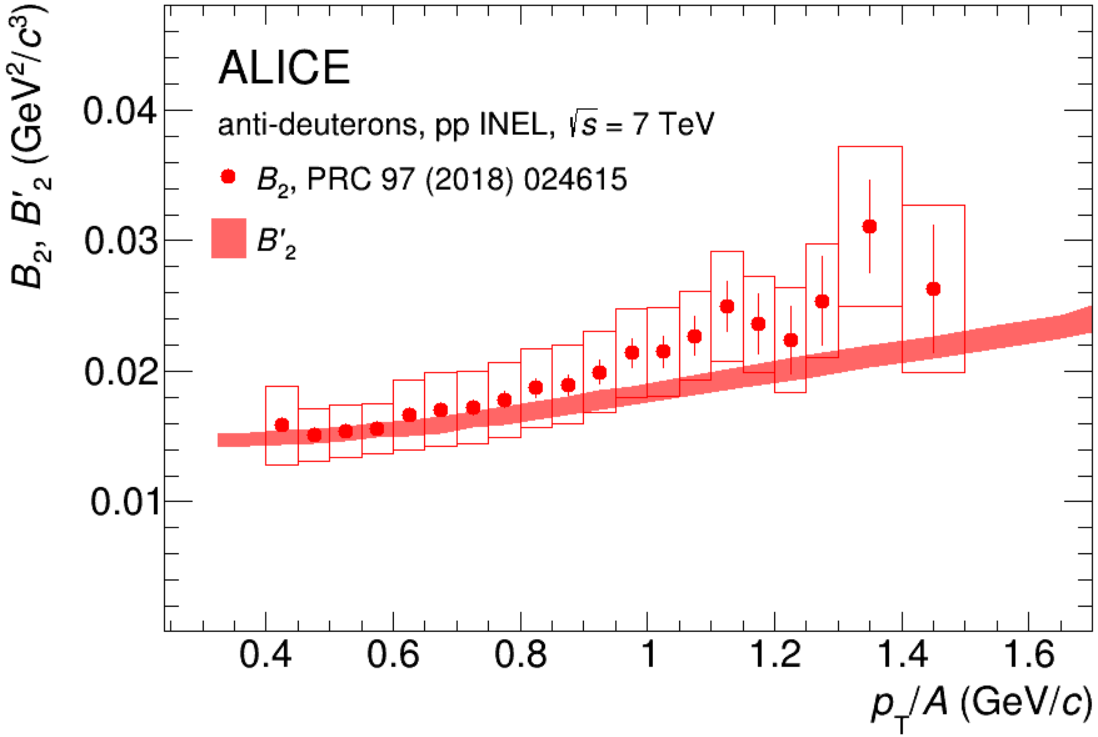
After ALICE



K. Blum, EMMI Workshop 2017

B_2'

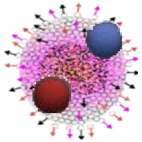


B_2' of anti-deuterons as a function of the transverse momentum per nucleon p_T/A compared with the experimental data for B_2 measured in inelastic pp collisions at √s = 7 TeV

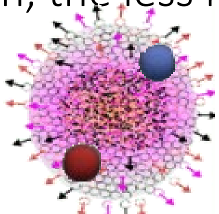
$$B_2' = \frac{\sum_{i=\mathrm{I+II}}^{\mathrm{VIII\ to\ X}} (N_i/N)\, B_2^i\, (S_\mathrm{p}^i)^2}{\left(\sum_{i=\mathrm{I+II}}^{\mathrm{VIII\ to\ X}} (N_i/N)\, S_\mathrm{p}^i\right)^2}$$

Coalescence Model and HBT

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 is that they coalesce



(small fireball)



(large fireball)

In detail, it turns out [1] that the coalescence process is governed by the same "length of homogeneity in the source" which can be extracted from two particle Bose-Einstein correlation (HanburyBrown – Twiss (HBT) interferometry [2]): → $B_2 \sim 1/V_{eff}$

