RECENT RESULTS FROM ALICE

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste

MOTIVATION

- **(anti-)(hyper)nuclei are good probes of coalescence mechanism**
- **(anti-)(hyper)nuclei yields are sensitive to the freeze-out temperature in heavy-ion collision** due to their large mass (e.g. in the Thermal Model yield scales roughly $\propto e^{(-M/T_{chem})}$)
- light (anti-)(hyper)nuclei have small binding energy and small Λ separation energy,

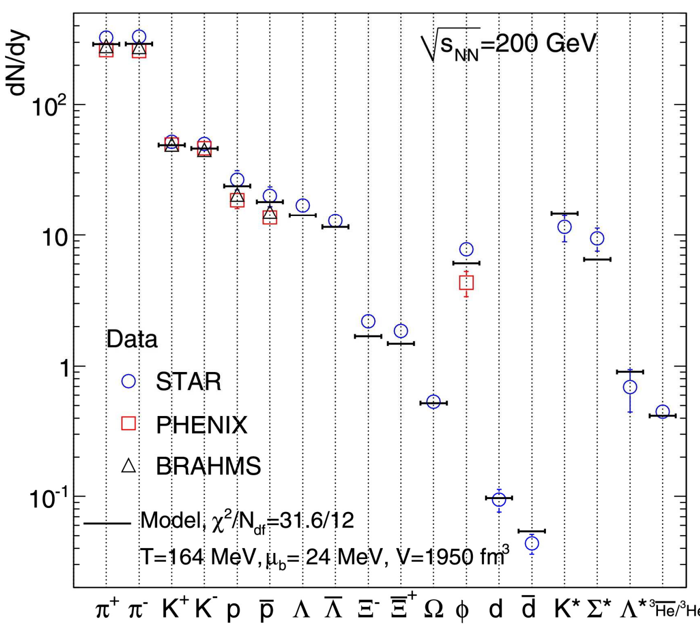
  e.g. $B_\Lambda(^3_\Lambda H) = 0.13 \pm 0.05$ MeV [H. Bando et al., Int. J. Mod. Phys. A 5 4021 (1990)] :
  - **they should dissociate in a medium with high T_{chem}** (~156 MeV) and be suppressed
  - if their yields equal to thermal model prediction ⇒ sign for **adiabatic (isentropic) expansion** in the hadronic phase
- A=3 (anti-)(^{3}He, t, $^3_\Lambda$H), a simple system of 9 valence quarks:
  - $^3_\Lambda$H / ^{3}He and $^3_\Lambda$H / t (and anti) ⇒ Λ-nucleon correlation (**local baryon-strangeness correlation**)
  - t / ^{3}He (and anti) ⇒ **local charge-baryon correlation**
- Anti-nuclei in nature:
  - **matter–antimatter asymmetry**

    [J.Adam et al. (ALICE Collaboration), Nature Phys. 11, no.10, 811 (2015)]
  - light nuclei measurements in high energy physics can be used in dark matter searches to estimate the background coming from the secondary anti-nuclei

(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

Statistical Thermal model

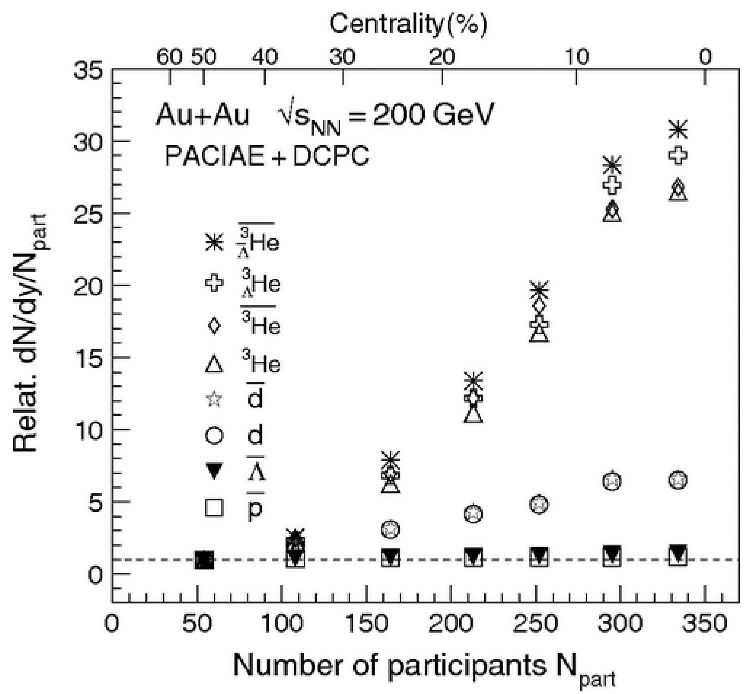
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $\propto e^{(-M/T_{chem})}$



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

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 freeze-out

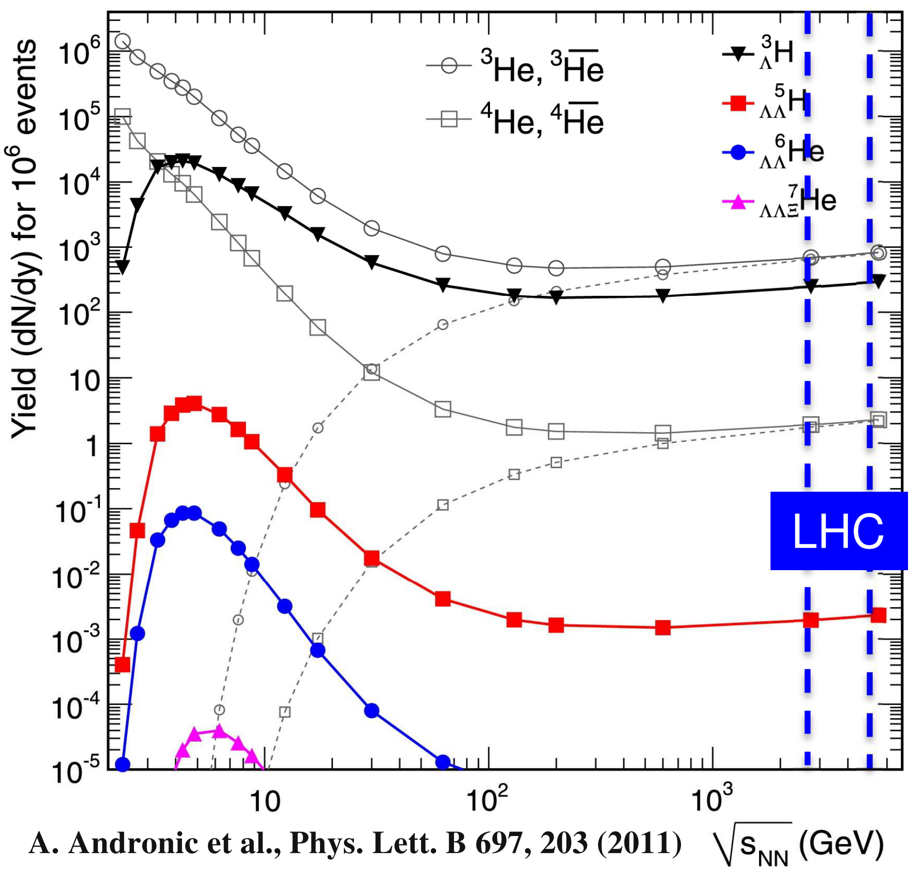


G. Chen et al., Phys. Rev. C 88, 034908 (2013)

ALICE

(ANTI-)(HYPER)NUCLEI PRODUCTION AT LHC

Production yield estimate of (anti-)(hyper)nuclei in central heavy-ion collisions at LHC energy based on thermal model:

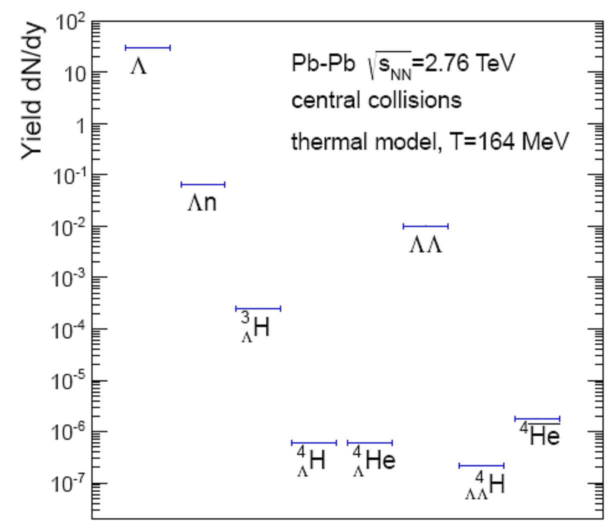


A. Andronic et al., Phys. Lett. B 697, 203 (2011)

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

	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

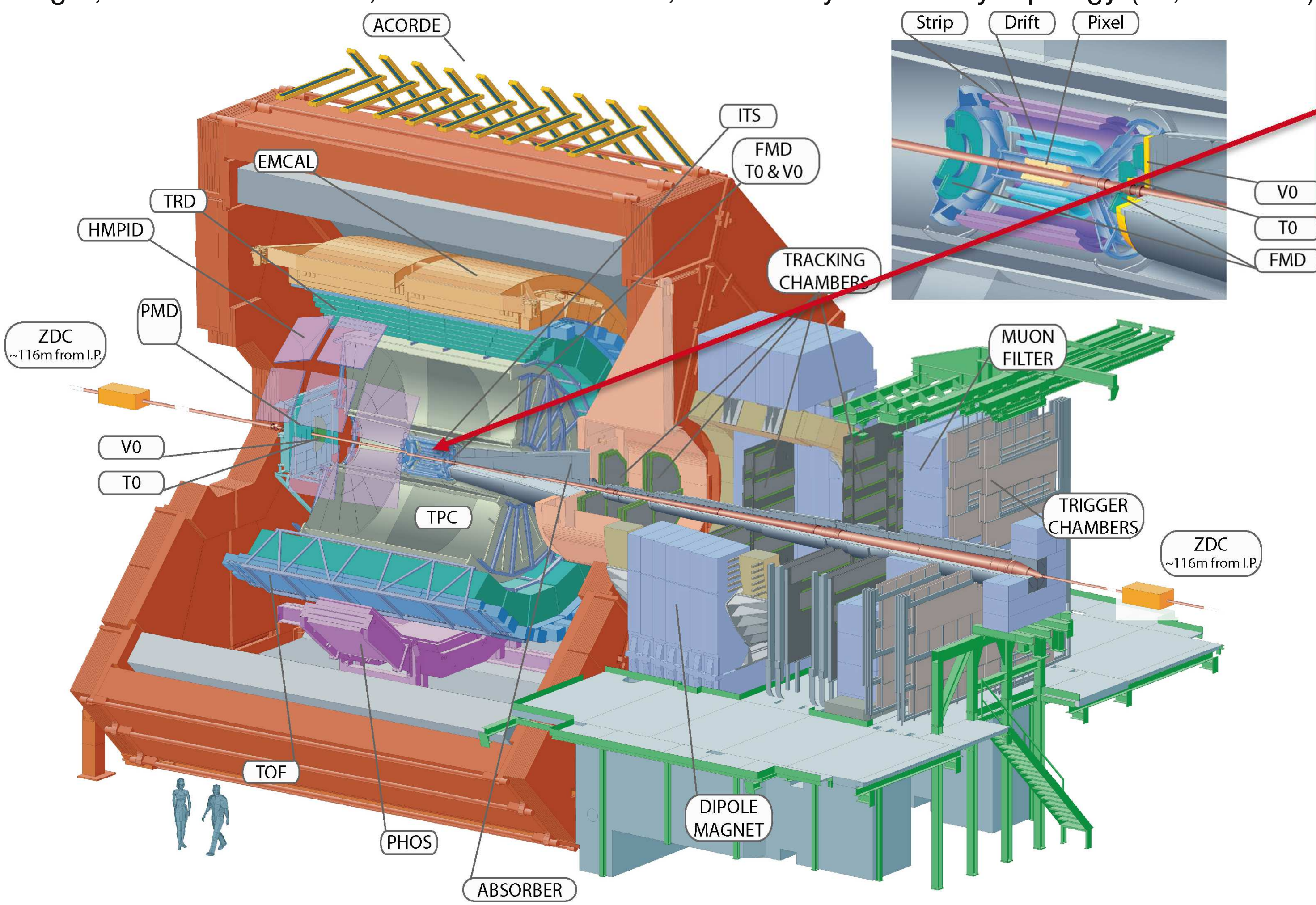
- ✓ Light nuclei
- ✓ Hypertriton
- ✓ Search for: Λn, ΛΛ dibaryons



A. Andronic, private communication

A LARGE ION COLLIDER EXPERIMENT

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

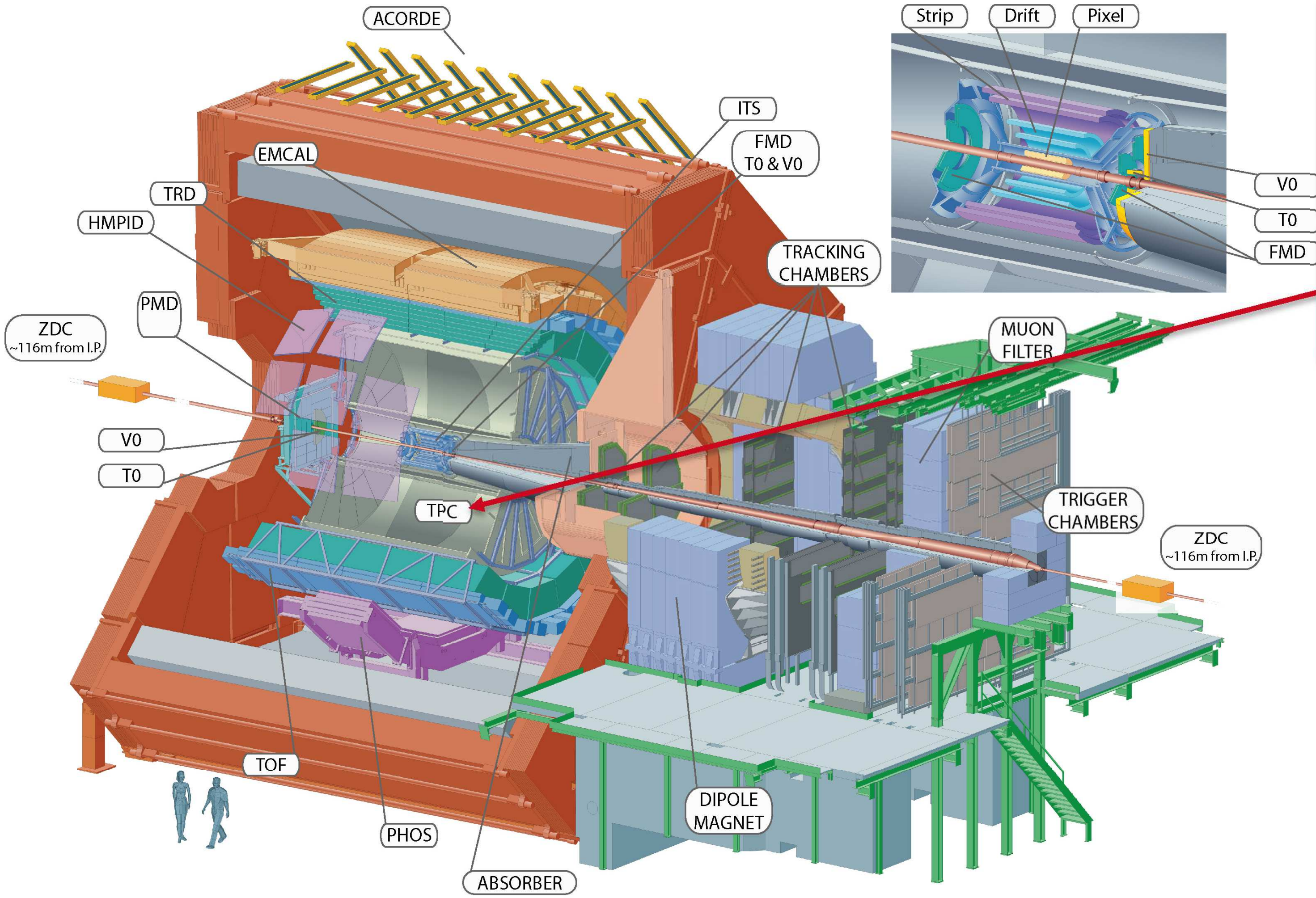


ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

A LARGE ION COLLIDER EXPERIMENT

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



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

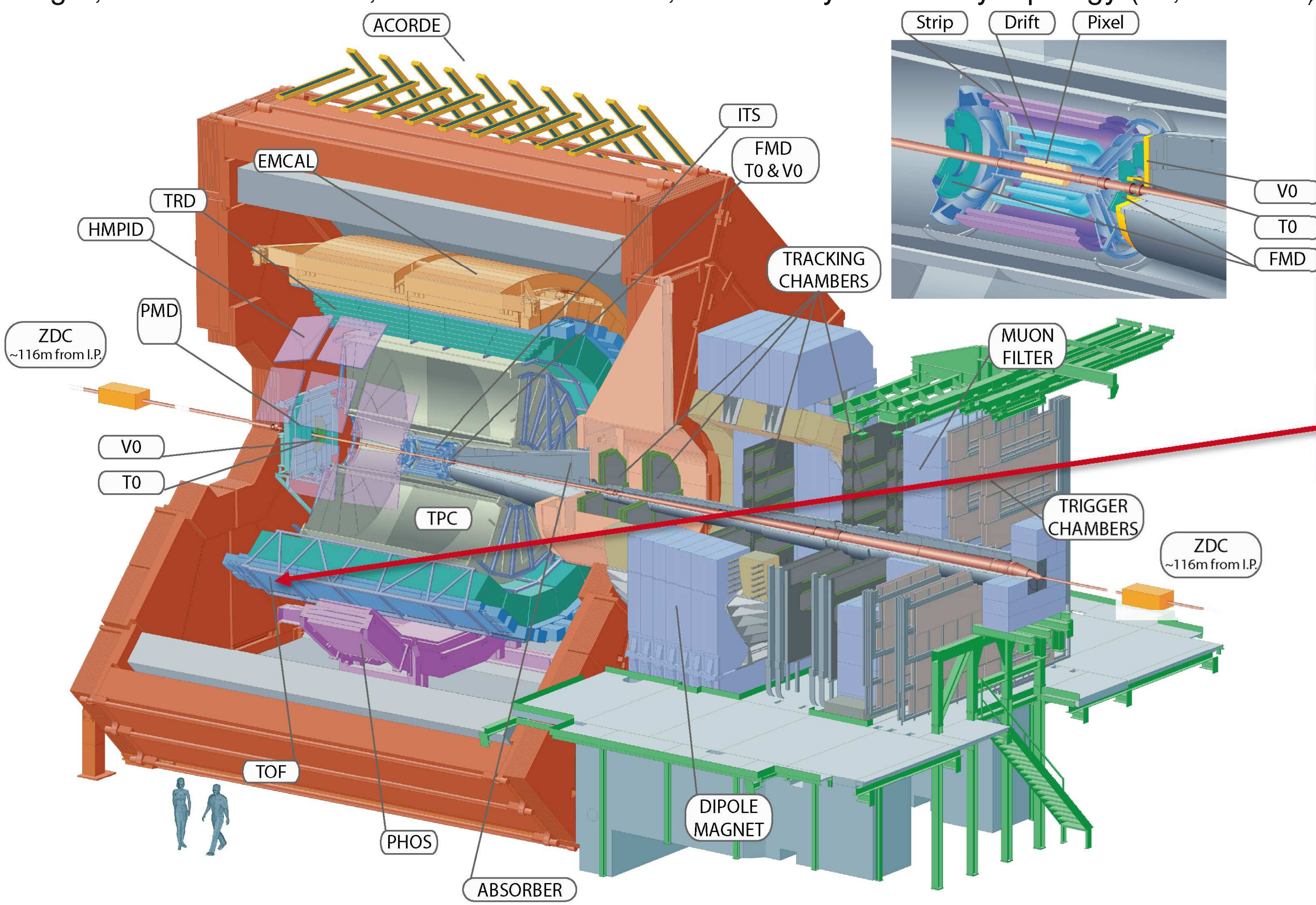
TPC: particle identification via dE/dx (allows also separation of charges).

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002

B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

A LARGE ION COLLIDER EXPERIMENT

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 decay topology (V^0, cascade)



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

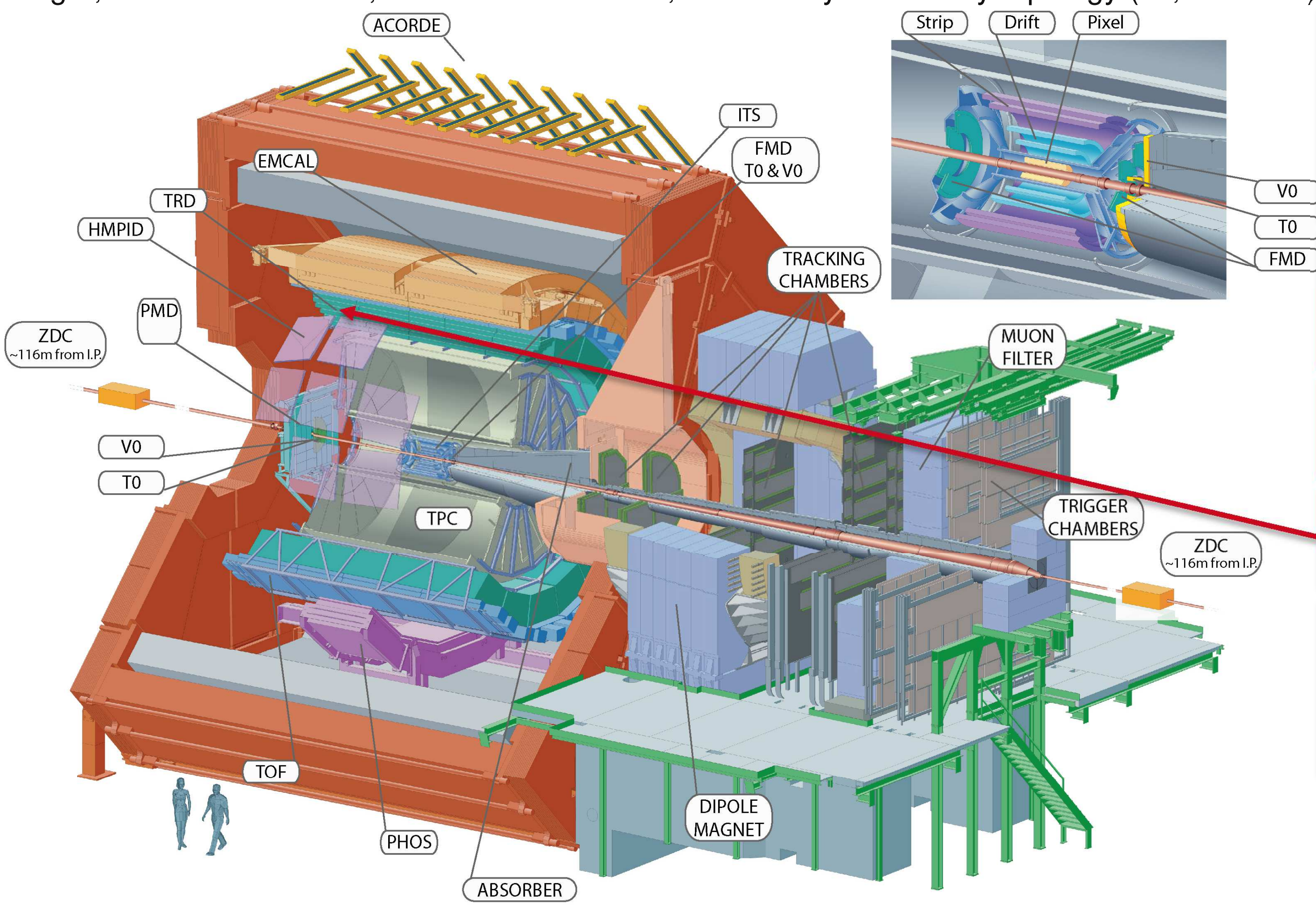
TPC: particle identification via d*E*/d*x* (allows also separation of charges).

