Light (Hyper-)Nuclei production at the LHC with ALICE

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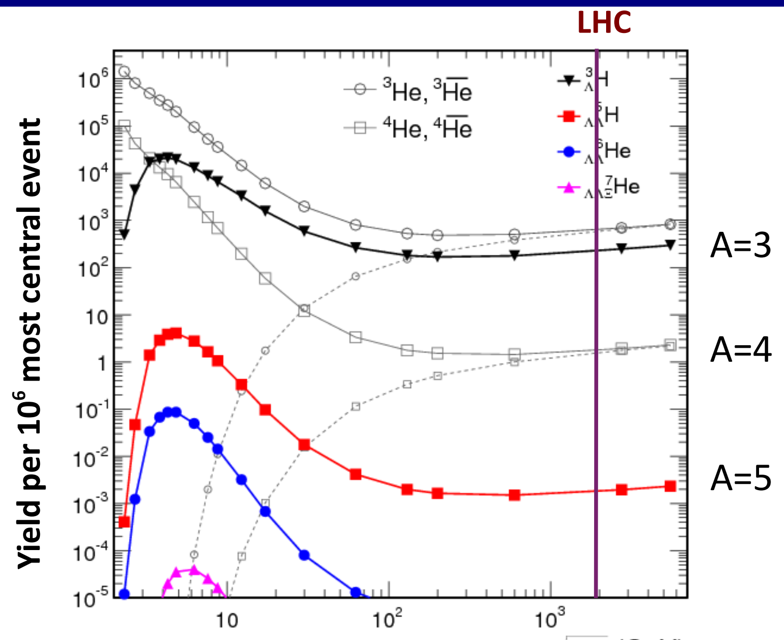
(Anti-)(Hyper)nuclei production

Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
  - Exponential dependence of the yield $\propto e^{(-m/T_{chem})}$



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

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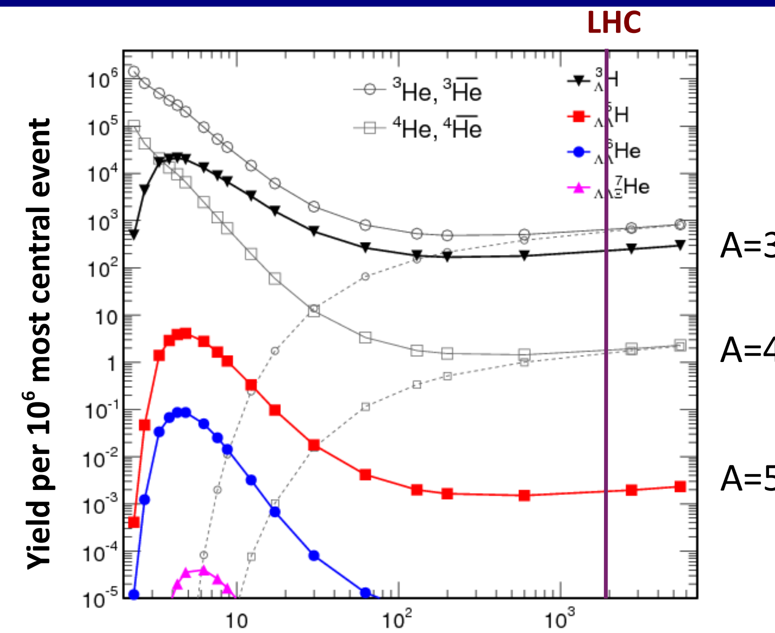

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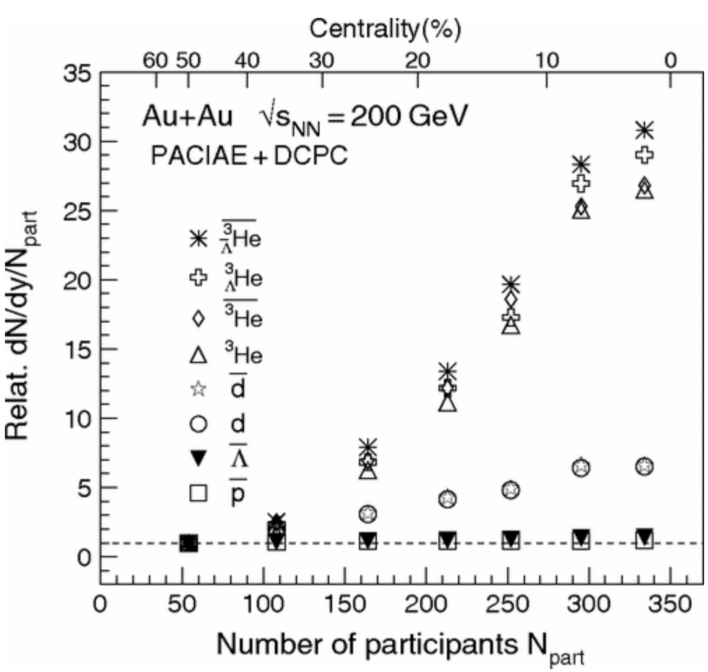


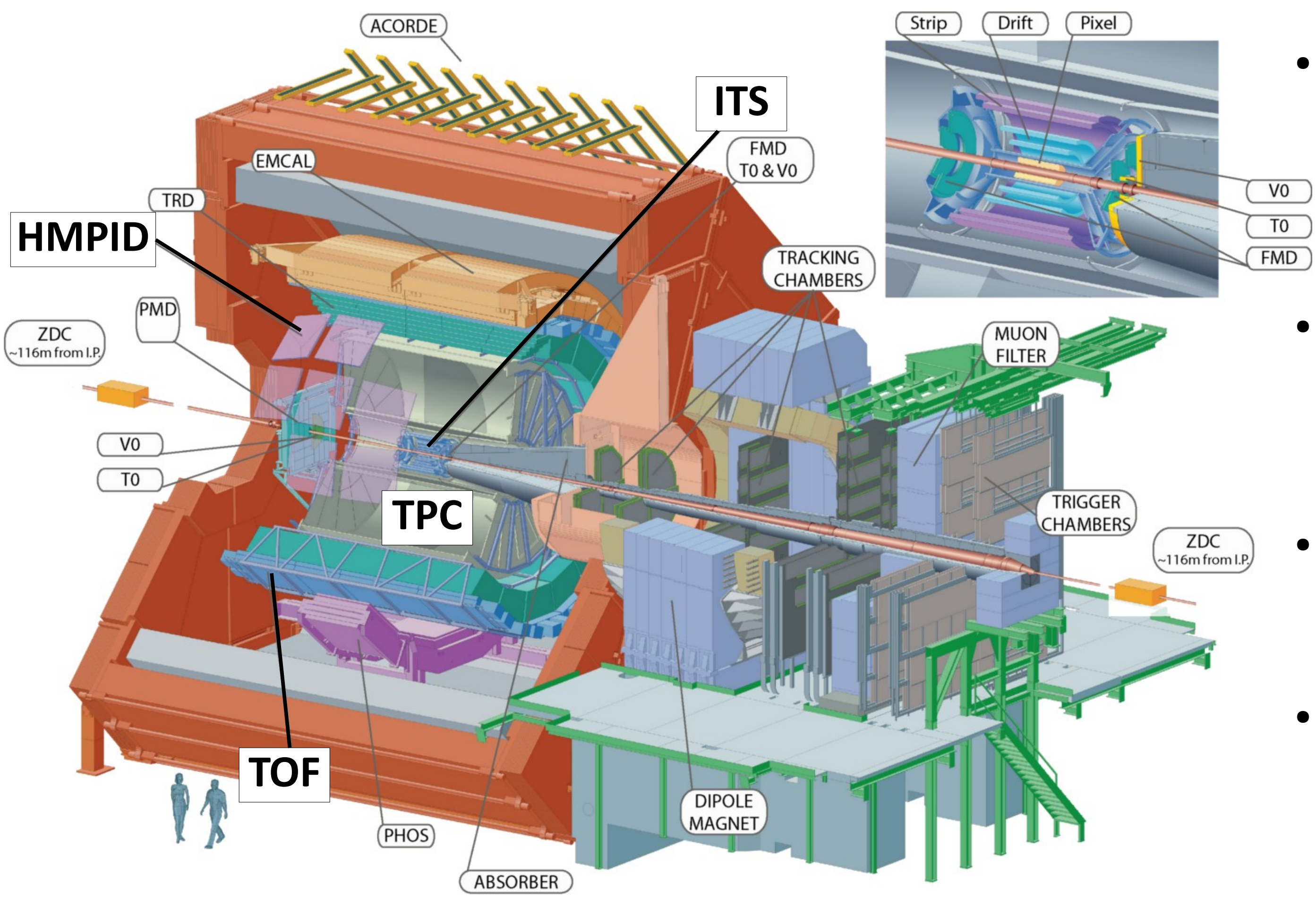
G. Chen et al., Phys. Rev. C 88, 034908 (2013)

Coalescence

- If baryons at freeze-out are close enough in phase space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons (Λ) and neutrons which have similar velocities after the kinetic freeze-out

ALICE

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: d*E*/d*x*, time-of-flight, transition radiation, Cherenkov radiation, calorimetry and topological decay (V0, cascade)



- **Inner Tracking System (ITS)**
  - Primary vertex
  - Tracking
  - PID via d*E*/dx
- **Time Projection Chamber (TPC)**
  - Global tracking
  - PID via d*E*/dx
- **Time Of Flight (TOF)**
  - PID via time-of-flight
- **HMPID**
  - PID via ring imaging Cherenkov

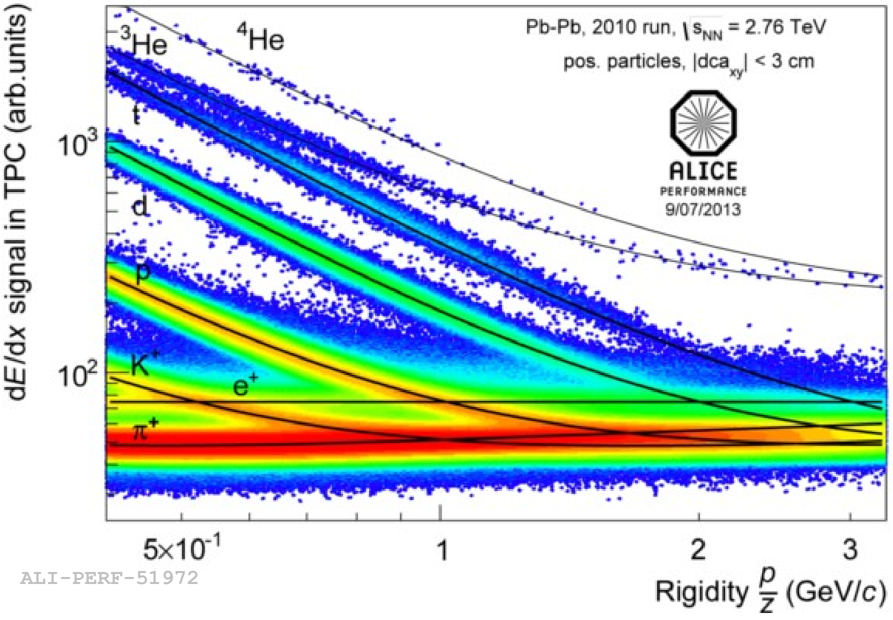
Nuclei Identification

Low momenta

Nuclei identification via dE/dx measurement in the TPC:

- dE/dx resolution in central Pb-Pb collisions: 7%

- Excellent separation of (anti-)nuclei from other particles over a wide range of momentum



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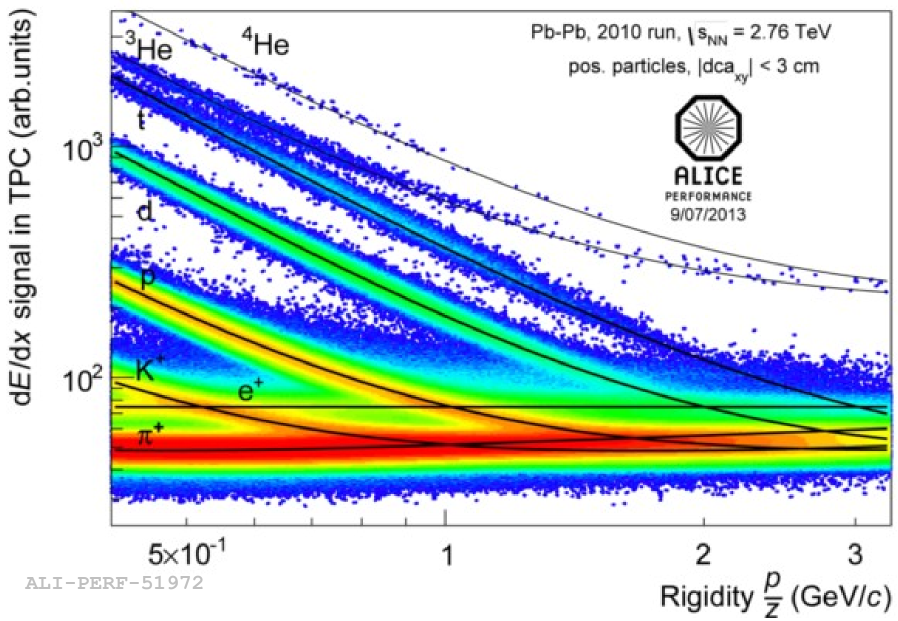

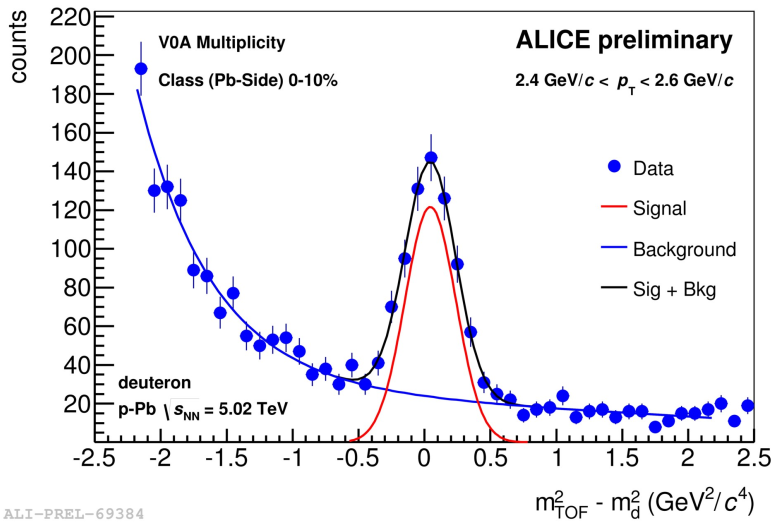

Higher momenta

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.
- ±3σ-cut around expected TPC dE/dx for deuterons reduces drastically the background from TPC and TOF mismatch

