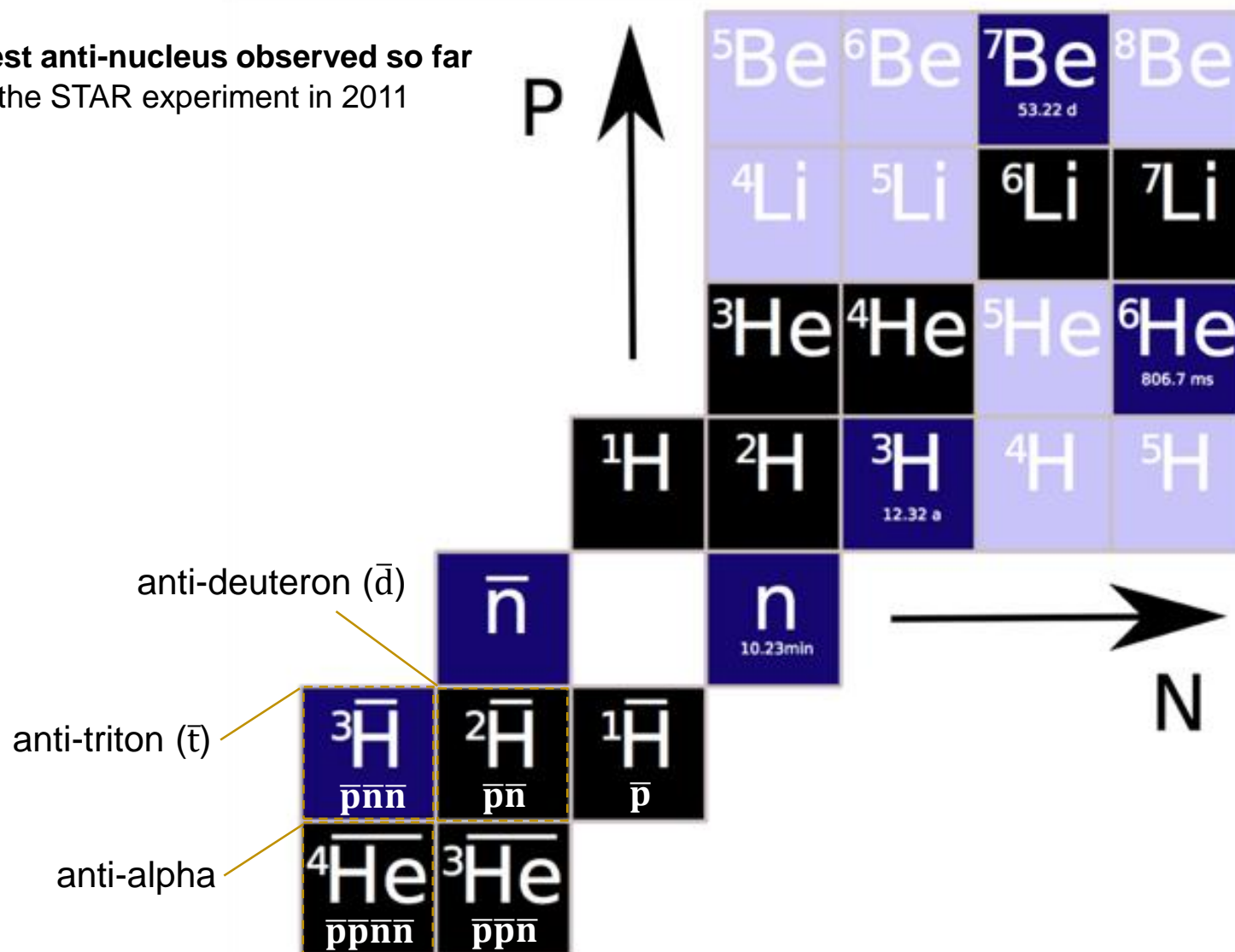# Production of light nuclei and anti-nuclei at the LHC

Manuel Colocci for the ALICE collaboration

University and INFN – Bologna (Italy)

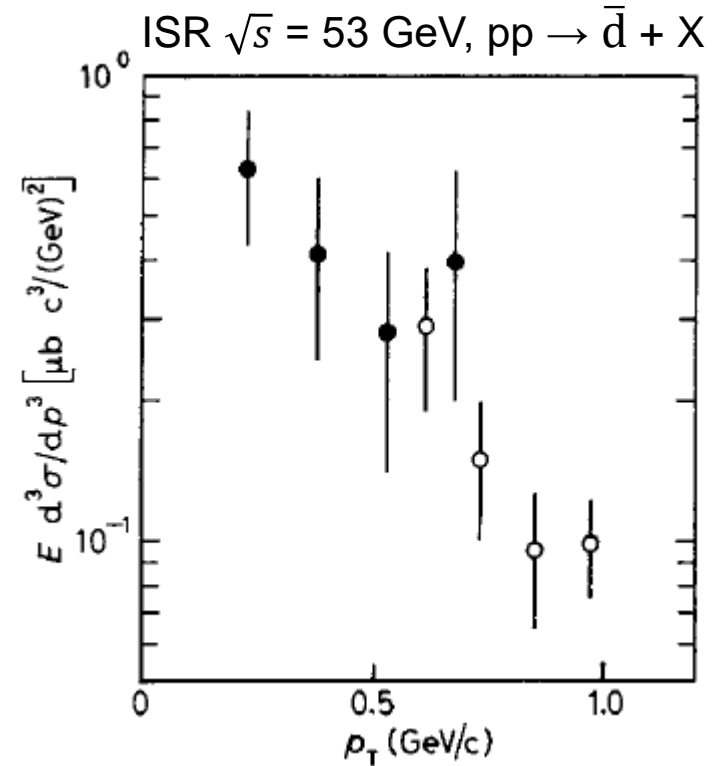# Light (anti-)nuclei chart

$^4\overline{\text{He}}$ is the heaviest anti-nucleus observed so far
Seen first by the STAR experiment in 2011

Why do we care so much?

Lack of experimental data in pp collisions

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

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

Lett. Nuovo Cim. 21 (1978) 198
Phys. Lett. 46B (1973) 265

Why do we care so much?

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- 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 Astroparticle Physics (e.g. AMS-02)

→ primordial anti-matter and Dark Matter searches

Nuclei probe last stages evolution of heavy-ion collisions

Testing fundamental symmetries

Search for strange matter

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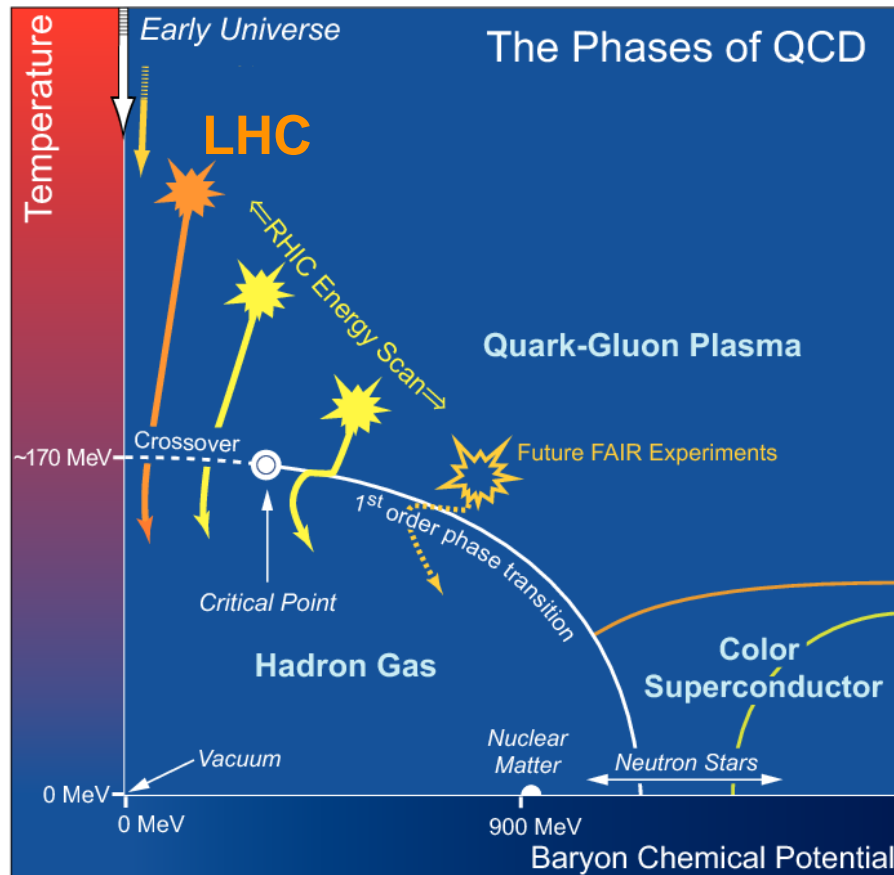
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Search for strange matter
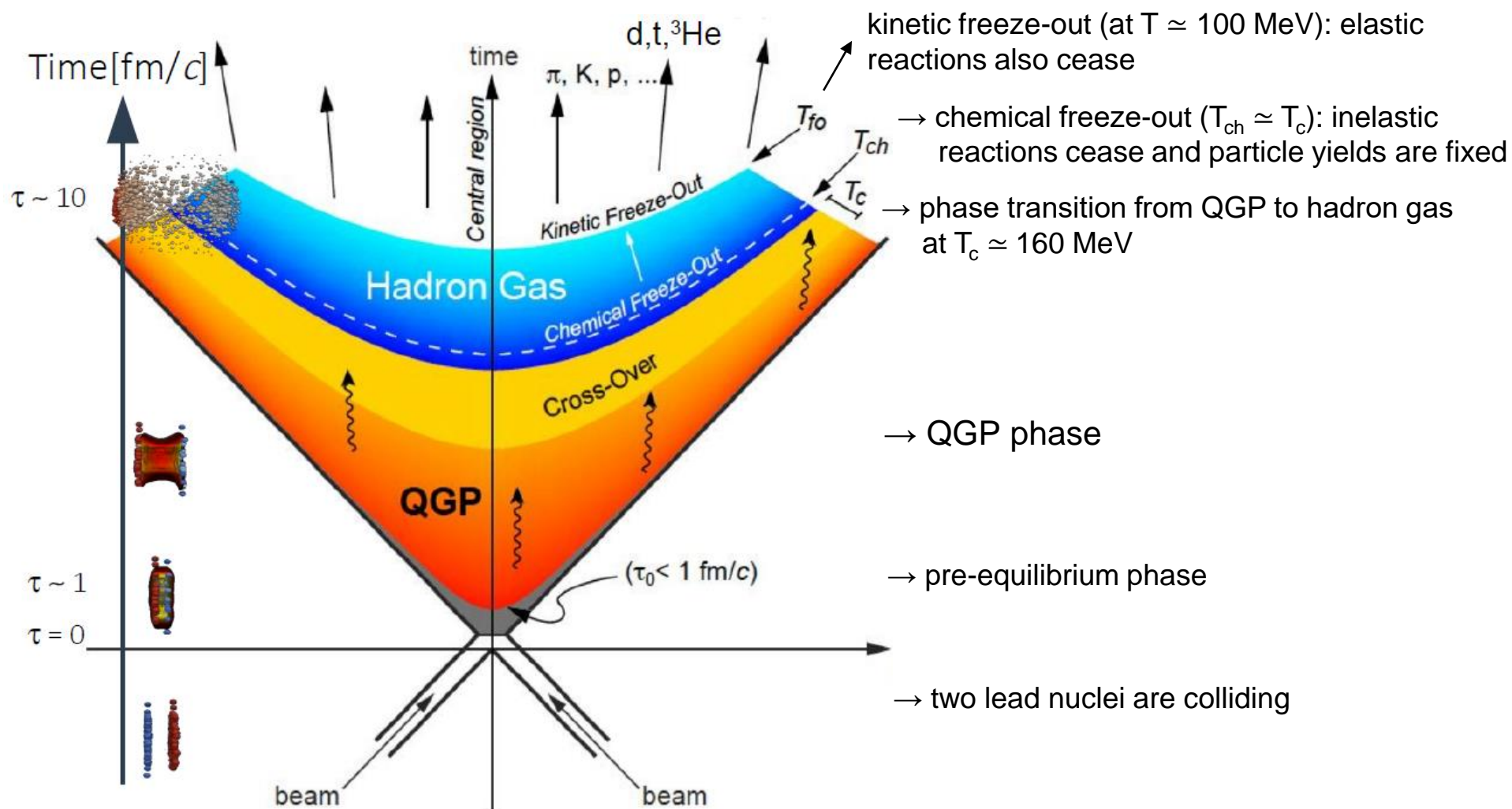
QCD phase diagram

The Phases of QCD

Heavy-ion collisions at the LHC produce very hot and dense nuclear matter

High temperature and low net baryon density at the LHC similar to those of **early universe**

In the **quark-gluon plasma (QGP)** the partons move freely over distances larger than the typical size of hadrons

Evolution of a heavy-ion collision

kinetic freeze-out (at T ≃ 100 MeV): elastic reactions also cease

→ chemical freeze-out (T_{ch} ≃ T_c): inelastic reactions cease and particle yields are fixed

→ phase transition from QGP to hadron gas at T_c ≃ 160 MeV

→ QGP phase

→ pre-equilibrium phase

→ two lead nuclei are colliding

Nuclei formation mechanisms

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 limiting temperature

- Abundances fixed at the chemical freeze-out

- Abundances $\propto \exp(-m/T_{ch})$

   → **strong sensitivity of nuclei (large m) on T_{ch}**

- Nuclei are loosely bound objects ("snowballs in hell")

   → nuclei might dissociate in the hadronic phase and re-formed later via coalescence

Coalescence

Nuclei form by coalescence of final-state nucleons after the kinetic freeze-out

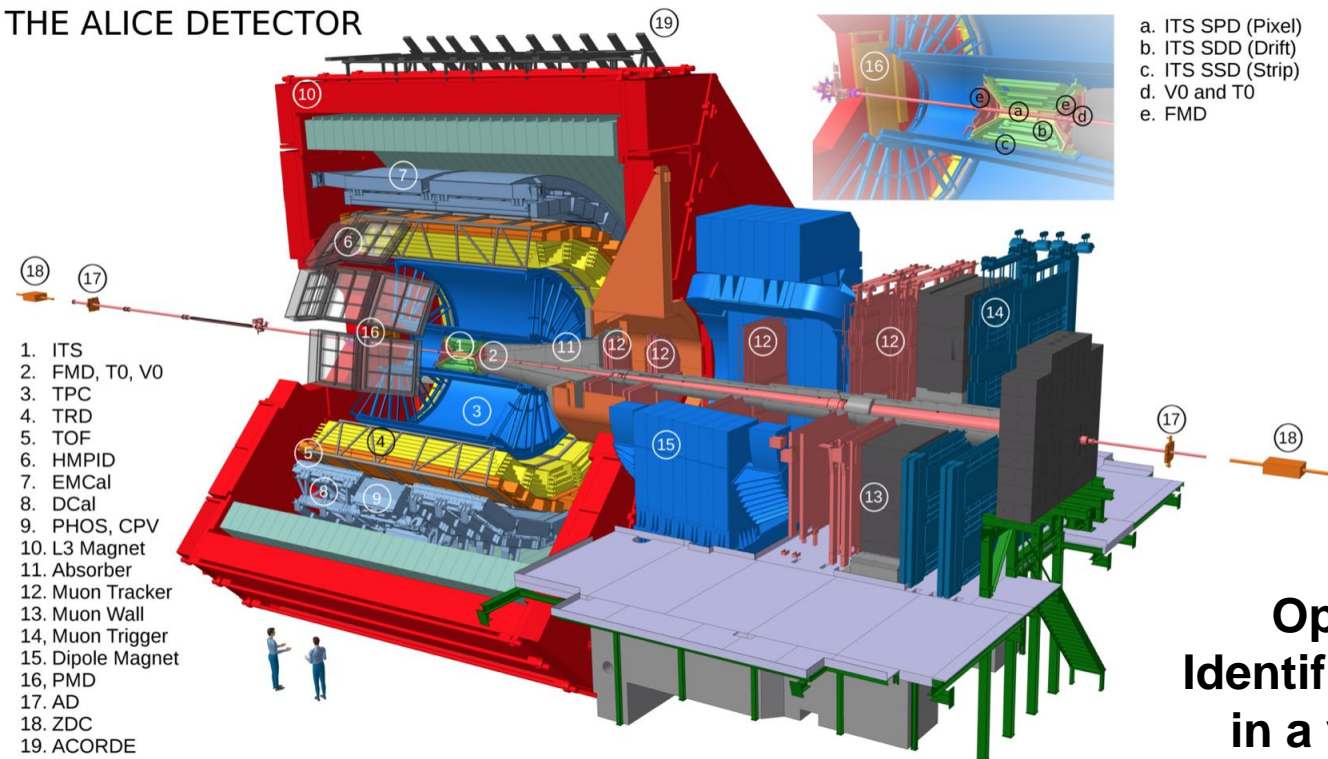Csernai and Kapusta, Phys. Rept. 131 (1986) 223
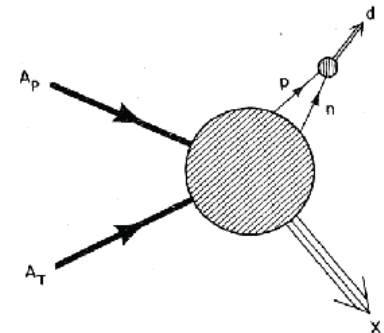
CERN accelerator complex
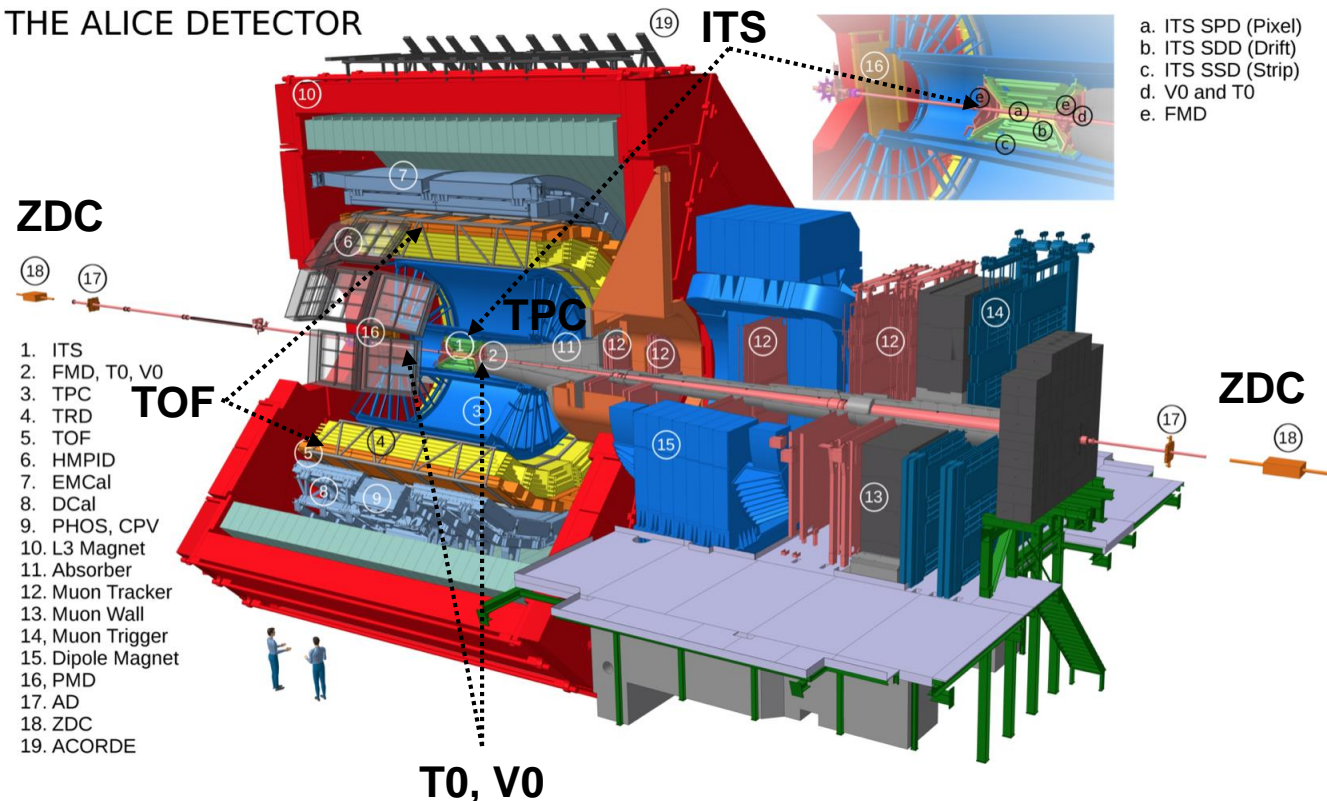
ALICE experiment

