Production of light (anti-)nuclei and exotica states in ALICE

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ALICE

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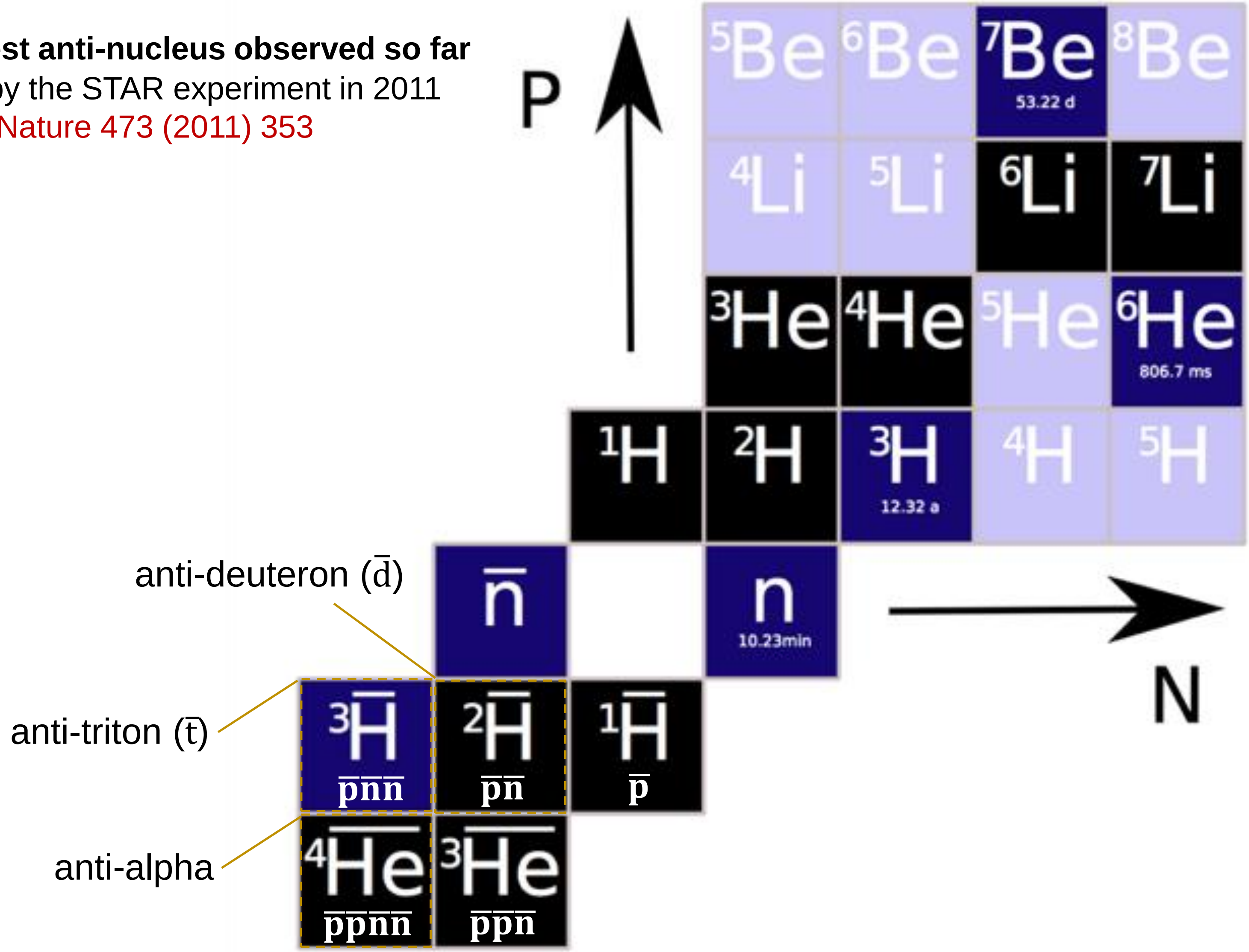
Light (anti-)nuclei chart

$^{4}\overline{\mathrm{He}}$ is the heaviest anti-nucleus observed so far

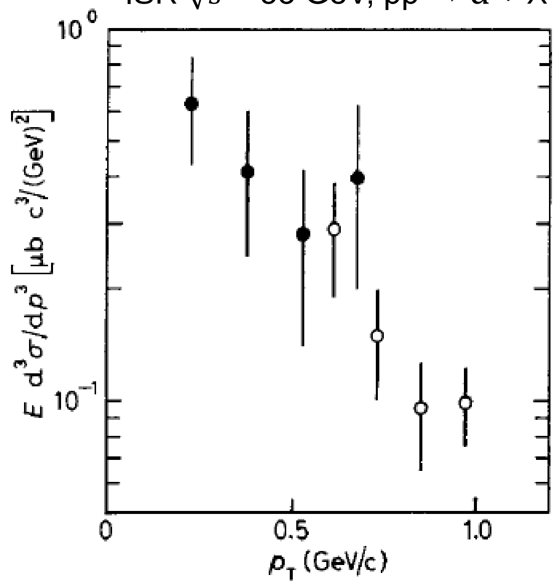
First observed by the STAR experiment in 2011

STAR, Nature 473 (2011) 353



Why studying light nuclei?

ISR $\sqrt{s}$ = 53 GeV, pp → $\bar{\mathrm{d}}$ + X



British-Scandinavian MIT, Lett. Nuovo Cim. 21 (1978) 198

Lack of experimental data in pp collisions

- anti-deuterons at CERN ISR
- anti-^{3}He and anti-tritons never observed in pp

Testing model predictions e.g. hadron coalescence

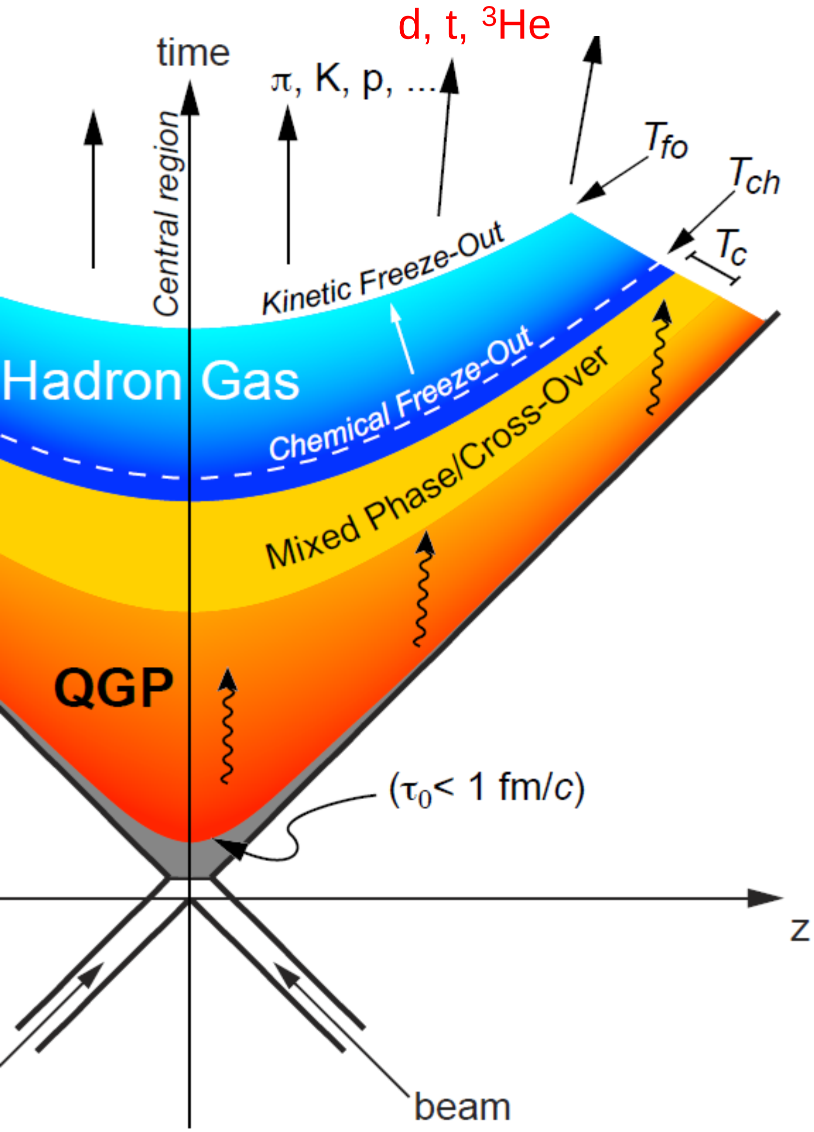
High interest in space-based experiments (AMS-02)

→ primordial anti-matter and Dark Matter searches

Nuclei probe last-stage evolution of heavy-ion collisions

Search for strange matter

Nuclei formation mechanisms



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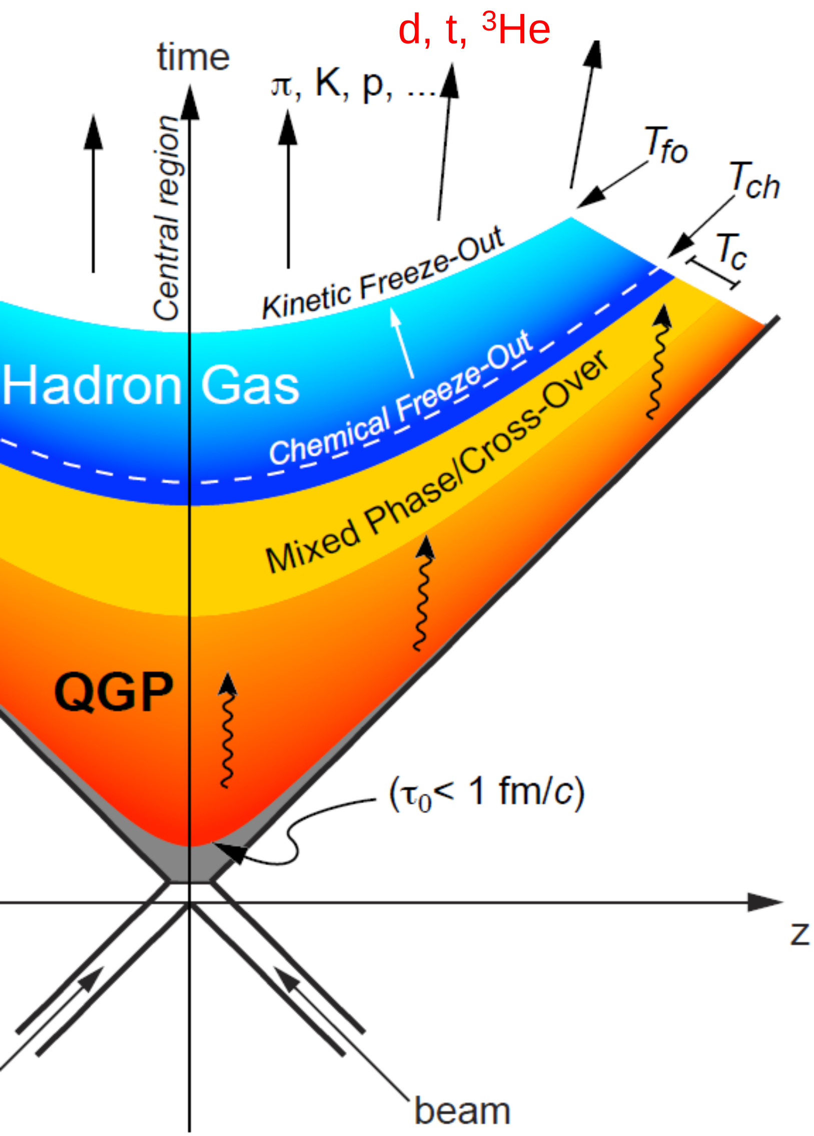


Thermal production
Andronic et al, Nature 561 (2018) 321

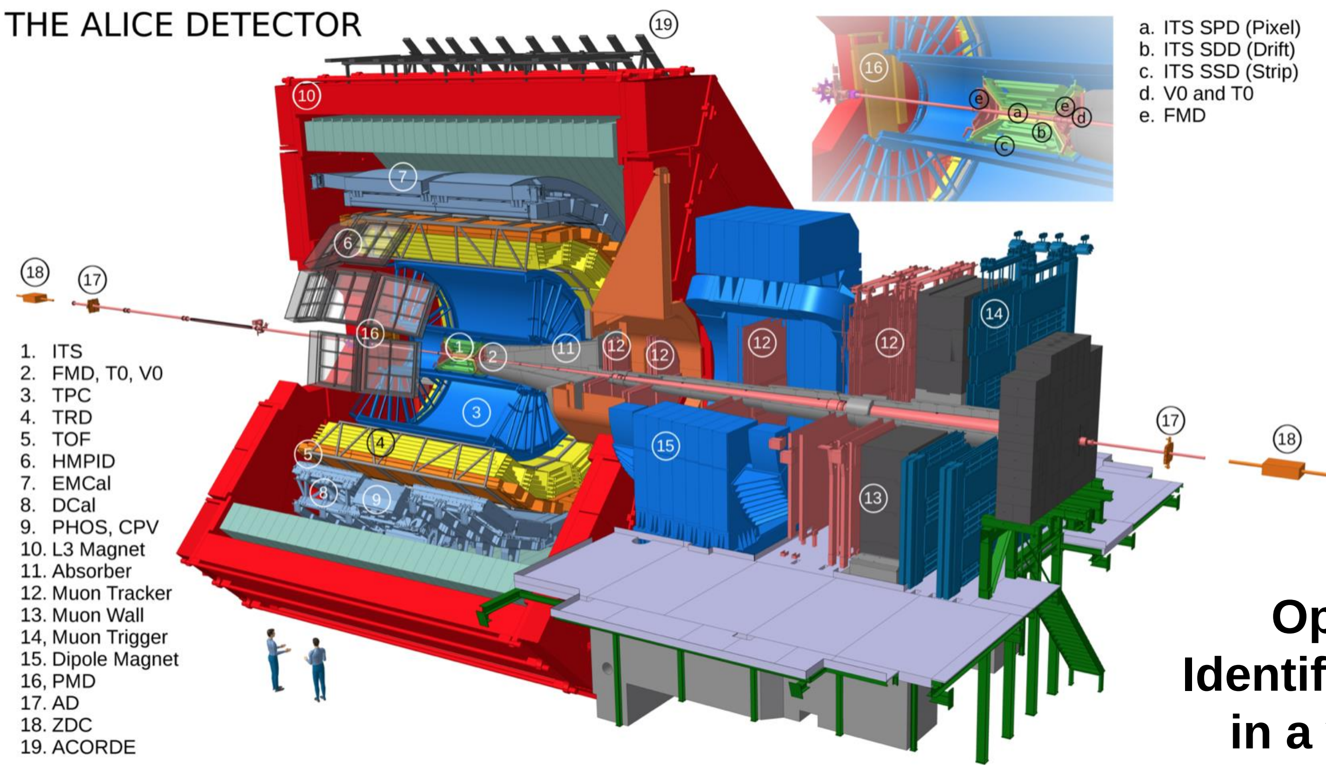
Thermodynamic approach to particle production extensively used in heavy-ion physics

- Hadrons emitted from the interaction region at the transition temperature (T_c)
- Chemical freeze-out temperature (T_{ch})
- Abundances fixed at equilibrium and $\propto \exp(-m/T_{ch})$
  → **strong sensitivity of nuclei (large m) to T_{ch}**
- Nuclei are loosely bound objects ("snowballs in hell")
  → nuclei might dissociate in the hadronic phase and be re-formed later via coalescence

Coalescence
Csernai and Kapusta, Phys. Rept. 131 (1986) 223

Nuclei form by merging of final-state nucleons which are close in phase space (x, p) after the kinetic freeze-out

ALICE experiment

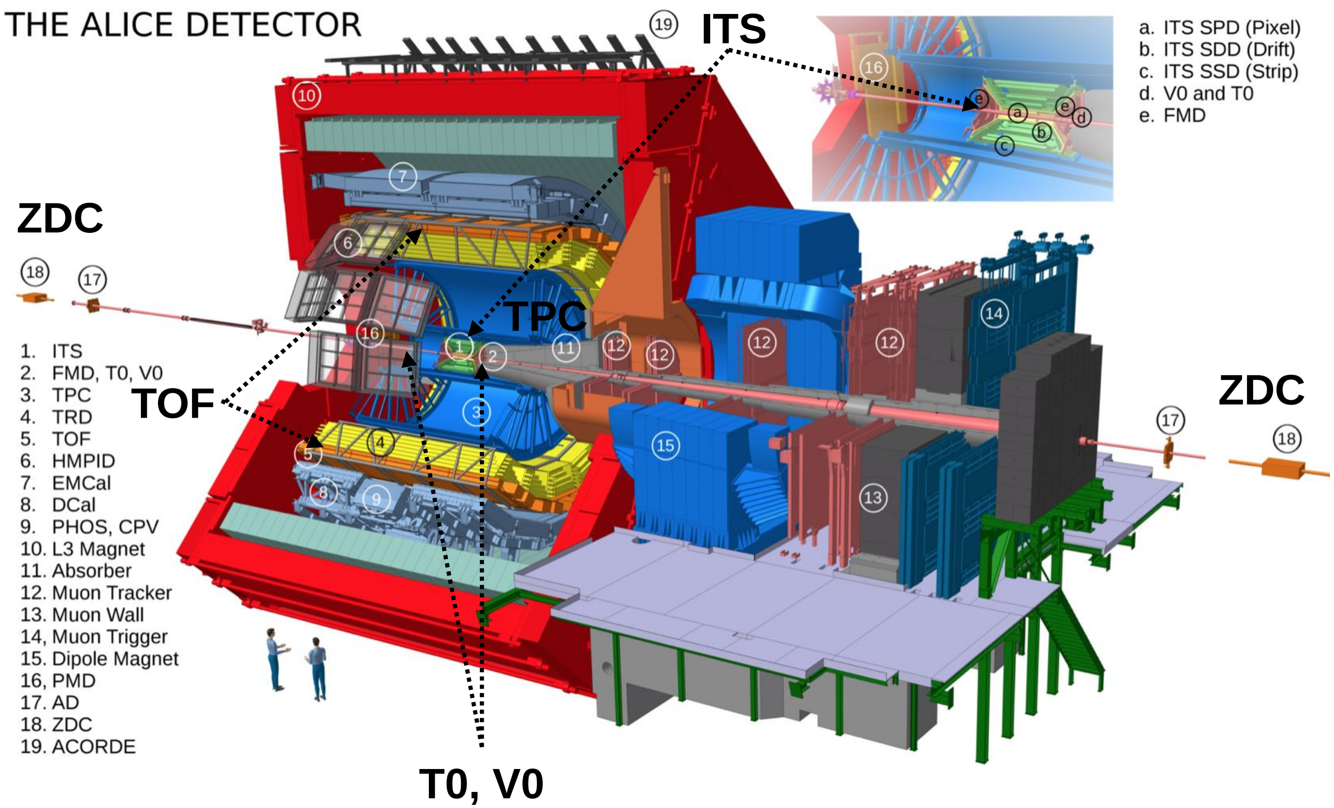


Optimized for Particle Identification at low momenta in a very high-multiplicity environment

Many particle detection techniques employed (17 detectors) / low material budget

Run 1 (2009-2013)	Run 2 (2015-2018)
pp 0.9, 2.76, 7, 8 TeV	pp 5.02, 13 TeV
p-Pb 5.02	p-Pb 5.02, 8.16 TeV
Pb-Pb 2.76 TeV	Pb-Pb 5.02 TeV Xe-Xe 5.44 TeV

ALICE experiment



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ITS ($|\eta|<0.9$)

