Overview of ALICE results on anti-nuclei and anti-hypernuclei

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for the ALICE Collaboration
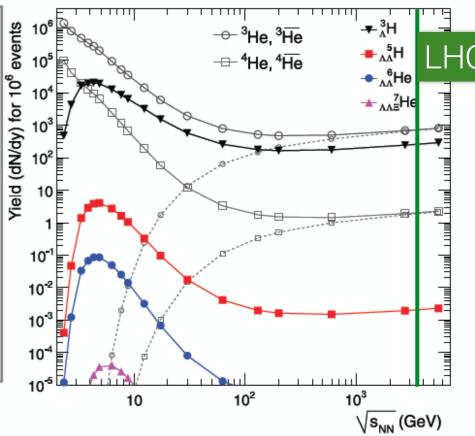
EMMI Workshop: Anti-matter, hyper-matter and exotica production at LHC

Thermal models

- Hadrons emitted from the interaction region in statistical equilibrium when the fireball reaches limiting temperature
- Abundances fixed at chemical freeze-out
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡ For nuclei (large m) strong dependence on T_{chem}

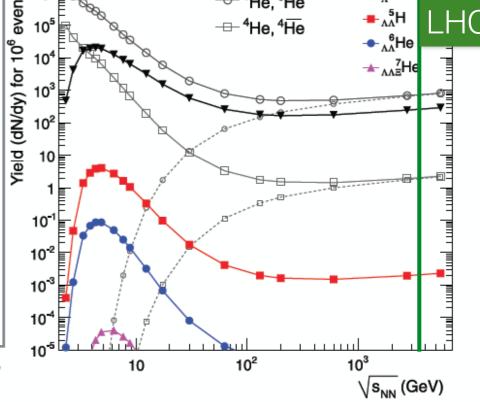A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995

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LHC

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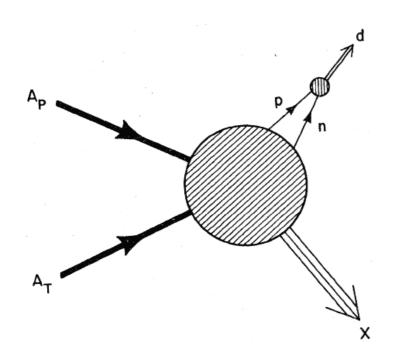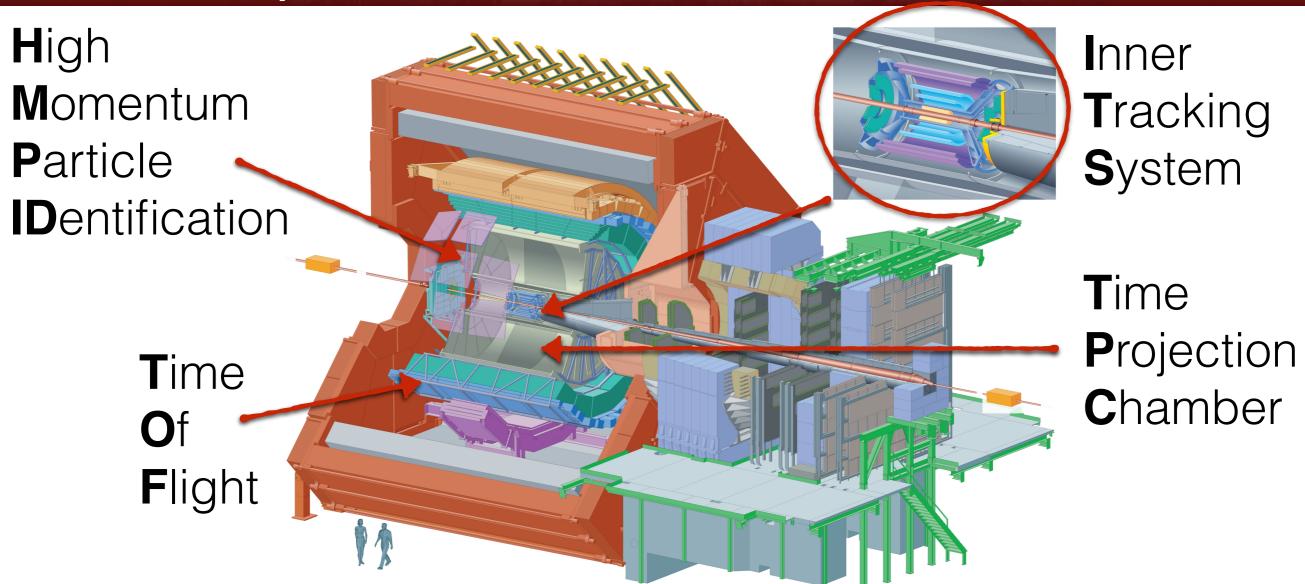

Coalescence models

- If (anti-)baryons are close in phase space after the kinetic freeze-out they can form a (anti-)nucleus
- (Anti-)nuclei produced at the chemical freeze-out might break and re-form during the time between the chemical freeze-out and the kinetic freeze-out.
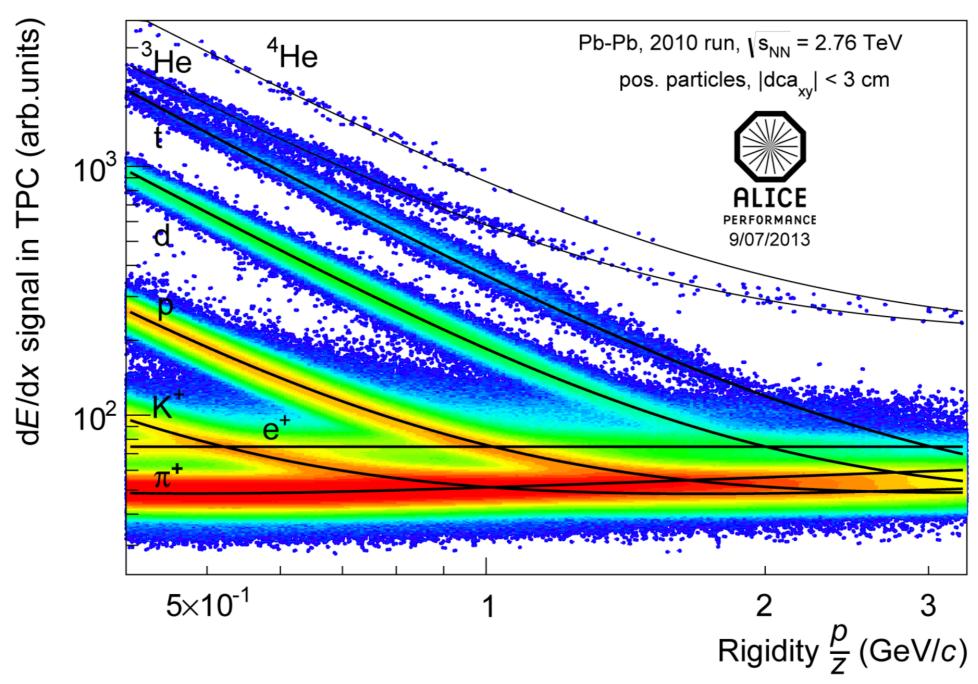
J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

2

High
Momentum
Particle
IDentification

Inner
Tracking
System

Time
Projection
Chamber

Time
Of
Flight

- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
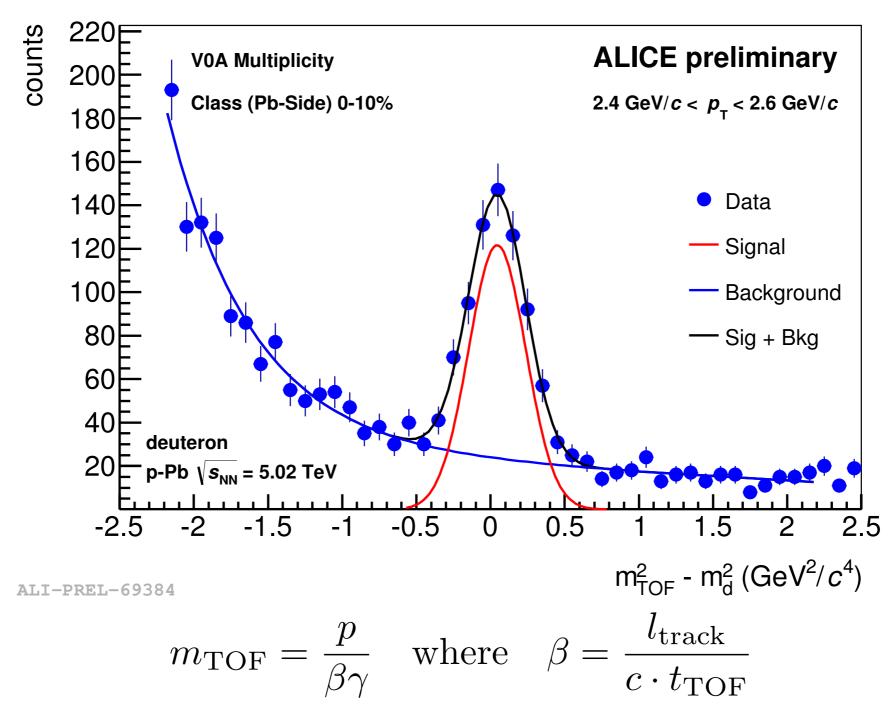- ➡ Most suited detector at the LHC to study the nuclei produced in the collisions

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Specific energy loss in the **T**ime **P**rojection **C**hamber volume provides an excellent PID for light nuclei.
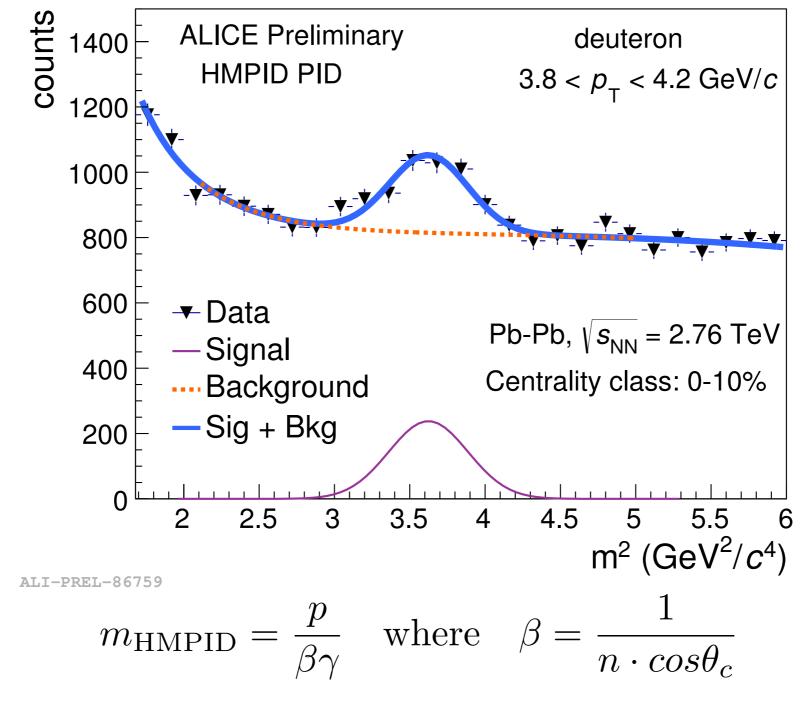
➡ $\sigma_{dE/dx} \sim 7\%$ (in Pb-Pb collisions)

ALI-PREL-69384

$$m_{\mathrm{TOF}} = \frac{p}{\beta\gamma} \quad \text{where} \quad \beta = \frac{l_{\mathrm{track}}}{c \cdot t_{\mathrm{TOF}}}$$

Tracking information + time of flight measured by the **T**ime **O**f **F**light detector
→ m of the particle

➡ $\sigma_{\text{time-of-flight}}$ ~ 85 ps (in Pb-Pb)

