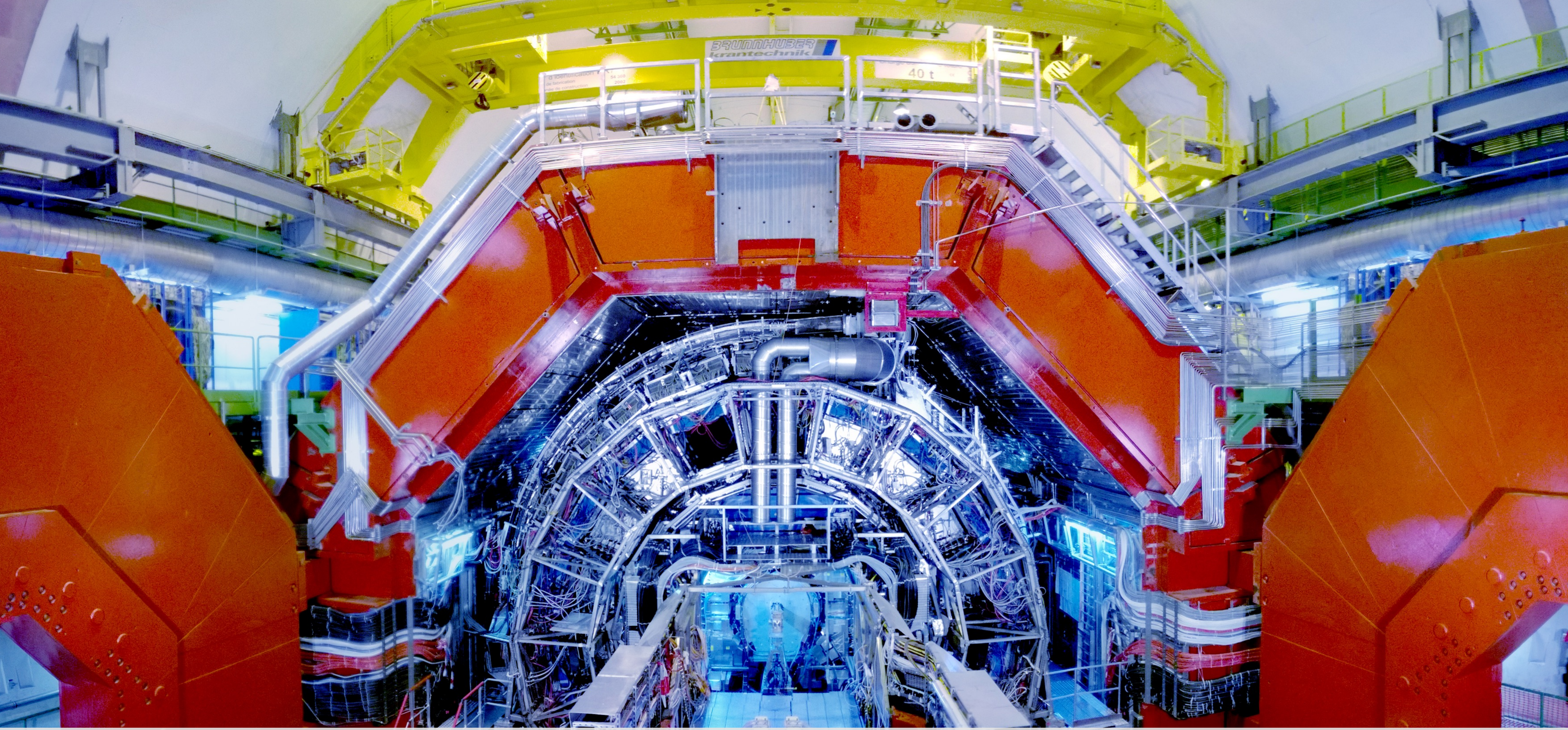


(Hyper-)nuclei and exotica production measured with ALICE at the LHC

Stefano Trogolo
University and INFN - Torino

on behalf of the ALICE Collaboration

South Padre Island
HOT QUARKS 2016
12-17 September

Outline

- [x] Introduction
- [ ] (Anti-)Nuclei
- [ ] (Anti-)Hypertriton
- [ ] Exotica searches
- [ ] Outlook and conclusion

Introduction

Motivation

- explore QCD and QCD-inspired model predictions for (unusual) multi-baryon states
- search for rarely produced anti- and hyper-matter
- test model predictions, e.g. thermal and coalescence, for both classes of phenomena

Collision systems

- to study the ordinary nuclear matter effects and the QCD matter at high temperature and energy density

ALICE integrated luminosities

p-p

$\sqrt{s}$	$\mathcal{L}_{\mathrm{INT}}$
900 GeV	0.33 nb^{-1}
2.76 TeV	46 nb^{-1}
7 TeV	5.4 pb^{-1}
8 TeV	9.7 pb^{-1}
13 TeV	8.02 pb^{-1}

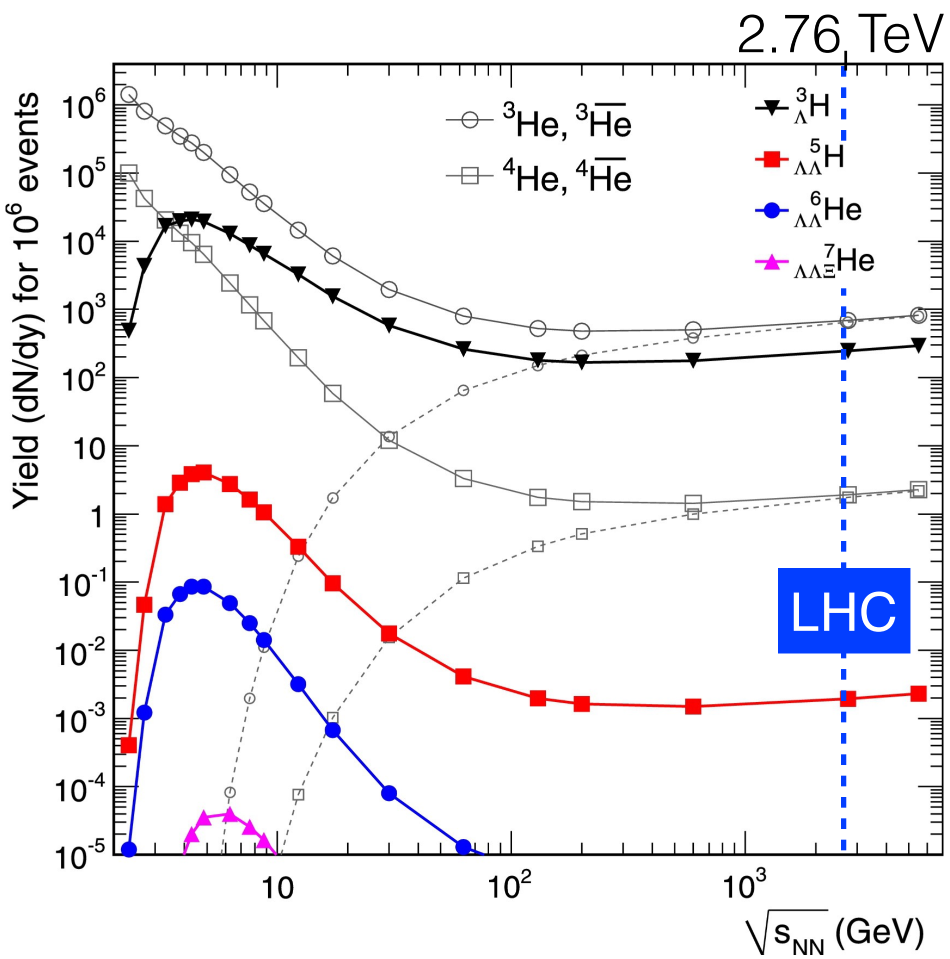
p-Pb and **Pb-p**

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

Pb-Pb

$\sqrt{s_{\mathrm{NN}}}$	$\mathcal{L}_{\mathrm{INT}}$
2.76 TeV	155 μb^{-1}
5.02 TeV	433 μb^{-1}

Introduction



Thermal model

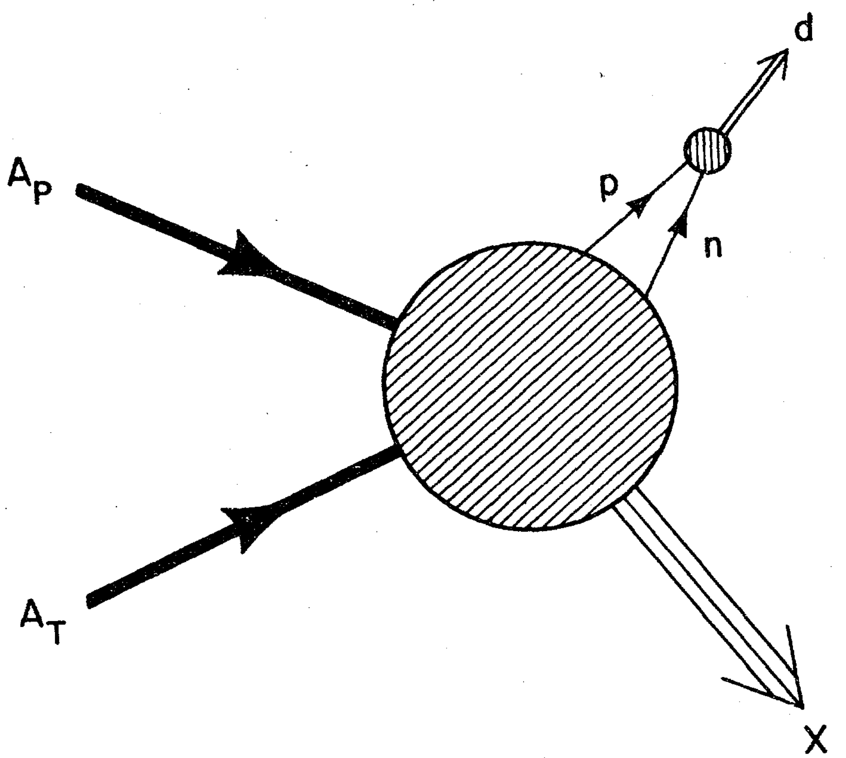
- Hadrons emitted from the interaction region in **statistical equilibrium** once the *chemical freeze-out* temperature is reached
- Key parameter is *chemical freeze-out* temperature T_{chem}
- Abundance of a species $\propto \exp(-m/T_{chem})$

➡ Hypernuclei: large m $\longrightarrow$ strong dependence on T_{chem}

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker. *Phys. Lett. B* 697, 203 (2011)

Coalescence model

- (Anti-)baryons close in **phase space** at the *kinetic freeze-out* can form a (anti-)(hyper-)nucleus
- (Anti-)(hyper-)nuclei formed at the *chemical freeze-out*:
  - might **break**
  - **regenerate** in the time interval between *chemical* and *kinetic freeze-out*



J. Kapusta *Phys. Rev. C* 21, 1301 (1980)

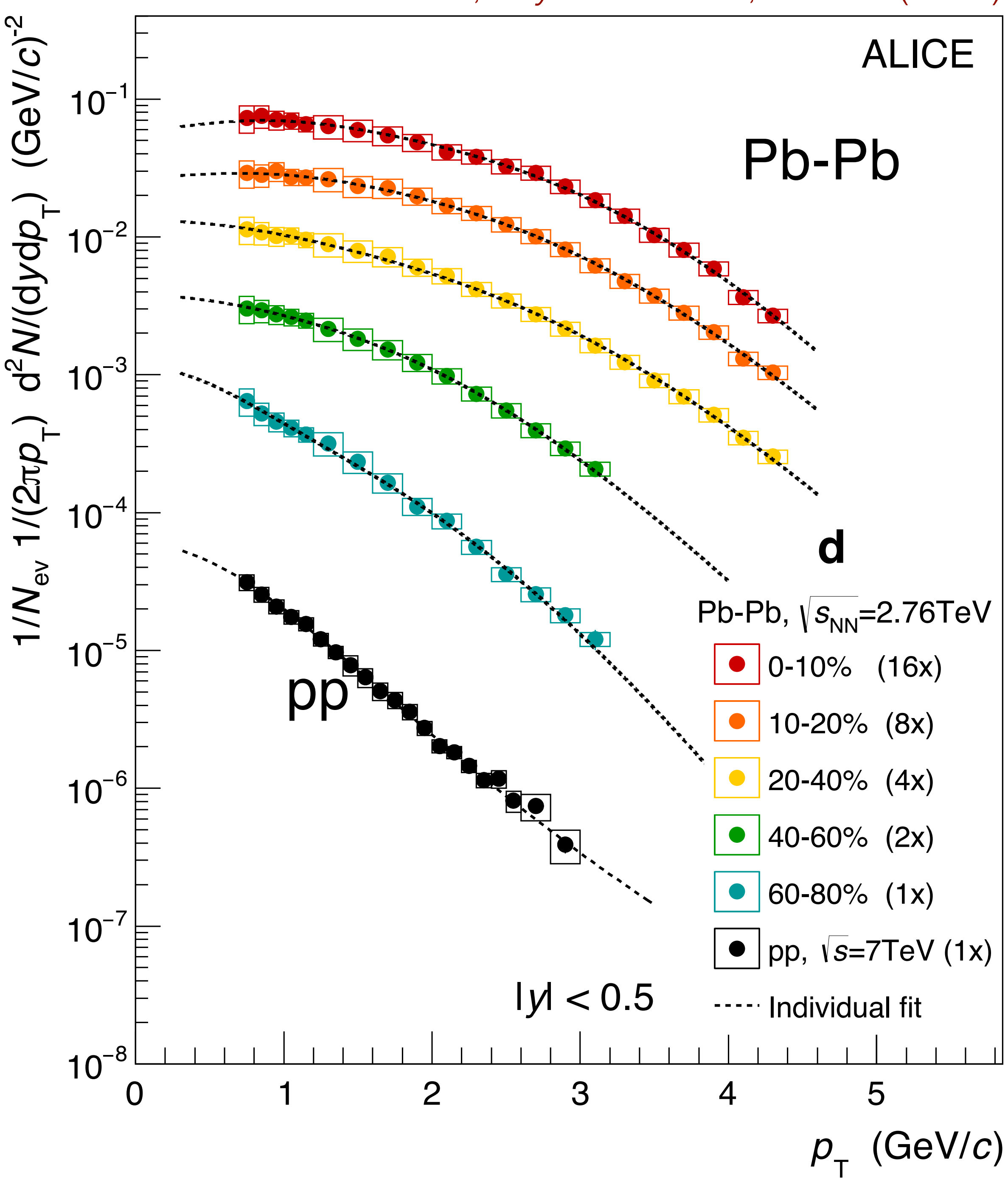
Outline

- ☑ Introduction
- ☑ (Anti-)Nuclei
  - [Phys. Rev. C 93, 024917 (2016)]
- ☐ (Anti-)Hypertriton
- ☐ Exotica searches
- ☐ Outlook and conclusion

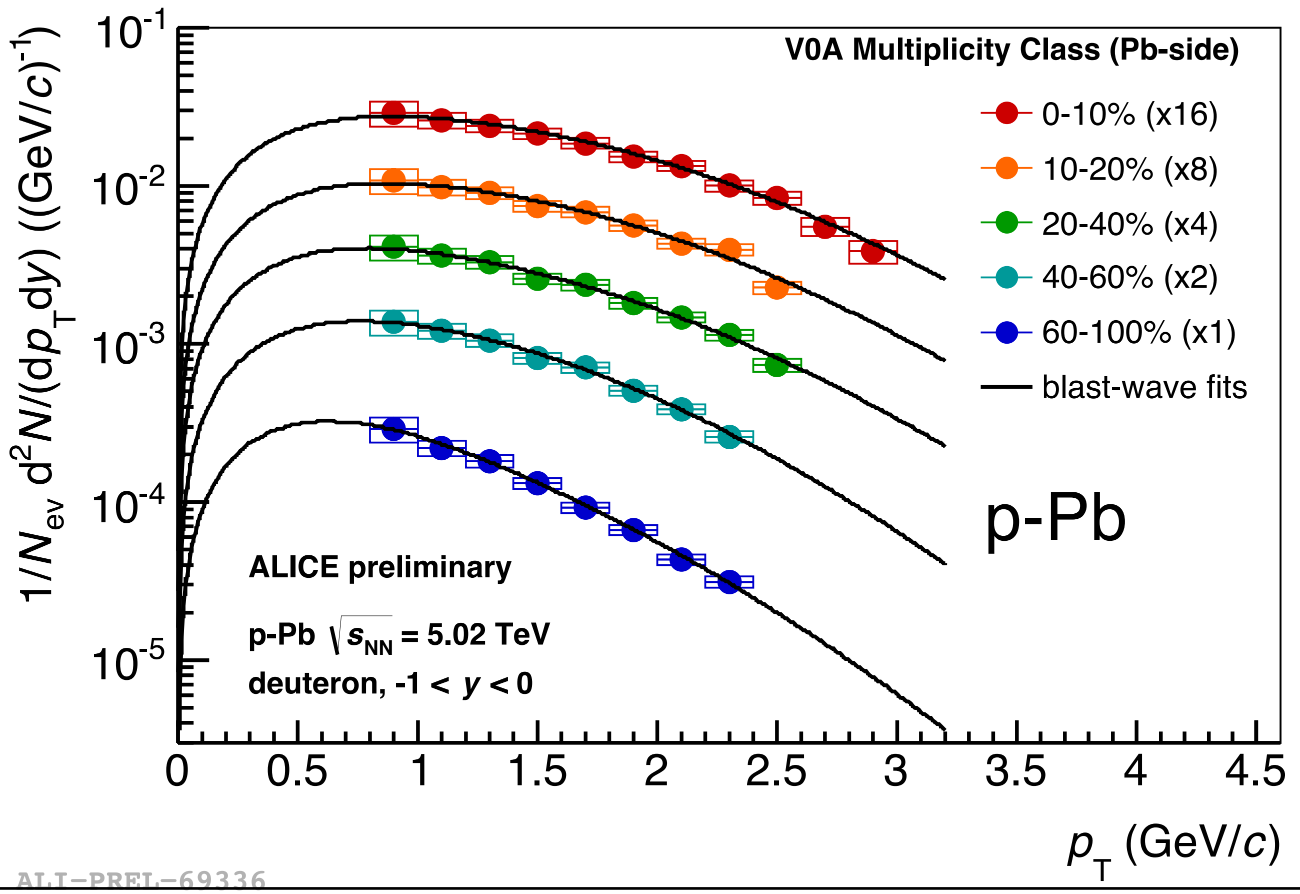
= published paper

Nuclei: *deuteron*

ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



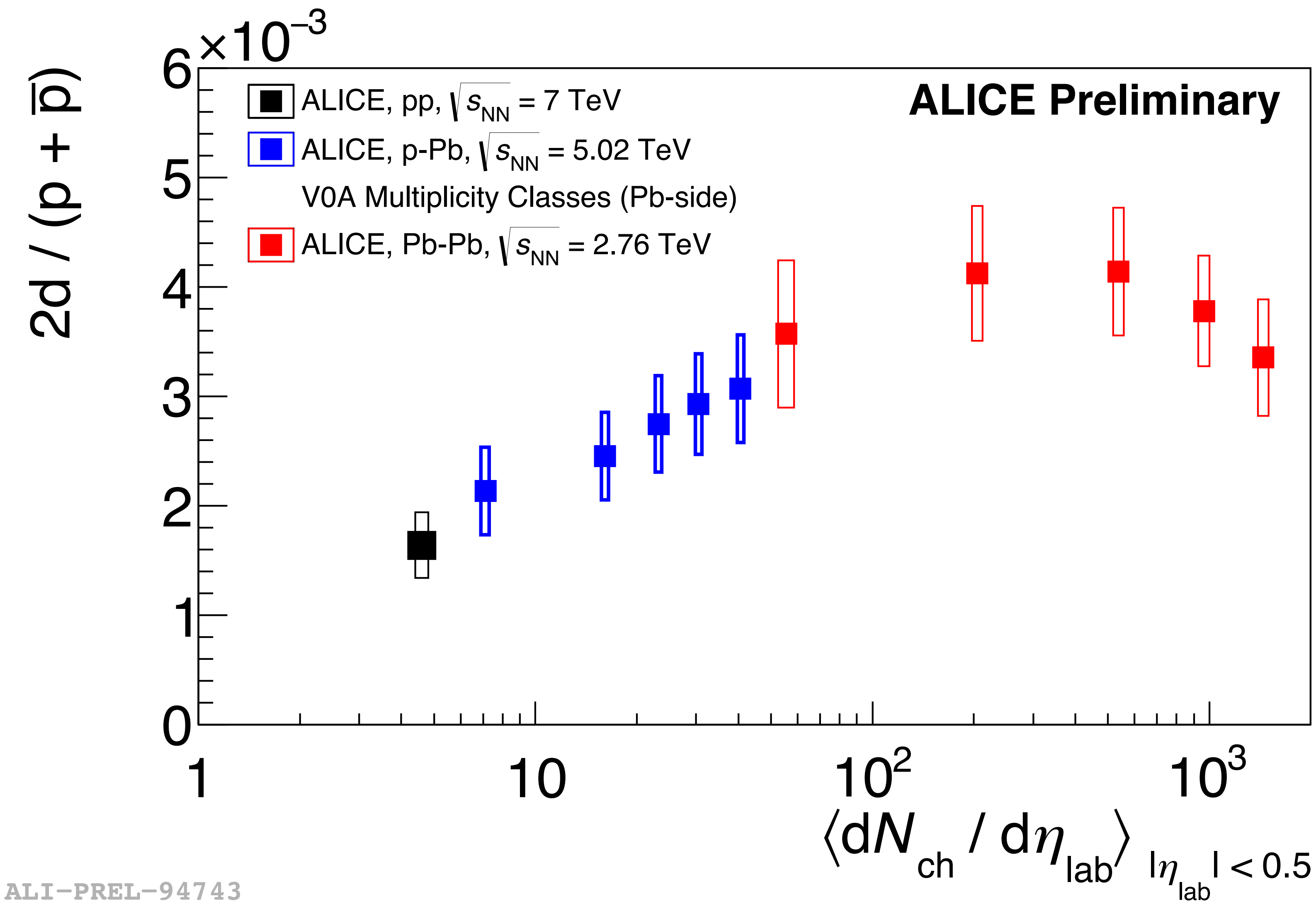
- **Hardening** of the spectra visible for increased **centrality** in Pb-Pb and **multiplicity** in p-Pb
- **Blast-Wave**[(1)] parametrisation fits the spectra well in p-Pb and Pb-Pb and is used to extract the **integrated yield ⟶ radial flow**
- **Levy-Tsallis**[(2)] distribution fits the **pp** spectra well



(1) E. Schnedermann et al. *Phys. Rev. C* 48, 2462 (1993)

(2) C. Tsallis. *Journal of Statistical Physics*, 52:479–487, (1988)

Nuclei: *d/p vs multiplicity*



- d/p ratio **increases** with **multiplicity** in p-Pb
- d/p at <u>low multiplicity</u> in **p-Pb** is **compatible** with the ratio measured in **pp**
- value at <u>high multiplicity</u> in **p-Pb** is **consistent** with the measurement in **Pb-Pb**