THE ALICE DETECTOR

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE
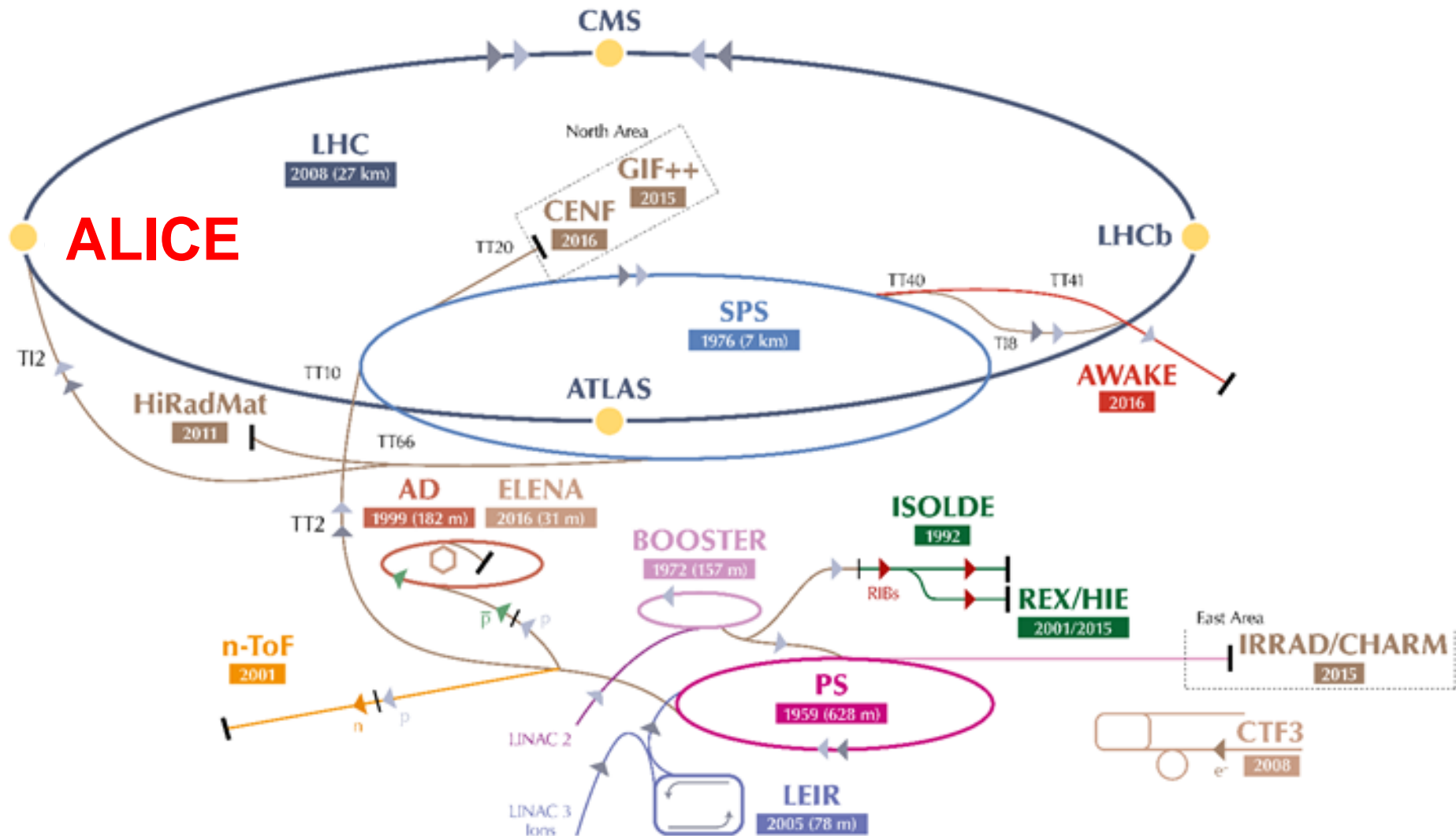
Optimized for Particle Identification at low momenta in a very high-multiplicity environment

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

THE ALICE DETECTOR

ITS

ZDC

TPC

TOF

ZDC

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1. ITS
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16, PMD
17. AD
18. ZDC
19. ACORDE

T0, V0

ITS (|η|<0.9)

6 layers silicon detectors

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

TPC (|η|<0.9)

Gas-filled cylindrical barrel, MWPC readout

Tracking, PID (dE/dx)

TOF (|η|<0.9)

Multigap RPC

PID (time-of-flight)

T0 (4.6<η<4.9 and -3.3<η<-3.0)

2 arrays of Cherenkov's (T0A, T0C)

Luminosity, vertex, event collision time

V0 (2.8<η<5.1 and -3.7<η<-1.7)

Forward arrays of scintillators (V0A and V0C)

Trigger, beam gas rejection, multiplicity, centrality

ZCD centrality determination

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

PID

Low momenta: TPC (dE/dx)   Higher momenta: TOF (m^2)

ALICE Coll. PRC 97 (2018) 024615
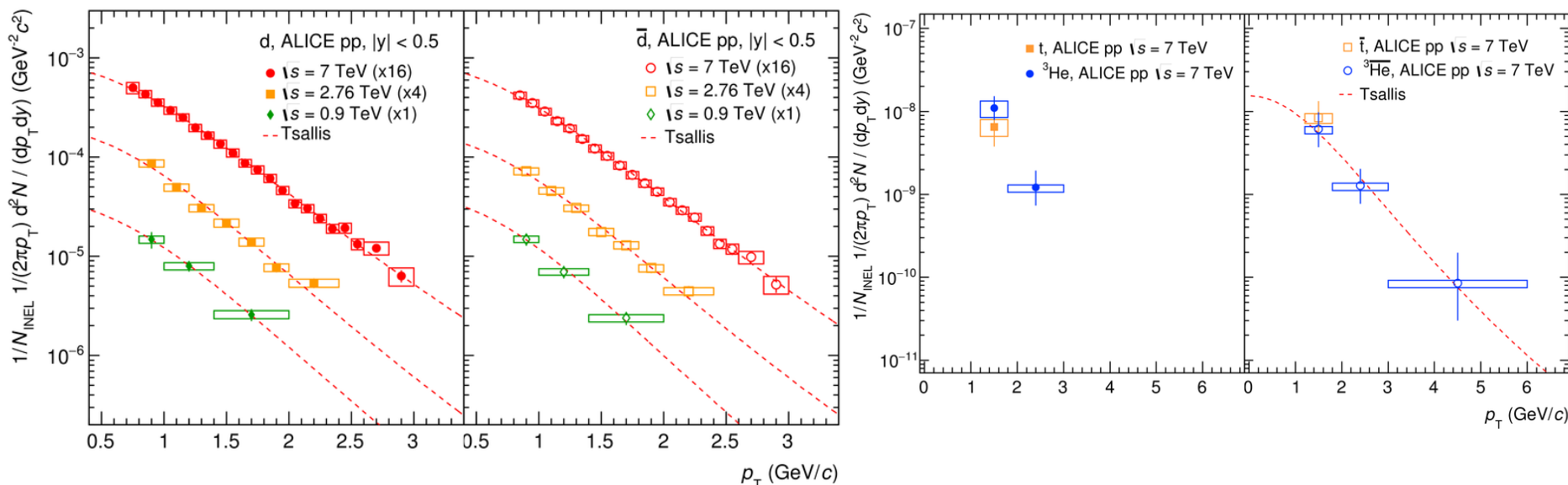

ALICE Coll. PRC 97 (2018) 024615
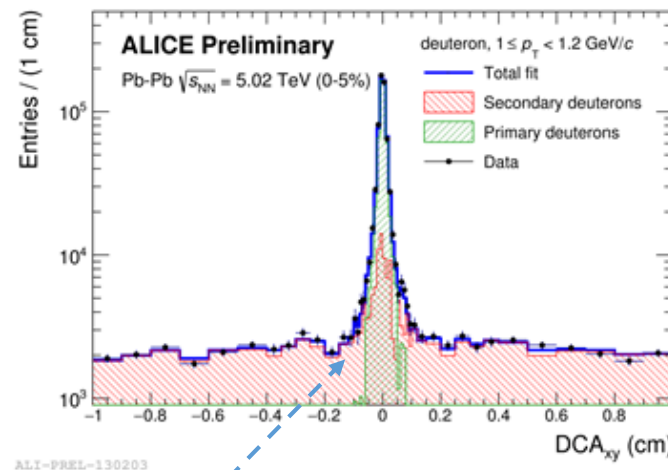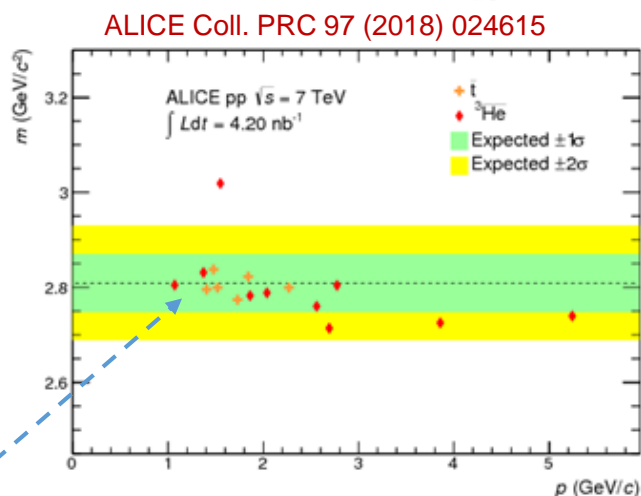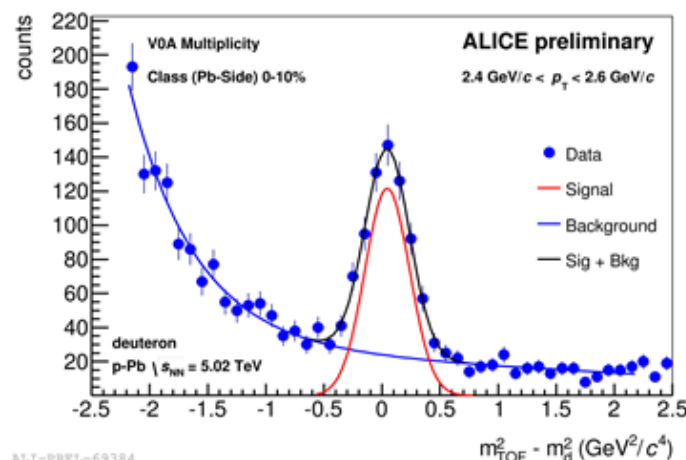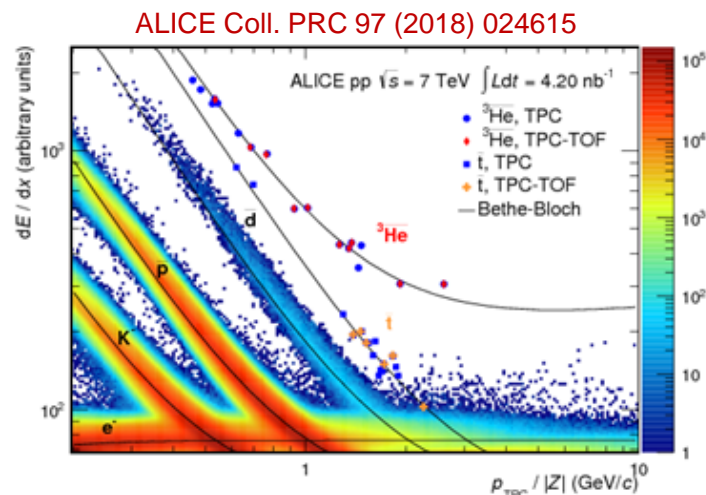
TPC+TOF: **6 anti-tritons** and **10 $^3\overline{\text{He}}$** candidates
→ **first ever observation in pp**

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 Coll. PRC 97 (2018) 024615

→ 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 Coll. NPA 971 (2018) 1

caveat: this penalty factor **may also depend on charged-particle multiplicity** → see e.g. d/p ratio

A = mass number

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

ALICE Coll. PRC 97 (2018) 024615
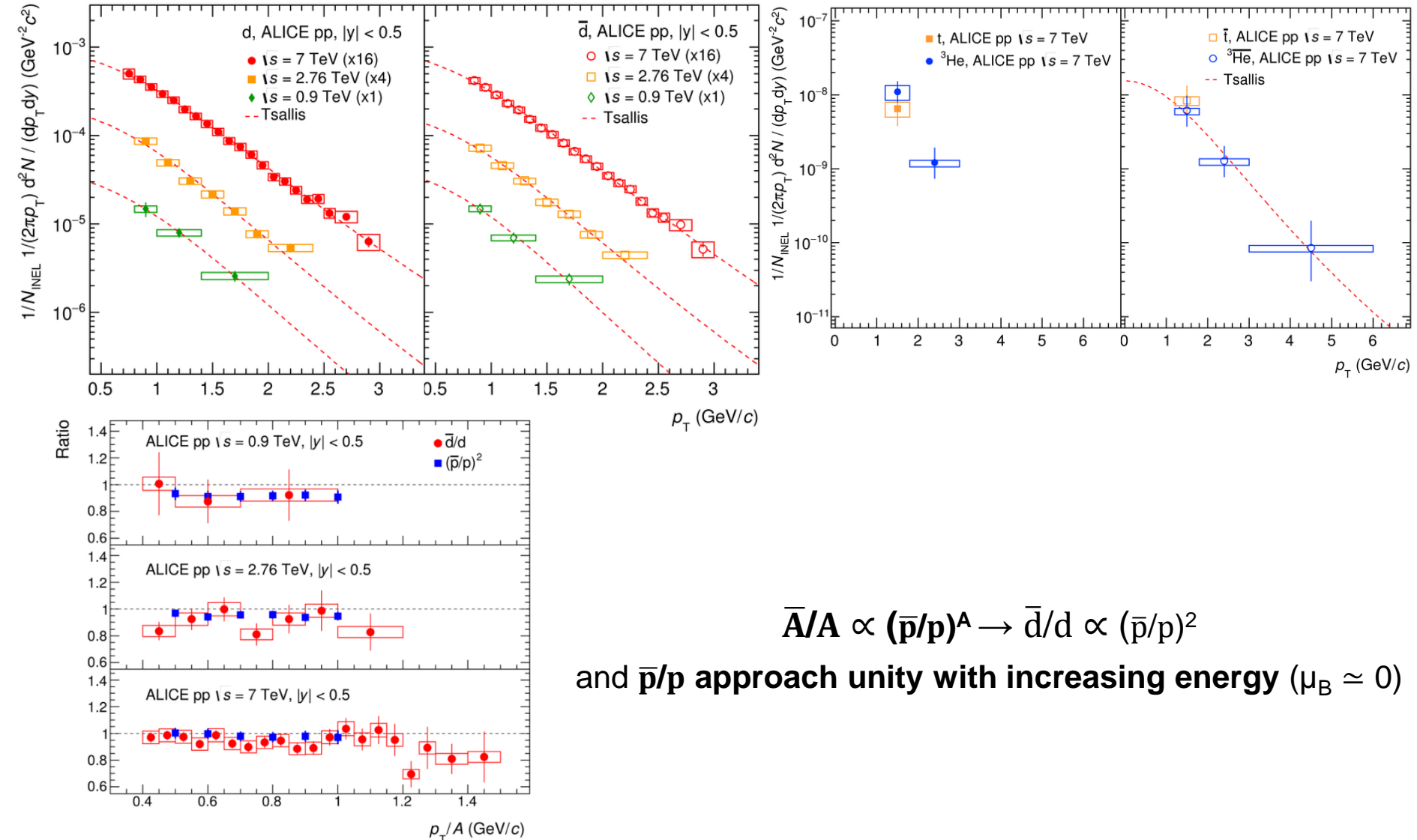
$$\overline{A}/A \propto (\overline{p}/p)^A \rightarrow \overline{d}/d \propto (\overline{p}/p)^2$$

and $\overline{p}/p$ approach unity with increasing energy ($\mu_B \simeq 0$)