6 layers silicon detectors

Trigger, vertex, tracking, PID (dE/dx)

TPC ($|\eta|<0.9$)

Gas-filled cylindrical barrel, MWPC readout

Tracking, PID (dE/dx)

TOF ($|\eta|<0.9$)

Multigap RPC

PID (time-of-flight)

T0 ($4.6<\eta<4.9$ and $-3.3<\eta<-3.0$)

2 arrays of Cherenkov's (T0A, T0C)

Luminosity, vertex, event collision time

V0 ($2.8<\eta<5.1$ and $-3.7<\eta<-1.7$)

Forward arrays of scintillators (V0A and V0C)

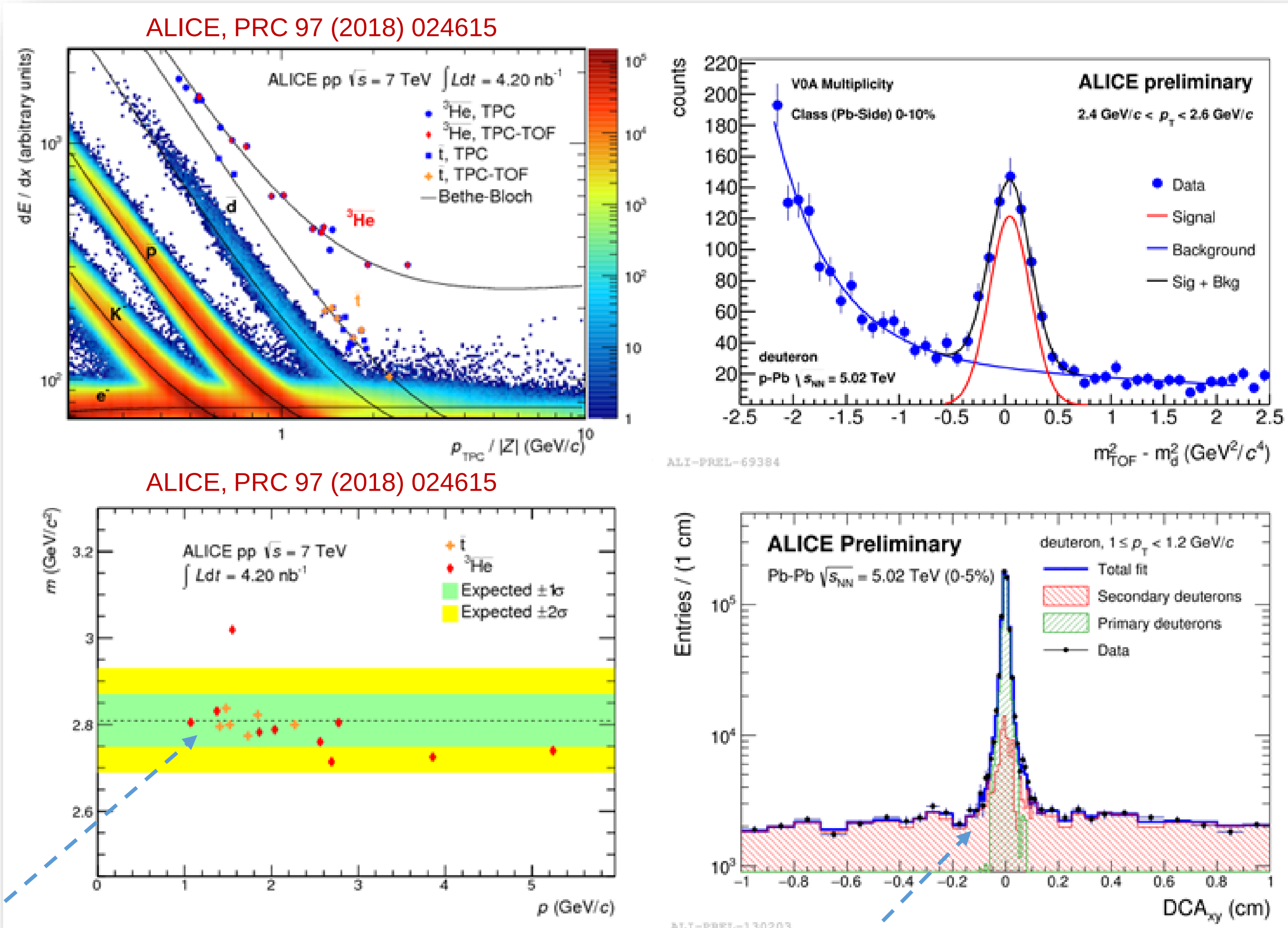
Trigger, beam gas rejection, multiplicity, centrality

ZCD centrality determination

PID

Low momenta: TPC (dE/dx)

Higher momenta: TOF (m^2)

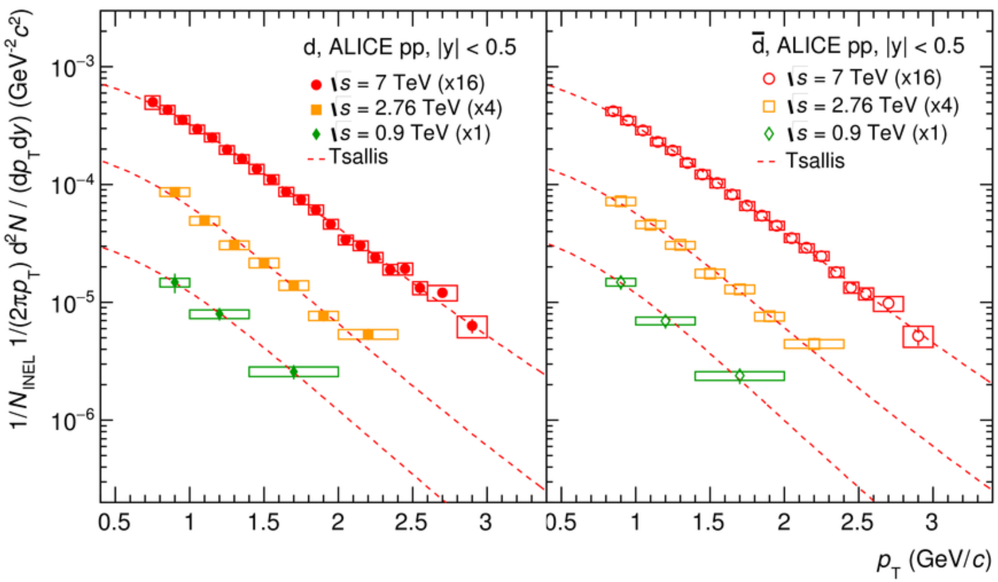


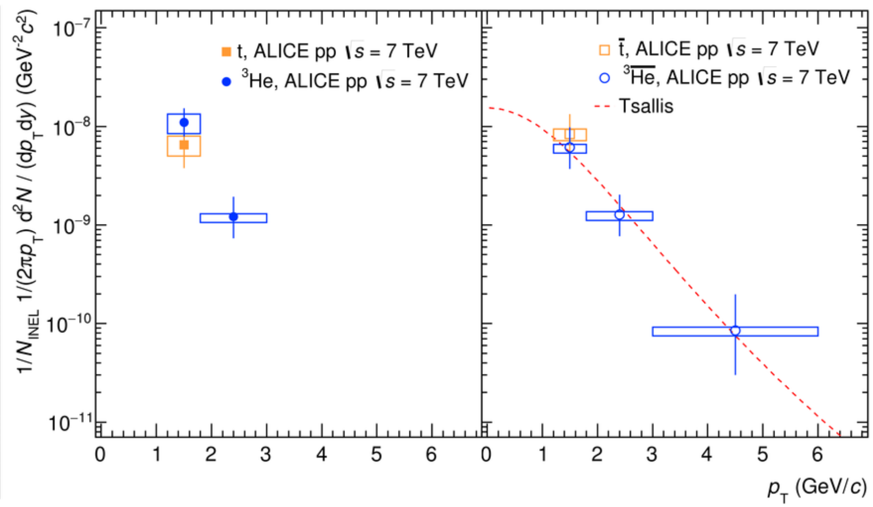
TPC+TOF: **6 anti-tritons** and **10 $^{3}\overline{\mathrm{He}}$** candidates
→ **first ever observation in pp**

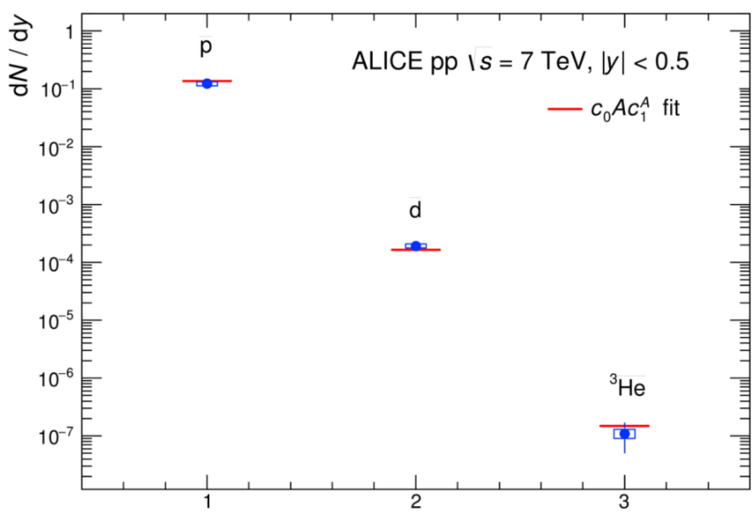
ITS: separation of primary and secondary nuclei (from material knock-out)

Deuterons, tritons and ^{3}He and their anti-nuclei in pp at LHC Run 1

ALICE, PRC 97 (2018) 024615







$\rightarrow$ reduction of the p_T integrated yield (dN/dy) is **about 1000 for each additional nucleon in pp**

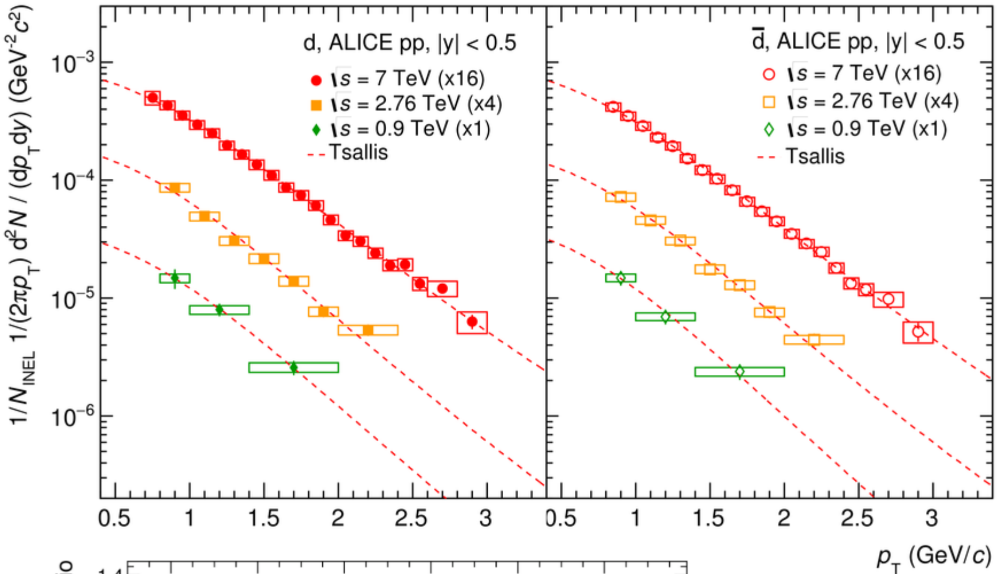
In p-Pb this penalty factor is about 600

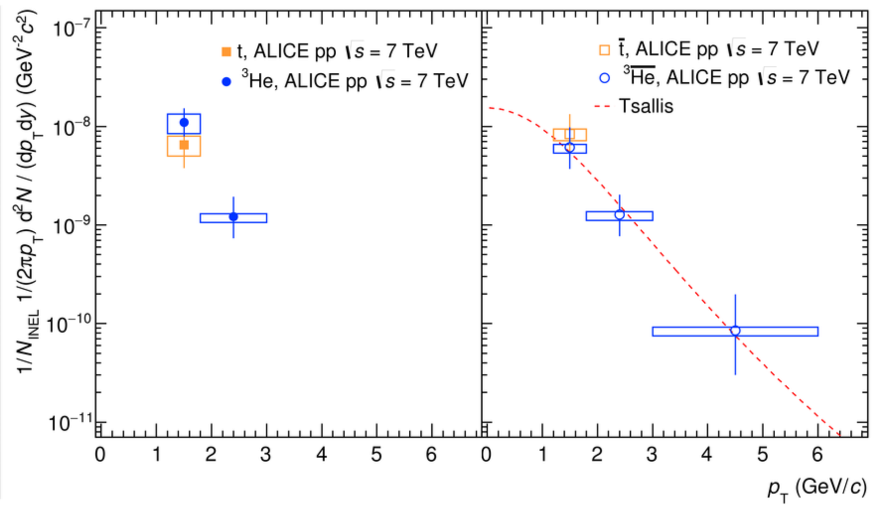
~300 in Pb-Pb collisions ALICE, NPA 971 (2018) 1

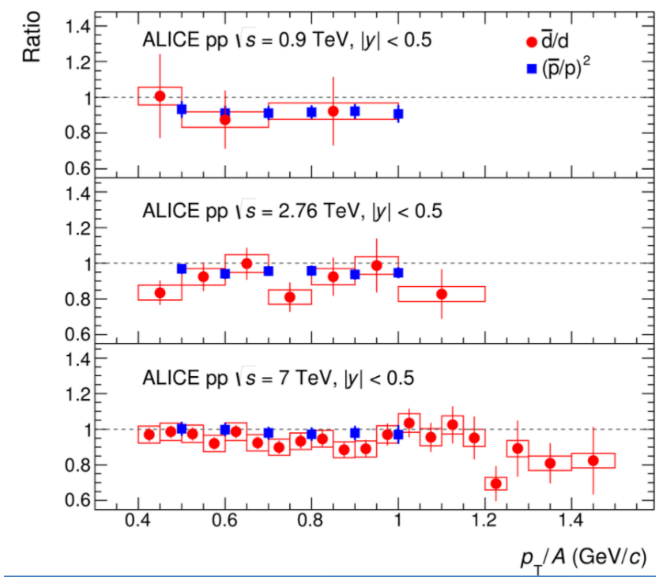
A = mass number

Deuterons, tritons and ^{3}He and their anti-nuclei in pp at LHC Run 1

ALICE, PRC 97 (2018) 024615







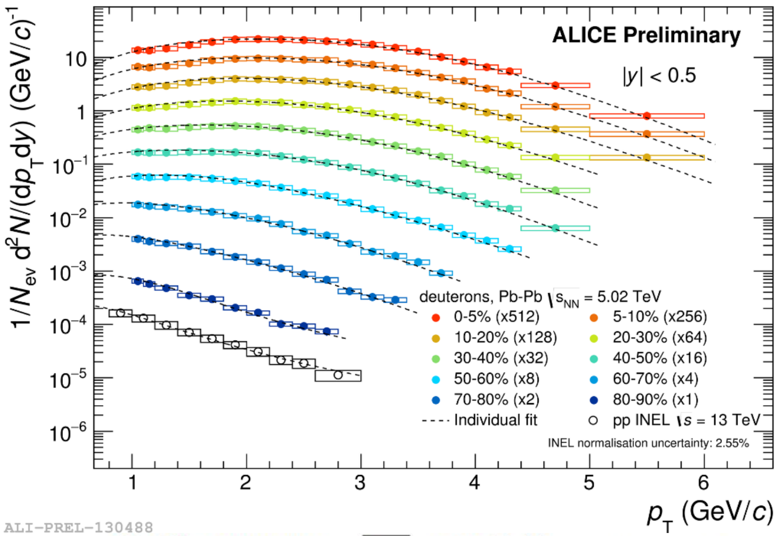
$$\bar{\mathbf{A}}/\mathbf{A} \propto (\bar{\mathbf{p}}/\mathbf{p})^{\mathbf{A}} \rightarrow \bar{\mathrm{d}}/\mathrm{d} \propto (\bar{\mathrm{p}}/\mathrm{p})^2$$

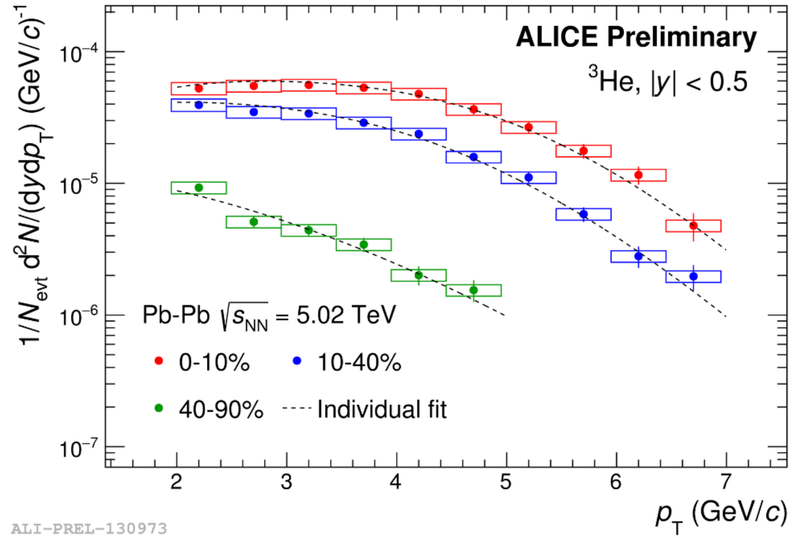
and **$\bar{\mathbf{p}}$/p approaches unity with increasing energy**