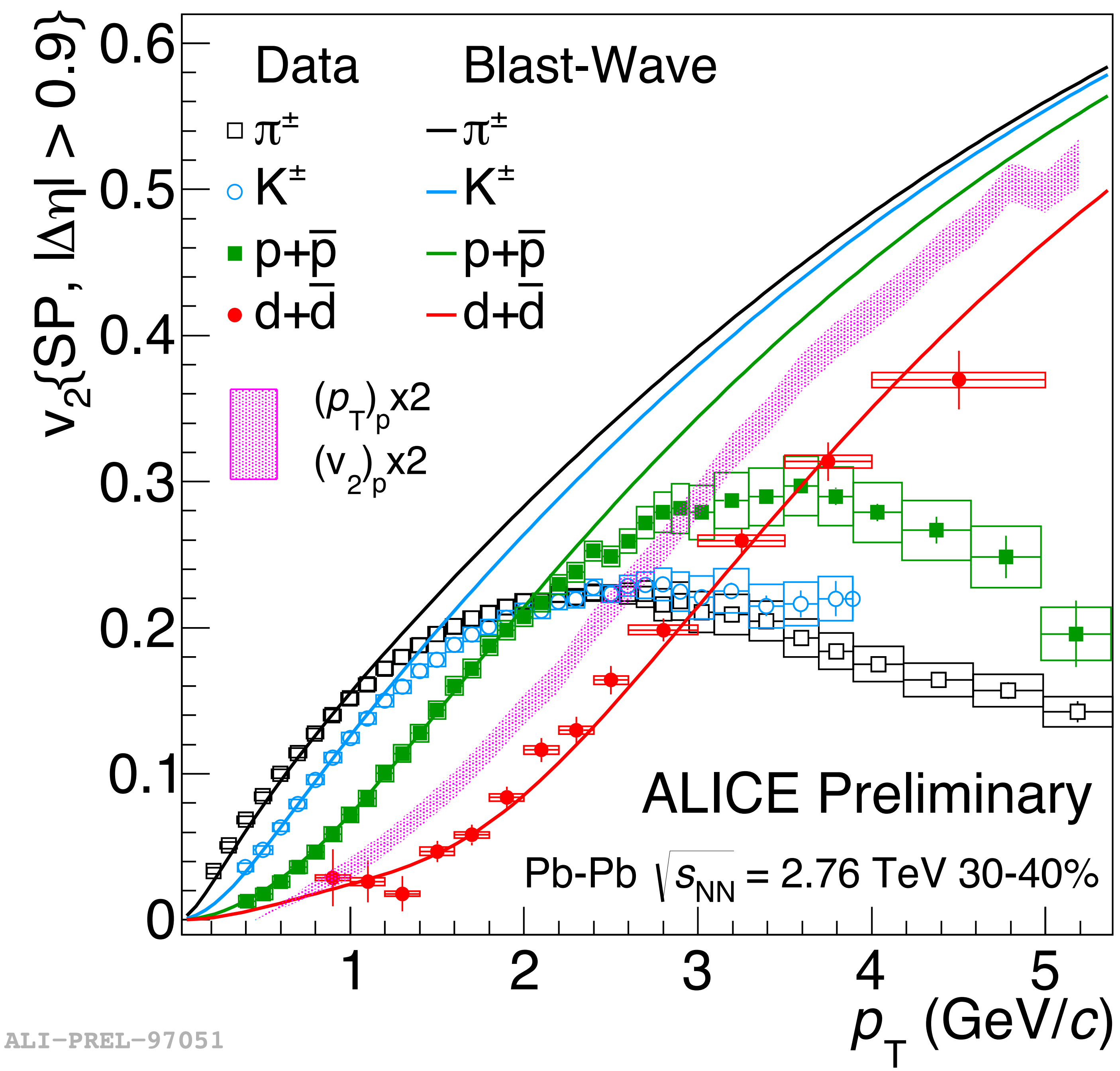
Thermal model (T_{chem}=156 MeV)

d/p = 3x10^{-3}

The **increase** of the d/p ratio with charged particle multiplicity from pp to Pb-Pb is consistent with the **coalescence picture**:

<u>increased deuteron production for higher nucleon densities</u>

Nuclei: *deuteron flow*



Measurement of **elliptic flow**:

- shows a significant v_2 for deuteron
- deuteron v_2 follows the **mass ordering** expected from **hydrodynamics** models
- a simple **coalescence model** (*magenta band*) is not able to reproduce the deuteron v_2
- a **Blast-Wave** parametrization obtained with lower mass species can describe the deuteron v_2 reasonably well

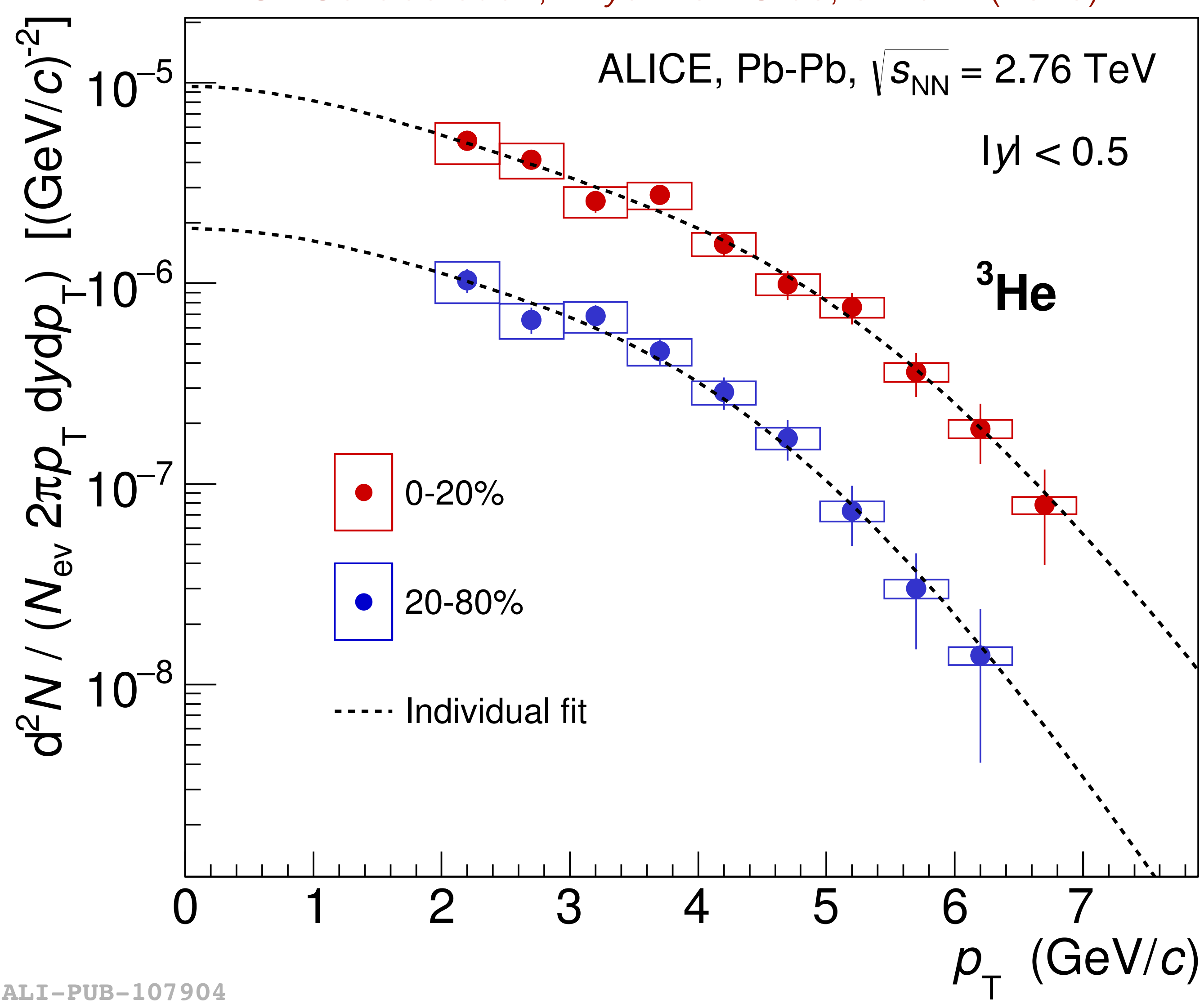
$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2v_1 cos(\varphi - \Psi_R) + 2v_2 cos(2(\varphi - \Psi_R)) + \ldots\right)$$

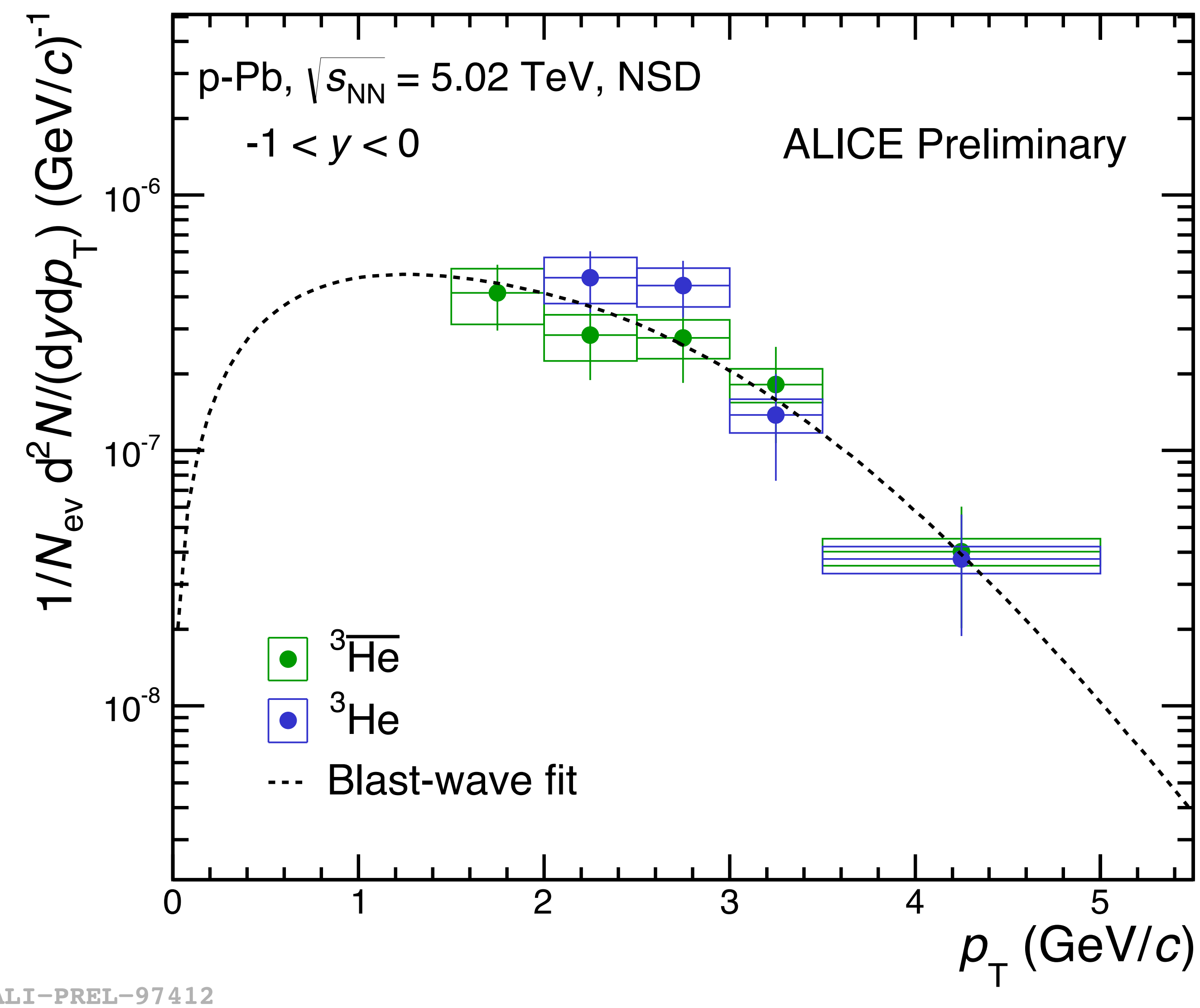
elliptic flow $v_2 = \langle cos(2(\varphi - \Psi_R))\rangle$

Nuclei: ^3He

- **Pb-Pb spectra** are obtained for two centrality classes and become **harder** when the **centrality** increases ⟶ **radial flow**
- **p-Pb spectrum** obtained for **N**on-**S**ingle **D**iffractive (NSD) collisions
- **Individual** Blast-Wave fits to the single spectra describe the data well

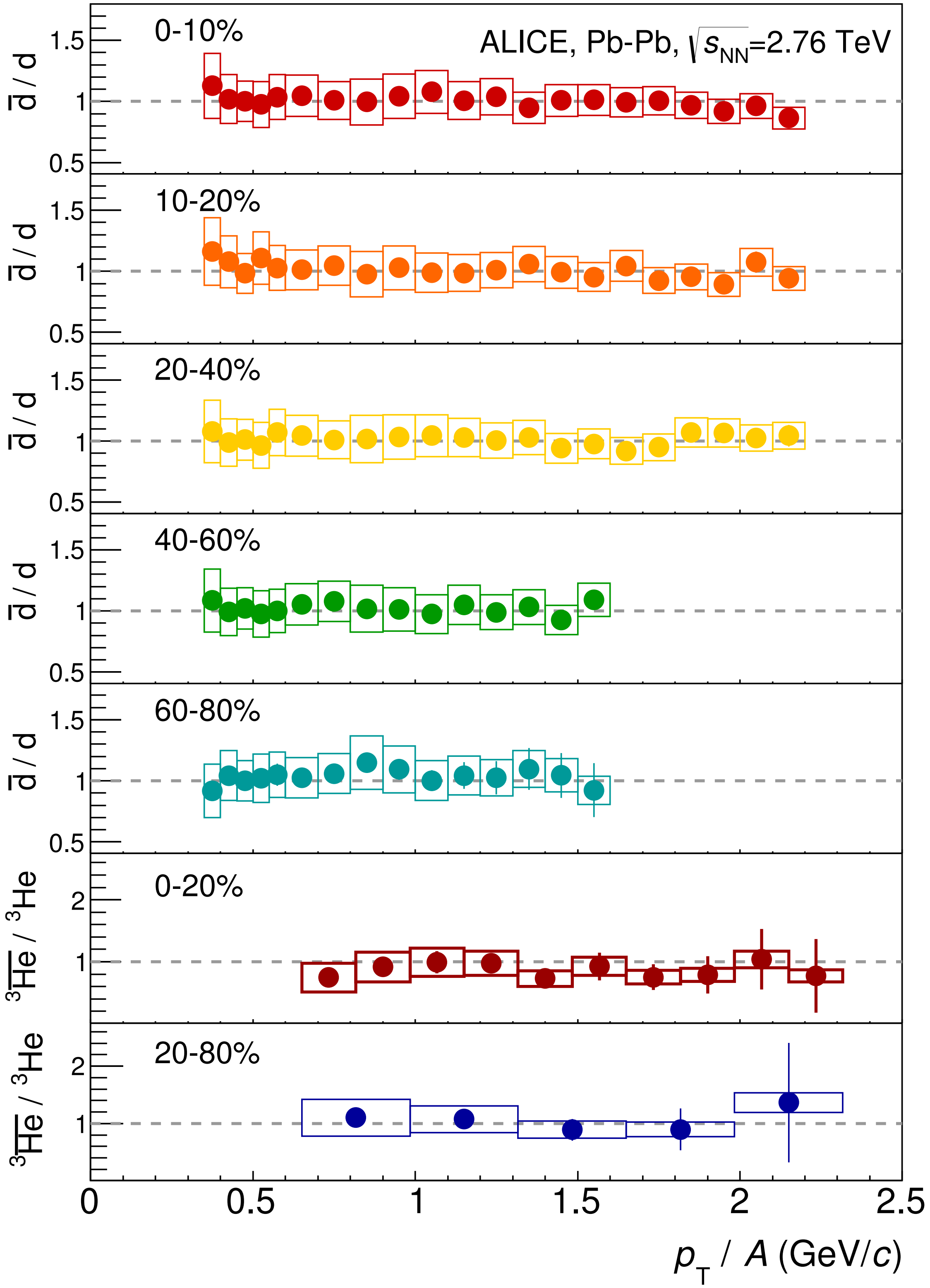
ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)





Nuclei: *matter vs antimatter*

ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



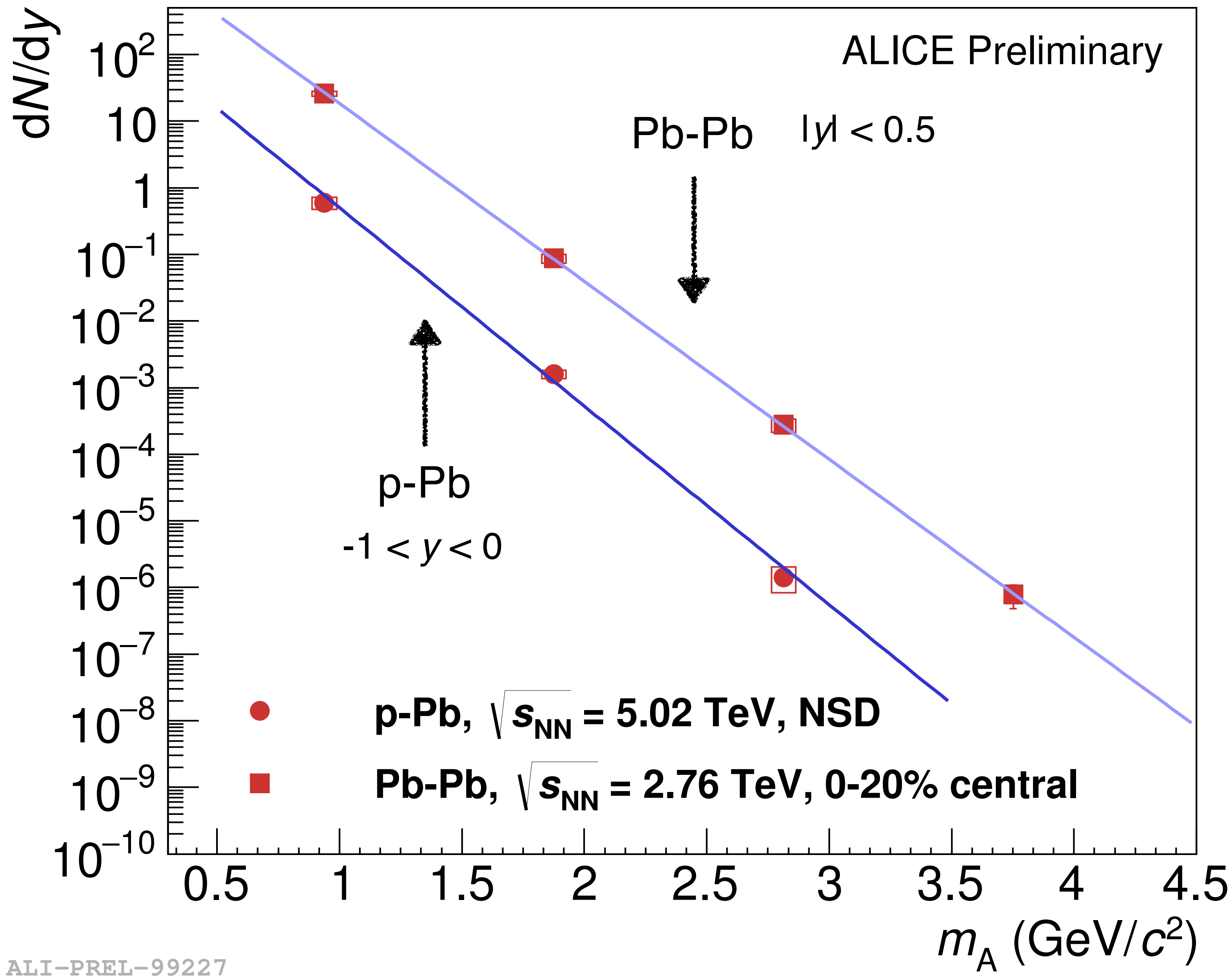
At the LHC energies the net baryon density is zero (*transparency regime*) in the central rapidity region

➡ no initial matter/anti-matter asymmetry

- **Anti-nuclei/Nuclei** ratios are in agreement with **unity**, as obtained for other lighter particles
- Ratios do not depend on the transverse momentum (p_T) and **centrality**
- Ratios are in agreement with **thermal** and **coalescence** model predictions

Nuclei: *mass dependence*

- Production yields as a function of nuclei mass m_A to study the mass dependence
- d*N*/d*y* measured:
  - **proton**, **deuteron**, **^{3}He** and anti-**alpha** in Pb-Pb
  - **proton**, **deuteron**, and **^{3}He** in p-Pb NSD
- Nuclei production yields follow an **exponential decrease** with mass (m_A) as predicted by thermal model



- Starting from the proton the penalty factor for adding one baryon is:
  - ➡ ~300 in Pb-Pb
  - ➡ ~600 in p-Pb

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- ☑ (Anti-)Hypertriton
    - Phys. Lett. B 754, 360-372 (2016)
- ☐ Exotica searches
- ☐ Outlook and conclusion

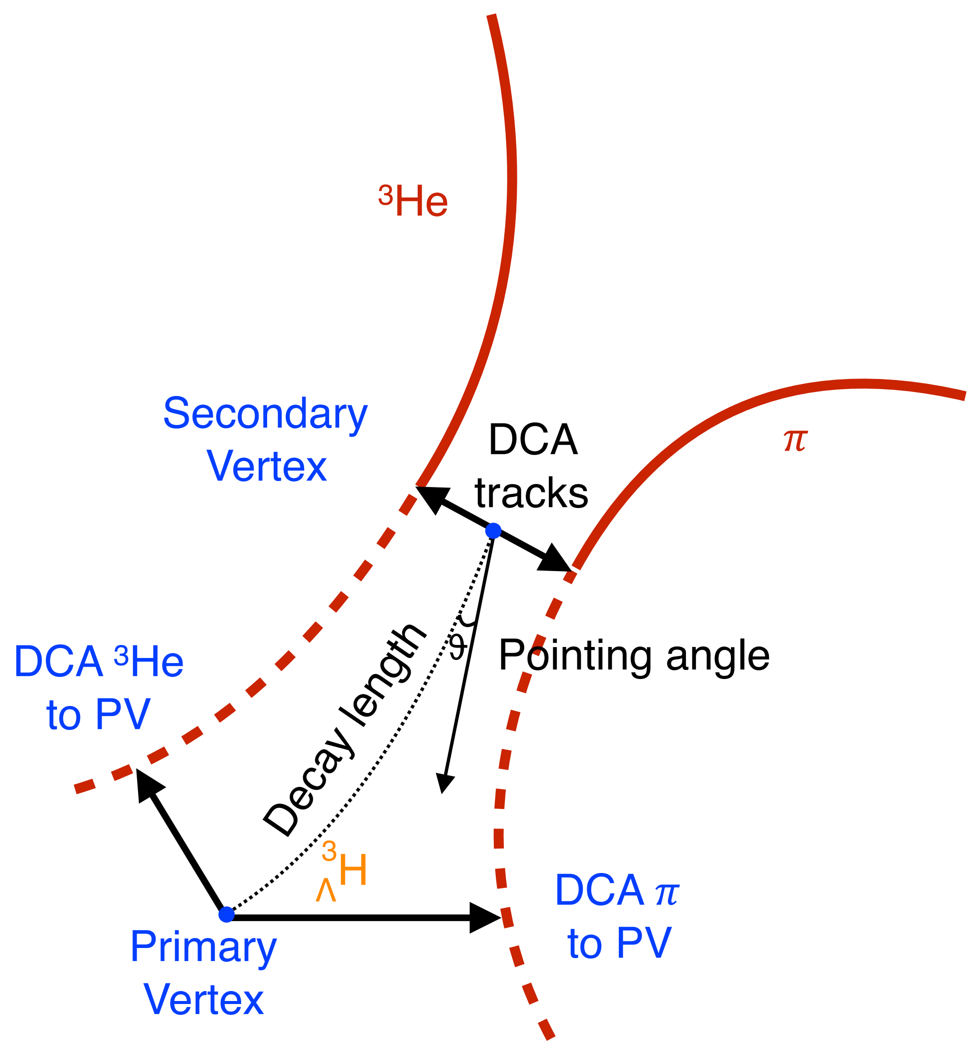
Hypertriton

Hypertriton: lightest known hypernucleus
bound state of **p**, **n** and **Λ**

Mass = 2.992 GeV/c^2

Decay Channels:

1. Mesonic
2. Non Mesonic



Mesonic decay

Charged	Neutral
$^{3}_{\Lambda}H \longrightarrow {}^{3}He+\pi^-$	$^{3}_{\Lambda}H \longrightarrow {}^{3}H+\pi^0$
$^{3}_{\Lambda}H \longrightarrow d+p+\pi^-$ WORK IN PROGRESS	$^{3}_{\Lambda}H \longrightarrow d+n+\pi^0$
$^{3}_{\Lambda}H \longrightarrow n+p+p+\pi^-$	$^{3}_{\Lambda}H \longrightarrow n+n+p+\pi^0$

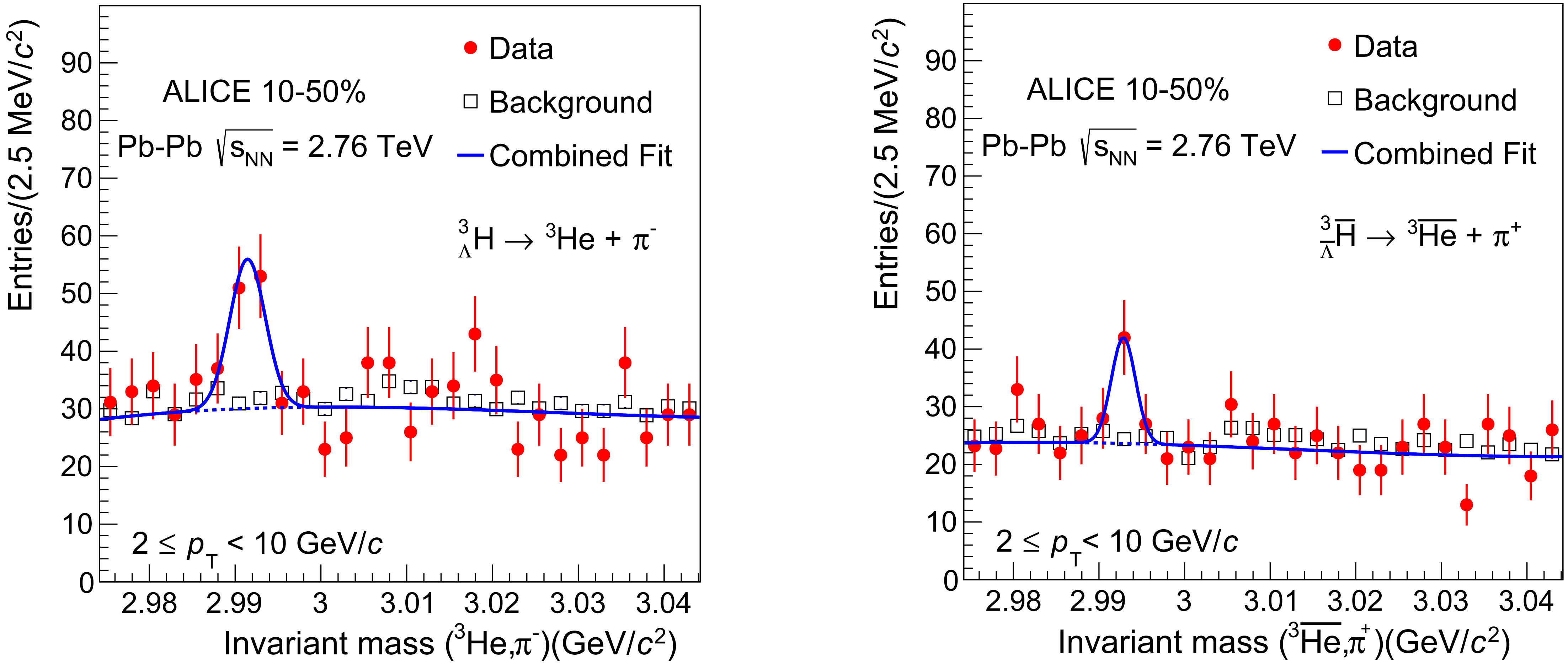
- Anti-hypertriton was first observed by STAR Collaboration
  Science 328,58 (2010)

- Study of the production in the accessible decay channels (charged products only)
  - 2 body (B.R.[3] ≅ 25%)
  - 3 body (B.R.[3] ≅ 41%)

[3] H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Hypertriton: *signal*

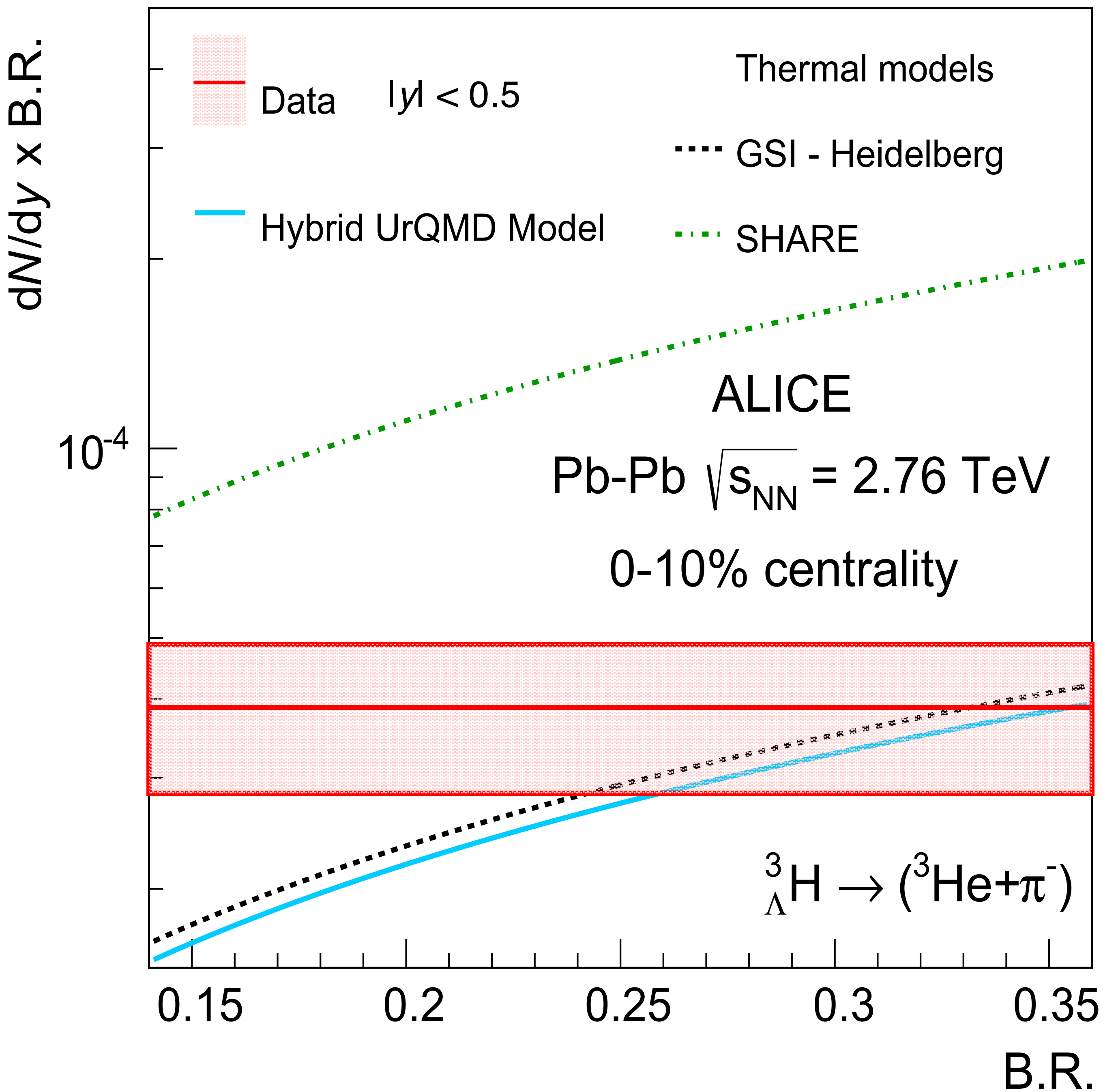
ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)



- Fit to the invariant mass spectrum
  - *signal*: Gaussian
  - *background*: 3rd degree polynomial
- Open square: background obtained from data (*rotation background* method) and used to tune the polynomial parameters
- Signal obtained for 3 p_T bins and 2 centrality classes (0-10% and 10-50%)

Hypertriton: *dN/dy x B.R.*

ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)



- Hypertriton B.R. is not well known; only constrained by the ratio between all charged channels containing a pion
- d*N*/d*y* x B.R. vs B.R. compared with three different theoretical models:
  - ✓ **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium
  - ✓ **GSI-Heidelberg**: equilibrium statistical model with T_{ch} = 156 MeV
  - \- SHARE: non-equilibrium thermal model with T_{ch} = 138.3 MeV, γ_q =1.63 and γ_s =2.08
- Theory[3], which assumes a value around 25%, gives a lifetime prediction close to the one of the free Λ

Hypertriton: *lifetime*

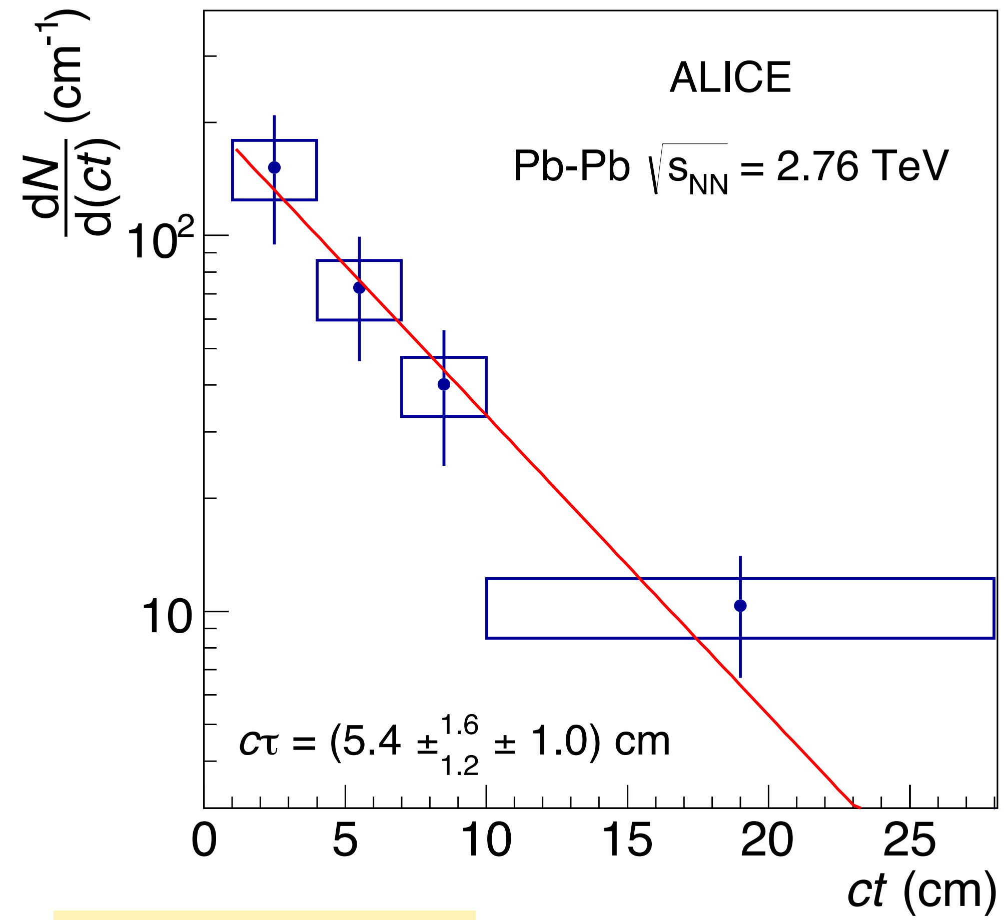
- Exponential fit to the d*N*/d(*ct*) distribution

$$\tau = \left(181^{+54}_{-39}(stat.) + 33(syst.)\right)\, ps$$

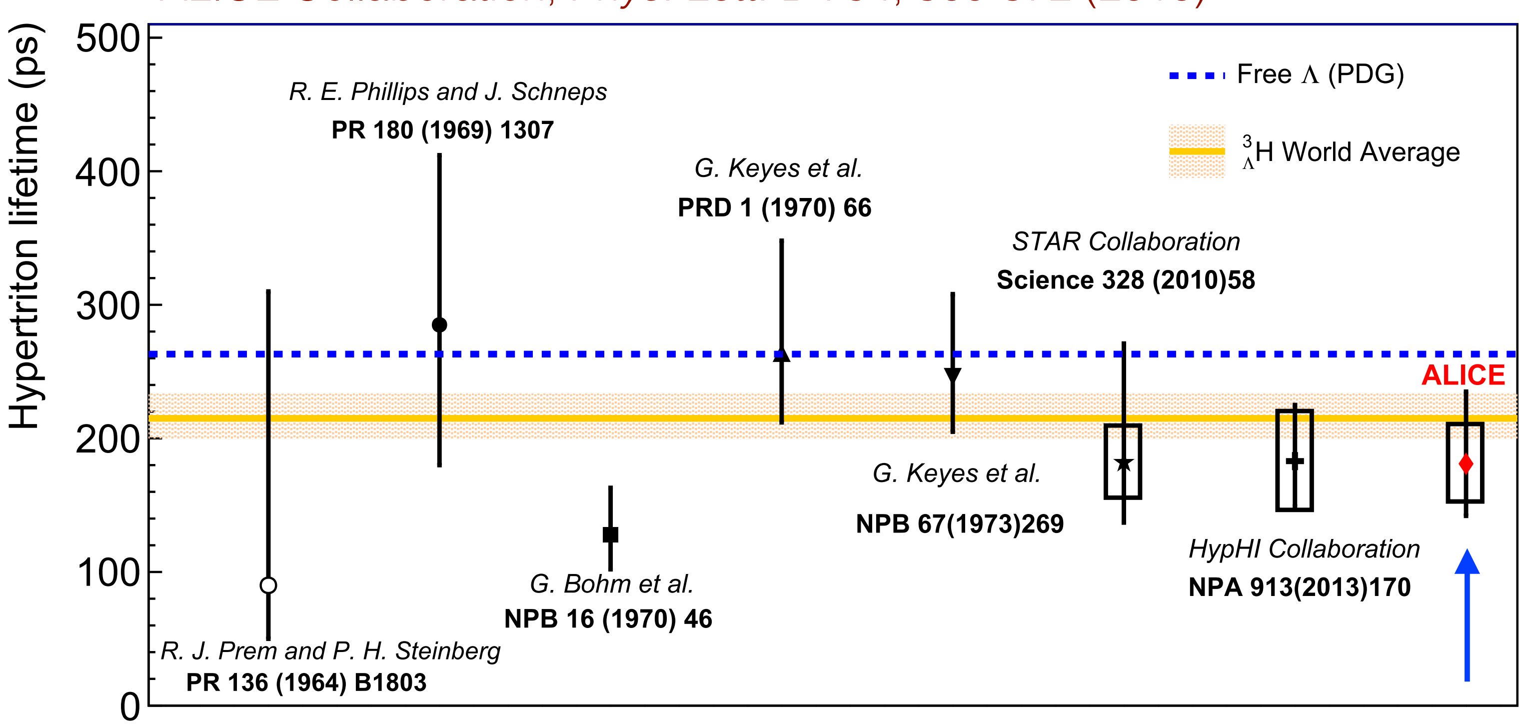
- Results compared with:
  - Free Λ lifetime ~263 ps (dotted line)
  - Statistical combination of experimental lifetime(4)

$$\tau = \left(216^{+19}_{-18}\right)\, ps$$

$^{3}_{\Lambda}$H World Average



ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)

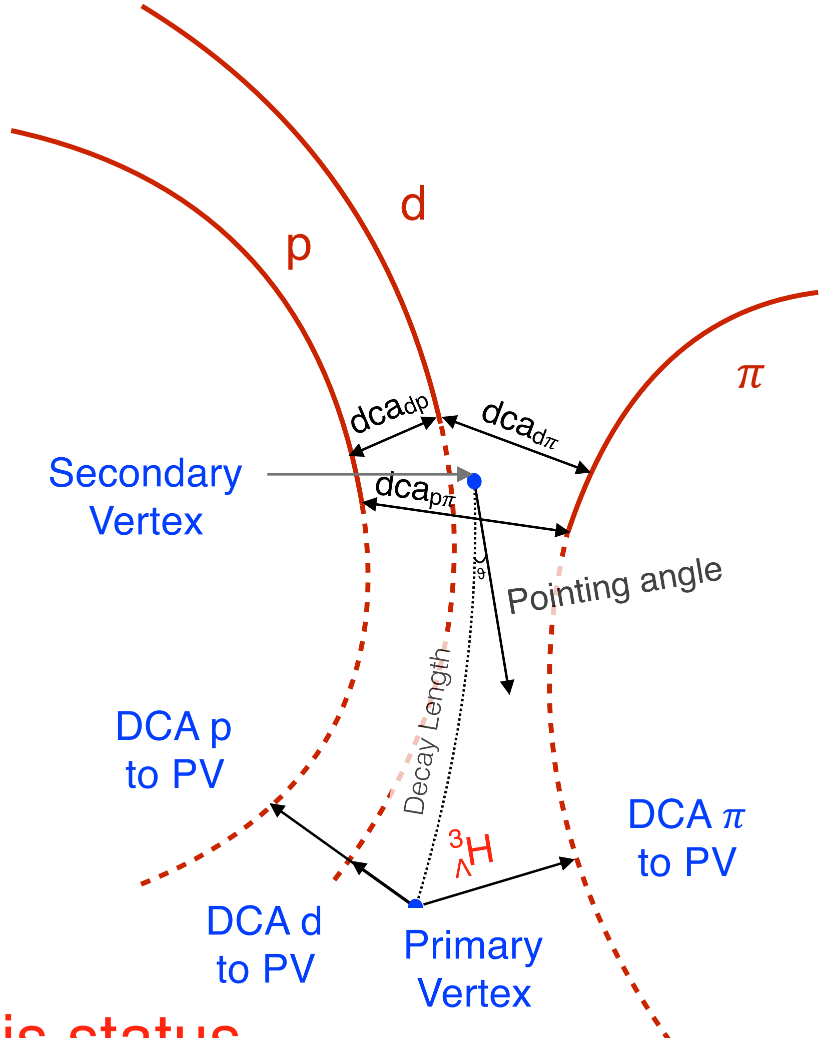


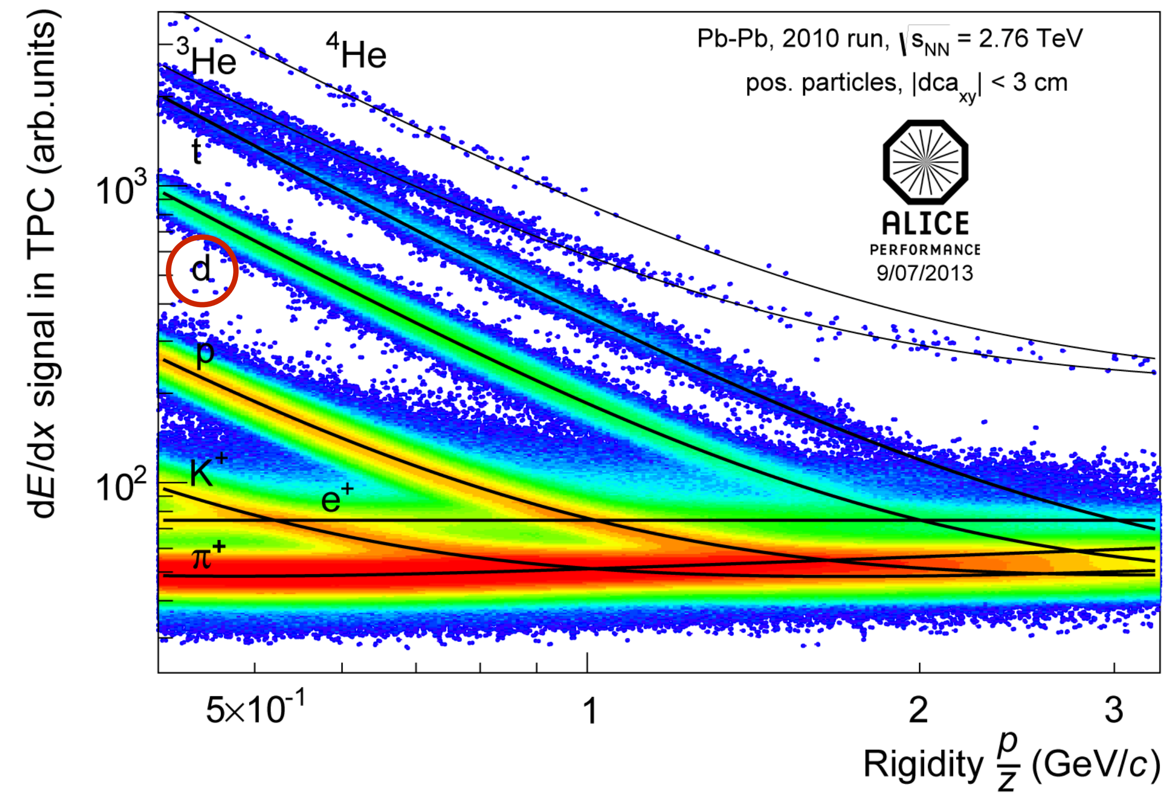
The "puzzle"

- Recently extracted value significantly below the free Λ
- Not expected from theory
- Currently the most precise results in heavy-ion experiments
- Better precision expected from larger data samples soon

(4) C.Rappold et al. Phys. Lett. B 728, 543-548 (2014)