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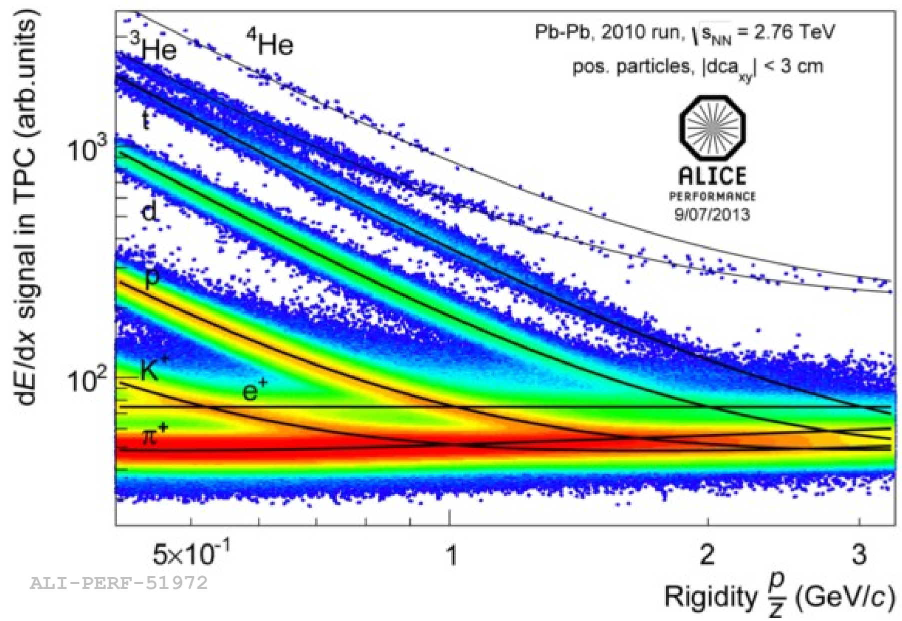
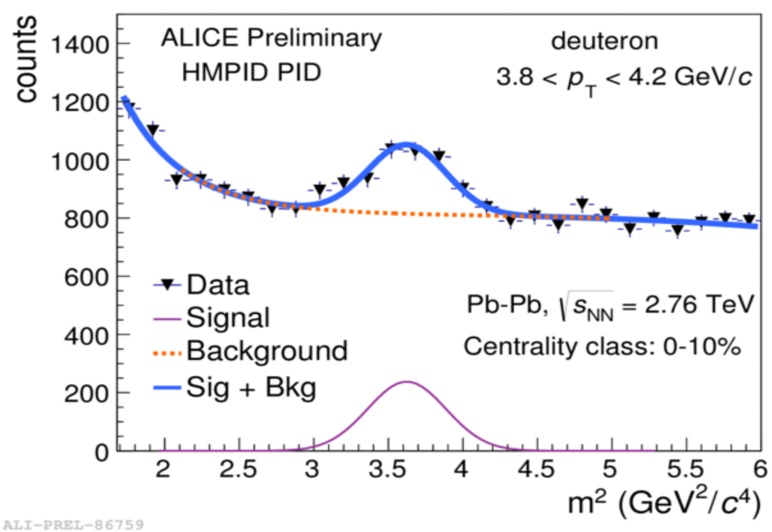




Higher momenta

HMPID

- At higher momenta nuclei in central Pb-Pb collisions are identified based on Cherenkov radiation with HMPID

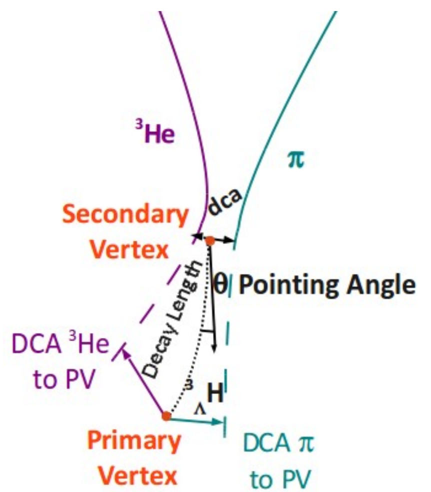
$$\cos\theta_{Cherenkov} = \frac{1}{n\beta} \qquad m^2 = p^2\left(n^2\cos^2\theta_{Cherenkov} - 1\right)$$

$({}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}})\ {}^{3}_{\Lambda}\mathrm{H}$ Identification

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

Mass = 2.991 GeV/c^2 $B_\Lambda = 0.13 \pm 0.05$ MeV Lifetime ~ 263 ps

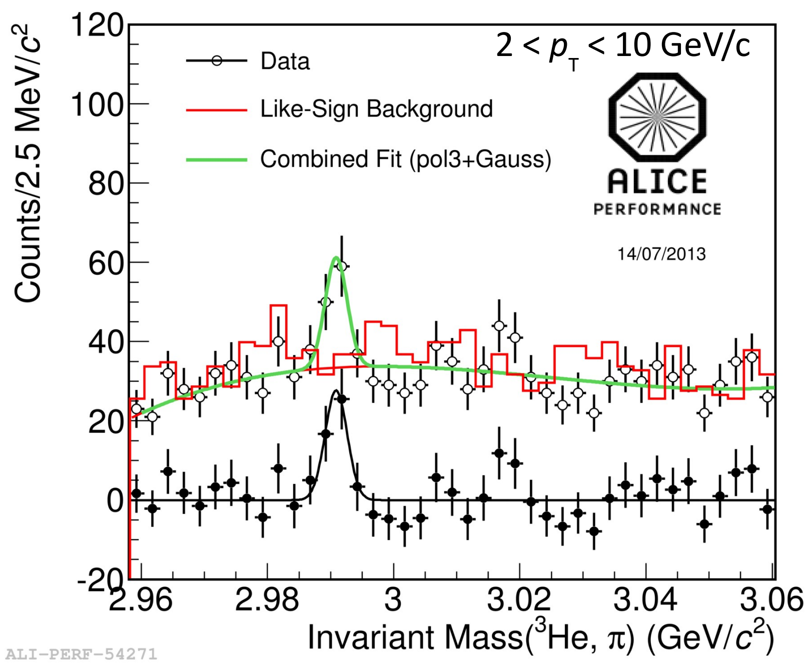
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^-$$
$${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^+$$



APPLIED CUTS:

- Cos(Pointing Angle) > 0.99
- DCA π to PV > 0.4 cm
- DCA between tracks < 0.7 cm
- $({}^{3}\mathrm{He},\pi)$ p_T > 2 GeV/c
- $|y| \leq 1$
- $c\tau$ > 1 cm

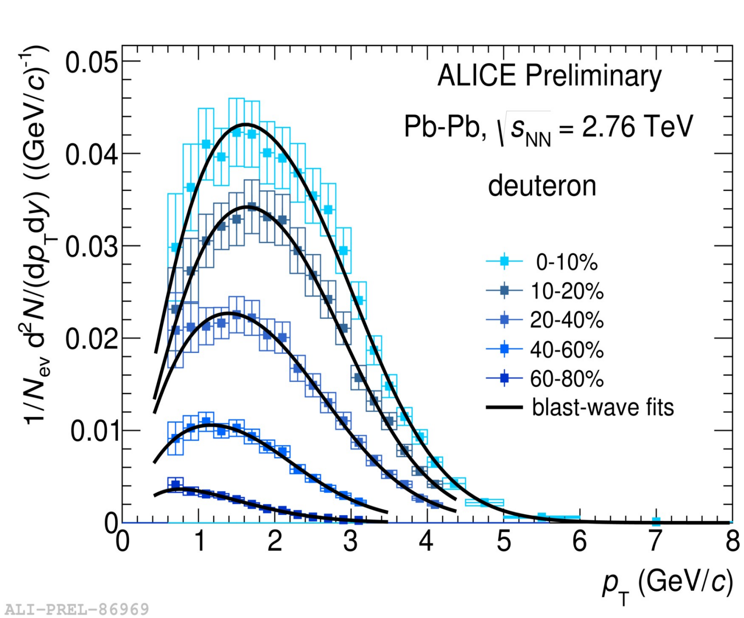
$({}^{3}\mathrm{He},\pi^-)$+ $({}^{3}\overline{\mathrm{He}},\pi^+)$ Invariant Mass spectrum

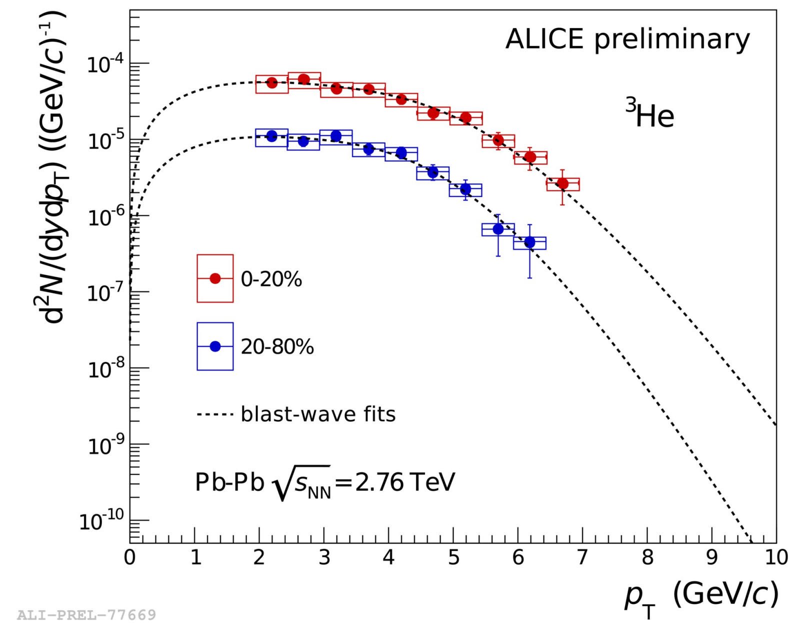


$\mu = 2.992 \pm 0.002$ GeV/c^2
$\sigma = (2.08 \pm 0.50)\times10^{-3}$ GeV/c^2

Results

Deuterons and ^{3}He in Pb – Pb





- Spectra are extracted in different centrality bins and fitted with a Blast-Wave function (simplified hydro model) for the extraction of yields (extrapolation to unmeasured region at low and high p_T)

Blast-Wave model: **E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)**

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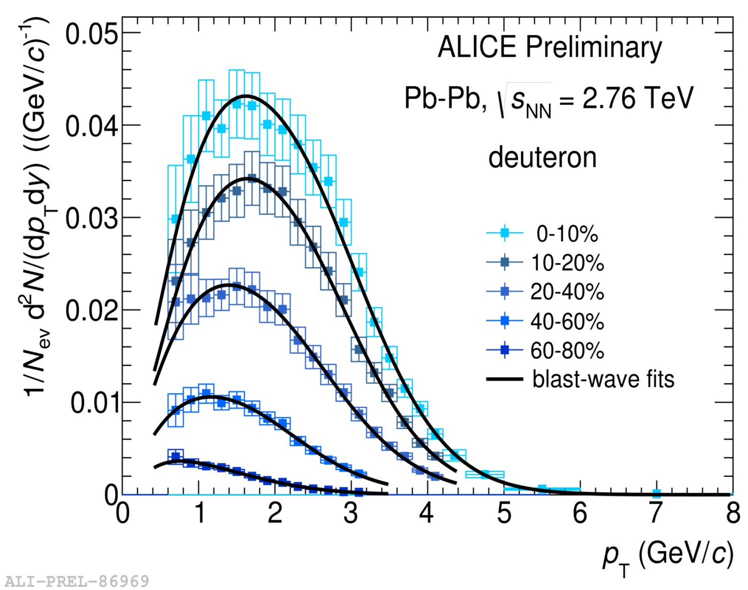

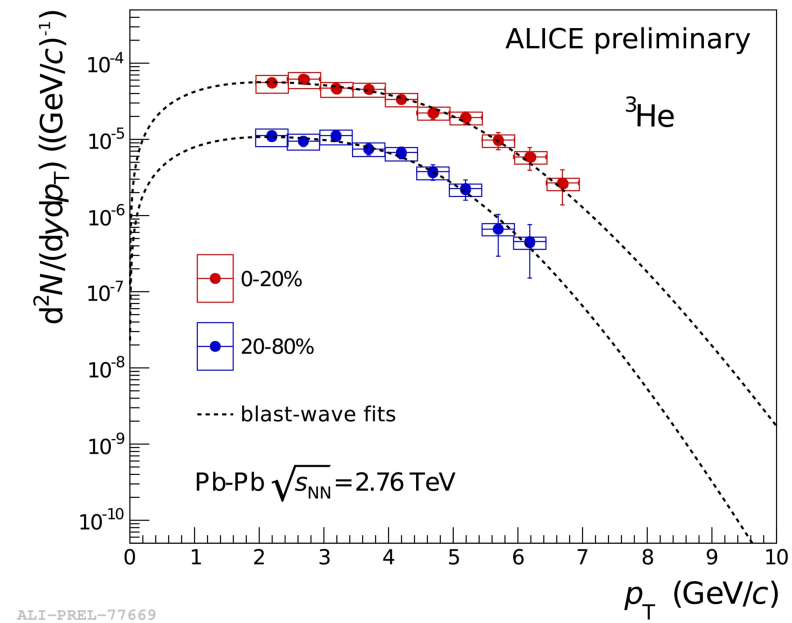

- Spectra are extracted in different centrality bins and fitted with a Blast-Wave function (simplified hydro model) for the extraction of yields (extrapolation to unmeasured region at low and high p_T)
- A hardening of the spectrum with increasing centrality is observed as expected in a hydrodynamic description of the fireball as a radially expanding source