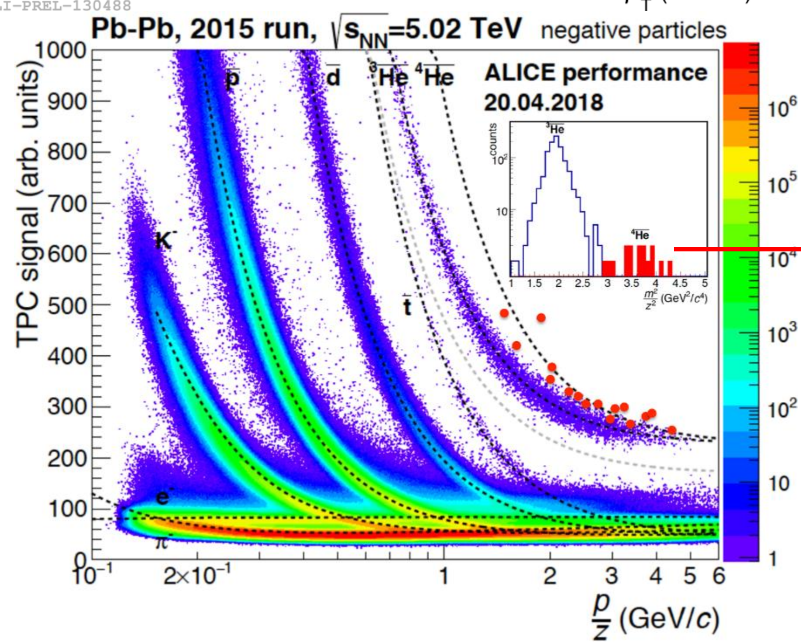
Pb-Pb

deuterons, ^{3}He and ^{4}He

ALICE-PUBLIC-2017-006





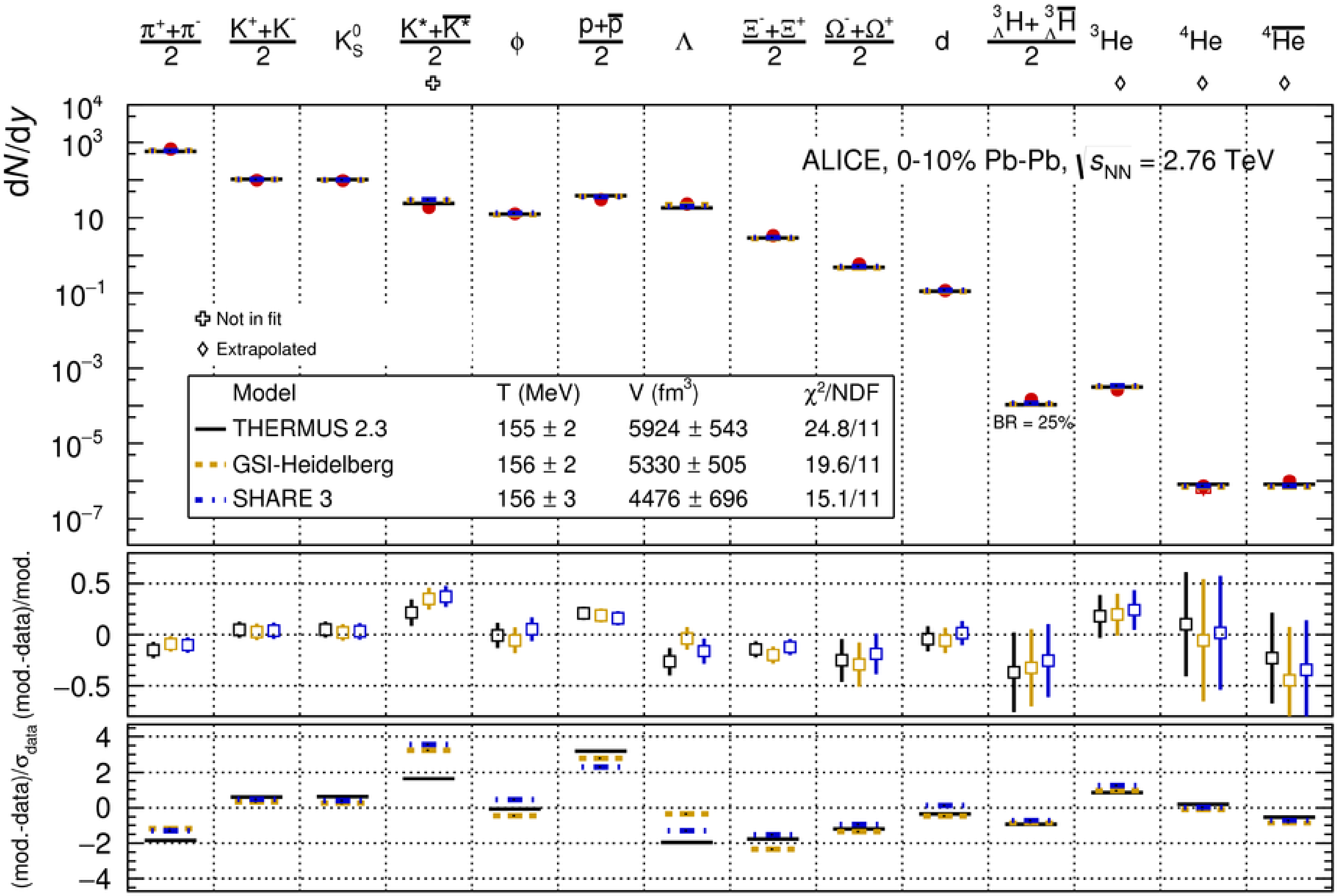


16 $^{4}\overline{\mathrm{He}}$ candidates in Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

2.76 TeV Pb-Pb published in
NPA 971 (2018) 1

Thermal model fit

ALICE, PRC 97 (2018) 024615



Thermal model successfully reproduces particle yields in Pb-Pb at 2.76 TeV

different model implementations fit nuclei and even hypertriton

if *only* nuclei are fitted, the temperature is 154 $\pm$ 4 MeV

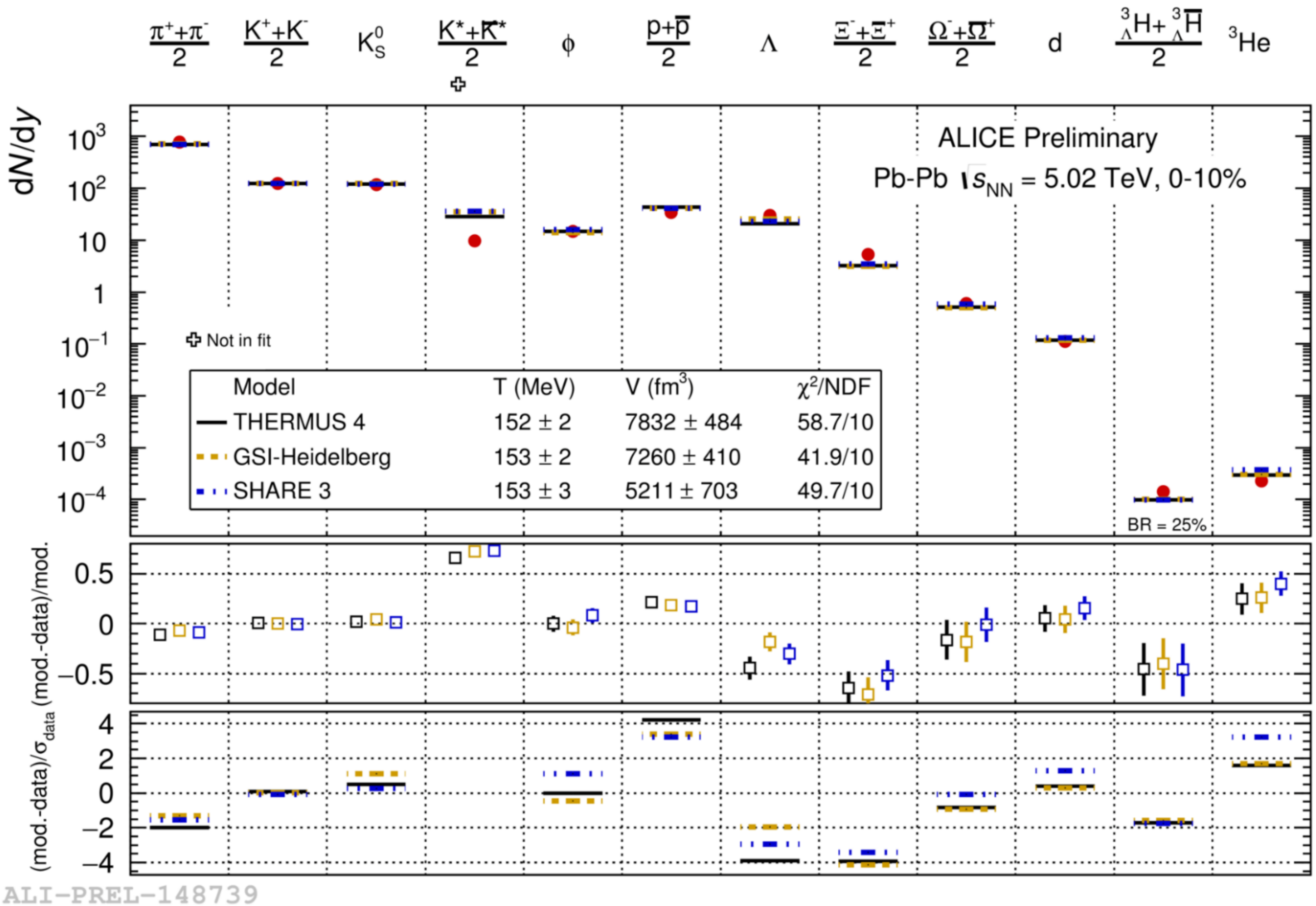
→ hint for nuclei production at hadronization

THERMUS: Weaton et al. CPC 180 (2009) 84

GSI-Heidelberg: Andronic et al., Nature 561 (2018) 321

SHARE 3: Torrieri et al., CPC 185 (2014) 2056

Thermal model fit



For LHC Run 2, improved reconstruction and analysis technique reduced the uncertainties

Tensions with thermal model are larger

→ does the model need further tuning? Eigen volume corrections, particle lists and BR, rescattering, S-matrix etc.

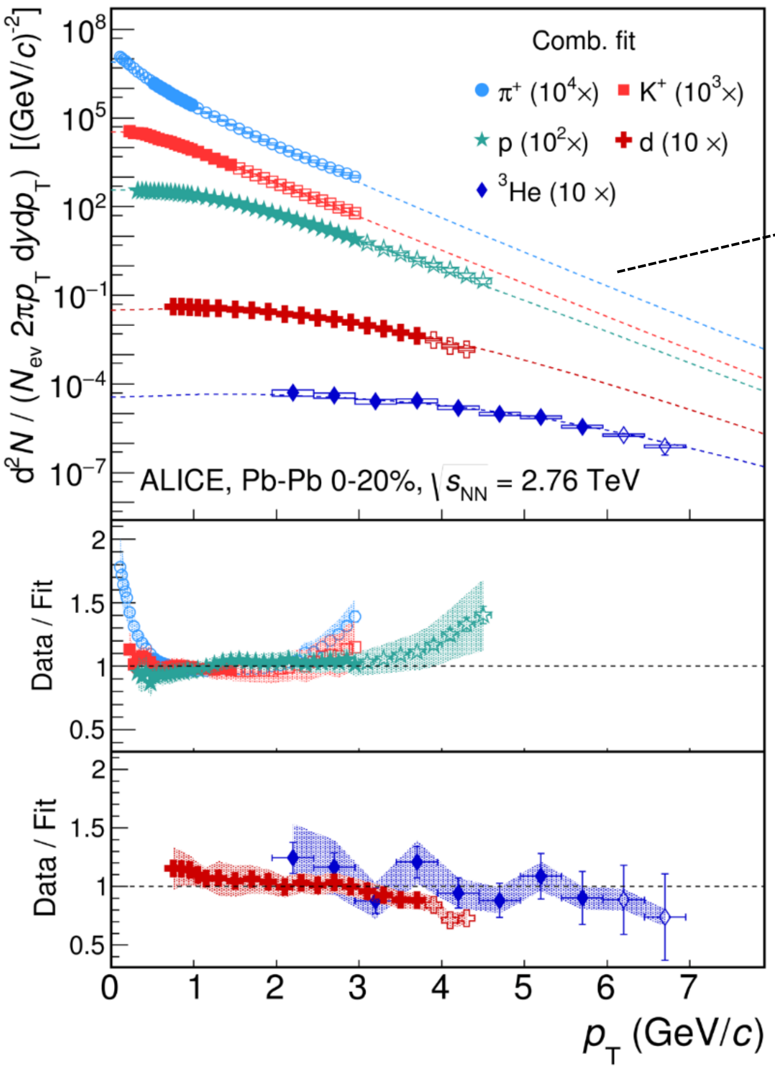
THERMUS: Weaton et al. CPC 180 (2009) 84

GSI-Heidelberg: Andronic et al., Nature 561 (2018) 321

SHARE 3: Torrieri et al., CPC 185 (2014) 2056

Blast-Wave model fit

ALICE, PRC 93 (2016) 024917



Blast-Wave (BW)
[Schnedermann, Sollfrank and Heinz, PRC 48 (1993) 2462]
hydrodynamics-inspired model describing particle production assuming a radially expanding thermalized source

BW fits simultaneously π, K, p and d, ^{3}He

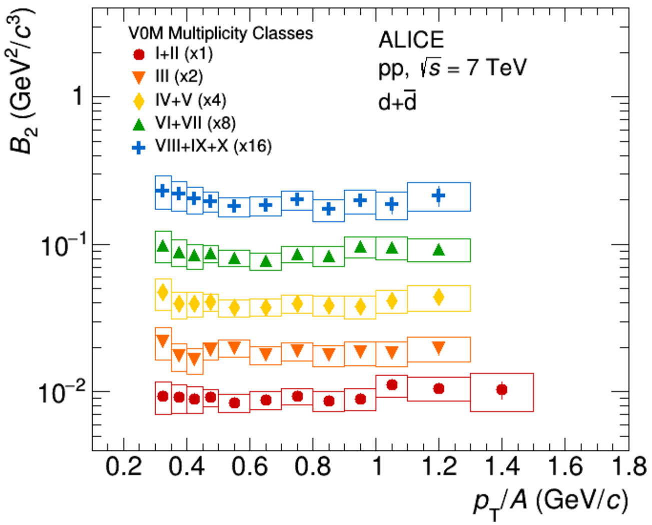
→ kinetic freeze-out conditions for nuclei identical to those of other light flavor hadrons

pp

Testing coalescence models

Coalescence parameter B_2

ALICE, arXiv:1902.09290v1 [nucl-ex] 25 Feb 2019

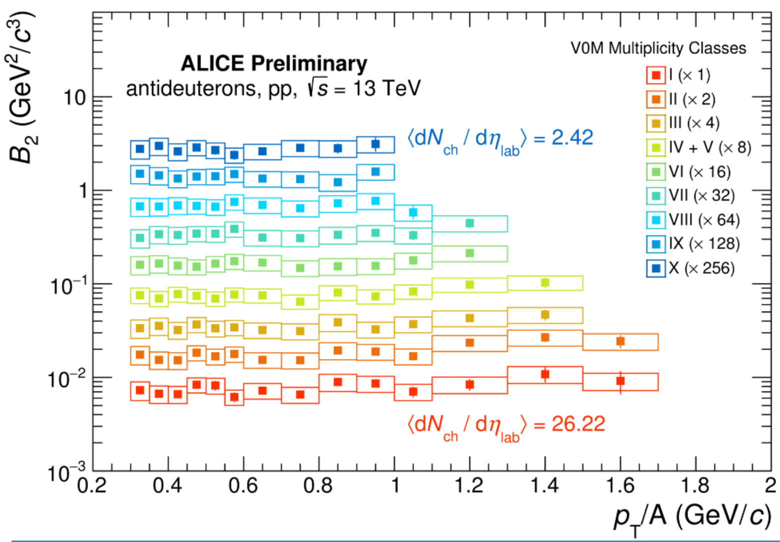


B_A relates the formation of composite nuclei to the one of primary protons and neutrons through a simple power law

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

where $p_p = p_A/A$

i.e. deuteron ∝ B_2 x proton^2



ALI-PREL-146141

→ **B_2 doesn't show p_T dependence, in agreement with simplest coalescence model:**

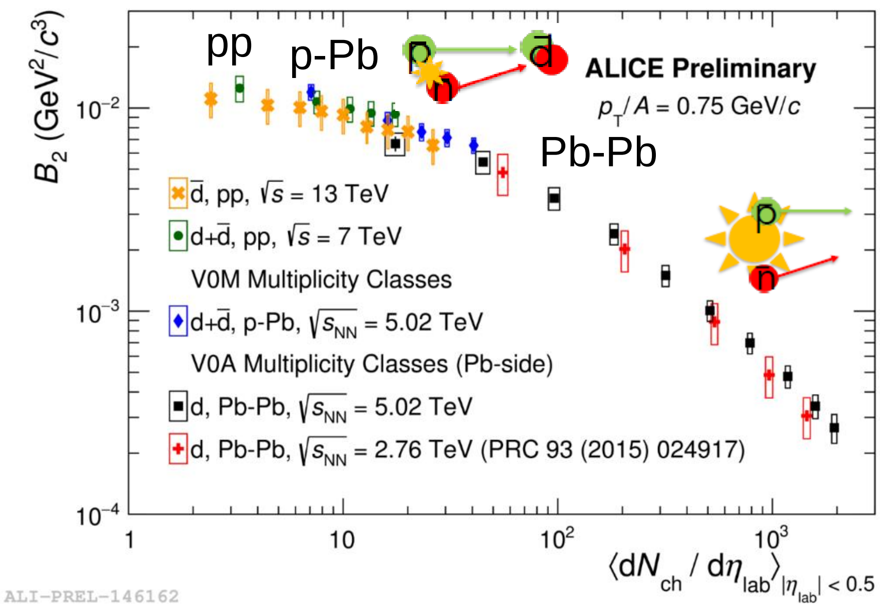
Butler and Pearson, PR 129 (1963) 836
see also Csernai and Kapusta, PR 131 (1986) 223

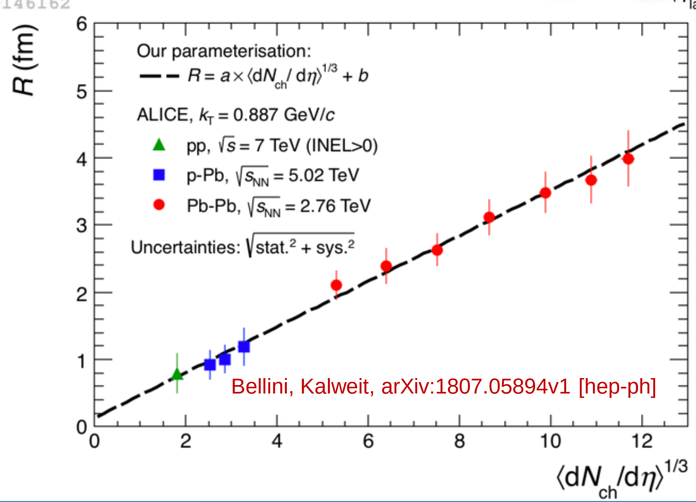
- "point-like" particle-emitting source (i.e. hadronic emission region smaller than the nucleus size)

- no correlations in the proton and neutron momentum distributions

Testing coalescence models

Multiplicity dependence of B_2





Coalescence probability suppressed with multiplicity by the increasing size of the hadronic emission region (quantified by HBT radii)

$$B_A \propto V^{1-A} \rightarrow B_2 \propto \frac{1}{V}$$

→ **effect quantified in refined Coalescence models:**

Scheibl and Heinz, PRC 59 (1999) 1585

$$B_2 = \frac{3\pi^{3/2}\langle \mathcal{C}_d \rangle}{2 m_t \mathcal{R}_\perp^2(m_t) \mathcal{R}_\parallel(m_t)}$$

Blum et al., PRD 96 (2017) 103021

$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left(\left(\frac{R(p_t)}{1\ \mathrm{fm}} \right)^2 + 2.6 \left(\frac{b_2}{3.2\ \mathrm{fm}} \right)^2 \right)^{-\frac{3}{2}}$$