TOF: particle identification via time-of-flight

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

A LARGE ION COLLIDER EXPERIMENT

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



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

TPC: particle identification via dE/dx (allows also separation of charges).

TOF: particle identification via time-of-flight

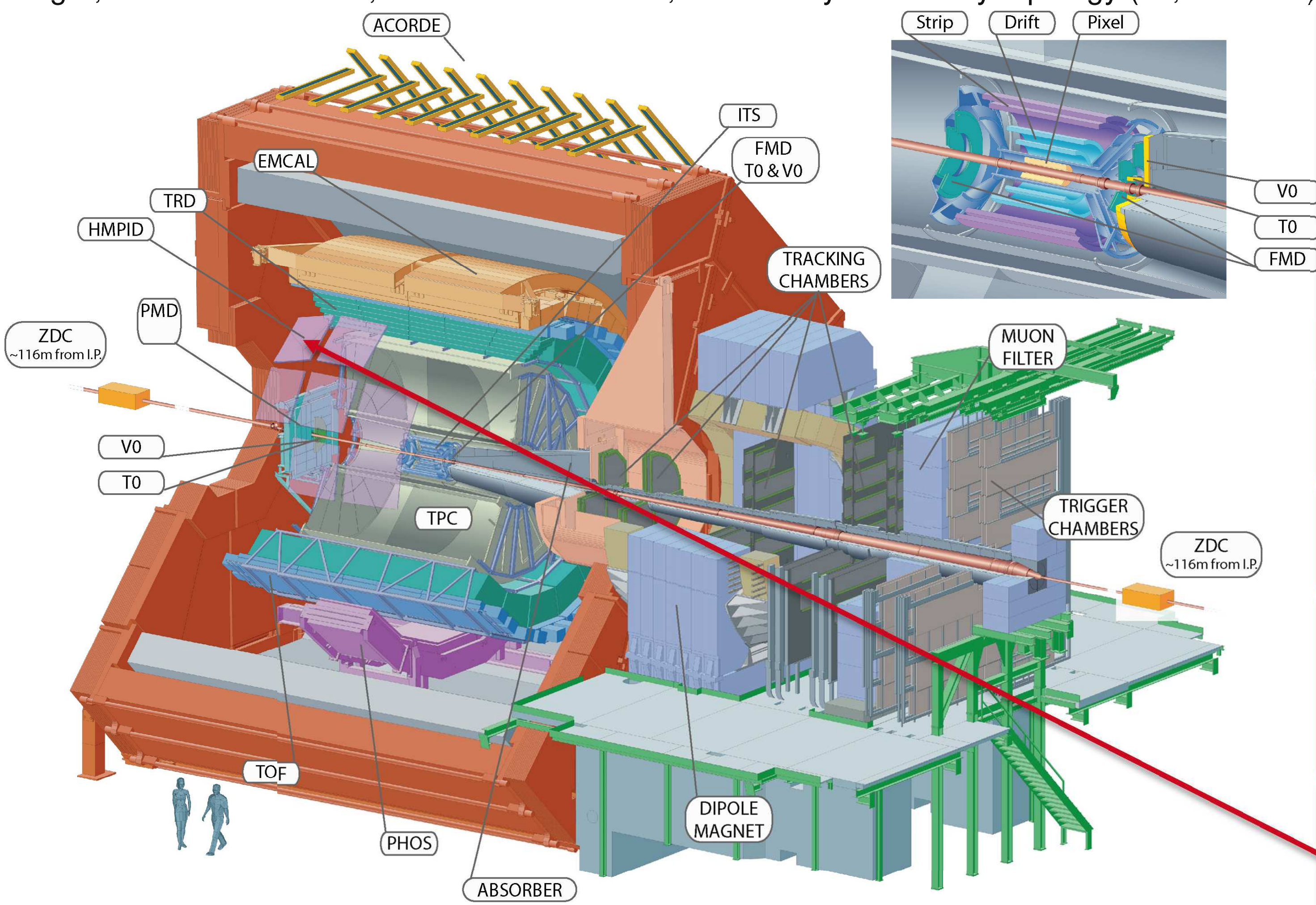
TRD: electron identification via transition radiation

ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

A LARGE ION COLLIDER EXPERIMENT

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



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

TPC: particle identification via dE/dx (allows also separation of charges).

TOF: particle identification via time-of-flight

TRD: electron identification via transition radiation

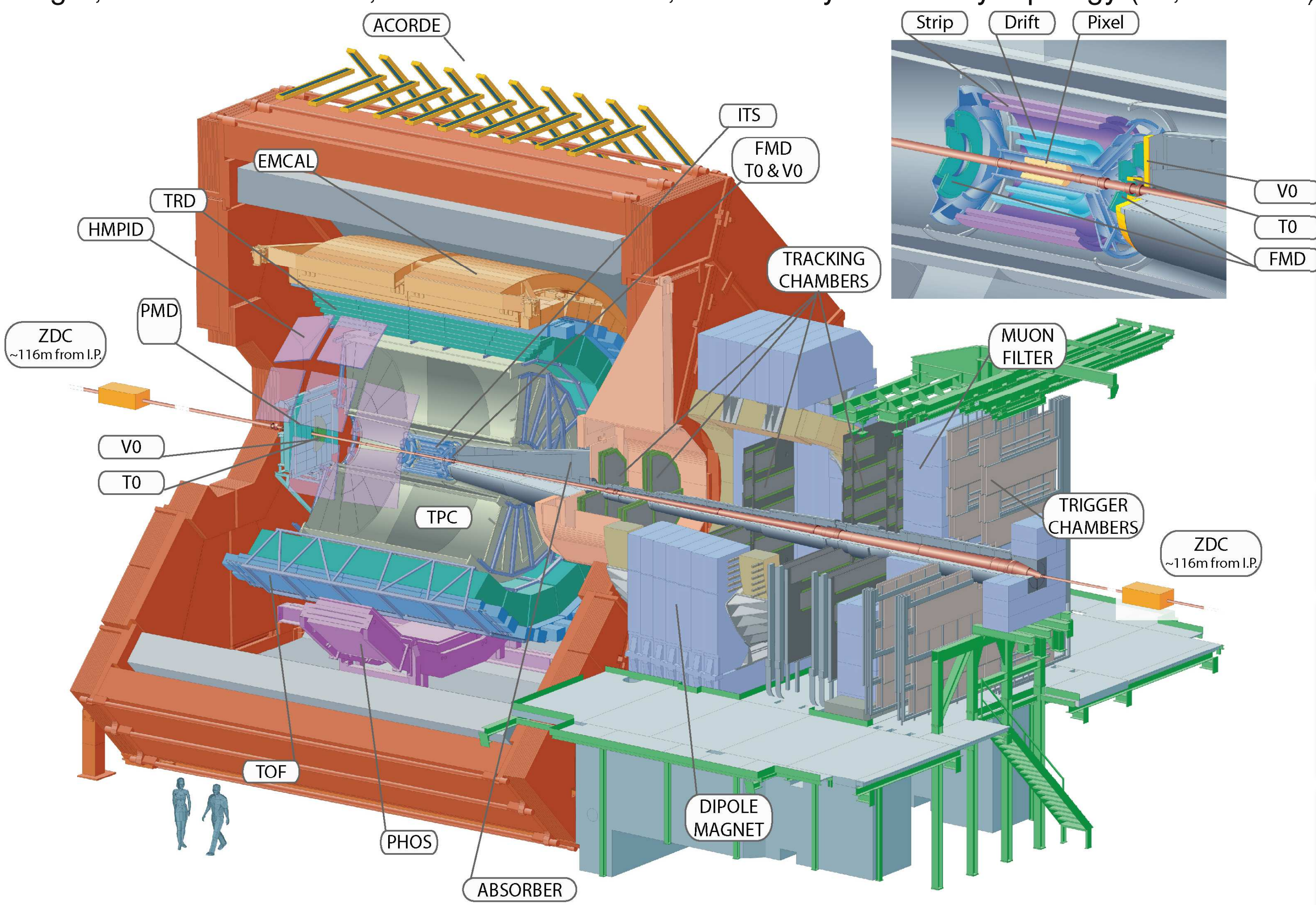
ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

HMPID: particle identification via Cherenkov radiation

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

A LARGE ION COLLIDER EXPERIMENT

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



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

TPC: particle identification via dE/dx (allows also separation of charges).

TOF: particle identification via time-of-flight

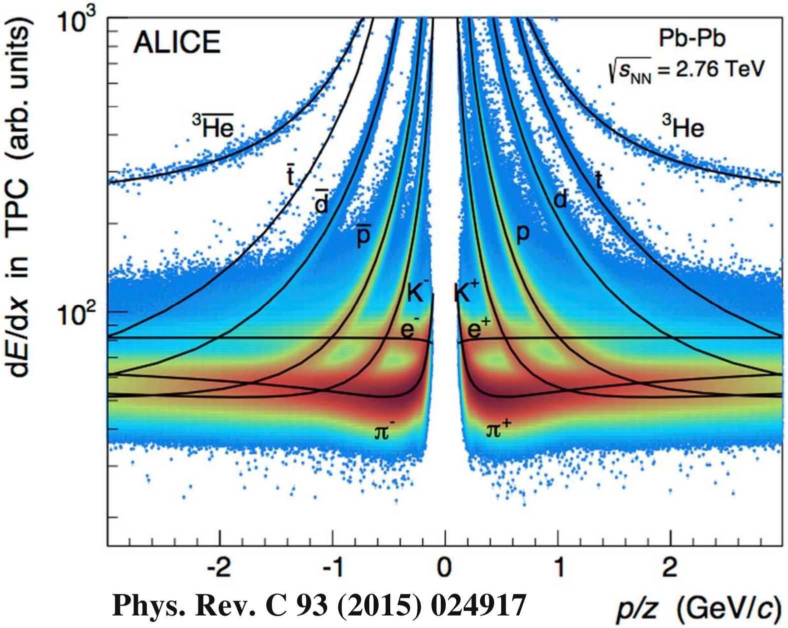
TRD: electron identification via transition radiation

ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

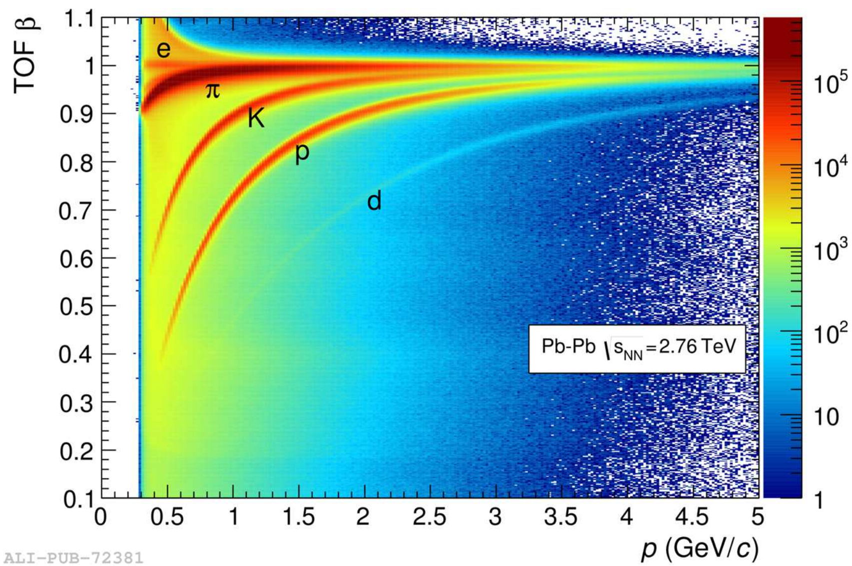
HMPID: particle identification via Cherenkov radiation

ALICE is ideally suited for the identification of light (anti-)(hyper)nuclei

NUCLEI IDENTIFICATION



Phys. Rev. C 93 (2015) 024917



Low momenta

Nuclei identification via d*E*/d*x* measurement in the TPC:

- d*E*/d*x* resolution in central Pb-Pb collisions: ~6.5%
- Excellent separation of (anti-)nuclei from other particles over a wide momentum range
- About **10 anti-alpha candidates** identified out of 23x10^6 events by combining TPC and TOF particle identification

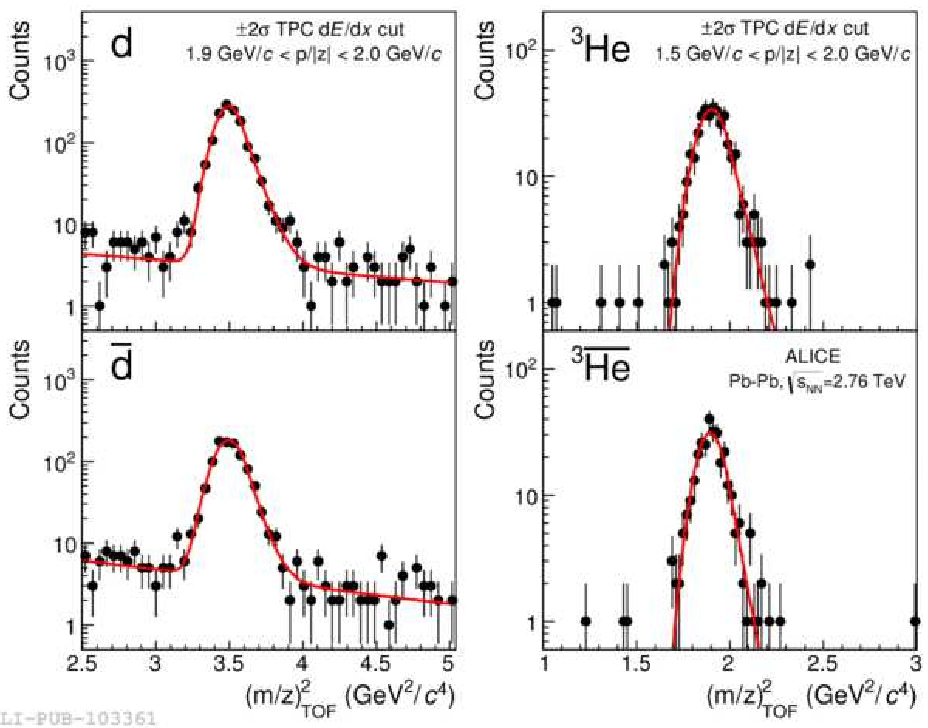
Higher momenta

Excellent TOF performance:

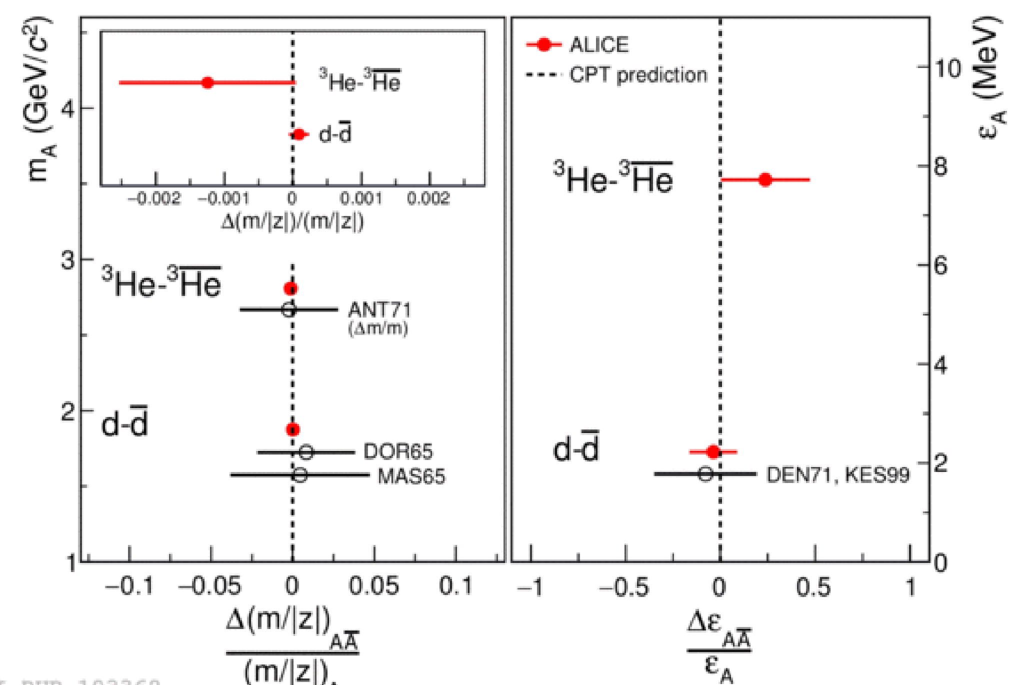
- σ_{TOF} ≈ 85 ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range
- Velocity measurement with the TOF detector is used to evaluate the m^2 distribution and to subtract background from the signal in each p_T-bin by fitting the m^2 distribution

PRECISE MASS MEASUREMENT

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



- The precise measurement of the mass difference between nuclei and their anti-counterparts allows one 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"

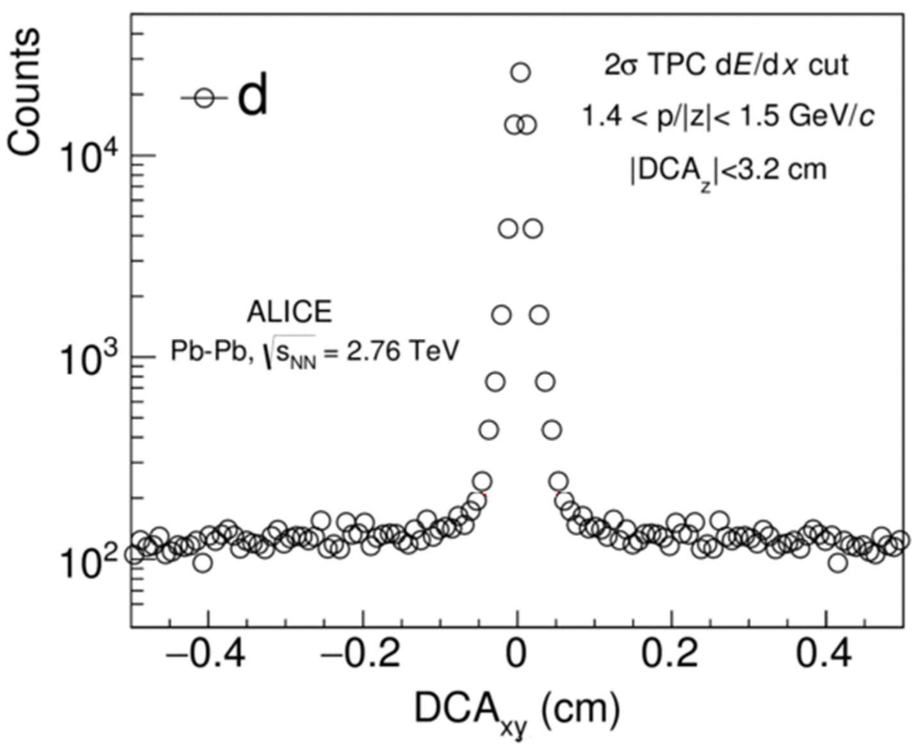


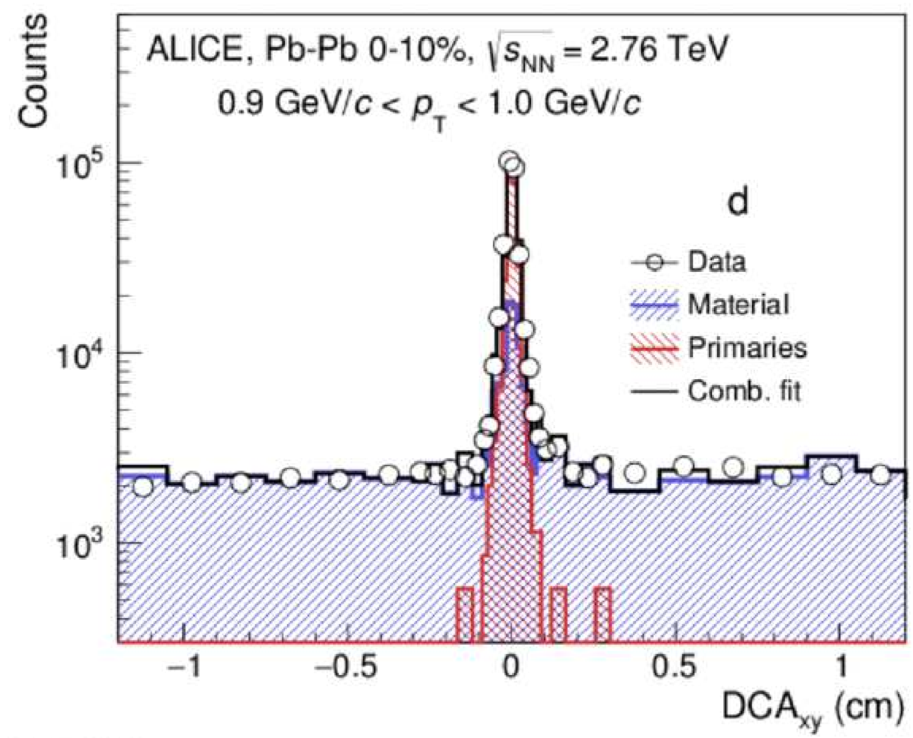
✓ Masses and binding energies of nuclei and anti-nuclei are compatible within uncertainties

