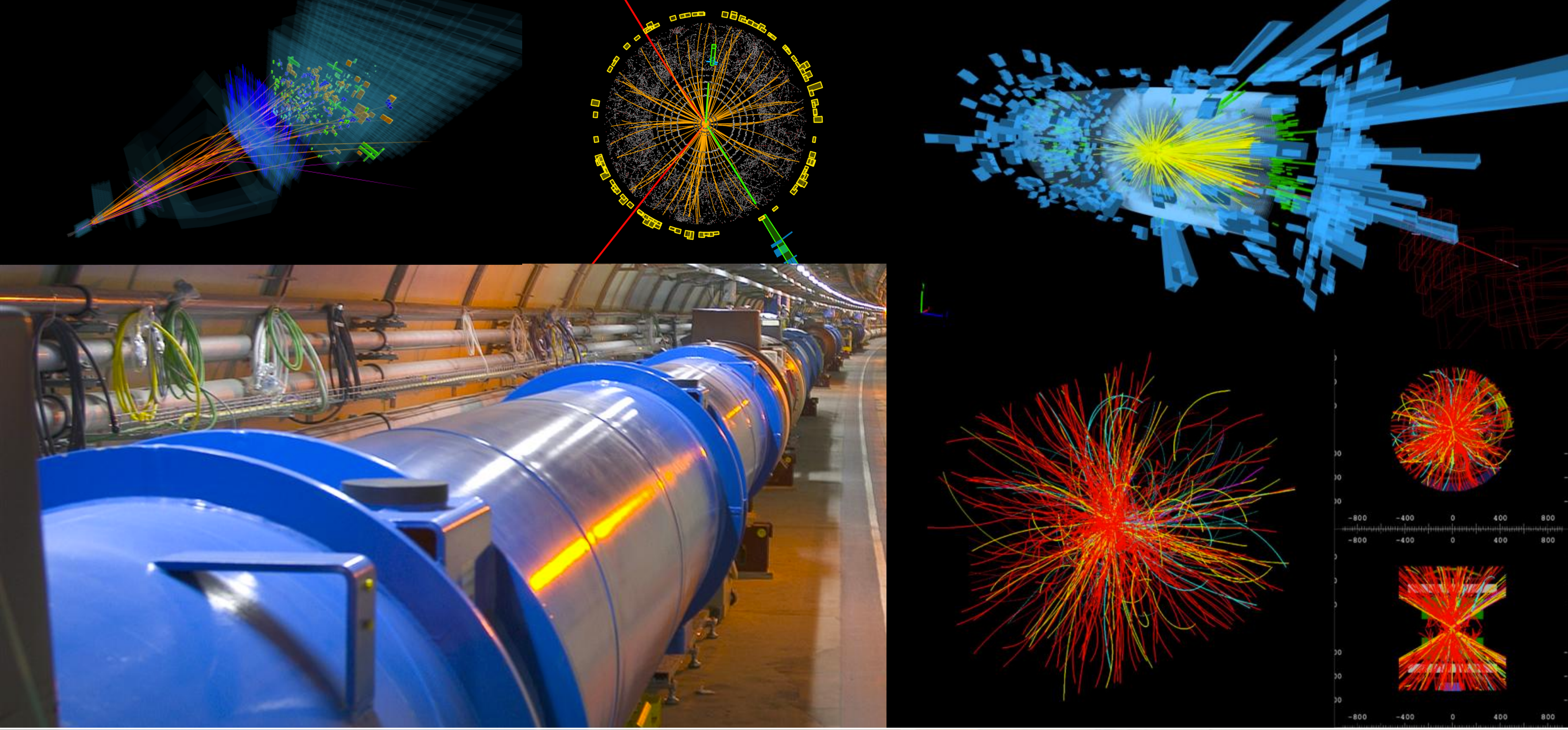


Overview of results on anti-nuclei and anti-hypernuclei at the LHC

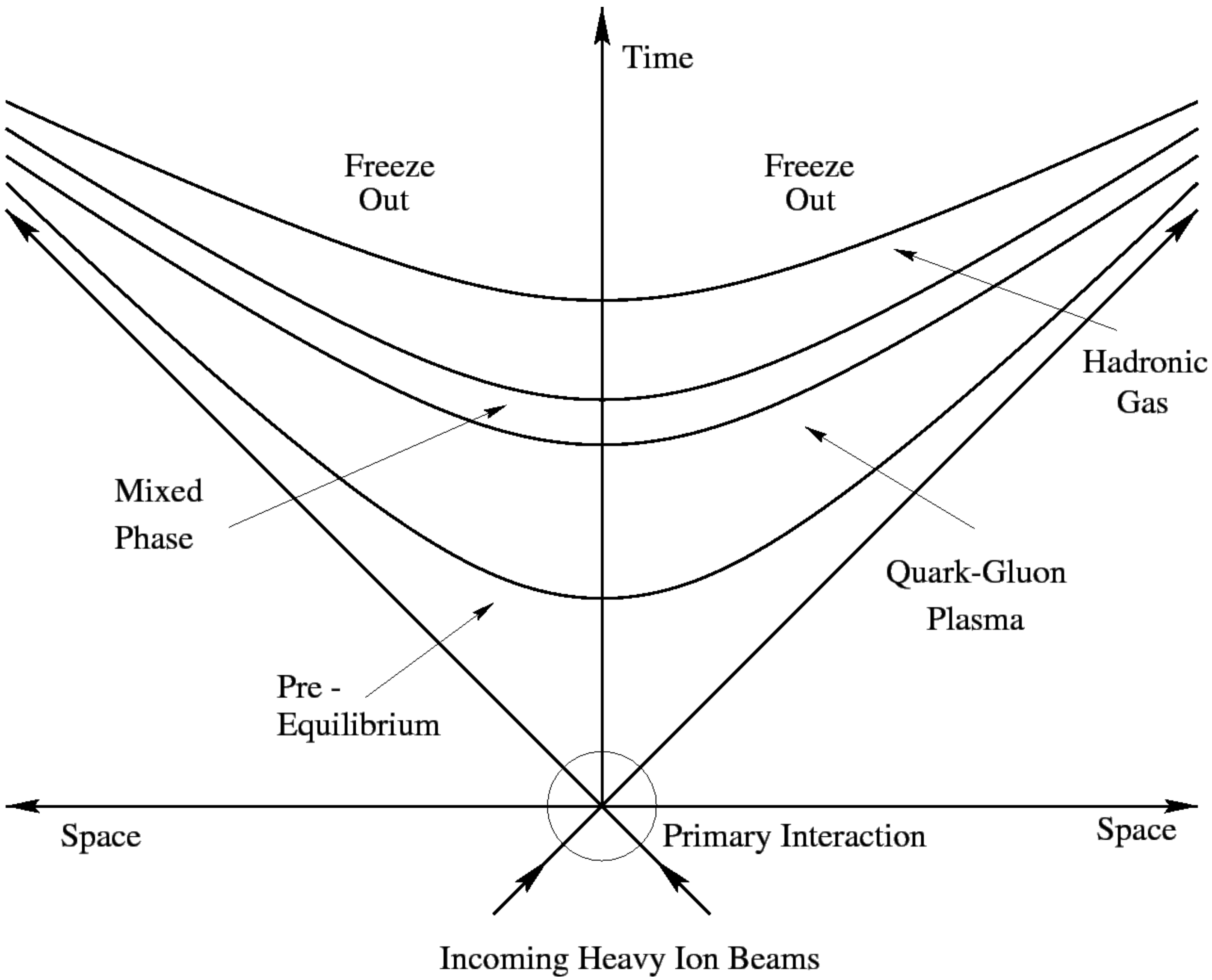
Maximiliano Puccio
Università & INFN Torino

LHCP2015 - September 1st 2015, Saint Petersburg

Light nuclei as soft probes

In high energy Heavy Ions collisions

- a dense and hot partonic phase is created and undergoes a rapid expansion
- hydrodynamical models are used to describe this rapid expansion
- as a result of this evolution it is possible to observe collective phenomena



Soft probes

- Low p_T (p_T < 2 GeV/c) light flavoured particles coming from the interaction region
- Their constituents are produced in the late stages of the collisions
- They are useful to study the freeze-out conditions

Light nuclei are soft probes and as they are loosely bound composite objects it is interesting to study their production in HI collisions.