Looking to the sky

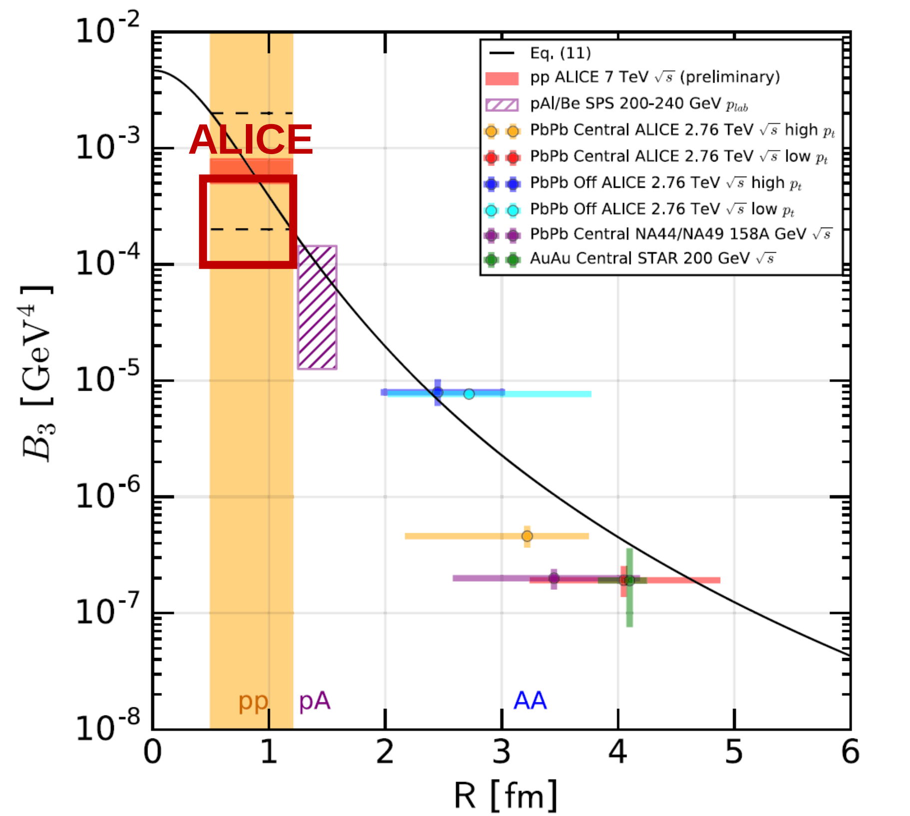
Blum et al., PRD 96 (2017) 103021

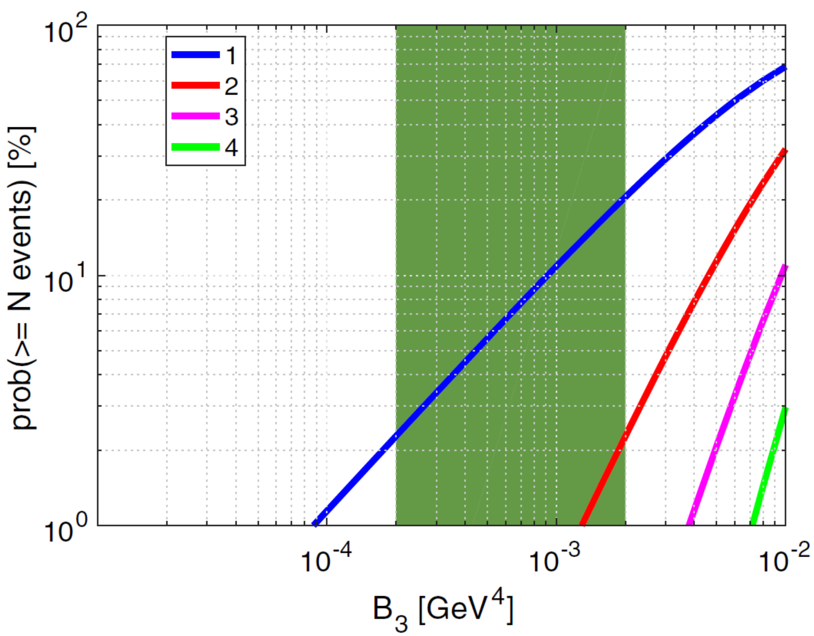
B_3 (B_2) at LHC can constrain
***secondary* anti-nuclei flux near Earth**
induced by CRs interactions with interstellar matter (H, ^{3}He mainly)

$$\frac{B_3}{\mathrm{GeV}^4} \approx 0.0024\left(\left(\frac{R(p_t)}{1\ \mathrm{fm}}\right)^2 + 0.8\left(\frac{b_3}{1.75\ \mathrm{fm}}\right)^2\right)^{-3}$$

Essential for primordial anti-matter and Dark Matter searches

→ CR anti-deuterons and anti-^{3}He suggested as probe of DM annihilation





← Poisson probability for detecting N (1, 2, …) secondary $^3\overline{\mathrm{He}}$ events in 5-yr analysis of AMS-02

Hypernuclei

Hypertriton

Hypertriton ($^{3}_{\Lambda}\mathrm{H}$) is the lightest strange nucleus (pnΛ)

- $^{3}_{\Lambda}\mathrm{H}$ seen for the first time in 1952 in cosmic rays

- anti-$^{3}_{\Lambda}\mathrm{H}$ first observed by the STAR experiment in 2010 Science 328 (2010) 58

$^{3}_{\Lambda}\mathbf{H}$

m = 2.991 GeV

B_{Λ} = 0.13 ± 0.05 MeV

unstable, (week) decay modes

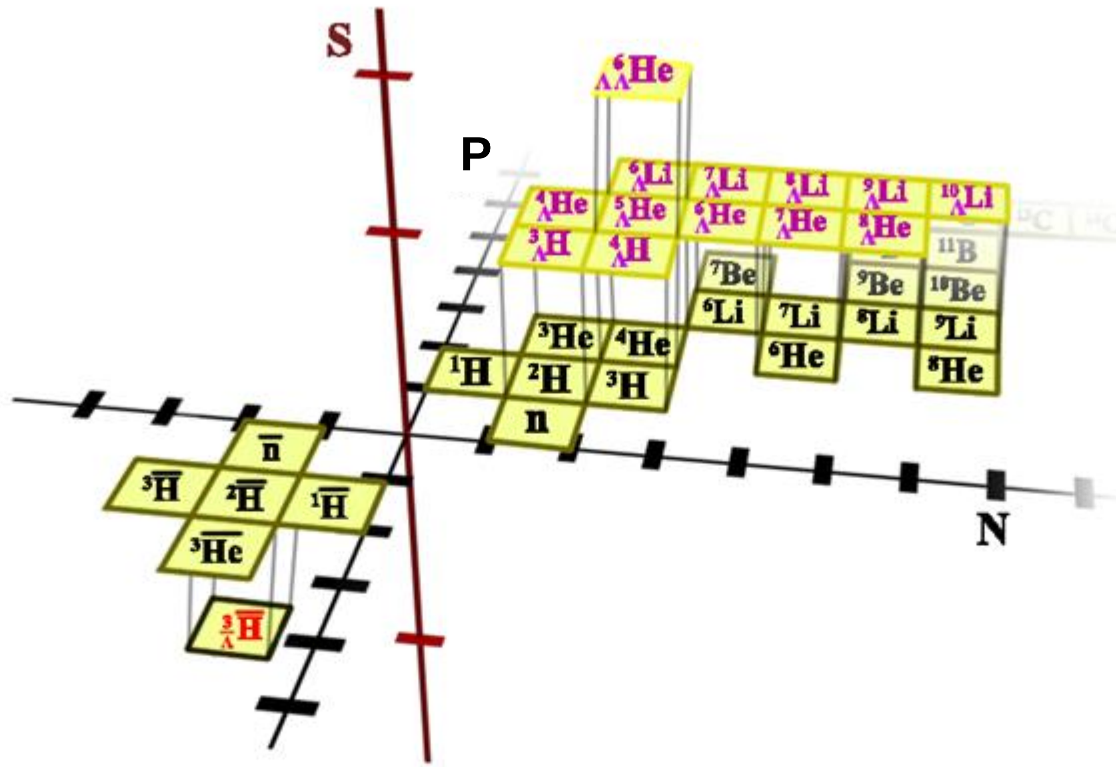
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ (+ c.c.) (B.R. 25%)

$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$ (B.R. 13%)

$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$ (B.R. 41%)

$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{0}$ (B.R. 21%)

B. R. not well known
only few theoretical calculations available
Kamada et al., PRC 57 (1998) 4



$(^{3}_{\Lambda}\mathrm{H})\,^{3}_{\Lambda}\mathrm{H}$ identification in ALICE

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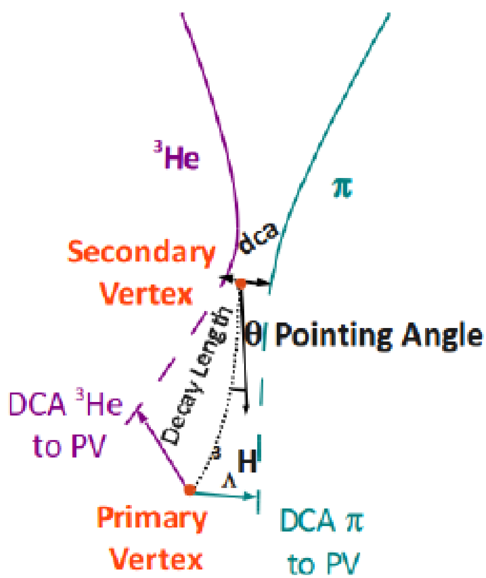

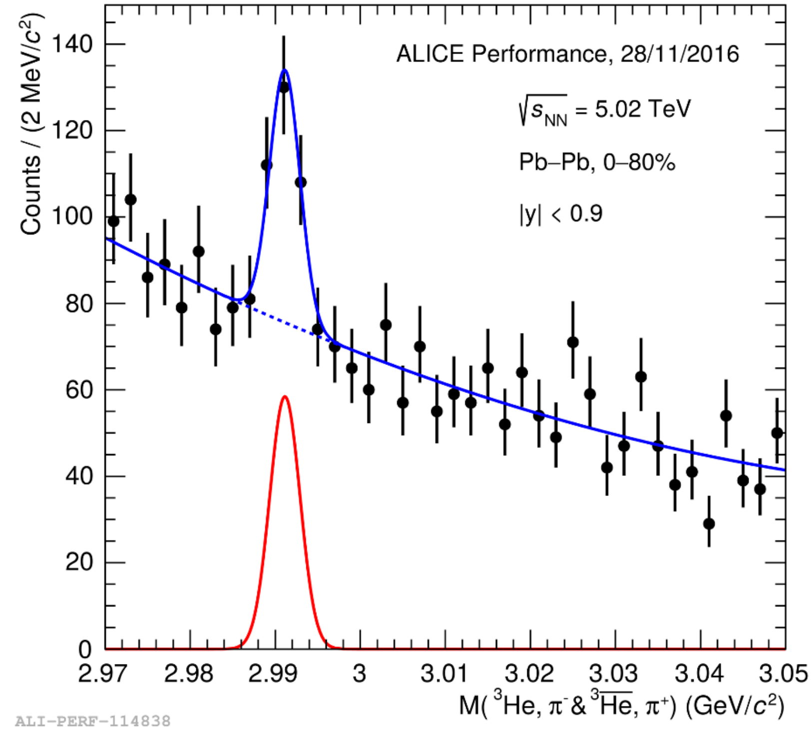

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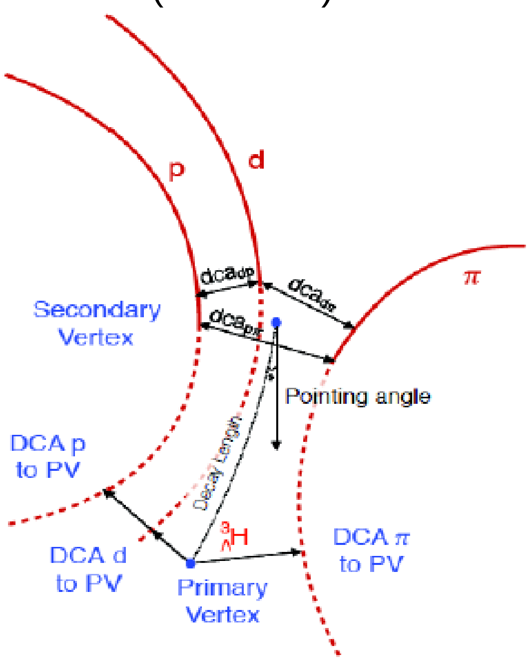
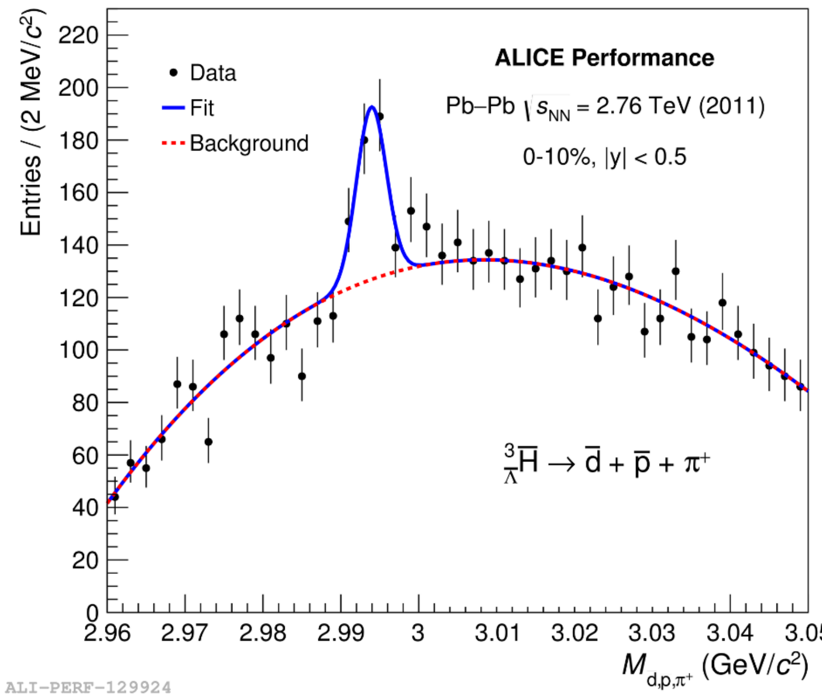
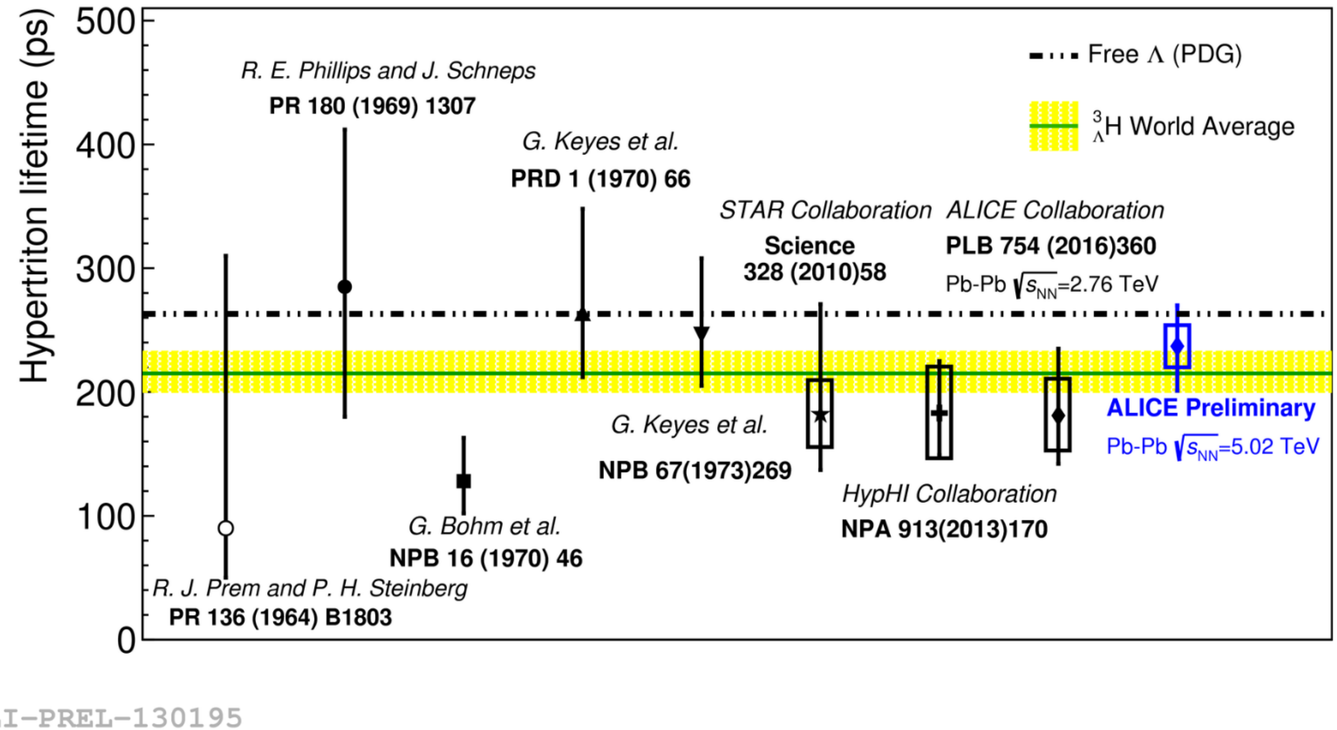




${}^{3}_{\Lambda}$H lifetime



free Λ lifetime (PDG)
262 ± 2 ps

${}^{3}_{\Lambda}$H world average
216^{+16}_{-19} ps

- very small B_{Λ} (130 keV) led to the hypothesis that the ${}^{3}_{\Lambda}$H lifetime is slightly below the free Λ
- few theoretical predictions available
  - first one by Dalitz and Rayet (1966) → τ range 239.5 – 255.5 ps
  - more recent by Congleton (1992) and Kamada (1998) → τ range 232 – 256 ps

- higher ALICE accuracy can be reached in the near future

→ latest 2018 Pb-Pb run is being analyzed and 3-body decay channel may also help

… few words about the upgrade

ALICE has started a huge upgrade in preparation for LHC Run3 and Run4
→ expected Pb-Pb $\int\mathcal{L}$ = 10 nb^{-1} at 50 kHz collision rate

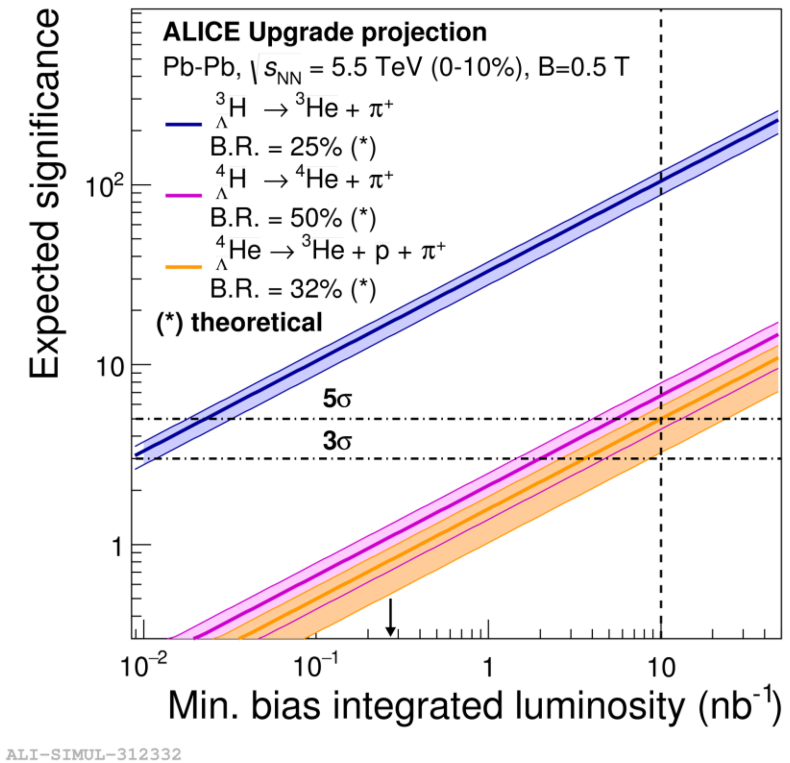
Citron et al., arXiv:1812.06772 [hep-ph] 25 Feb 2019