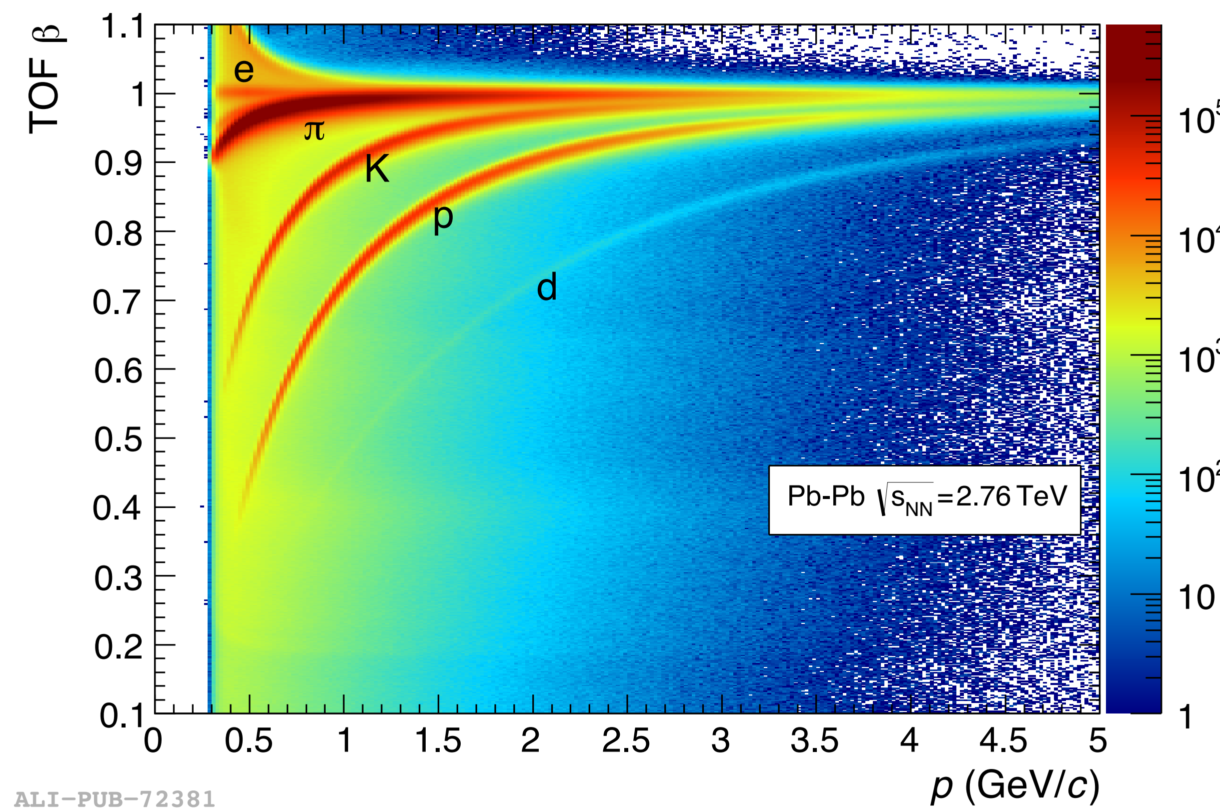
Hypertriton: *3 body decay*



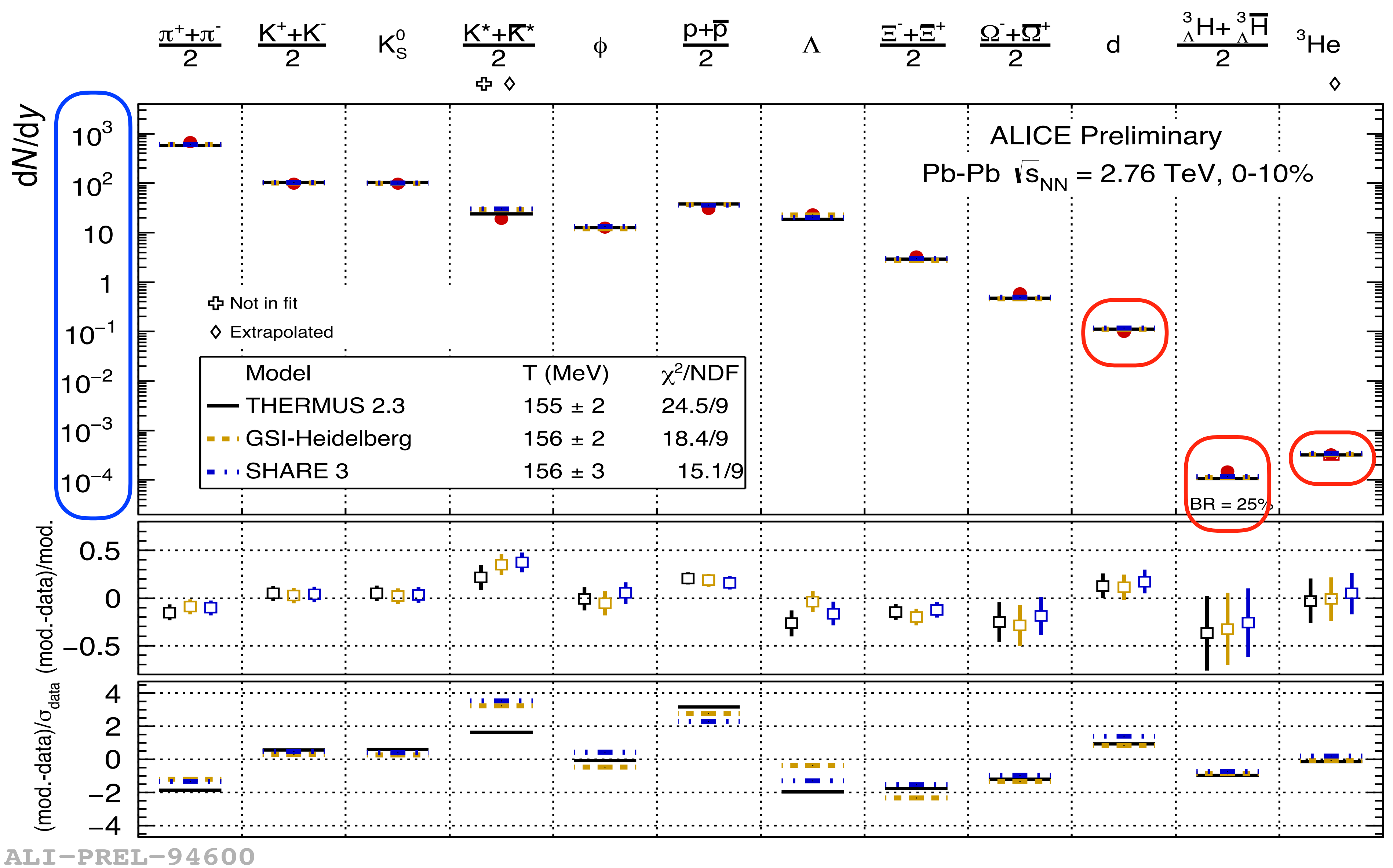


Analysis status

- PID with **T**ime **P**rojection **C**hamber as starting point
- Addition of **T**ime-**O**f-**F**light PID for deuteron
- Study the best set of topological selections:
  - DCA from primary and secondary vertices
  - DCA between tracks
  - Normalised decay length, *ct* and cosine of pointing angle



Thermal Fit: *nuclei and hypertriton*



Model reference

- THERMUS:
  Wheaton et al., Comput. Phys Commun., 180 84
- GSI-Heidelberg:
  Andronic et al., Phys Lett. B 697, 203
- SHARE:
  Petran et al., Comput. Phys. Commun., 185 Issue 7, 2056

- Production yields described over a wide range assuming thermodynamic equilibrium
- Nuclei and hypertriton production yields are included in the fit
- d*N*/d*y* in Pb-Pb collisions are well described by an equilibrium thermal model with a temperature

$$T_{chem} = 156 \pm 2 \text{ MeV}$$

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- Exotica searches
  - Phys. Lett. B 752, 267-277 (2016)
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Exotica: *invariant mass*

Search for strange exotic bound states is important as it could provide information on the *Λ-nucleon* and *Λ-Λ* interaction

H-dibaryon

- Theoretical uuddss bound states predicted by R.L. Jaffe
- Invariant mass $M_H < 2.231$ GeV/c²
- Search in the decay channel

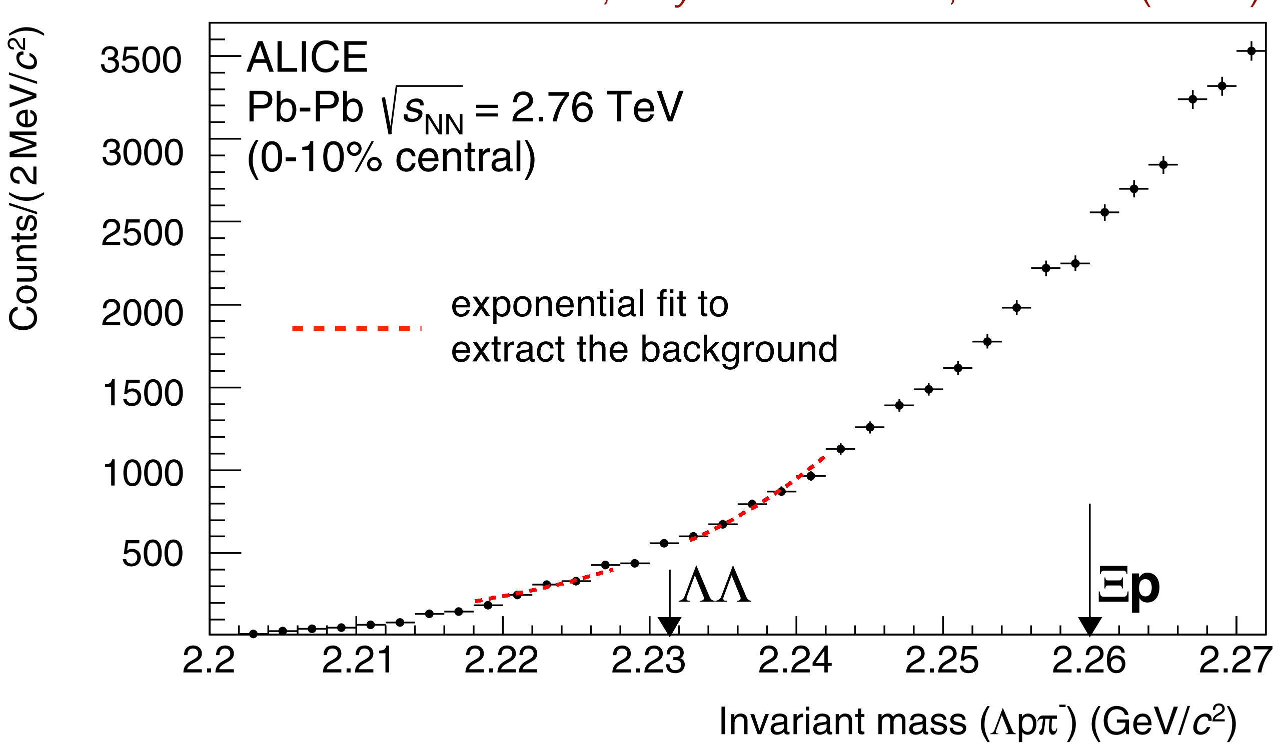
$$H \longrightarrow \Lambda p \pi^-$$

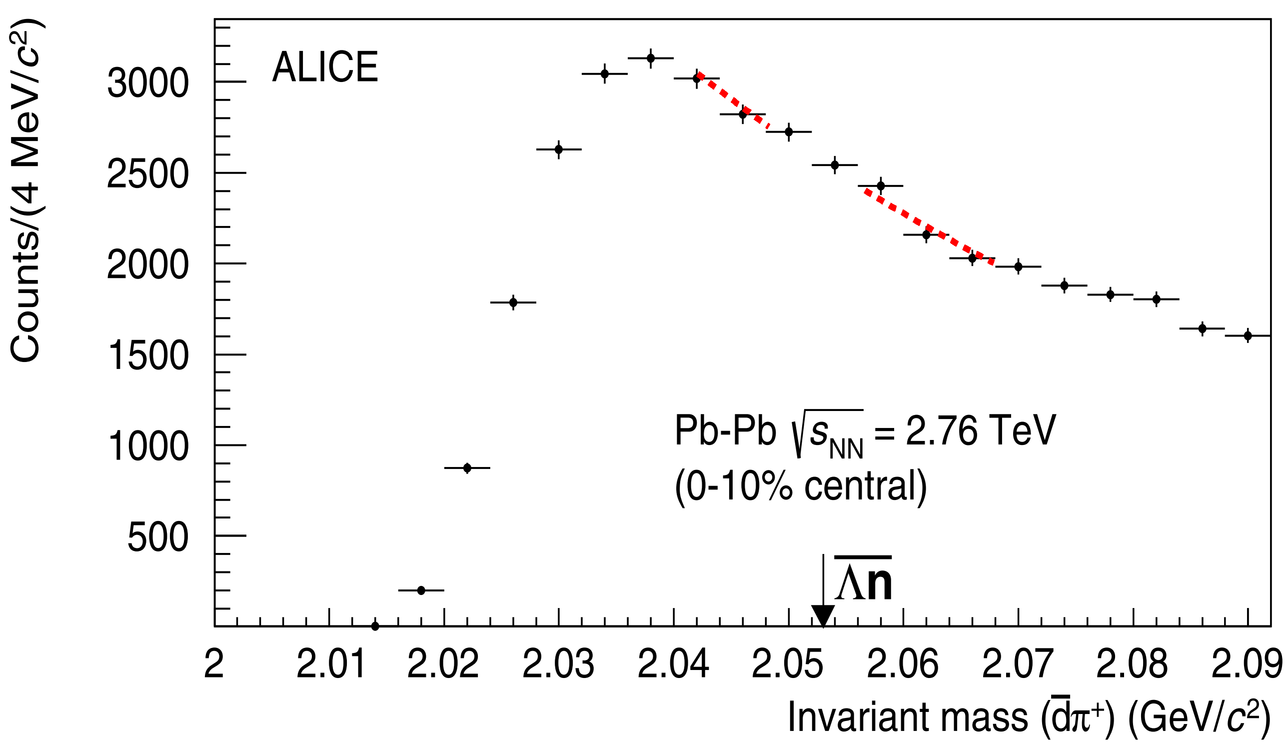
Λn

- Invariant mass $M_{\Lambda n} \cong 2.055$ GeV/c²
- Antimatter investigated here because of less secondary contamination
- Search in the decay channel

$$\overline{\Lambda n} \longrightarrow \overline{d}\pi^+$$

ALICE Collaboration, *Phys. Lett. B* 752, 267-277 (2016)





Exotica: *upper limits*

- No signal observed from invariant mass spectra ⟶ upper limit obtained (C.L. 99%)
- Upper limit on d*N*/d*y*

  H-dibaryon: B.R. = 64%[5] and free Λ lifetime

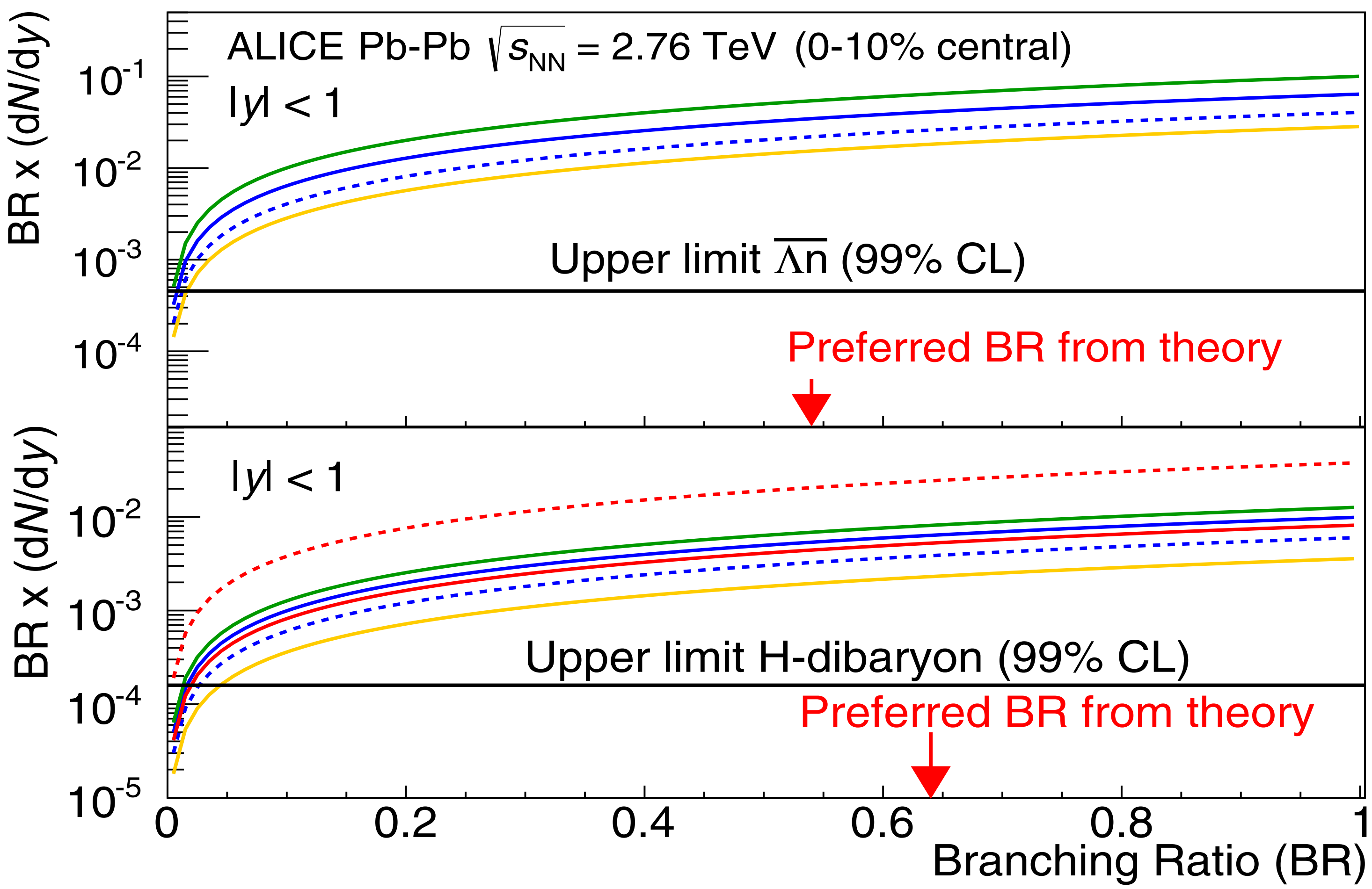
  ➡ d*N*/dy ~ 2.0x10^{-4} a factor ~30 below predictions

  Λn: B.R. = 54%[5] and free Λ lifetime

  ➡ d*N*/dy ~ 9.0x10^{-4} a factor ~45 below predictions

- B.R. dependence
  - using upper limit from free Λ lifetime assumption
  - **B.R. x d*N*/d*y*** upper limit is far away from the expectations for preferred B.R.
  - comparison with **thermal model**
  - only for H-dibaryon comparison also with **coalescence model** (red lines) because no calculation exists for Λn

ALICE Collaboration, *Phys. Lett. B* 752, 267-277 (2016)



[5] J.Schaffner-Bielich et al. Phys. Rev. Lett. 84, 4305 (2000)

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Outlook and conclusion

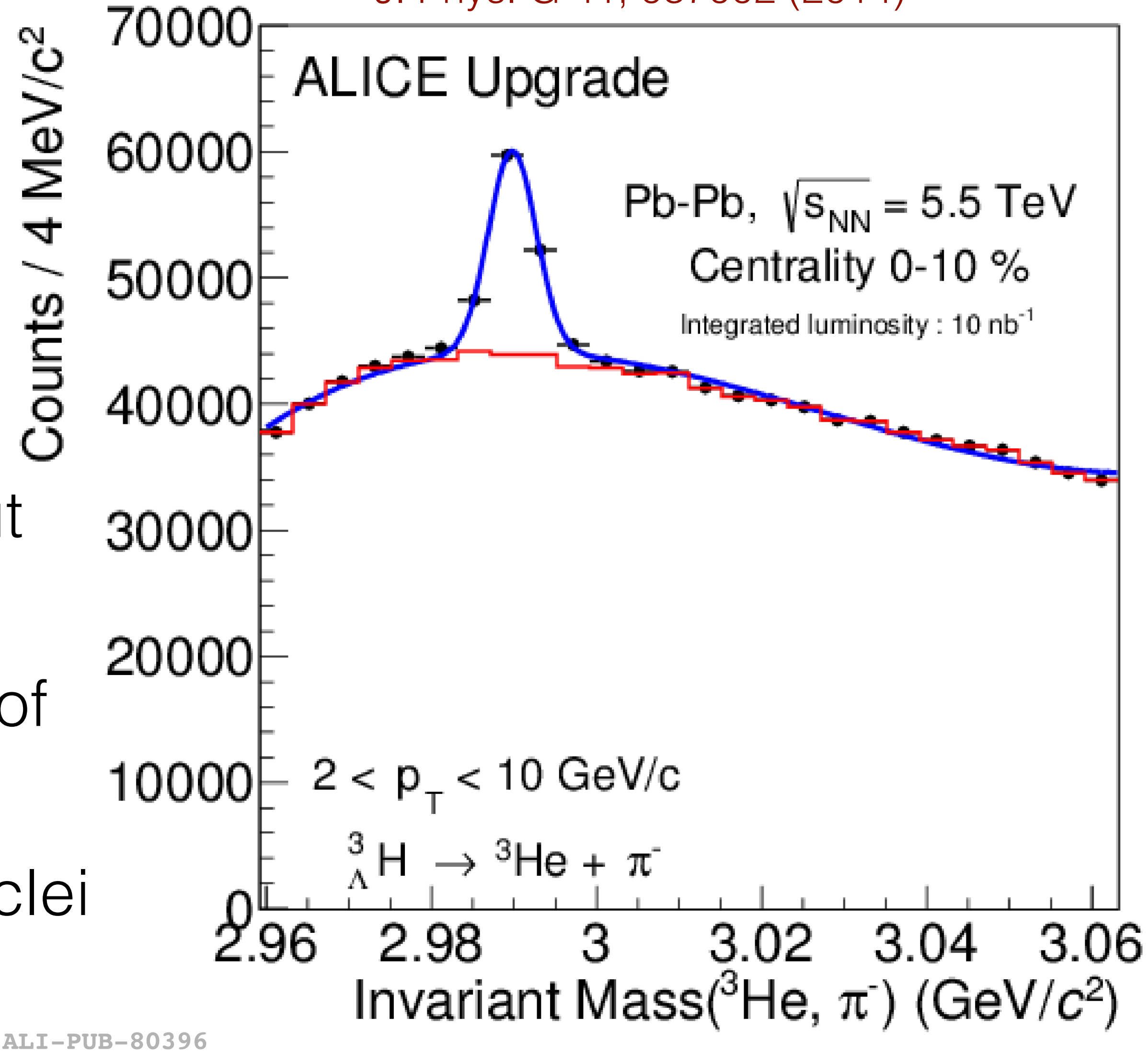
Run 2 (2015-2018)