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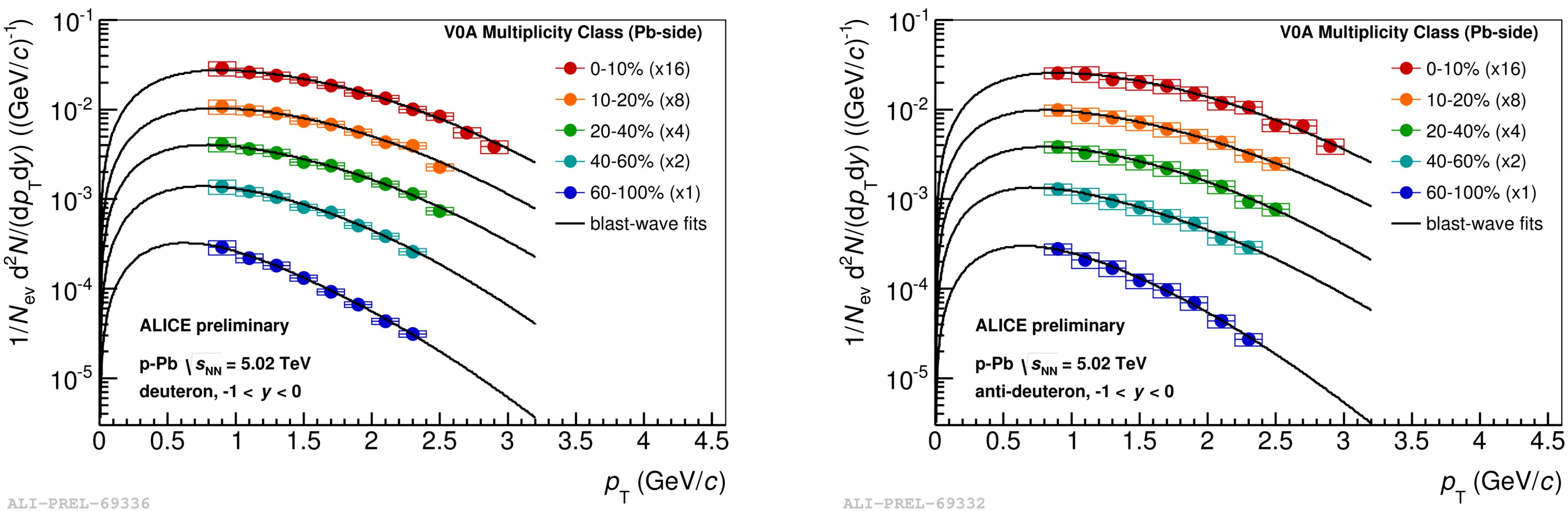
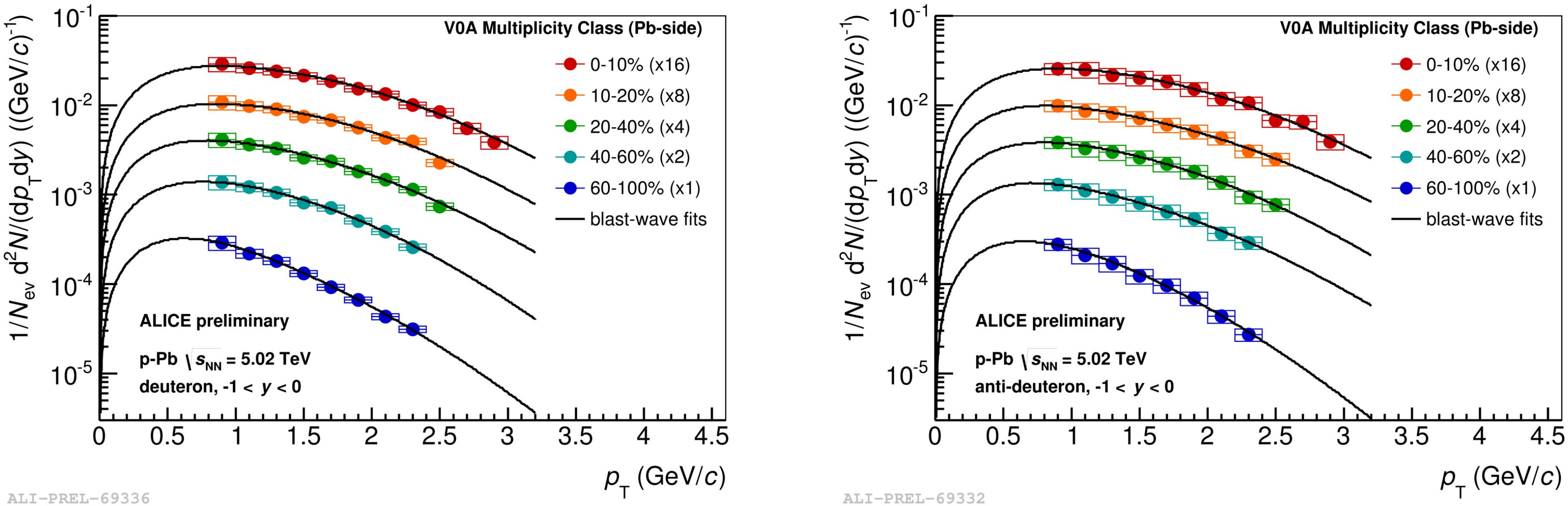
(Anti-)deuterons in p – Pb



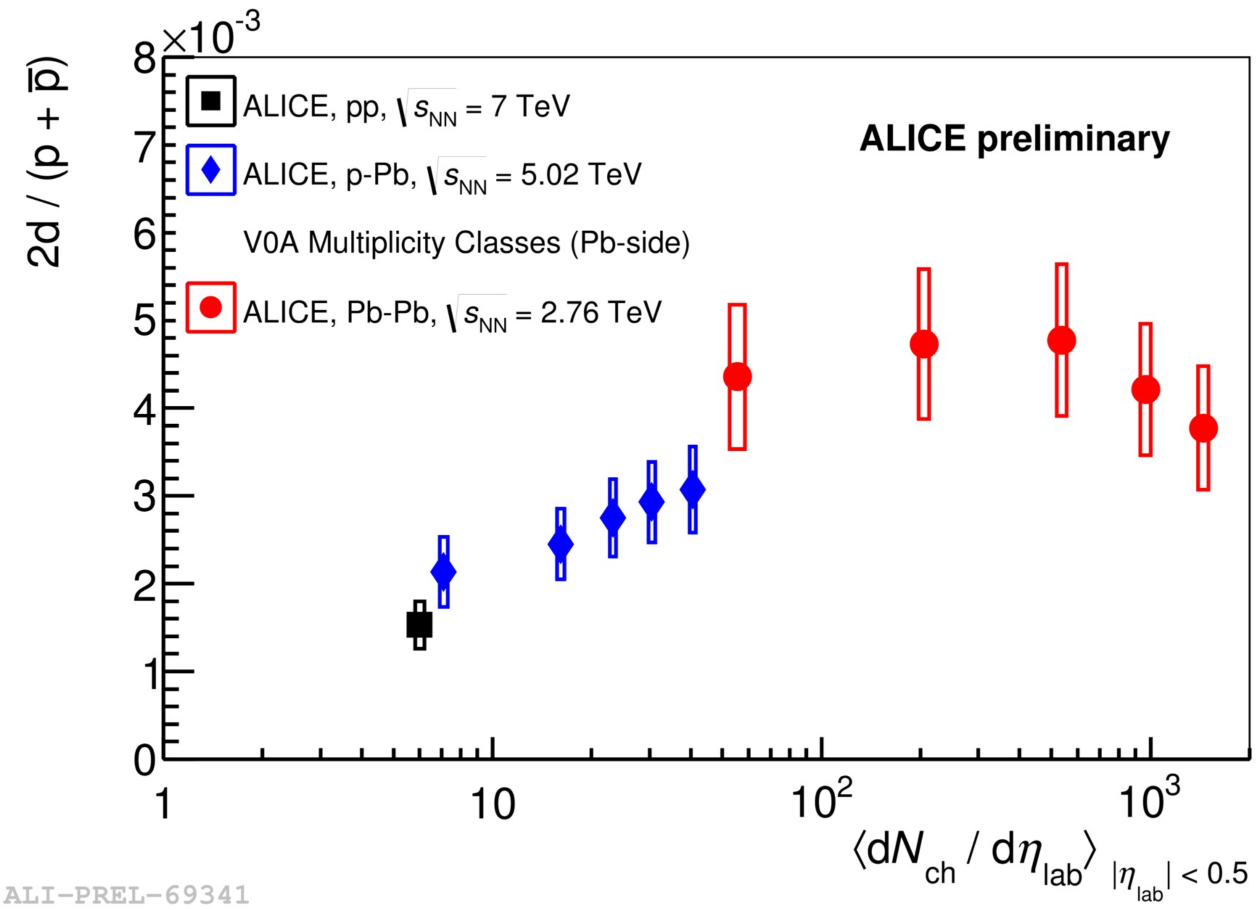
- Deuteron and anti-deuteron spectra extracted in different multiplicity bins and fitted with Blast-Wave functions for the extraction of yields

(Anti-)deuterons in p – Pb



- Deuteron and anti-deuteron spectra extracted in different multiplicity bins and fitted with Blast-Wave functions for the extraction of yields
- Also in p-Pb collisions spectra become harder with increasing multiplicity

Deuteron to proton ratio



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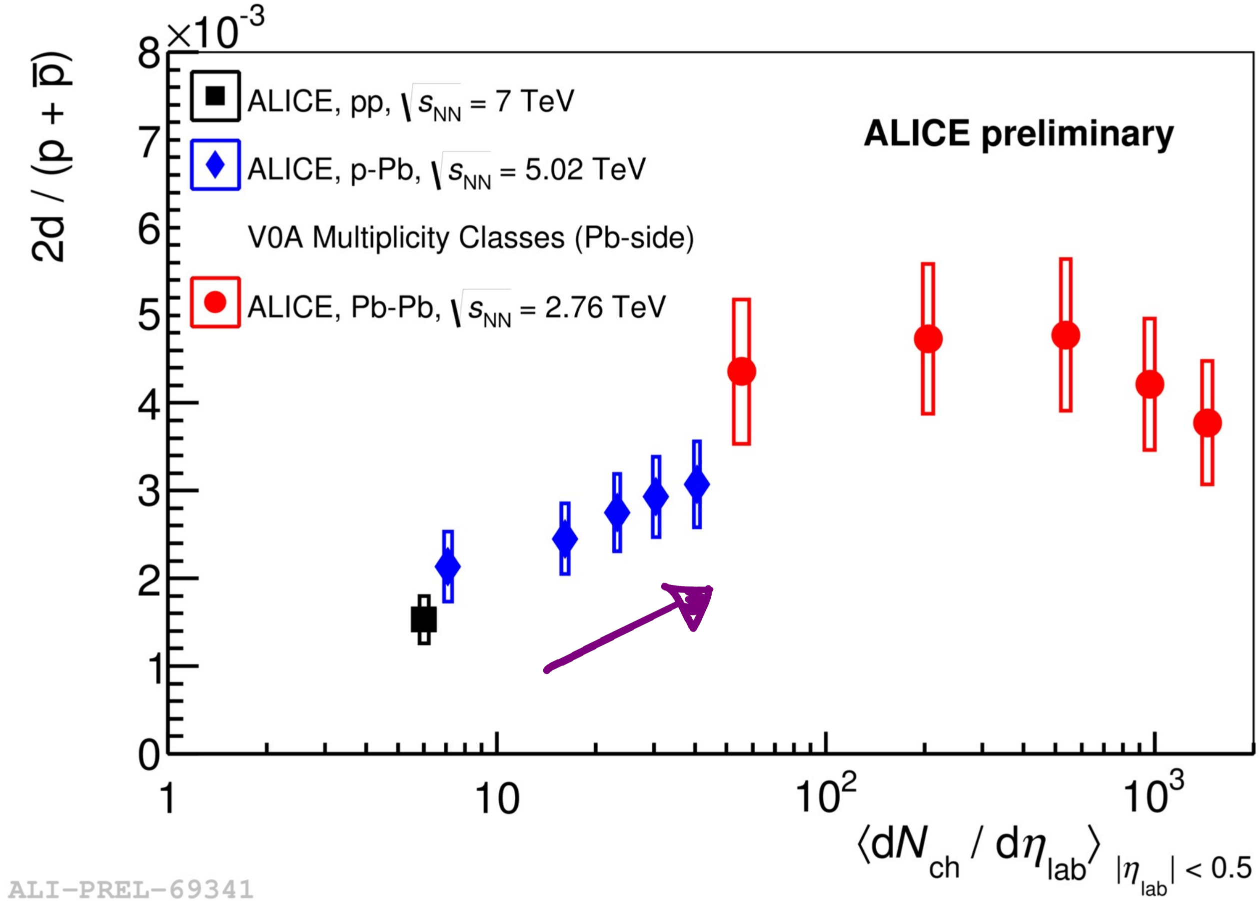