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ALI-PREL-86759

$$m_{\text{HMPID}} = \frac{p}{\beta\gamma} \quad \text{where} \quad \beta = \frac{1}{n \cdot cos\theta_c}$$
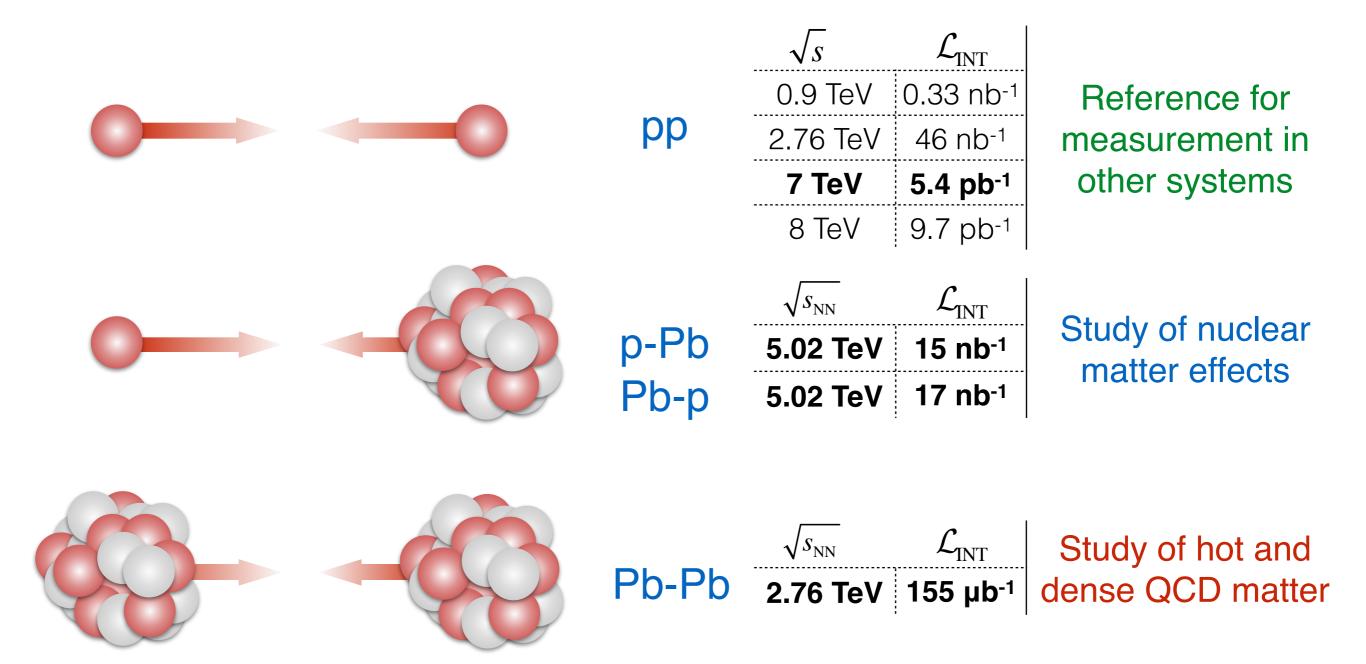
Tracking information + **H**igh **M**omentum **P**article **ID**entification detector (Cherenkov light detector) signal

→ m of the particle

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Collision systems at the LHC

pp

$\sqrt{s}$	$\mathcal{L}_{INT}$
0.9 TeV	0.33 nb^{-1}
2.76 TeV	46 nb^{-1}
7 TeV	**5.4 pb^{-1}**
8 TeV	9.7 pb^{-1}

Reference for measurement in other systems

p-Pb
Pb-p

$\sqrt{s_{NN}}$	$\mathcal{L}_{INT}$
5.02 TeV	**15 nb^{-1}**
5.02 TeV	**17 nb^{-1}**

Study of nuclear matter effects

Pb-Pb

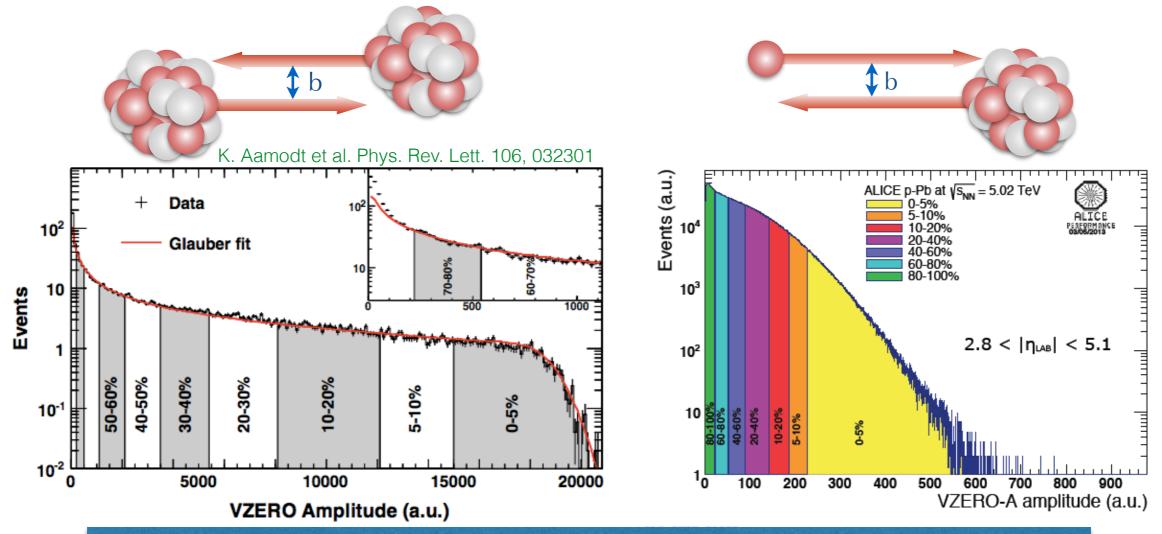| $\sqrt{s_{NN}}$	$\mathcal{L}_{INT}$
2.76 TeV	**155 µb^{-1}**

Study of hot and dense QCD matter

Three collision systems: unique opportunity to further study hadronisation and the strong interaction at extreme regimes of energy density

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The centrality of a collision is defined by the impact parameter *b*:

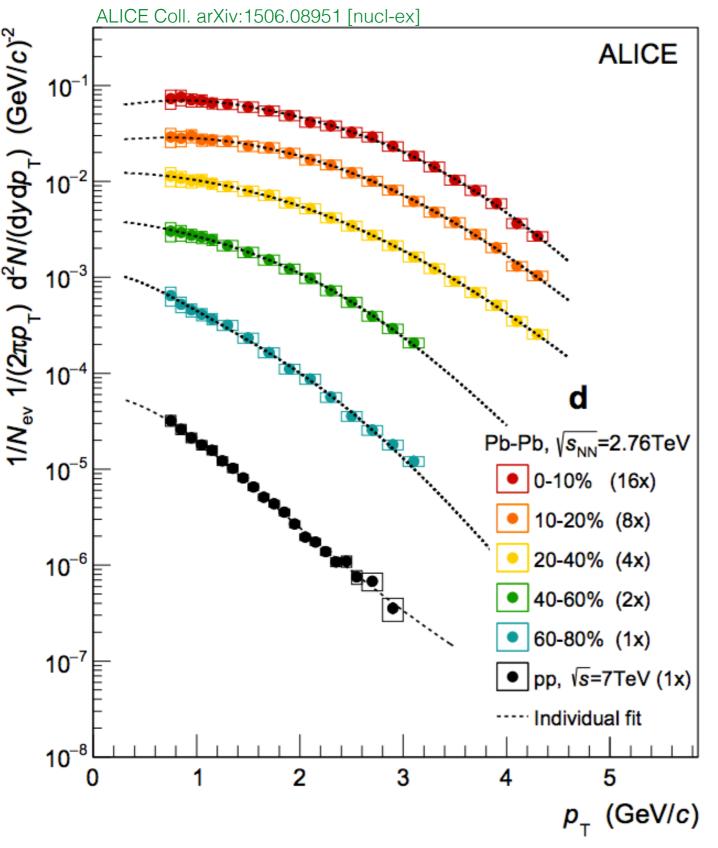*Most central collision ⇔ Smallest b*

Experimentally it is possible to correlate the charged particle multiplicity to *b* by fitting data with the function shape predicted by the Glauber model.

The correlation between charged particle mult. and impact parameter in p-Pb is broader.

K. Aamodt et al. Phys. Rev. Lett. 106, 032301

ALICE p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

$2.8 < |\eta_{LAB}| < 5.1$

V-ZERO is a scintillator hodoscope used for centrality estimation and for the trigger.

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Deuteron production in pp and Pb-Pb

pp

Invariant production spectrum is well fitted by the Levy-Tsallis function in pp

$$\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = p_{\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}y}\frac{(n-1)(n-2)}{nC(nC + m_0(n-2))}\left(1 + \frac{m_{\mathrm{T}} - m_0}{nC}\right)^{-1}$$

where m_0 is the reference mass of the deuteron and n,C are fit parameters.

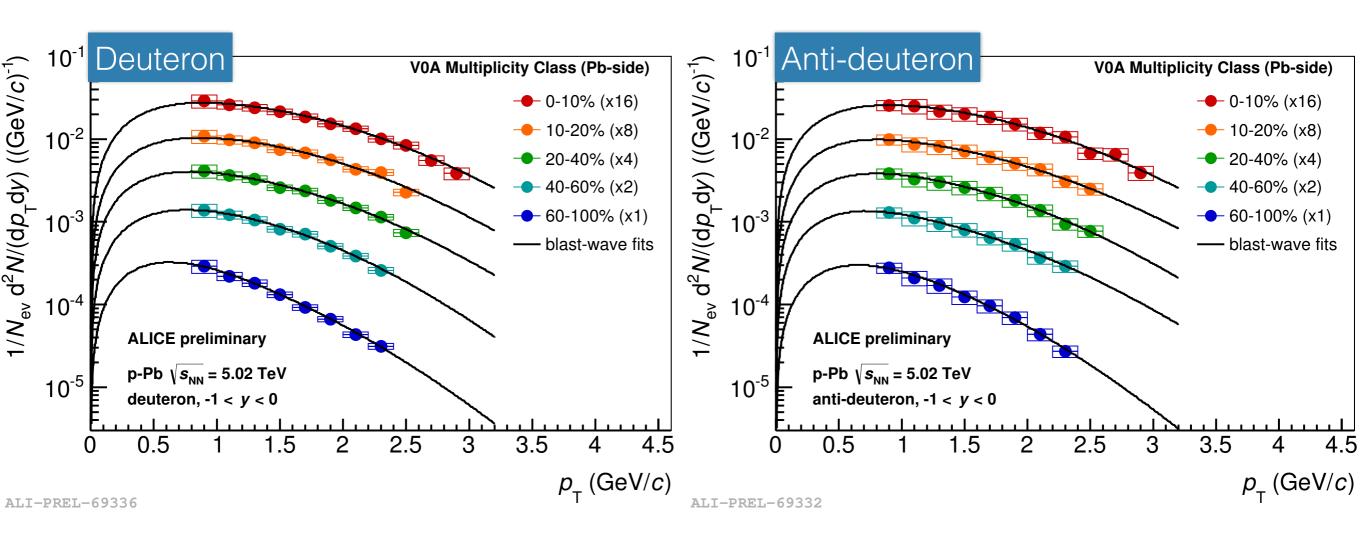C. Tsallis. J.Statist.Phys. 52 479-487(1988)

Pb-Pb

- The Blast-Wave (BW) function fits well the data.
- Characteristic hardening of the spectrum with increasing centrality.
- These fits are used for the extrapolation of the yield to the unmeasured region at low and high p_{T}.

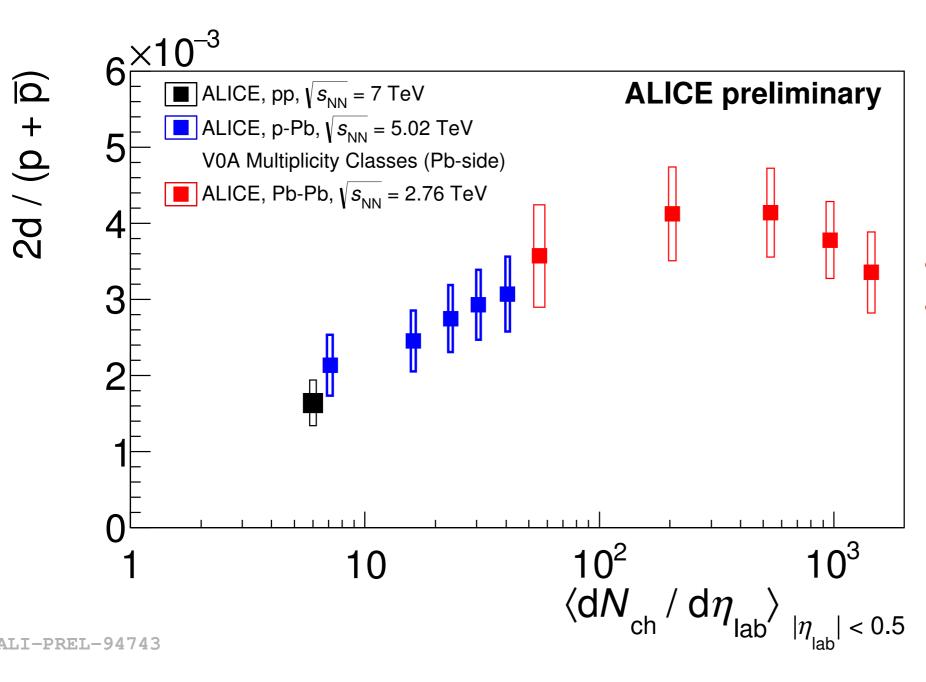Blast wave model: E. Schnedermann et al., Phys. Rev. C48, 2462 (1993)

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The Blast-Wave function fits well the data also in this case.