✓ Measurement confirms the CPT invariance for light nuclei

SECONDARY CONTAMINATION

- The measurement of nuclei is strongly affected by background from knock-out from material
- Rejection is possible by fitting the DCA_{XY} distributions with templates

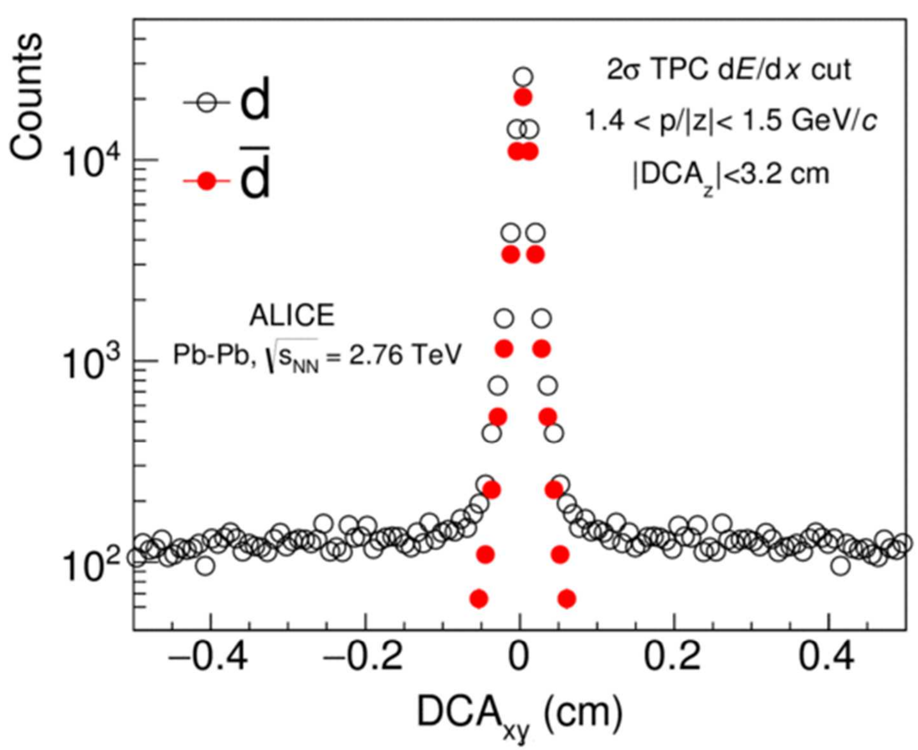


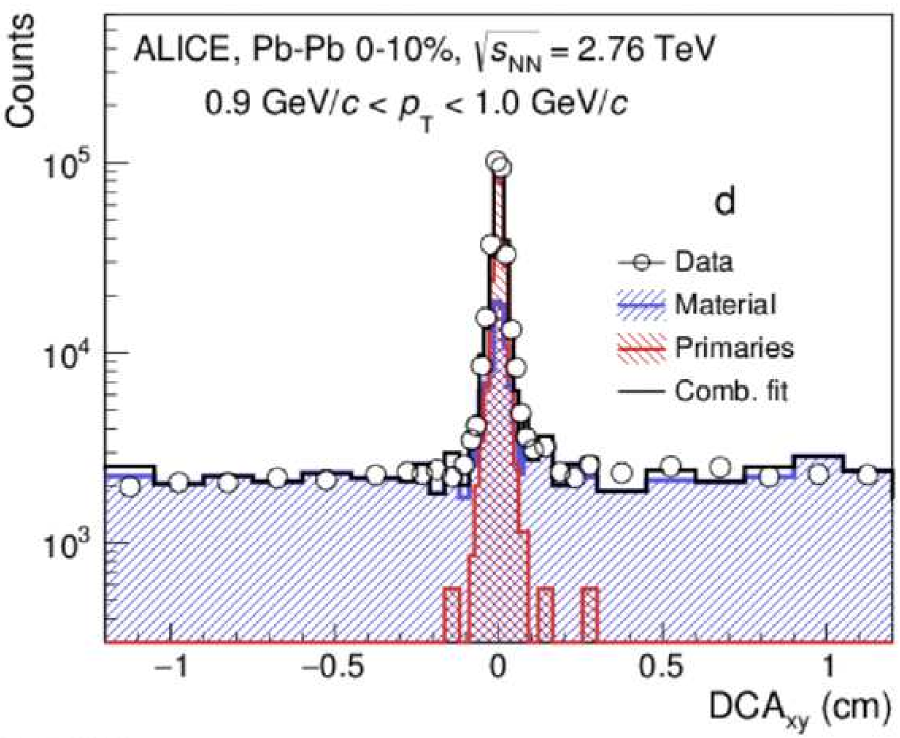


ALI-PUB-107762

SECONDARY CONTAMINATION

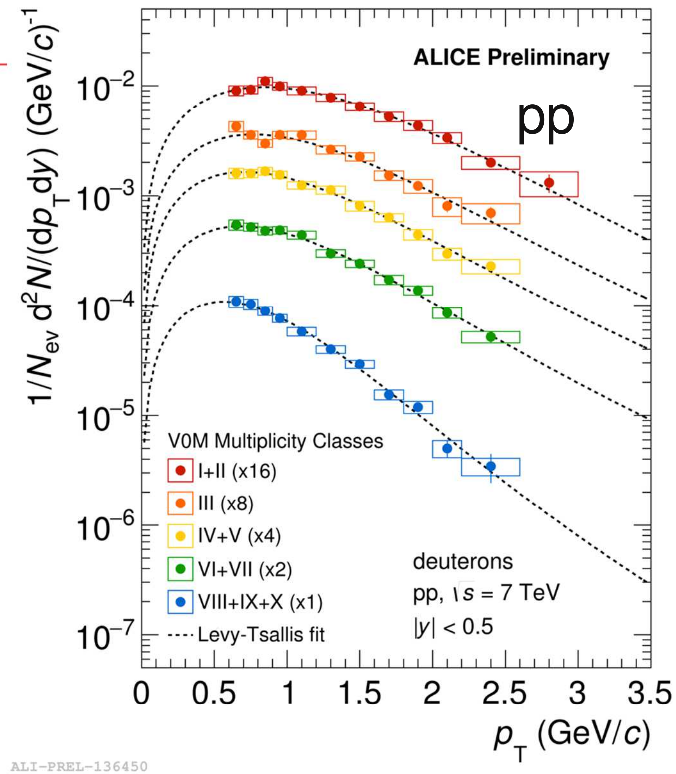
- The measurement of nuclei is strongly affected by background from knock-out from material
- Rejection is possible by fitting the DCA_{XY} distributions with templates
- Not relevant for anti-nuclei. However, their measurement suffers from large systematics related to unknown hadronic interaction cross-sections of anti-nuclei in material



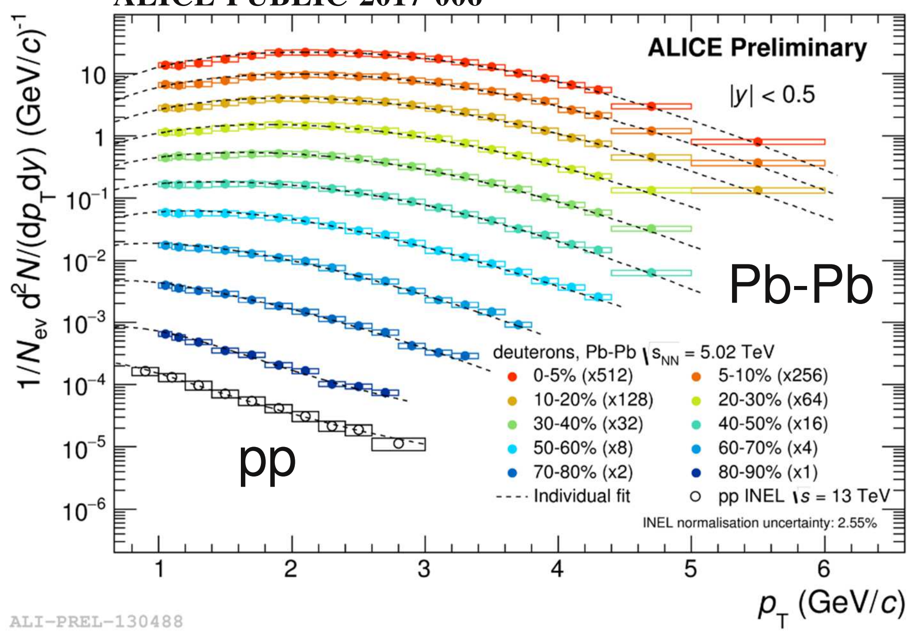


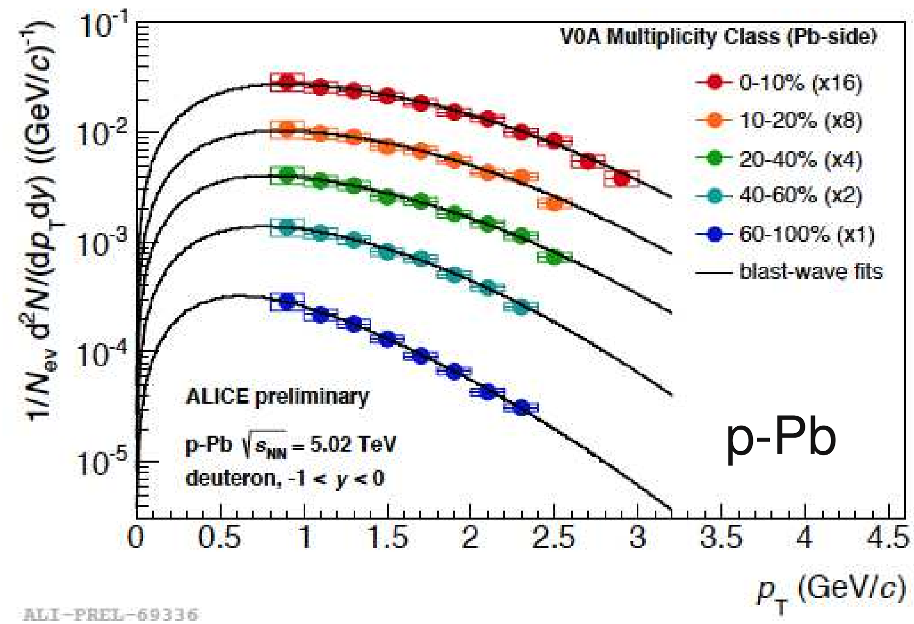
DEUTERON p_T SPECTRA

- Spectra become harder with increasing multiplicity in Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp and p-Pb spectrum show no sign of radial flow

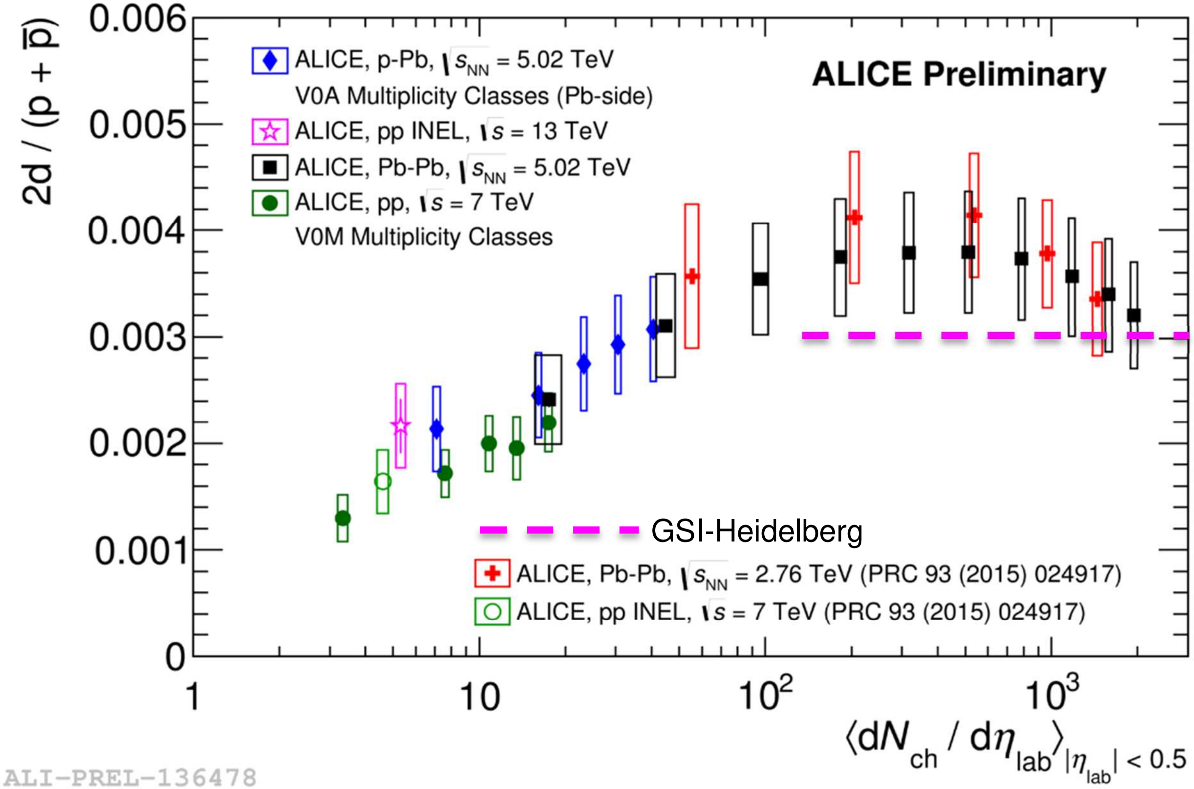


ALICE-PUBLIC-2017-006



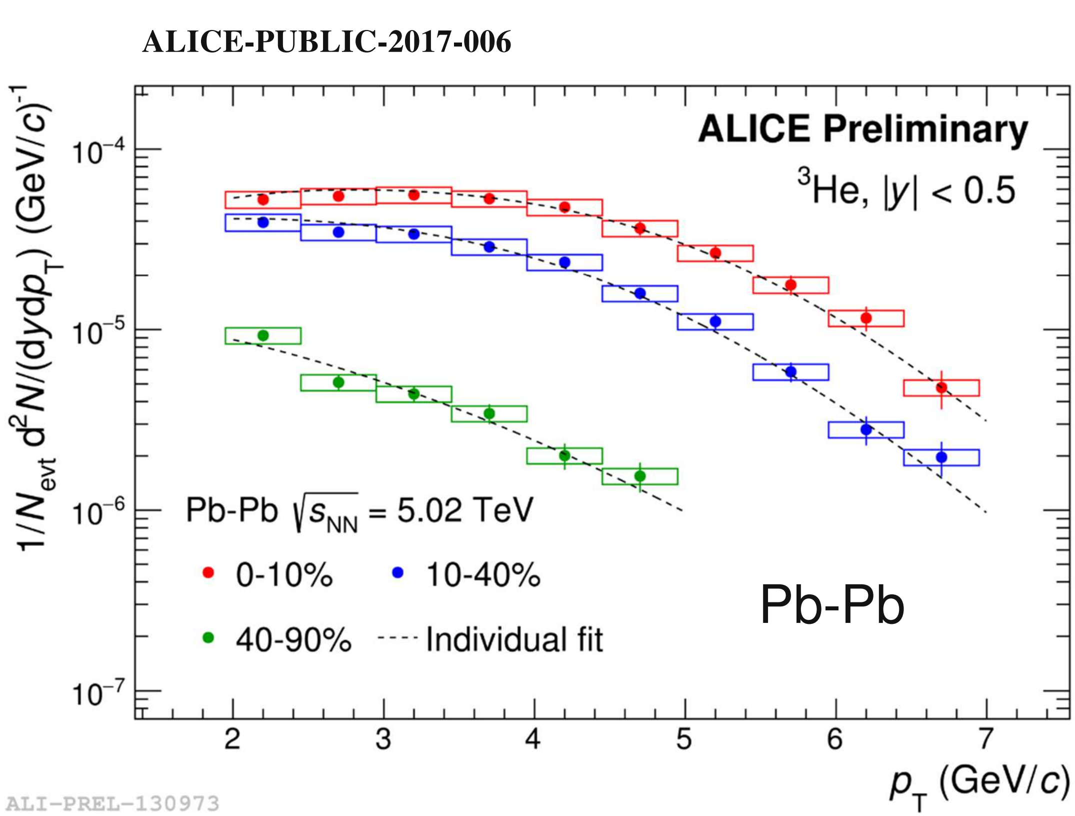


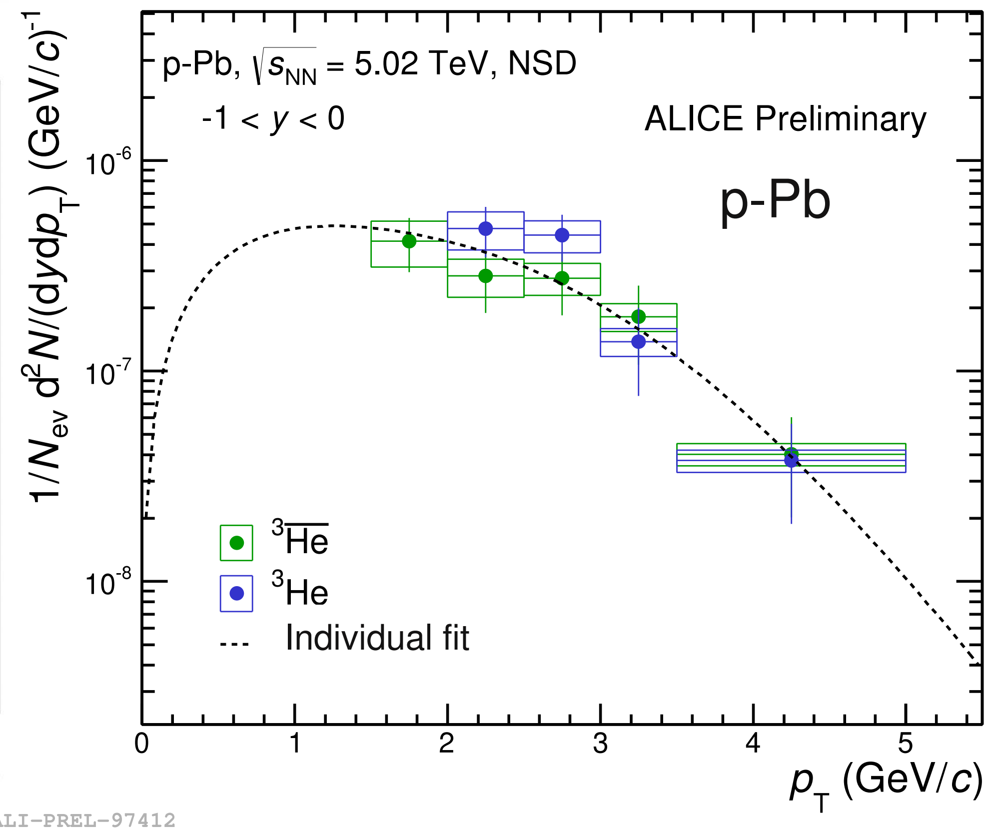
DEUTERON TO PROTON RATIO



- No significant centrality dependence in Pb-Pb
- Ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions
- d/p ratio increases when going from pp to p-Pb and peripheral Pb-Pb, until it reaches the grand canonical thermal model value (d/p ~ $3x10^{-3}$ at T_{ch}= 156 MeV)

3-HELIUM

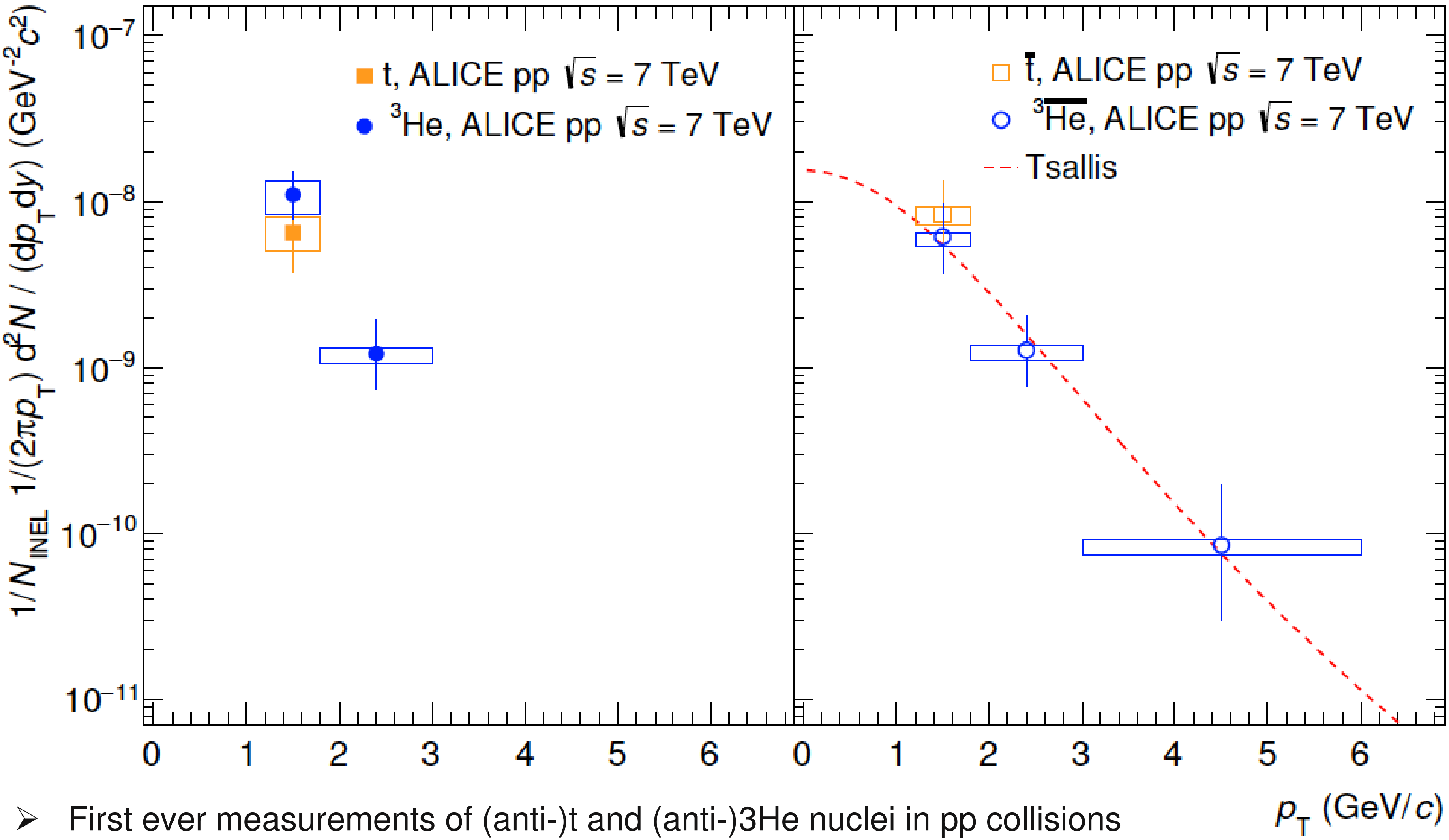




- Dashed curves represent individual Blast-Wave fits
- Spectrum obtained in 3 centrality classes in Pb-Pb and for NSD collisions in p-Pb