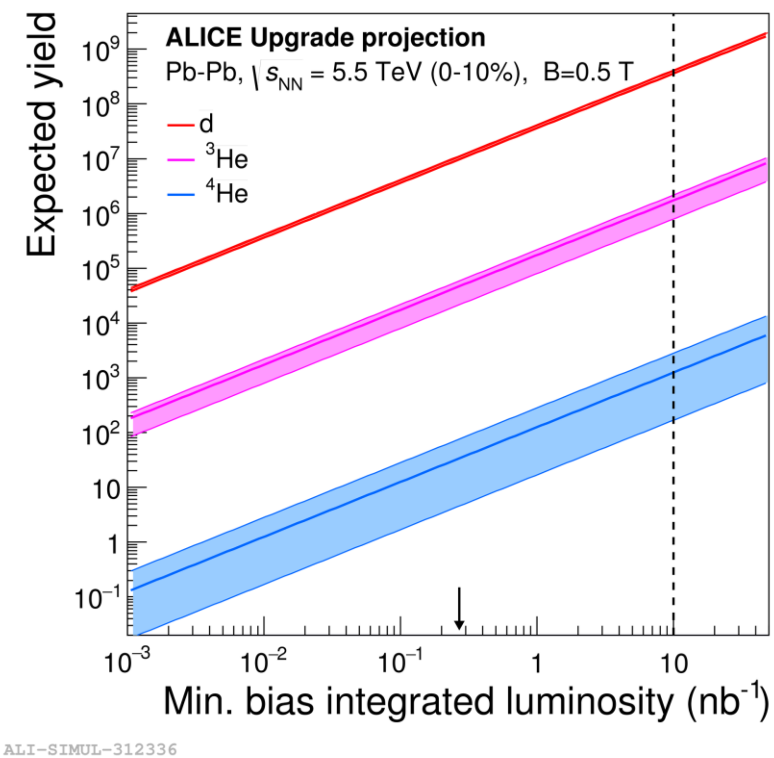
Quantity	design	achieved				upgrade
Year	(2004)	2010	2011	2015	2018	$\geq$2021
Weeks in physics	-	4	3.5	2.5	3.5	-
Fill no. (best)		1541	2351	4720	7473	-
Beam energy $E[Z\ \mathrm{TeV}]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\ \mathrm{TeV}]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{\mathrm{NN}}}$ [TeV]	5.52	2.51		**5.02**	**5.02**	5.52
Bunch intensity N_b [10^8]	0.7	1.22	1.07	2.0	2.2	1.8
No. of bunches k_b	592	137	338	518	733	1232
Pb norm. emittance ϵ_N [μm]	1.5	2.	2.0	2.1	2.0	1.65
Pb bunch length σ_z m	0.08	0.07–0.1				0.08
β^* [m]	0.5	3.5	1.0	0.8	0.5	0.5
Pb stored energy MJ/beam	3.8	0.65	1.9	8.6	13.3	21
Luminosity L_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	0.03	0.5	3.6	6.1	7
NN luminosity L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$\boxed{43}$	1.3	22.	156	$\boxed{264}$	$\boxed{303}$
Integrated luminosity/experiment [$\mu\mathrm{b}^{-1}$]	1000	9	160	433,585	900,1800	10^4
Int. NN lumi./expt. [pb^{-1}]	43	0.38	6.7	19,25.3	39,80	4.3×10^5

… few words about the upgrade

ALICE has started a huge upgrade in preparation for LHC Run3 and Run4
→ expected Pb-Pb $\int\mathcal{L}$ = 10 nb^{-1} at 50 kHz collision rate

Possibility to investigate A=4 (anti-)hypernuclei and A=5 (anti)nuclei and improve accuracy for A=3 (hyper)nuclei





Citron et al., arXiv:1812.06772 [hep-ph] 25 Feb 2019

Conclusions

Unique tracking/PID capability of ALICE allows one to clearly identify **light nuclei and anti-nuclei at the LHC energies**

Thermal statistical model describes reasonably well not only hadrons but also **loosely bound objects**

Validity of hadron-coalescence models tested at LHC
→ it is clear now that we need refined models
to fully account for observations

Valuable **inputs** (B_2 and B_3) **for Astroparticle Physics provided**

One of the most **accurate** $^{3}_{\Lambda}\mathrm{H}$ **lifetime** measurement **reported**

Possibility to **look for rarer anti-nuclei signals** and to improve accuracy for A=3 (hyper)nuclei in the **future LHC runs**

Thanks for your attention

Backup

LHC runs

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	2018	5.02	~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

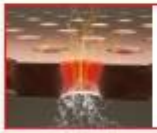
ALICE in Run 3 and Run 4

New Inner Tracking System (ITS)

- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

New Muon Forward Tracker (MFT)

- CMOS Pixels, MAPS technology
- Vertex tracker at forward rapidity



New TPC Readout Chambers (ROCs)

- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

New Fast Interaction Trigger detector (FIT)

- Centrality, event plane

FoCal proposal (Run 4)

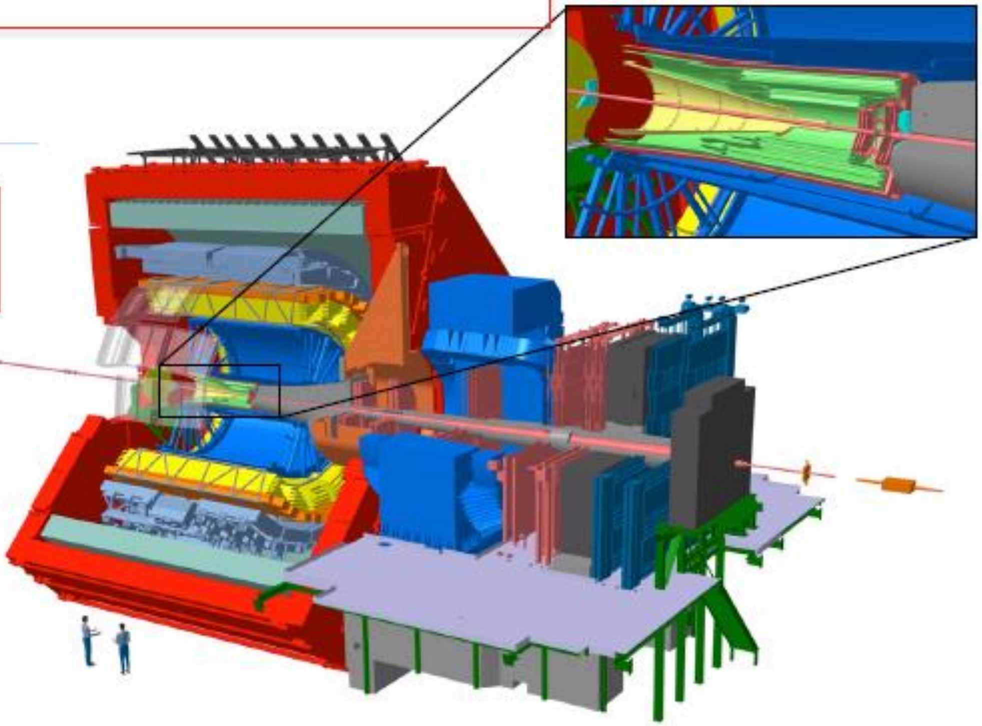
- Measure forward direct photons

Readout upgrade

- TOF, TRD, MUON, ZDC, Calorimeters

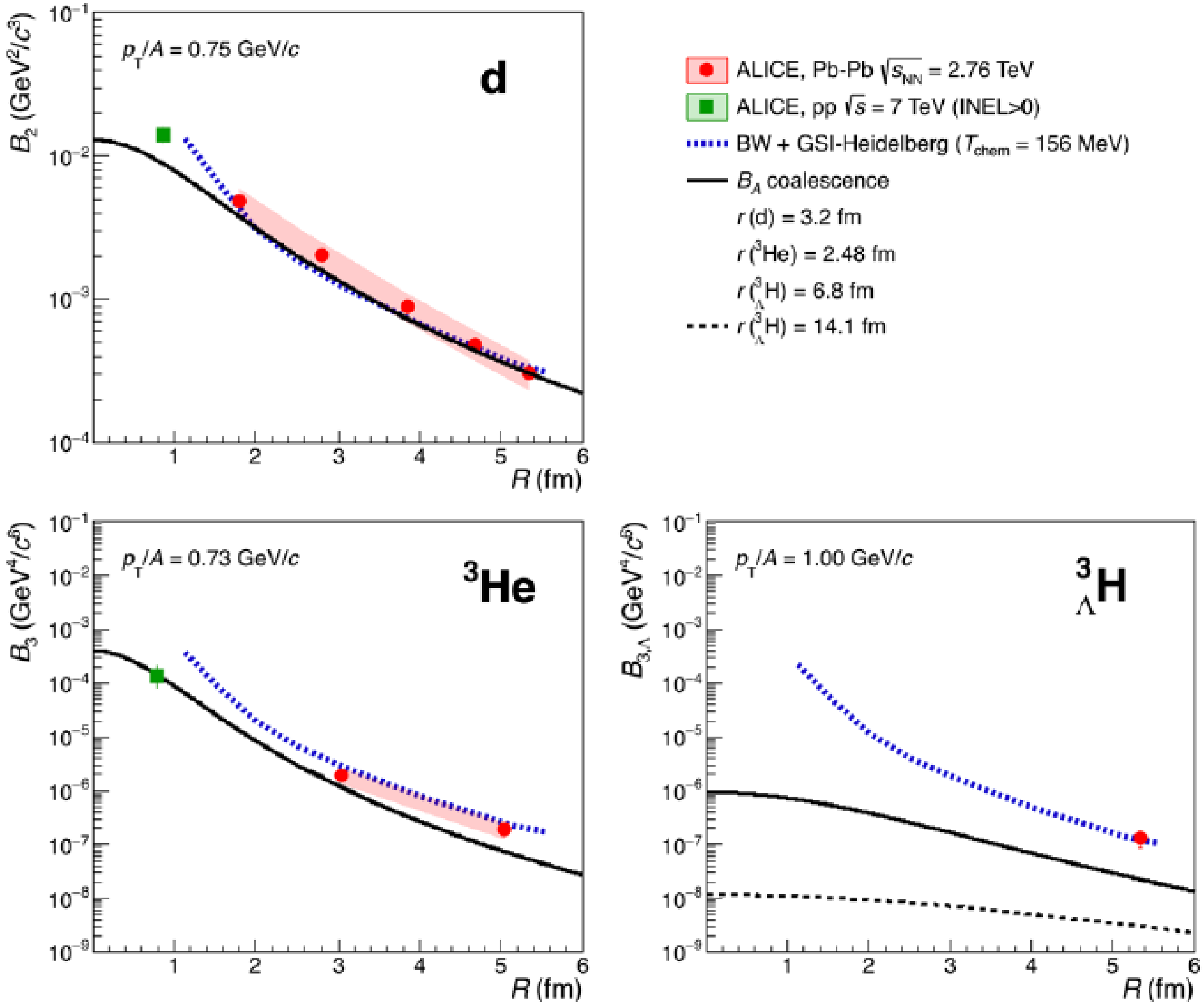
Integrated Online-Offline system (O^2)

- Record MB Pb-Pb data at 50 kHz

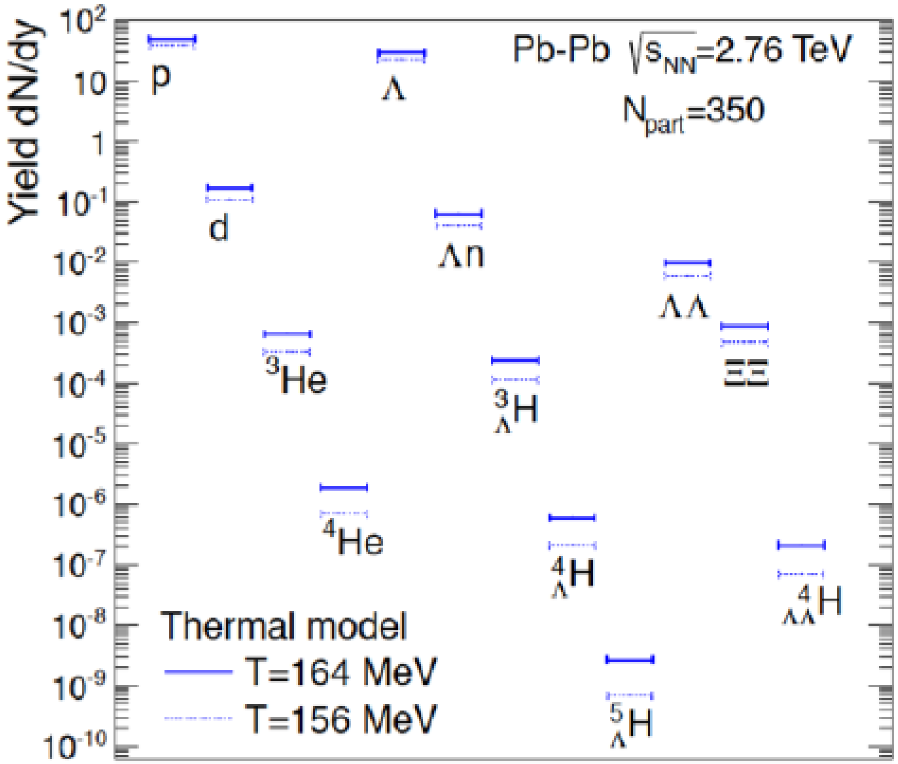


Still on coalescence

Bellini, Kalweit, arXiv:1807.05894v1 [hep-ph]



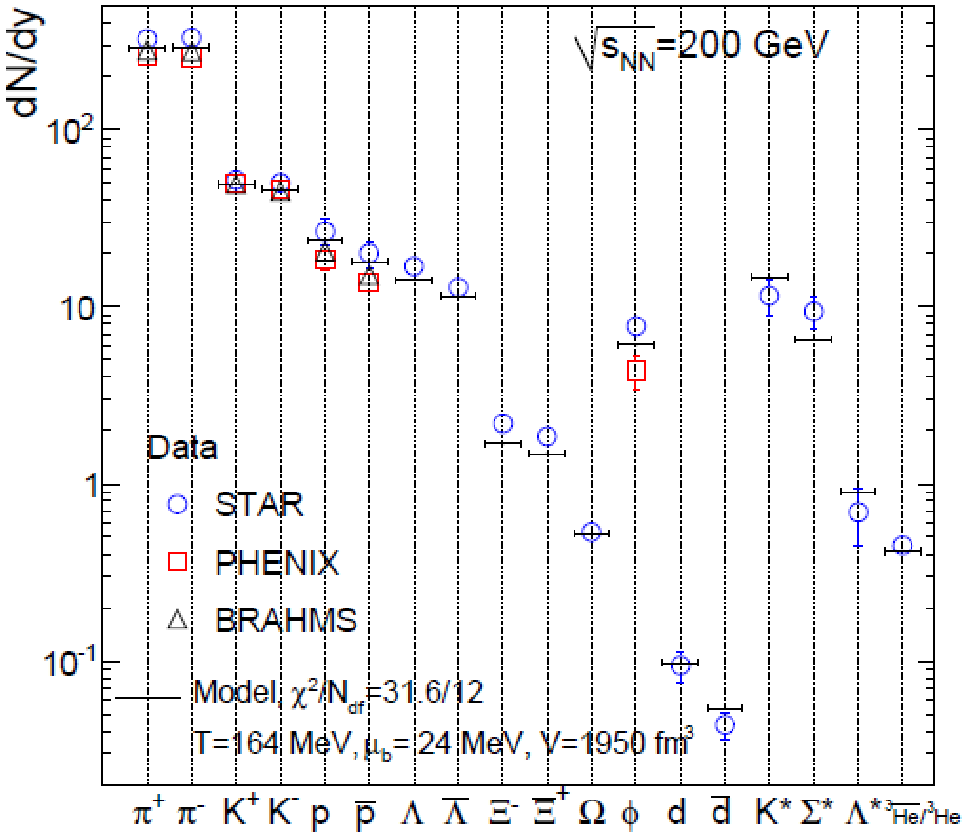
Thermal model expectations



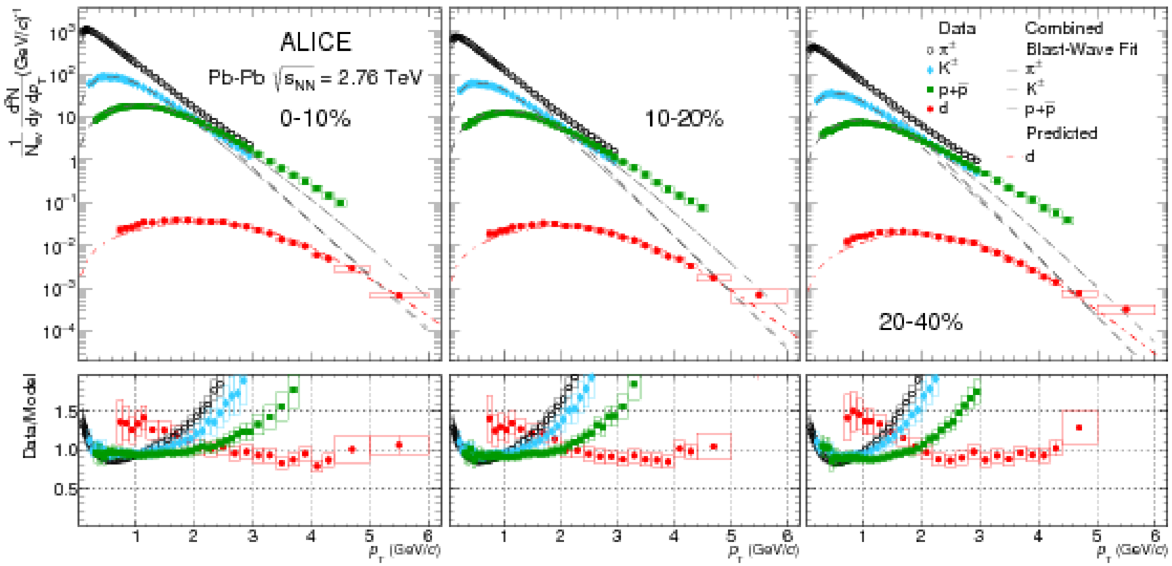
A.Andronic, private communication, model described in Andronic *et al.*, PLB 697, 203 (2011) and references therein