ALI–PREL–69336

ALI–PREL–69332

The spectra become harder with increasing multiplicity
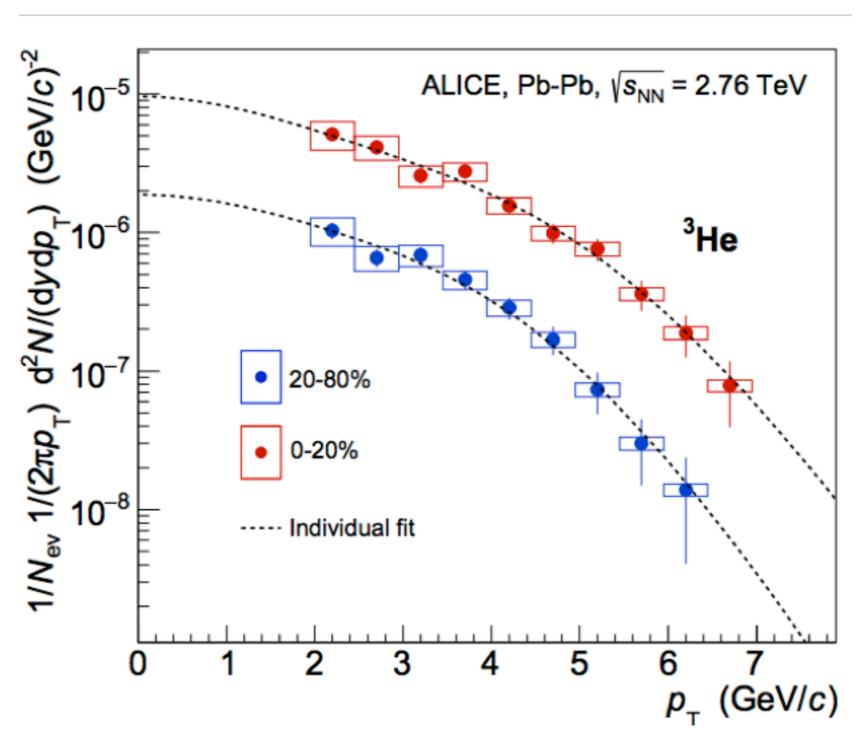
d / p ratio

ALI-PREL-94743

- Rise with multiplicity
- No further increase in Pb-Pb collisions within errors

The d/p ratio increases with the charged particle multiplicity: this is consistent with the coalescence picture
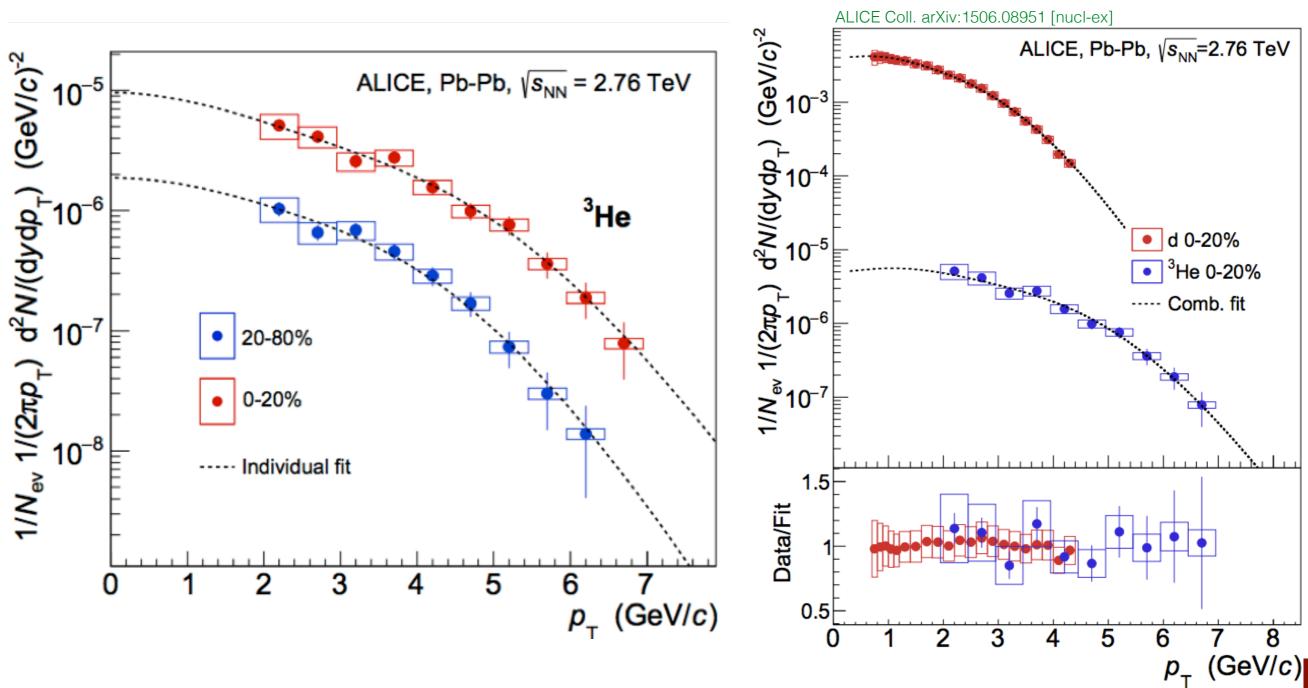
The individual Blast-Wave fits describe well the data.

(Anti-)³He production in Pb-Pb

It is possible to fit simultaneously deuteron and ³He to extract common parameters. The simultaneous fit describes well the data and the common kinetic freeze-out temperature is $T_{kin}=83\pm22$ MeV

BW model fit:

- gives insight into the kinetic freeze-out conditions
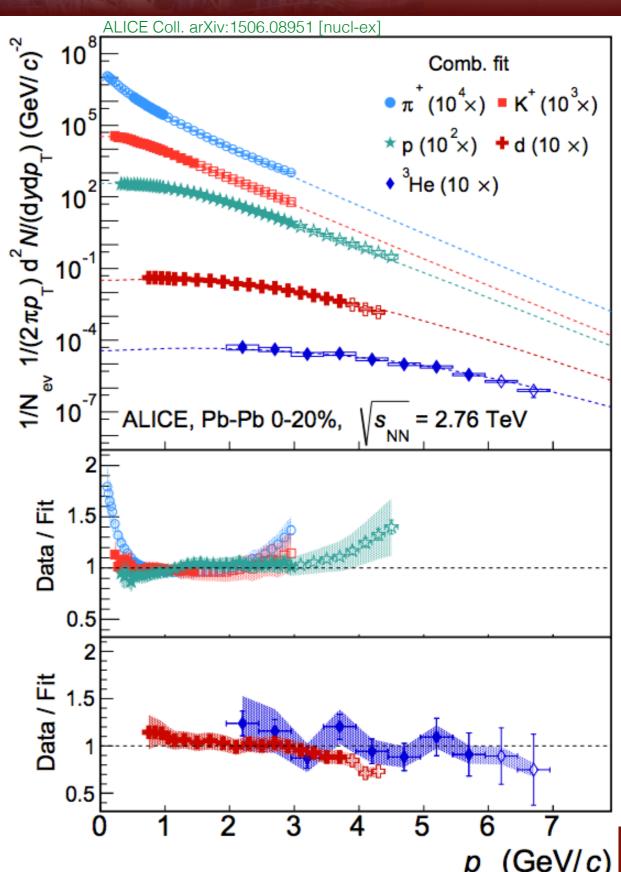- does not describe hard processes that contribute to particle production at high p_T

Fit parameters
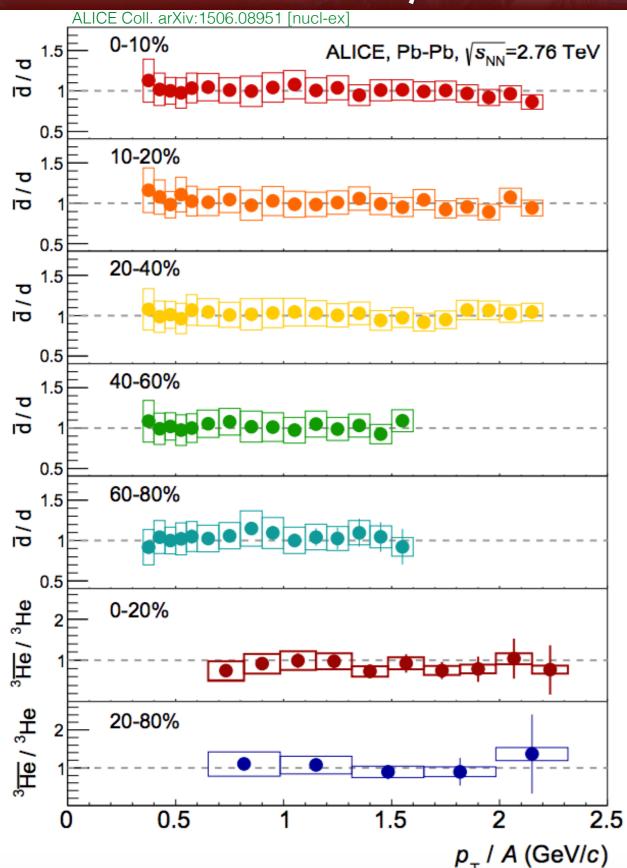$<\beta> = 0.632 \pm 0.01$
$T_{kin} = 113 \pm 12$ MeV
$n = 0.72 \pm 0.03$

With respect to the fit performed without the nuclei the $<\beta>$ decreased while the T_{kin} increased but they are compatible within the uncertainties.

Solid symbols denote the spectra points used for the fit.

ALICE Coll. arXiv:1506.08951 [nucl-ex]

Comb. fit
π^+ $(10^4 \times)$ K^+ $(10^3 \times)$
p $(10^2 \times)$ d $(10 \times)$
^{3}He $(10 \times)$

ALICE, Pb-Pb 0-20%, $\sqrt{s_{NN}} = 2.76$ TeV

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ALICE Coll. arXiv:1506.08951 [nucl-ex]

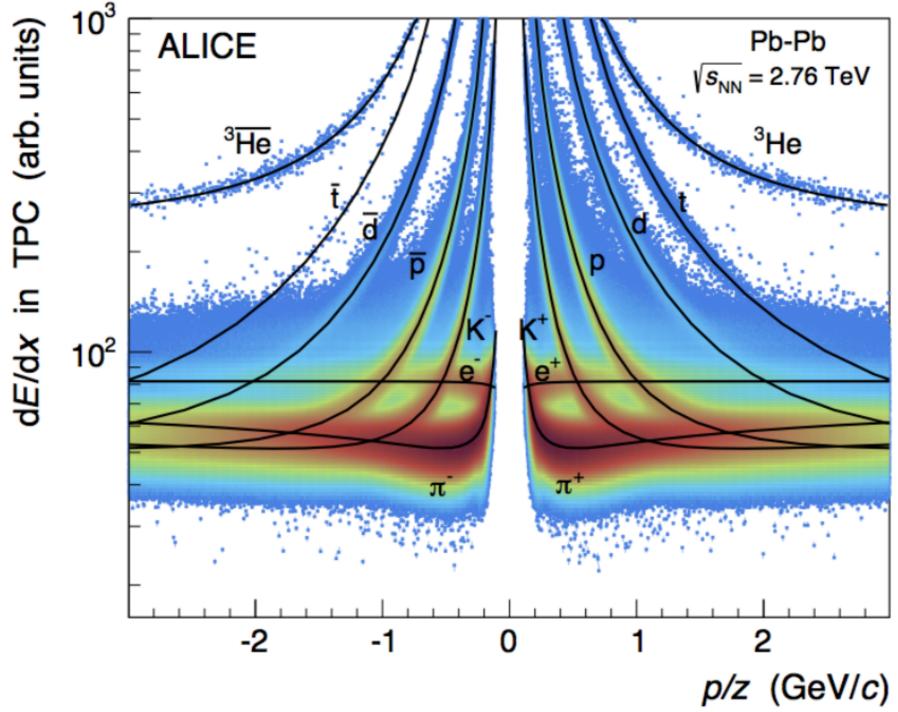The ratio nuclei / anti-nuclei is compatible with one

The same ratio is seen for other particle species measured at the LHC

A large fraction of the systematic uncertainties on the determination of the ratios is due to the limited knowledge of the cross sections of anti-nuclei interacting with the material of the detector.