- Rise with multiplicity in p-Pb

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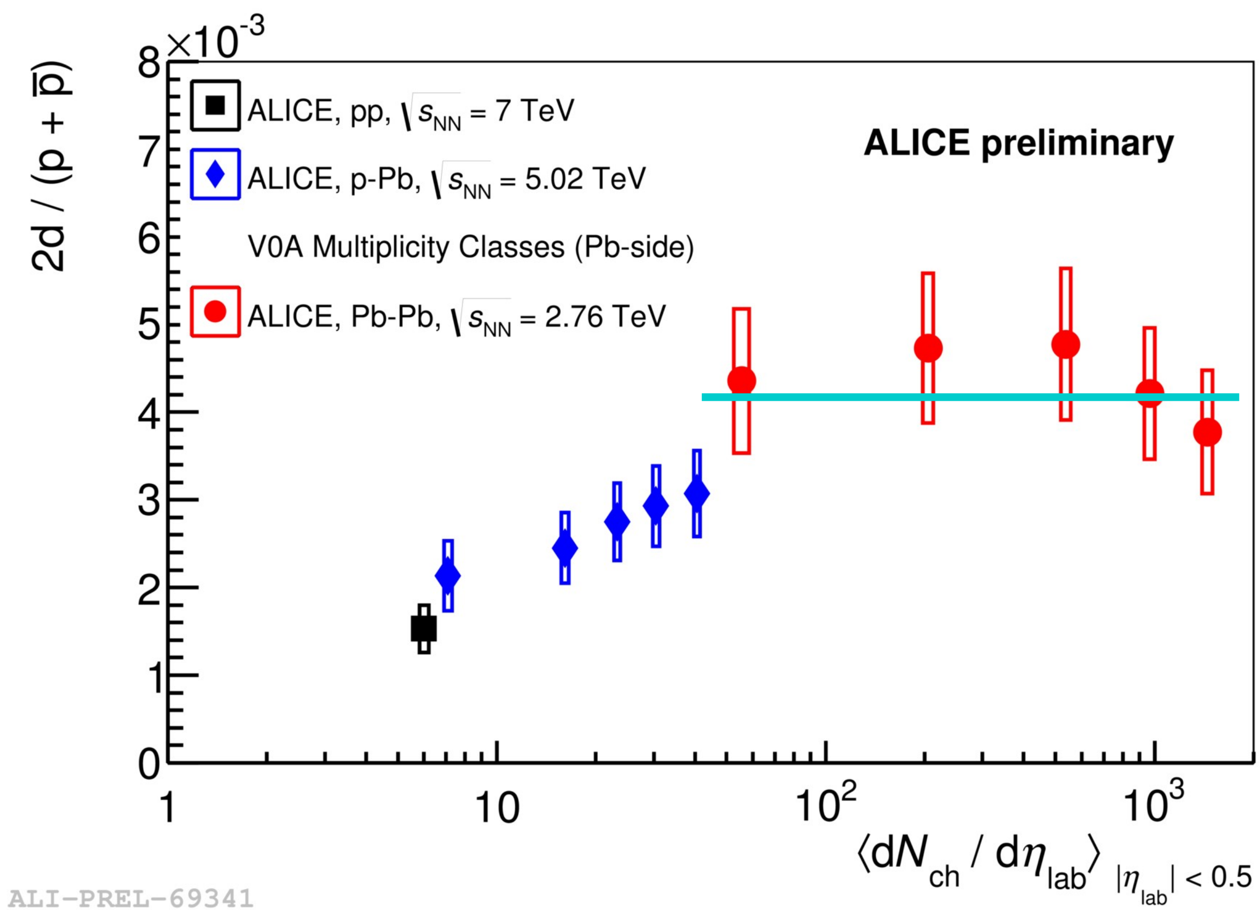
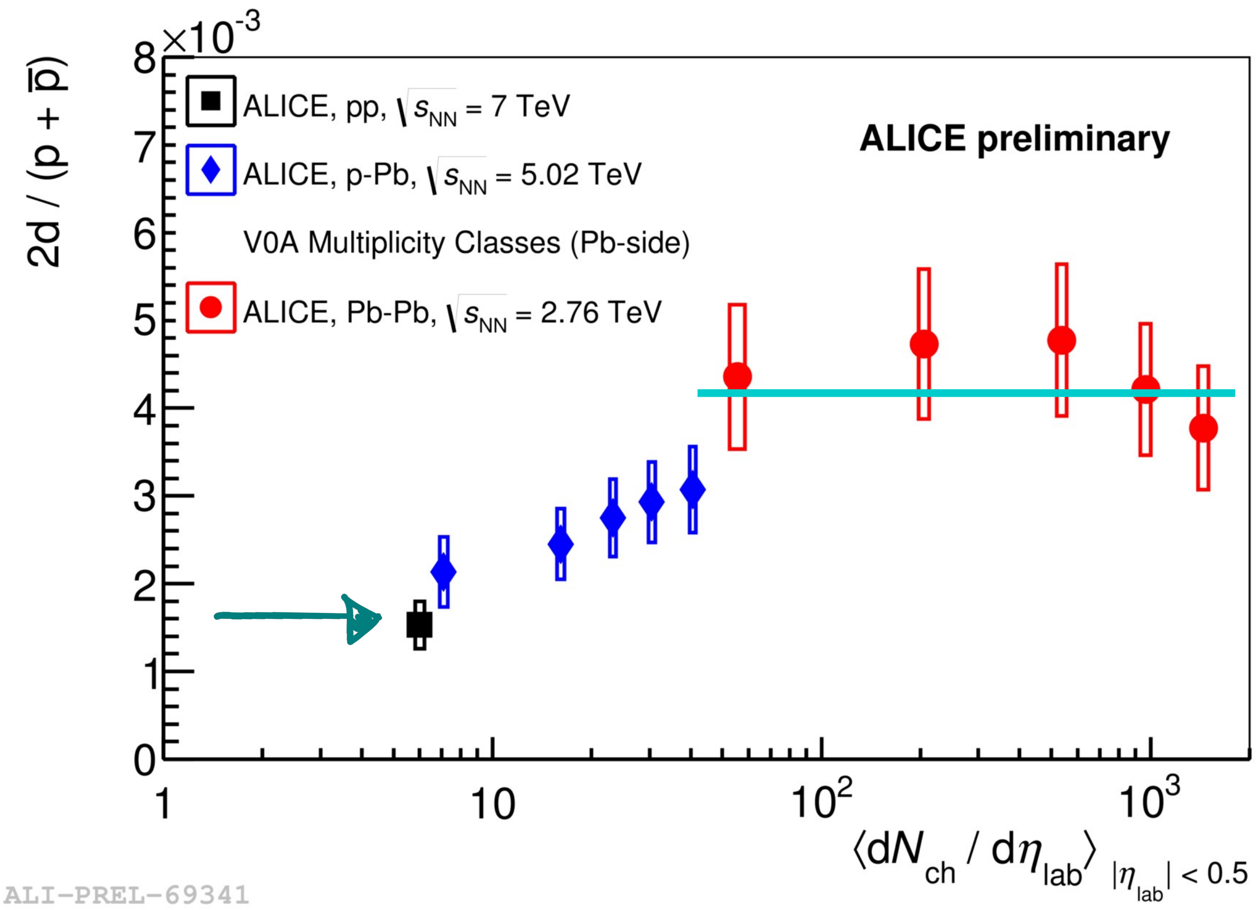


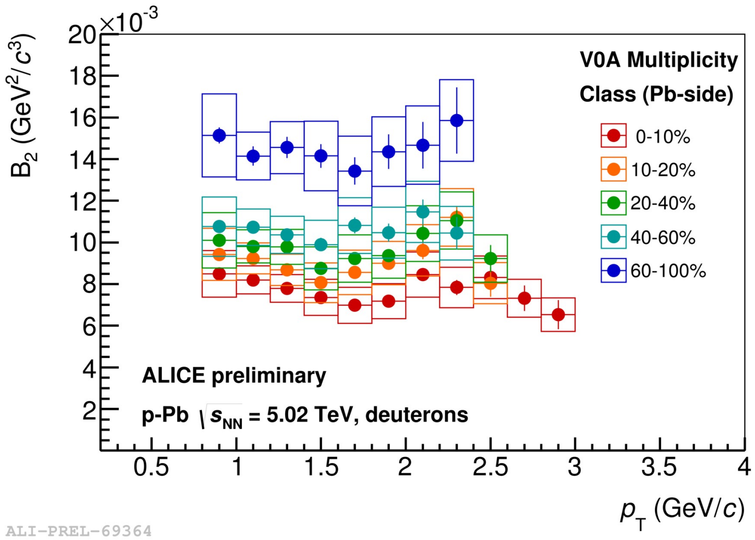
- Rise with multiplicity in p-Pb
- No significant centrality dependence in Pb-Pb

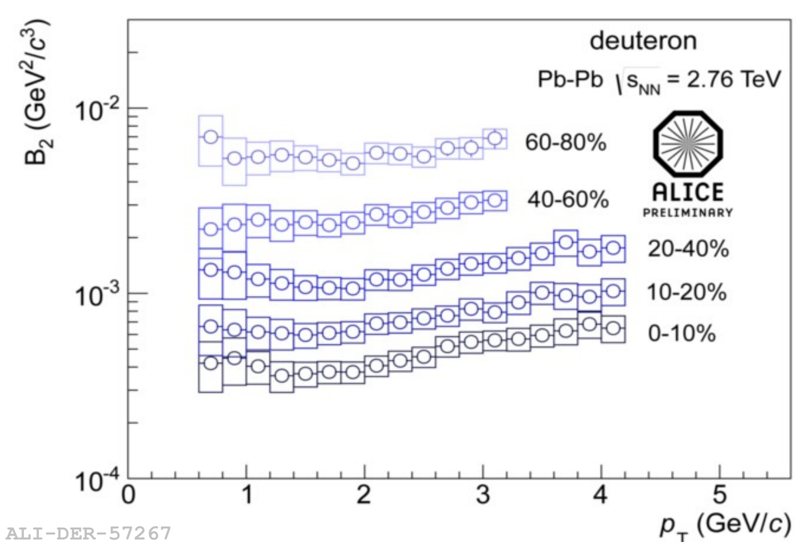
Deuteron to proton ratio



- Rise with multiplicity in p-Pb
- No significant centrality dependence in Pb-Pb
- Ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions

Deuterons B_2





Within a coalescence approach, the formation probability of deuterons can be quantified through the parameter B_2

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_d^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3} \right)^2}$$

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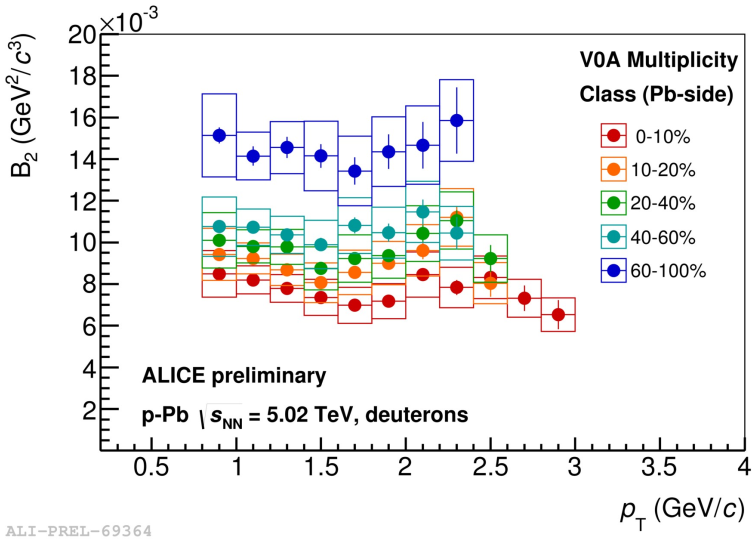

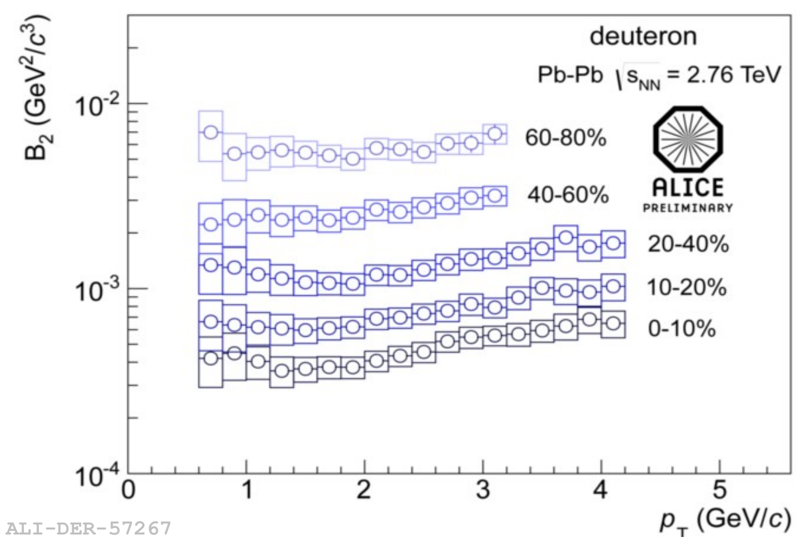

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First order prediction of coalescence model:

- Flat B_2 vs p_T and no dependence on multiplicity/centrality

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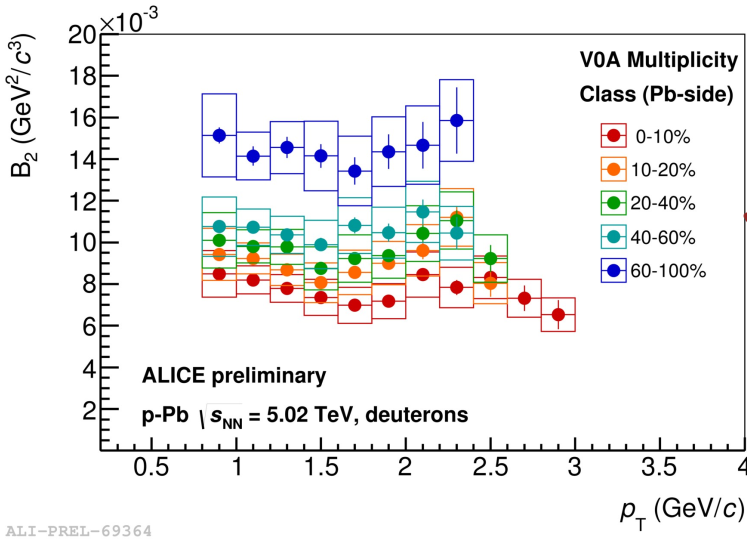

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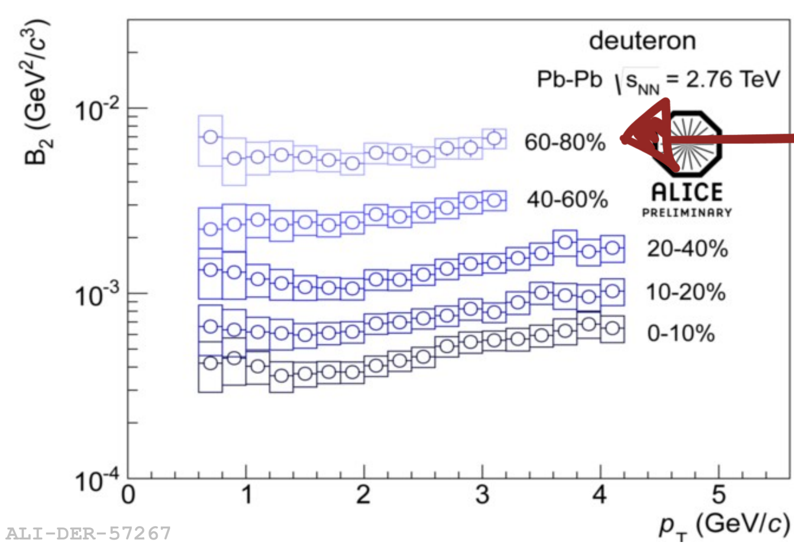