- for **Pb-Pb** an increase of statistics by a factor ~10 is expected
- improvement of **Run 1** measurements and search for exotica signals
- study the hypertriton in the 3-body decay channel

Run 3-4 (2021-2023; 2026-2029)

- LHC will deliver more statistics
  ⟶ **Pb-Pb at 50 kHz collision rate**
- ALICE will upgrade the detectors to cope with this higher luminosity
- TPC upgrade: GEMs for continuous readout
- ITS upgrade: low material budget and more precise tracking for the identification of hyper-nuclei
- Physics analysis done for A=2 and A=3 nuclei and hyper-nuclei will be done also for A=4

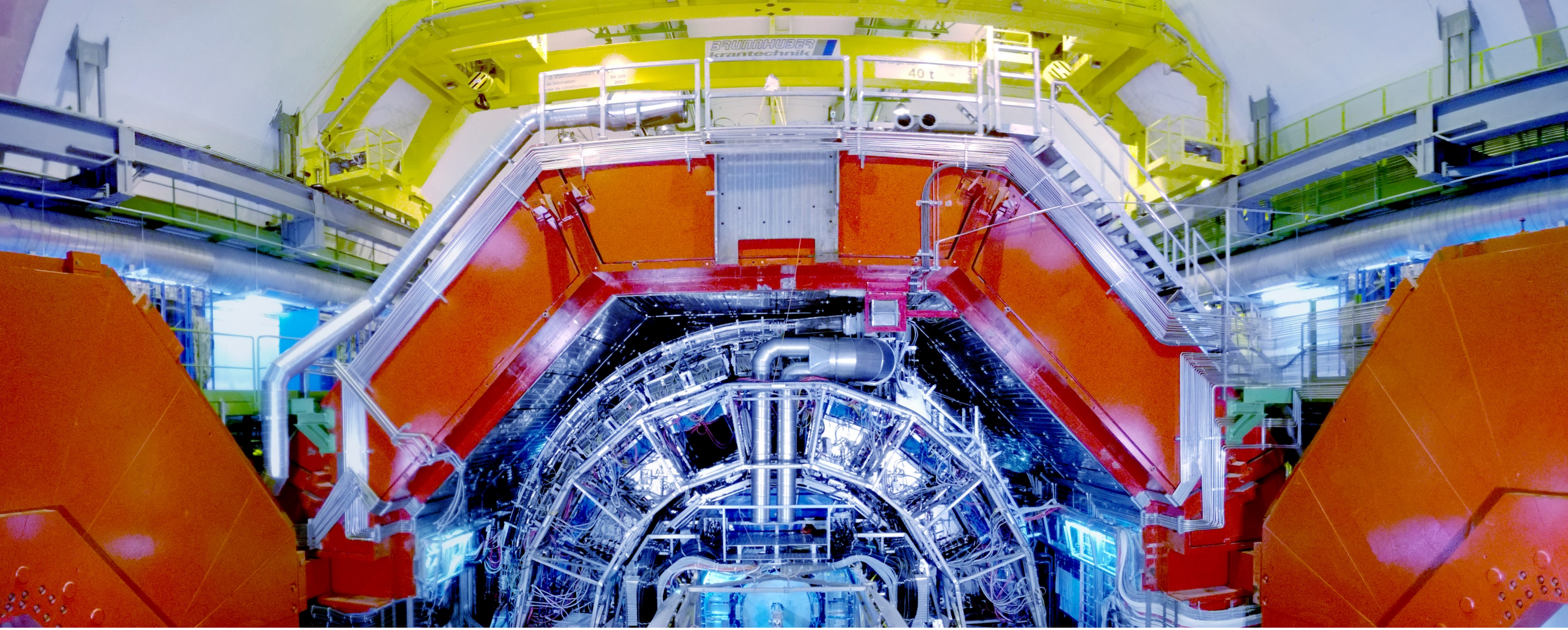
ALICE Collaboration, ITS upgrade TDR
J. Phys. G 41, 087002 (2014)



Outlook and conclusion

- ✓ ALICE's excellent **performance** allows the **detection** of light (anti-)(hyper-)nuclei and **search** for exotic bound states
- ✓ A **hardening** of deuteron and ^{3}He spectra is observed for **increasing** *centrality* in Pb-Pb and *multiplicity* in p-Pb collisions
- ✓ Measurement of deuteron **elliptic flow** shows a significant v_2 for semicentral Pb-Pb collisions
- ✓ **Thermal** and **coalescence** models describe the (anti-)(hyper-)nuclei data well
- ✓ Measured deuteron, ^{3}He, hypertriton and anti-alpha yields are in **good agreement** with the current best **thermal fit** from equilibrium thermal model (T_{chem} = 156 MeV)
- ✓ Hypertriton **lifetime** measurement is consistent with previous heavy-ions results but shows a **significant deviation** from free Λ lifetime
- ✓ **Upper limit** for the exotic bound states (**Λn** and **H-dibaryon**) are a factor ~25 below theoretical predictions
- ✓ New data and results are expected from the **LHC Run2** on the presented topics

Thank you for your attention



BACKUP

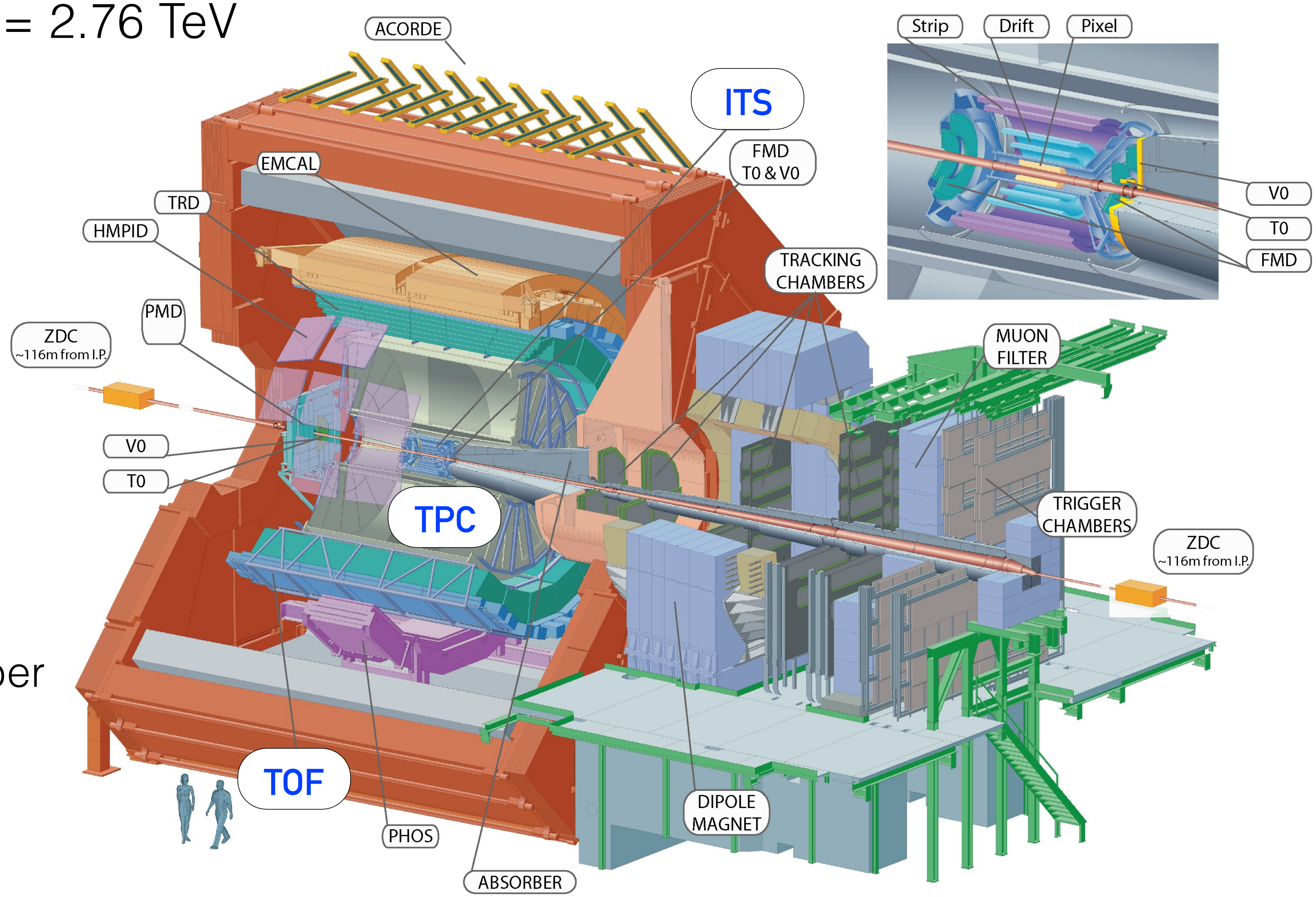
ALICE

A Large Ion Collider Experiment

- Designed for heavy-ion collisions
- Excellent Particle Identification (PID) capabilities and low material budget
- Suited for hypernuclei and exotica production study
- In Run1 Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Main detectors used for **(anti-)(hyper-)nuclei** and **exotica analysis**:

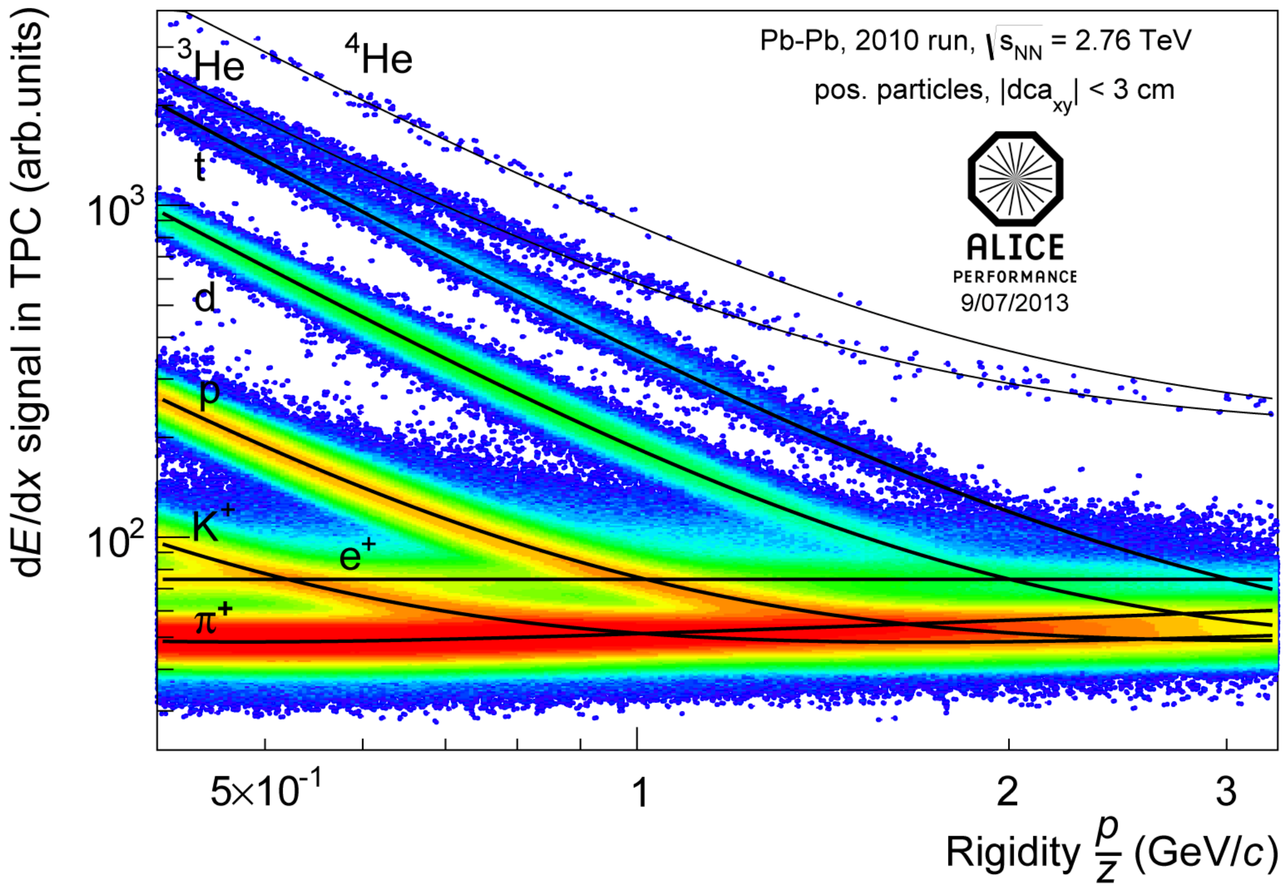
- Inner Tracking System
- Time Projection Chamber
- Time-Of-Flight



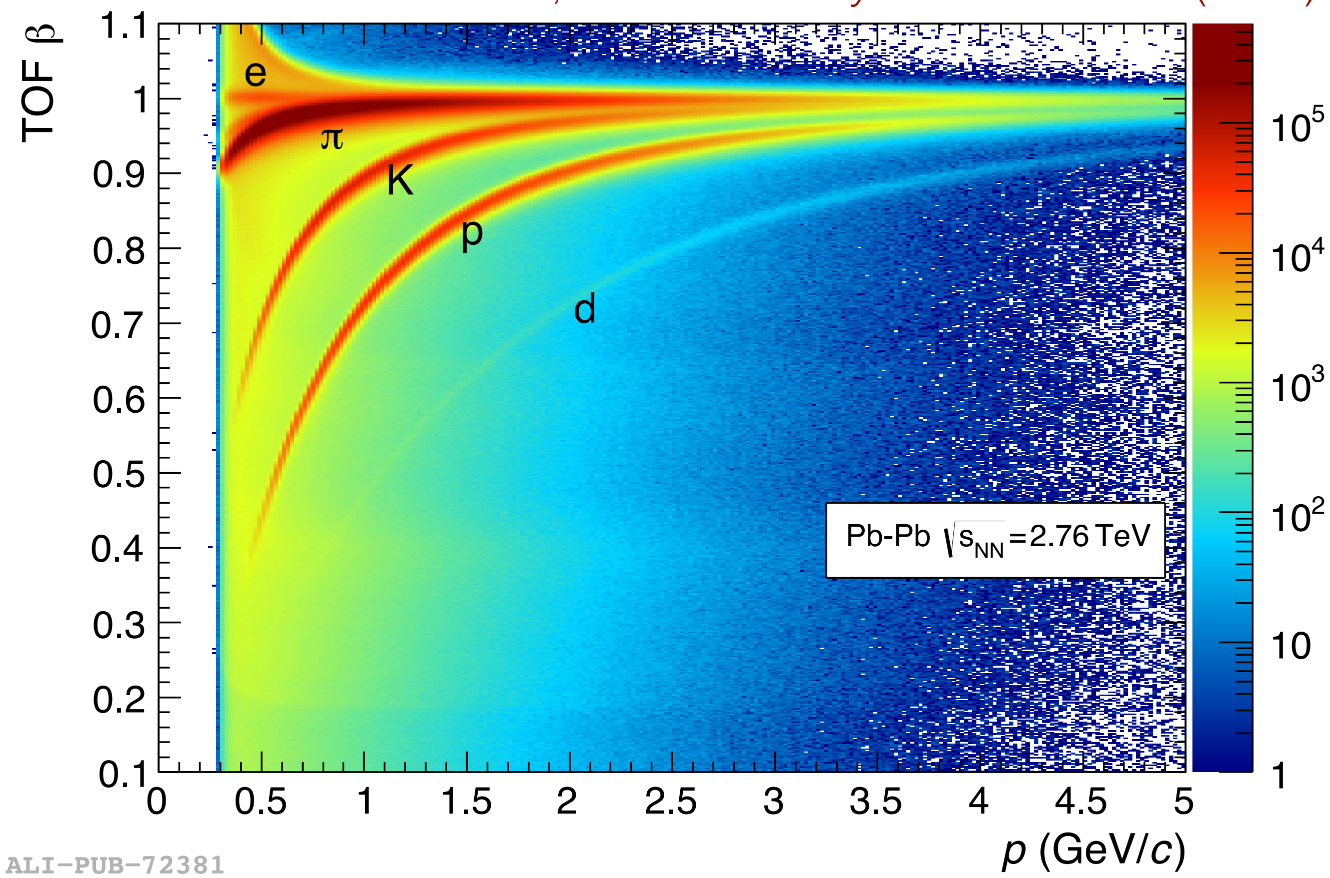
Particle Identification

Time Projection Chamber

- PID is done using the specific energy loss dE/dx
  - ➡ $\sigma_{dE/dx}$ ~ 7% (Pb-Pb collisions)
  - ➡ Clear nuclei separation: at $p/z \leq 2$ GeV/c excellent PID for light nuclei



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



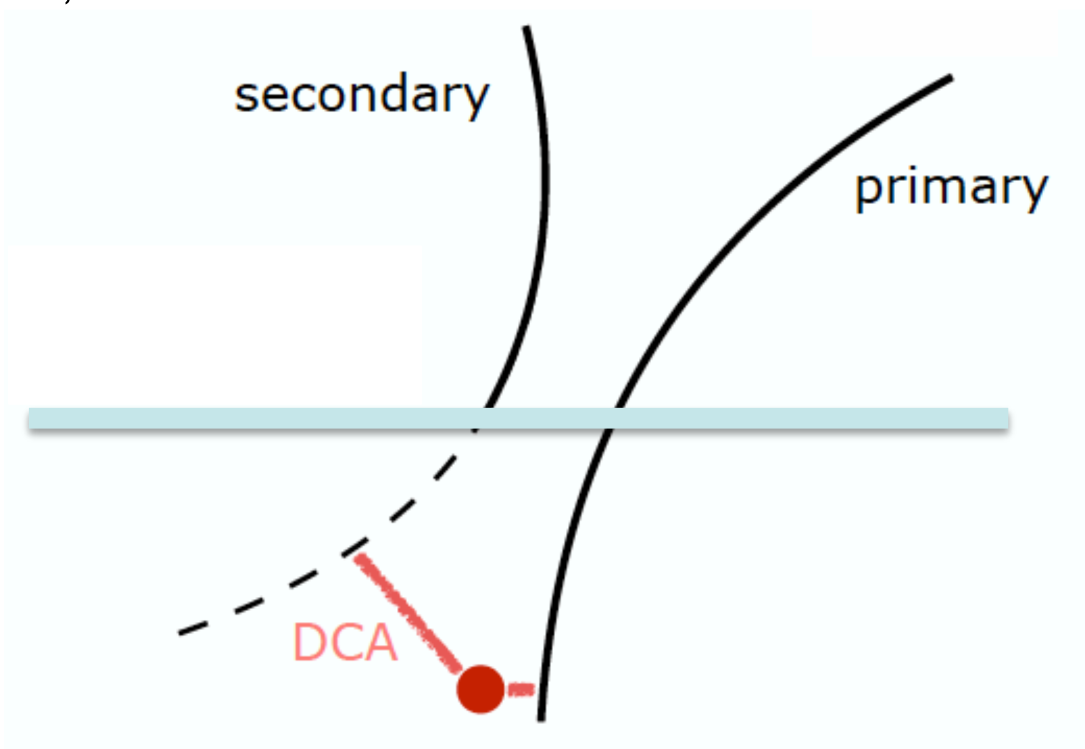
Time-Of-Flight

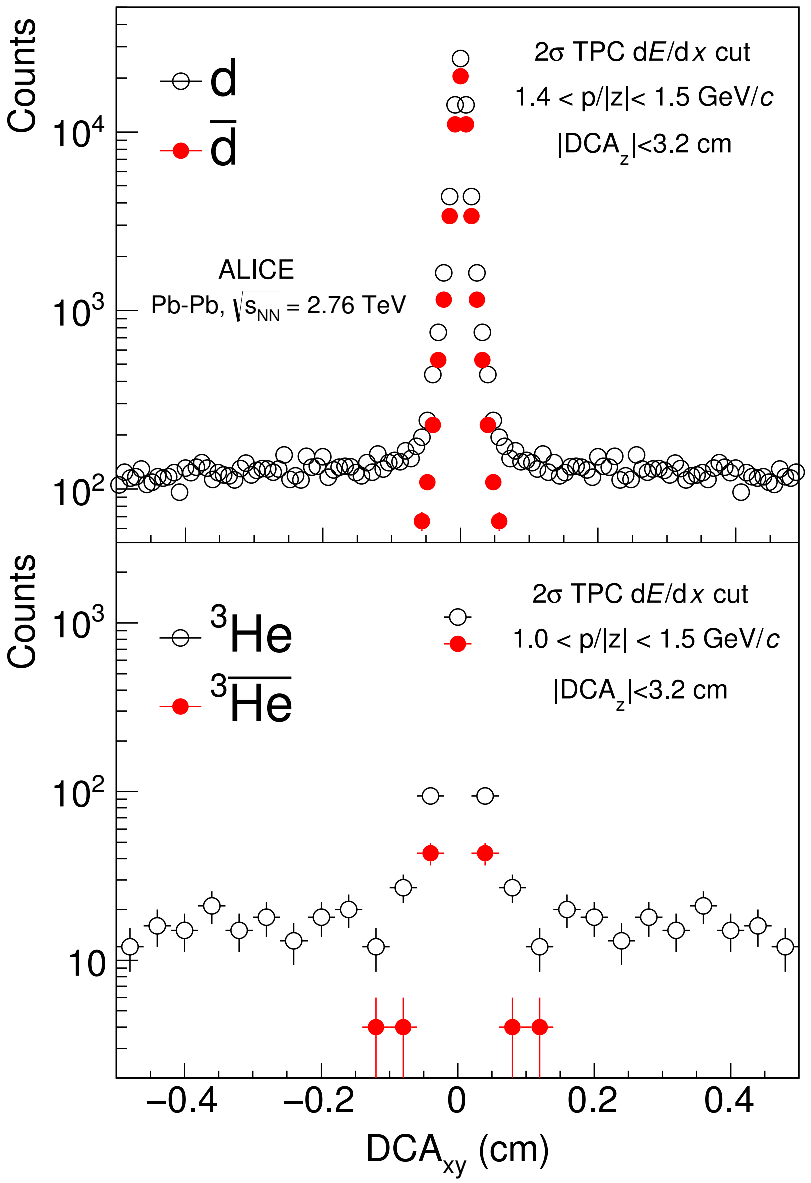
- PID is done using TOF to measure the β of the particles
  - ➡ σ_{TOF} ~ 85 ps (Pb-Pb collisions)
  - ➡ deuteron identification up to 4.5 GeV/c in Pb-Pb collisions

Vertexing and Tracking

Inner Tracking System

- Separation of particles coming from primary and secondary vertices
  - ➡ $\sigma_{DCA_{xy}}$ < 100 μm for p_T > 0.5 GeV/c (in Pb-Pb collisions)
  - ➡ Distance-of-Closest-Approach (DCA) can be used to separate **primary particles** (produced in the collision) from **secondary particles** (knock-out of the material)
  - ➡ Knock-out contribution is significant at low p_T but only for nuclei, not for anti-nuclei