Thermal model in STAR

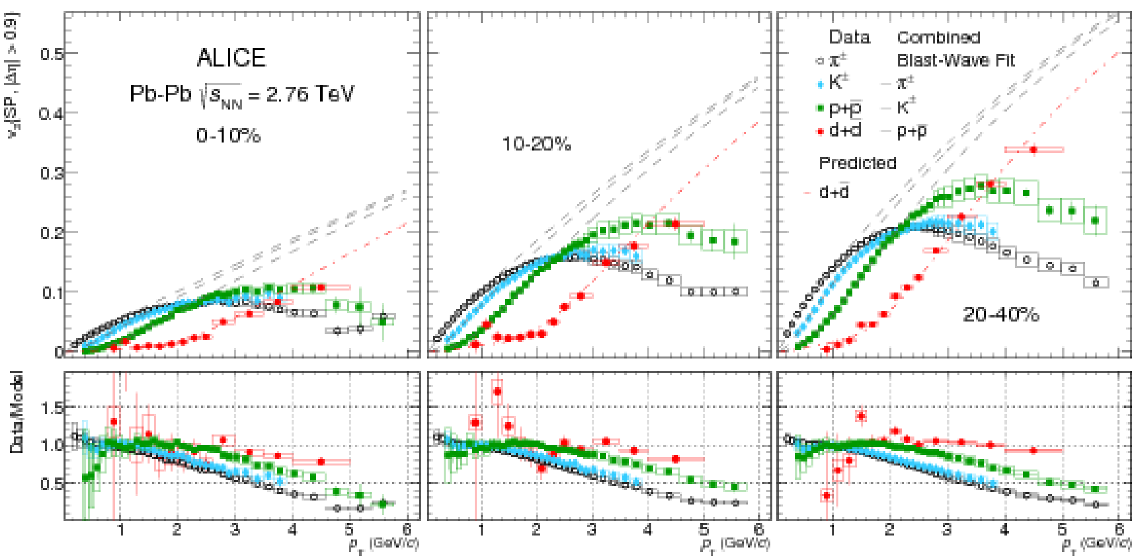
Andronic et al, PLB 697 (2011) 203



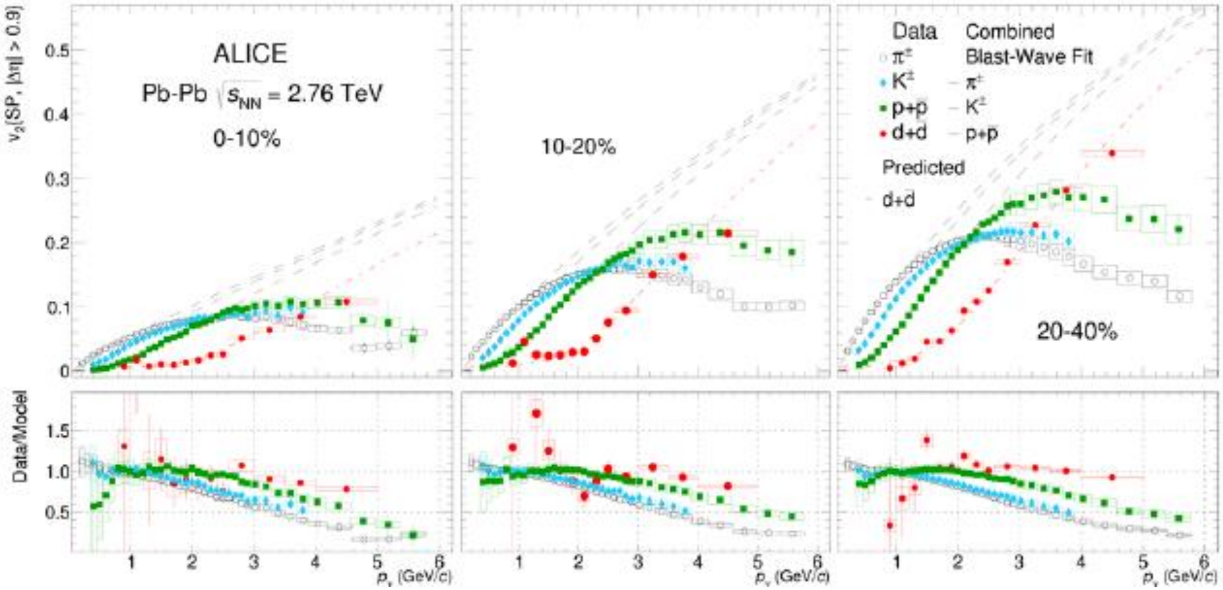
More on BW in Pb-Pb

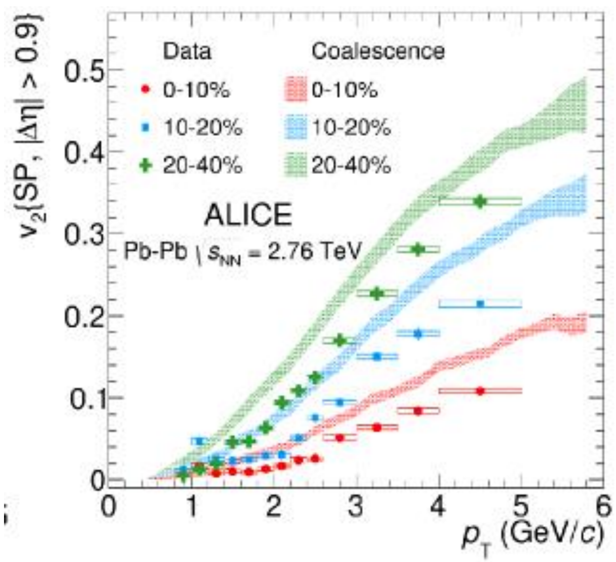


ALICE, EPJ. C77 (2017) 658

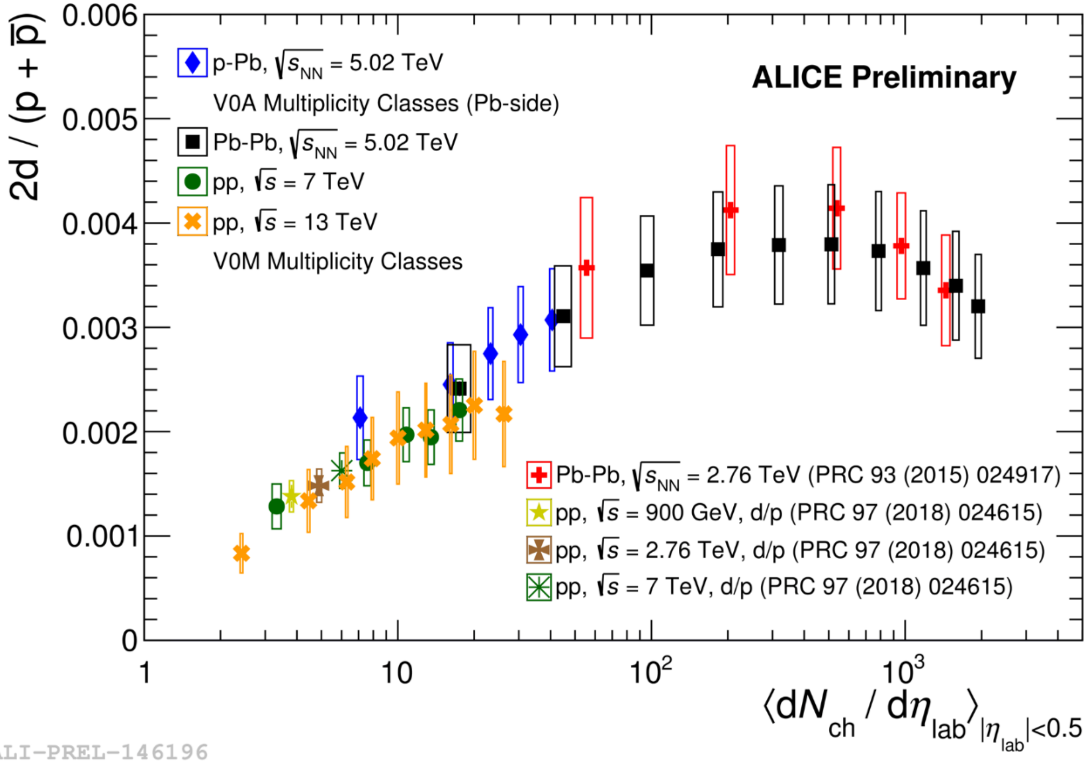


deuteron flow in Pb-Pb





deuteron/proton ratio



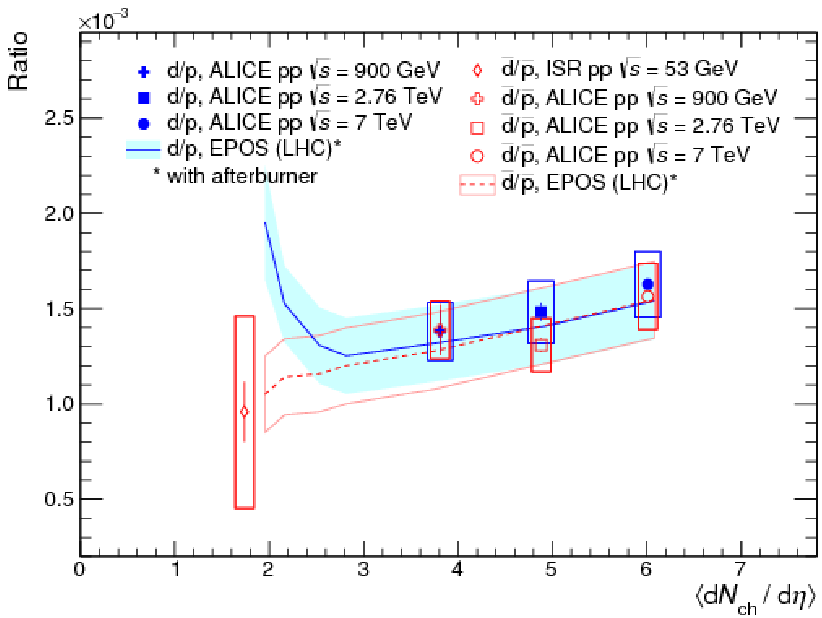
d/p higher for about a factor 2 in Pb-Pb w.r.t pp

d/p increases with multiplicity from pp to peripheral Pb-Pb

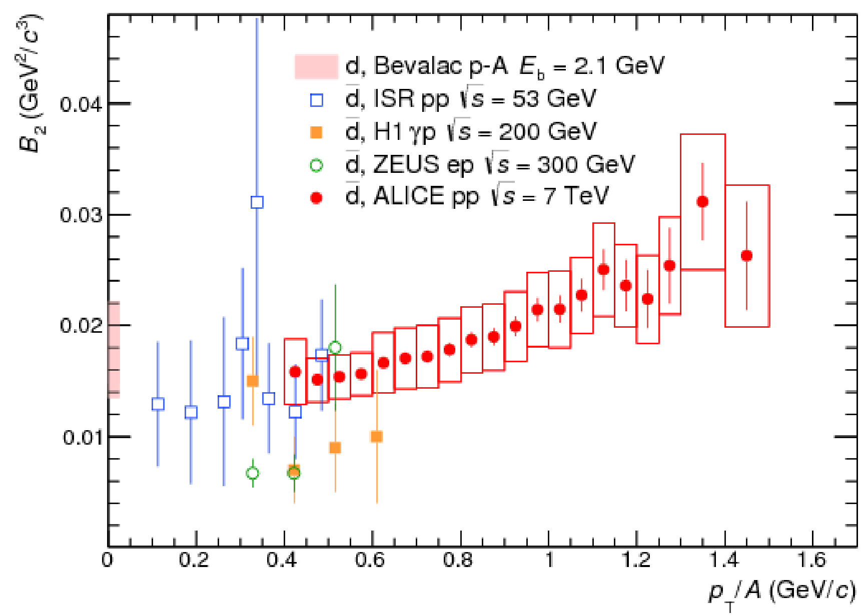
→ trend explained in Coalescence approaches as a result of enhanced **nucleon** multiplicity/**density**

thermal model predicts a flat ratio in central Pb-Pb → **work in progress for estimating correlation in uncertainties**

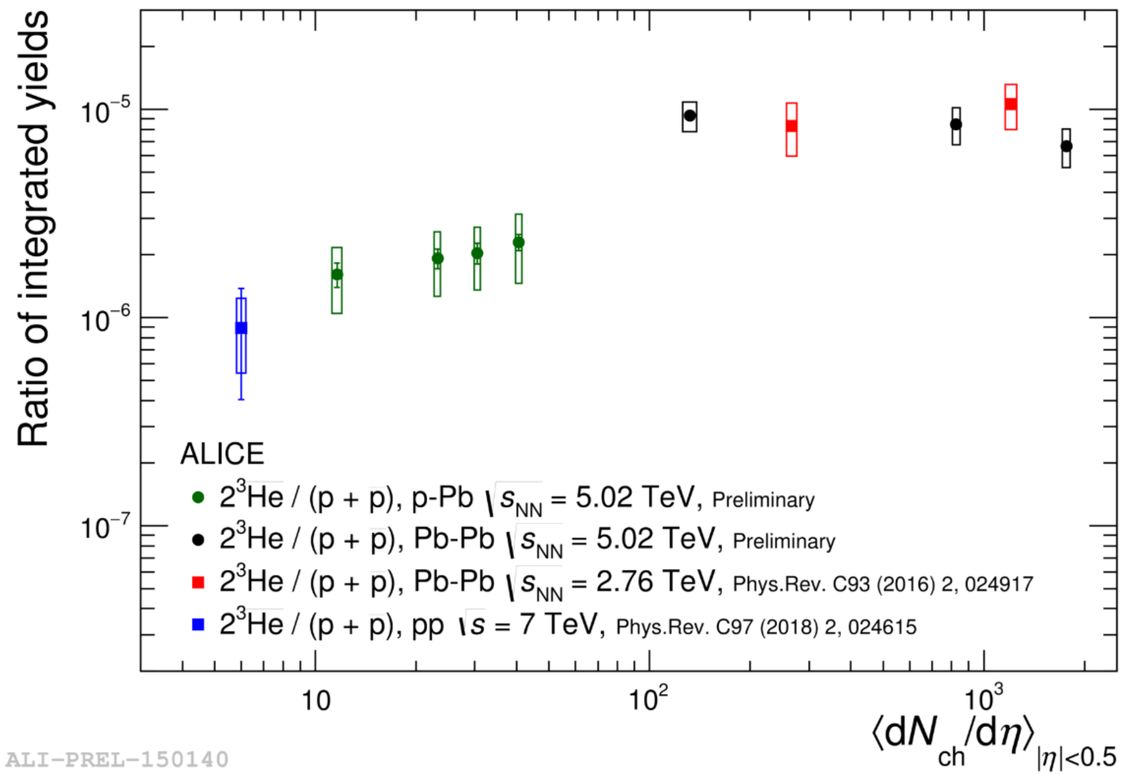
Lower energies



ALICE, PRC 97 (2018) 024615



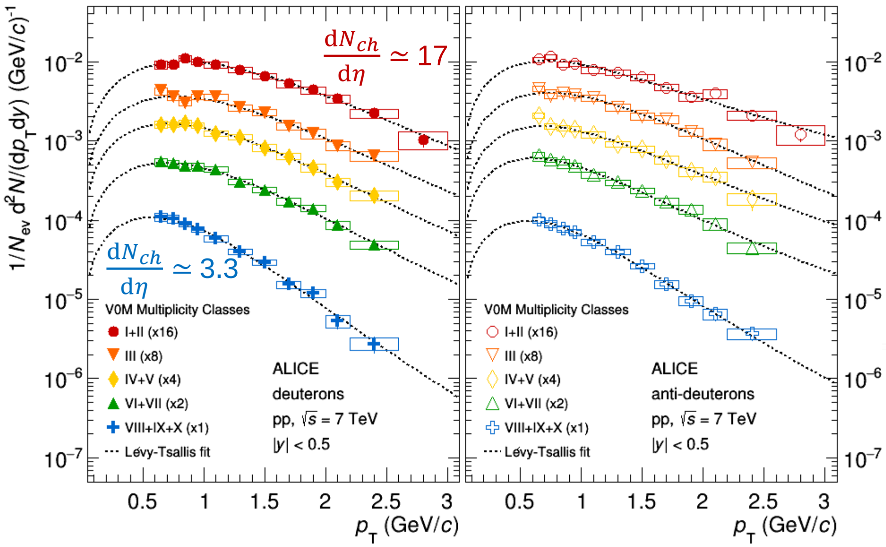
^{3}He/p ratio

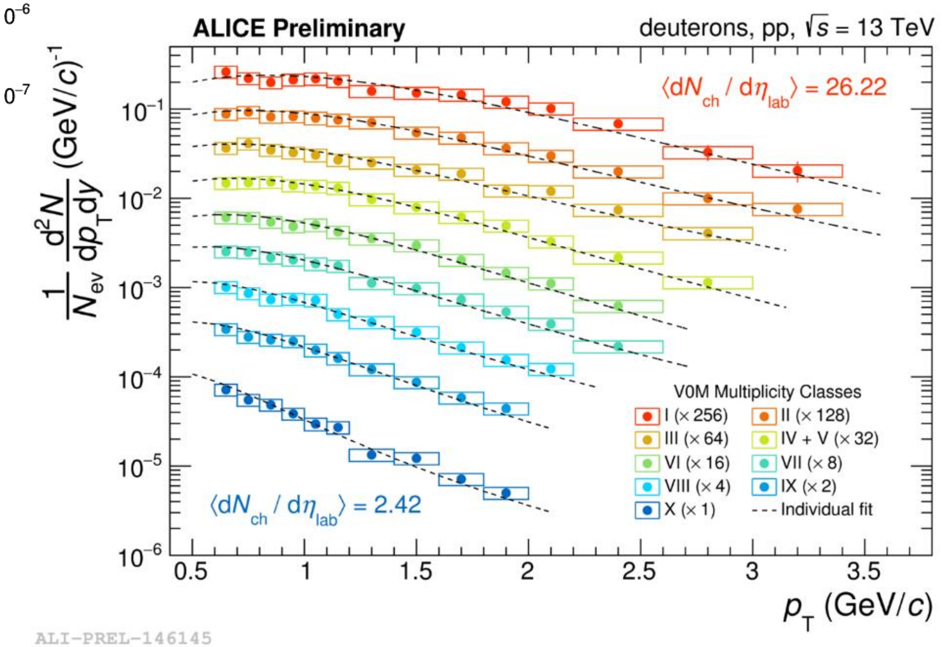


$$\frac{A}{p} \propto p^A$$

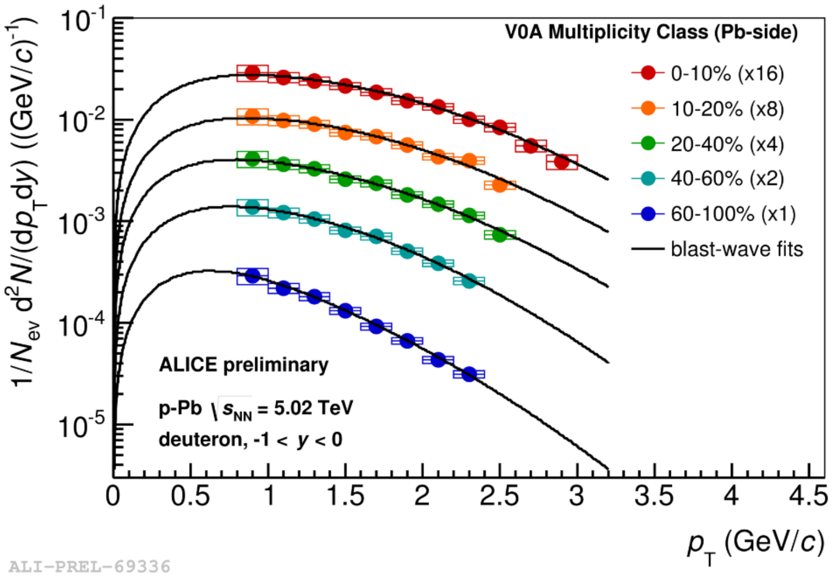
p_T spectra vs multiplicity (pp)

ALICE, arXiv:1902.09290v1 [nucl-ex] 25 Feb 2019
submitted to PLB





Deuterons and ^{3}He (p-Pb)