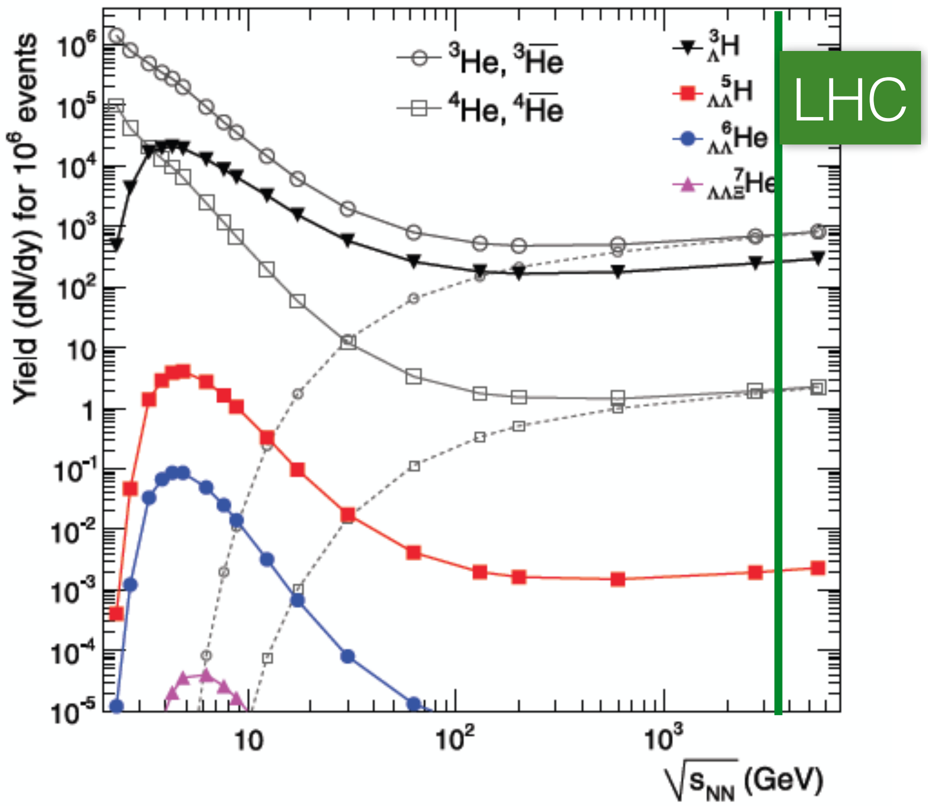
Nuclei production: theoretical approaches

Nuclei production: theoretical approaches

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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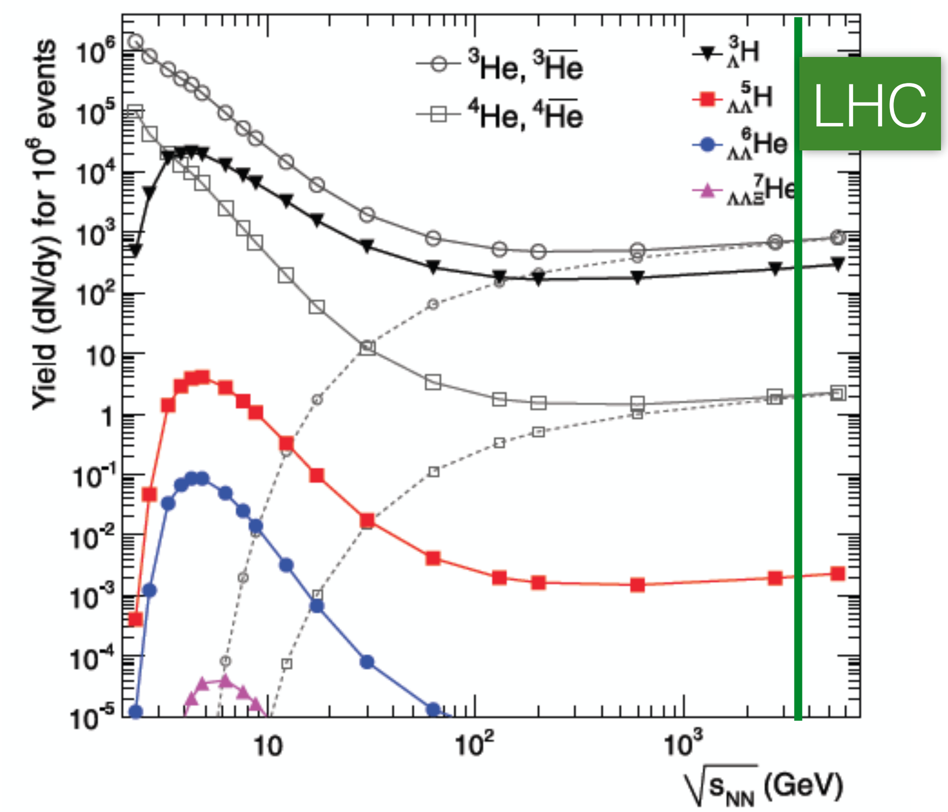
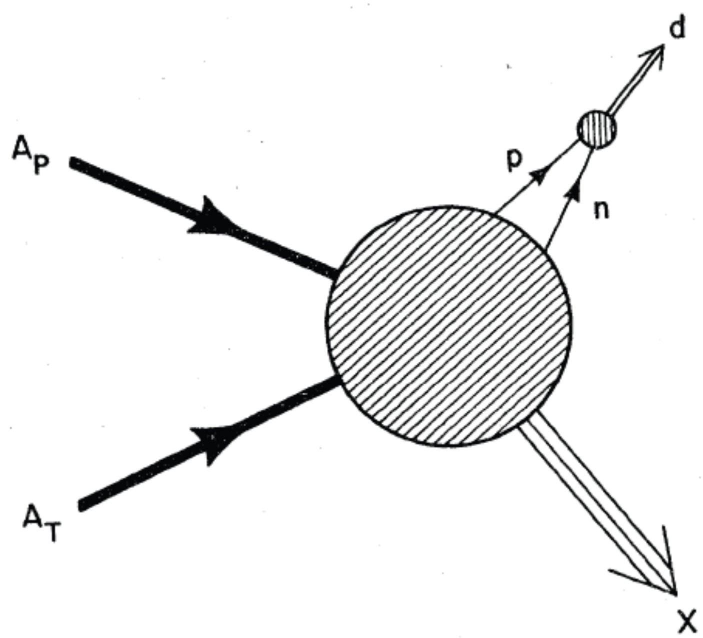