3-HELIUM AND TRITON

ALICE Collaboration, arXiv:1709.08522

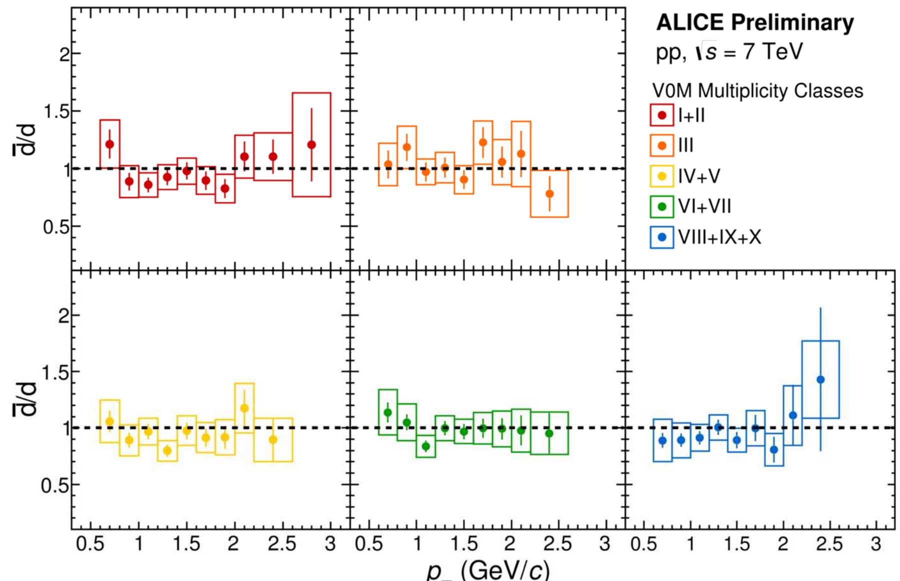


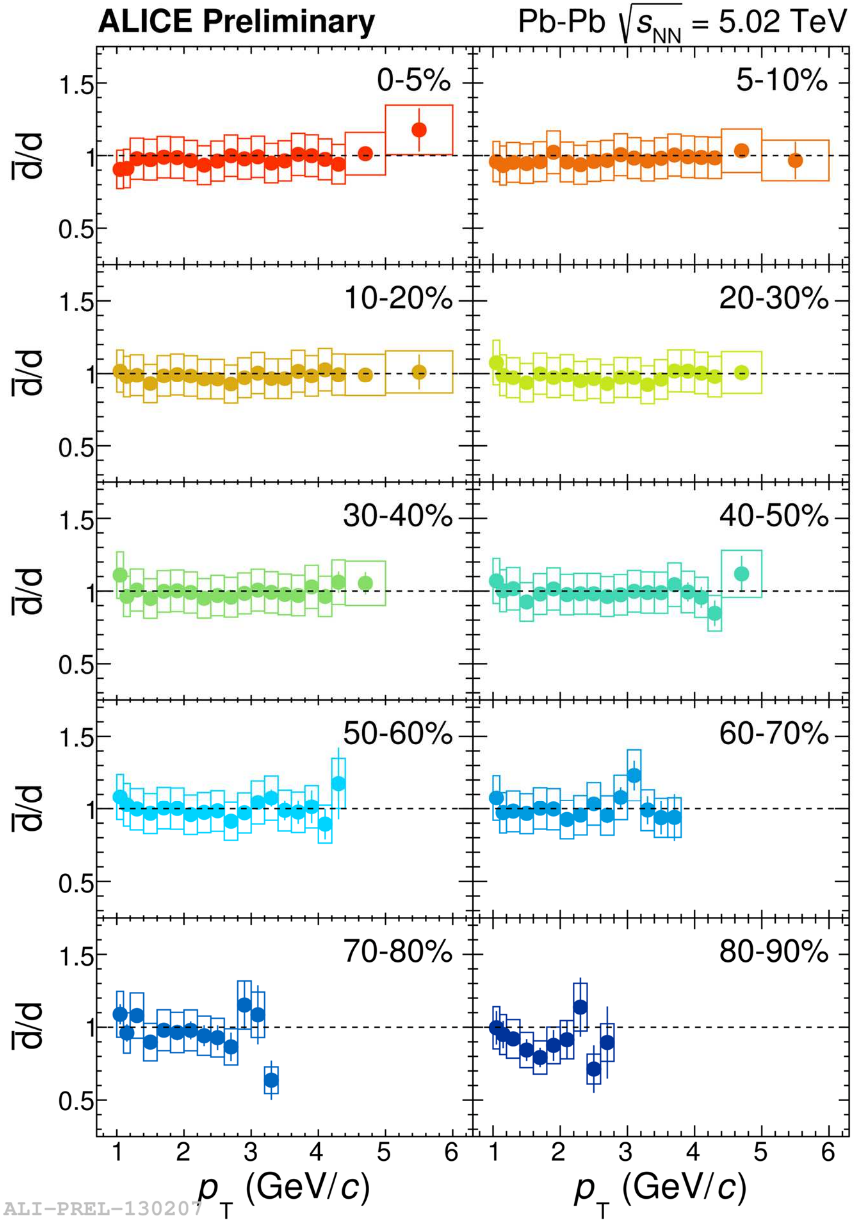
- First ever measurements of (anti-)t and (anti-)3He nuclei in pp collisions
- t and anti-t measurement difficult
- (anti-)t/(anti-)^{3}He agrees with unity

ANTI-NUCLEI PRODUCTION

ALICE-PUBLIC-2017-006

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light flavour species)
- Ratios exhibit constant behavior as a function of p_T and centrality
- Ratios are compatible with unity, in agreement with the coalescence and thermal model expectations
- Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally



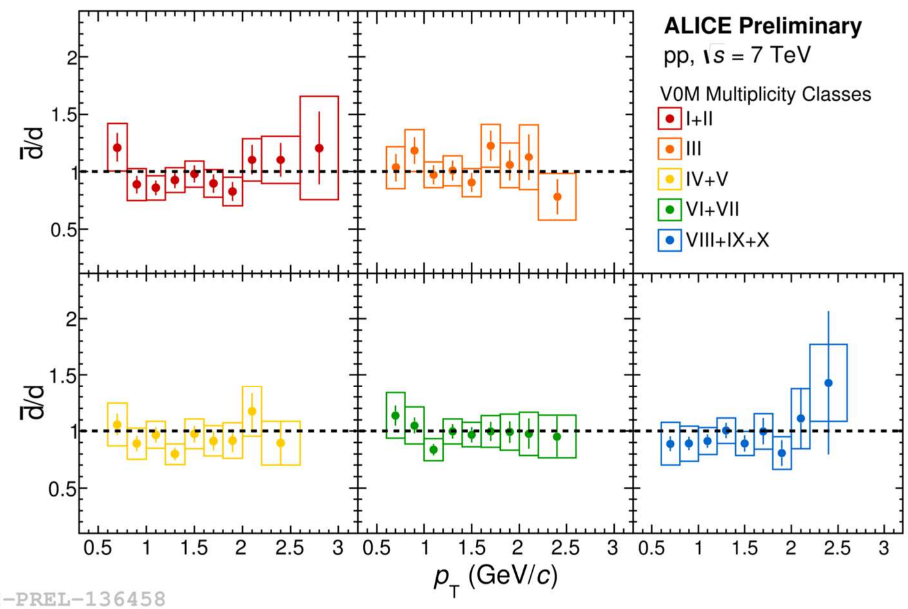


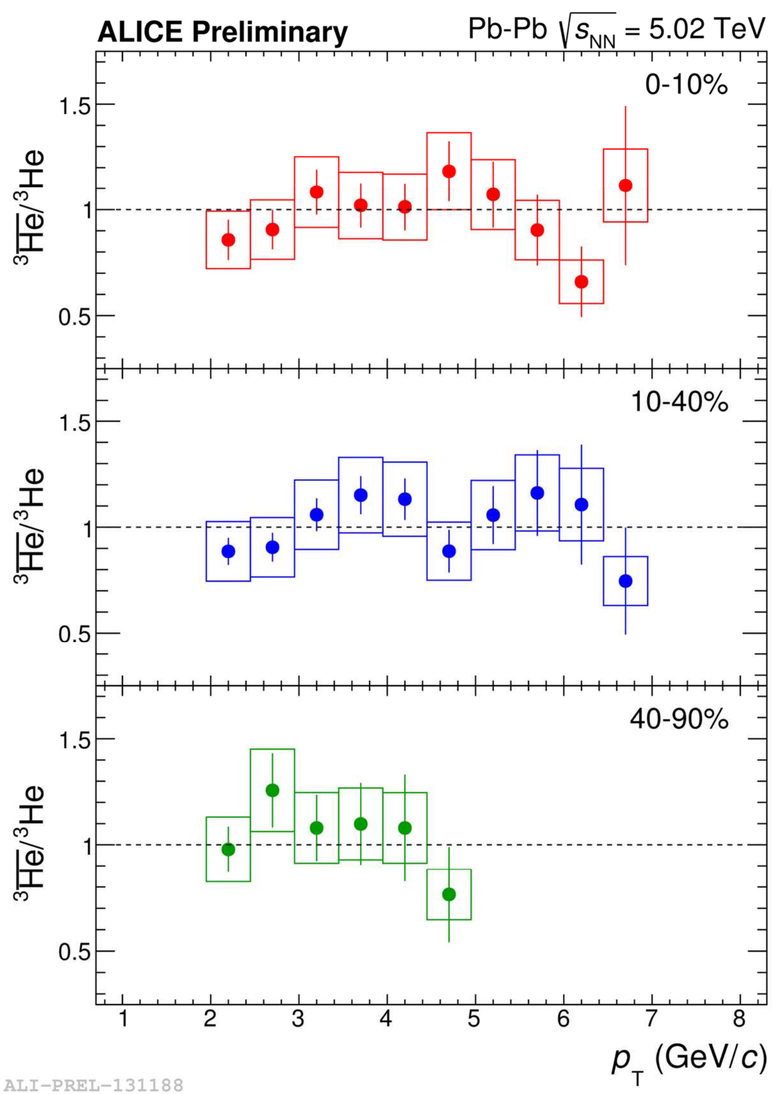
ANTI-NUCLEI PRODUCTION

ALICE

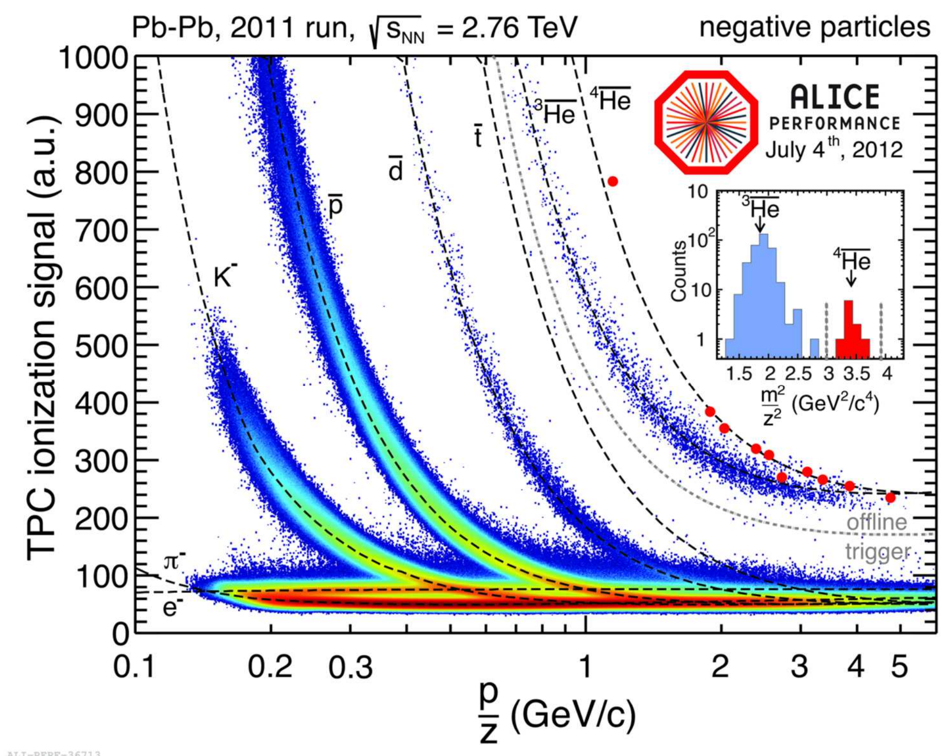
- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light flavour species)
- Ratios exhibit constant behavior as a function of p_T and centrality
- Ratios are compatible with unity, in agreement with the coalescence and thermal model expectations
- Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally

ALICE-PUBLIC-2017-006

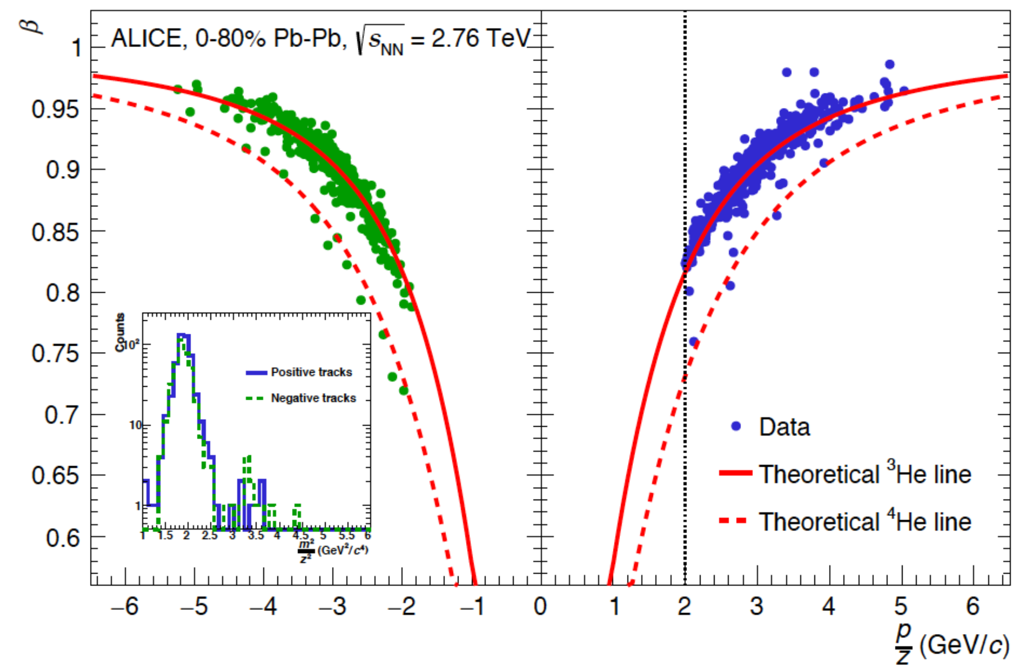




ANTI-ALPHA



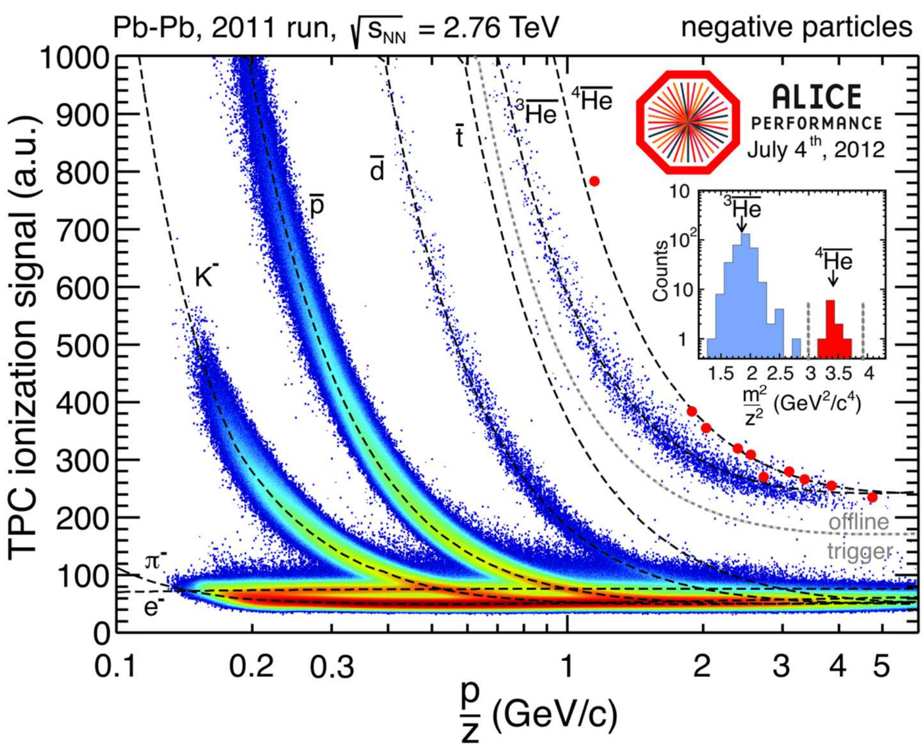
ALICE Collaboration, arXiv:1710.07531



For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF

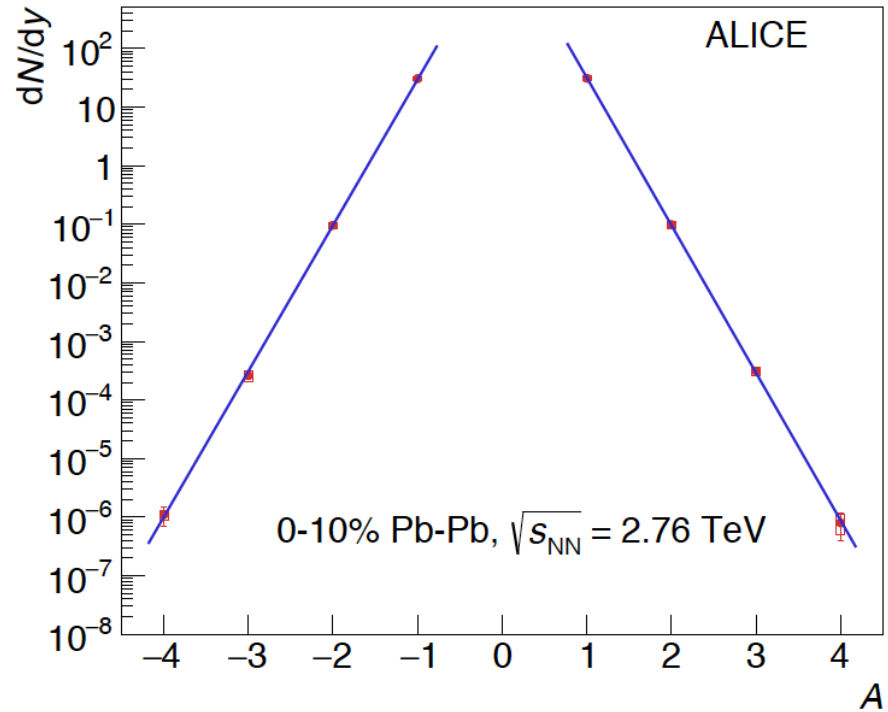
TOF β vs *p/z* after pre-selection of 3σ in TPC shows clear separation → Cut on Alpha's *p*/z needed to suppress secondary

NUCLEI PRODUCTION IN Pb-Pb



ALI-PERF-36713

ALICE Collaboration, arXiv:1710.07531



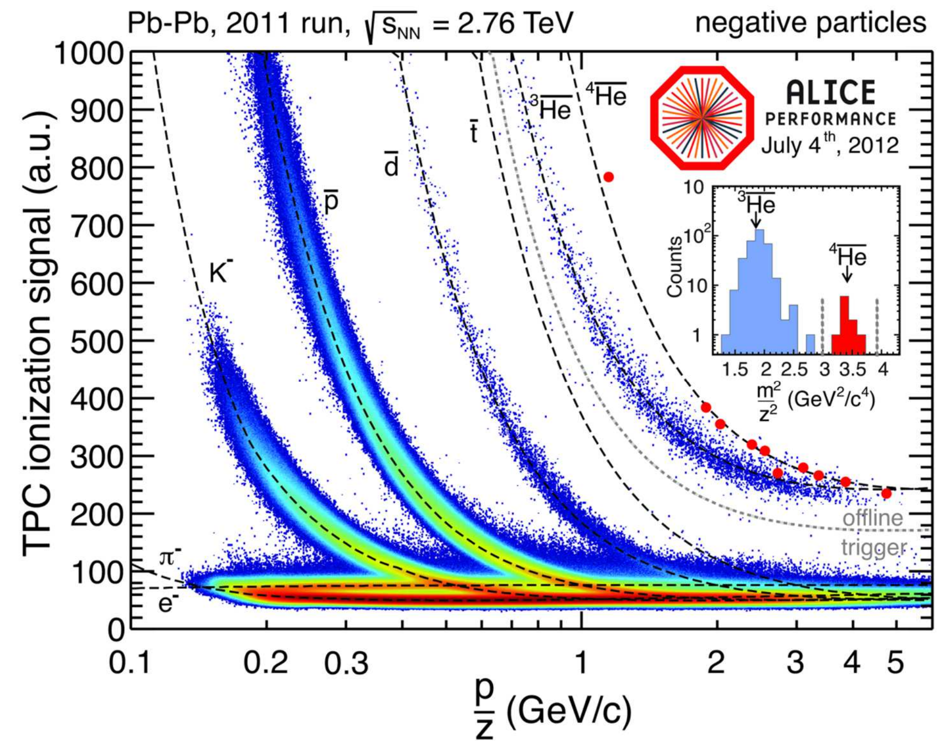
For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF

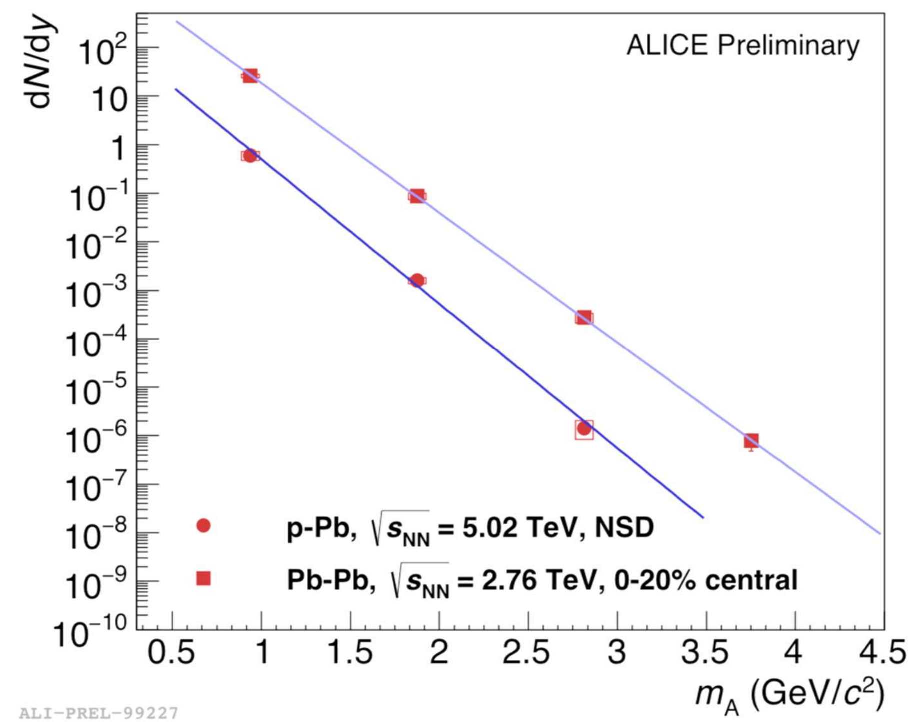
TOF β vs *p/z* after pre-selection of 3σ in TPC shows clear separation → Cut on Alpha's *p/z* needed to suppress secondary

Nuclei yields follow an exponential decrease with mass as predicted by the thermal model

In Pb-Pb the penalty factor for adding one baryon is ~350 (for particles and antiparticles)

NUCLEI PRODUCTION IN Pb-Pb and in p-Pb





For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF

TOF β vs *p/z* after pre-selection of 3σ in TPC shows clear separation → Cut on Alpha‘s *p*/*z* needed to suppress secondary

Nuclei yields follow an exponential decrease with mass as predicted by the thermal model

In Pb-Pb the penalty factor for adding one baryon is ~350 (for particles and antiparticles)

And in p-Pb the penalty factor is ~600

(ANTI-)HYPERTRITON IDENTIFICATION

Decay Channels

$${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{He}} + \pi^{+}$$

$${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{H} + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{H}} + \pi^{0}$$

$${}^{3}_{\Lambda}\mathrm{H} \to \mathrm{d} + \mathrm{p} + \pi^{-} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to \overline{\mathrm{d}} + \overline{\mathrm{p}} + \pi^{+}$$

$${}^{3}_{\Lambda}\mathrm{H} \to \mathrm{d} + \mathrm{n} + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to \overline{\mathrm{d}} + \overline{\mathrm{n}} + \pi^{0}$$

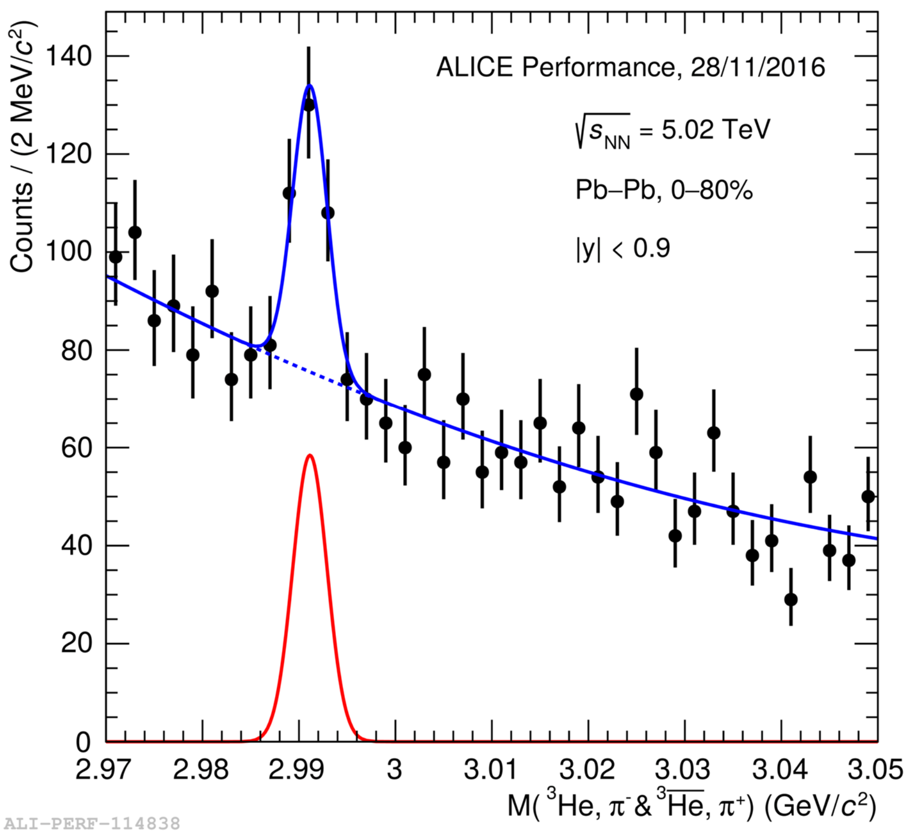
${}^{3}_{\Lambda}\mathrm{H}$ search via two-body decays into charged particles:

- Two body decay: lower combinatorial background
- Charged particles: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

Signal extraction:

- Identify ${}^{3}\mathrm{He}$ and π
- Evaluate (${}^{3}\mathrm{He}$,π) invariant mass
- Apply topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background

New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



ALICE

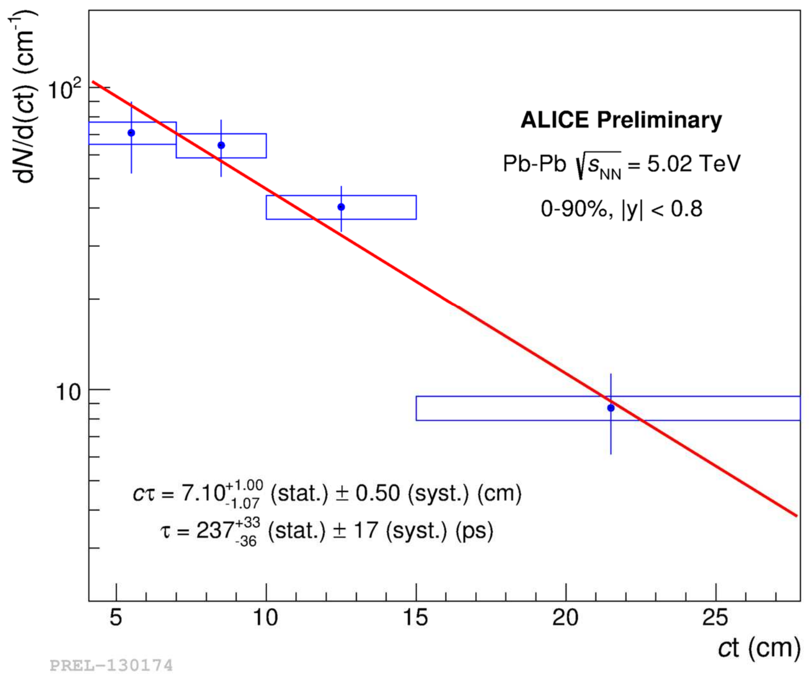
HYPERTRITON LIFETIME DETERMINATION

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

$$N(t) = N(0)\, e^{-\frac{t}{\tau}}$$

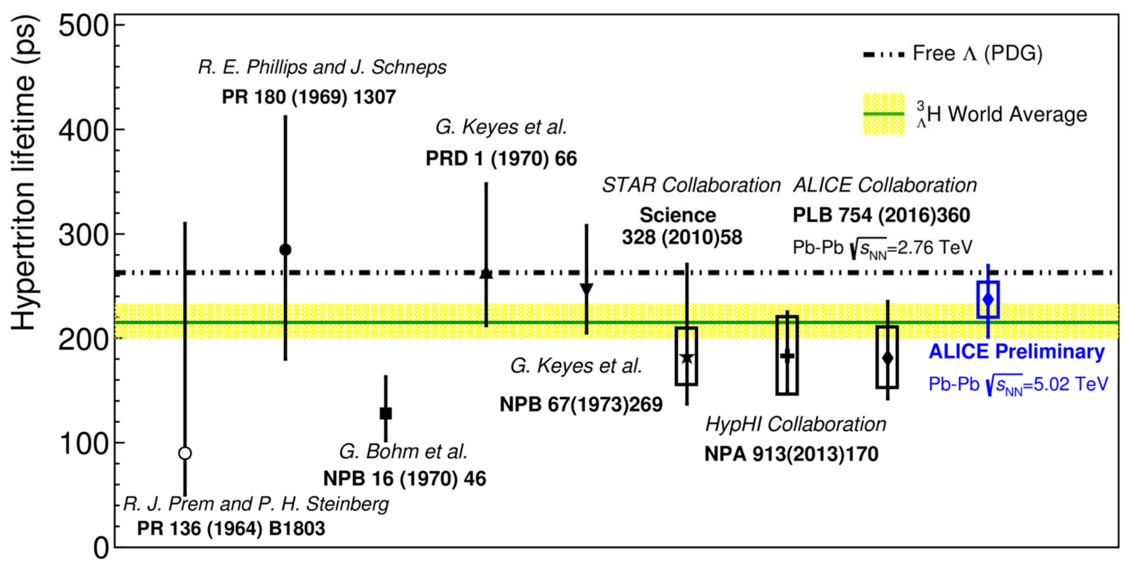
where $t = L/(\beta\gamma c)$ and $\beta\gamma c = p/m$ with m the hypertriton mass, p the total momentum and L the decay length

New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



$$c\tau = \left(7.10^{+1.00}_{-1.07}(stat.) \pm 0.50(syst.)\right) cm$$

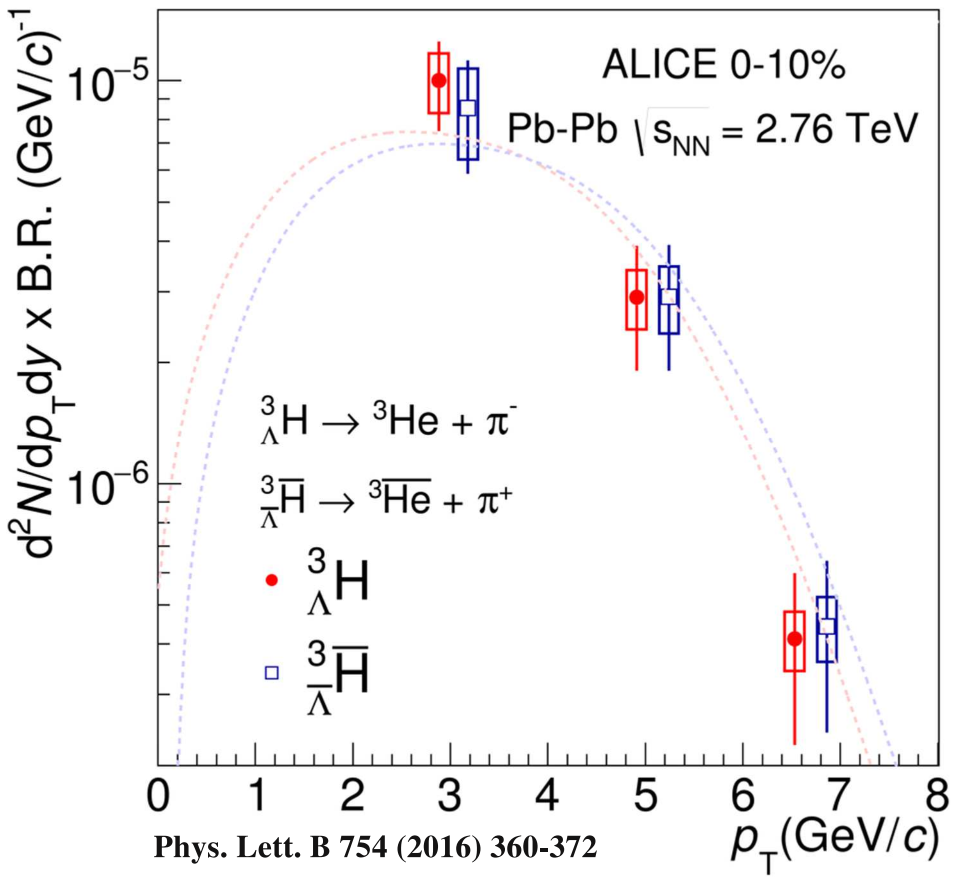
$$\tau = \left(237^{+33}_{-36}(stat.) \pm 17(syst.)\right) ps$$



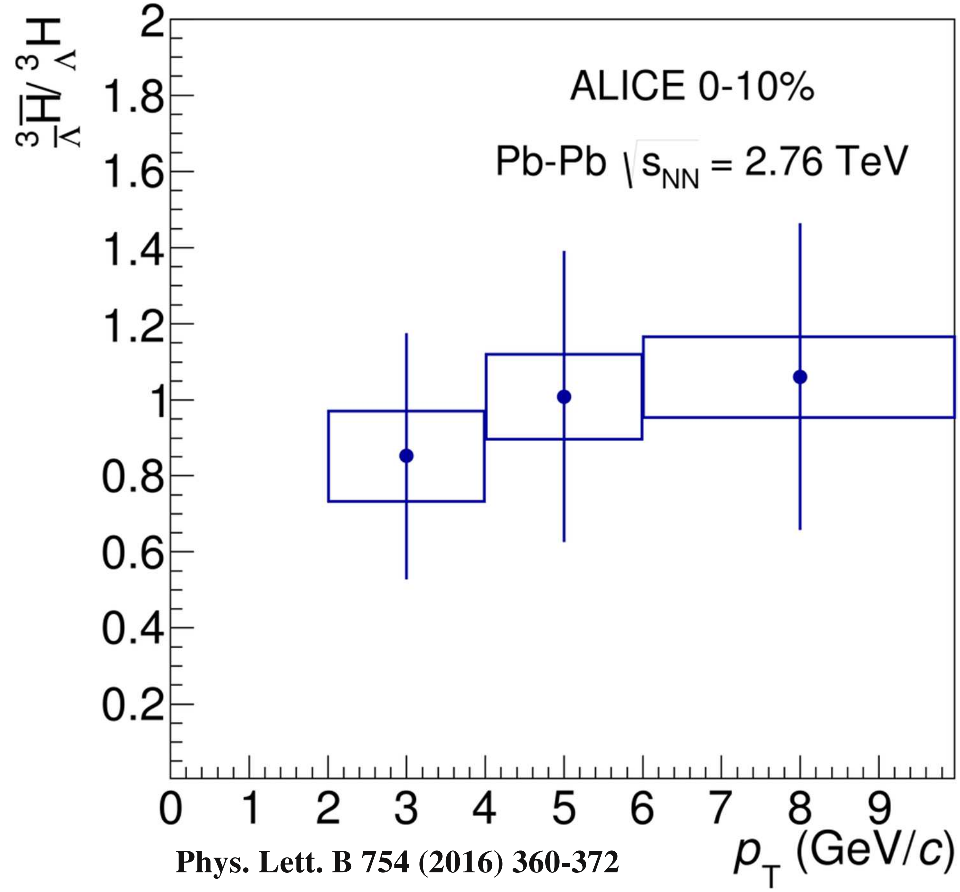
- Previous heavy-ion experiment results show a trend well below the free Λ lifetime
- ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free Λ lifetime

ALICE

(ANTI-)HYPERTRITON YIELDS



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



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

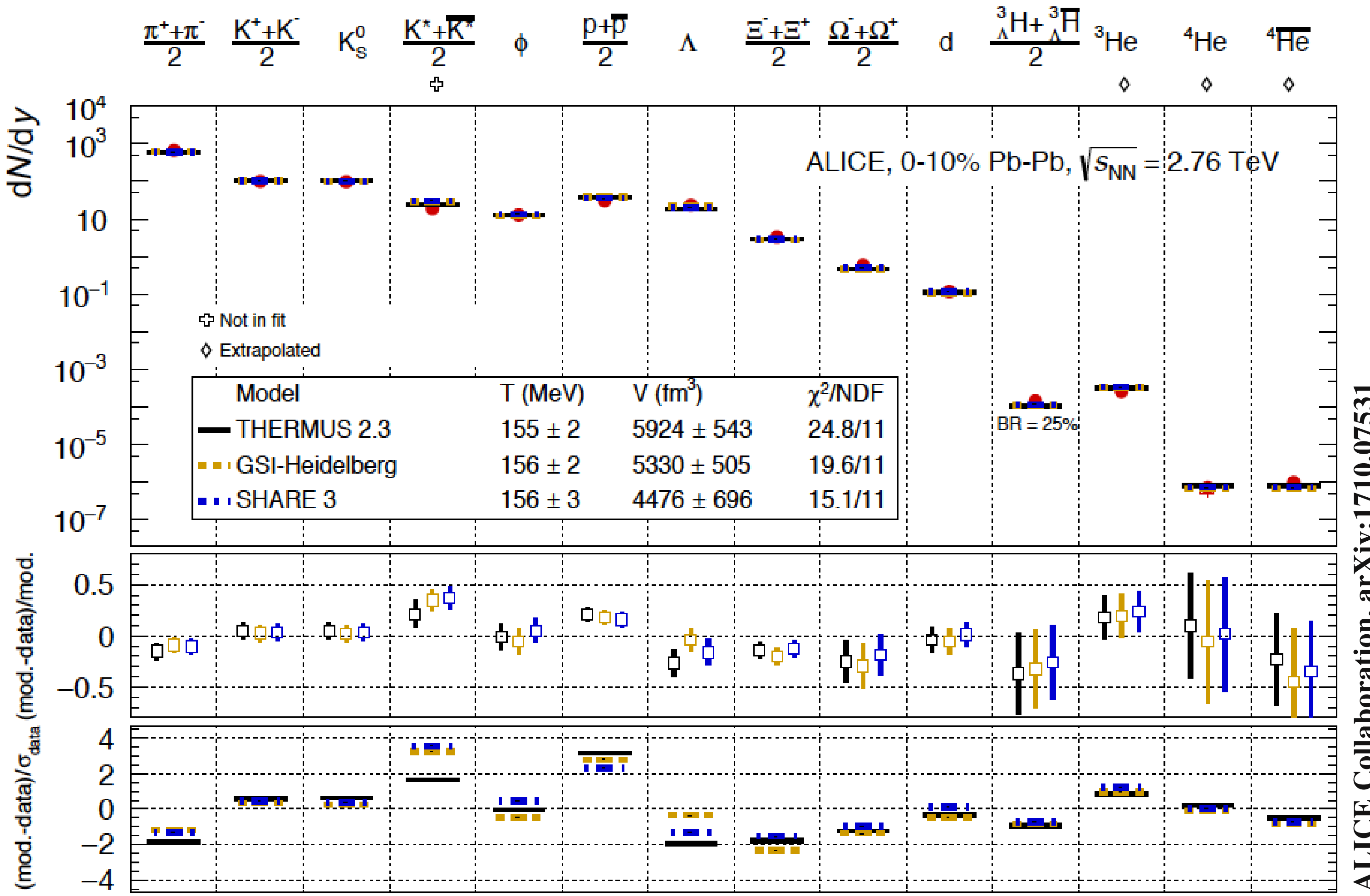
dN/dy x B.R. ($^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi$) yield extracted in three p_T bins for central (0-10%) events for $^{3}_{\bar{\Lambda}}\bar{H}$ and $^{3}_{\Lambda}H$ separately

Anti-hypermatter / Hypermatter Ratio: $R = \frac{^{3}_{\bar{\Lambda}}\bar{H}}{^{3}_{\Lambda}H}$

STATISTICAL-THERMAL MODEL: R=0.95
(Cleymans et al, PRC84(2011) 054916)

COALESCENCE MODEL: $\bar{p}/p \sim \bar{\Lambda}/\Lambda \sim 1$

THERMAL MODEL FITS



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)

Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV

Including nuclei in the fit causes no significant change in T_{ch}

ALICE

Λn AND H-DIBARYON SEARCH

H-Dibaryon: hypothetical *udsuds* bound state

- First predicted by Jaffe [Jaffe, PRL 38, 195617 (1977)]
- Several predictions of bound and also resonant states.
- Recent Lattice models predict weakly bound states [Inoue et al., PRL 106, 162001 (2011), Beane et al., PRL 106, 162002 (2011)]

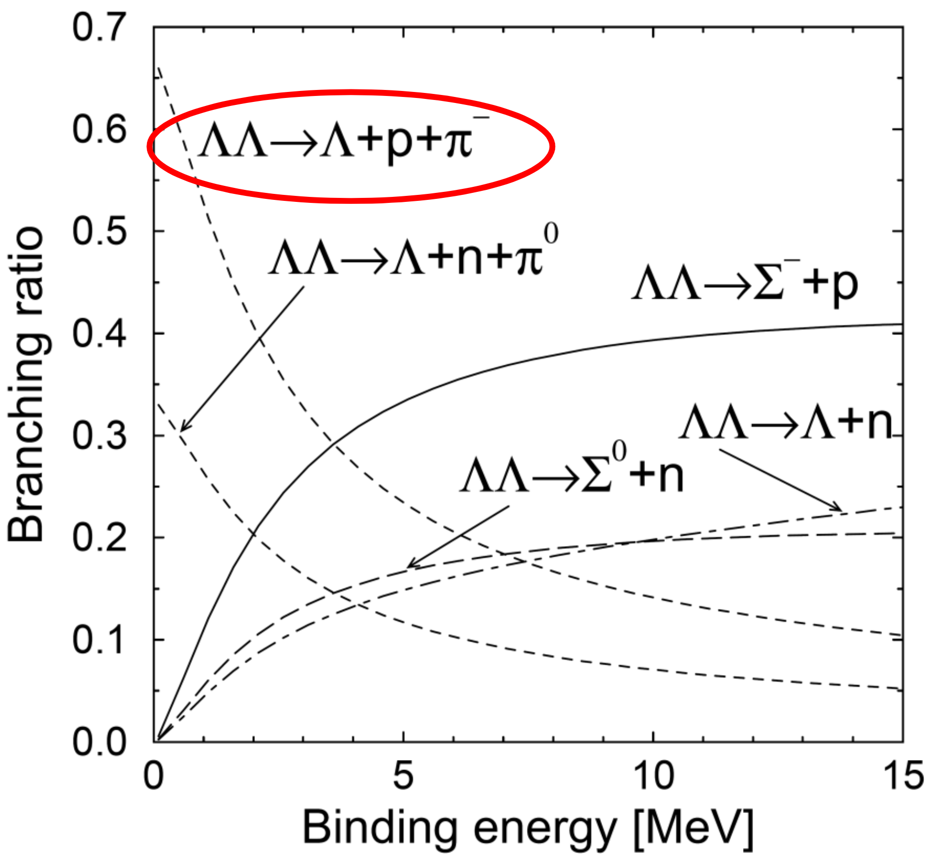
If H-Dibaryon is bound: $m_H < \Lambda\Lambda$ threshold

- measurable channel H → Λpπ but BR depends on binding energy

Bound state of **Λn** ?