Blast-Wave PRC 48 (1993) 2462

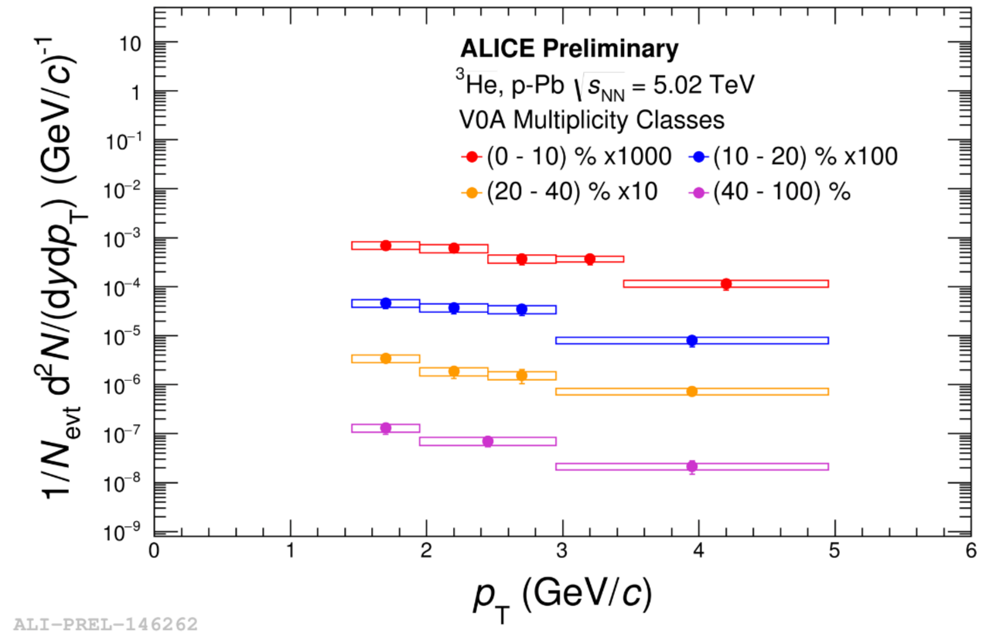
inspired hydrodynamic model describing lighter hadron spectra in p-Pb

→ used for extrapolating deuteron spectra in the unmeasured low/high p_T regions

First multiplicity dependent results of (anti-)^{3}He in p-Pb

2016 $\sqrt{s_{NN}}$ = 5.02 TeV data sample

(x 5 available 2013 statistics)



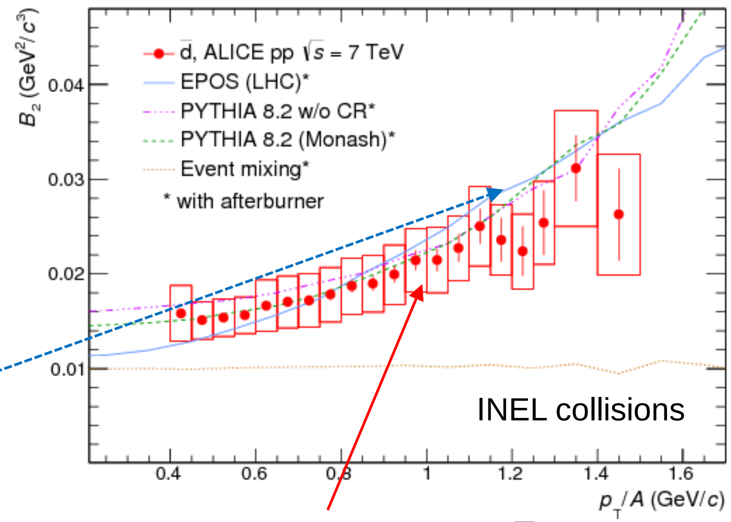
Testing Coalescence models

Still on p_T dependence

when integrating over all multiplicities B_2 is observed to increase with p_T

result was reproduced by QCD-inspired event generators (PYTHIA/EPOS)
+ coalescence-based afterburner
model accounting for correlations between nucleons

ALICE, PRC 97 (2018) 024615

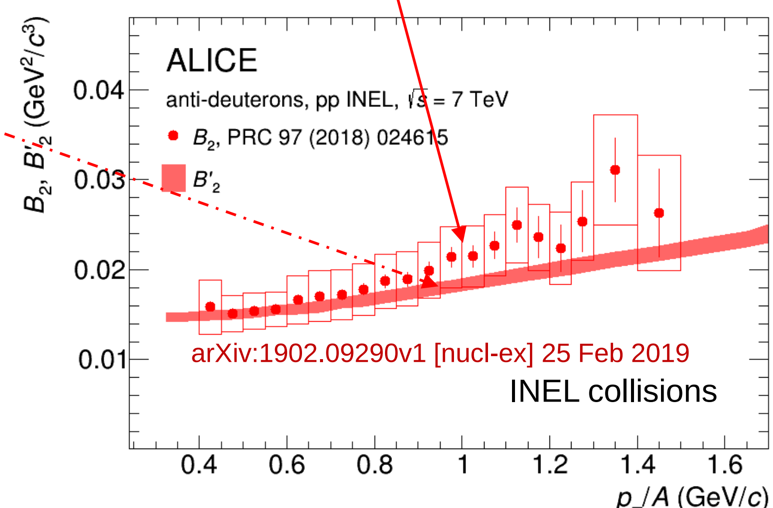


anti-deuterons, pp $\sqrt{s}$ = 7 TeV

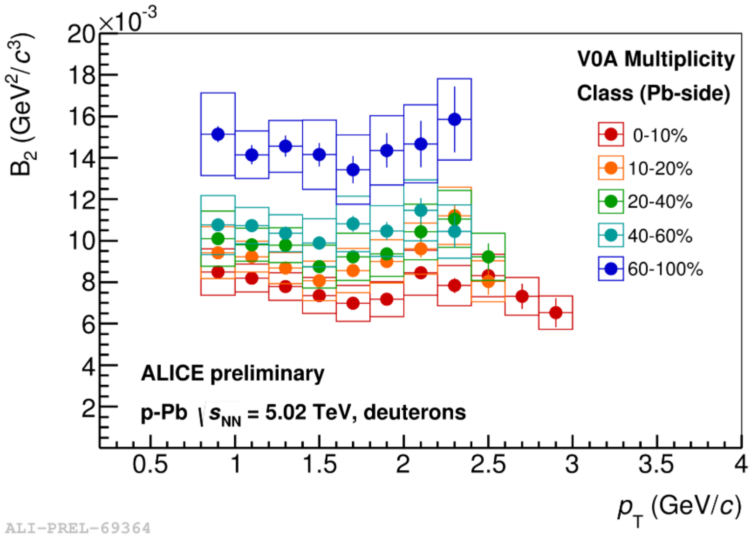
Simple Coalescence
also predicts observed trend

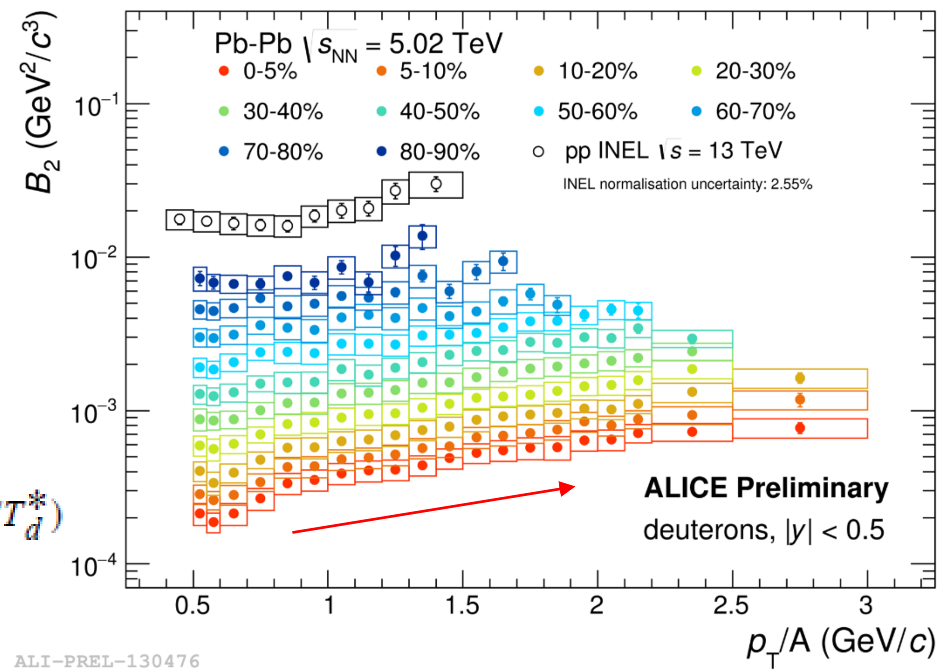
→ **evolution of the primary proton spectra across multiplicity can also explain the result**

→ no need to introduce hard scattering effects



B_2 (p-Pb and Pb-Pb)



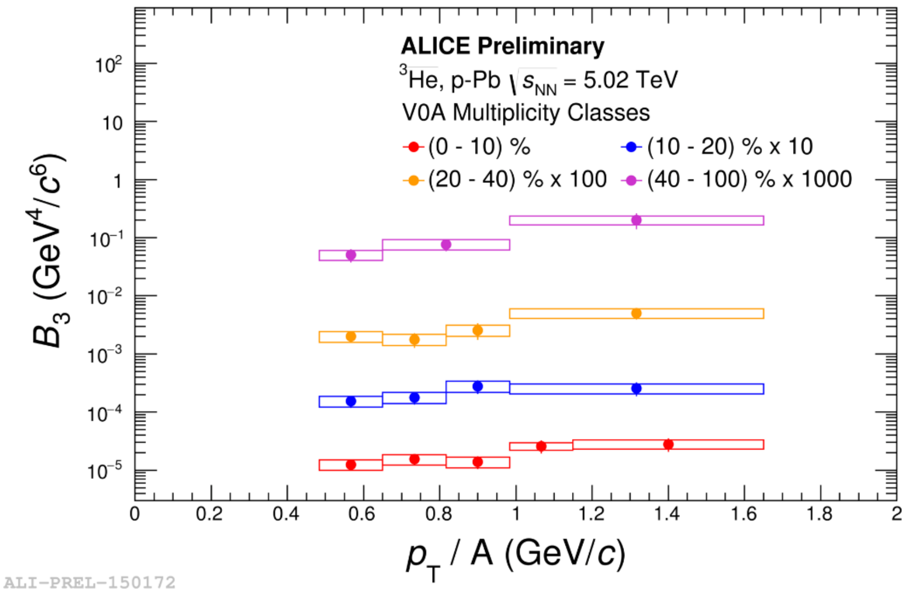


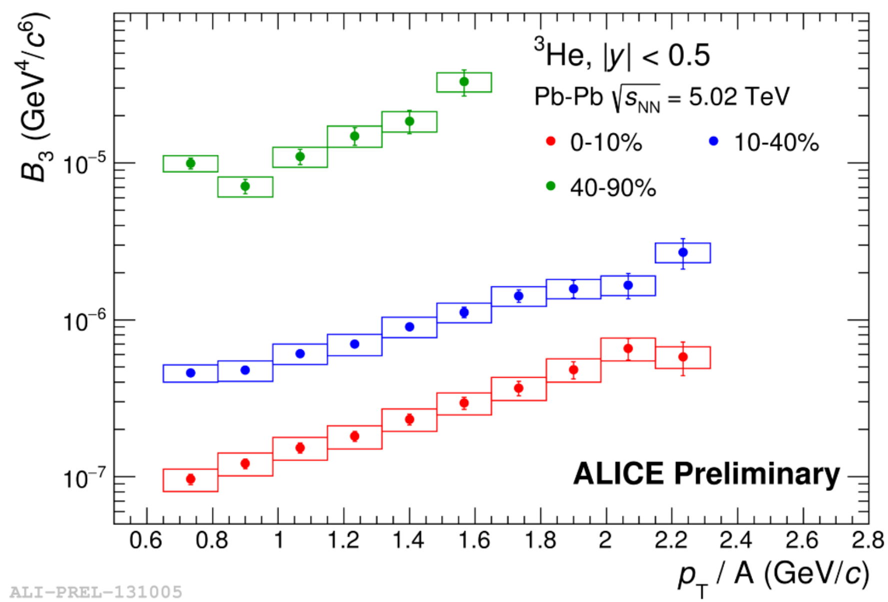
Scheibl and Heinz, PRC 59 (1999) 1585

$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2 m_t \mathcal{R}_\perp^2(m_t)\mathcal{R}_\parallel(m_t)} e^{2(m_t - m)(1/T_p^* - 1/T_d^*)}$$

more boxlike transverse density profiles are preferred in heavy-ion collisions…

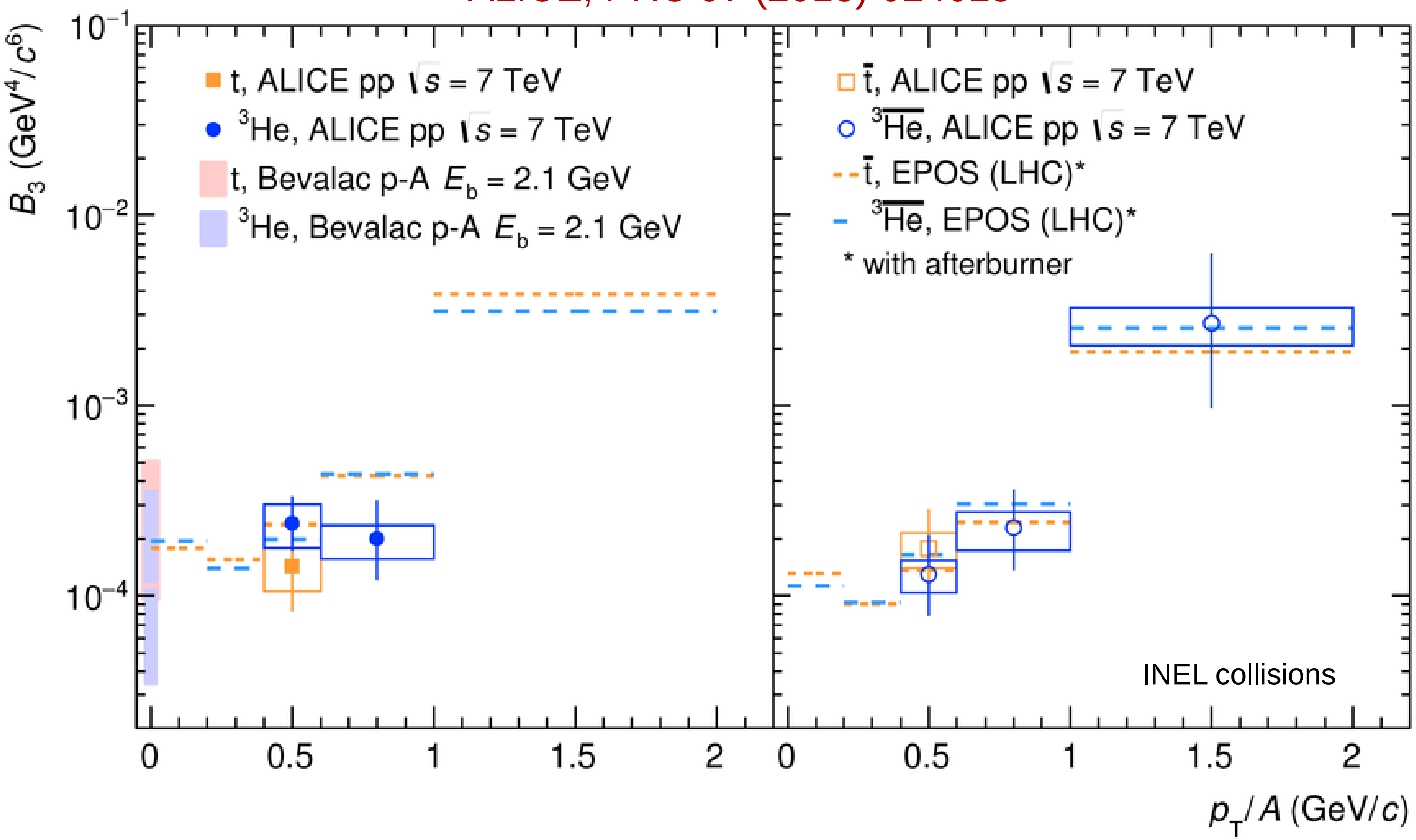
B_3 (p-Pb and Pb-Pb)





Coalescence parameter B_3

ALICE, PRC 97 (2018) 024615



→ **First ever determination of B_3 of (anti-)^{3}He and (anti-)tritons in pp collisions**

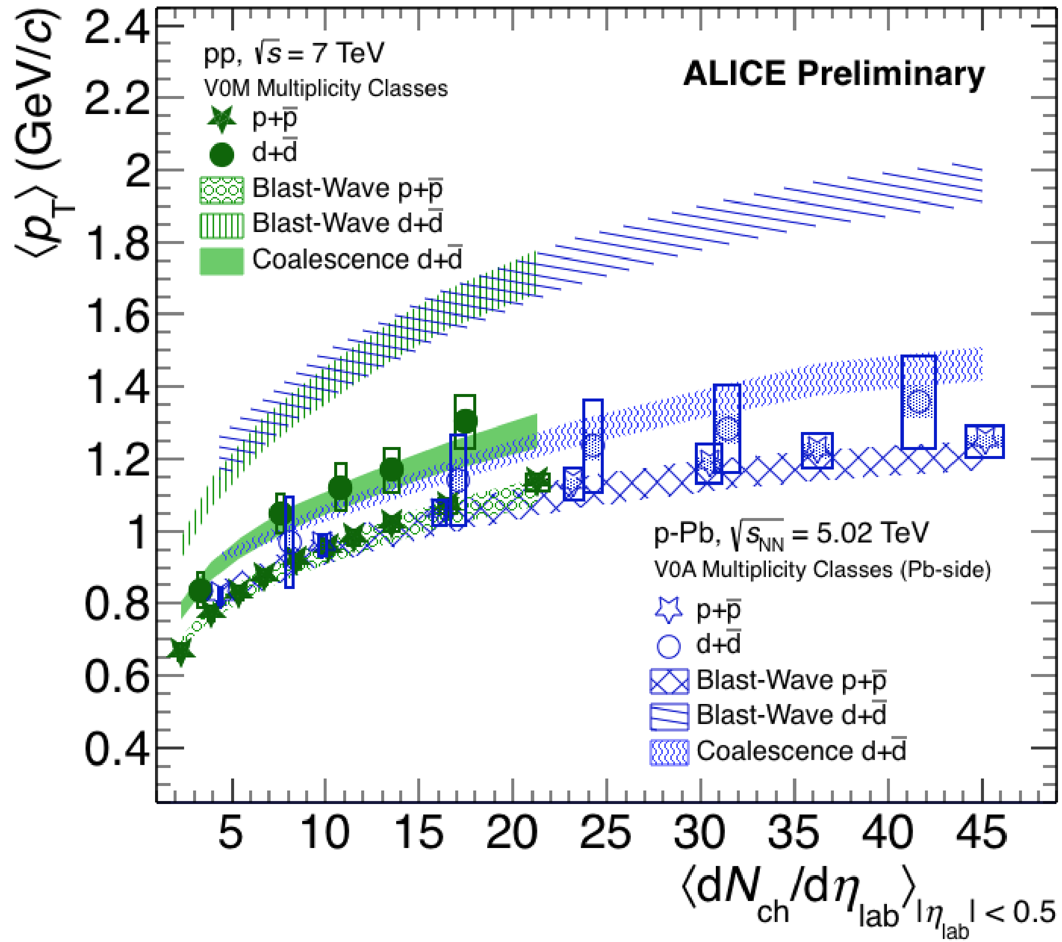
Testing Blast-Wave model

Deuteron mean transverse momentum $\langle p_T \rangle$

Hardening of deuteron spectra with multiplicity observed, protons as well

$\langle p_T \rangle$ of deuterons and protons found to be compatible in p-Pb (only)

→ fully hydrodynamic-inspired approach (**Blast-Wave**) **doesn't describe simultaneously nuclei and lighter hadrons** production in pp and p-Pb