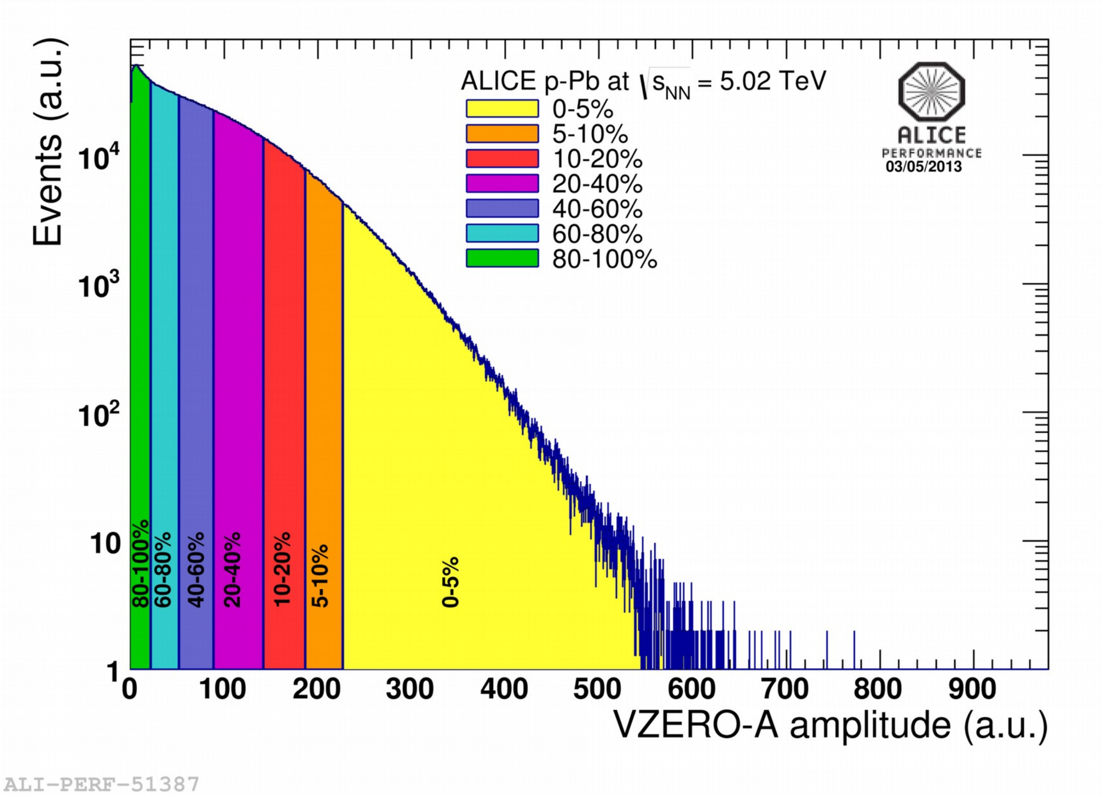
$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2 m_t \Re_T^2(m_t)\Re_p^2(m_t)} e^{2(m_t - m)\left(\frac{1}{T^* p} - \frac{1}{T^* d}\right)}$$

The strong decrease of B_2 with centrality in Pb-Pb collisions can be naturally explained as an increase in the emitting volume: particle densities are relevant and not absolute multiplicities

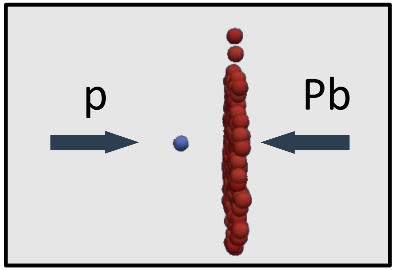
[1]R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)
[2]A review can be found in : U. Heinz, Nucl. Phys. A 610 , 264c (1996)

Centrality of the collisions: p-Pb and pp

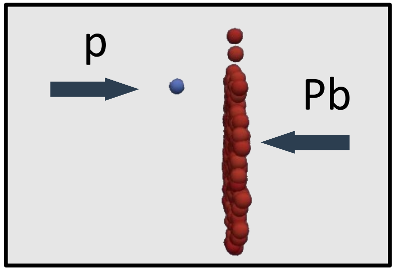
Multiplicity estimator: slices in VZERO-A (V0A) amplitude



Central collision



Peripheral collision



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