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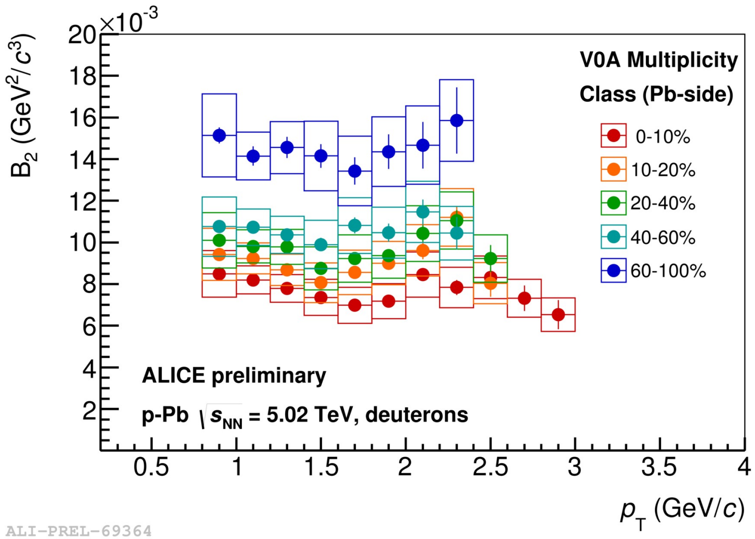

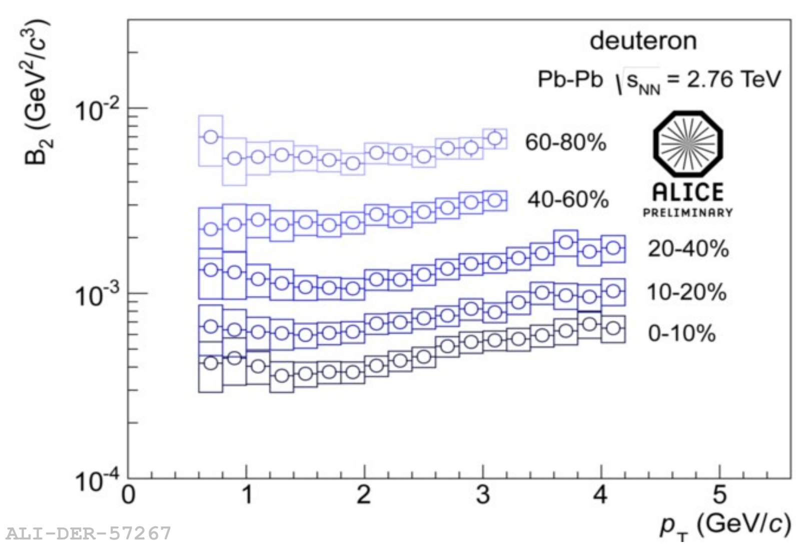

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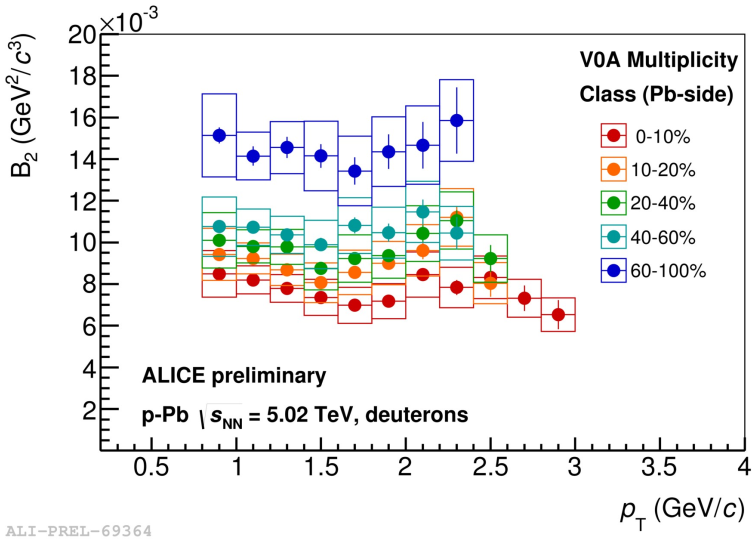
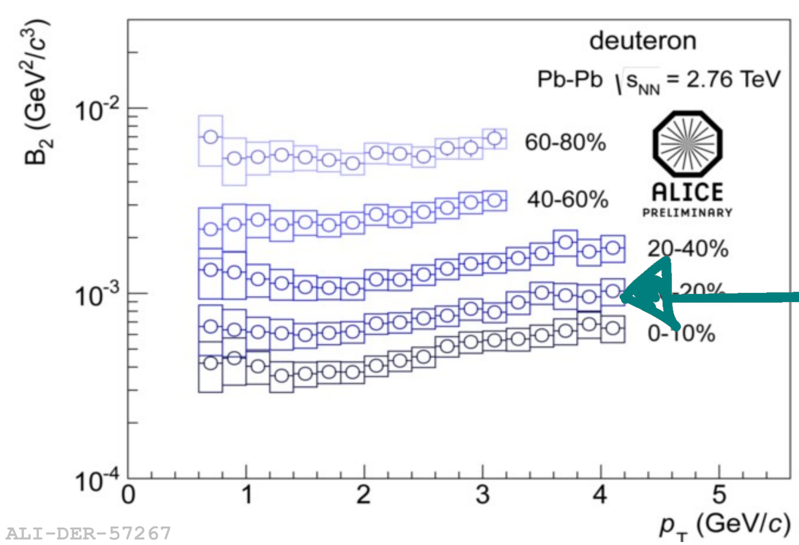
Second order prediction of coalescence model:

- B_2 scales like HBT radii
  - ➢ decrease with centrality in Pb-Pb is explained as an increase in the source volume
  - ➢ increasing with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT

Deuterons B_2





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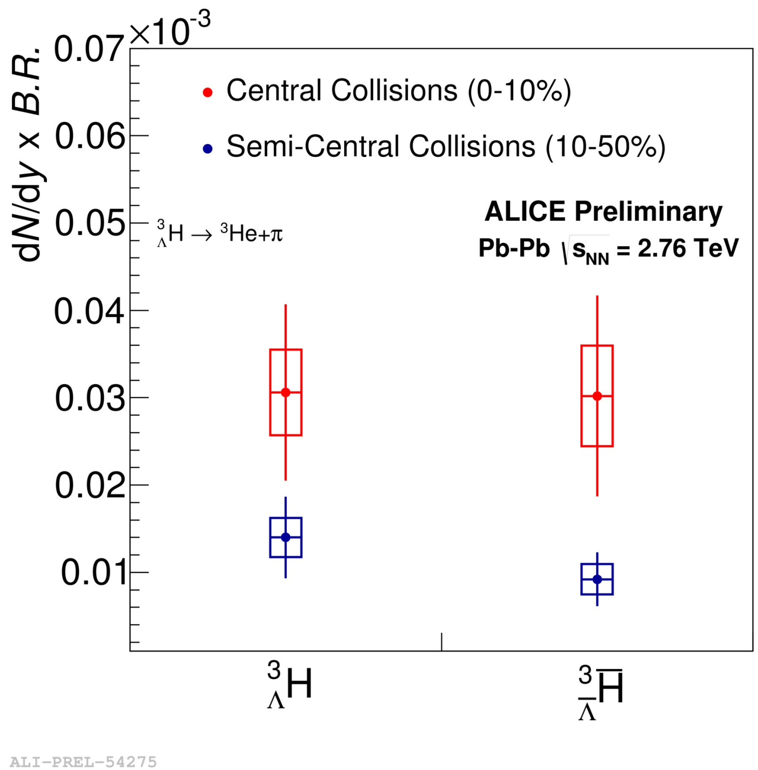
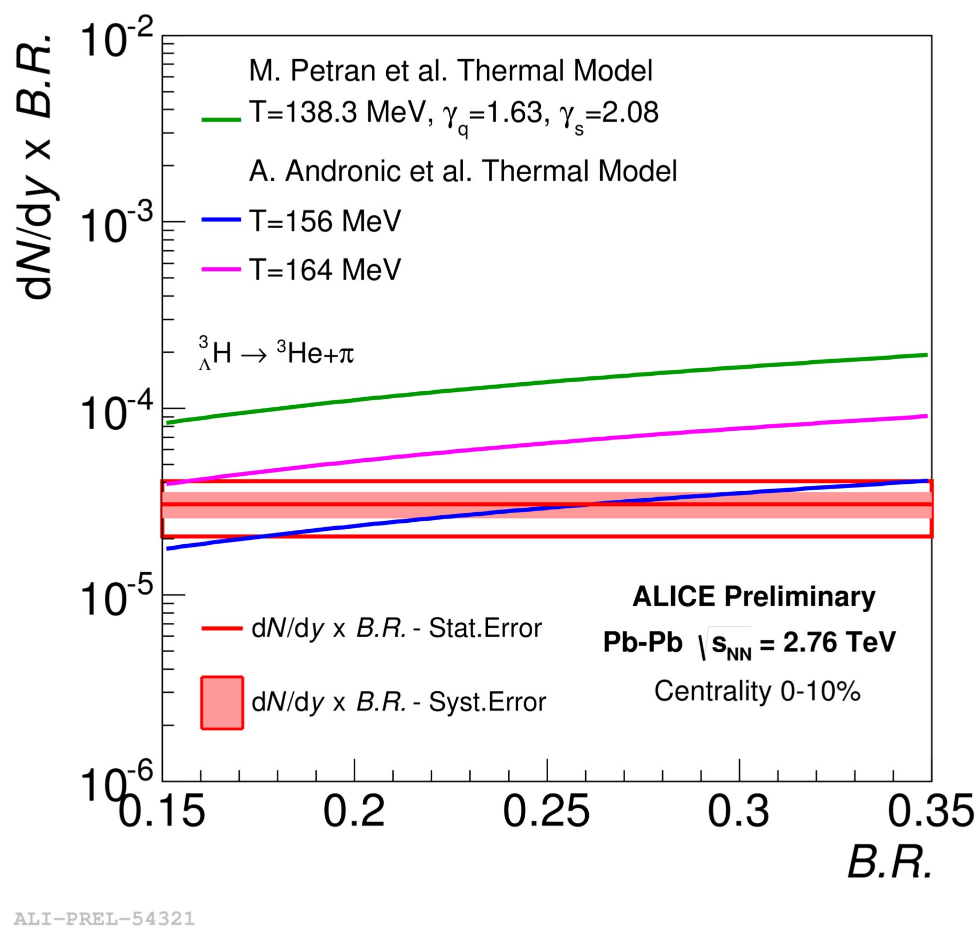
  - ➢ increasing with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT
  - ✔ Observed in central Pb-Pb collisions

$({}^{3}_{\bar{\Lambda}}\overline{H})\ {}^{3}_{\Lambda}H$ dN/dy

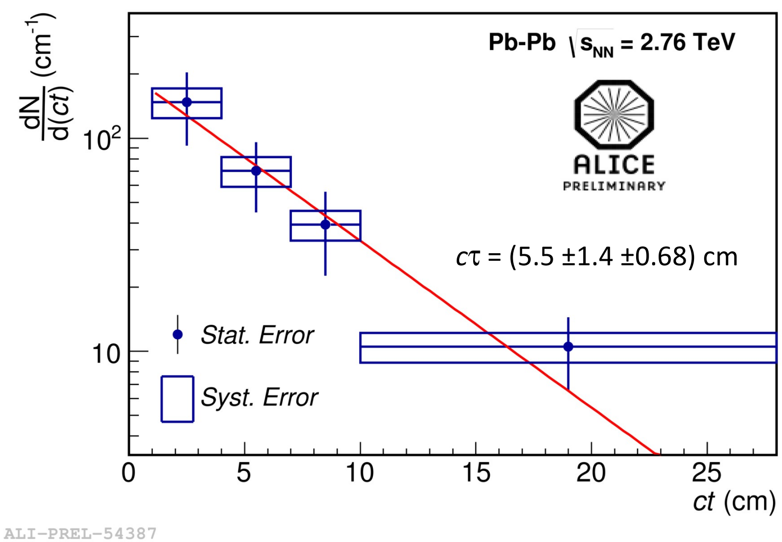


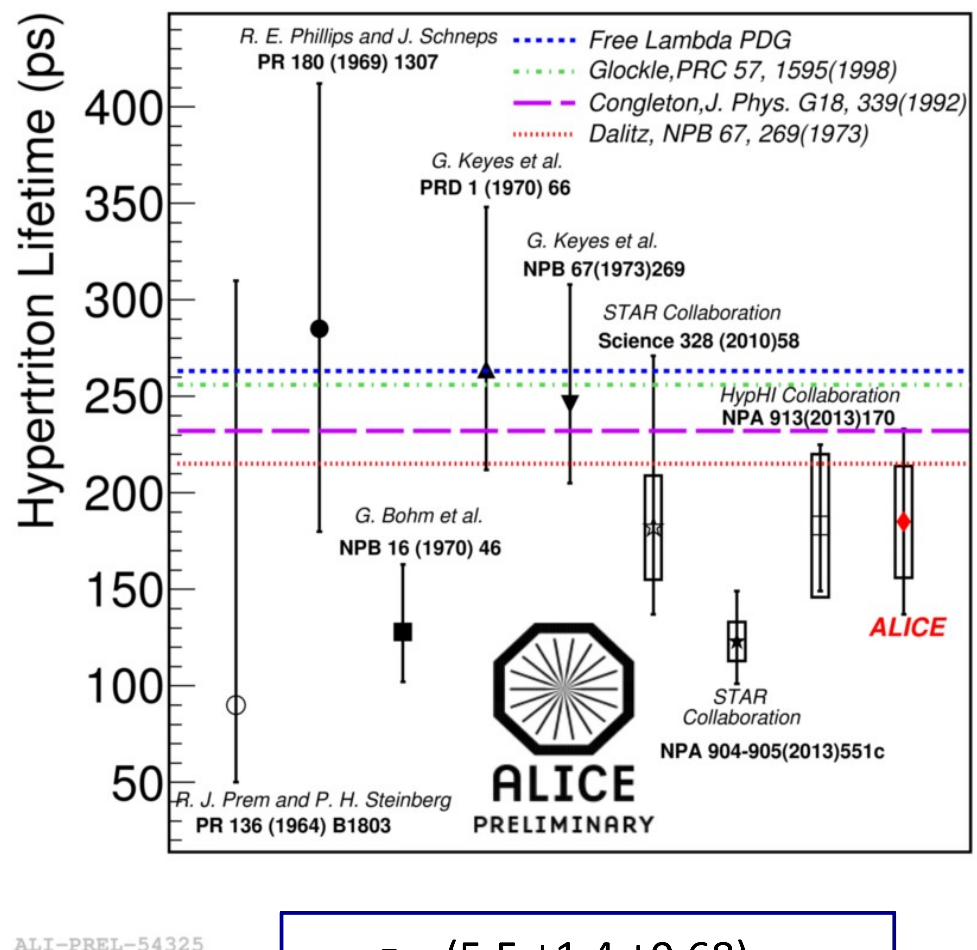


Yield extracted in two centrality bins
dN/dy in good agreement with thermal model prediction from Andronic et al. for T_{chem} = 156 MeV