What about lead-lead?
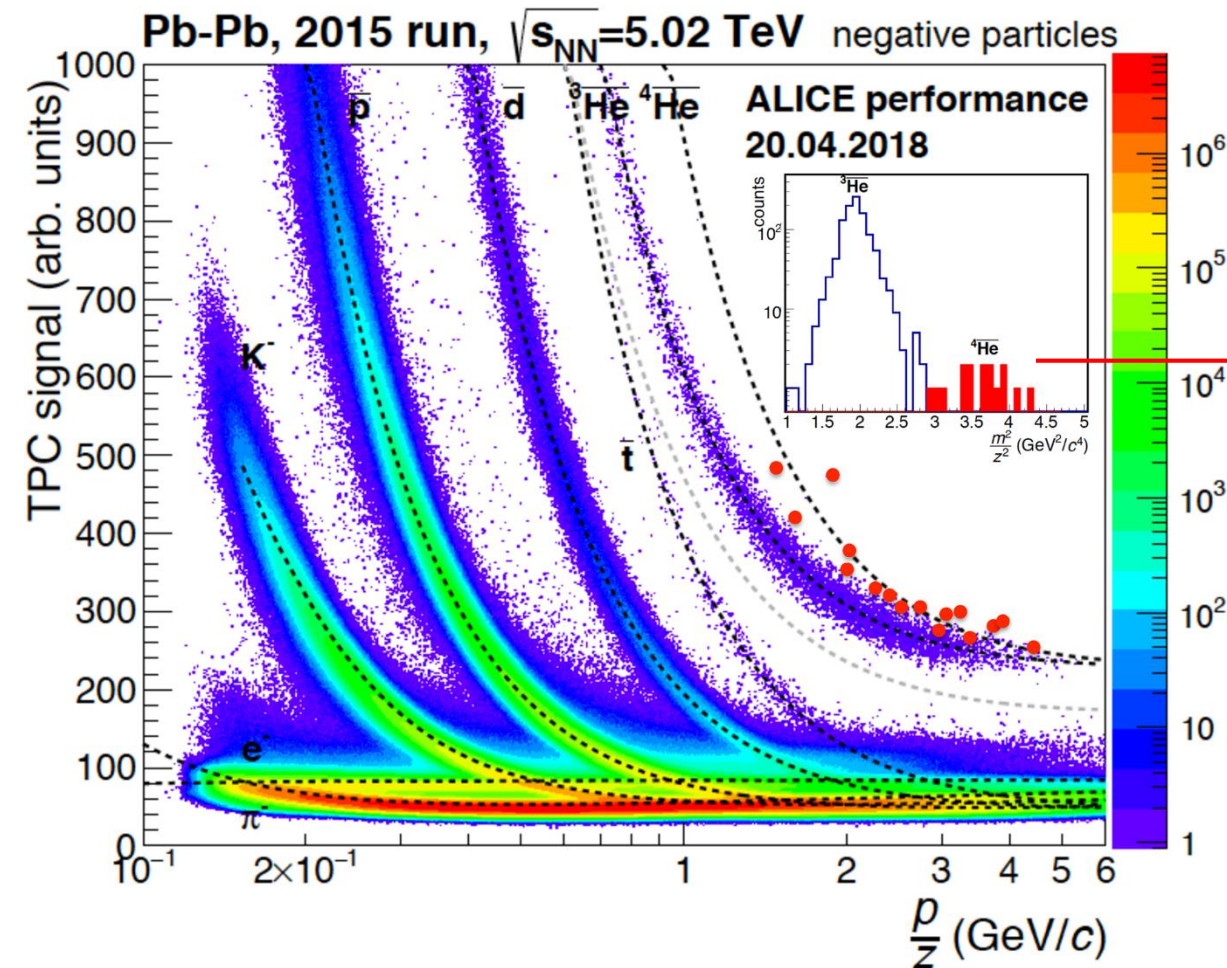
16 $^4\overline{\text{He}}$ candidates in Pb-Pb at 5.02 TeV

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

What about lead-lead?
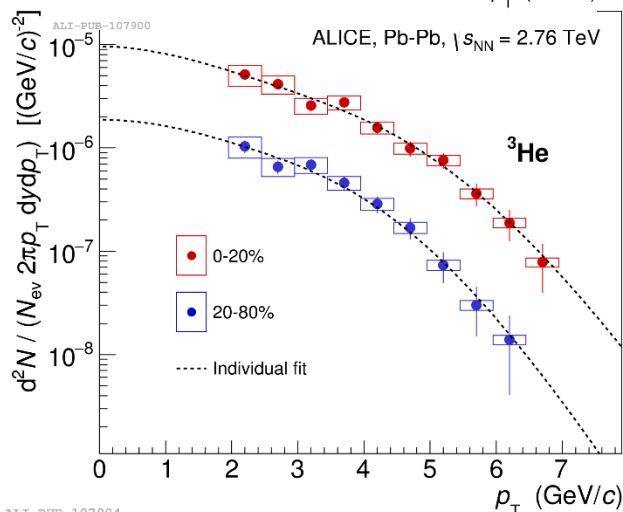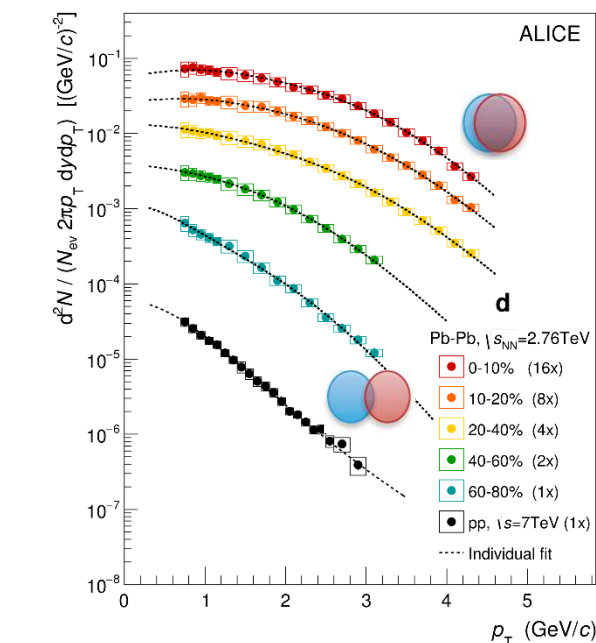
ALICE Coll. PRC 93 (2016) 024917
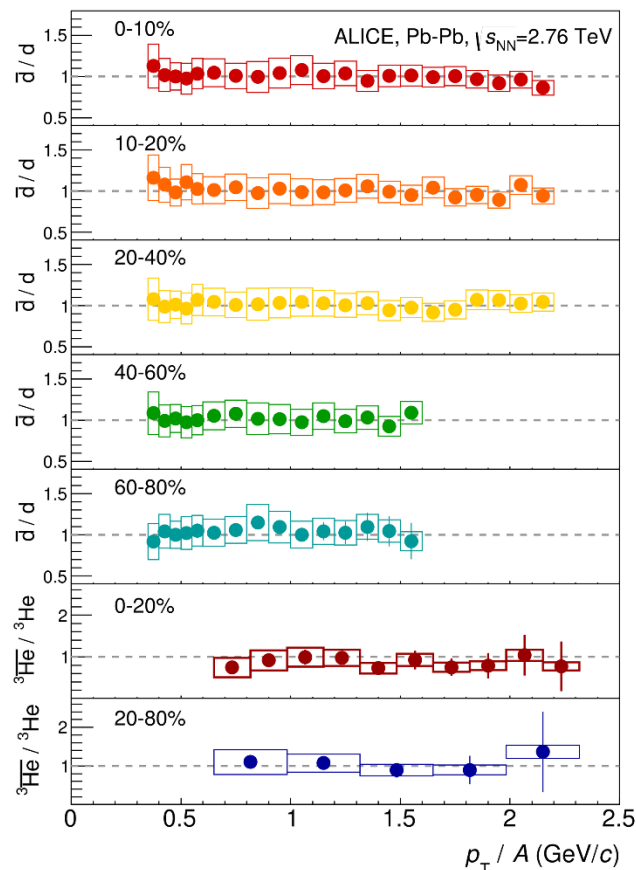
anti-nuclei/nuclei ratio consistent with unity
independently of p_T and centrality

What about lead-lead?

ALICE Coll. PRC 93 (2016) 024917
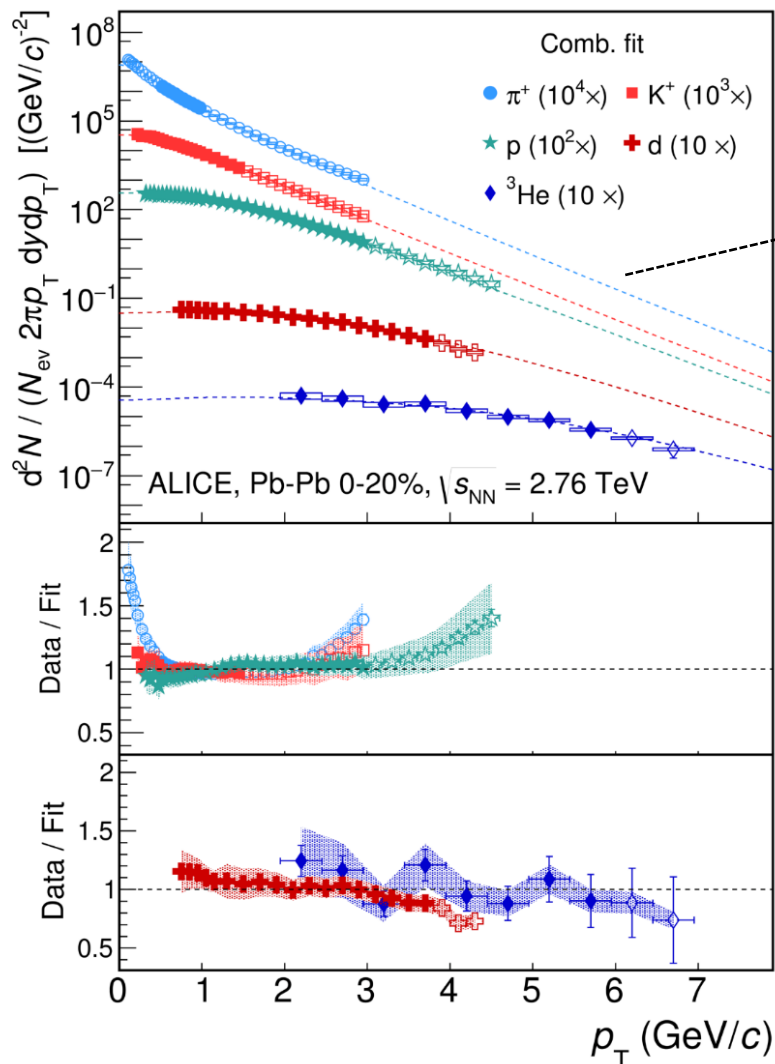
Blast-Wave (BW) PRC 48 (1993) 2462: hydrodynamic-inspired model describing particle production assuming a radially expanding thermalized source

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

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

What about lead-lead?

Preliminary 5.02 TeV Pb-Pb published in ALICE-PUBLIC-2017-006
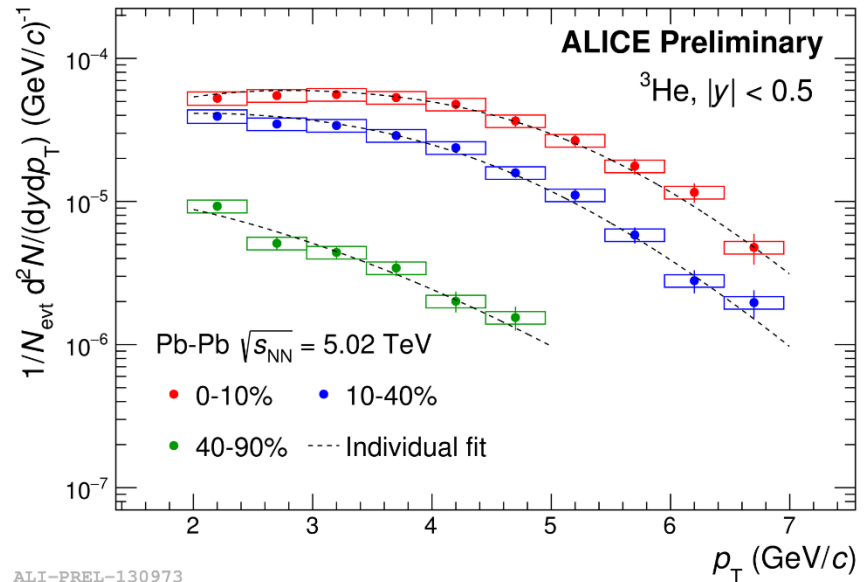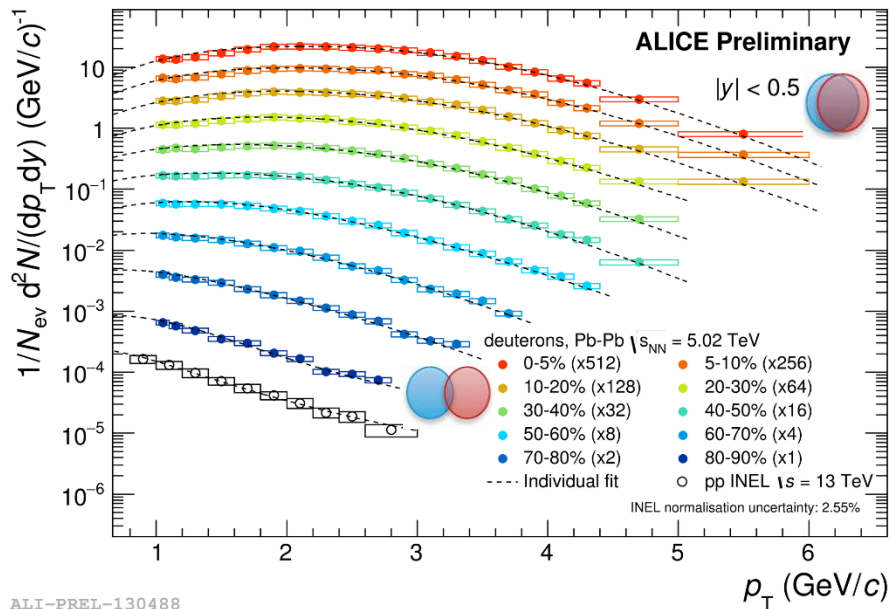
Thermal model

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

- starting point: grand-canonical partition function **Z** for a relativistic ideal quantum gas of hadrons

- once the partition function is known all other thermodynamic quantities (such as the particle density n) can be calculated

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial \mu} \qquad P = \frac{\partial(T\ln Z)}{\partial V} \qquad s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

- **only two free parameters are needed** (T_{ch}, μ_B). V cancels if particle ratios (n_i/n_j) are considered

- macroscopic model → internal structure of nuclei is ignored

Thermal model

Light nuclei are fragile objects i.e. they have a small binding energy (2.2 MeV for deuteron) then it is not clear if thermal model applies to nuclei

$\rightarrow$ indeed light nuclei might dissociate in the hadronic phase at $T_{ch} \simeq 160$ MeV

$\rightarrow$ however it is the entropy per baryon that determines nuclei production yield and this is fixed at the chemical freeze-out
Siemens and Kapusta, PRL 43 (1979) 1486

$\rightarrow$ agreement with thermal model is a sign for an adiabatic (isentropic) expansion in the hadronic phase