Centrality

Theory

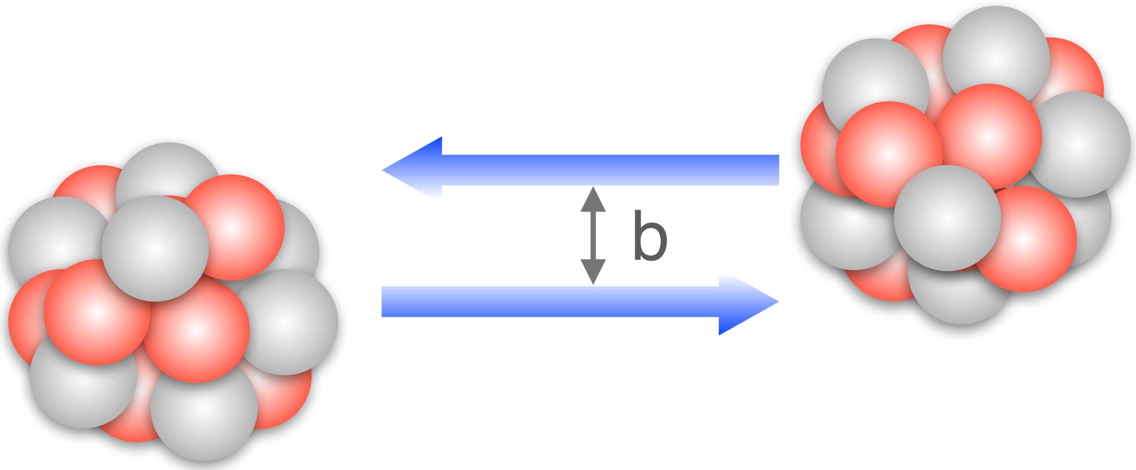
The centrality of the collision is defined by the impact parameter vector ***b***

Most central collision ⇔ Smallest ***b***

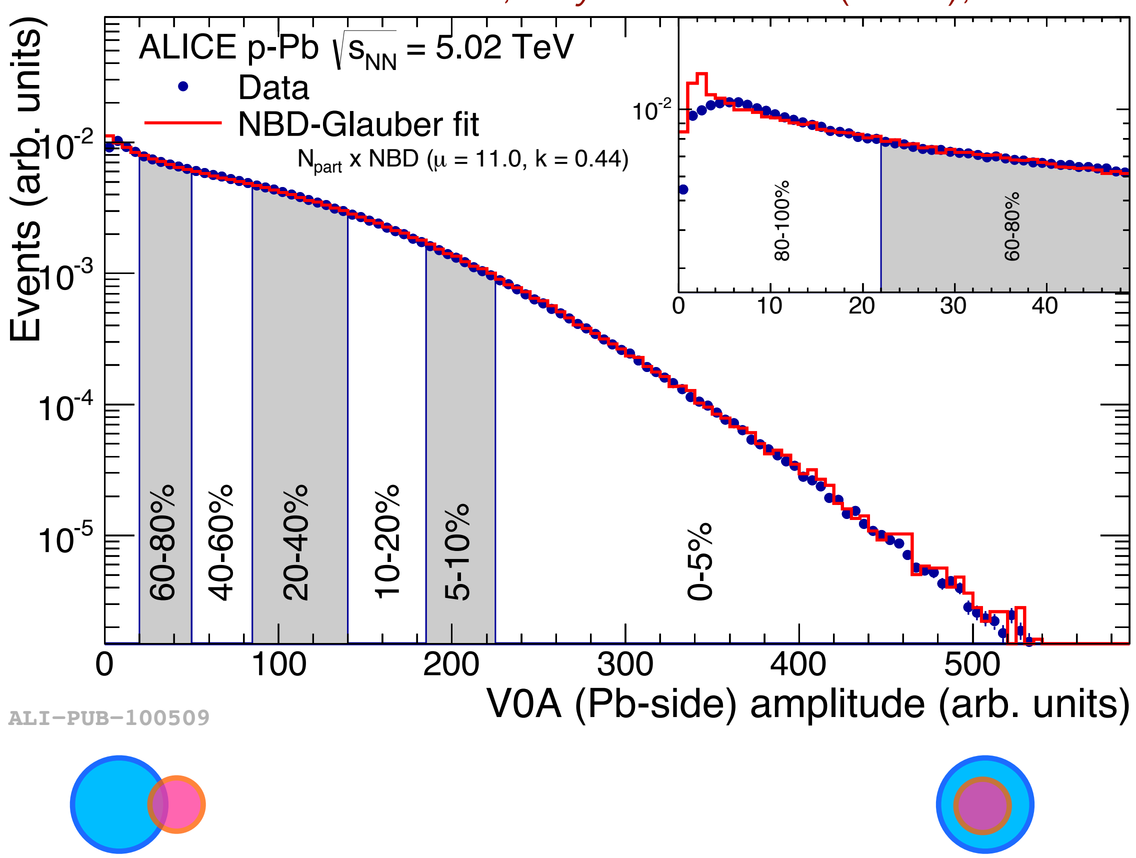
Experimentally

It is possible to correlate the track multiplicity to an impact parameter value by fitting data with predictions from Glauber model.

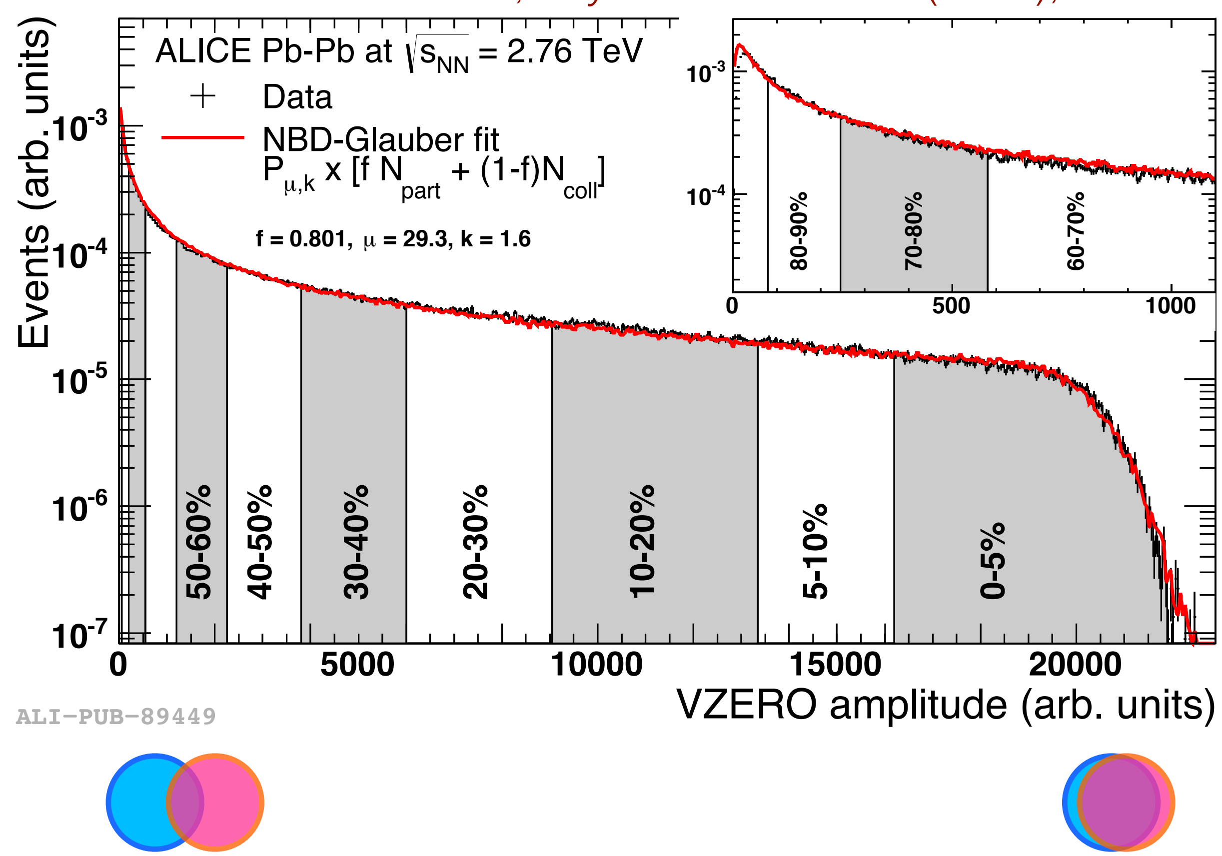
Heavy Ion collision



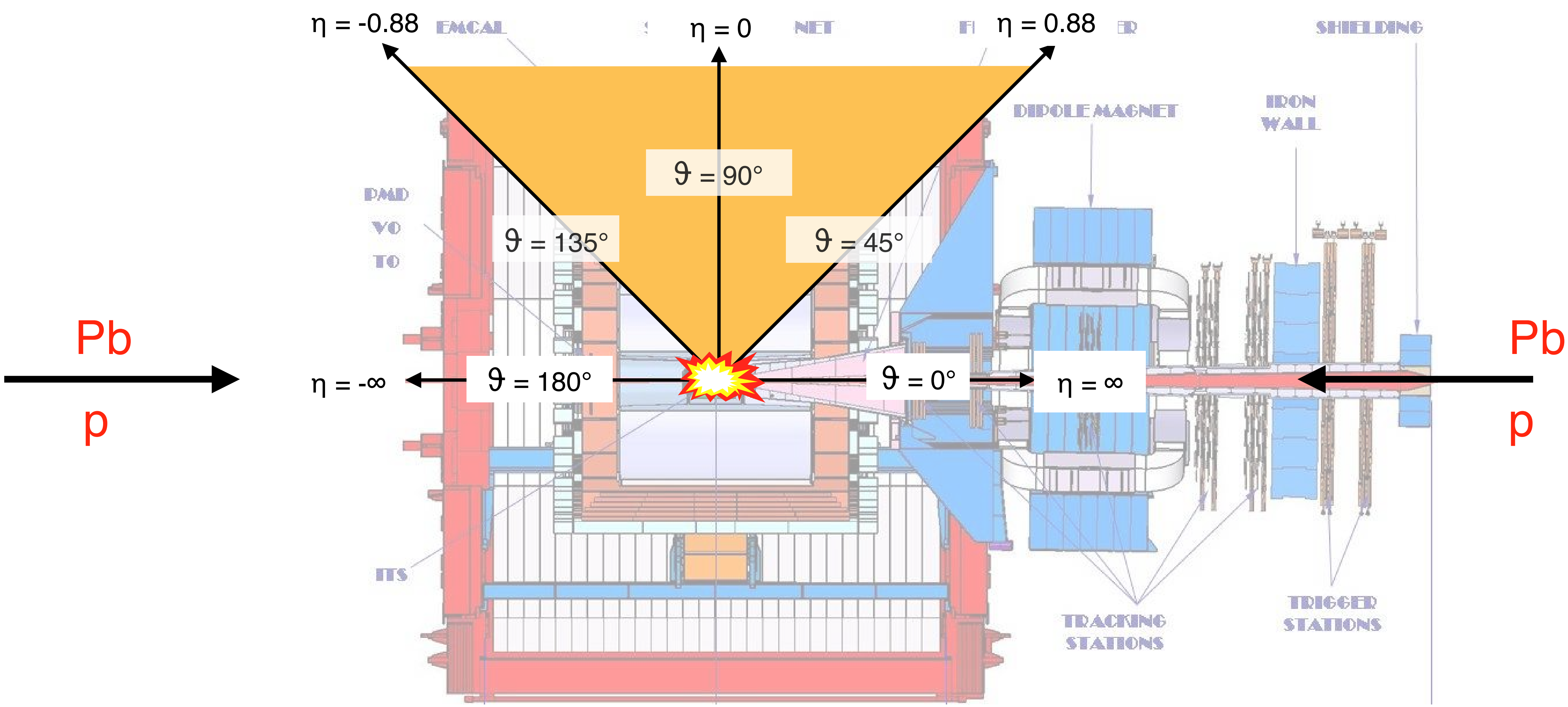
ALICE Collaboration, *Phys. Rev. C* 91 (2015), 064905



ALICE Collaboration, *Phys. Rev. Lett.* 106 (2011), 032301

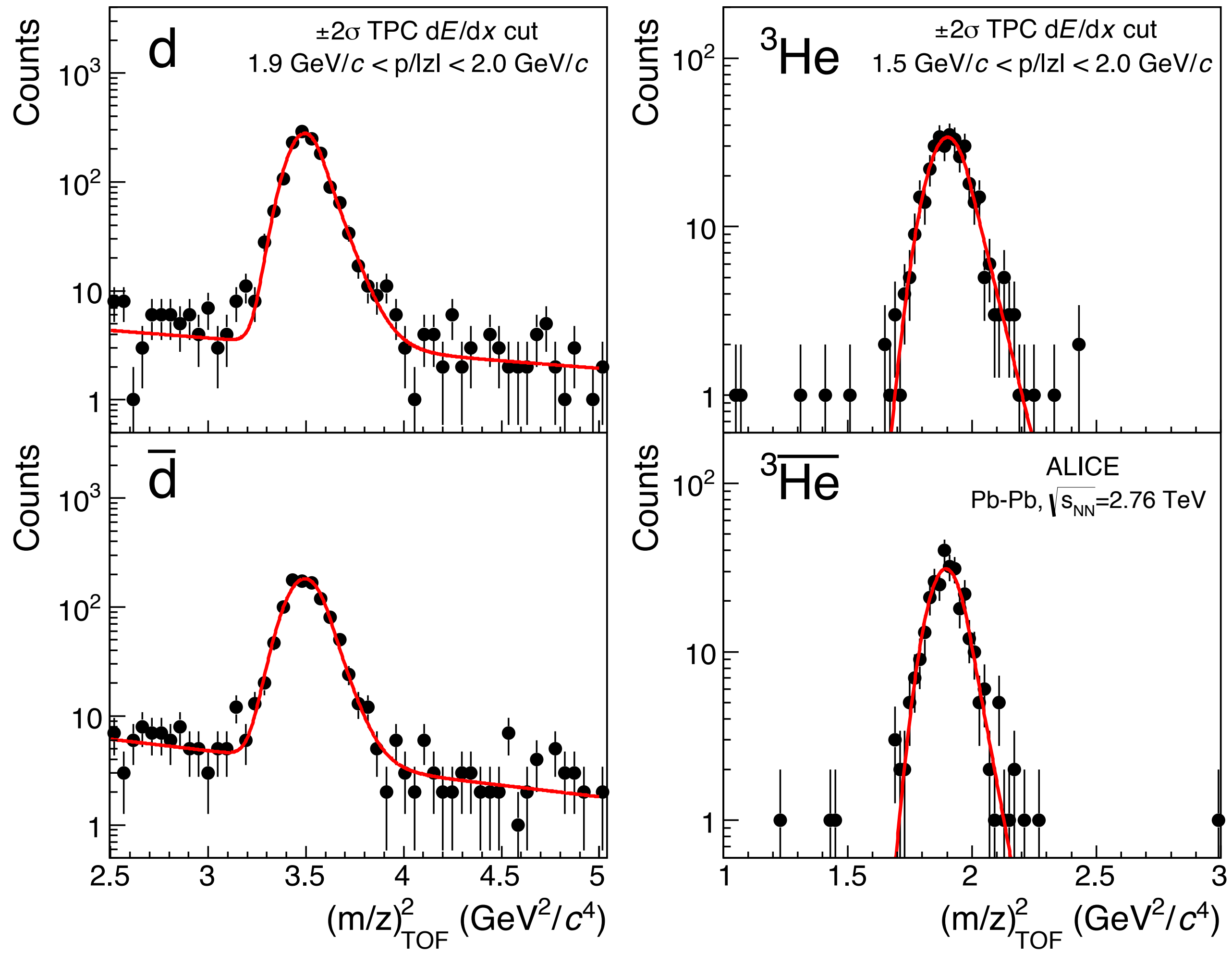


Central region



Nuclei: *CPT invariance test*

ALICE Collaboration, *Nature Phys.* 11, 811-814 (2015)

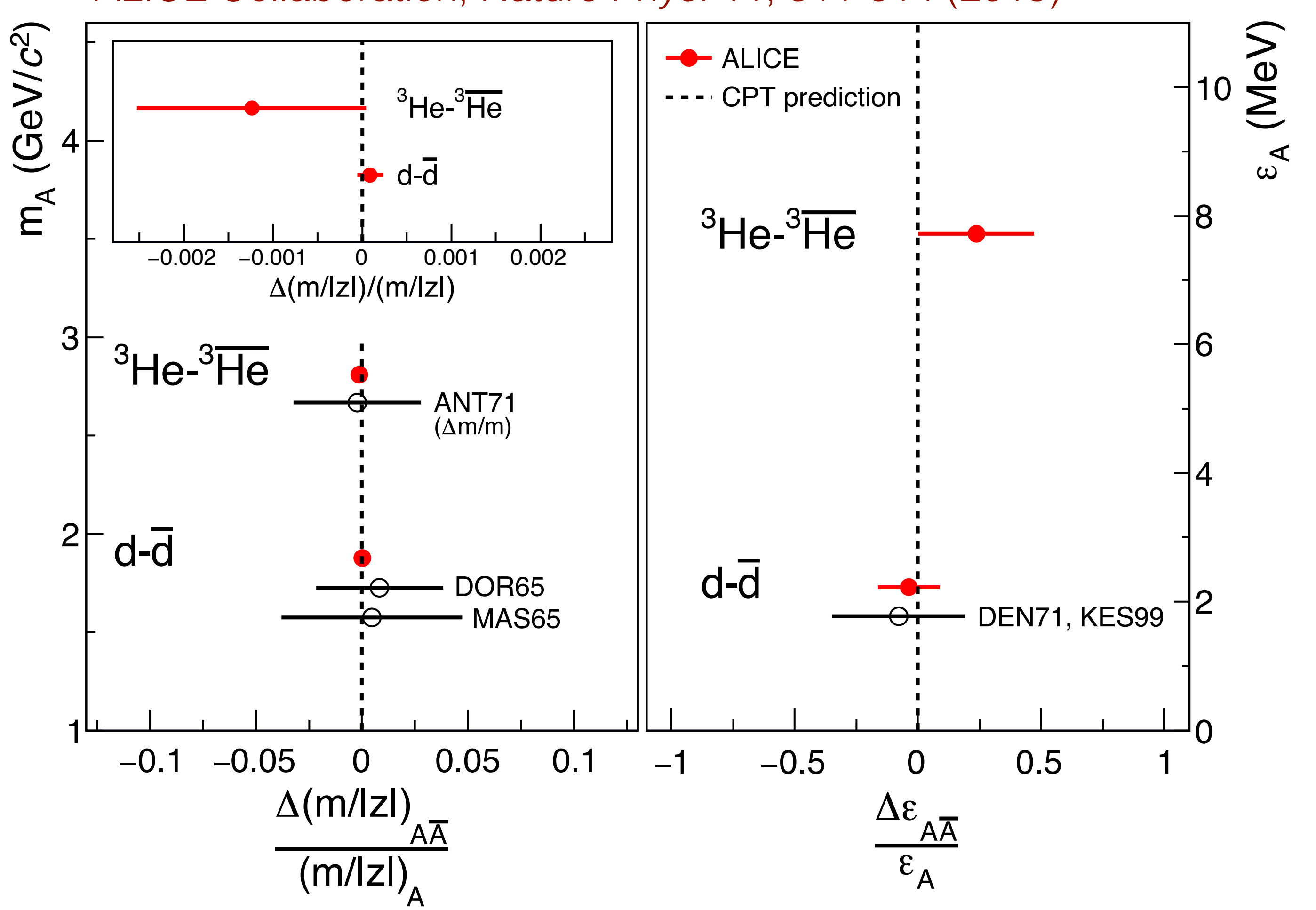


- Precise measurement of (anti-)nuclei mass difference

  → probe any difference in nucleon anti-nucleon interaction

- CPT invariance test of residual QCD "nuclear force" by looking at the mass difference between nuclei and anti-nuclei

ALICE Collaboration, *Nature Phys.* 11, 811-814 (2015)



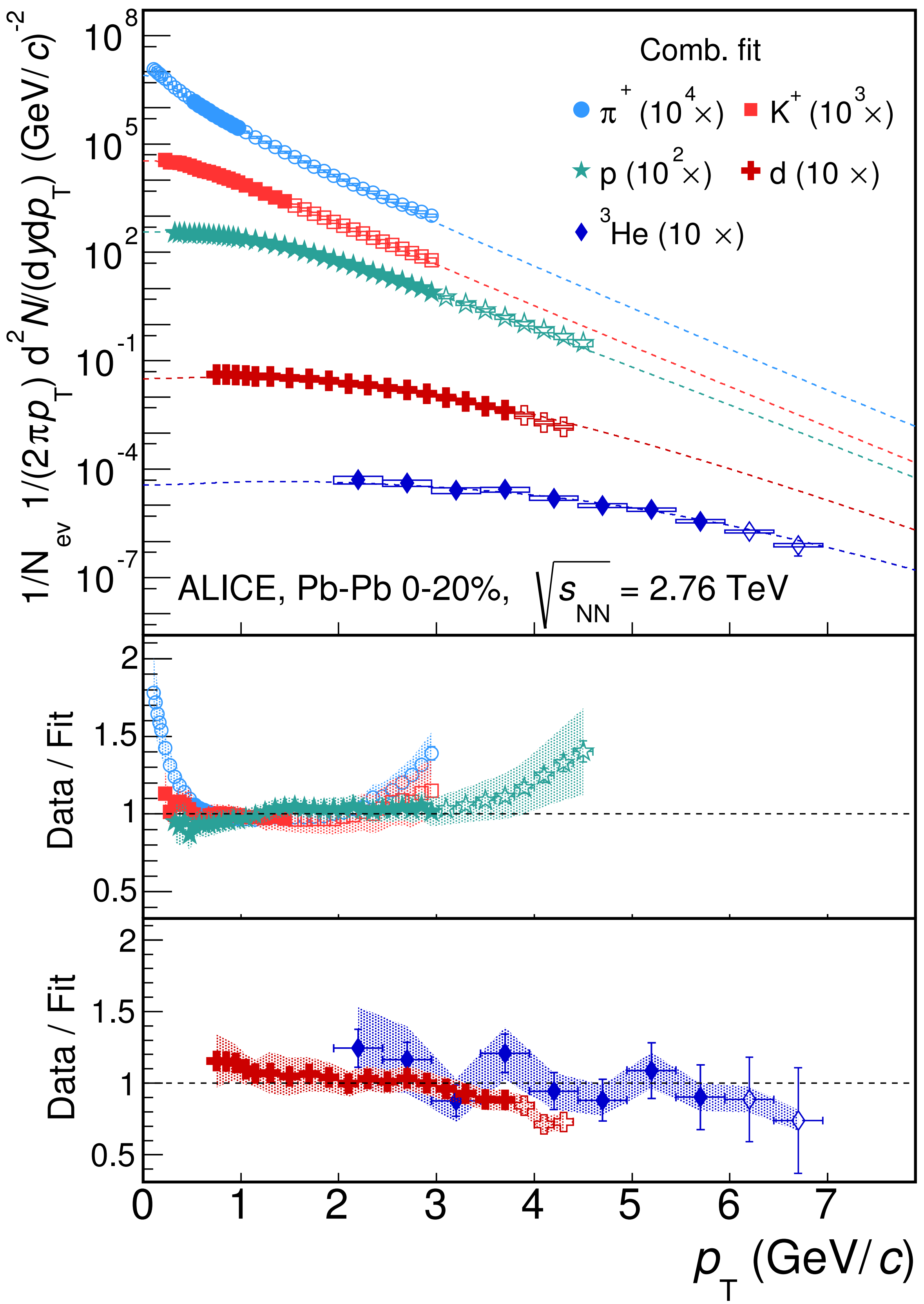
- Binding energy definition
  $\varepsilon_A = Zm_p + (A-Z)m_n - m_A$