M. Petráň et al., Phys. Rev. C 88, 034907 (2013)
A. Andronic et al., Phys. Lett. B 697, 203 (2011)

$^{3}_{\Lambda}$H Lifetime determination





Direct decay time measurement is difficult (~ps), but the excellent determination of primary and decay vertex allows measurement of lifetime via:

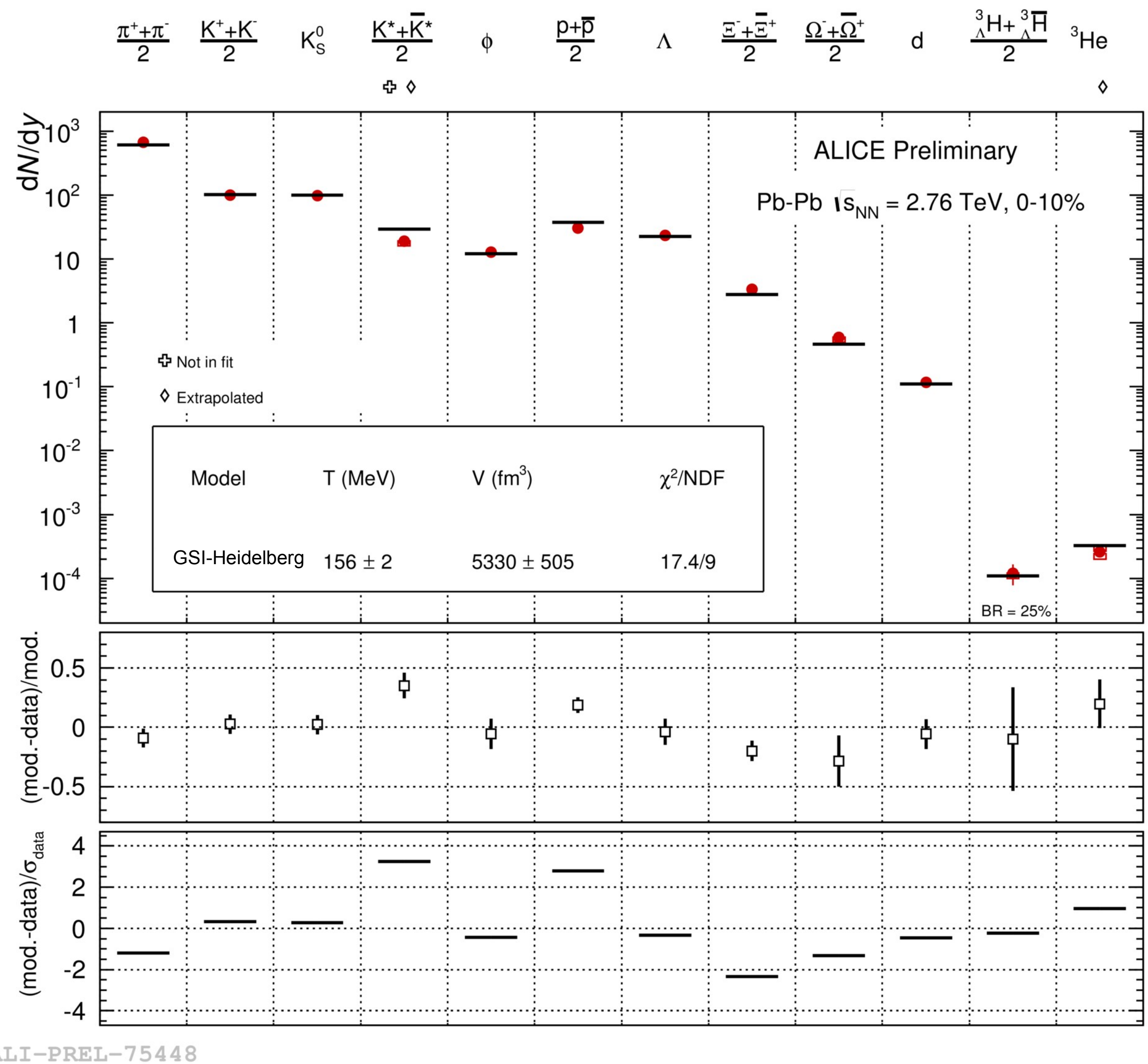
$$N(t) = N(0)\exp\left(-\frac{L}{\beta\gamma c\tau}\right)$$

Where $c\tau = mL/p$ (cm)
With m the hypertriton mass, L the decay length and p the total momentum

$c\tau$ = (5.5 ±1.4 ±0.68) cm

τ = 185 ± 48 ± 29 ps

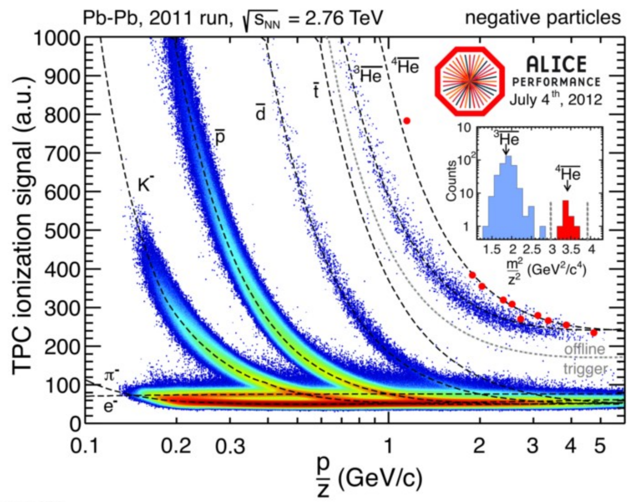
Thermal model fit to ALICE data



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)

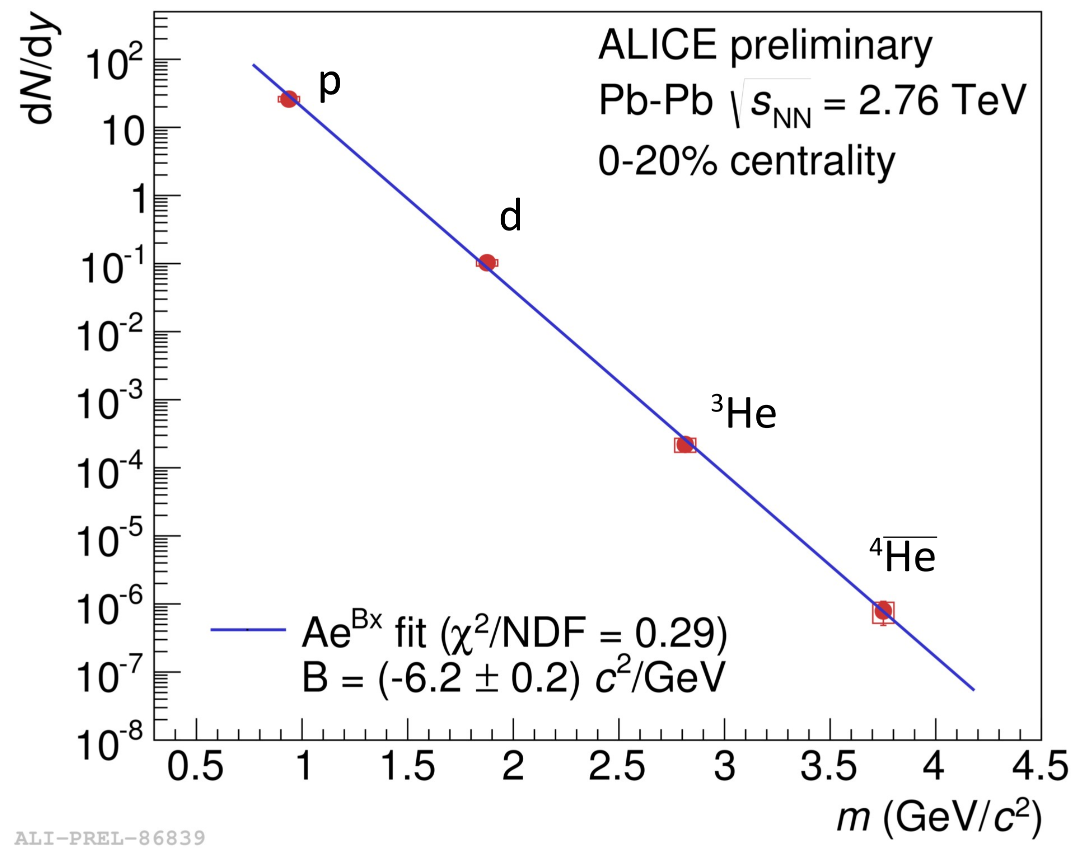
Nuclei in Pb – Pb



Thermal model prediction:

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

- Nuclei follow nicely the exponential fall predicted by the model
- Each added baryon gives a factor of ~300 less production yield



Searches for weakly decaying exotic bound states

- **H-Dibaryon** : Hypothetical bound state of *uuddss* ($\Lambda\Lambda$) first predicted by Jaffe in a bag model calculation.

    R.L. Jaffe, Phys. Rev. Lett. 38, 195 (1977), erratum ibid 38, 617 (1977)

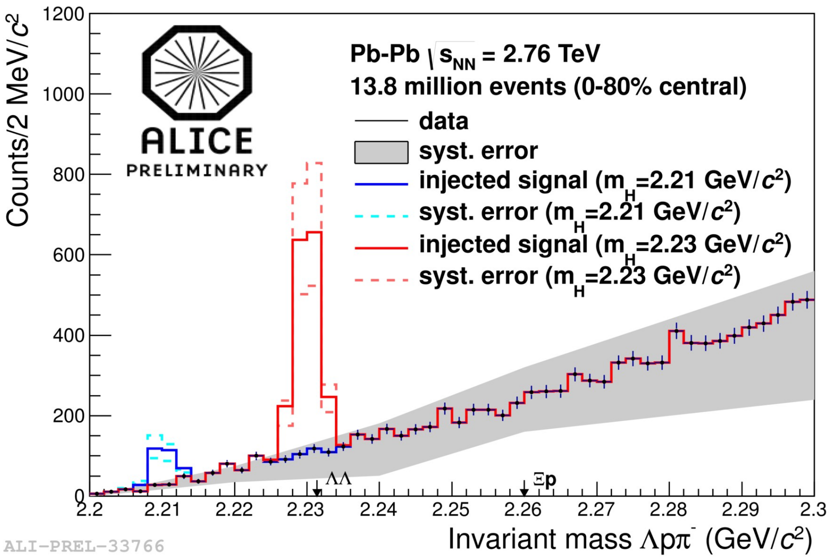
- Bound state of **Λn** ?
    - HypHI experiment at GSI sees evidence of a new state: $\Lambda n \rightarrow d + \pi^-$

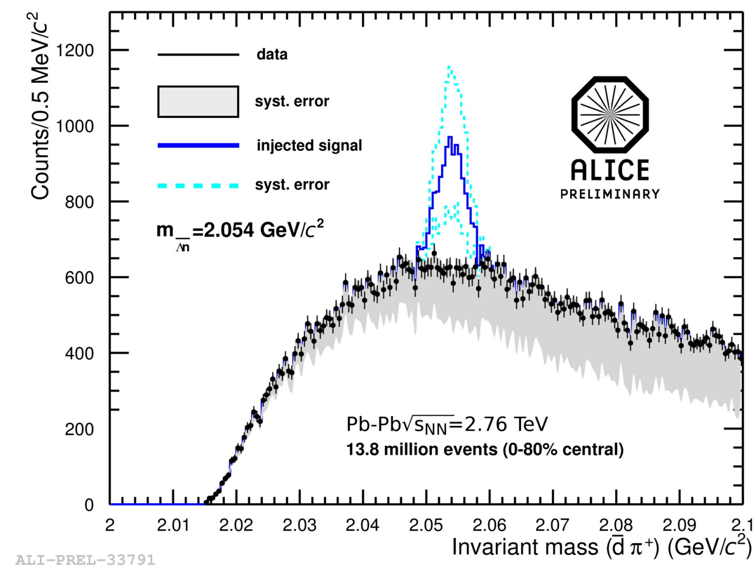
    C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)

H-Dibaryon and ΛN bound state

Expected strongly bound and lightly bound H-Dibaryon signal (thermal model prediction)

Expected Λn bound states signal in ($\Lambda n \rightarrow d\pi^-$) (thermal model prediction)





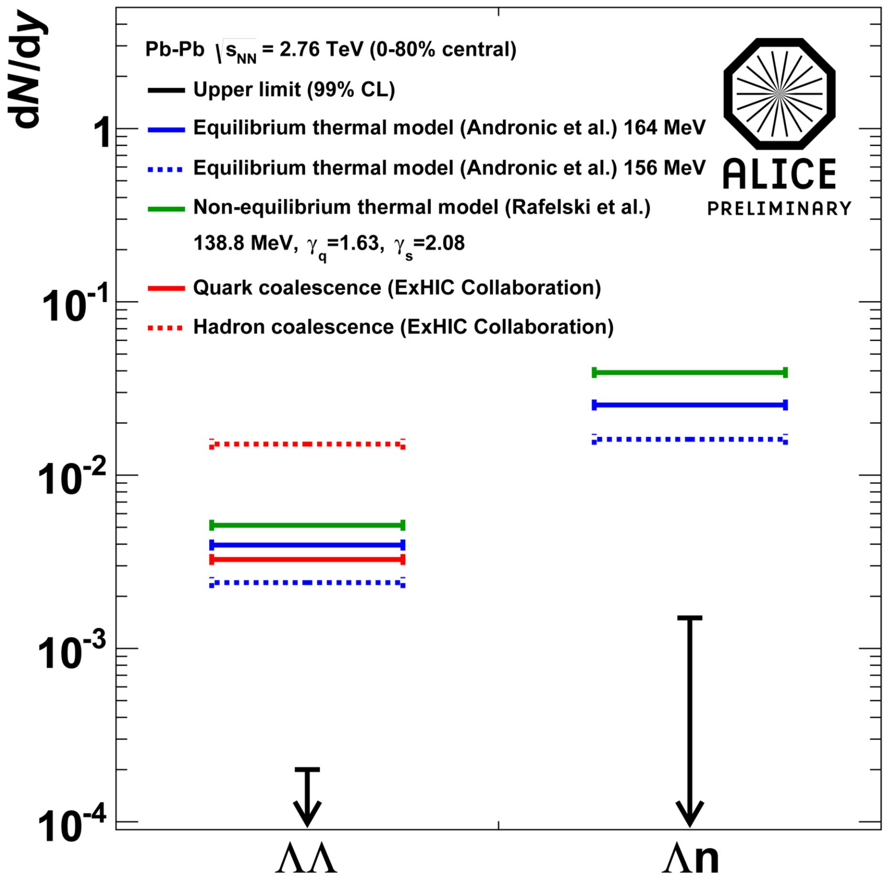
No signal visible → upper limits

For a strongly bound H:
$dN/dy \leq 8.4 \times 10^{-4}$ (99% CL)