Thermal model fit

ALICE Coll. PRC 97 (2018) 024615
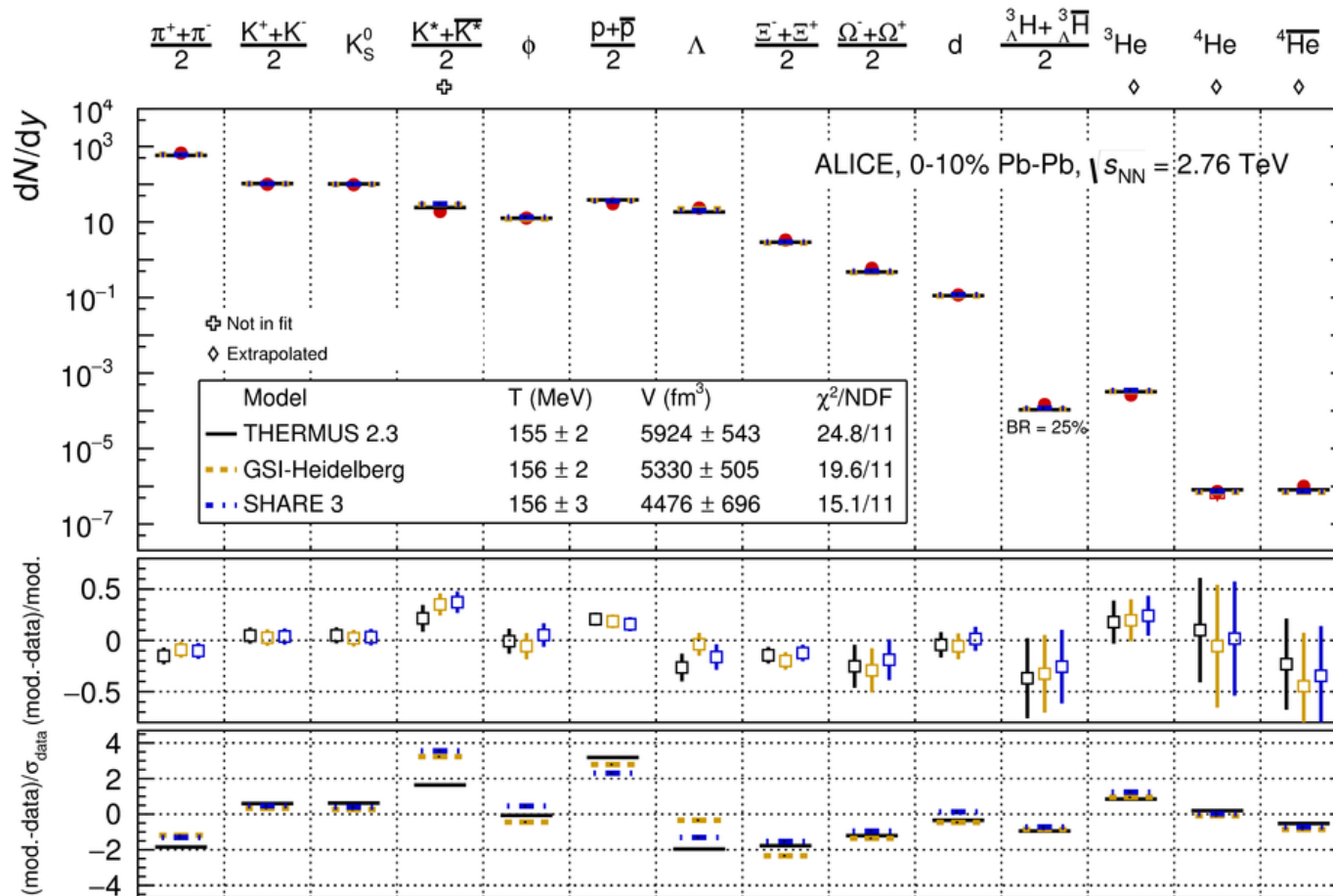
Thermal model is successfully reproducing particle yields in Pb-Pb at 2.76 TeV

different model implementation fit nuclei and even hypertriton

if *only* nuclei are fitted, the temperature is 154 ± 4 MeV

$\rightarrow$ hint for nuclei production at the 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

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 0-10%

✚ Not in fit

Model	T (MeV)	V (fm³)	χ²/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

BR = 25%
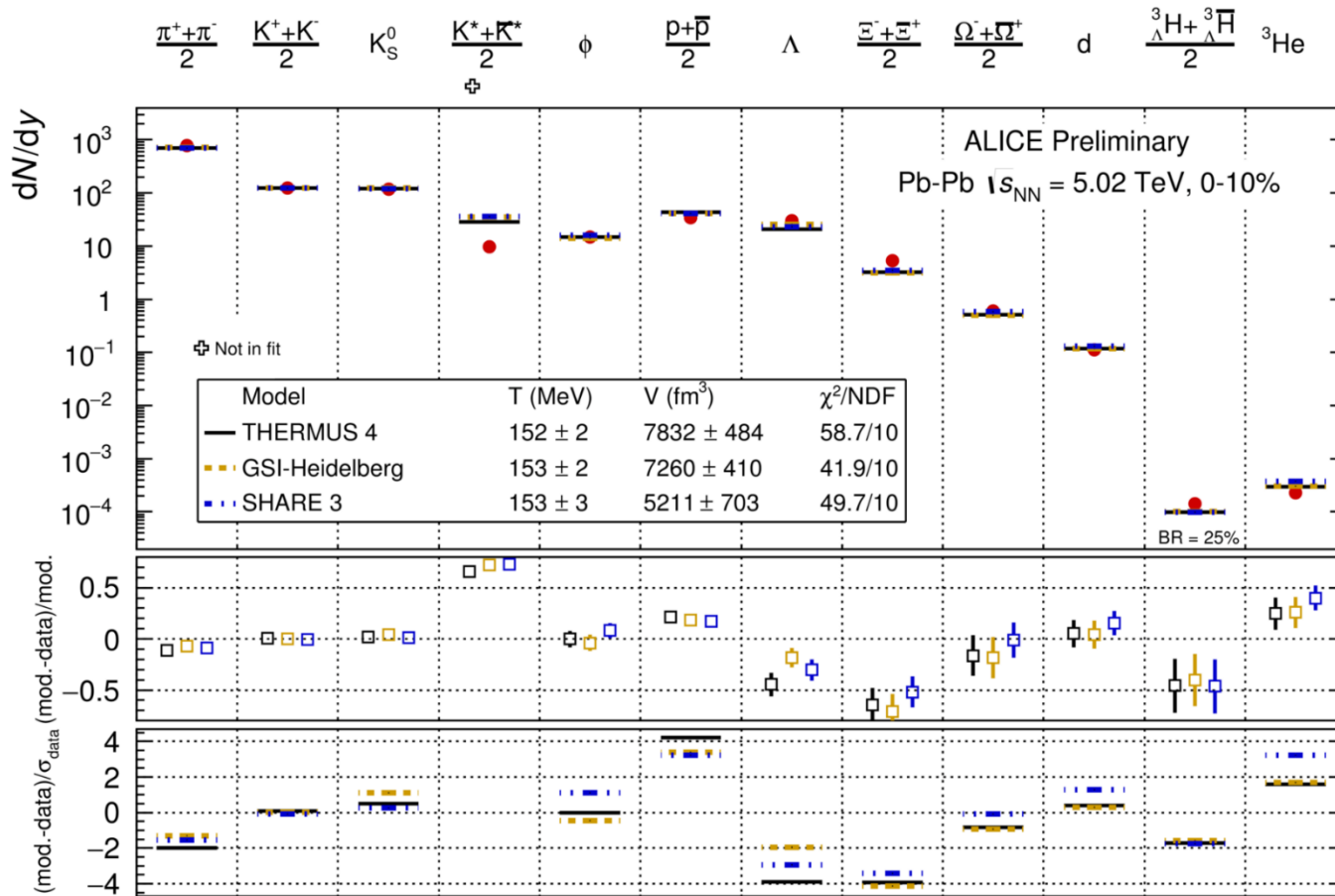
ALI-PREL-148739

At the LHC Run 2 improved reconstruction and analysis technique reduced the uncertainties

Tensions with thermal model are larger
THERMUS 5.7σ
GSI-Heidelberg 4.3σ
SHARE 3 5σ

→ 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

p_T spectra vs multiplicity

new results in pp based on multiplicity selection

arXiv:1902.09290v1 [nucl-ex] 25 Feb 2019
submitted to PLB
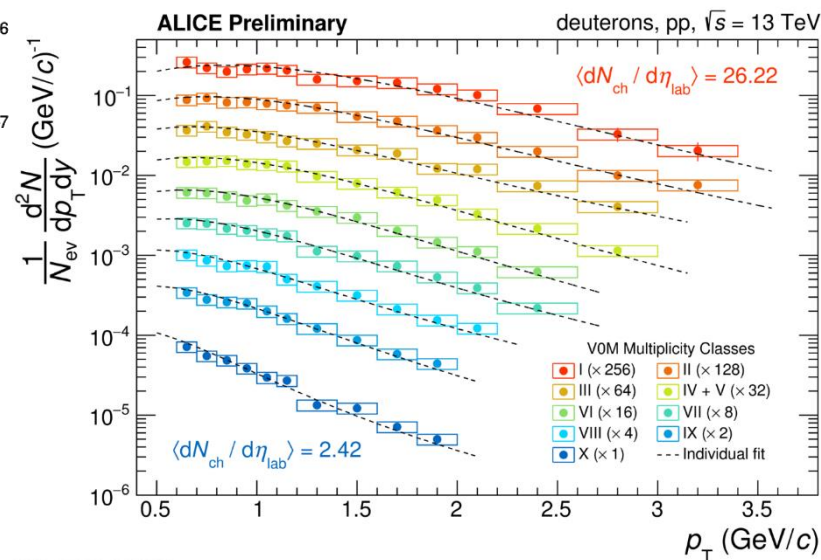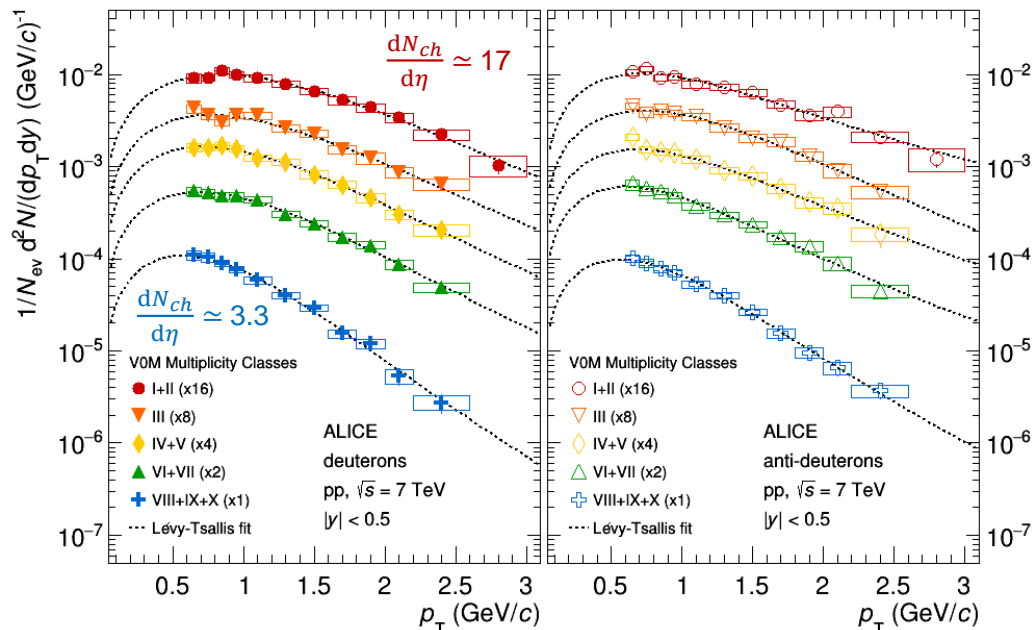
Testing Coalescence models
Coalescence parameter B_A

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

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

where $p_\mathrm{p} = p_A/A$.

Testing Coalescence models
Coalescence parameter B_2

arXiv:1902.09290v1 [nucl-ex] 25 Feb 2019
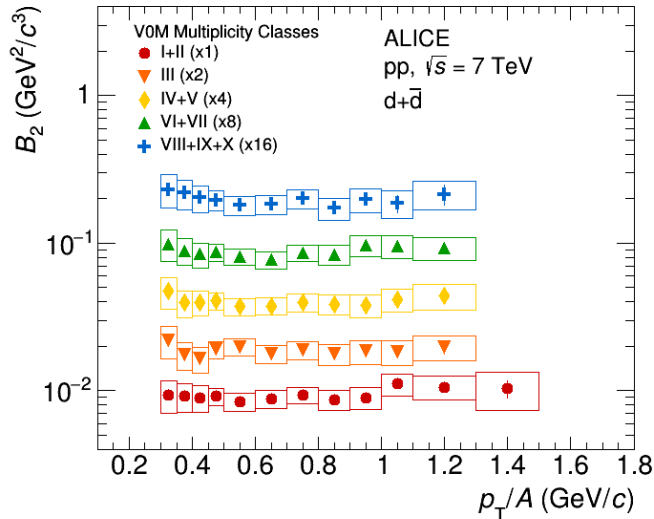
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^A$$

i.e. deuteron $\propto B_2$ x proton^2

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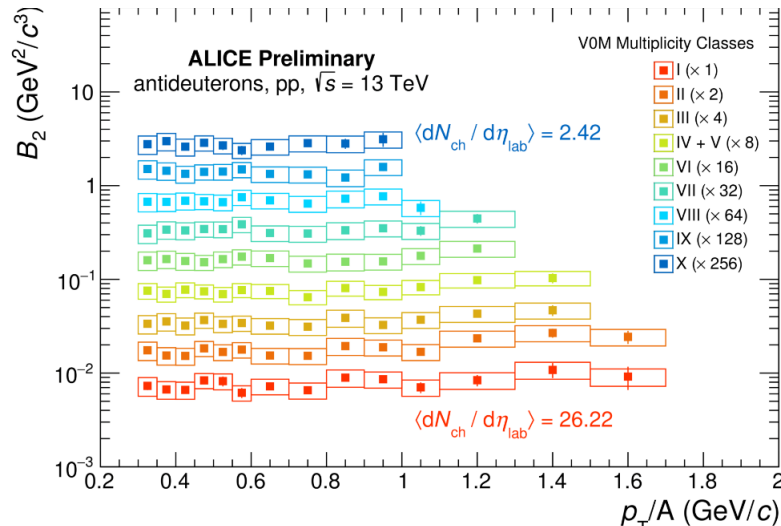
- "point-like" particle-emitting source (i.e. hadronic emission region smaller than the nucleus size)

- no correlations in the proton and neutron momentum distributions

Testing Coalescence models
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

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

ALICE Coll. PRC 97 (2018) 024615
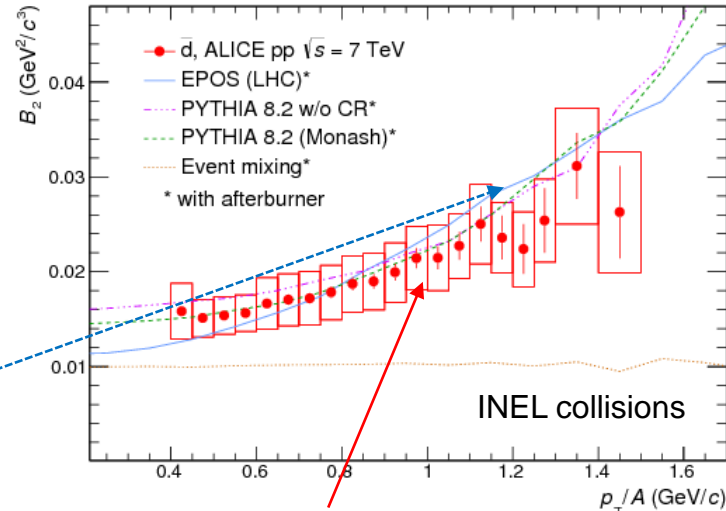
anti-deuterons, pp $\sqrt{s}$ = 7 TeV
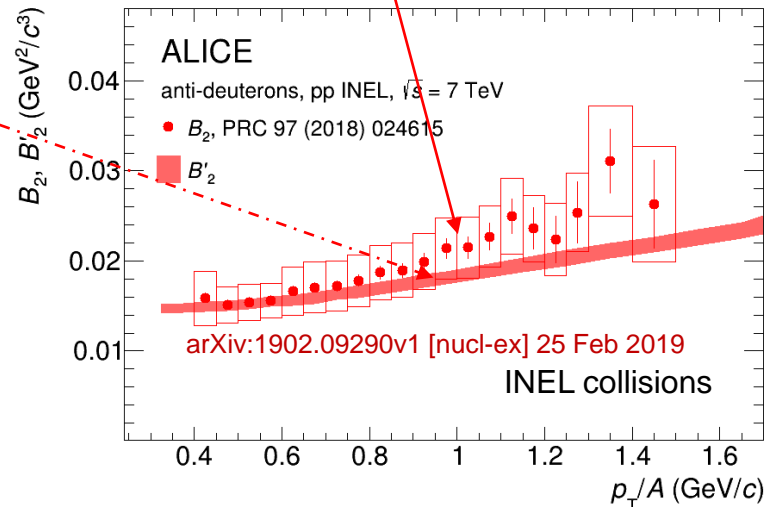
Testing Coalescence models
Multiplicity dependence of B_2
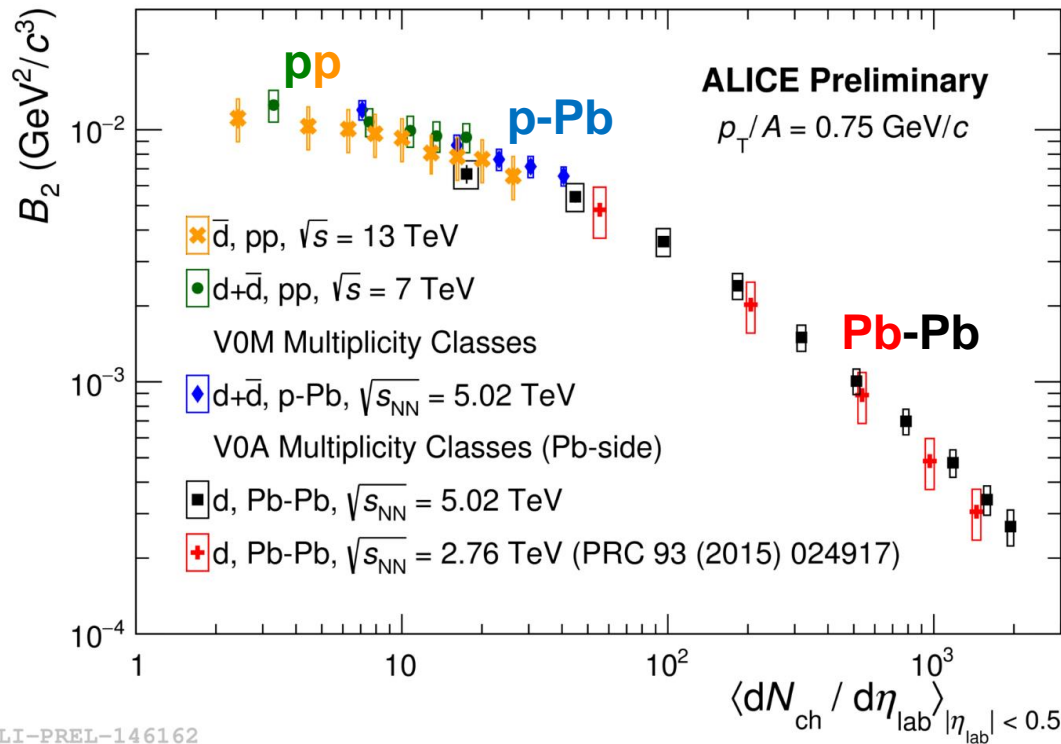
ALI-PREL-146162