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

✓ Measurement confirms the CPT invariance for light nuclei

Nuclei: *Blast-Wave simultaneous fit*

ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



- Simultaneous **Blast-Wave fit** π^+, K^+, p, d and ^{3}He spectra for central Pb-Pb collisions

  → $\langle\beta\rangle = 0.632 \pm 0.01$

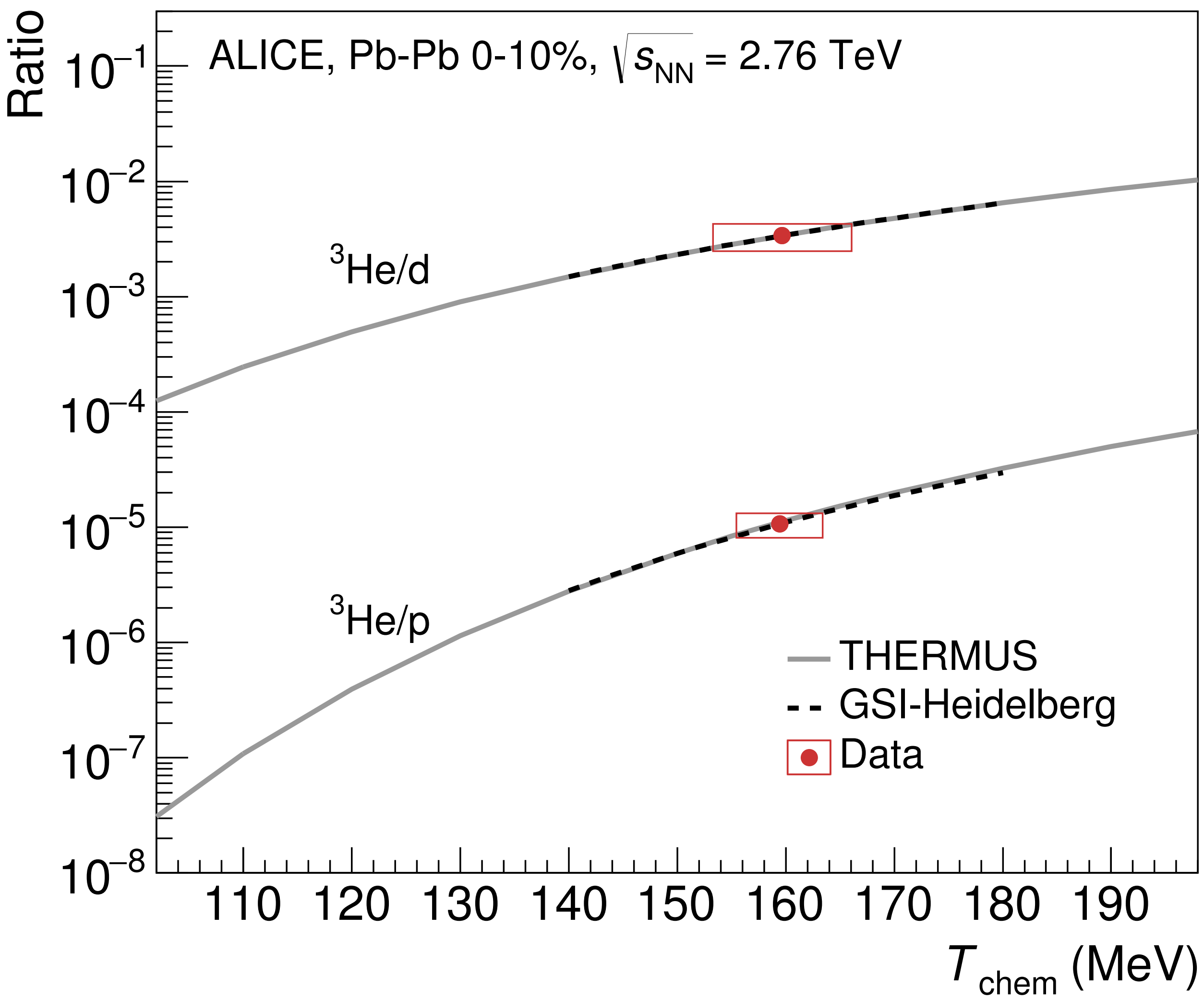
  → $T_{kin} = 113 \pm 12$ MeV

- These values are close to those obtained when only π, K and p are used
  ALICE Collaboration, *Phys. Rev. C* 88, 044910 (2013)

- All particles are described rather well with this simultaneous fit

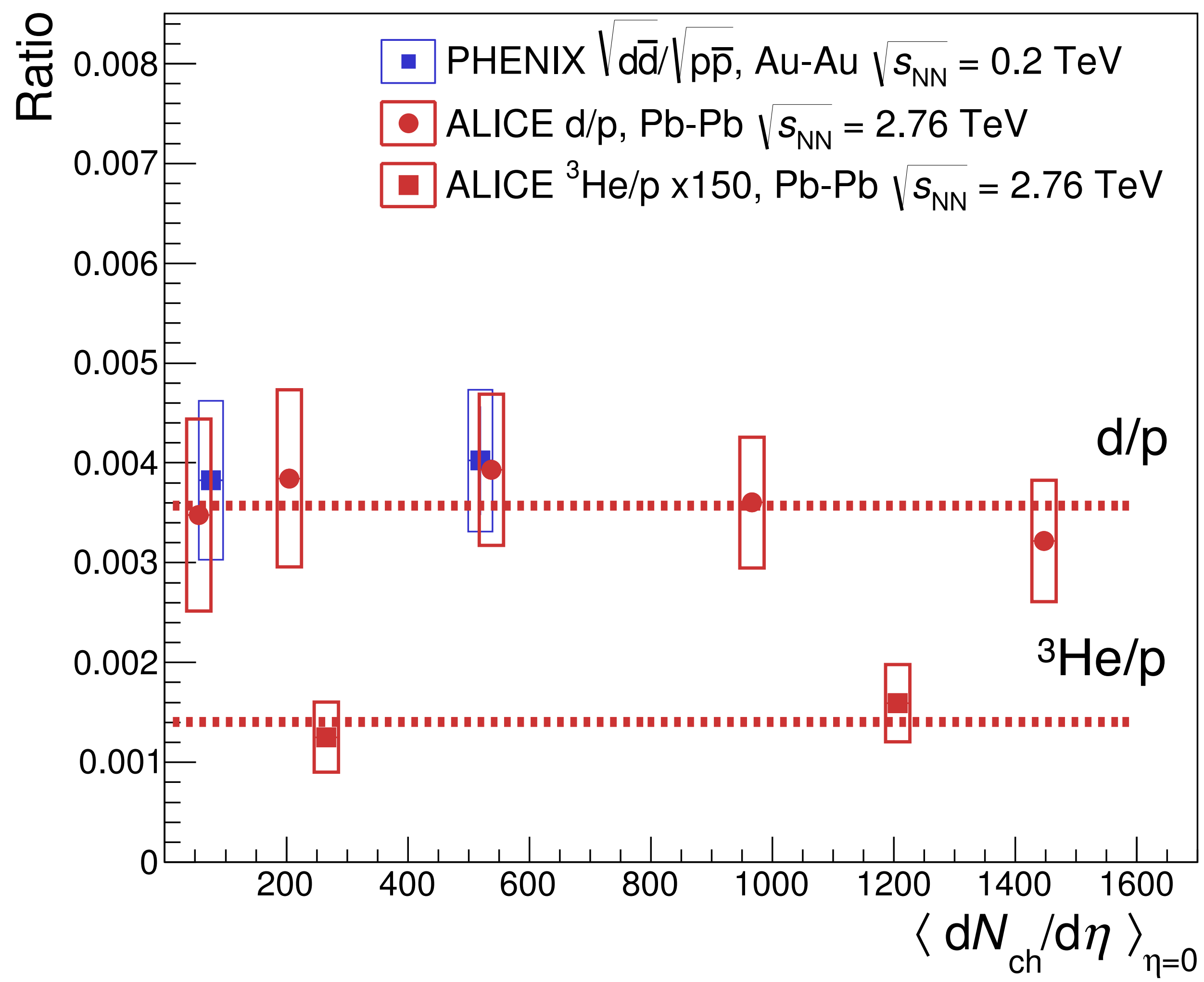
Nuclei: *ratios between species*

ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



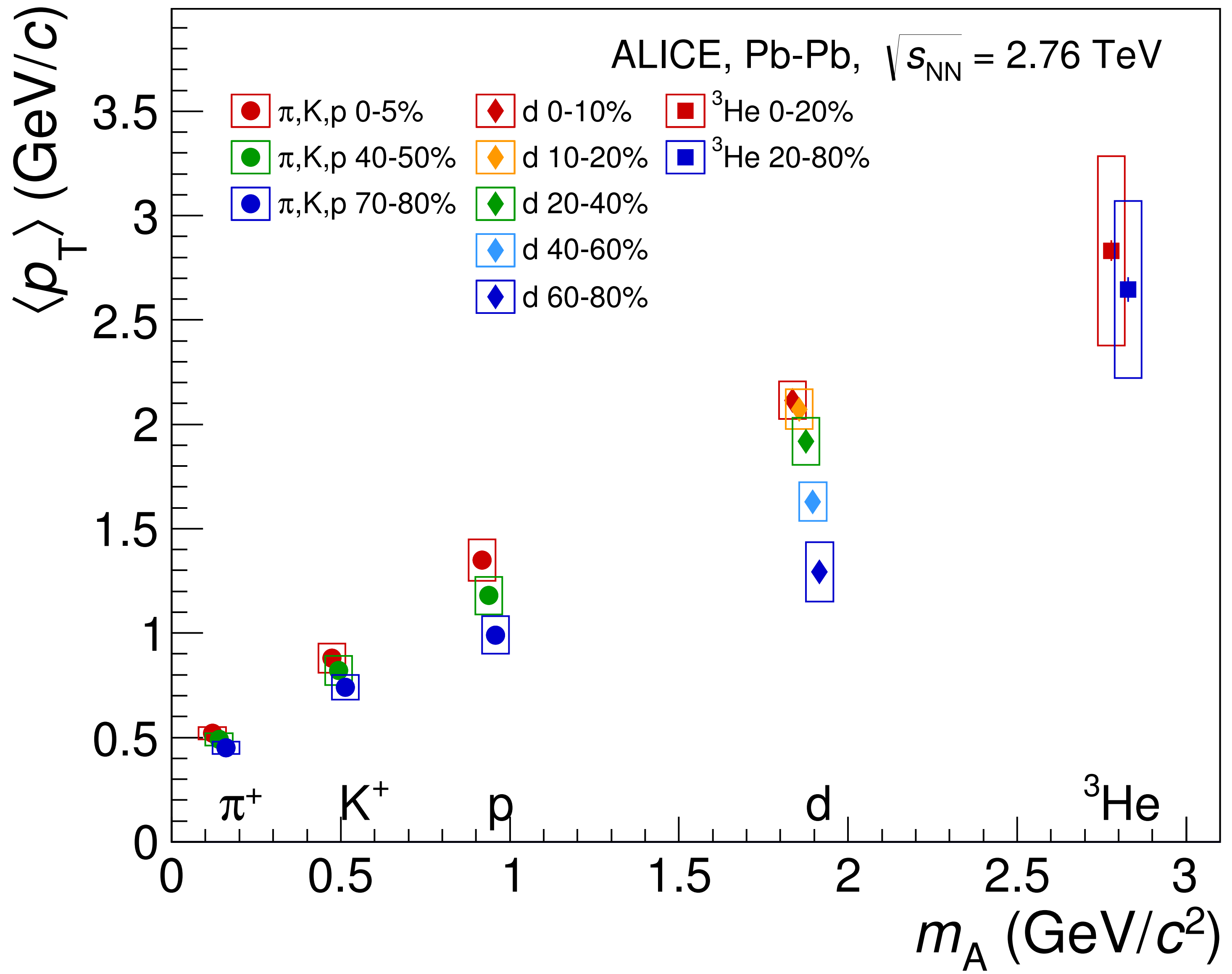
- ^{3}He/d and ^{3}He/p ratios are in agreement with thermal model values

- d/p ratio agrees well with "averaged" measurement at RHIC



Nuclei: *mean* p_T

ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)

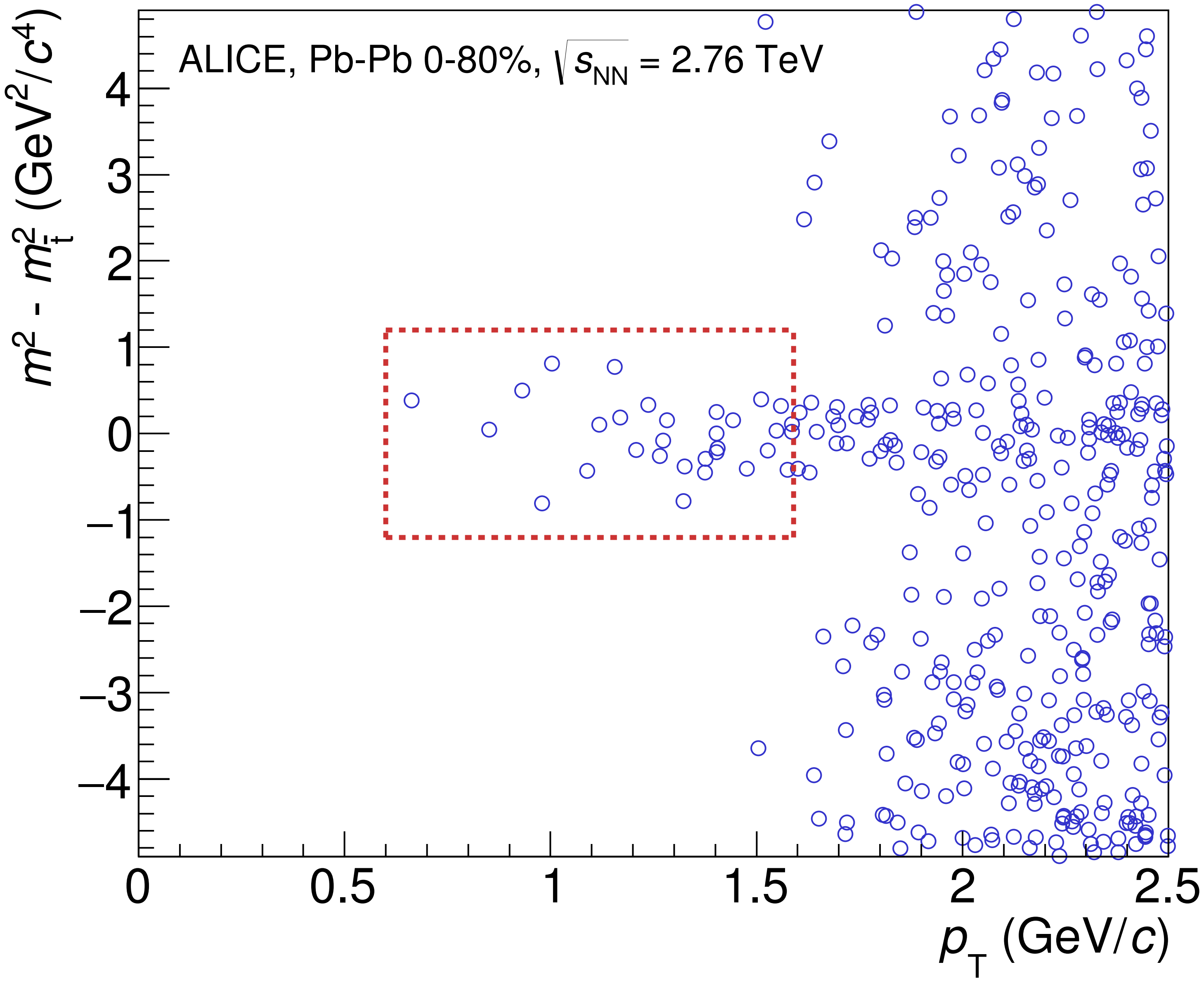


- mean transverse momentum $<p_T>$ as a function of the particle mass
- $<p_T>$ increases with particle mass

  → particles are emitted from a radially expanding source

Nuclei: *anti-tritons*

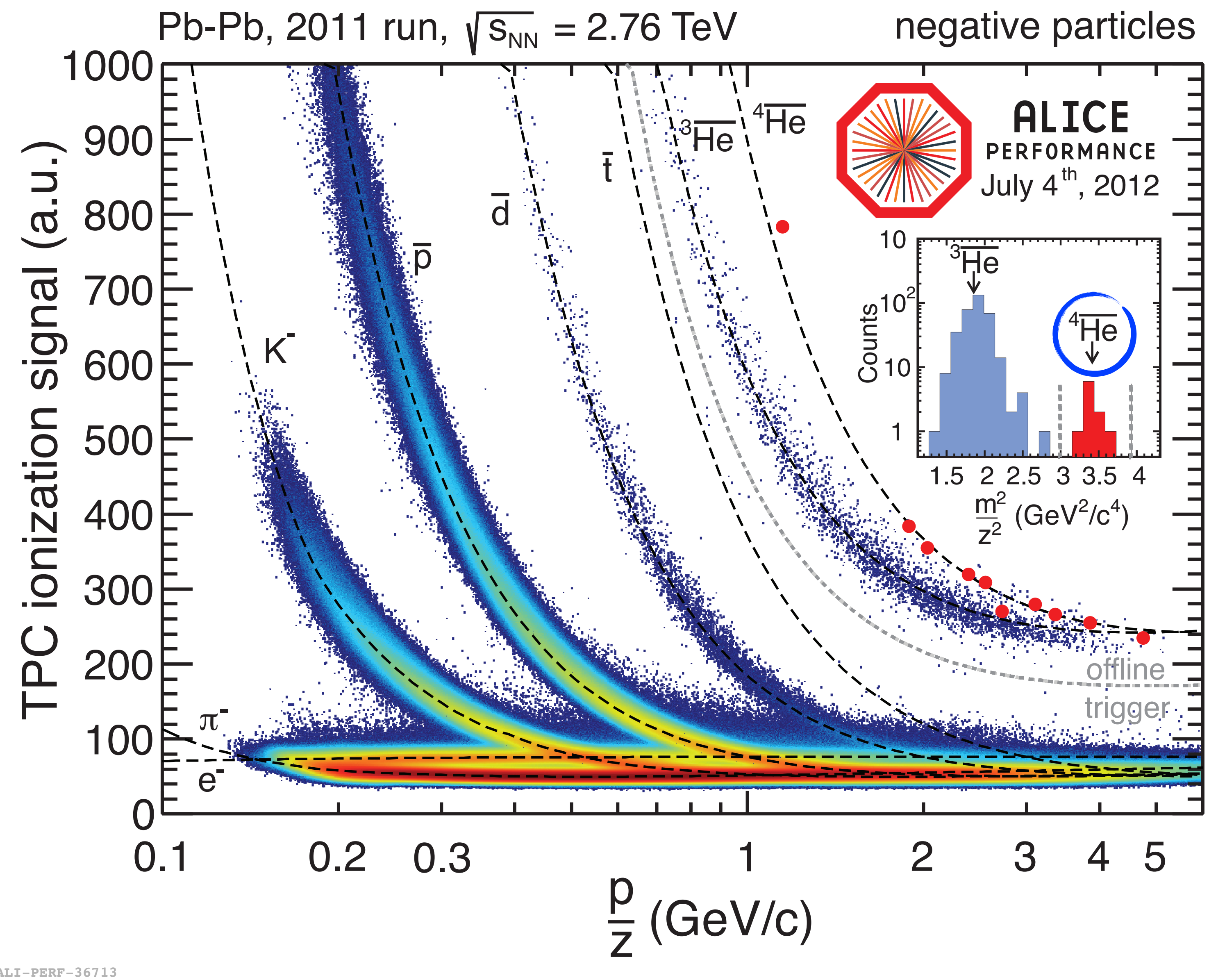
ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



- 31 anti-triton candidates are observed
- for p_T> 1.6 GeV/c the contamination increases rapidly → signal and background cannot be easily distinguished

Nuclei: *anti-alpha*

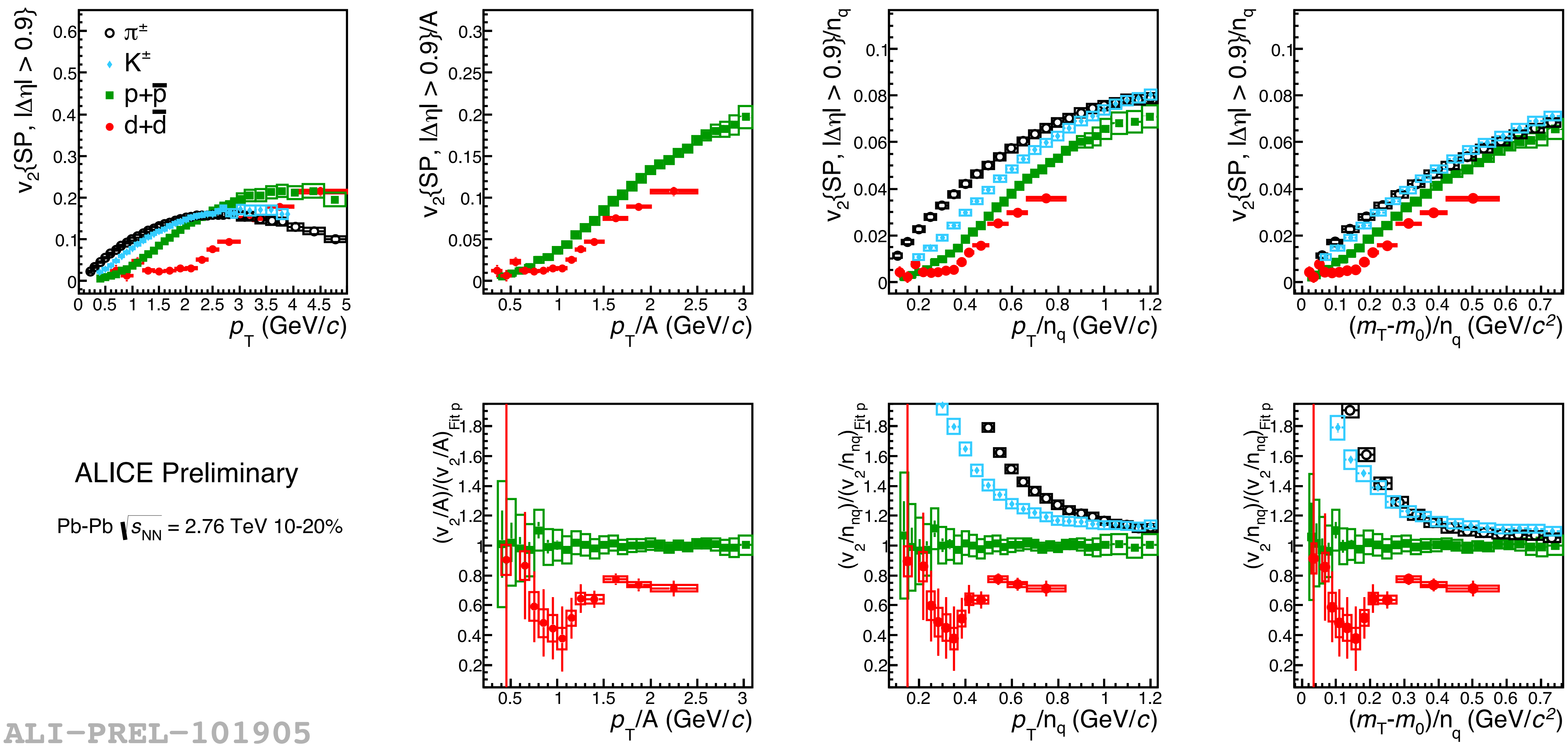
ALICE Collaboration, *Phys. Rev. C* 93, 024917 (2016)