Only those tracks which pass the pre-selection done by applying a 3σ cut on the TPC dE/dx are considered as anti-triton candidates.

M. Puccio - (Anti-)(Hyper-)matter production at LHC with ALICE - EMMI Workshop 2015

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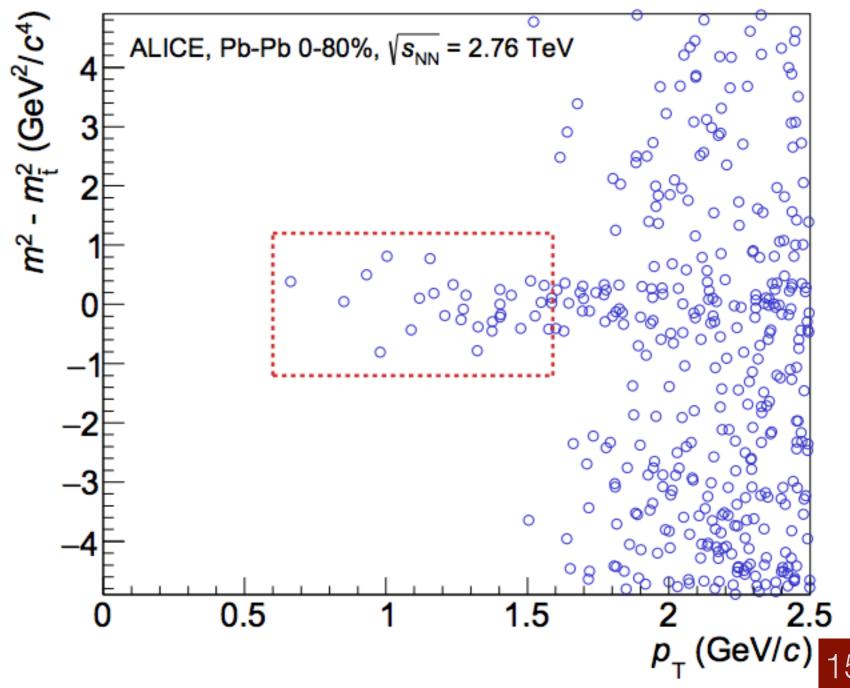
- 31 anti-tritons can be identified unambiguously

- In this kinematic range, extrapolations place the expected anti-triton yield somewhere between 11 and 40 particles

ALICE, Pb-Pb 0-80%, $\sqrt{s_{NN}}$ = 2.76 TeV

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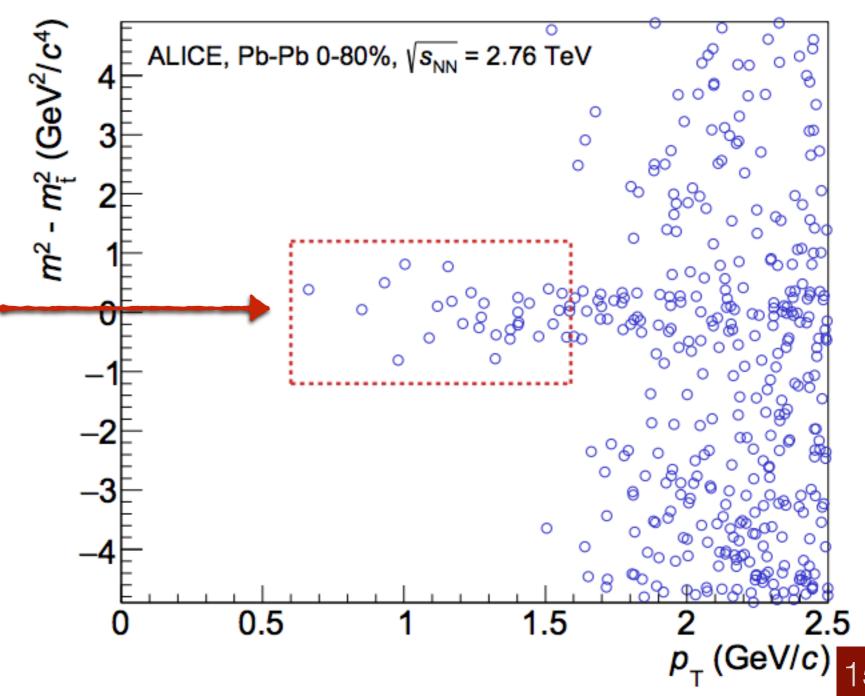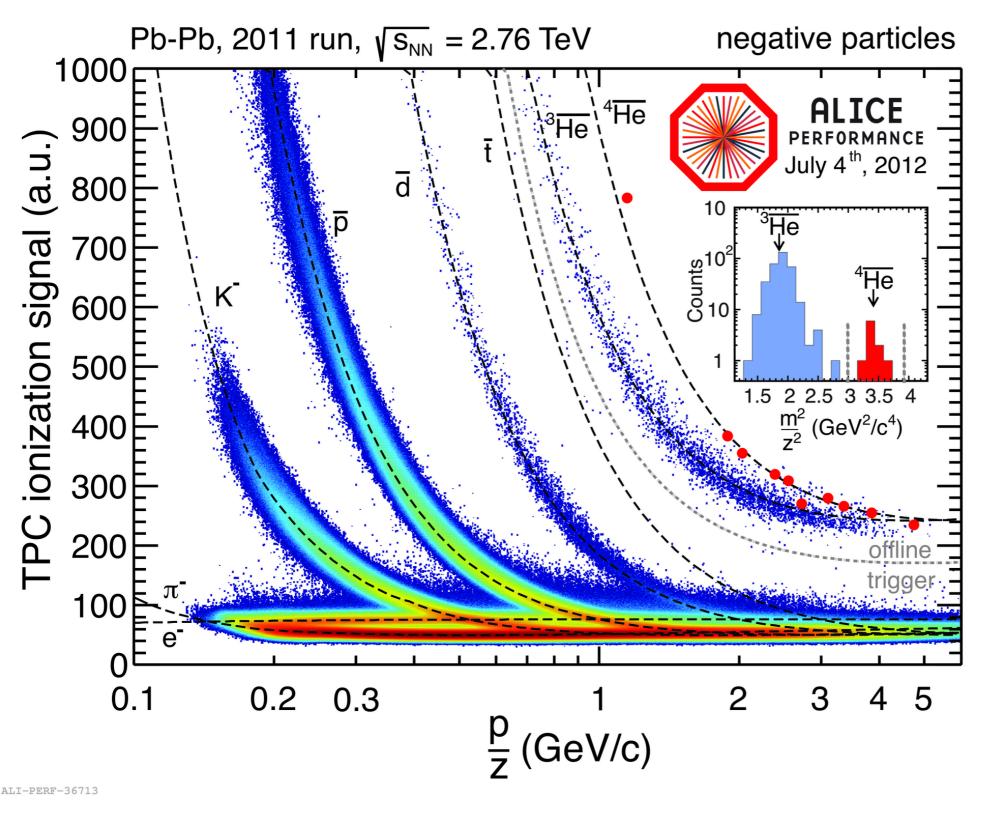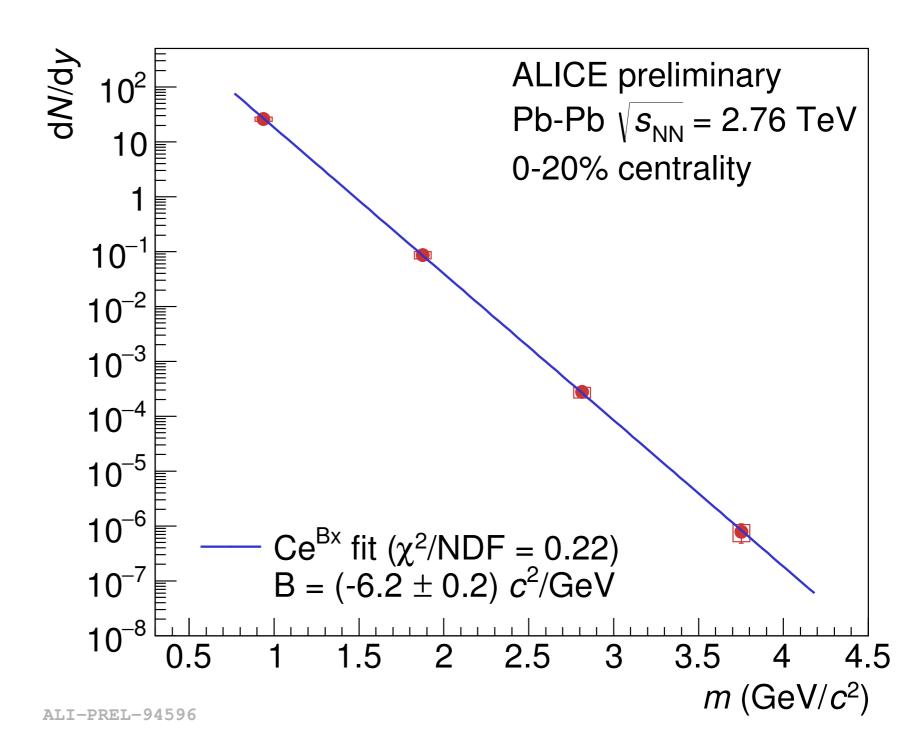

ALICE, Pb-Pb 0-80%, $\sqrt{s_{NN}}$ = 2.76 TeV

$m^2 - m_{\bar{t}}^2$ (GeV^2/c^4)
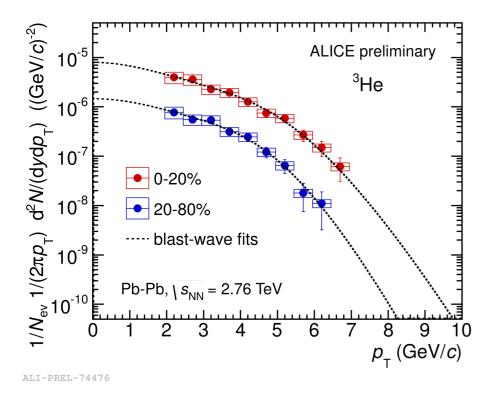
p_T (GeV/c)