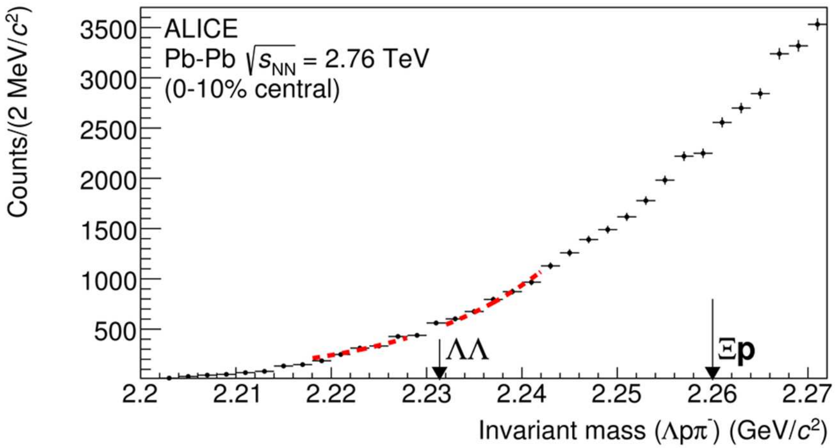
- HypHI experiment at GSI sees evidence of a

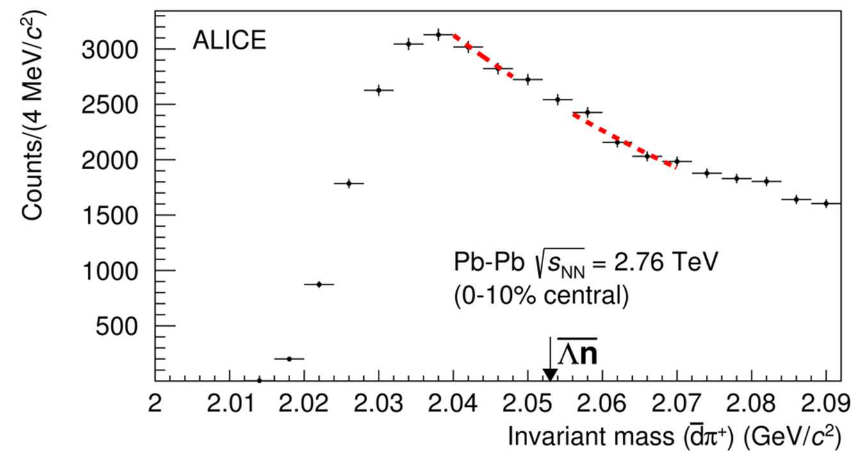
new state: **Λn → d + π⁻** [C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)]



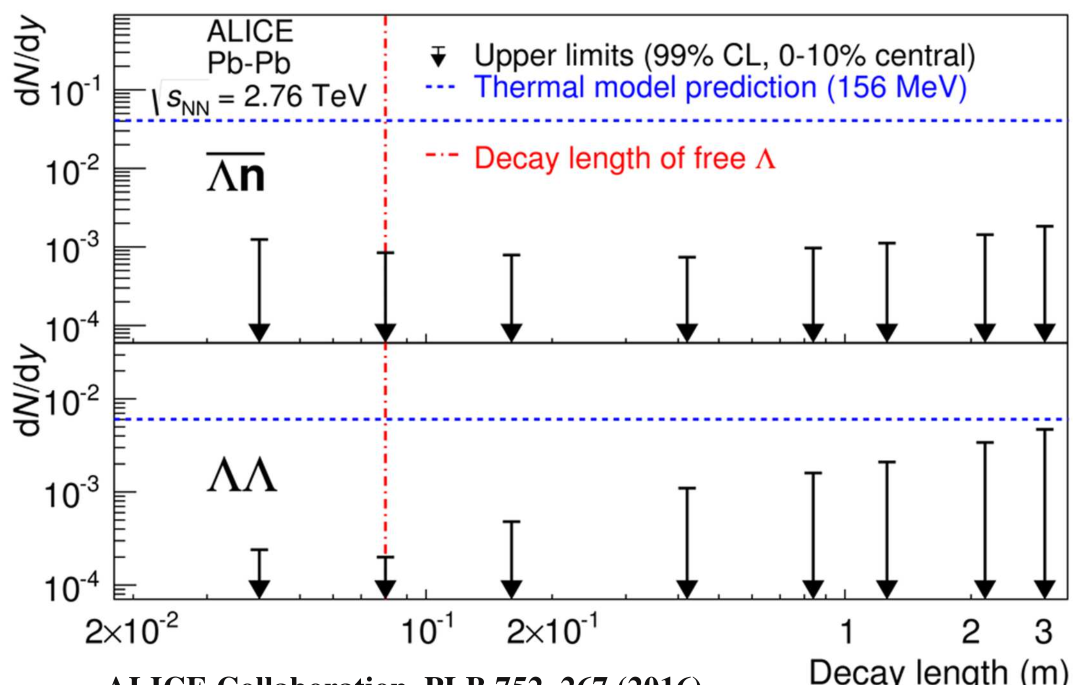
Schaffner-Bielich et al., PRL 84, 4305 (2000)

Λn AND H-DIBARYON SEARCH





- No signal visible
- The upper limits for exotica are lower than the thermal model expectation by a factor 20
- Thermal models with the same temperature describe precisely the production yield of deuterons, ^{3}He and $^3_\Lambda$H
- The existence of such states with the assumed B.R., mass and lifetime is questionable



ALICE Collaboration, PLB 752, 267 (2016)

ALICE

COALESCENCE PARAMETER B_A

- If baryons at freeze-out are close enough in phase space (i.e. geometrically and in momentum) 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:

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

- For A=2:

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

Measured deuteron p_T-spectra

Measured proton p_T-spectra

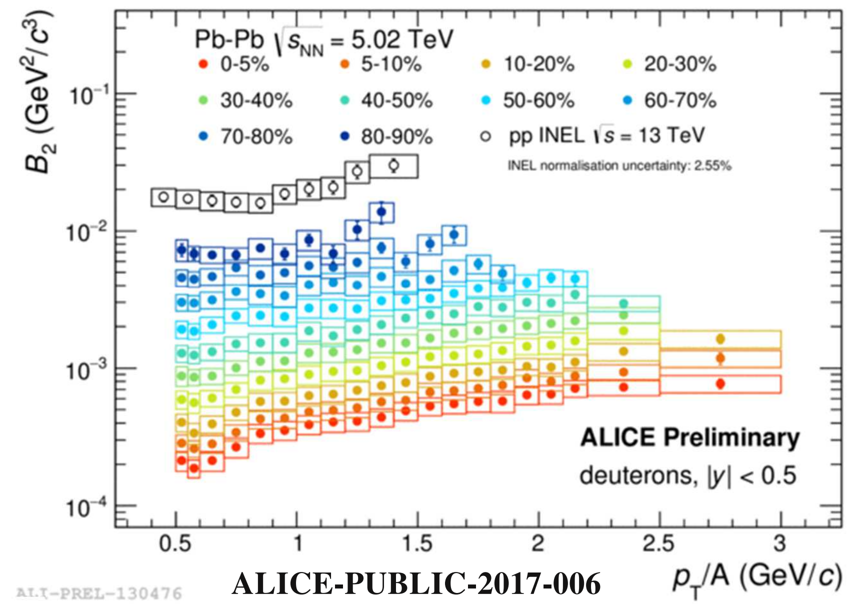
ALICE

COALESCENCE PARAMETER B_2

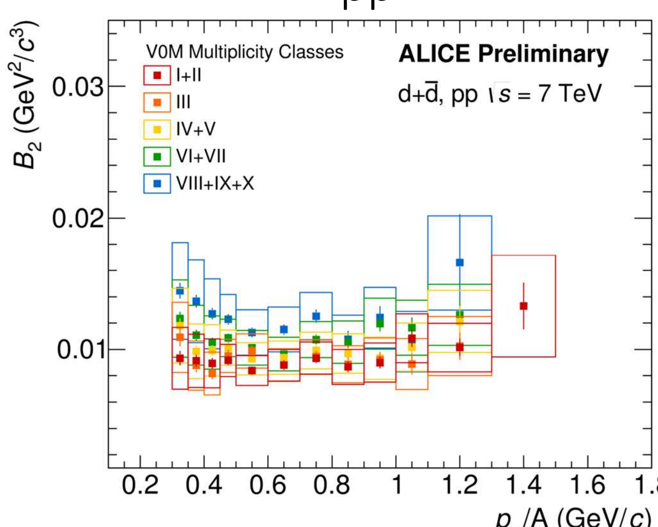
$$B_2 = E_d \frac{d^3 N_d}{dp_d^3} \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^{-2}$$

- Coalescence parameter B_2 decreases with centrality in Pb-Pb and increases with p_T
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced
- Flat behavior for pp and no dependence on multiplicity

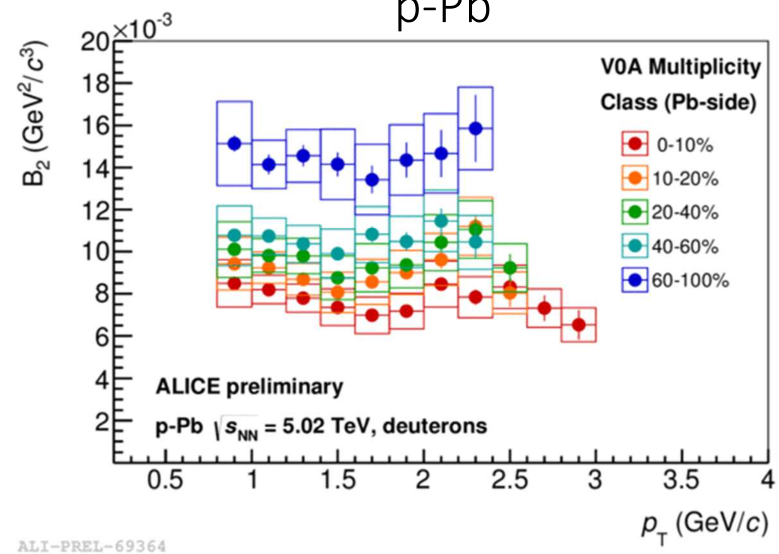
Pb-Pb



pp



p-Pb



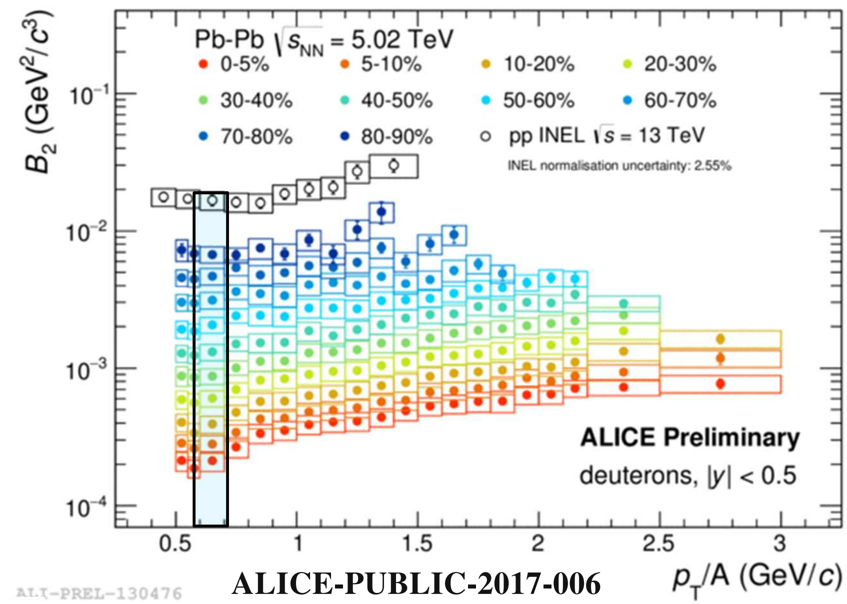
ALICE

COALESCENCE PARAMETER B_2

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

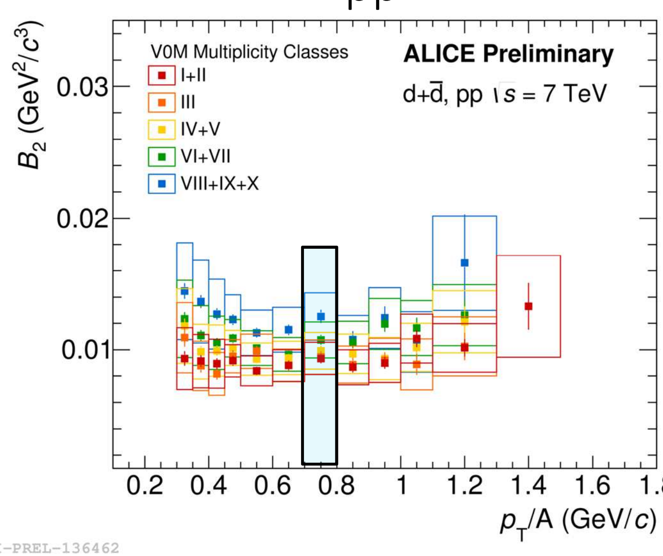
- Coalescence parameter B_2 decreases with centrality in Pb-Pb and increases with p_T
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced
- Flat behavior for pp and no dependence on multiplicity

Pb-Pb

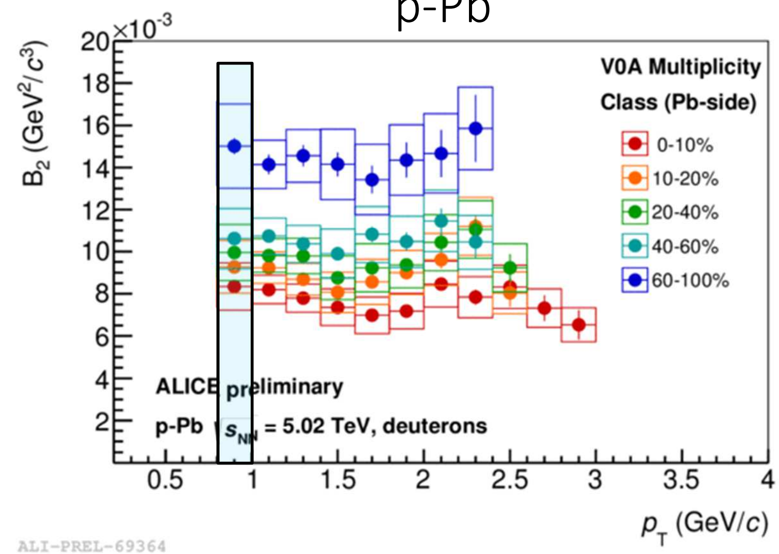


ALICE-PUBLIC-2017-006

pp

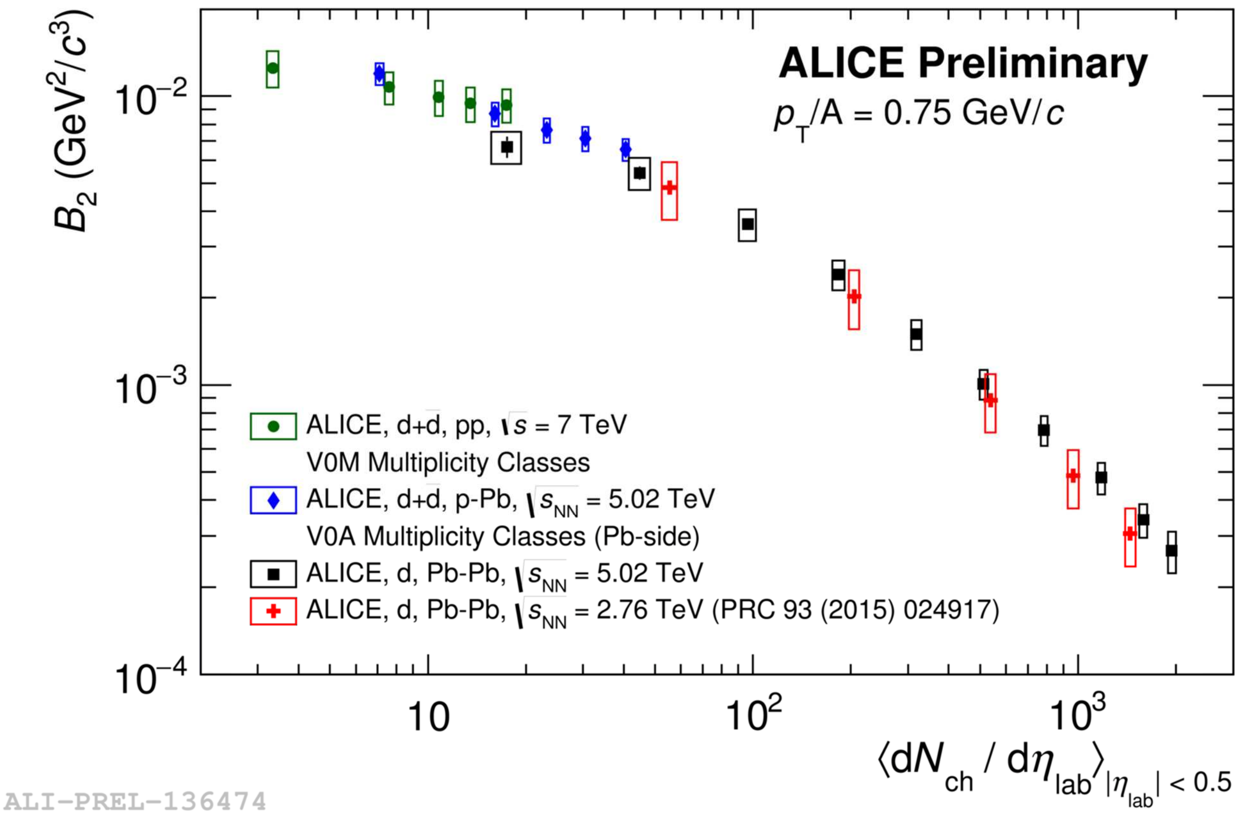


p-Pb



p_T/A = 0.75 GeV/c

COALESCENCE PARAMETER B_2



Simple coalescence model

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

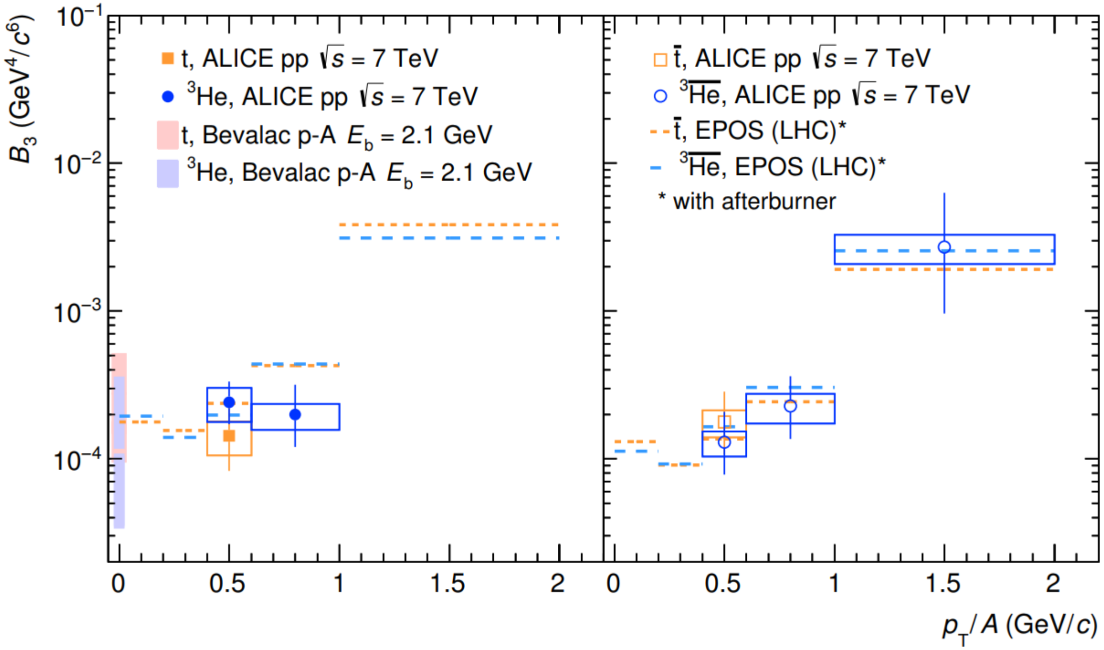
More elaborated coalescence model takes into account the volume of the source:

- B_2 scales like HBT radii (*)
- 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 in HBT
- Qualitative agreement in central Pb-Pb collisions