- For the full statistics of 2011 Pb-Pb collisions
  → ALICE observed 10 anti-alphas using TPC and TOF detectors
- First observed by STAR Nature 473, 353 (2011)

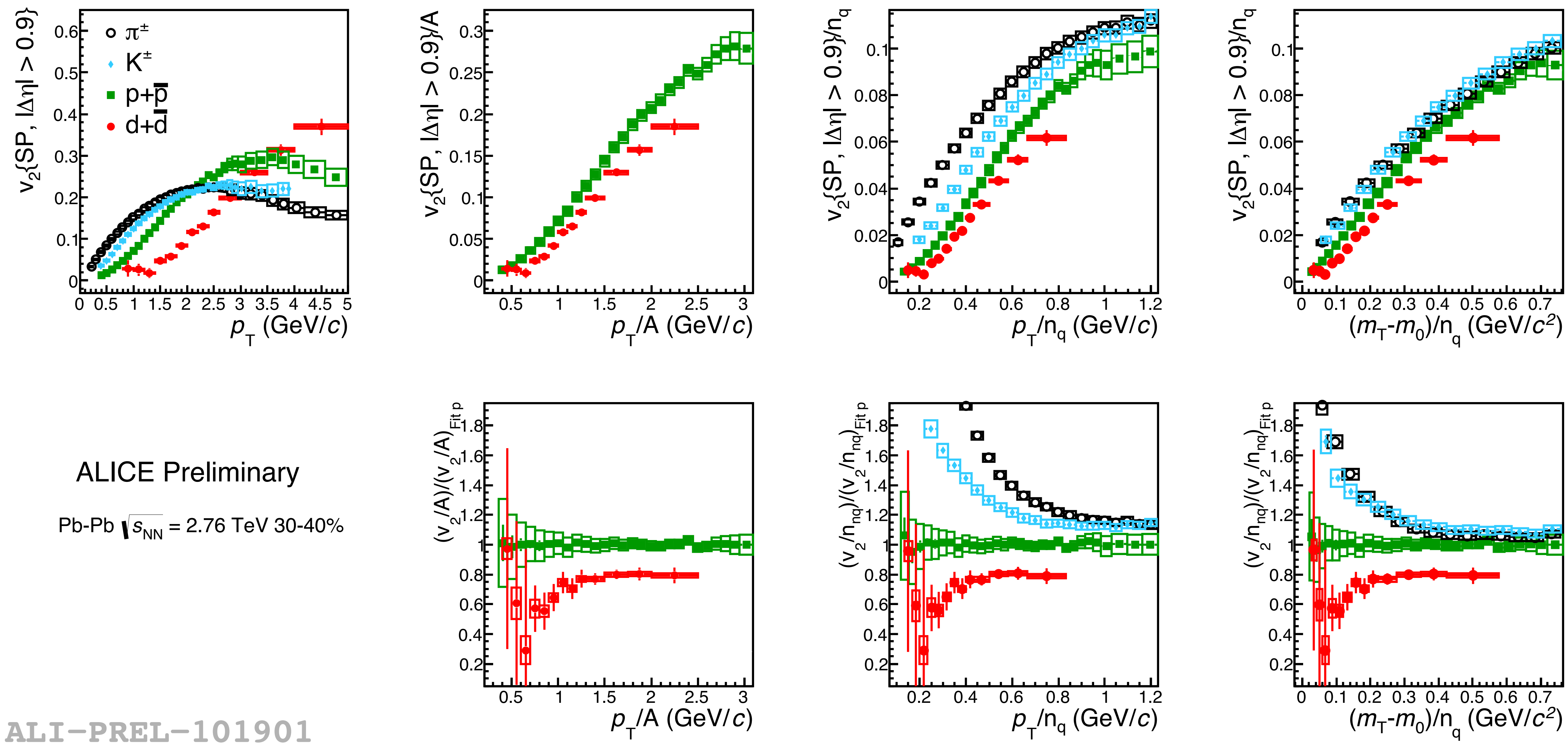
Nuclei: *deuteron elliptic flow*

- Centrality 10-20%



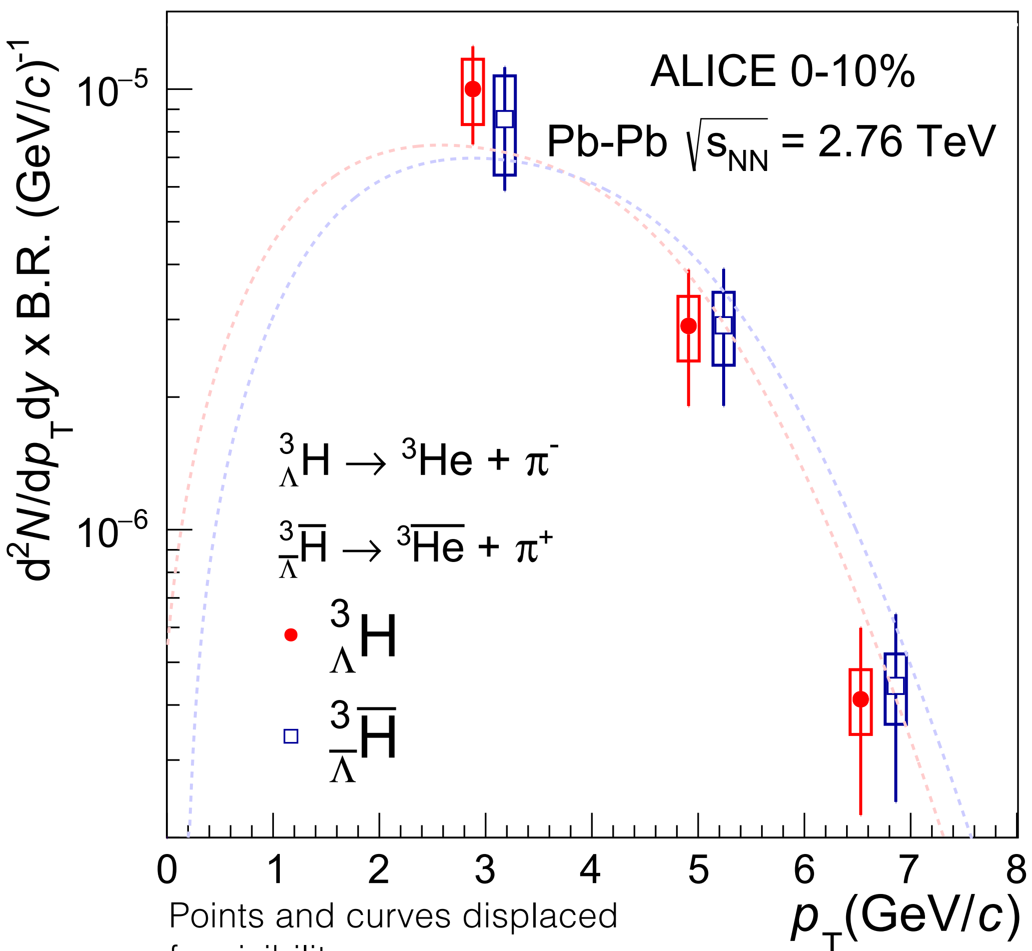
Nuclei: *deuteron elliptic flow*

- Centrality 30-40%



Hypertriton: p_T spectra

ALICE Collaboration,
Phys. Lett. B 754, 360-372 (2016)



Points and curves displaced for visibility

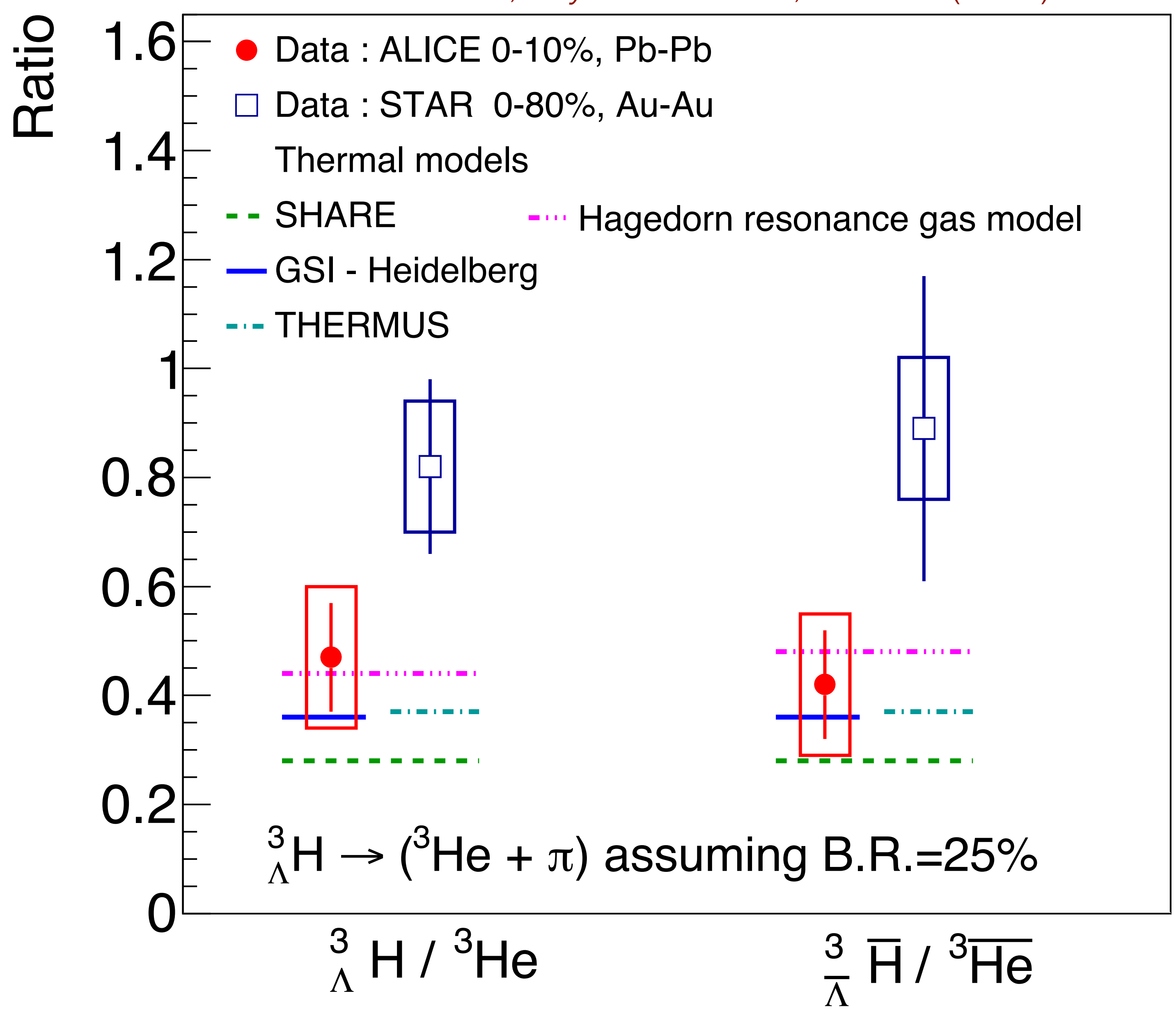
- ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\overline{H}$ signal from 2 GeV/c to 10 GeV/c:
  - 0-10% centrality ⟶ 3 p_T bins
  - 10-50% centrality ⟶ unique p_T bin (2 ÷ 10 GeV/c)
- Blast-Wave(2) fit to the spectrum to obtain p_T integrated production yield (0-10%)
- Function parameters:
  - β_r is the transverse velocity
  - T_{fo} = kinetic freeze-out temperature
- Parameters taken from deuteron analysis(3) leaving the normalisation free

Centrality	${}^{3}_{\Lambda}H$ x B.R. x 10^{-5}	${}^{3}_{\bar{\Lambda}}\overline{H}$ x B.R. x 10^{-5}
0-10%	3.86 ±0.77(stat.)± 0.68(syst.)	3.47 ±0.81(stat.)± 0.69(syst.)
10-50%	1.31 ±0.37(stat.)± 0.28(syst.)	0.85 ±0.29(stat.)± 0.17(syst.)

(2) E. Schnedermann, J. Sollfrank, U. Heinz. *Phys. Rev. C* 48, 2462 (1993)
(3) ALICE Collaboration, Phys. Rev. C 93 (2016) 024917

Hypertriton: *thermal model*

ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)



- Ratio $^3_\Lambda H/^3He$ and $^3_{\bar{\Lambda}}\overline{H}/^3\overline{He}$
  - ✓ ^3He yields are taken from Phys. Rev. C 93 (2016) 024917
- STAR (*open square*) ratios results:
  - ✓ compatible with one within uncertainties
  - ✓ phase-space population for *s* quark similar to that of *light* quarks at RHIC energies
- ALICE (*filled circle*) ratios results:
  - ✓ lower than STAR but in agreement with thermal model predictions

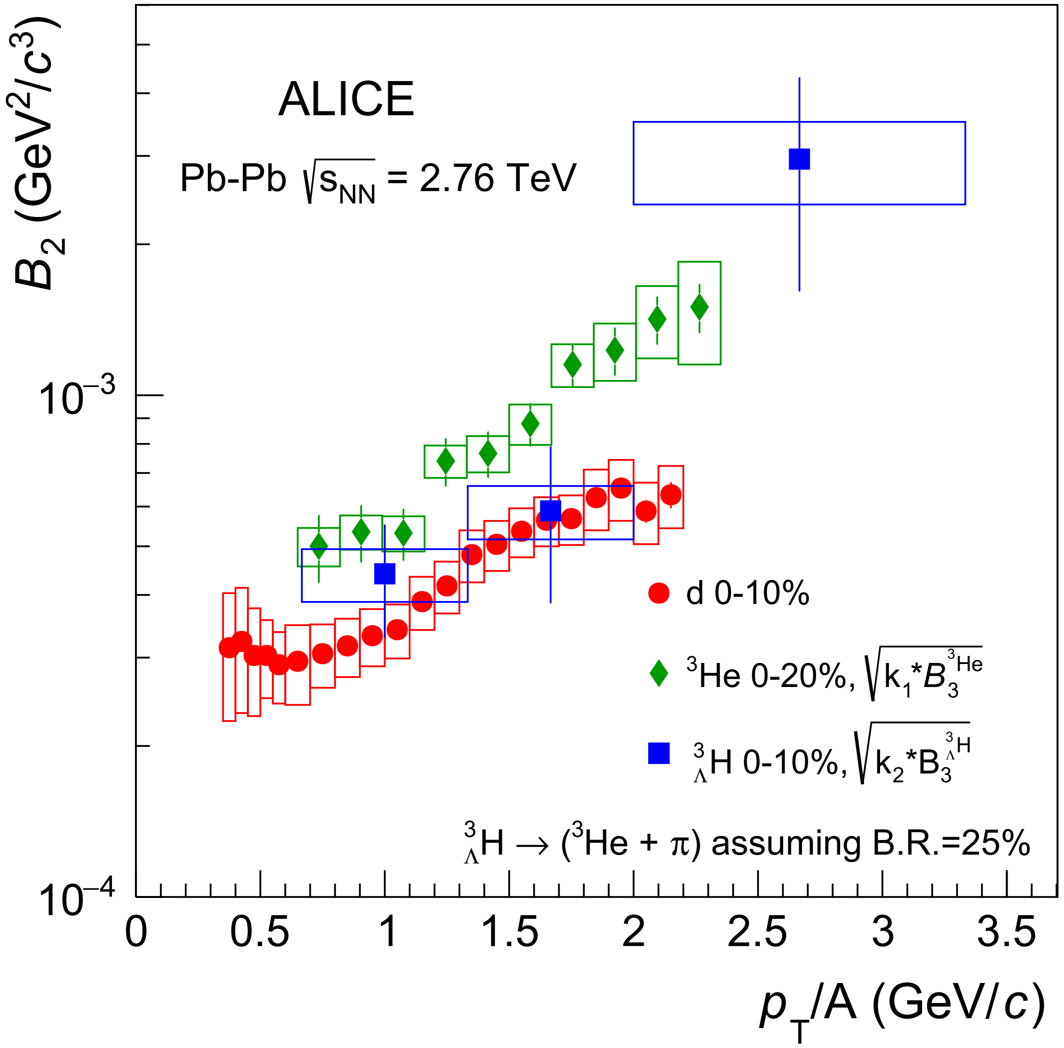
Hypertriton: *coalescence parameter*

Naive approach recipe

- Λ, p and n close in the phase space at the *kinetic freeze-out* can form a(n) (anti-)hypertriton
- Formation probability can be quantified through the coalescence parameter B_A
- B_A is expected to be independent from p_T and centrality

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

ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)



- B_3 is computed for $^3_\Lambda$H according to the above equation
  - $^3_\Lambda$H measured p_T spectra from this analysis
  - p and Λ spectra respectively from [4] and [5]
- $B_3^{^3_\Lambda H}$ is compared with B_2^d and $B_3^{^3He}$ obtained in [6]
  - ^{3}He B_3 is scaled to B_2 through the scaling factor k_1
  - $^3_\Lambda$H B_3 is scaled to B_2 through the scaling factor k_2

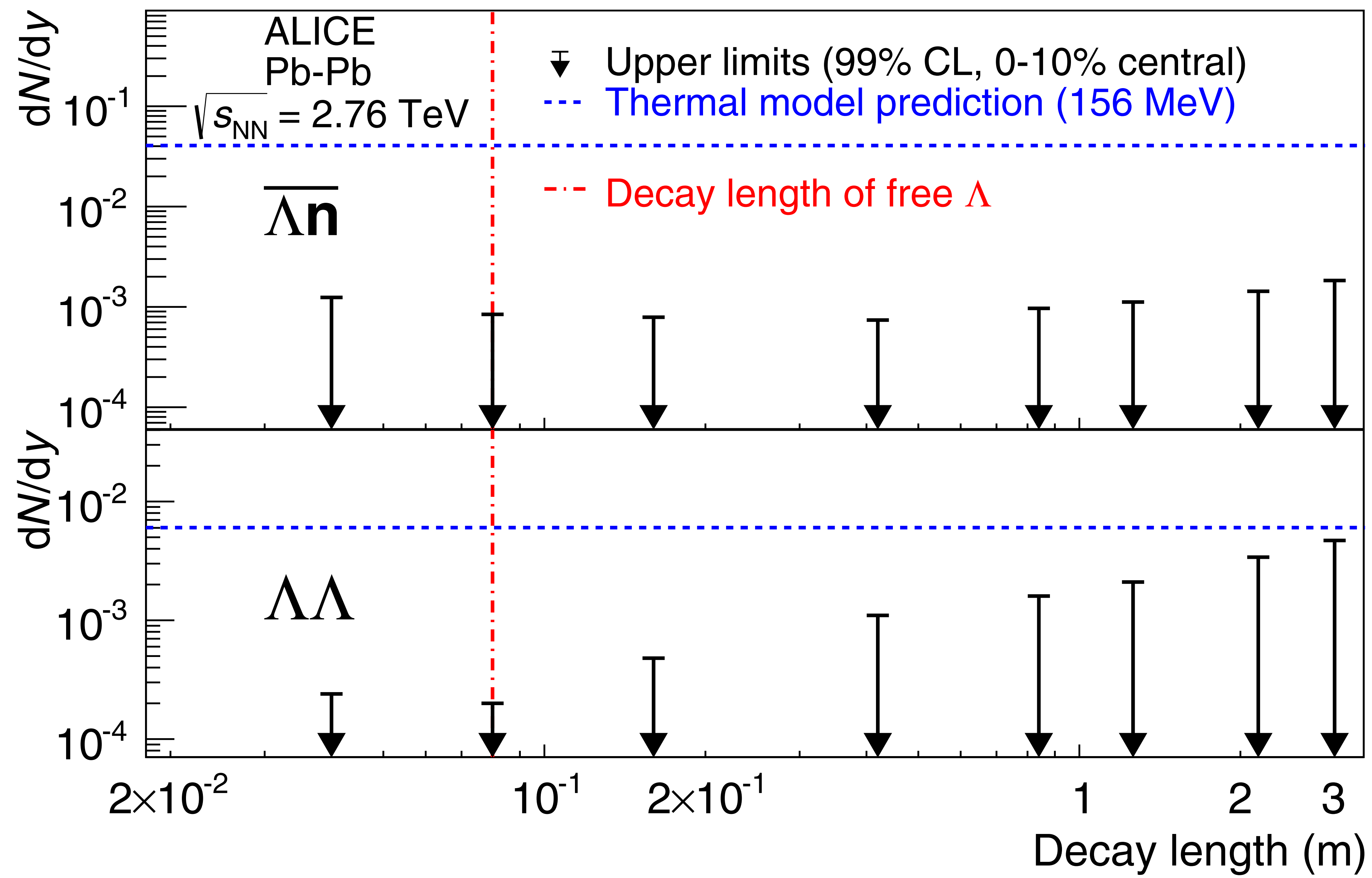
$$k_1 = \frac{m_d^2}{M_{^3He} m_p} \qquad k_2 = \frac{m_d^2 m_\Lambda}{m_p^2 M_{^3_\Lambda H}}$$

- $^3_\Lambda$H coalescence parameter is not flat as function of p_T contrary to the simple coalescence model predictions
- Model does not take into account characteristics of the emitting source
- Behaviour similar to the one observed for d and ^{3}He

[4] ALICE Collaboration Phys. Rev. C 88, (2013) 044910
[5] ALICE Collaboration Phys. Rev. Lett. 11, (2013) 22301
[6] ALICE Collaboration Phys. Rev. C 93 (2016) 024917

Exotica: *decay length dependence*

ALICE Collaboration, *Phys. Lett. B* 752, 267-277 (2016)



- Search for a bound state of Λn and ΛΛ shows no hint of signal
  - ➡ upper limit set for different value of decay length
  - ➡ red line: decay length of free Λ used also for d*N*/d*y* calculation (slide 21)