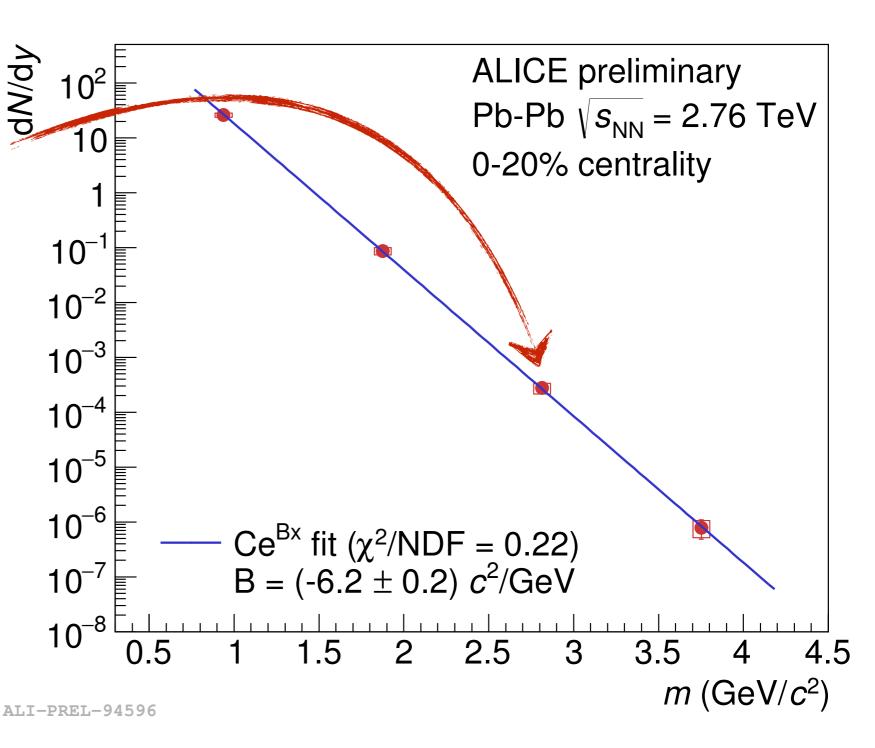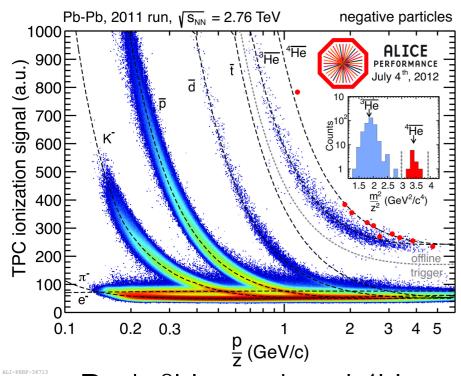Pb-Pb, 2011 run, $\sqrt{s_{NN}}$ = 2.76 TeV — negative particles

- TPC allows to separate particles with Z=2 from Z=1 particles over the full momentum range.
- Using also the TOF PID it is possible to measure about 10 anti-⁴He
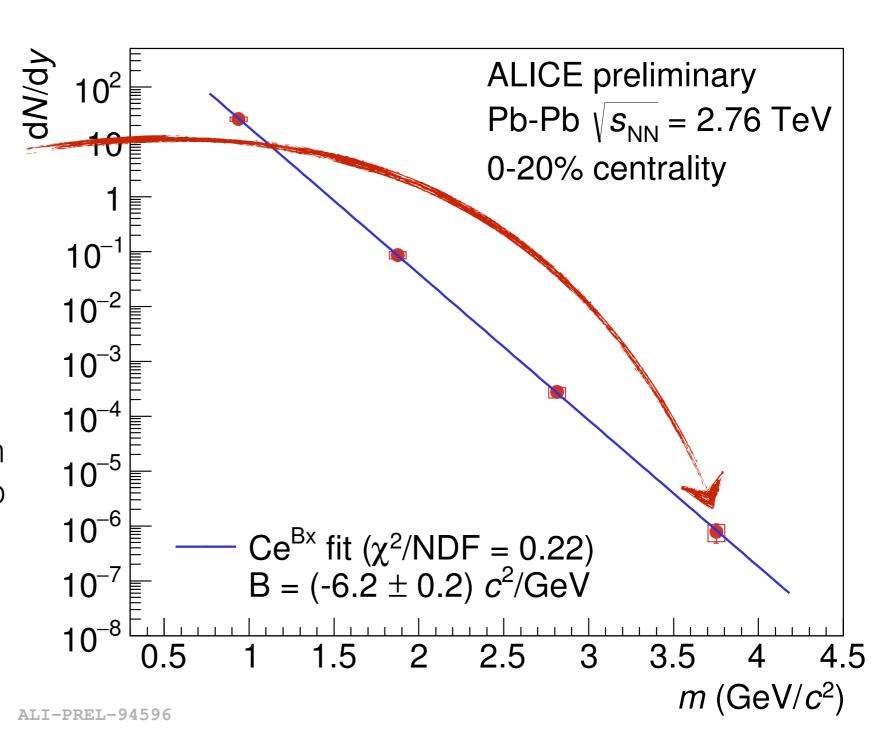
ALI-PERF-36713

ALI−PREL−94596

ALICE preliminary

^{3}He

0-20%

20-80%

blast-wave fits

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

$\dfrac{1}{N_{ev}} \dfrac{1}{(2\pi p_T)} d^2N/(dy dp_T)$ $((GeV/c)^{-2})$

p_T (GeV/c)

ALI−PREL−74476

Both ^{3}He and anti-^{4}He integrated yields have been measured and compared to deuteron and proton integrated yields

dN/dy

ALICE preliminary
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
0-20% centrality

Ce^{Bx} fit (χ^2/NDF = 0.22)
B = (-6.2 ± 0.2) c^2/GeV

m (GeV/c^2)

ALI−PREL−94596

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Pb-Pb, 2011 run, $\sqrt{s_{NN}} = 2.76$ TeV — negative particles

ALICE PERFORMANCE July 4th, 2012

ALI-PERF-36713
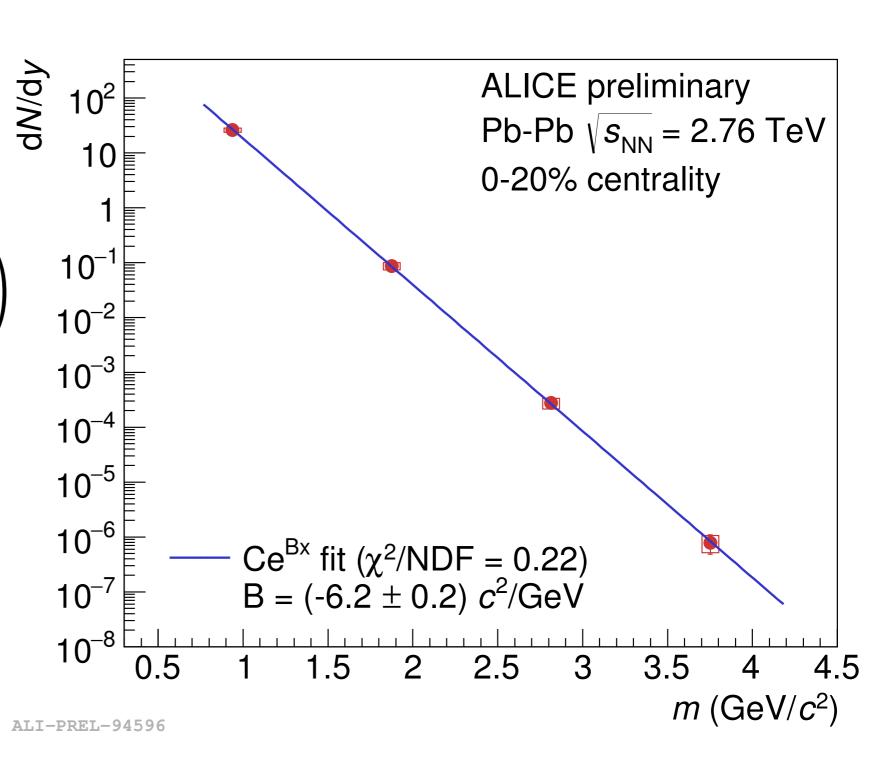
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ALICE preliminary
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
0-20% centrality

Ce^{Bx} fit (χ^2/NDF = 0.22)
B = (-6.2 ± 0.2) c^2/GeV

ALI-PREL-94596

Thermal model predicts:

$$\frac{\mathrm{d}N}{\mathrm{d}y} \propto exp\left(-\frac{m}{T_{\text{chem}}}\right)$$

- Verified with nuclei!
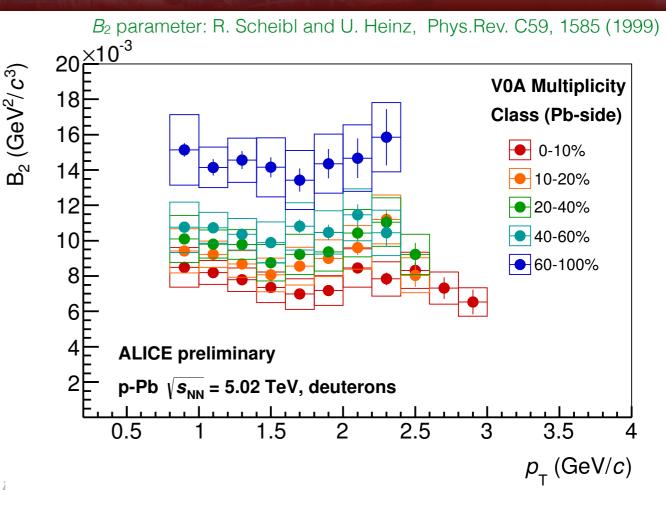- Each nucleon added gives a penalty of a factor ~300 in the integrated yield

ALICE preliminary
Pb-Pb $\sqrt{s_{\text{NN}}}$ = 2.76 TeV
0-20% centrality

Ce^{Bx} fit (χ^2/NDF = 0.22)
B = (-6.2 ± 0.2) c^2/GeV

ALI-PREL-94596

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Coalescence parameter B₂

The **coalescence parameter**, defined as:

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

is predicted to be p_T independent by the simplest formulation of coalescence model.

This is observed in p-Pb collisions.

ALICE preliminary

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV, deuterons

V0A Multiplicity Class (Pb-side)
- 0-10%
- 10-20%
- 20-40%
- 40-60%
- 60-100%

Coalescence parameter B_2

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is predicted to be p_T independent by the simplest formulation of coalescence model.
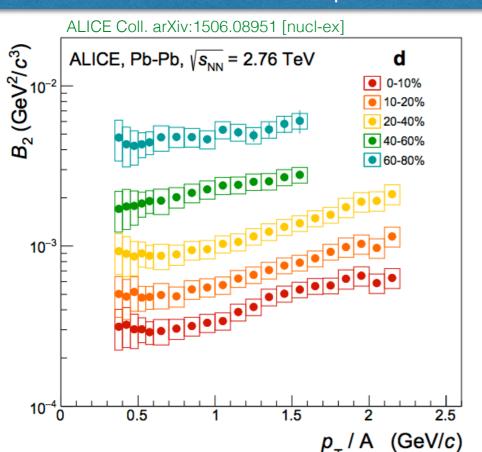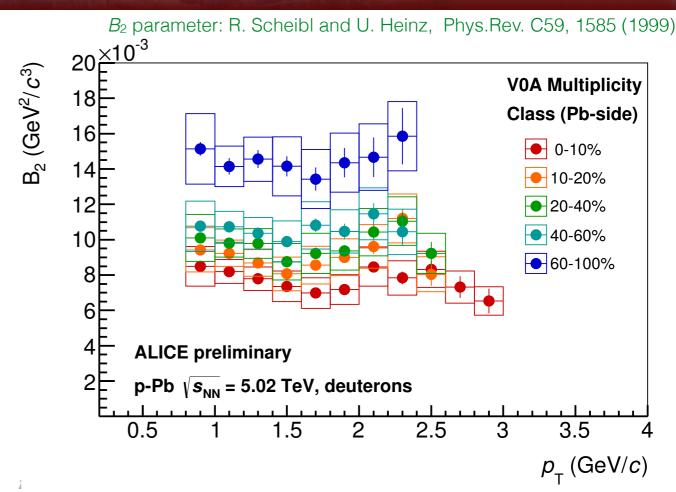
This is observed in p-Pb collisions.

ALICE Coll. arXiv:1506.08951 [nucl-ex]

The coalescence parameter gets smaller as the events are more central. This is due to the increasing size of the emitting source.

The B_2 depends on p_T in central events, which could be explained by looking at the Hanbury Brown and Twiss radii dependence of the B_2.
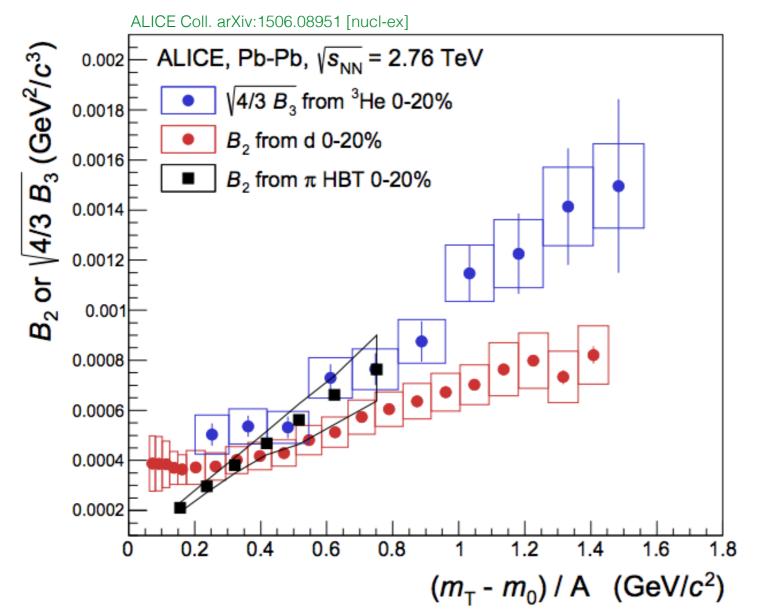
The coalescence parameter can be expressed as a function of the HBT radii:

$$B_2 = \frac{3\pi^{3/2}\langle C_{\mathrm{d}}\rangle}{2m_{\mathrm{T}}R_{\perp}^2(m_{\mathrm{T}})R_{\parallel}(m_{\mathrm{T}})}$$

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

A rough agreement is found in terms of magnitude and the dependence on p_{T}.