(*) R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

COALESCENCE PARAMETER B_3

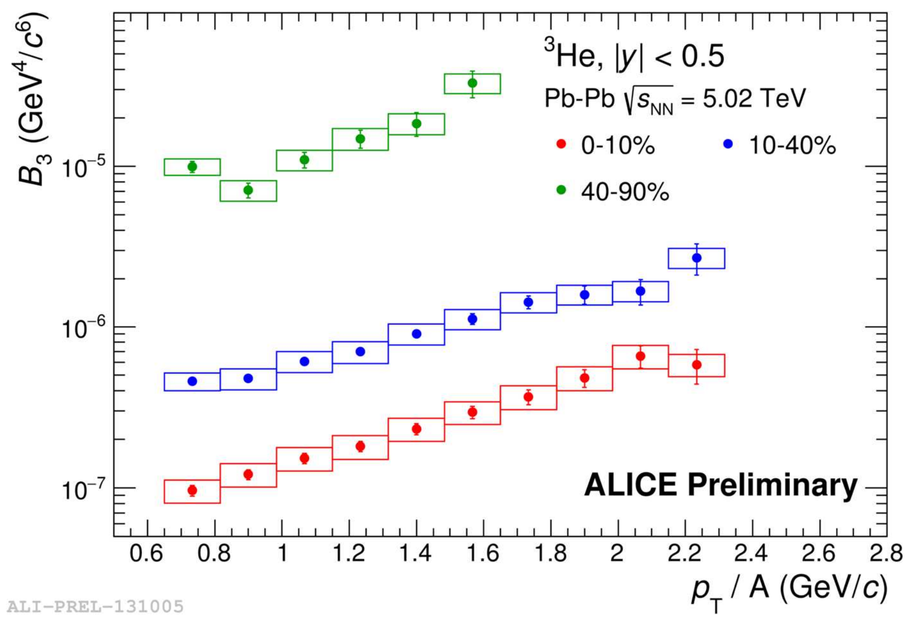
pp



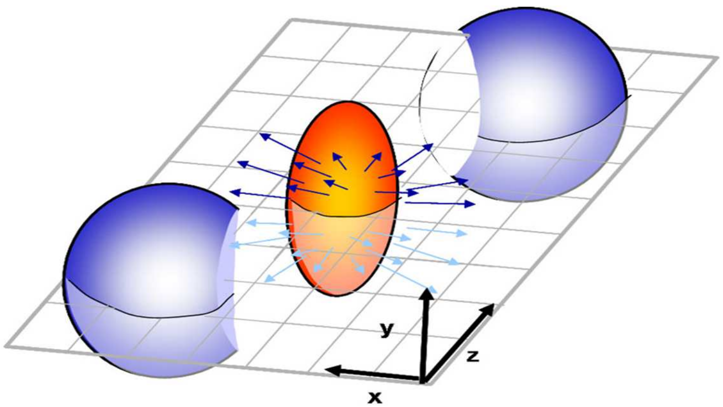
- B_3 of ($\bar{t}$)t and ($^3\overline{He}$)^{3}He measured in pp and Pb-Pb collisions
- First ever measurements of the B_3 of t and ^{3}He in pp collisions

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

Pb-Pb

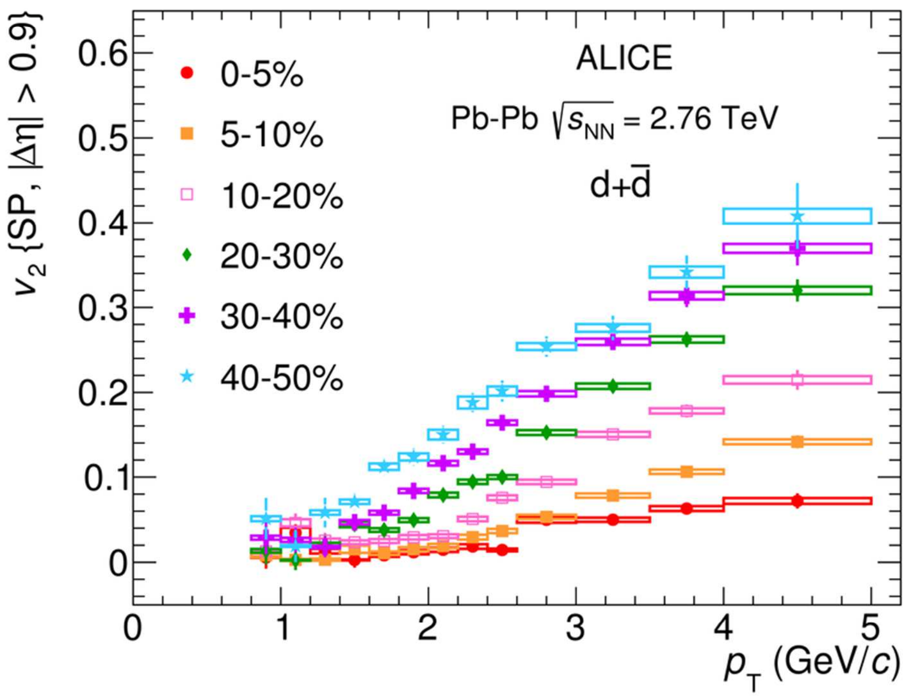


DEUTERON v_2 FOR DIFFERENT CENTRALITIES



- A significant v_2 is observed for deuterons
- The value of $v_2(p_T)$ increases progressively from central to semi-central collisions

ALICE Collaboration, Eur. Phys. J. C 77, 658 (2017)



- Angular distribution of reconstructed charged particles can be expanded into a Fourier series w.r.t. symmetry plane:

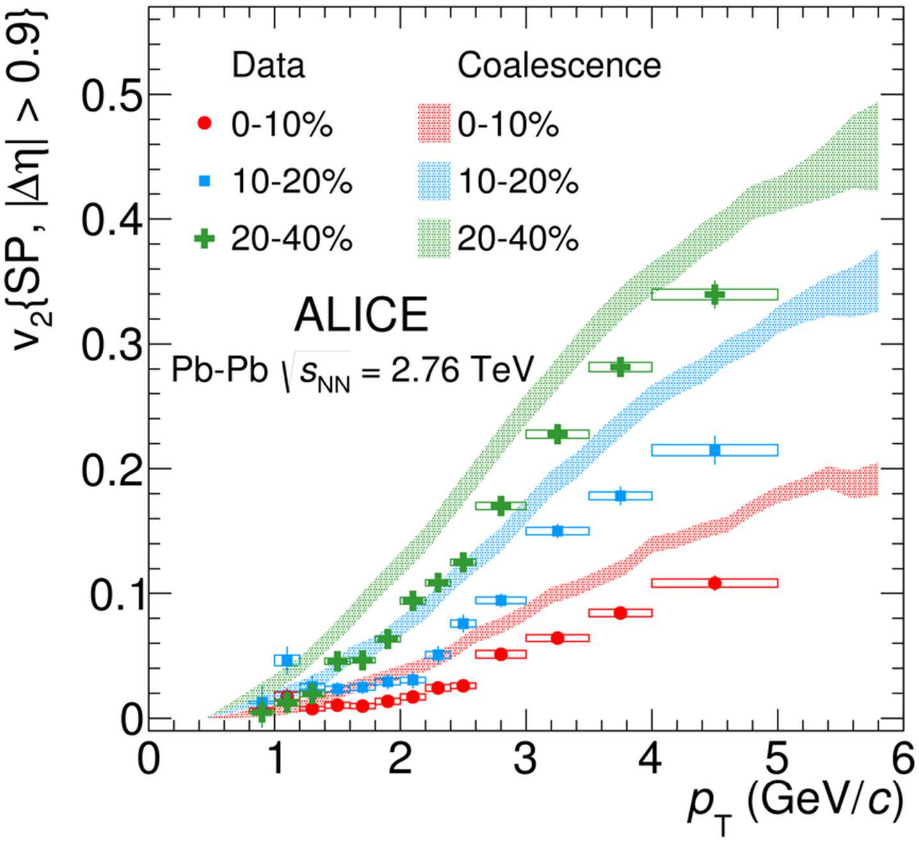
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_n\right)\right)\right)$$

$$v_n = \langle \cos\left(n(\varphi - \Psi_n)\right)\rangle$$

- Elliptic flow (v_2) is sensitive to the system evolution:
  It probes initial conditions and constrains particle production mechanisms

DEUTERON v_2 FOR DIFFERENT CENTRALITIES

ALICE Collaboration, Eur. Phys. J. C 77, no. 10, 658 (2017)



- A significant v_2 is observed for deuterons
- The value of v_2 (p_T) increases progressively from central to semi-central collisions
- If protons have only elliptical flow
- And if the light nucleus is formed by simple coalescence, v_2 can be expressed as

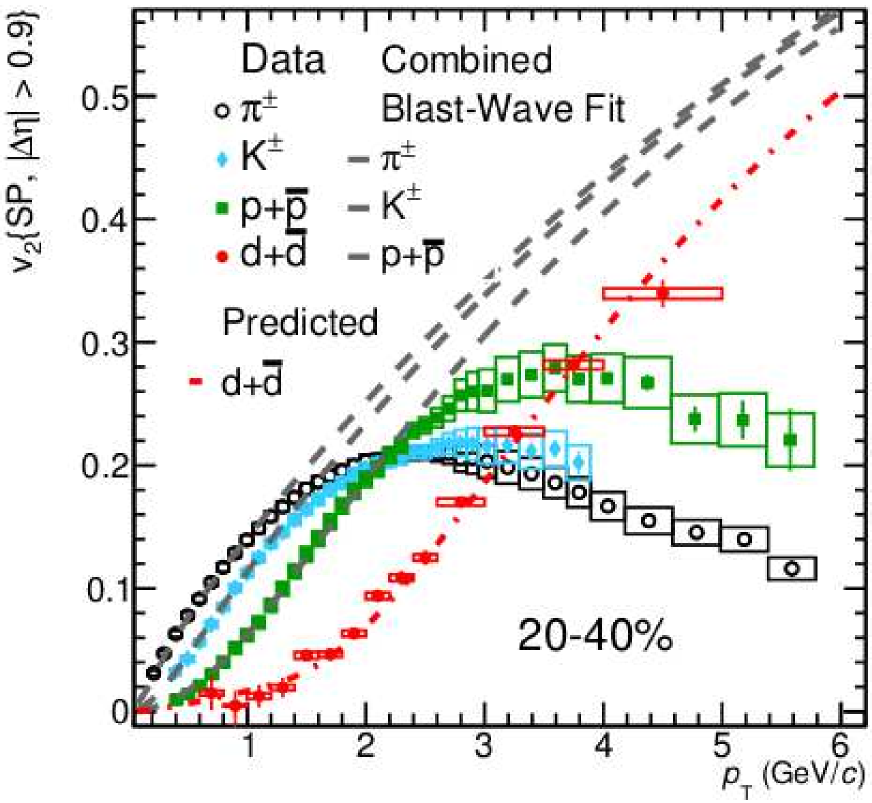
$$v_{2,\mathrm{d}}(p_\mathrm{T}) = \frac{2v_{2,\mathrm{p}}(p_\mathrm{T}/2)}{1 + 2v_{2,\mathrm{p}}^2(p_\mathrm{T}/2)}$$

- Such a simple coalescence model is not able to reproduce the measured elliptic flow of deuterons

ALICE

DEUTERON v_2 FOR DIFFERENT CENTRALITIES

ALICE Collaboration, Eur. Phys. J. C 77, no. 10, 658 (2017)



- Simplified hydro model (Blast-Wave) is able to describe spectra and flow at the same time, suggesting an early "freeze out"

- A significant v_2 is observed for deuterons
- The value of v_2 (p_T) increases progressively from central to semi-central collisions
- If protons have only elliptical flow
- And if the light nucleus is formed by simple coalescence, v_2 can be expressed as

$$v_{2,\mathrm{d}}(p_\mathrm{T}) = \frac{2v_{2,\mathrm{p}}(p_\mathrm{T}/2)}{1+2v_{2,\mathrm{p}}^2(p_\mathrm{T}/2)}$$

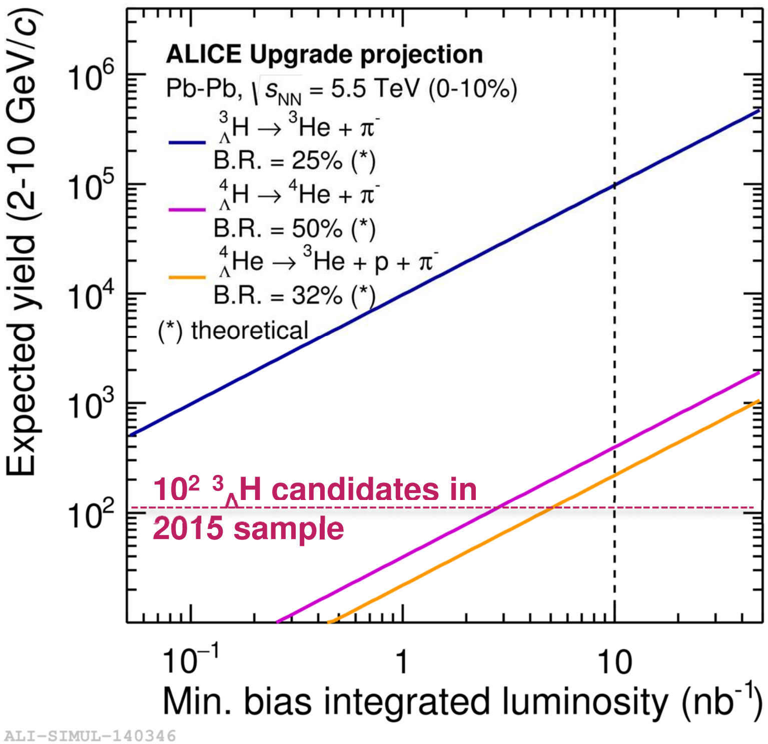
- Such a simple coalescence model is not able to reproduce the measured elliptic flow of deuterons

OUTLOOK – ALICE UPGRADE

At the end of Pb-Pb during RUN2 (Nov. 2018) the expected statistics for A=2,3 is >2x

During the Long Shutdown 2 (2019-2020):

- **New Inner Tracking System (ITS)**
  - ✓ improved pointing precision
  - ✓ less material -> thinnest tracker at the LHC
- **Upgrade of Time Projection Chamber (TPC):**
  - ✓ new GEM technology for readout chambers
  - ✓ continuous readout
  - ✓ faster readout electronics
- **High Level Trigger (HLT):**
  - ✓ new architecture
  - ✓ on line tracking & data compression
  - ✓ 50kHz Pb-Pb event rate



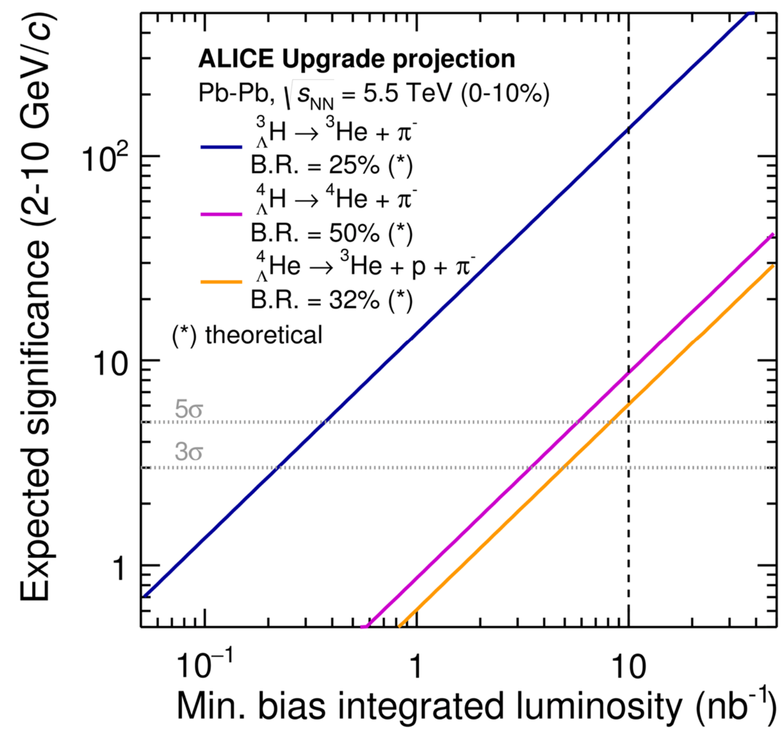
At the end of RUN3 (2023):
the expected Integrated Luminosity: ~10 nb^{-1} (~8x10^9 collisions in the 0-10% centrality class)

OUTLOOK – ALICE UPGRADE

At the end of Pb-Pb during RUN2 (Nov. 2018) the expected statistics for A=2,3 is >2x

During the Long Shutdown 2 (2019-2020):

- **New Inner Tracking System (ITS)**
  - ✓ improved pointing precision
  - ✓ less material -> thinnest tracker at the LHC
- **Upgrade of Time Projection Chamber (TPC):**
  - ✓ new GEM technology for readout chambers
  - ✓ continuous readout
  - ✓ faster readout electronics
- **High Level Trigger (HLT):**
  - ✓ new architecture
  - ✓ on line tracking & data compression
  - ✓ 50kHz Pb-Pb event rate



At the end of RUN3 (2023):
the expected Integrated Luminosity: ~10 nb^{-1} (~8x10^{9} collisions in the 0-10% centrality class)

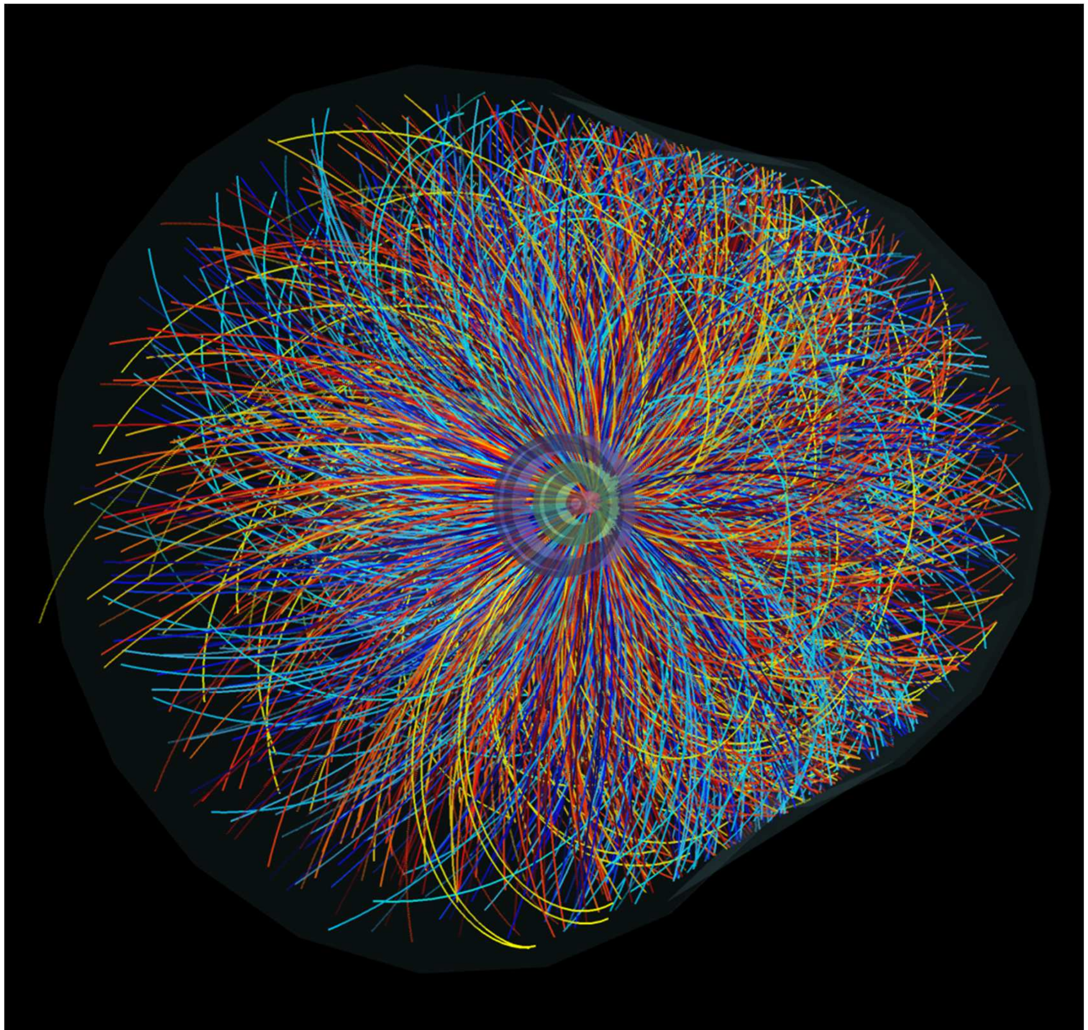
All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4

CONCLUSIONS

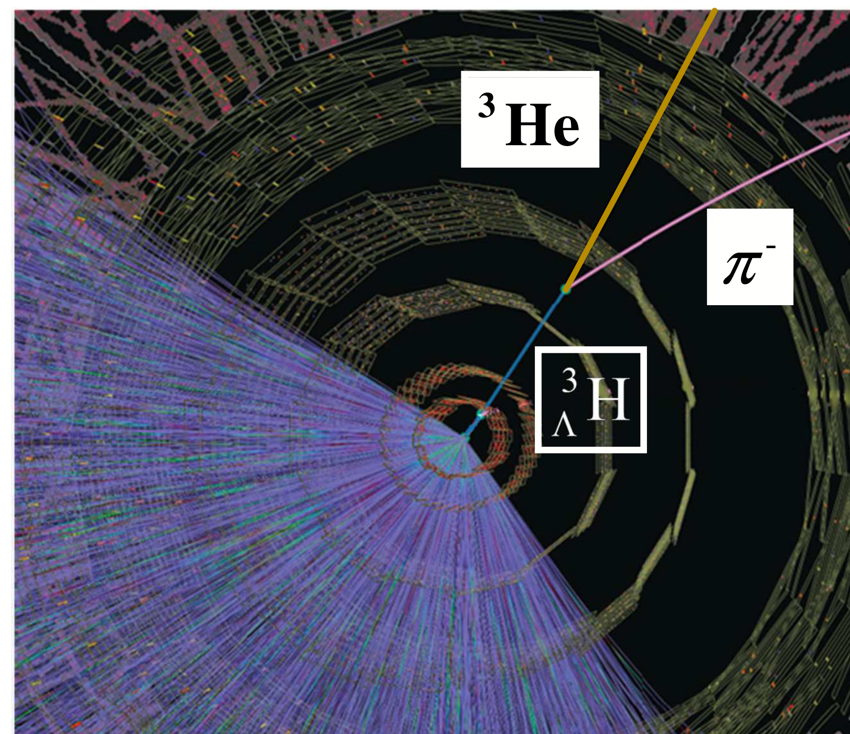
- ✓ Excellent **ALICE** performance allows for **detection of light (anti-)nuclei and (anti-)hypernuclei** and upper limit determination of exotic bound states
- ✓ Large production of nuclear clusters measured by ALICE as predicted by the thermal model
- ✓ Thermal (Pb-Pb) and coalescence models (pp, p-Pb) describe the (anti-)(hyper)nuclei data rather well
- ✓ Light nuclei "puzzle": deuteron yield and $v_2(p_T)$ in Pb-Pb collisions suggest an early "freeze out", while large effects of re-interactions (favoring late stage coalescence) should be expected
- ✓ **ALICE** preliminary **hypertriton lifetime** result from Pb-Pb at 5.02 TeV is **close to the the free Λ lifetime**
- ✓ Upper limits of production yield for searched exotica (Λn and ΛΛ) are 20 times below the thermal model expectation
- ✓ **Future LHC runs**, RUN2 and RUN3, and ALICE upgrades will **allow for precise study** of **(anti-)(hyper)nuclei** production yield (and lifetime)
- ✓ New and more precise data are expected from the LHC in the next years !