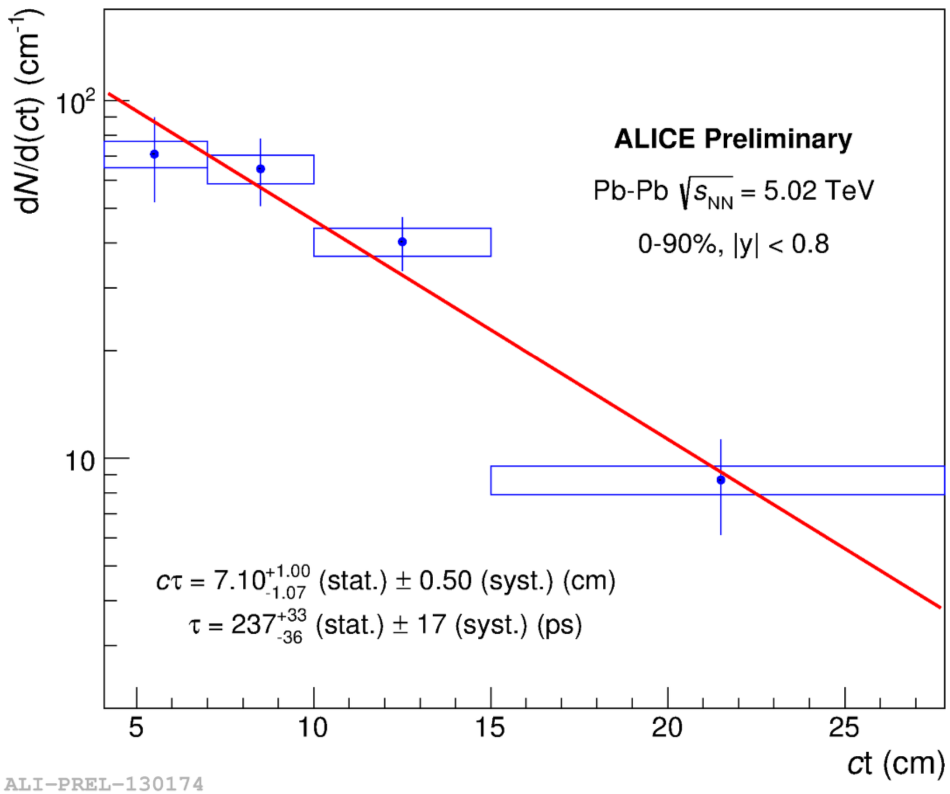
different scenario in Pb-Pb

BW fits concurrently d, ^{3}He and π/K/p

see ALICE Coll. PRC 93 (2015) 024917

Blast-Wave PRC 48 (1993) 2462: hydrodynamic-inspired model describing particle production assuming a radially expanding thermalized source

${}^{3}_{\Lambda}\mathrm{H}$ lifetime in ALICE

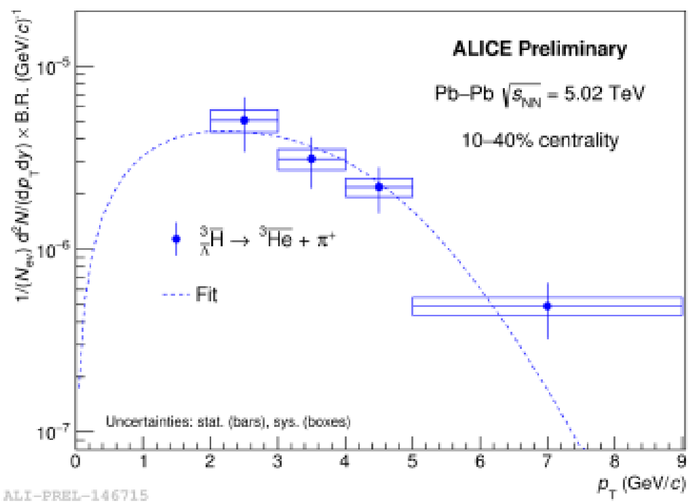


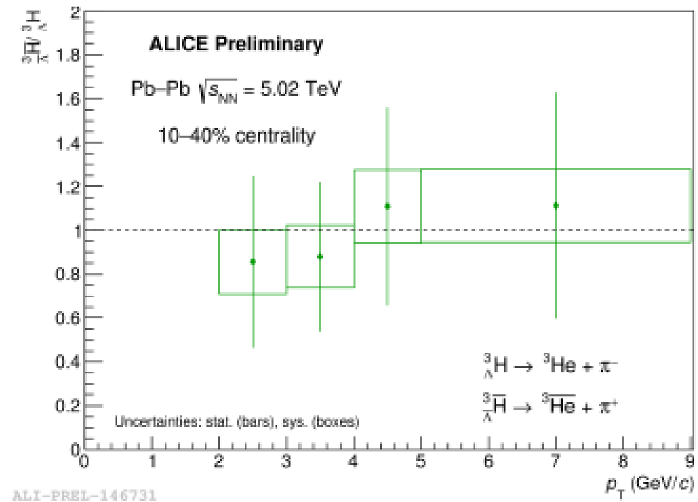
Fit to the corrected ${}^{3}_{\Lambda}\mathrm{H}$ dN/d(ct) spectrum for estimating the lifetime

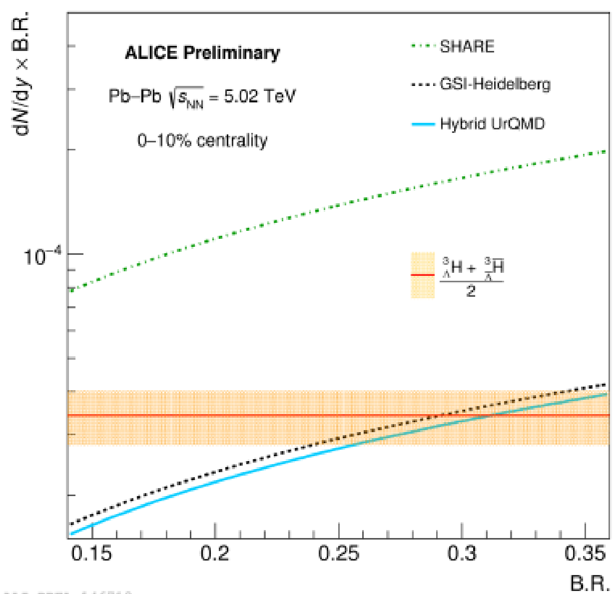
$$N(t) = N(0)\exp(-L/\beta\gamma c\tau)$$

where $c\tau = mLc/p$

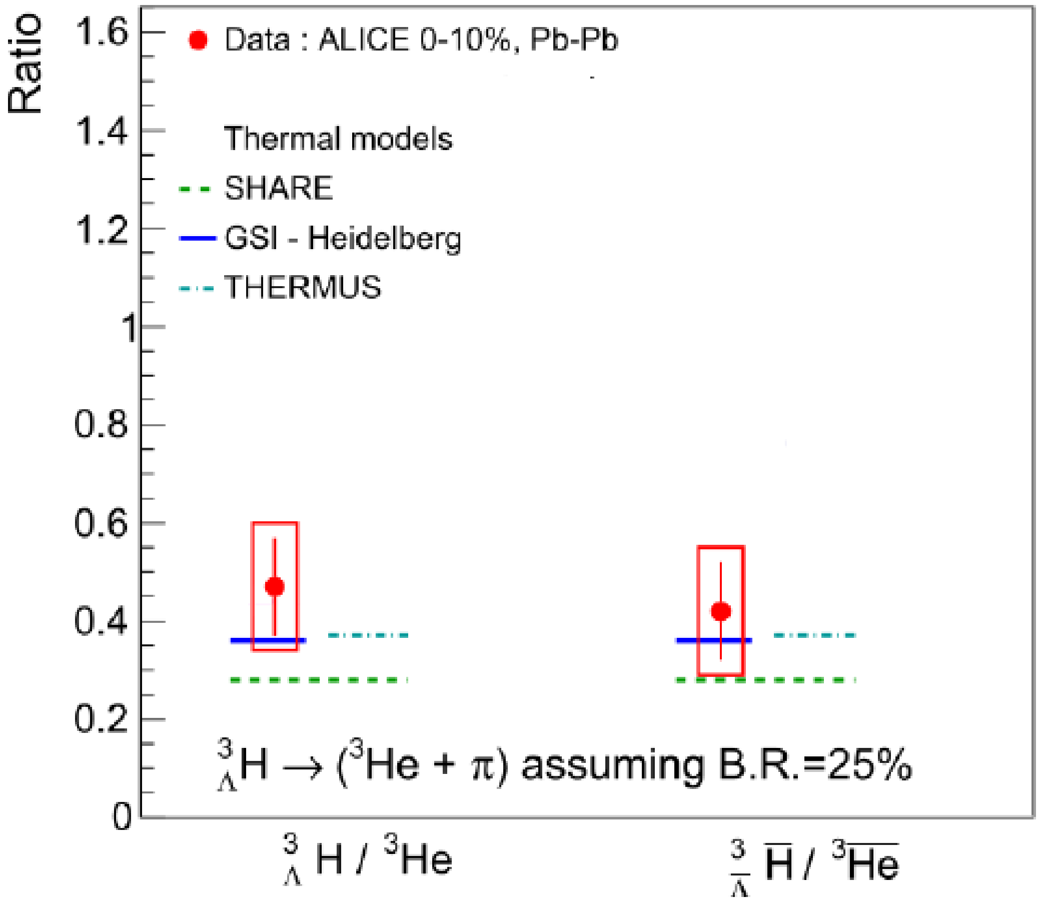
$^{3}_{\Lambda}$H spectra and yield







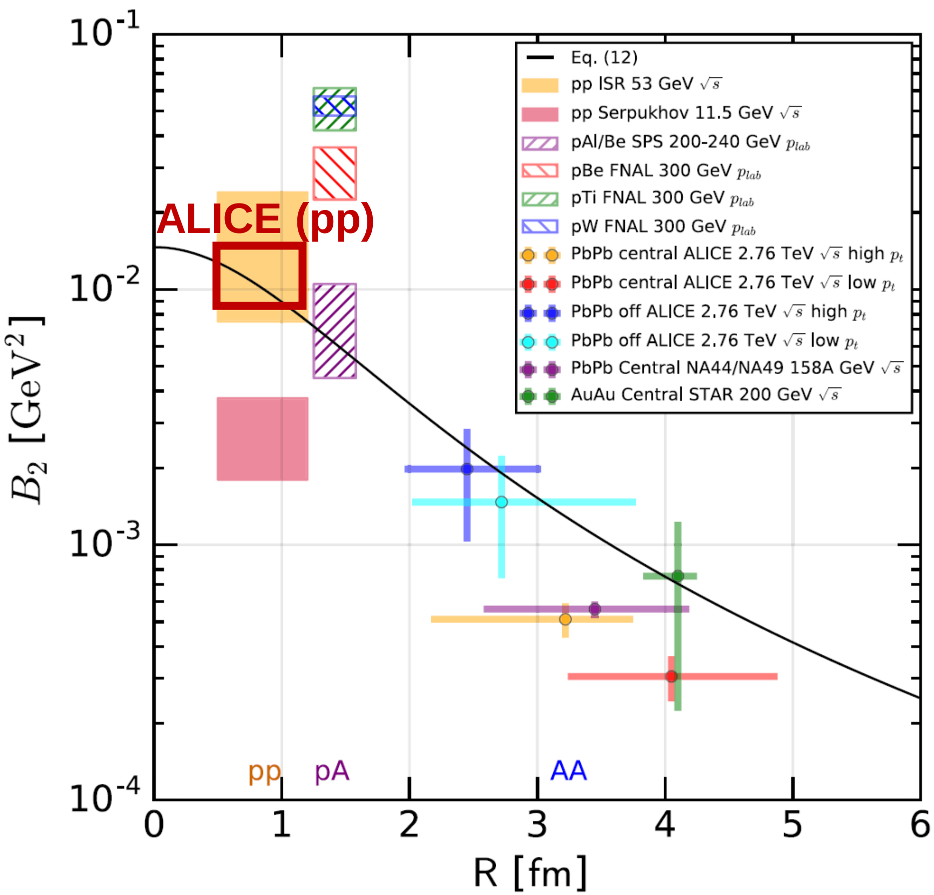
$^{3}_{\Lambda}\mathrm{H}$ / $^{3}\mathrm{He}$ ratio



in good agreement with (equilibrium) thermal model prediction for Tch = 156 MeV such as GSI-Heildeberg model

Andronic et al., Nature 561 (2018) 321

B_2



Blum et al., PRD 96 (2017) 103021

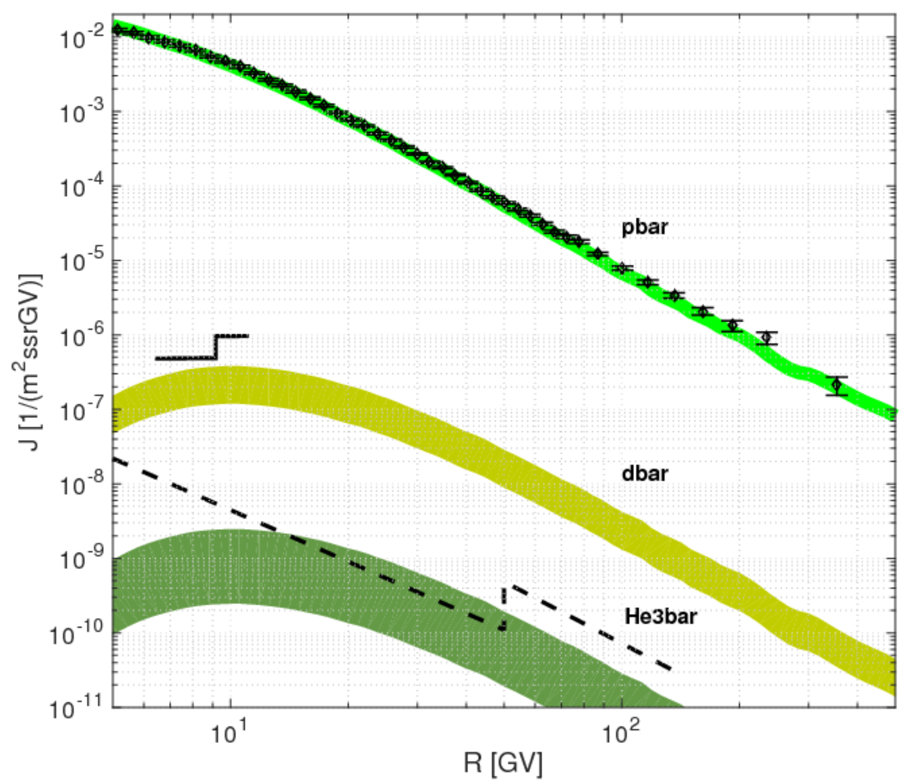
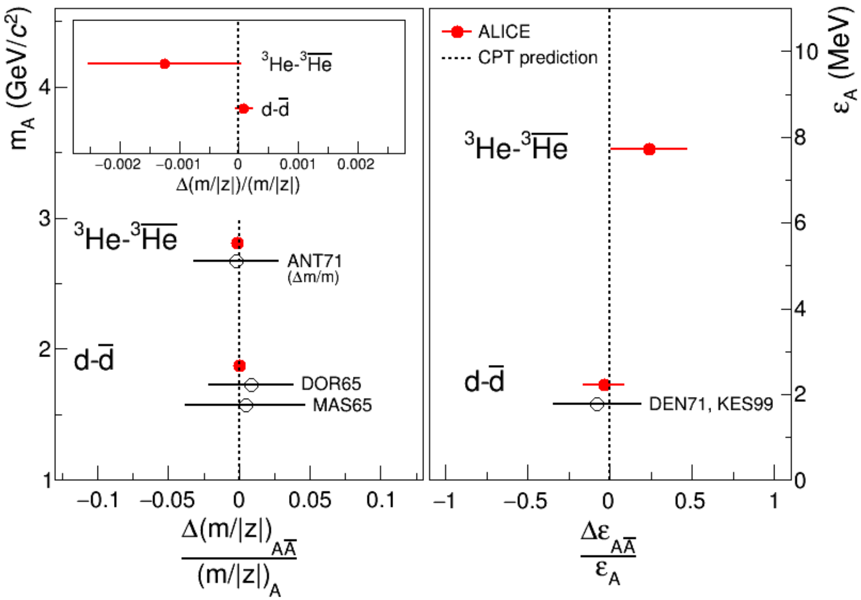
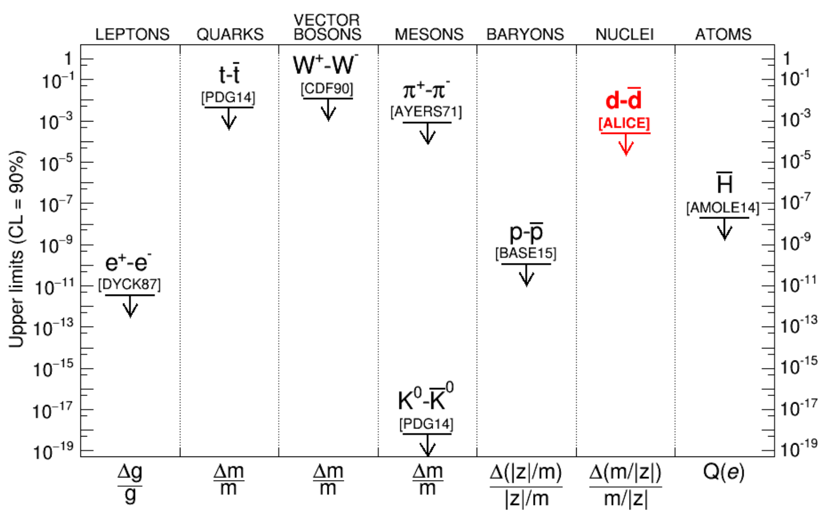


FIG. 1. Predicted flux of $\bar{p}, \bar{d}, \overline{^3\mathrm{He}}$. AMS02 $\bar{p}$ data are taken from Ref. [28]. AMS02 $\bar{d}$ flux sensitivity (5-yr, 95% C.L.) in the kinetic energy range 2.5–4.7 GeV/nuc, as estimated in Ref. [11], is shown by solid line. AMS02 $\overline{^3\mathrm{He}}$ flux sensitivity (5-yr, 95% C.L.), derived from the $\overline{^3\mathrm{He}}$/He estimate of Ref. [27], is shown by dashed line.

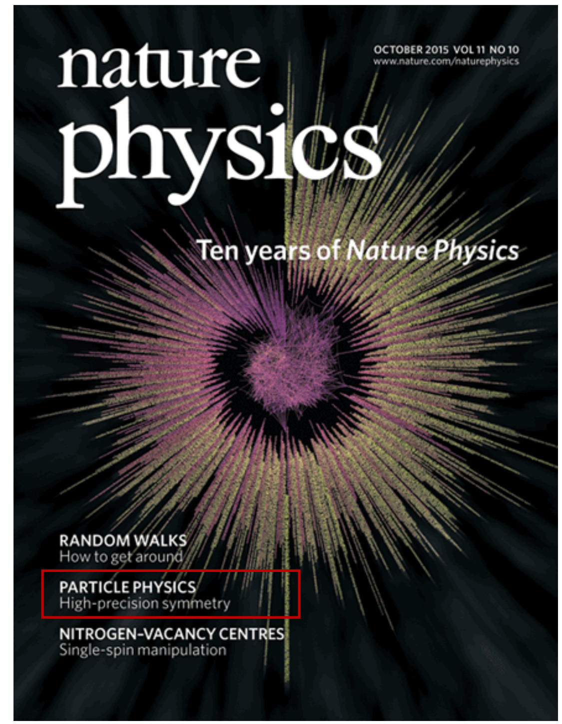
Rare CPT test provided

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





Mass difference nuclei/anti-nuclei constraints CPT symmetry in nucleon-nucleon interactions



→ these tests *independently* verify each *distinct* prediction of CPT symmetry