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

$$B_A \propto V^{1-A} \rightarrow B_2 \propto \frac{1}{V}$$
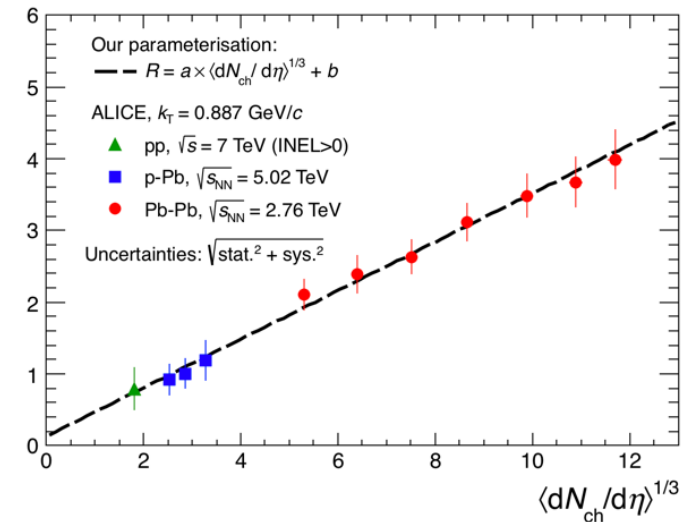
Bellini, Kalweit, arXiv:1807.05894v1 [hep-ph]

Testing Coalescence models
Multiplicity dependence of B_2
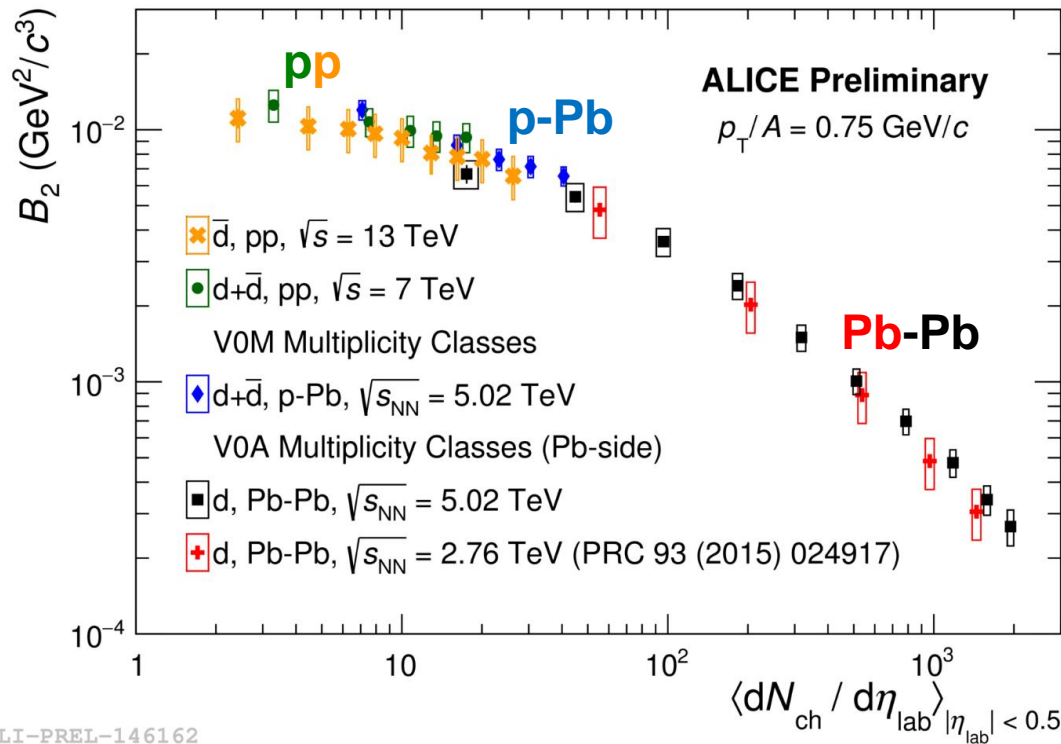
ALI-PREL-146162

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

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

Scheibl and Heinz, PRC 59 (1999) 1585

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

Blum et al., PRD 96 (2017) 103021

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

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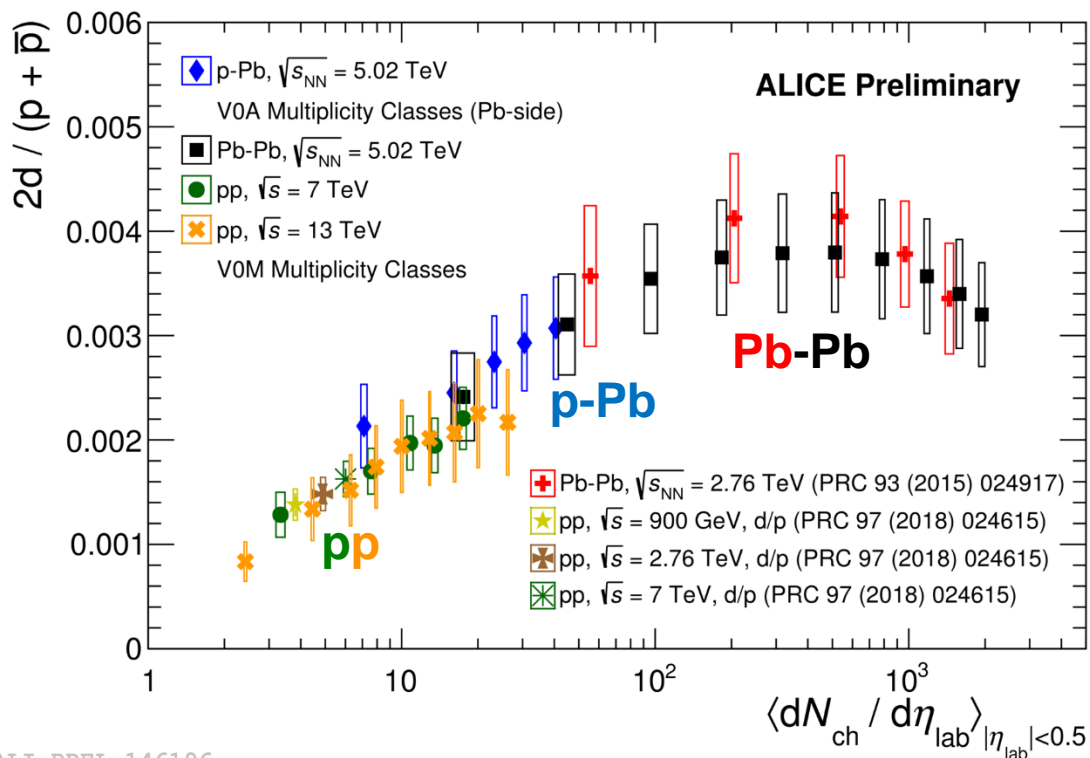
d/p higher for about a factor 2 in Pb-Pb w.r.t pp

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**

ALI-PREL-146196

Coalescence parameter B_3

ALICE Coll. PRC 97 (2018) 024615
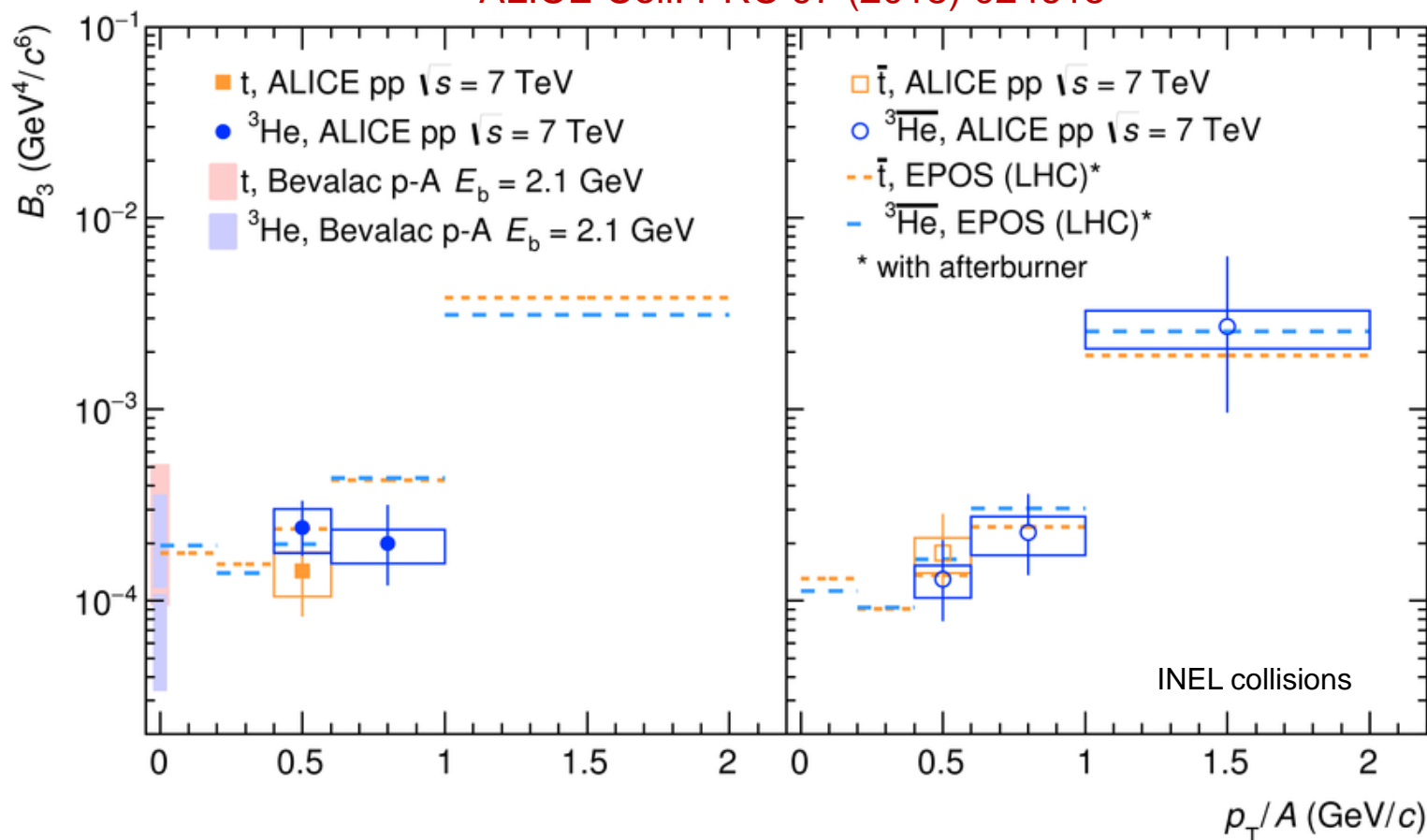
→ **First ever determination of B_3 of (anti-)^{3}He and (anti-)tritons in pp collisions**

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)

Essential for primordial anti-matter and Dark Matter searches

→ CR anti-deuterons and anti-^{3}He suggested as probe of DM annihilation
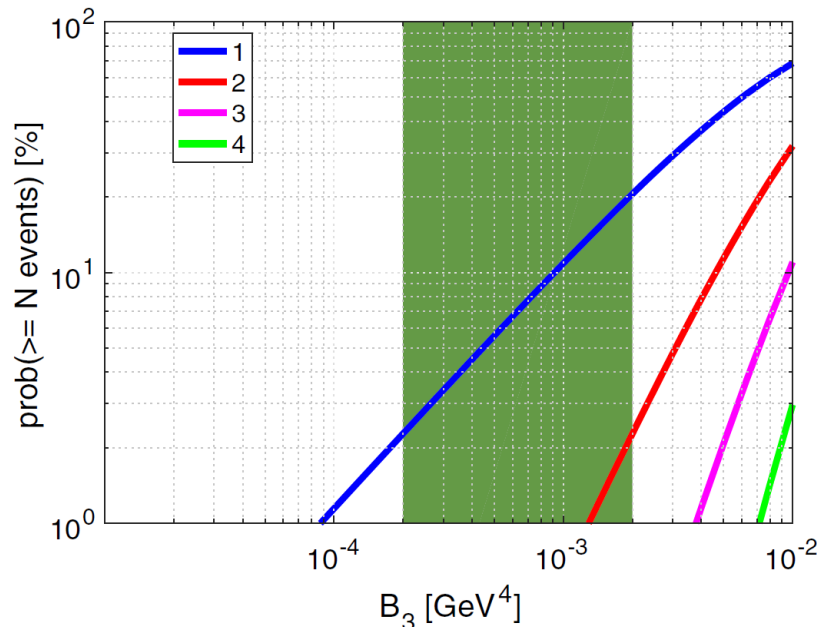
$$\frac{B_3}{\text{GeV}^4} \approx 0.0024 \left(\left(\frac{R(p_t)}{1\ \text{fm}} \right)^2 + 0.8 \left(\frac{b_3}{1.75\ \text{fm}} \right)^2 \right)^{-3}$$
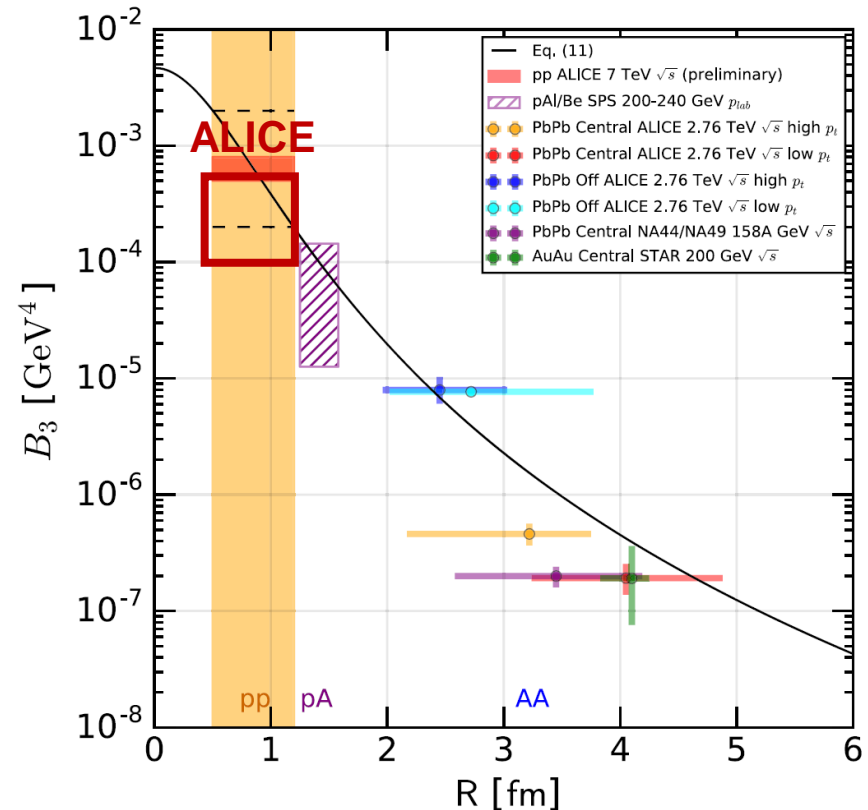
← Poisson probability for detecting N (1, 2, …) secondary $^3\overline{\text{He}}$ events in 5-yr analysis of AMS-02

Rare CPT test provided

ALICE Coll., Nature Phys. 11 (2015) 811
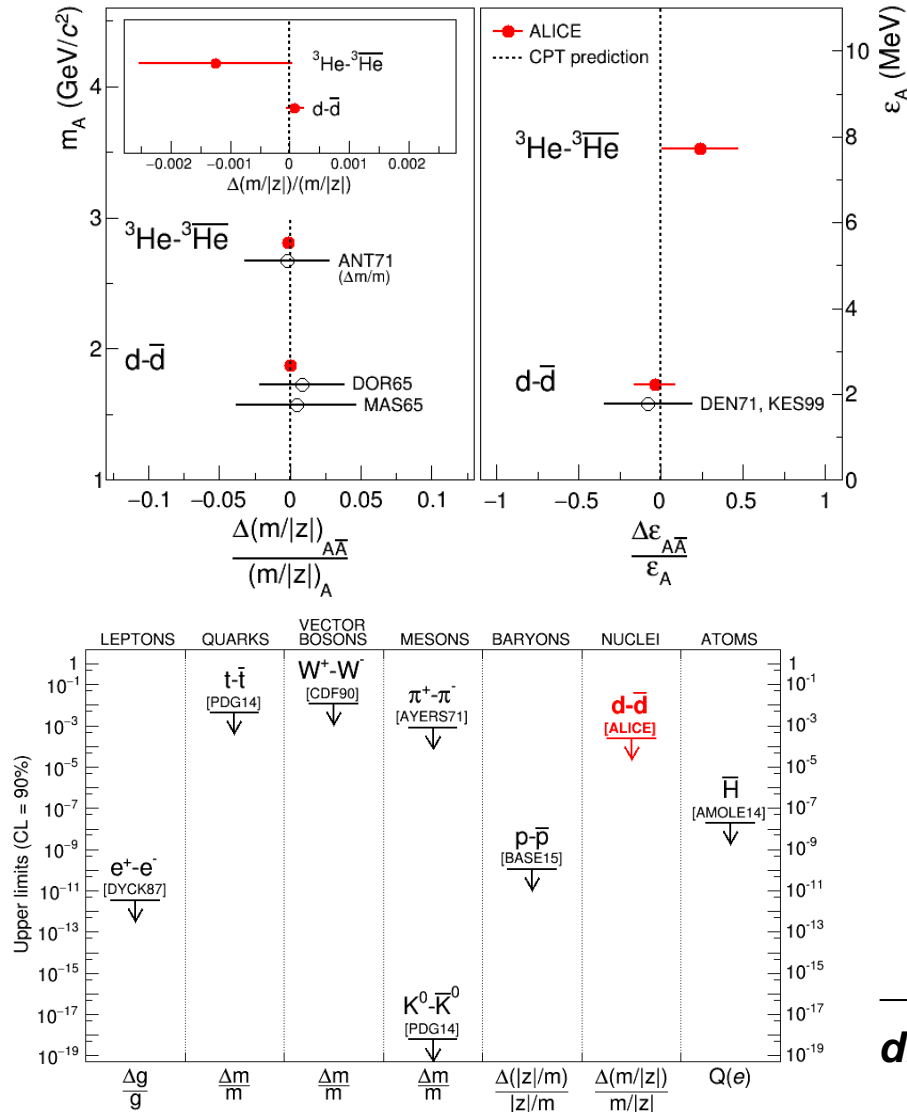
**Mass difference nuclei/anti-nuclei
constraints CPT symmetry
in nucleon-nucleon interactions**
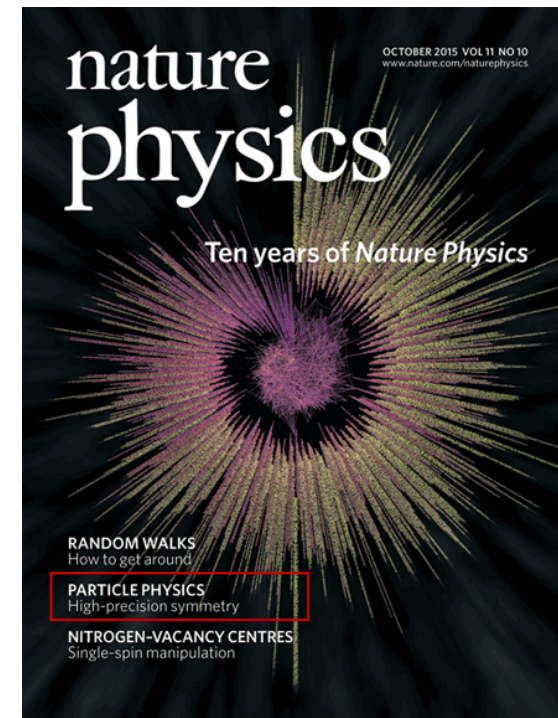
→ **these tests *independently* verify each
distinct prediction of CPT symmetry**