THE EXPERIMENTAL CHALLENGE

The challenge: extract the $^{3}_{\Lambda}H$ signal from an overwhelming background



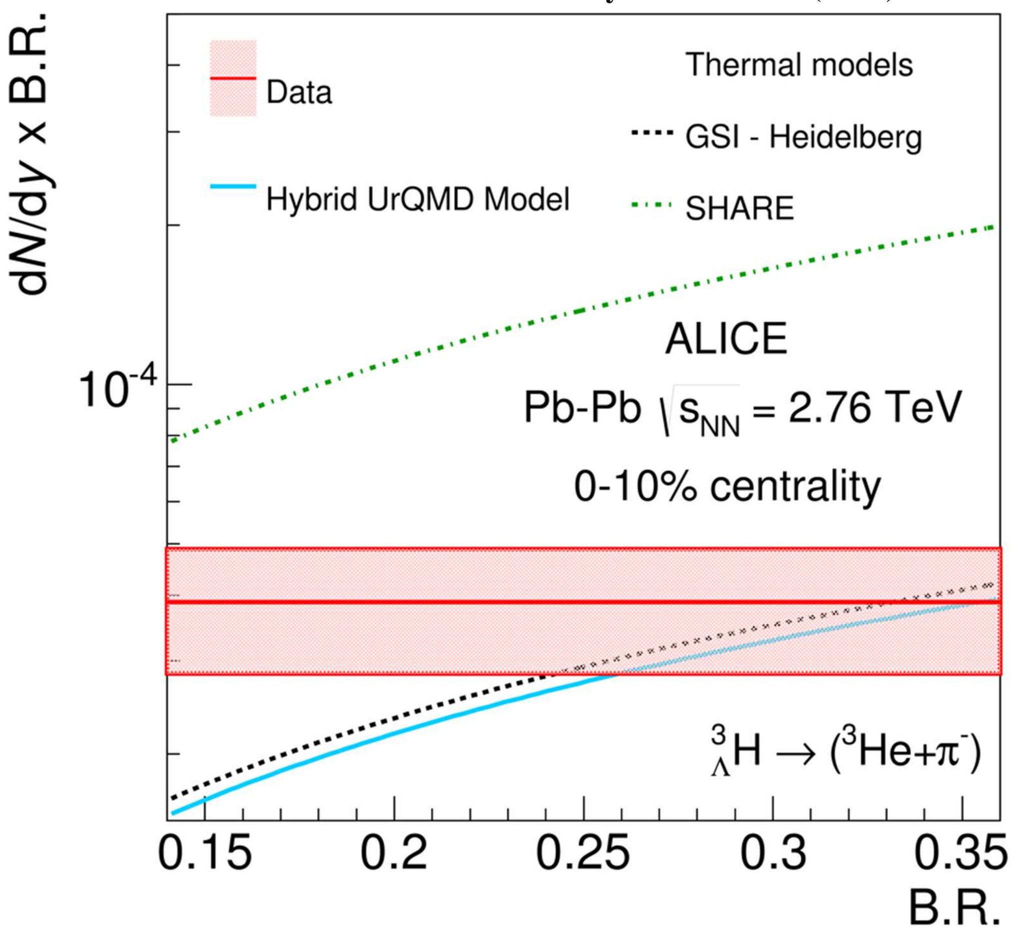
At $\sqrt{s_{NN}}$ =	2.76 TeV	5.02 TeV
Centrality	**$dN_{ch}/d\eta$ ($\|\eta\| < 0.5$)**	
0-5 %	1601 ± 60	1943 ± 54



K. Aamodt et al. (ALICE Collaboration) Phys. Rev. Lett. 106, 032301 (2011) ; J. Adam et al (ALICE Collaboration) Phys. Rev. Lett. 116, 222302 (2016)

COMPARISON WITH THEORETICAL PREDICTIONS

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



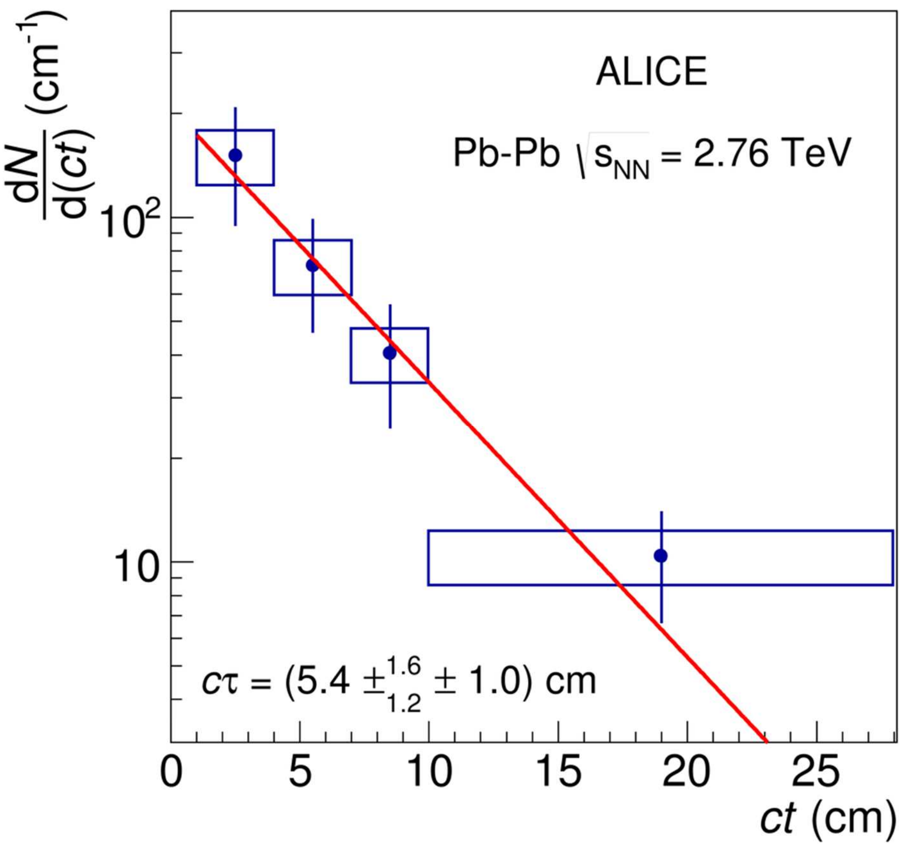
Three different theoretical predictions drawn as a function of BR($^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$) after being multiplied by BR:

- ✓ **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium (**J. Steinheimer et al., Phys. Lett. B 714, 85 (2012)**)
- ✓ **GSI-Heidelberg**: equilibrium statistical model with T_{chem}=156 MeV (**A. Andronic et al., Phys. Lett. B 697, 203 (2011)**)
- – **SHARE**: non-equilibrium thermal model with T_{chem}=138.3 MeV (**M. Petráň et al., Phys. Rev. C 88, 034907 (2013)**)

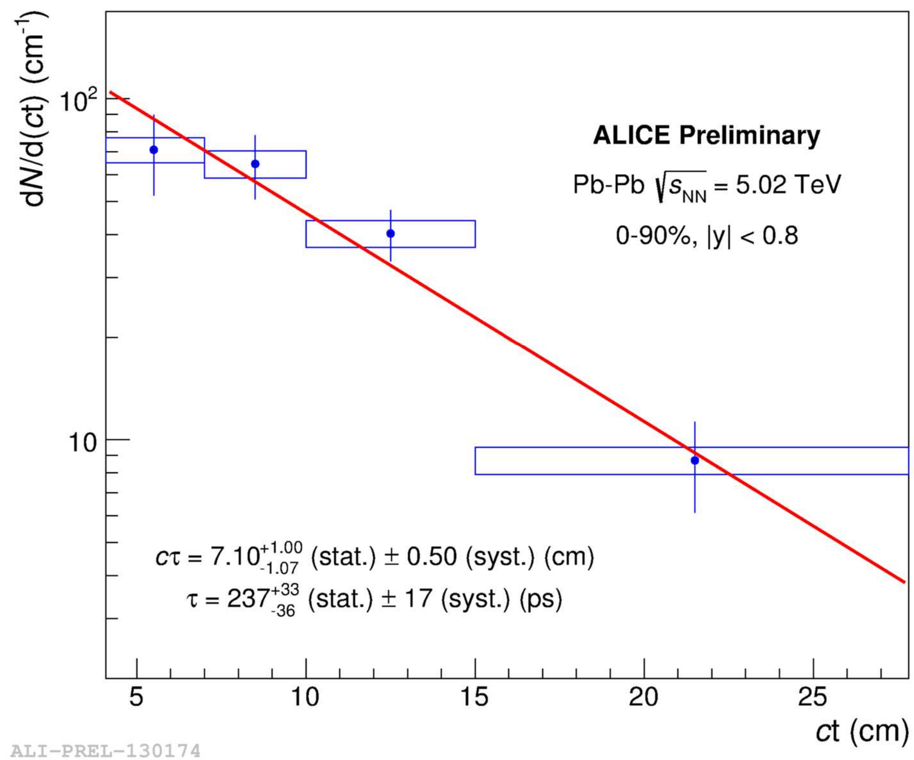
- Great sensitivity to theoretical models parameters
- Non–equilibrium statistical thermal model (Petráň-Rafelski SHARE) provides better global fitting (χ^2~1) to lower mass hadrons but **misses $^{3}_{\Lambda}$H** and light nuclei
- Experimental data closest to equilibrium thermal model with T_{chem} = 156 MeV and to Hybrid UrQMD

HYPERTRITON LIFETIME DETERMINATION

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



New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$

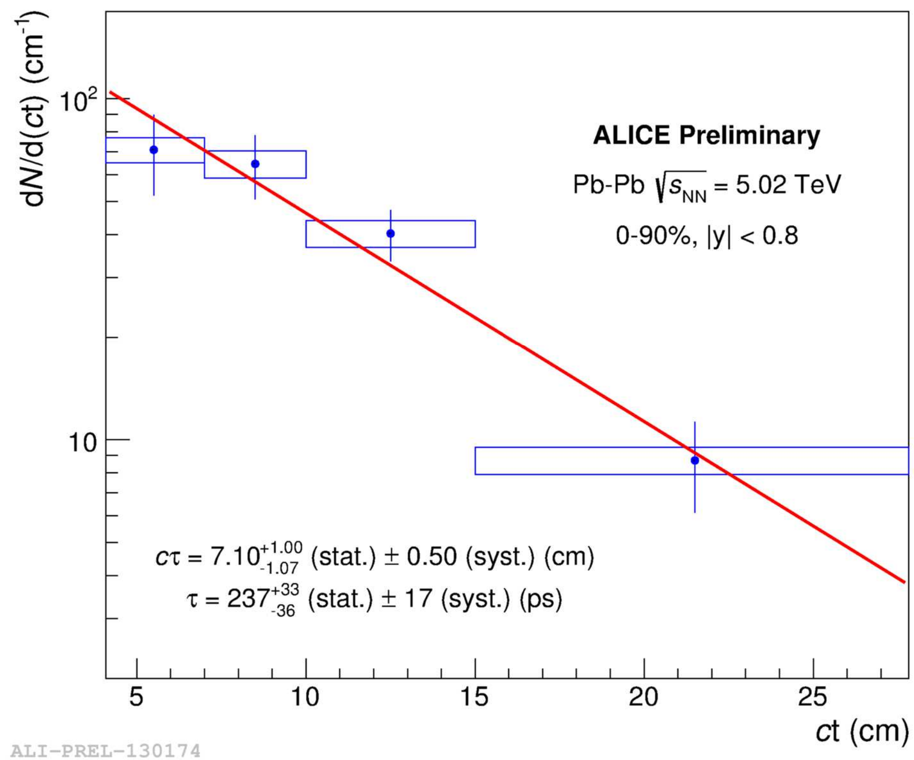
$$c\tau = \left(7.10^{+1.00}_{-1.07}(stat.) \pm 0.50(syst.)\right) cm$$
$$\tau = \left(237^{+33}_{-36}(stat.) \pm 17(syst.)\right) ps$$

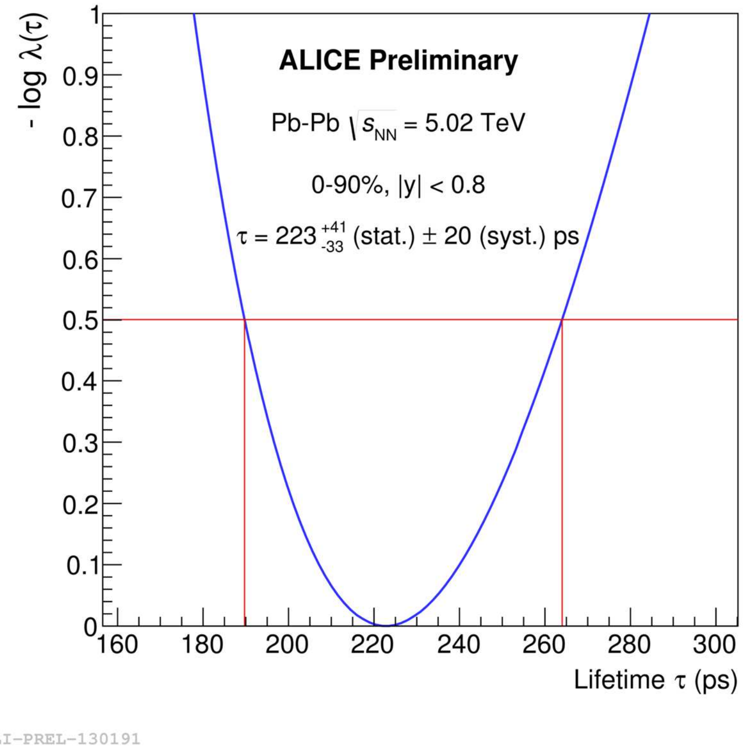
HYPERTRITON LIFETIME DETERMINATION

Two methods for estimation:

- *ct* spectra fit (exponential fit to the differential yield in different *ct* bins)
- *ct* unbinned fit as crosscheck method

New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV

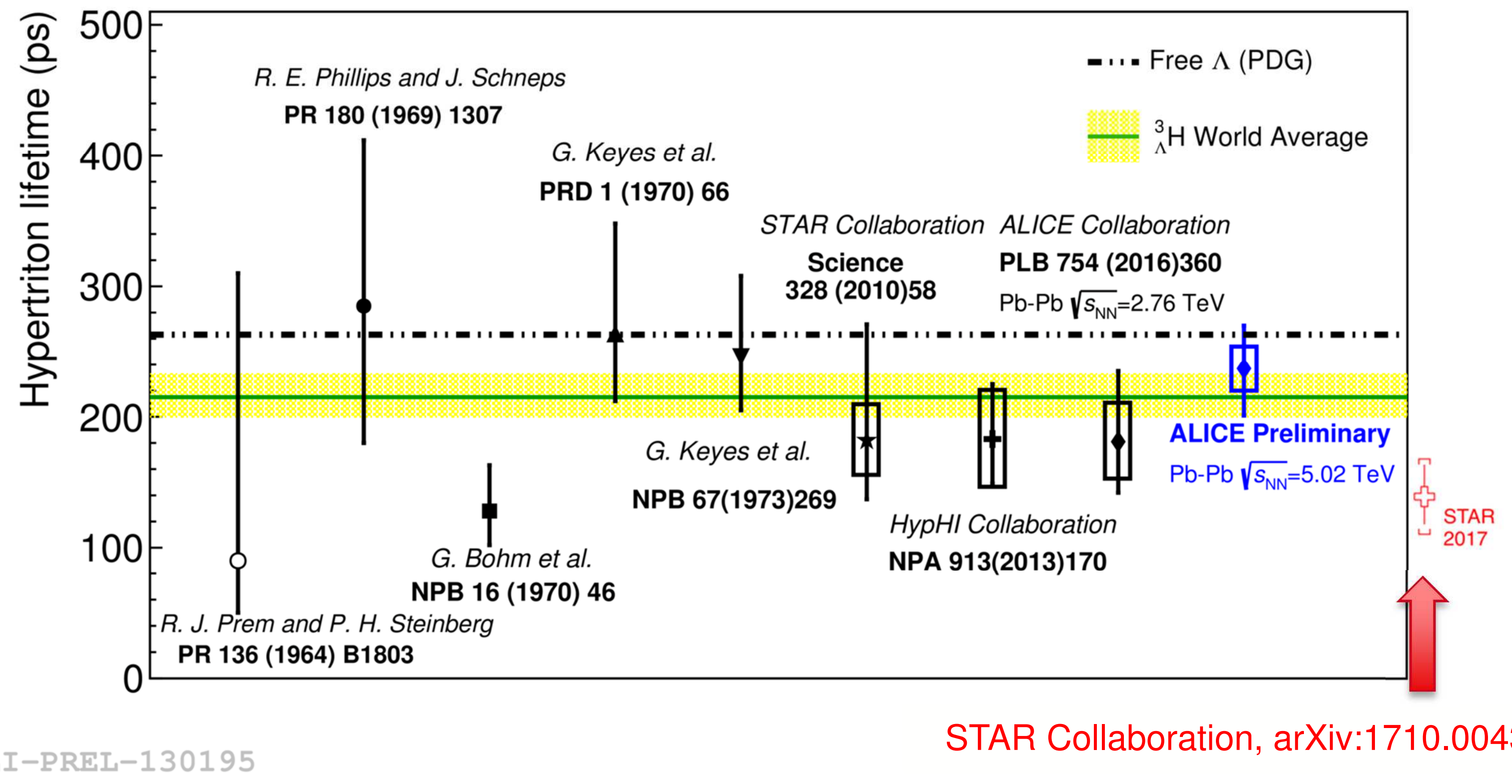




$$c\tau = \left(7.10^{+1.00}_{-1.07}(stat.) \pm 0.50(syst.)\right) cm$$

$$\tau = \left(237^{+33}_{-36}(stat.) \pm 17(syst.)\right) ps$$

HYPERTRITON LIFETIME WORLD AVERAGE

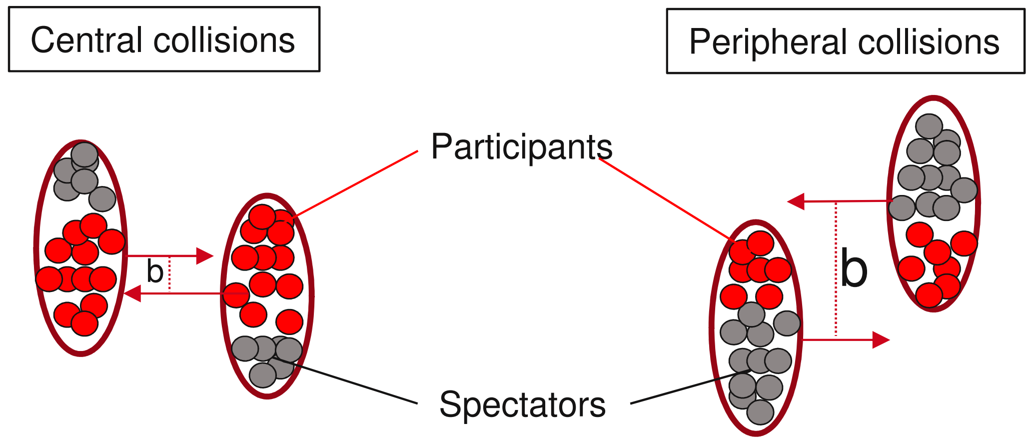


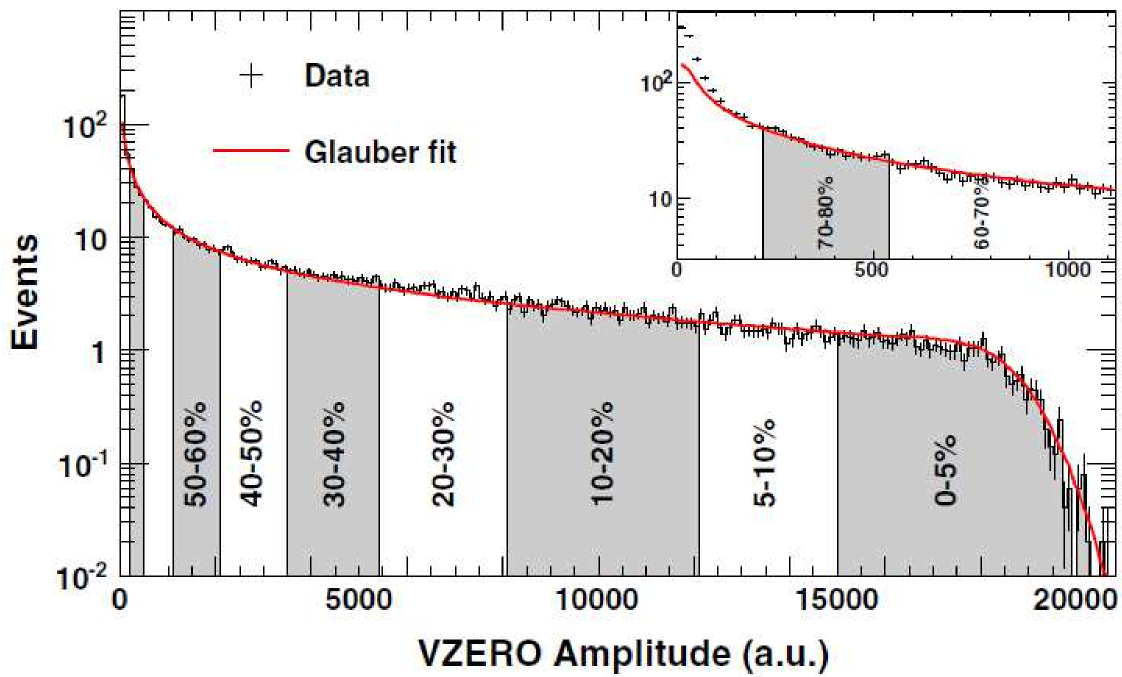
STAR Collaboration, arXiv:1710.00436v1 [nucl-ex]

$$\tau = \left(142^{+24}_{-21}(stat.) \pm 31(syst.)\right) ps$$

- Previous heavy-ion experiment results show a trend well below the free Λ lifetime
- ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free Λ lifetime
- STAR result from Au-Au collision is about 50% shorter than the free Λ lifetime
- The puzzle of the $^{3}_{\Lambda}$H lifetime is still open

COLLISION GEOMETRY





K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 106, 032301 (2011)

- Nuclei are extended objects
- Geometry not directly measurable
- Centrality (percentage of the total cross section of the nuclear collision) connected to observables via Glauber model

- Data classified into centrality percentiles for which the average impact parameter, number of participants, and number of binary collisions can be determined