ALICE Coll. arXiv:1506.08951 [nucl-ex]

The coalescence parameter for a nucleus *i* with A nucleons is defined as:

$$E_i\frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A\left(E_{\mathrm{p}}\frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3}\right)^A$$

From this it is possible to derive a recursive formula. For instance for the ³He:

$$B_3 = B_2^2\left(\frac{M_{^3He}\cdot m}{M_d^2}\right) \approx \frac{3}{4}B_2^2$$

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Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Decay modes

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

$$^{3}_{\Lambda}\text{H} \rightarrow ^{3}\text{He} + \pi^{-}$$

$$^{3}_{\Lambda}\text{H} \rightarrow ^{3}\text{H} + \pi^{0}$$

$$^{3}_{\Lambda}\text{H} \rightarrow \text{d} + \text{p} + \pi^{-}$$

$$^{3}_{\Lambda}\text{H} \rightarrow \text{d} + \text{n} + \pi^{0}$$

+ anti-hypertriton counterpart

20

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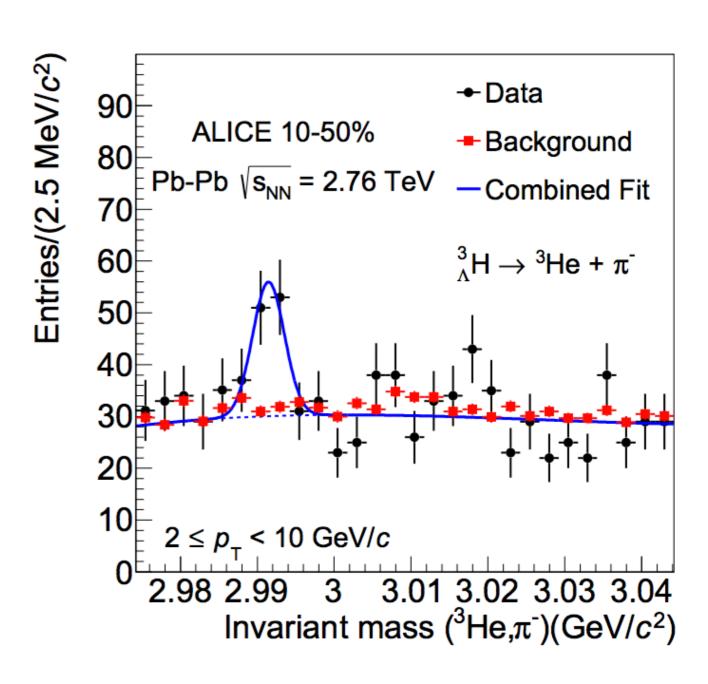
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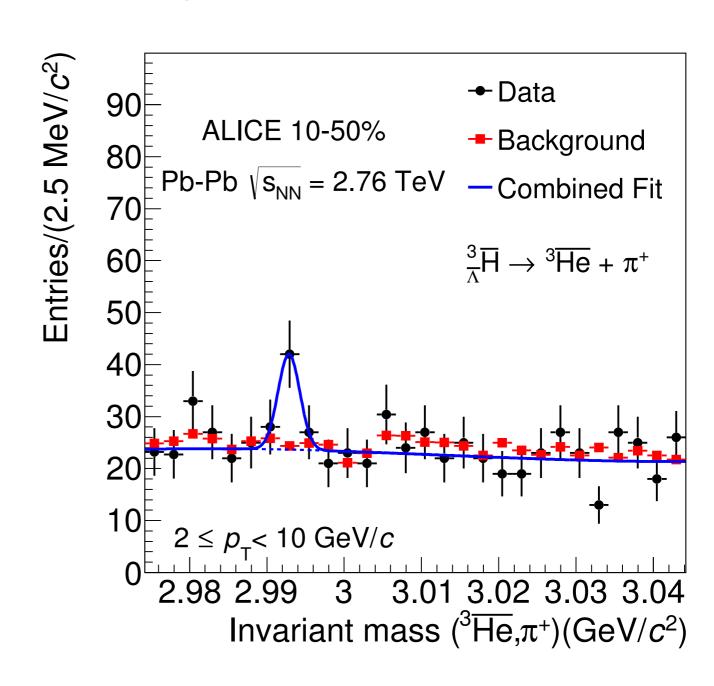 - reduce combinatorial background
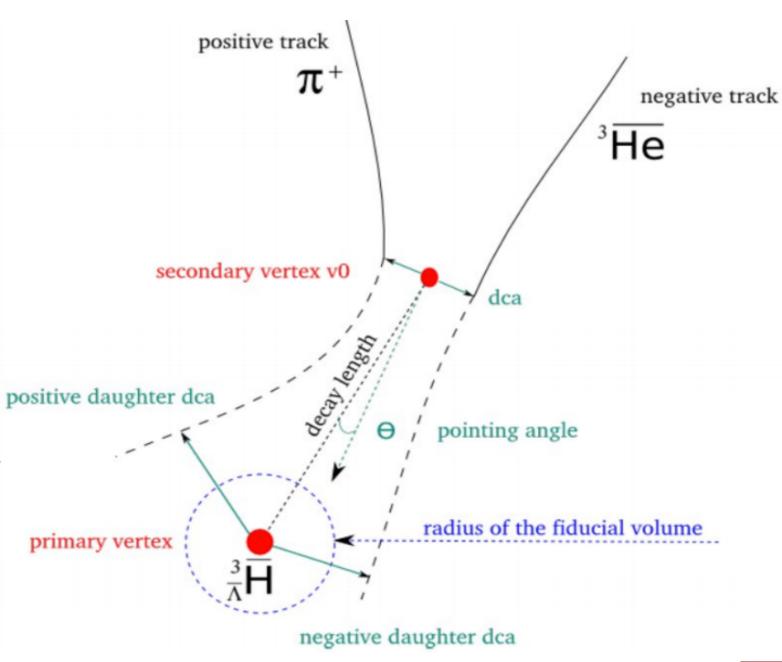
(Anti-)Hyper-triton in Pb-Pb

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Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

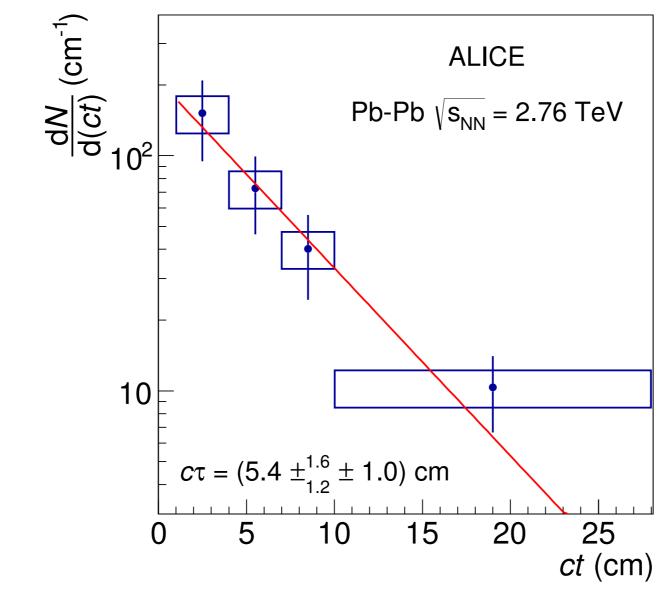Mass = 2.991 GeV/c^2
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Signal Extraction:
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ALICE 10-50%
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

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

2 ≤ p_T < 10 GeV/c

Entries/(2.5 MeV/c^2)

Invariant mass ($^3\overline{He},\pi^+$)(GeV/c^2)

- Data
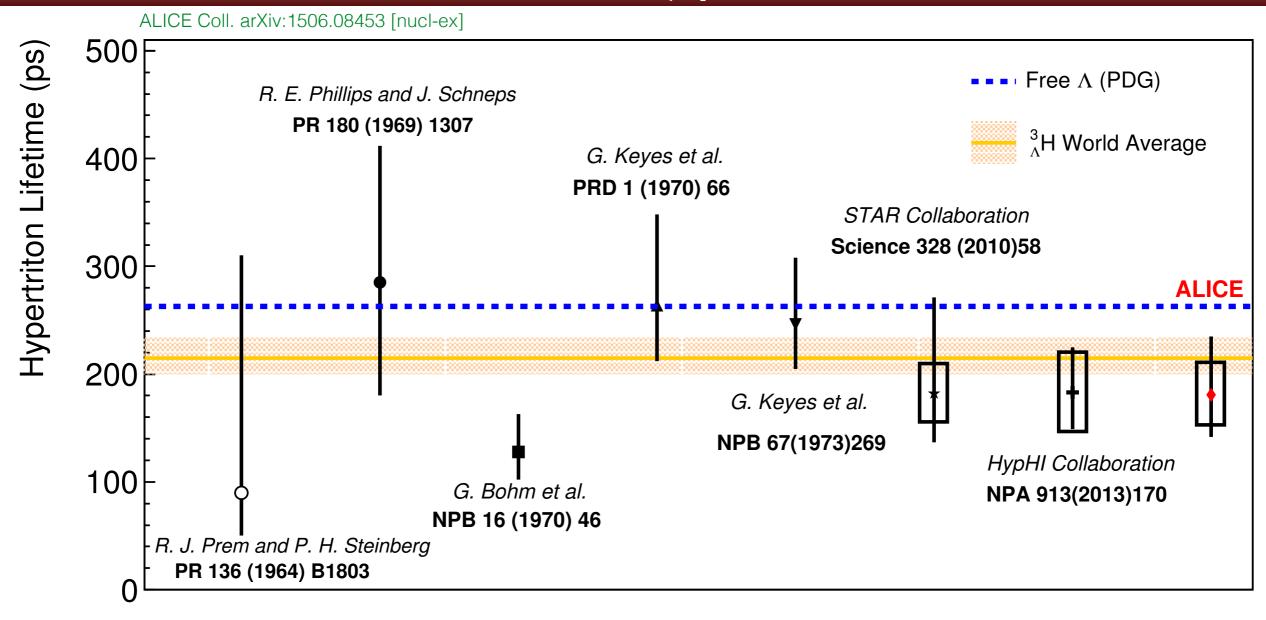- Background
- Combined Fit

From the exponential fit to the differential yield in different ct bins it is possible to extract the lifetime of the hyper-triton