Hypertriton

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

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

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

$_\Lambda^3 H$

m = 2.991 GeV

$B_\Lambda = 0.13 \pm 0.05$ MeV
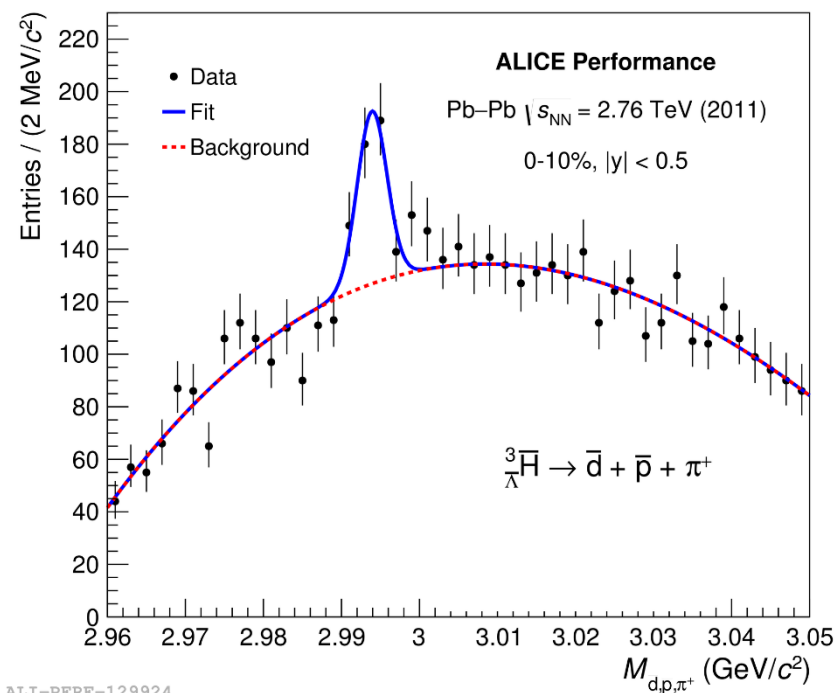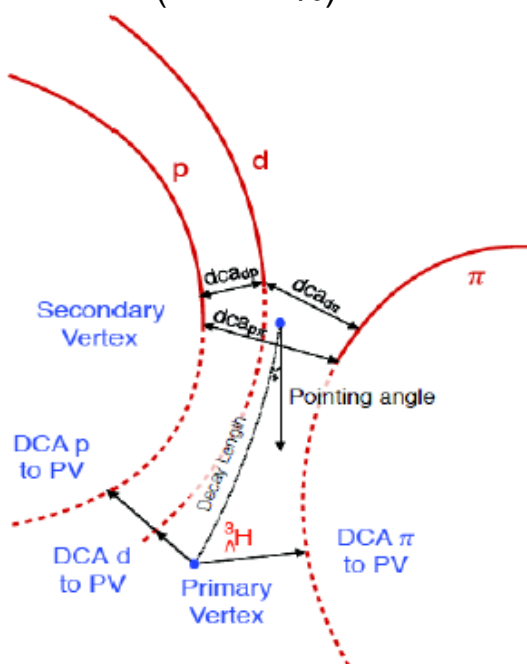
unstable, (week) decay modes:

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

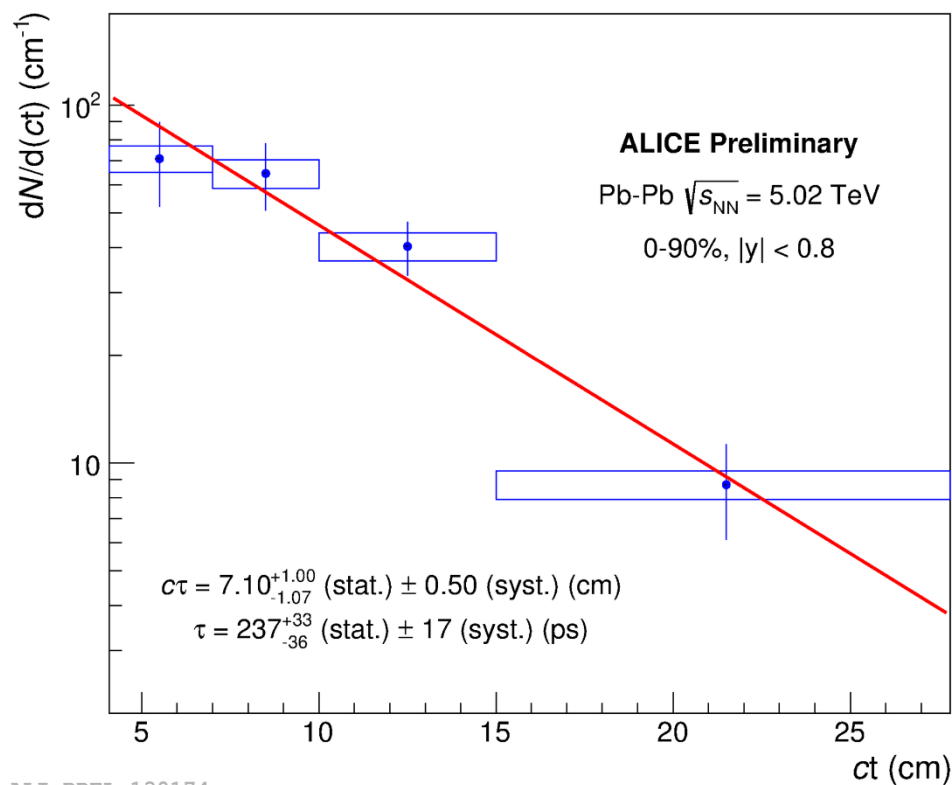$_\Lambda^3 H \rightarrow {}^3 H + \pi^0$ (B.R. 13%)

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

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

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

$\binom{3}{\Lambda}\text{H}$ $^3_\Lambda\text{H}$ identification in ALICE

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

m = 2.991 GeV

B_Λ = 0.13 $\pm$ 0.05 MeV

unstable, (week) decay modes:

$^3_\Lambda\text{H} \to\ ^3\text{He} + \pi^-$ (+ c.c.)	(B.R. 25%)
$^3_\Lambda\text{H} \to\ ^3\text{H} + \pi^0$	(B.R. 13%)
$^3_\Lambda\text{H} \to d + p + \pi^-$	(B.R. 41%)
$^3_\Lambda\text{H} \to d + p + \pi^0$	(B.R. 21%)

ALICE Performance, 28/11/2016
$\sqrt{s_{NN}}$ = 5.02 TeV
Pb–Pb, 0–80%
$|y| < 0.9$

ALI–PERF–114838

^{3}He
π
Secondary Vertex
dca
θ Pointing Angle
DCA ^{3}He to PV
Decay Length
Λ^3H
DCA π to PV
Primary Vertex

$\left(^{3}_{\Lambda}\text{H}\right)^{3}_{\Lambda}\text{H}$ identification in ALICE

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

m = 2.991 GeV

B_{Λ} = 0.13 $\pm$ 0.05 MeV

unstable, (week) decay modes:

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

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

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

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

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

ALI-PREL-130174

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

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

where $c\tau = mLc/p$

$_\Lambda^3 H$ lifetime
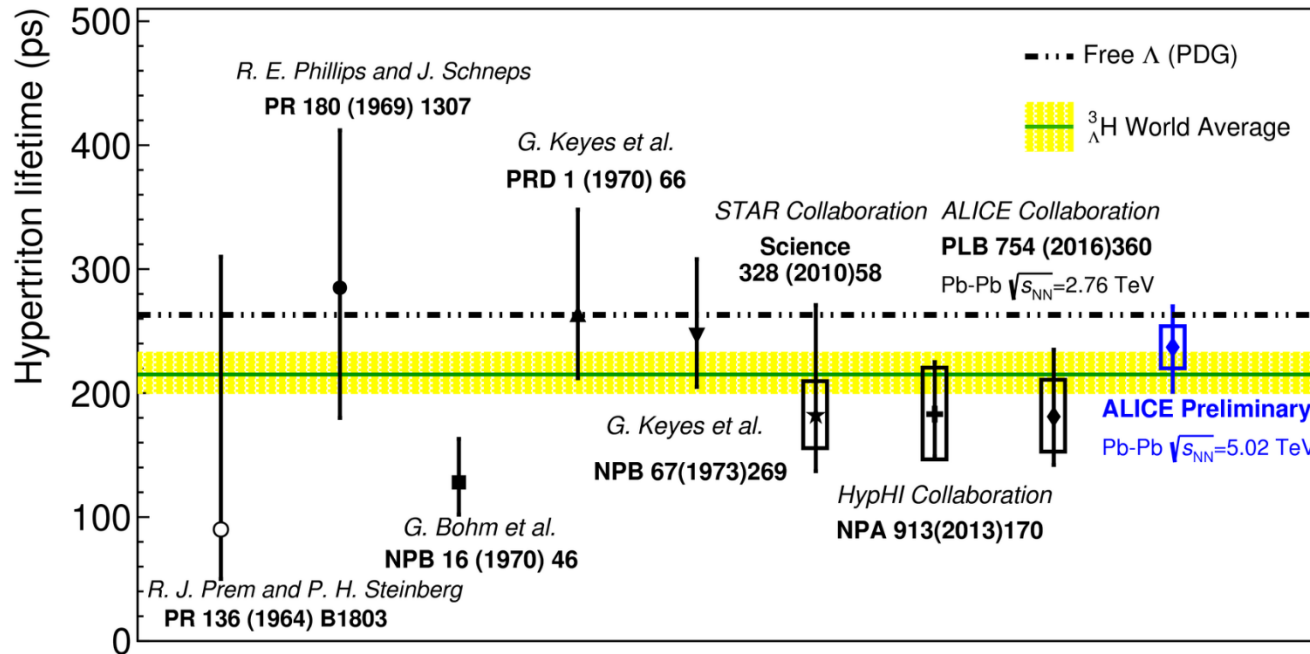
free Λ lifetime (PDG)
262 ± 2 ps

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

ALI−PREL−130195

- very small B_Λ (130 keV) led to the hypothesis that the $_\Lambda^3 H$ 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 of LHC Run3 and Run4
→ expected Pb-Pb L_{DEL} = 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	≥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 $\sqrt{s_{NN}}$ [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} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	43	1.3	22.	156	264	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 of LHC Run3 and Run4
→ expected Pb-Pb L_{DEL} = 10 nb^{-1} at 50 kHz collision rate

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

Citron et al., arXiv:1812.06772 [hep-ph] 25 Feb 2019
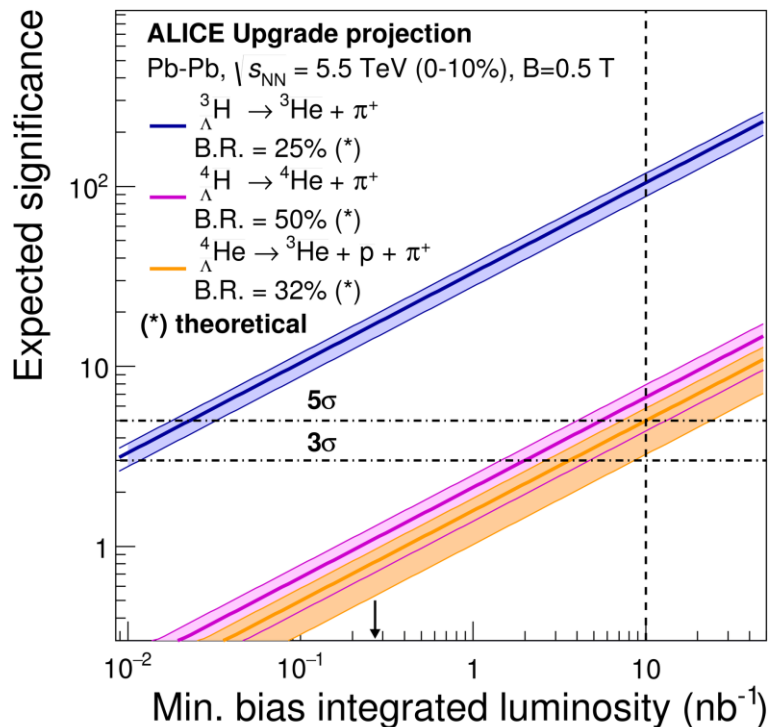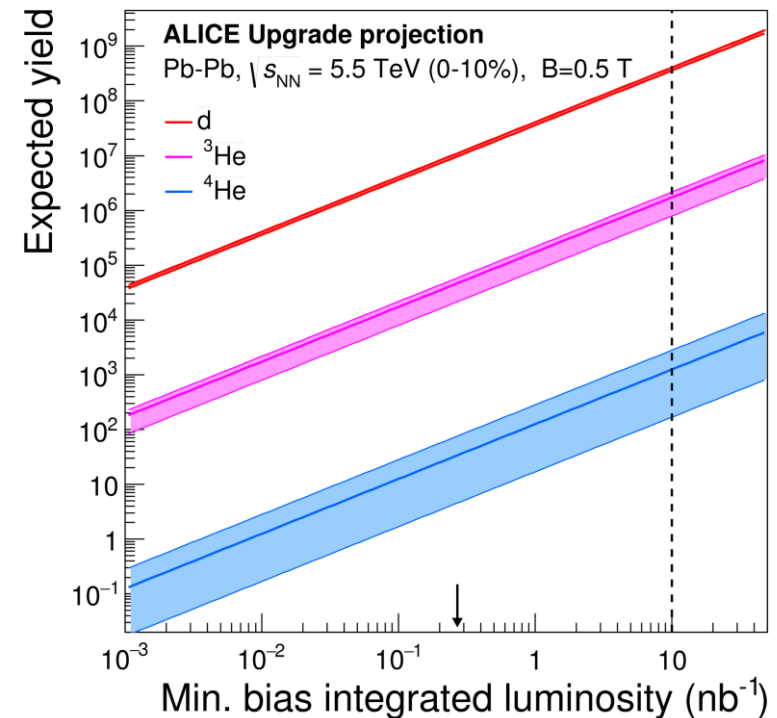
ALI-SIMUL-312332

ALI-SIMUL-312336

Conclusions

Unique tracking/PID capability of ALICE allows one to clearly identify rare composite particles as light nuclei and anti-nuclei at LHC

Thermal statistical model describes quite well also loosely bound objects

Validity of hadron-coalescence model LHC tested
$\rightarrow$ it is clear now we need refined models
to fully account for observations (also) in pp

Inputs (B_2 and B_3) for Astroparticle Physics provided

Rare CPT test reported

One of the most accurate lifetime measurement carried out

and … let's cross the fingers for future LHC runs!