For a lightly bound H:
$dN/dy \leq 2 \times 10^{-4}$ (99% CL)

No signal visible → upper limit
$dN/dy \leq 1.5 \times 10^{-3}$ (99% CL)

Comparison to different models



- The upper limits for exotica are lower than the thermal model expectation by a factor 10
- Thermal model with the same temperature describe precisely the production yield of deuterons , ^{3}He and $^{3}_{\Lambda}$H

→ At least factor 10 between models and estimated upper limit

→ The existence of such states with the assumed B.R., mass and lifetime is questionable

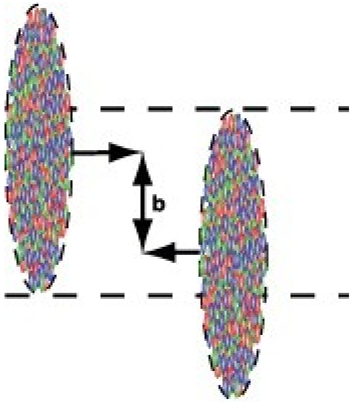
Conclusions

- Excellent ALICE performance allows detection of light (anti-)nuclei, (anti-)hypernuclei and other exotic bound states
- A hardening of the spectrum with increasing centrality is observed both in Pb-Pb and p-Pb collisions
- The d/p ratio rises with multiplicity in p-Pb collisions, while no significant centrality dependence is observed in Pb-Pb collisions
- Coalescence parameter B_2 is independent from p_T in p-Pb and peripheral Pb-Pb collisions, while it increases with p_T in central Pb-Pb collisions. A decrease with centrality is also observed in Pb-Pb collisions
- The measured $^{3}_{\Lambda}H$ lifetime (185 ± 48 ± 29 ps) is consistent with previous measurements
- Measured deuteron, ^{3}He, hypertriton and anti-alpha yields are in agreement with the current best thermal fit from equilibrium thermal model (T_{chem} = 156 MeV)
- H-Dibaryon and Λn search in Pb-Pb with ALICE: no visible signal → Upper limits are at least an order of magnitude lower than predictions of several models

BACKUP

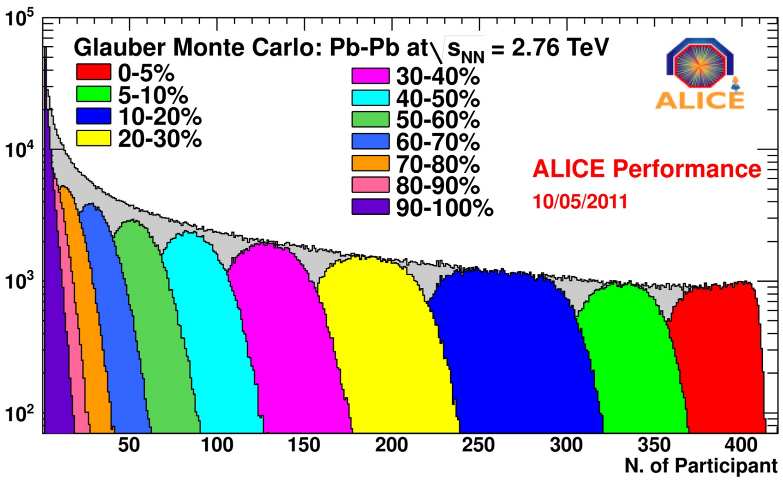
Centrality in Pb – Pb

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

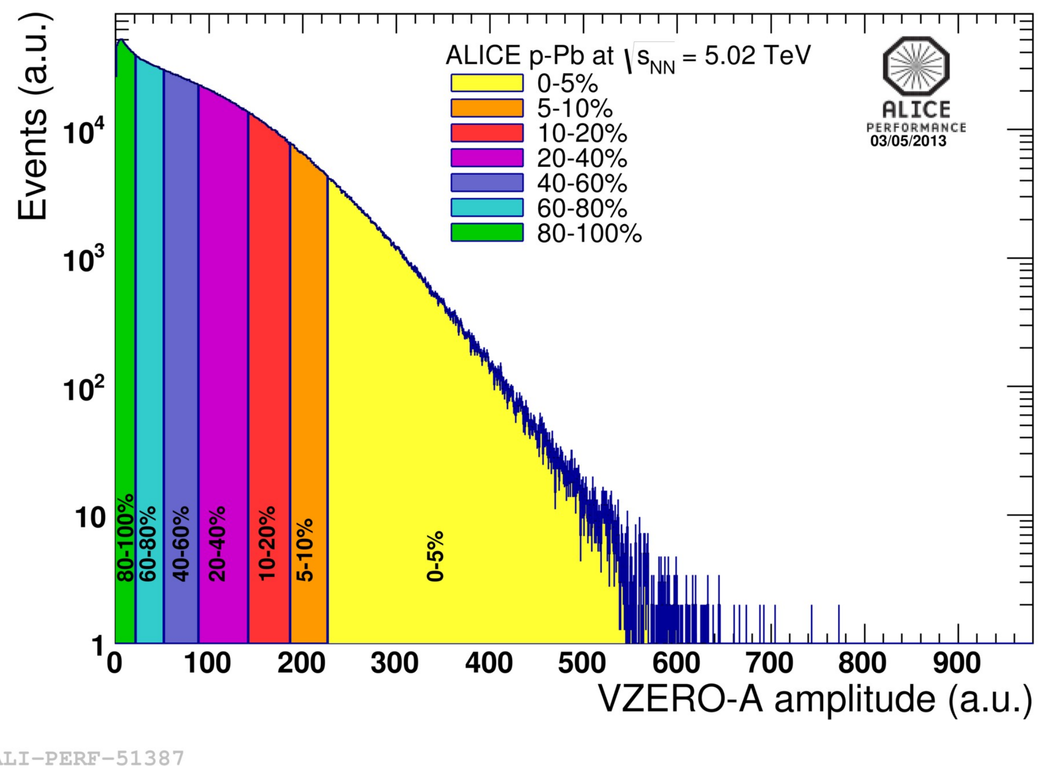


Geometrical picture of AA collisions with the Glauber model:

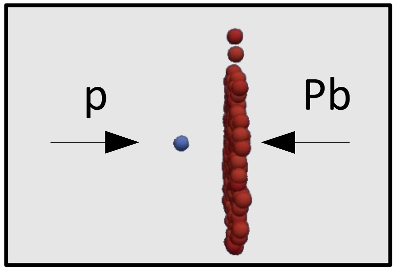
- Random relative position of nuclei in transverse plane Woods-Saxon distribution of nucleons inside nucleus
- Straight-line nucleon trajectories
- N-N cross-section (σ_{NN} = 64 ± 5 mb) independent of the number of collisions the nucleons suffered before

Centrality in p – Pb

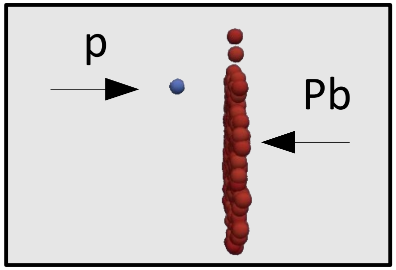
Multiplicity estimator: slices in VZERO-A (V0A) amplitude



Central collision



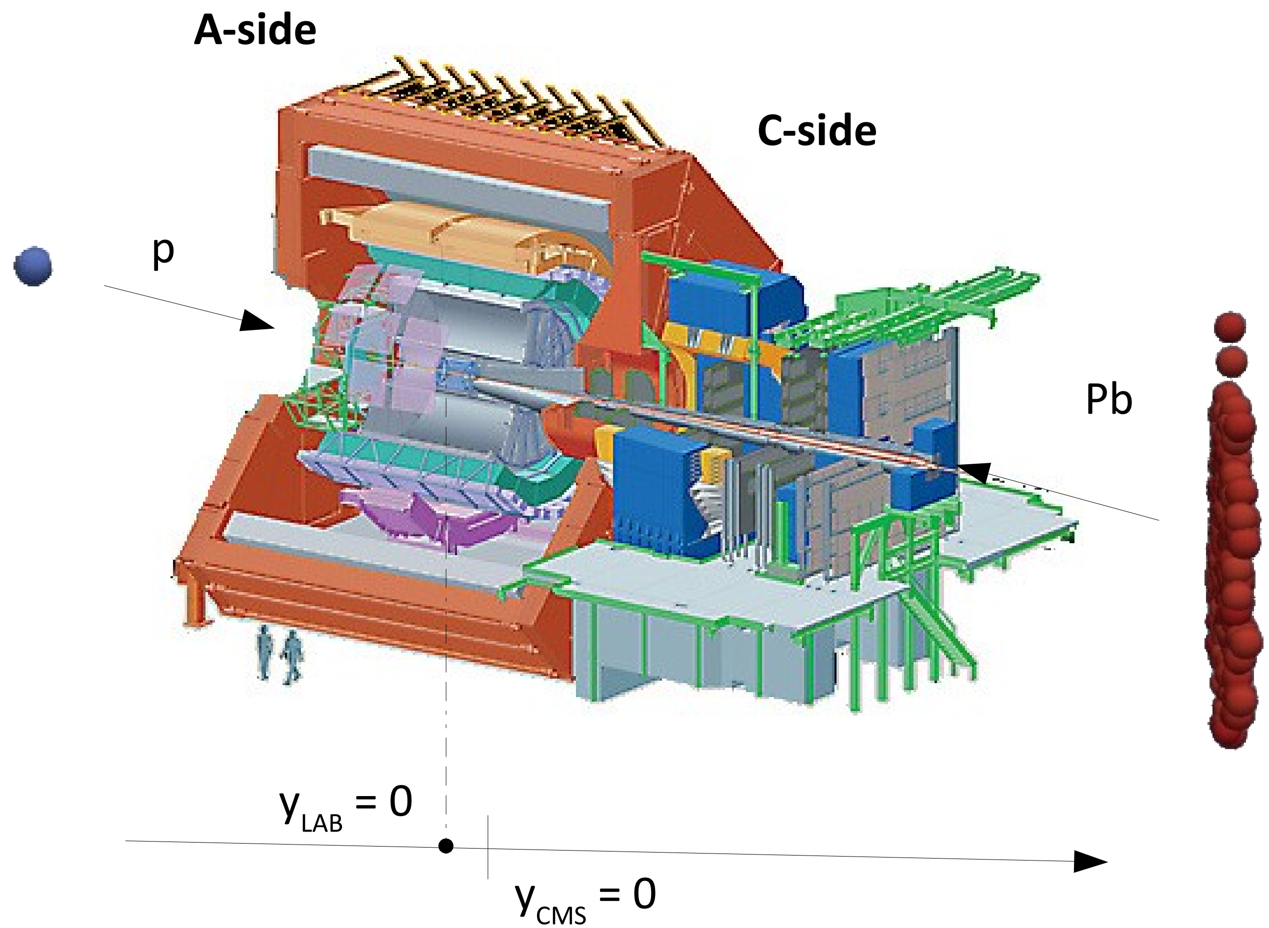
Peripheral collision



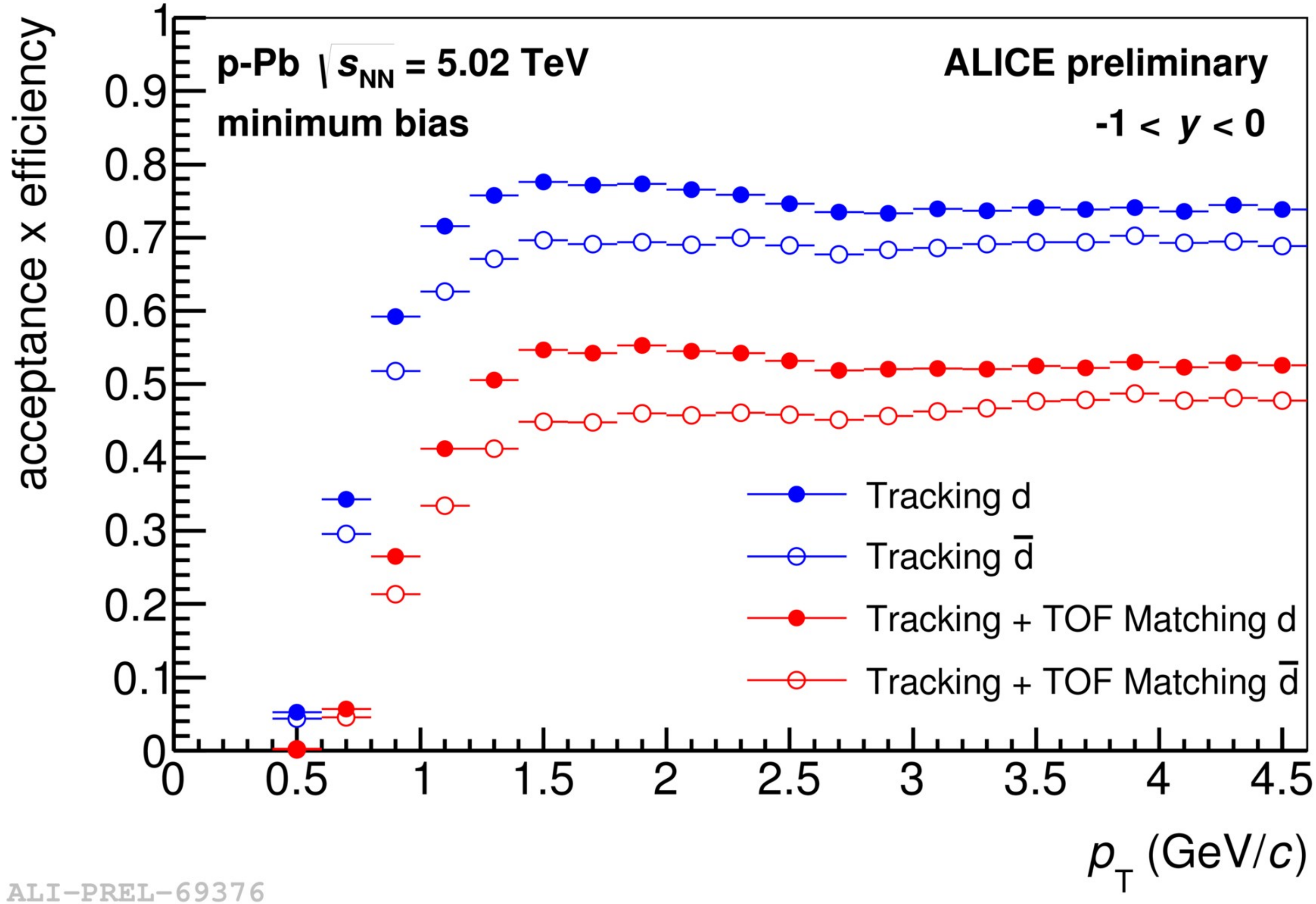
Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb

Rapidity definition in p – Pb

Asymmetric energy/nucleon in the two beams → CMS moves with rapidity $|\Delta y_{CMS}| = 0.465$



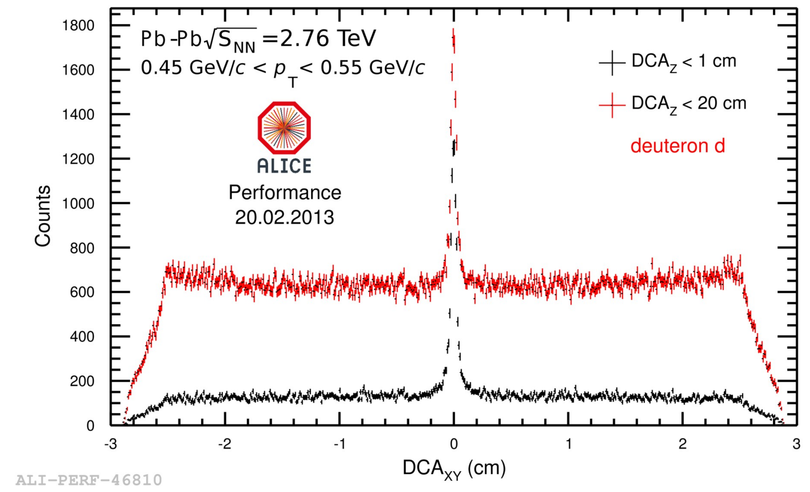
Efficiency Correction

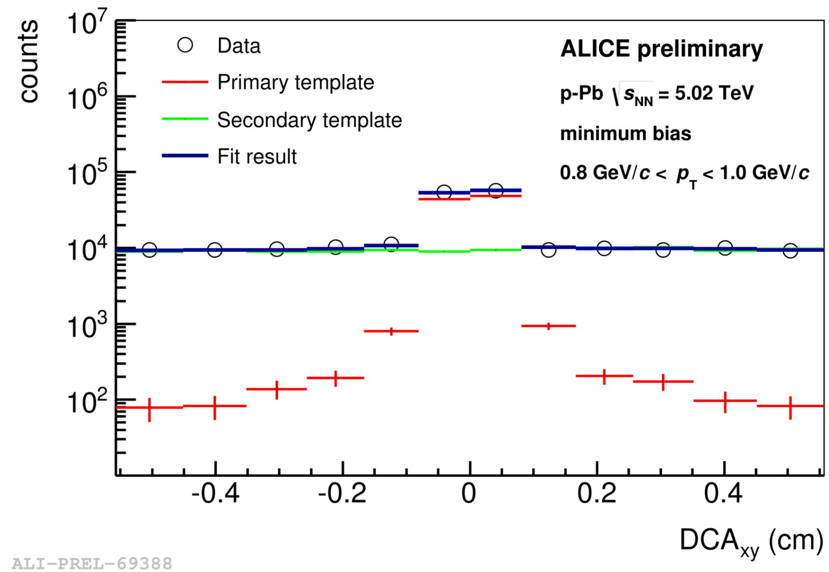


Nuclei Identification : Secondaries

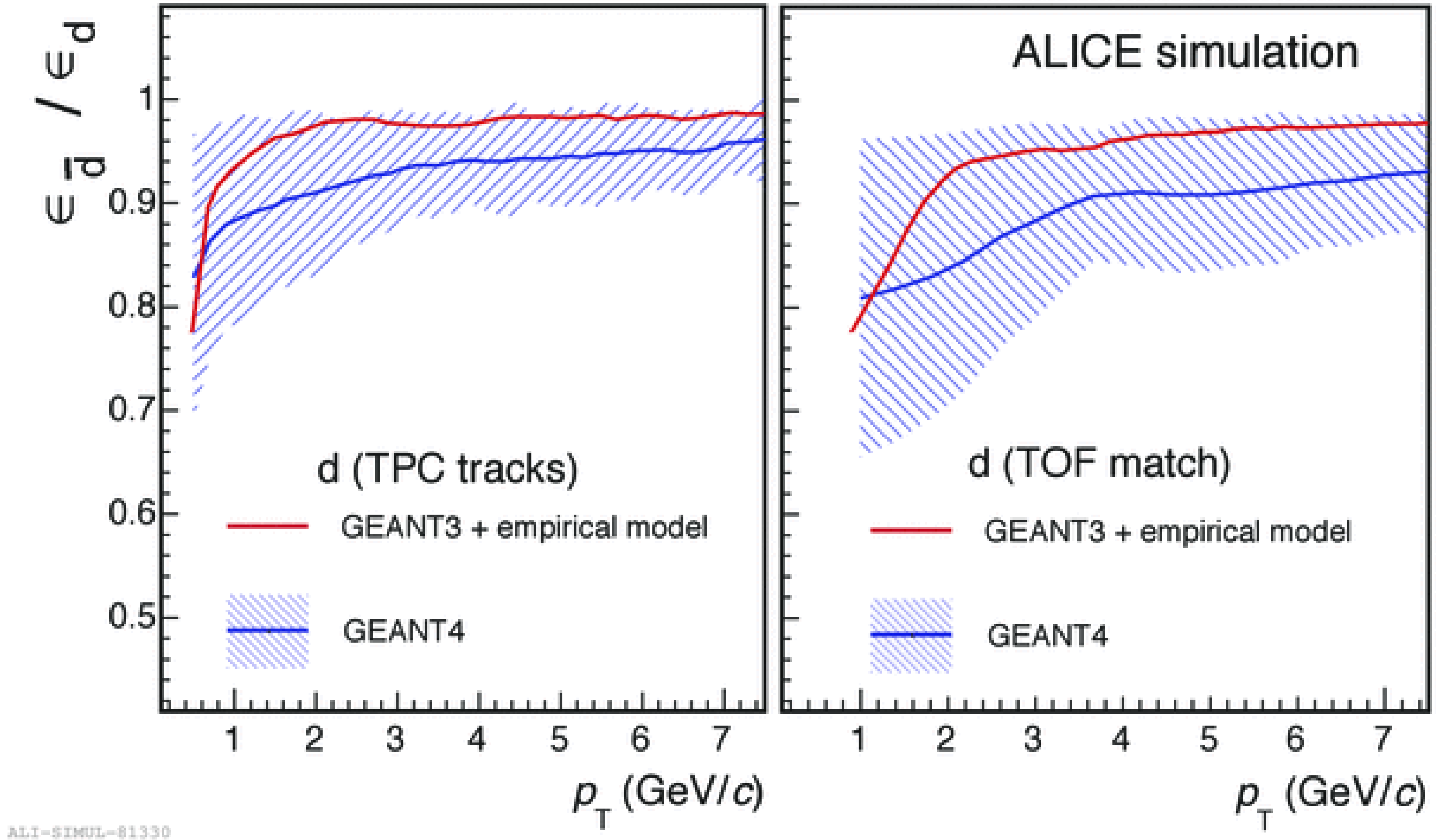
Nuclei from knock-out reactions constitute a large background at low momenta in all nuclei measurements. Knock-out reactions are not relevant for anti-nuclei secondaries

Rejection is possible restricting DCA_Z and fitting the DCA_{XY} distribution with MC templates





Absorption Correction

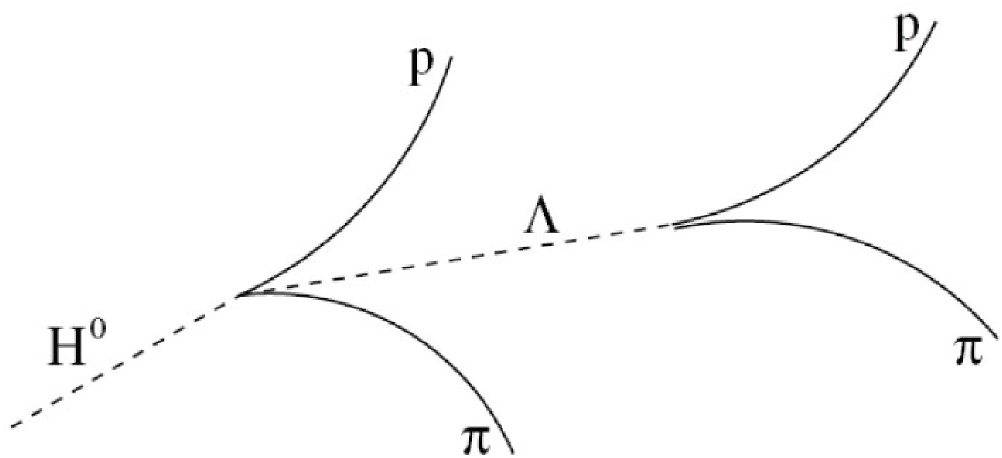


For the anti-deuteron spectra an additional correction is necessary due to the absorption

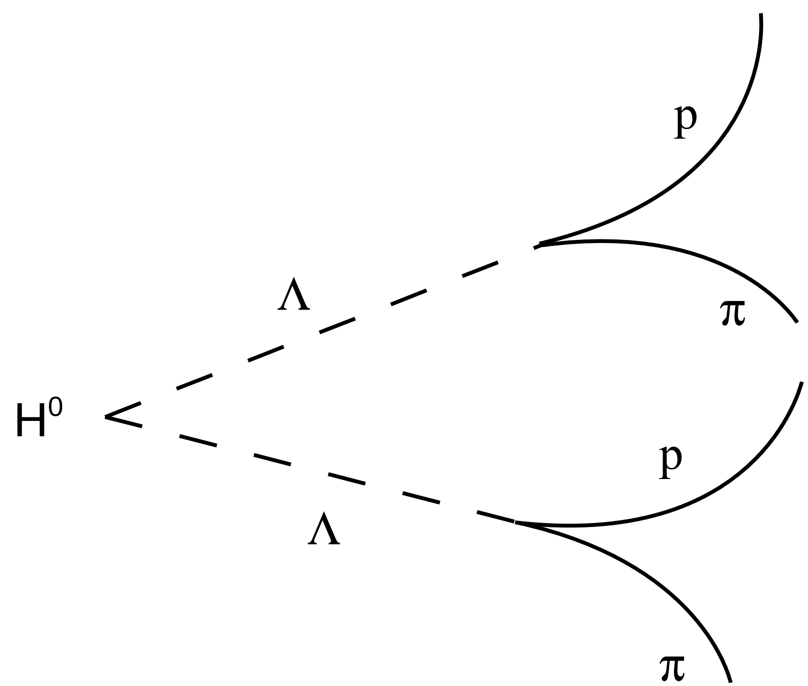
H-Dibaryon

Two cases:

- $m_H < \Lambda\Lambda$ threshold
  - weakly bound:
    measurable channel
    $H \rightarrow \Lambda p \pi$
  - $2.2\ \mathrm{GeV}/c^2 < m_H < 2.231\ \mathrm{GeV}/c^2$



- $m_H > \Lambda\Lambda$ threshold
  - resonant state:
    measurable channel
    $H \rightarrow \Lambda\Lambda$
  - $m_H > 2.231\ \mathrm{GeV}/c^2$



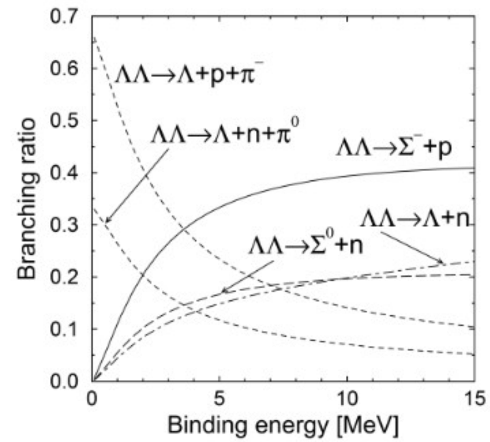
H-Dibaryon and ΛN bound state

Expected H-Dibaryon yield at the LHC (thermal model prediction):

$$N = \underbrace{3.1 \cdot 10^{-3}}_{dN/dy} \times \underbrace{2}_{y} \times \underbrace{1.38 \cdot 10^{7}}_{events} \times \underbrace{0.0385}_{Eff.} \times \underbrace{0.64}_{BR(\Lambda)} = 2110$$

lightly bound:
2110 x 0.64 = 1350

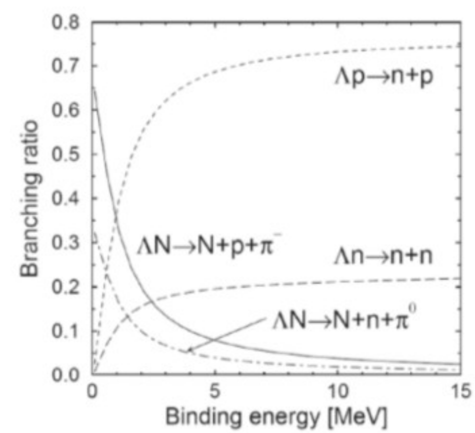
strongly bound:
2110 x 0.1 = 211



Jürgen Schaffner-Bielich et al., PRL 84, 4305 (2000)

Expected Λn bound states yield at the LHC in ($\Lambda n \to d\pi^-$) (Thermal model prediction):

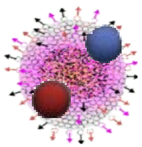
$$N = \underbrace{1.6 \cdot 10^{-2}}_{dN/dy} \times \underbrace{2}_{y} \times \underbrace{1.38 \cdot 10^{7}}_{events} \times \underbrace{0.0255}_{Eff.} \times \underbrace{0.35}_{BR(\Lambda n)} = 4000$$



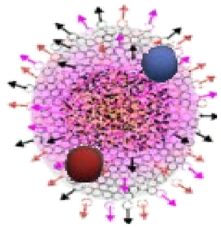
Jürgen Schaffner-Bielich, private communication

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)