ALICE

$$\tau(181^{+54}_{-39}(\text{stat.}) \pm 33(\text{syst})) \text{ ps}$$
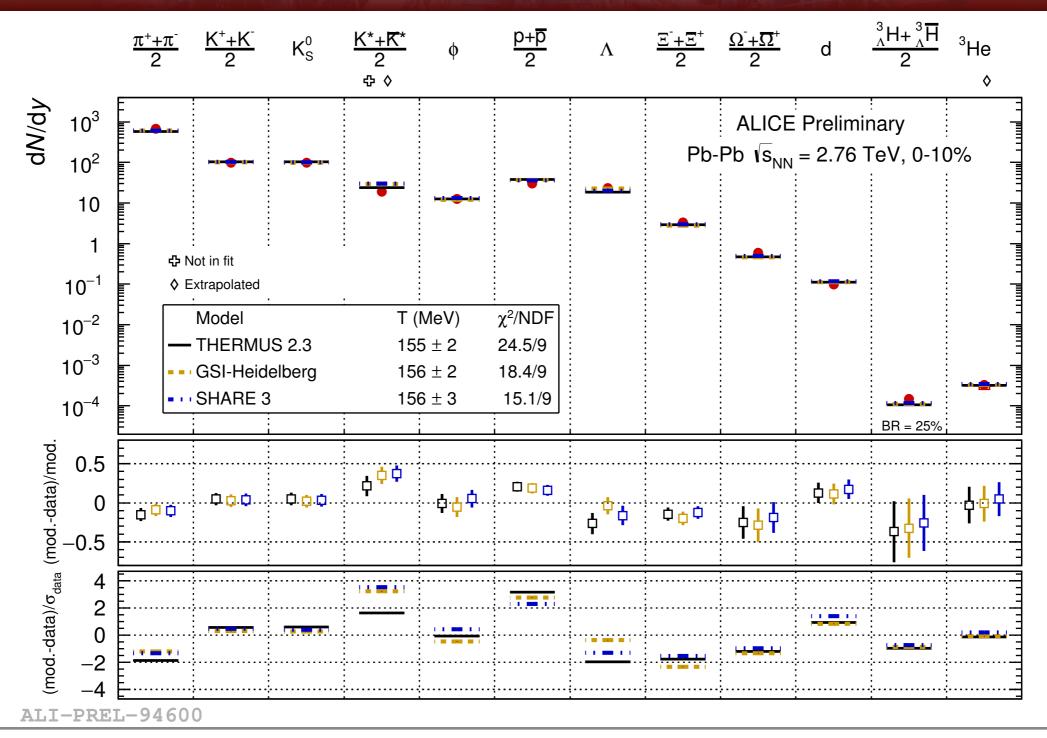
World average

$$\tau = 215^{+18}_{-16} \text{ ps}$$

ALICE Coll. arXiv:1506.08453 [nucl-ex]

From the exponential fit to the differential yield in different *ct* bins it is possible to extract the lifetime of the hyper-triton

ALICE

$$\tau(181^{+54}_{-39}(\text{stat.}) \pm 33(\text{syst})) \text{ ps}$$

World average

$$\tau = 215^{+18}_{-16} \text{ ps}$$

ALI−PREL−94600

Grand canonical thermal fit for 0-10% central Pb-Pb collisions, with different thermal models. All models fit the abundances with T ≈ 156 MeV. The predictions of all of them miss the yield of protons and K*.

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Thermal models describe with high accuracy the abundance of different particle species. They can also predict the abundances of exotic weakly decaying dibaryon states, such as:

- ΛΛ (H-dibaryon):
  - predicted by Jaffe in bag model calculations

    R. L. Jaffe, PRL 38, 195 (1977)

  - lattice calculations suggest a lightly bound state or resonance close to Ξp threshold
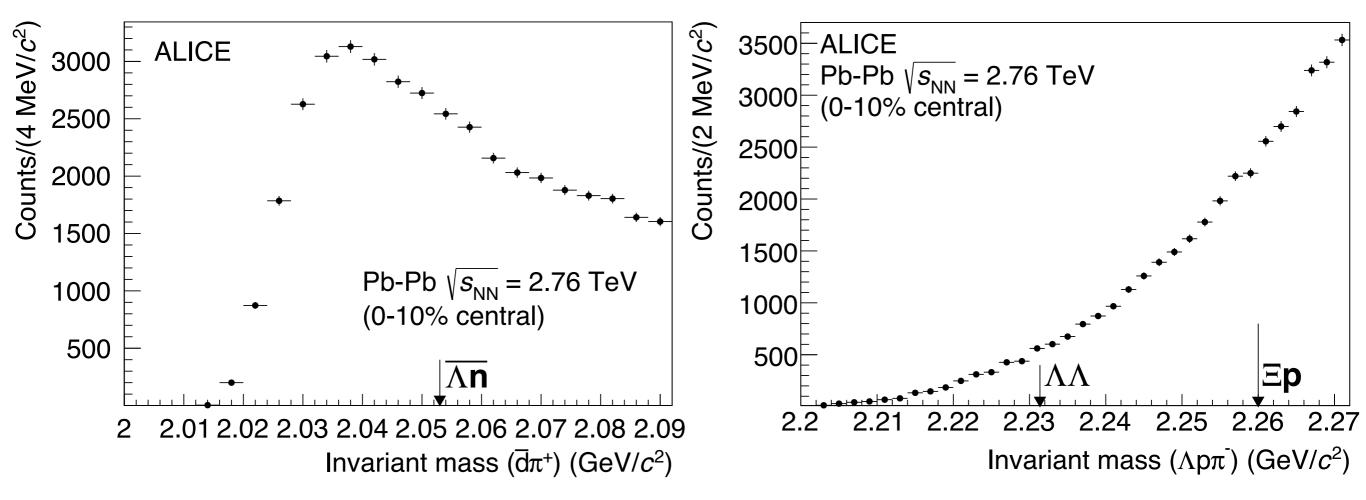   T. Inoue et al., PRL 106, 162001 (2011) and S. R. Beane et al., PRL 106, 162002 (2011)
  - Predicted yield: 211 - 2110 (in 14M events)
- Λn-bar bound state
  - Predicted yield: ~4000 (in 14M events)

Both ΛΛ and Λn-bar should be measurable with the statistics available in ALICE according to the thermal models predictions.
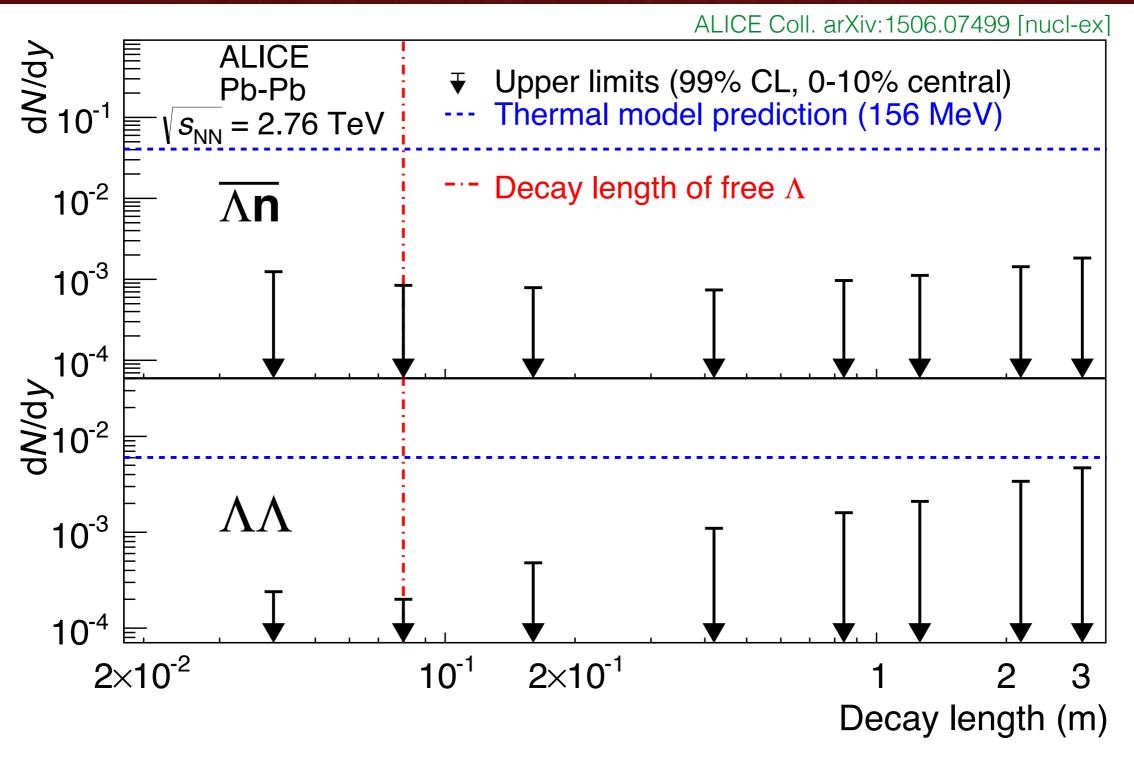
23

ALICE Coll. arXiv:1506.07499 [nucl-ex]

The arrows indicate the sum of the masses of the constituents.

No signal visible in the invariant mass spectra. From the non-observation it is possible to compute the upper limits for the production rates.
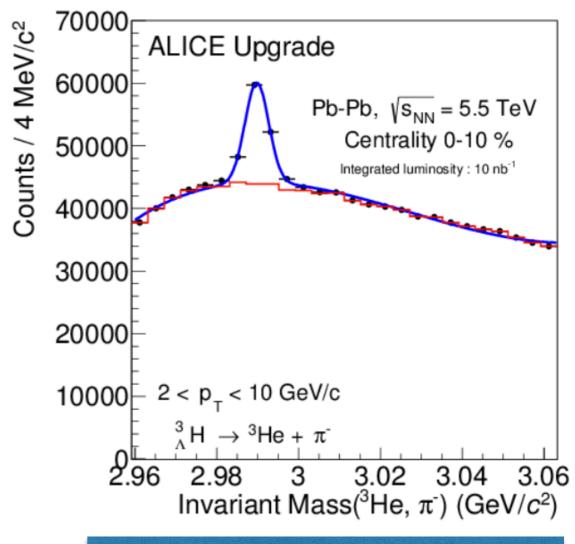
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Upper limits

Upper limit of the d*N*/d*y* in the assumption of 64% branching ratio for the H-dibaryon and 54% for the Λn-bar state.

- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)

- Upgraded ALICE apparatus will be able to cope with the new high luminosity environment

- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei.

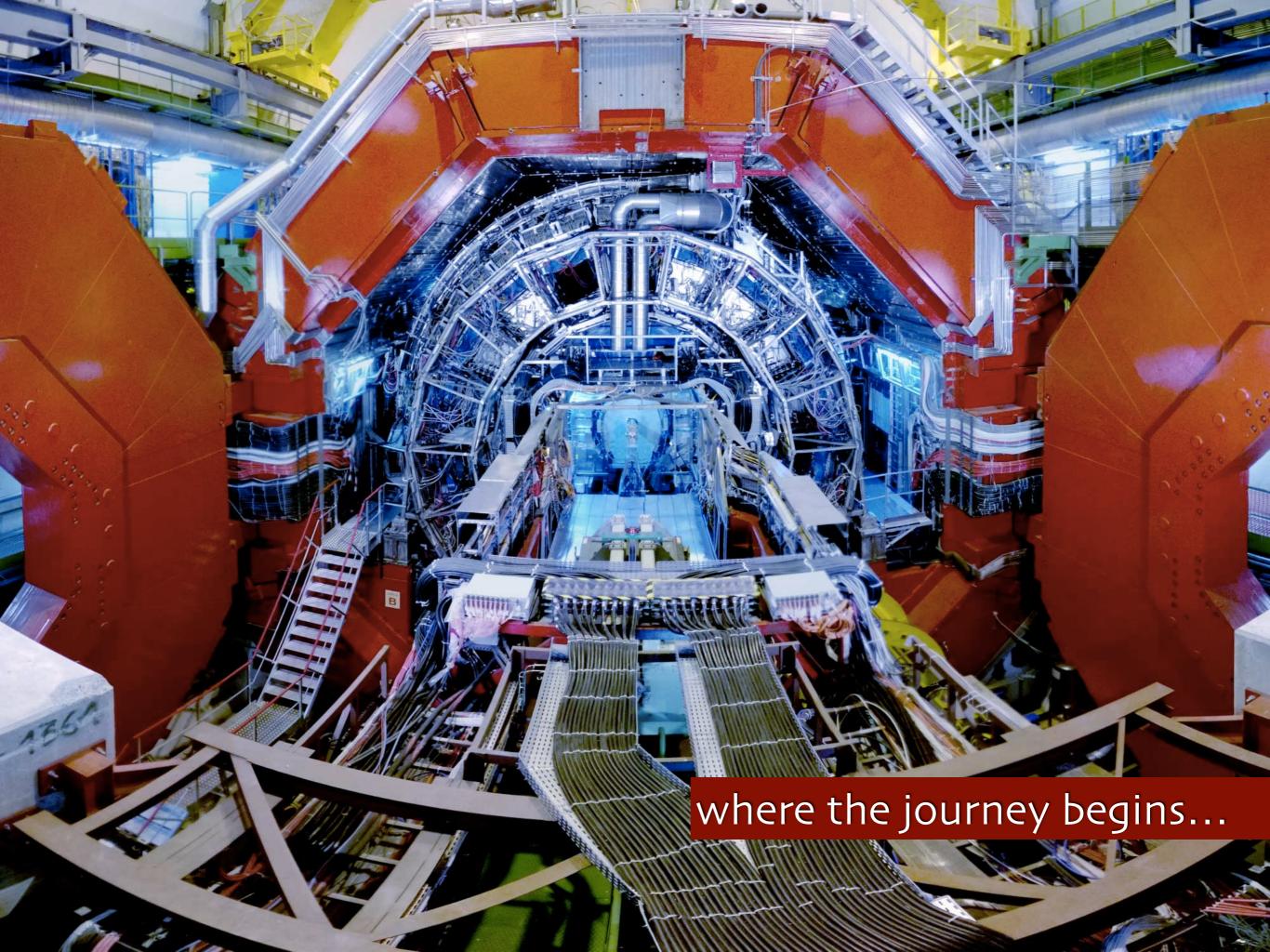- All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4.