Thanks for your attention

Backup

Spare slide

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
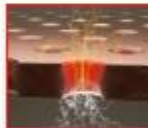
New TPC Readout Chambers (ROCs)
- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

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 (O²)
- Record MB Pb-Pb data at 50 kHz
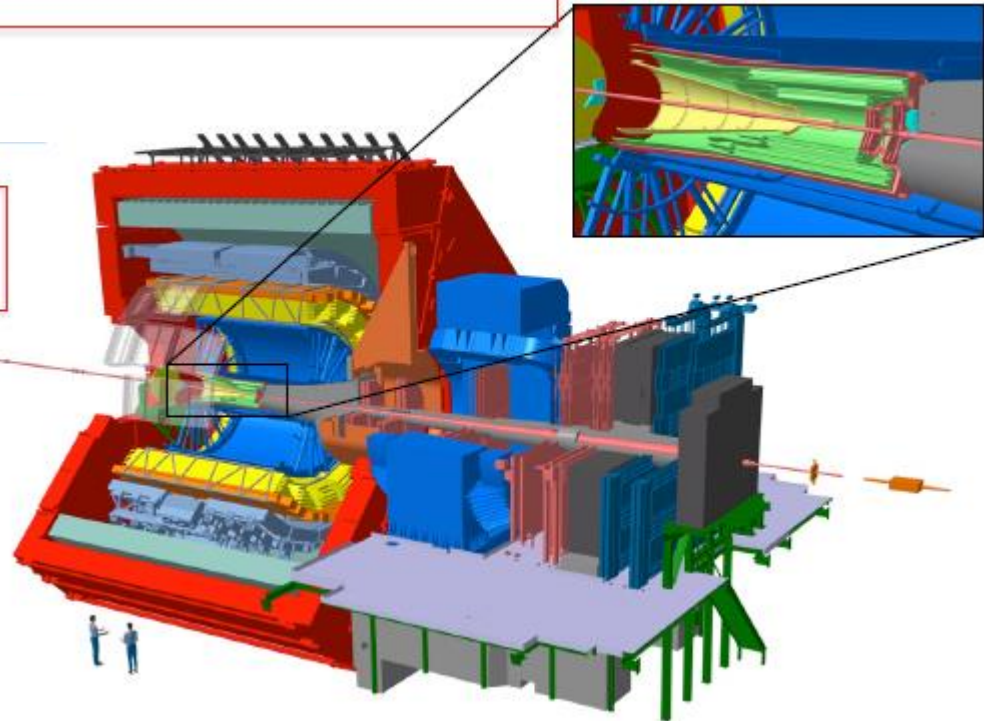
More on BW in Pb-Pb
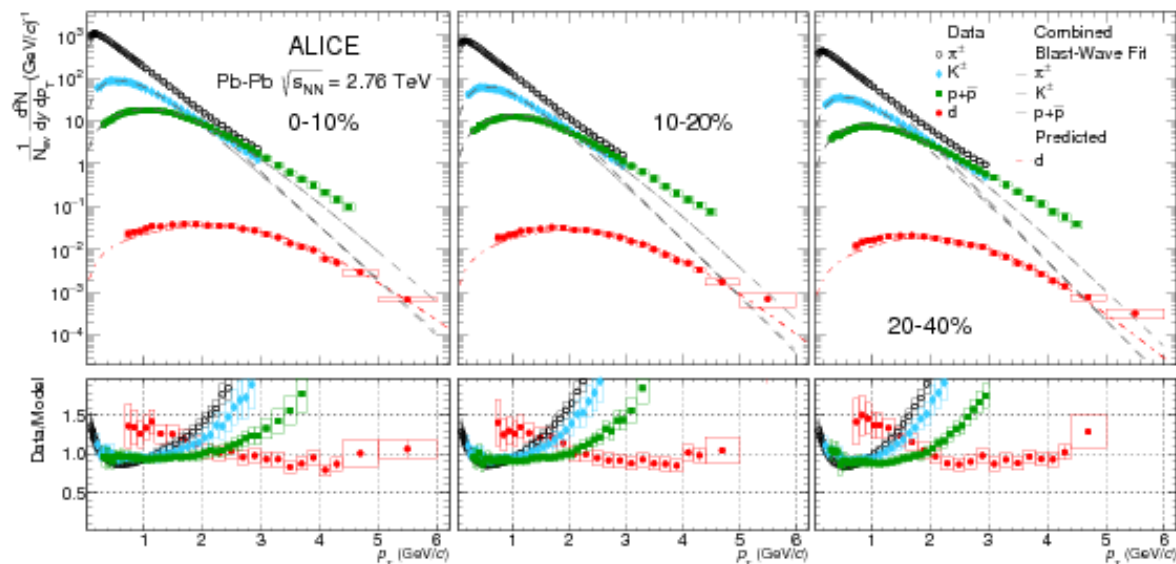
ALICE Coll. EPJ. C77 (2017) 658
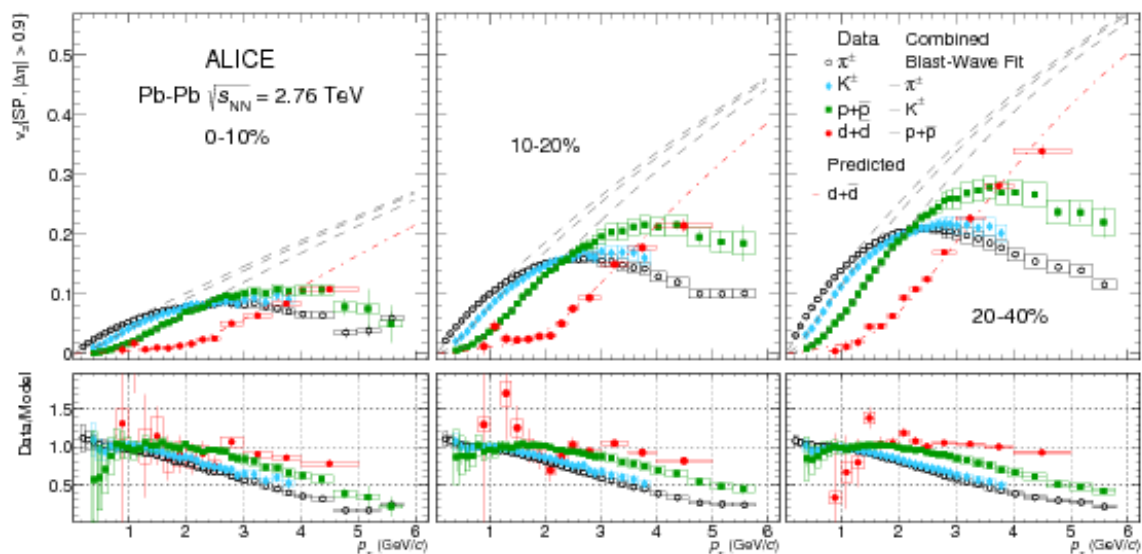
Spare slide
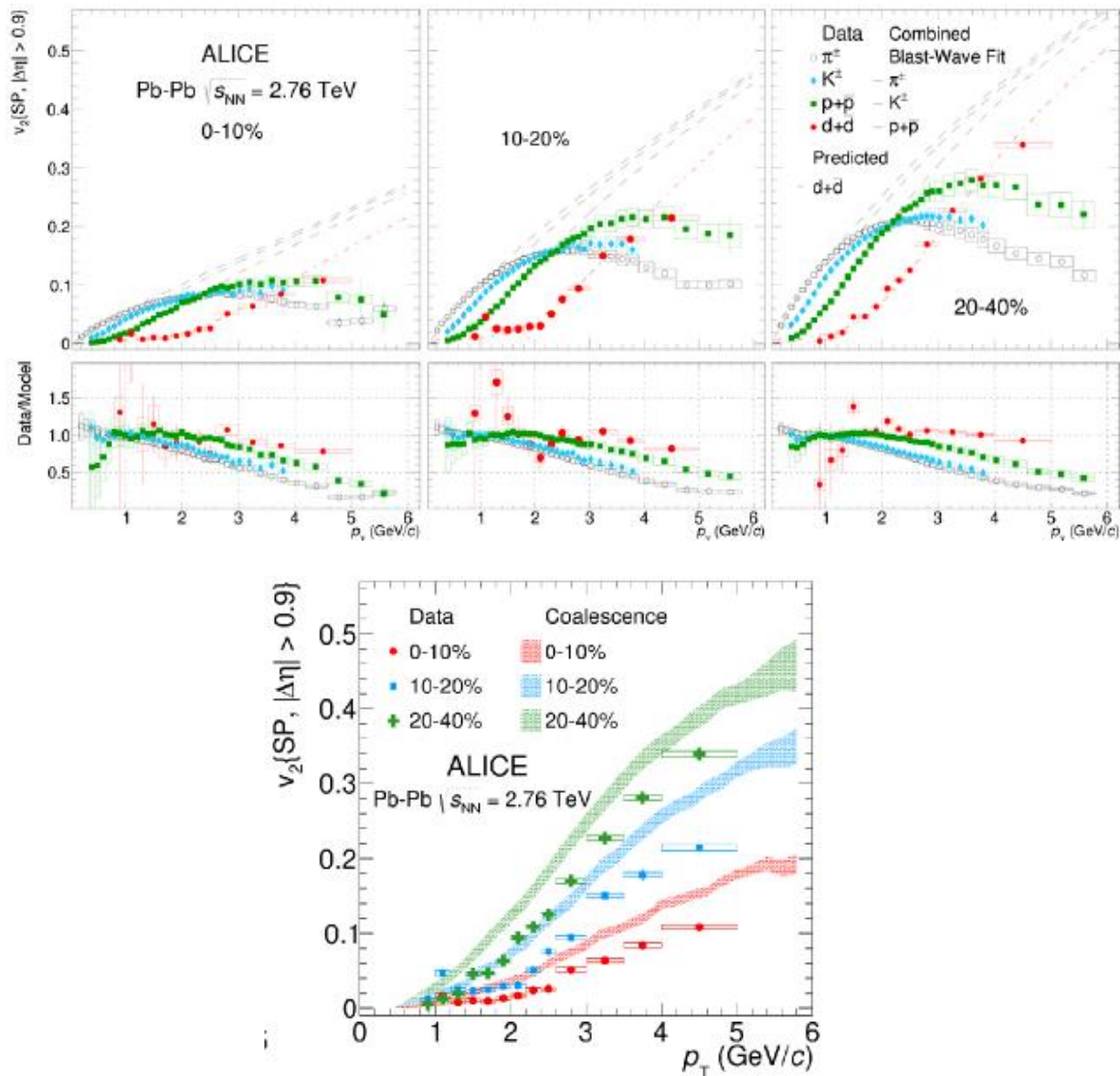
B_2 (p-Pb and Pb-Pb)

ALI-PREL-69364

Scheibl and Heinz, PRC 59 (1999) 1585
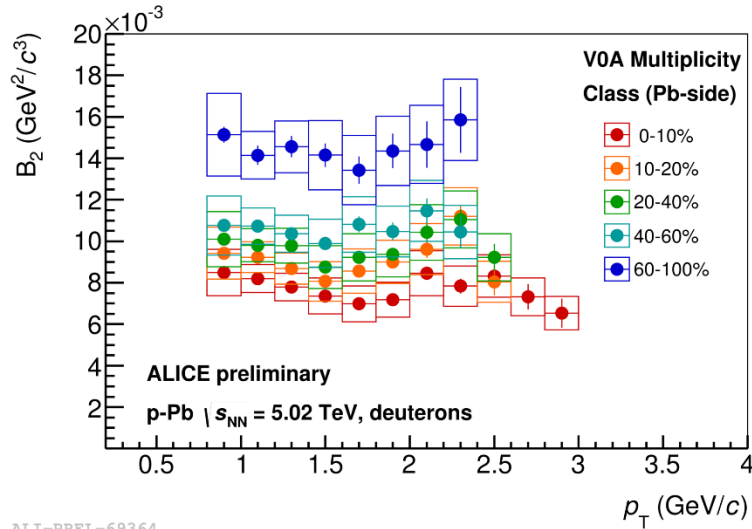
$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_t \mathcal{R}_\perp^2(m_t) \mathcal{R}_\parallel(m_t)} e^{2(m_t - m)(1/T_p^* - 1/T_d^*)}$$
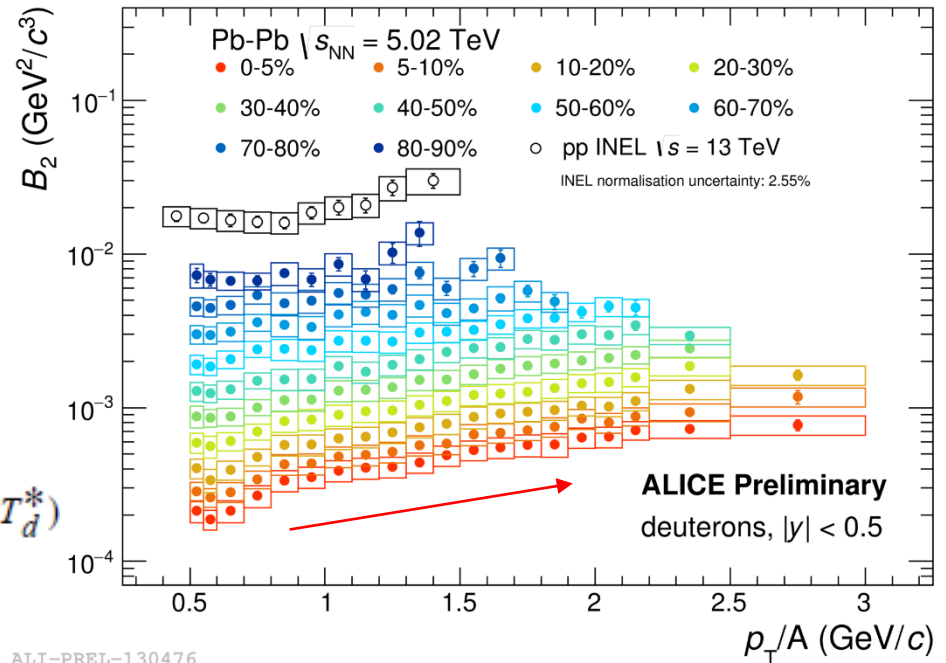
ALI-PREL-130476

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

Spare slide
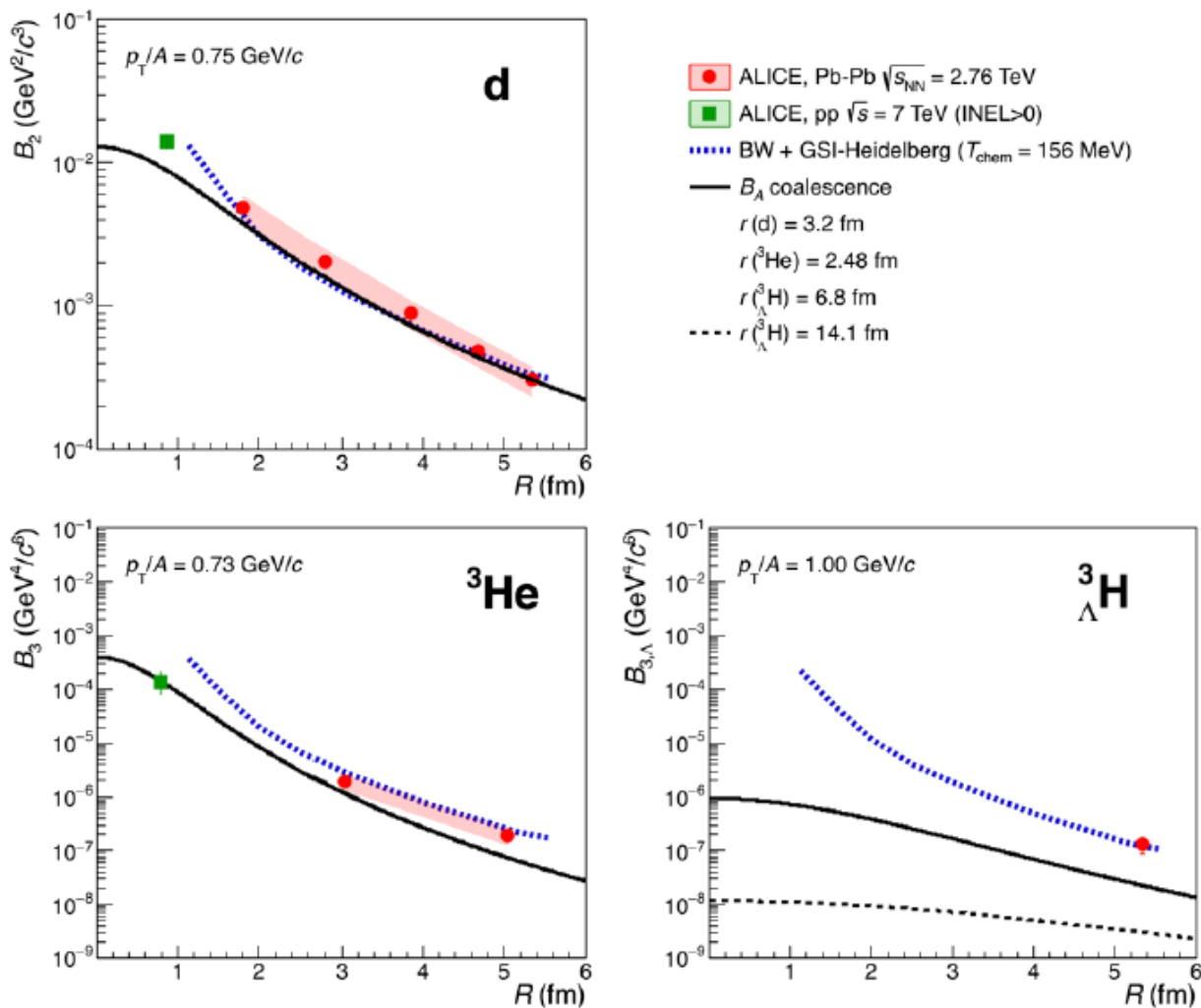
³He/p ratio (first look)
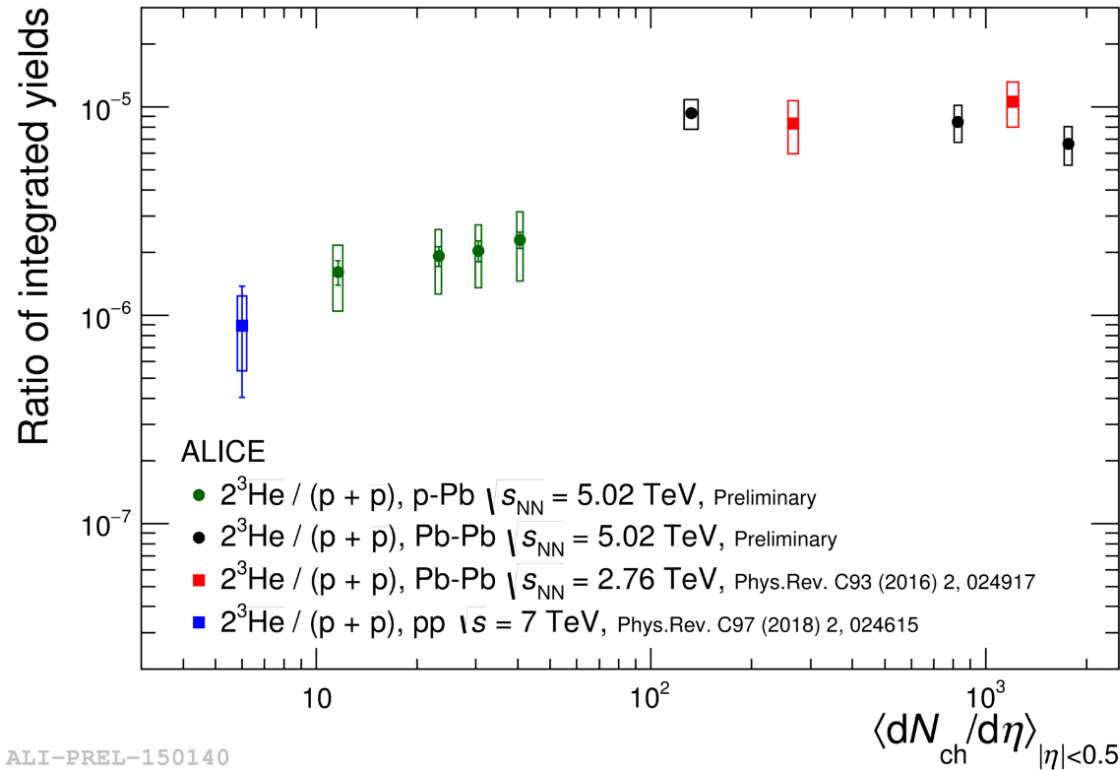
$$\frac{A}{p} \propto p^A$$

$^{3}_{\Lambda}H$ spare plots
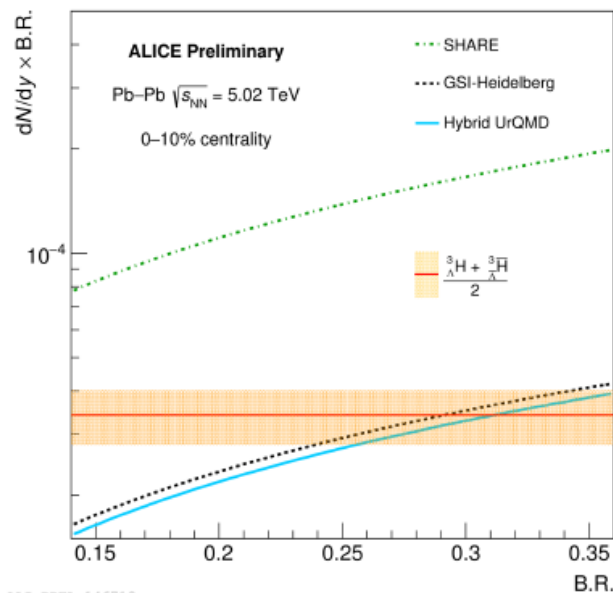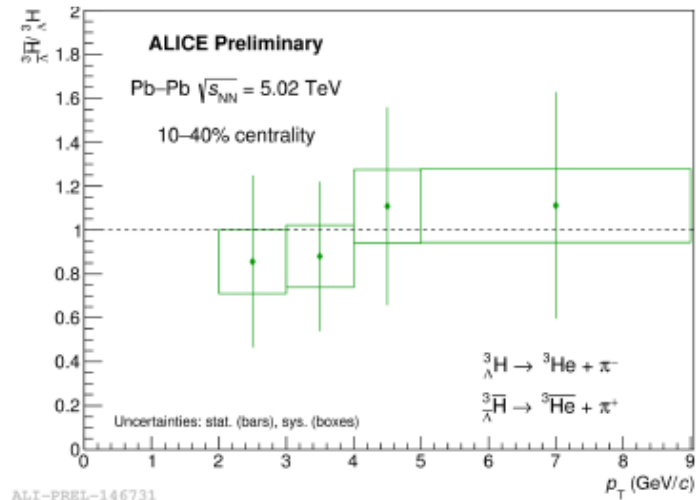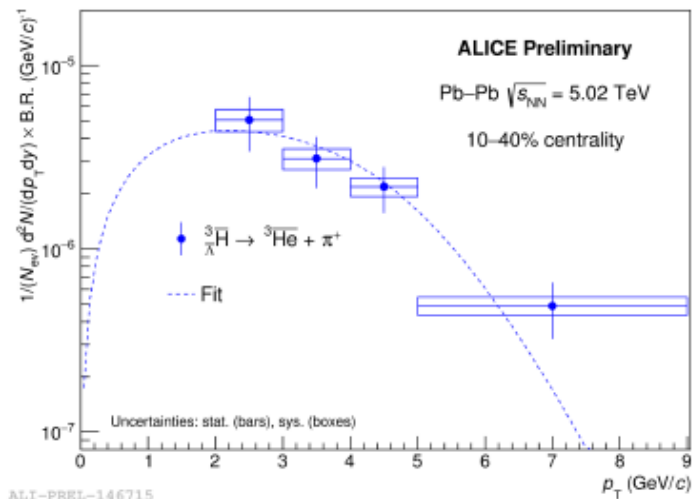
$^3_\Lambda$H / ^{3}He **ratio**
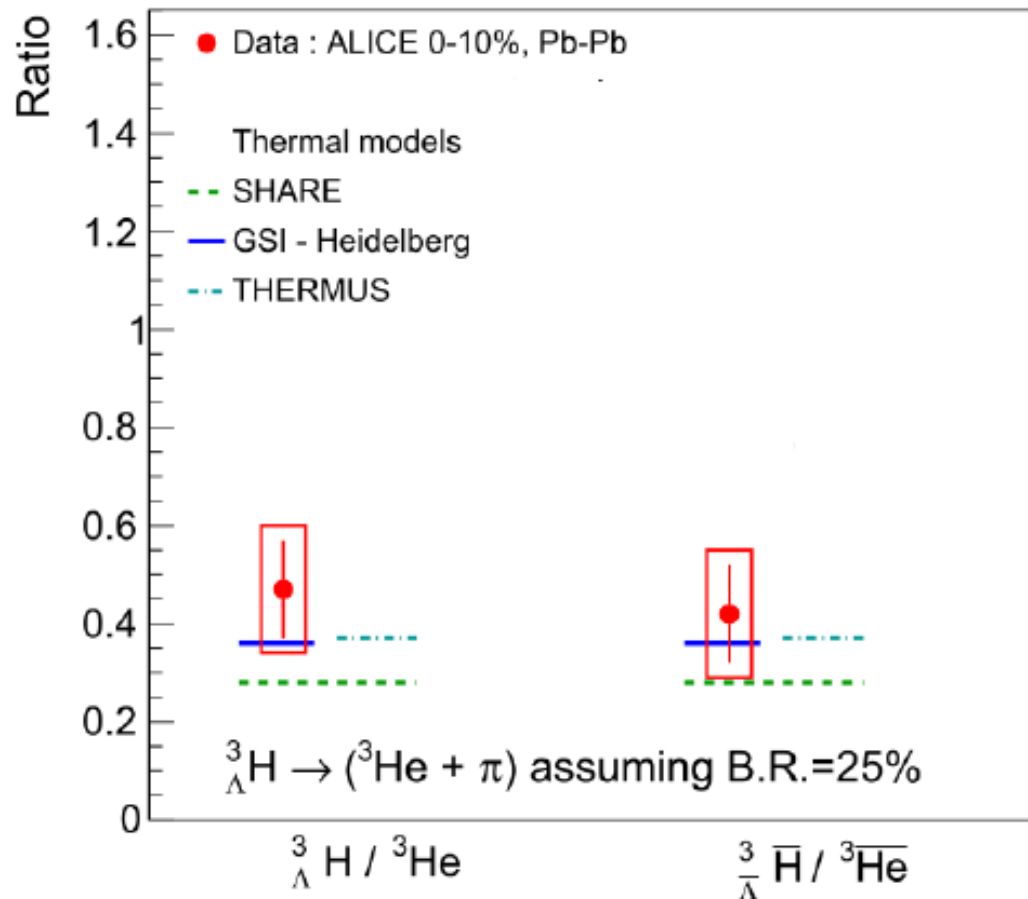
in good agreement with (equilibrium) thermal model prediction for Tch = 156 MeV such as GSI-Heildeberg model

Andronic et al., Nature 561 (2018) 321
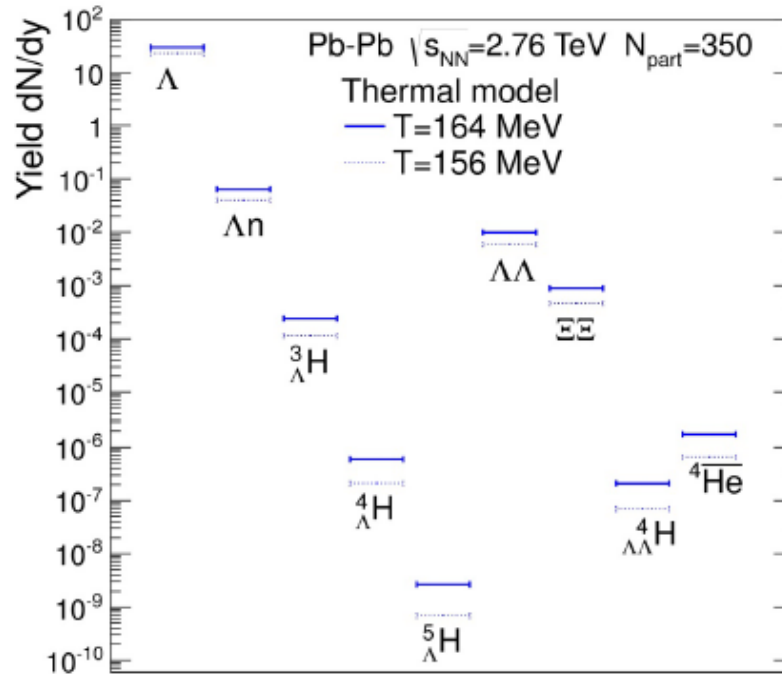
A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

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

Lower energies

ALICE Coll. PRC 97 (2018) 024615

B_2

ALICE (pp)

Legend:
- Eq. (12)
- pp ISR 53 GeV $\sqrt{s}$
- pp Serpukhov 11.5 GeV $\sqrt{s}$
- pAl/Be SPS 200-240 GeV p_{lab}
- pBe FNAL 300 GeV p_{lab}
- pTi FNAL 300 GeV p_{lab}
- pW FNAL 300 GeV p_{lab}
- PbPb central ALICE 2.76 TeV $\sqrt{s}$ high p_t
- PbPb central ALICE 2.76 TeV $\sqrt{s}$ low p_t
- PbPb off ALICE 2.76 TeV $\sqrt{s}$ high p_t
- PbPb off ALICE 2.76 TeV $\sqrt{s}$ low p_t
- PbPb Central NA44/NA49 158A GeV $\sqrt{s}$
- AuAu Central STAR 200 GeV $\sqrt{s}$
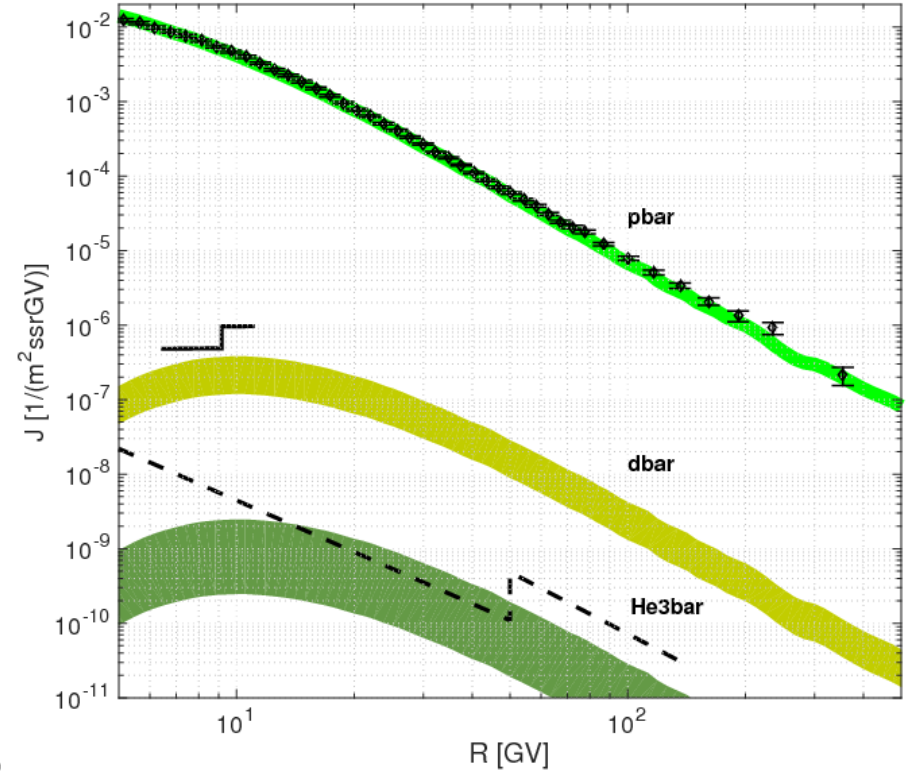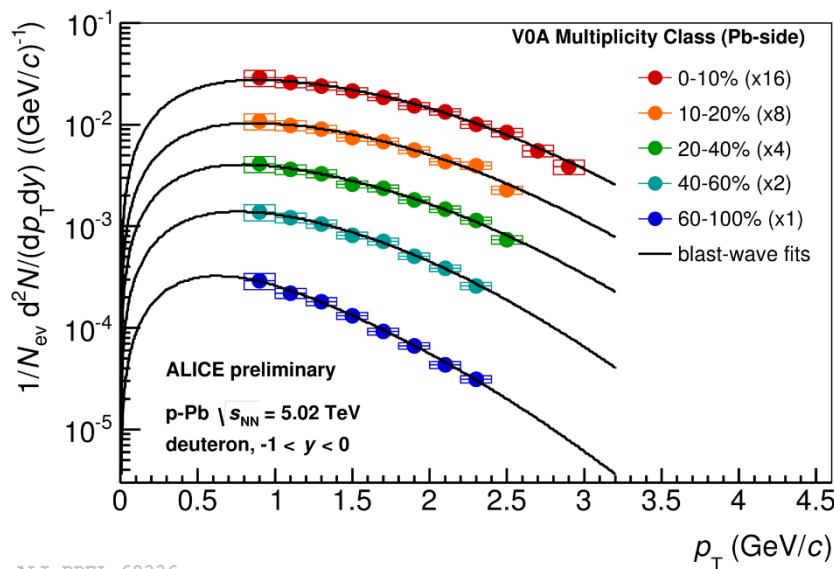
Blum et al., PRD 96 (2017) 103021

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.

Deuterons and ³He (p-Pb)

ALI-PREL-69336

Blast-Wave PRC 48 (1993) 2462

inspired hydrodynamic model describing lighter hadron spectra in p-Pb

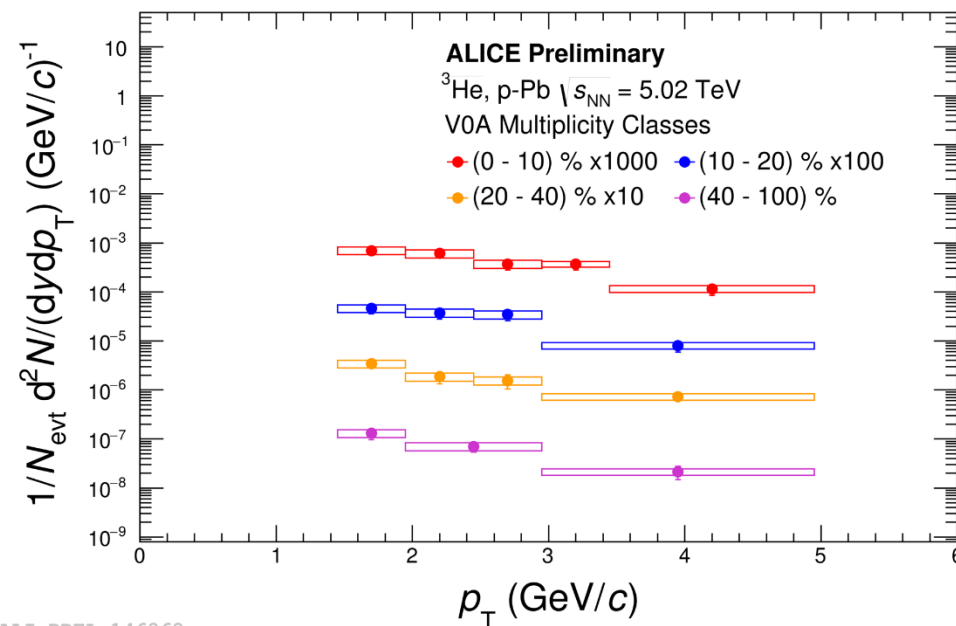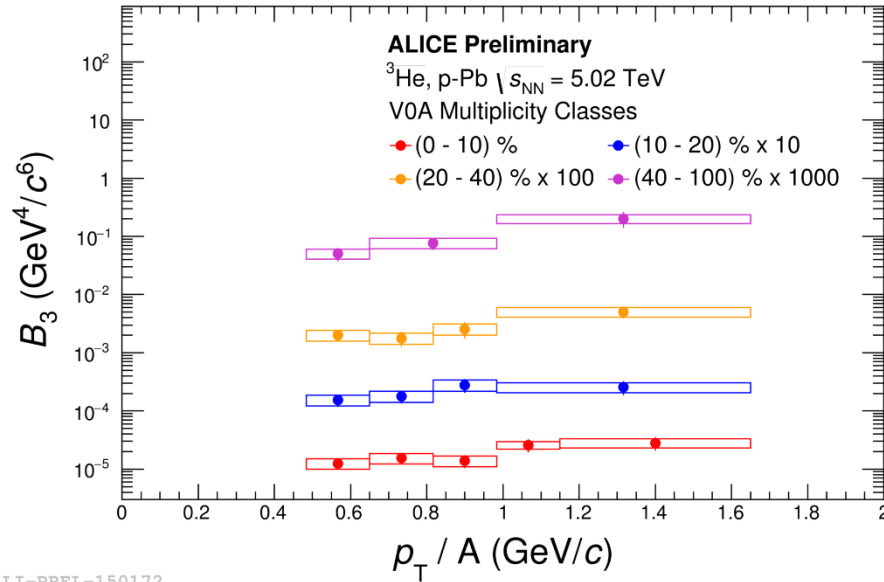→ used for extrapolating deuteron spectra in the unmeasured low/high p_T regions

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

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

(x 5 available 2013 statistics)

ALI-PREL-146262

B_3 (p-Pb and Pb-Pb)