ALICE Upgrade

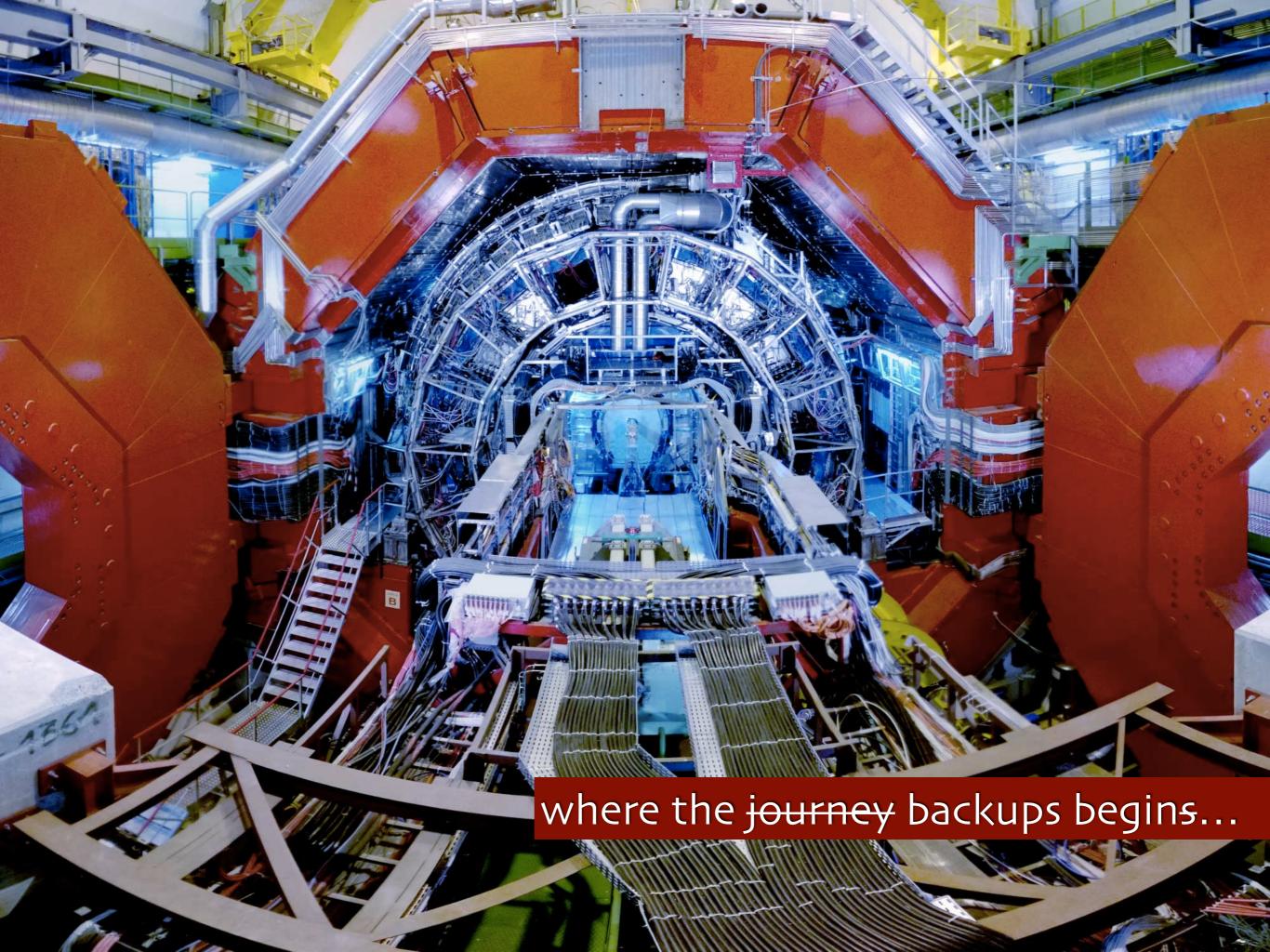Pb-Pb, $\sqrt{s_{NN}} = 5.5$ TeV
Centrality 0-10 %
Integrated luminosity : 10 nb^{-1}

$2 < p_T < 10$ GeV/c

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

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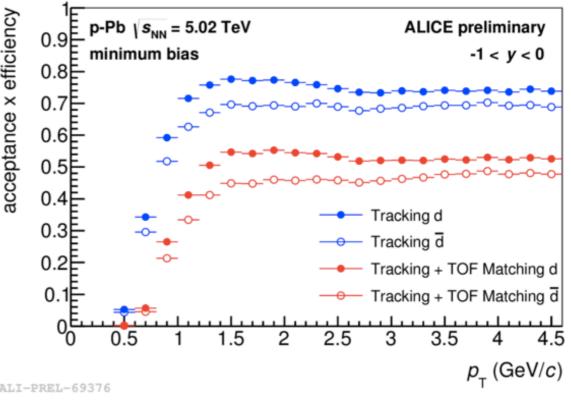|	State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	Yield
Numbers for $L_{int} = 10$ nb^{-1}	$^{3}_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
	$^{4}_{\Lambda}H$	2×10^{-7}	50%	7 %	110
	$^{4}_{\Lambda}He$	2×10^{-7}	32%	8 %	130

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- The nuclei production (up to A=4) has been measured by ALICE experiment.

- Both coalescence and thermal model are successful in the description of particular aspects of the measurements:

  - Integrated yields are well described by thermal models

  - The trend of the coalescence parameter and of the d/p ratio could be described by the coalescence model

- Hyper-triton measurement shows the high performance of the experimental apparatus and will further benefit from the increase of statistics.

- The data from ALICE do not support the existence ΛΛ and Λn-bar.

- ALICE is looking forward to LHC Run 2 to extend the current measurements and put tighter constraints on theoretical models.
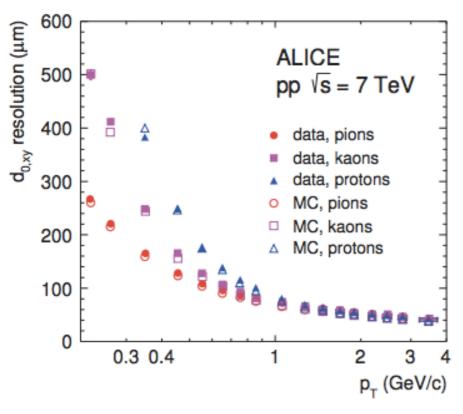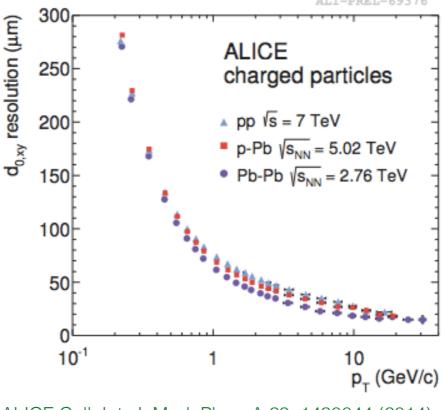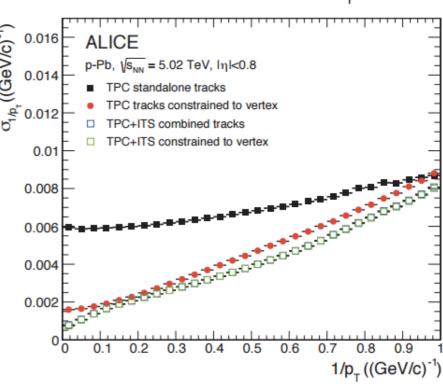
where the journey begins…

where the ~~journey~~ backups begins…

- **Tracking efficiency x acceptance is fundamental to measure the production spectra of charged particle.**
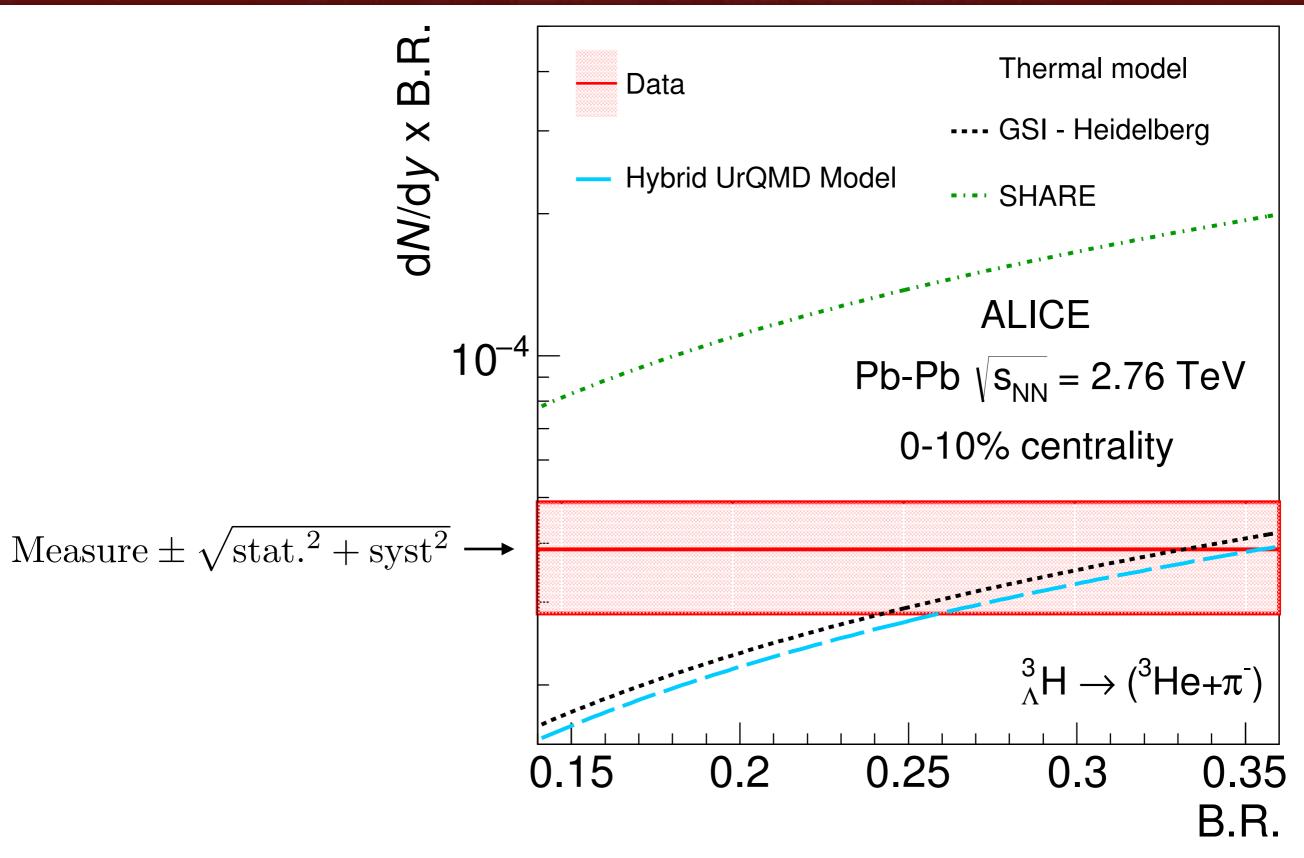- **Tracking efficiency depends on charged particle multiplicity.**

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

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ALICE Coll. arXiv:1506.07499 [nucl-ex]

ALICE Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV (0-10% central)

Upper limit $\overline{\Lambda n}$ (99% CL)

Preferred BR from theory

Upper limit H-dibaryon (99% CL)

Preferred BR from theory

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