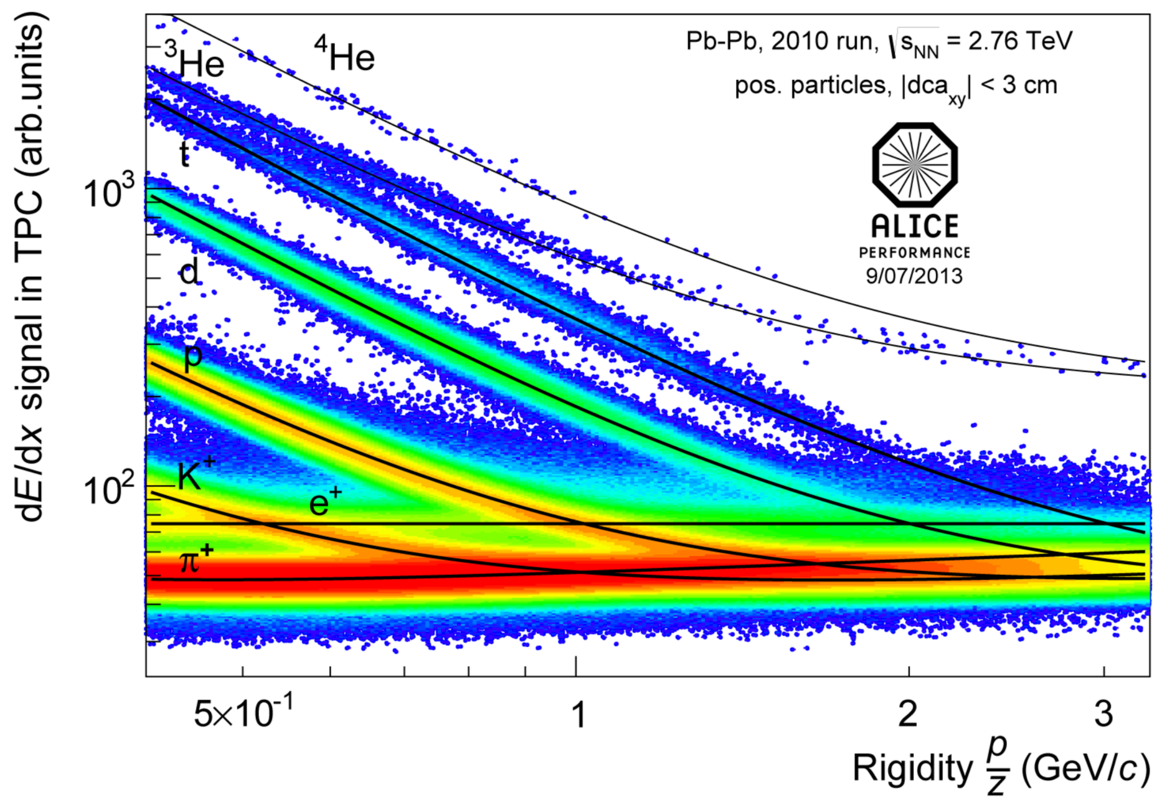


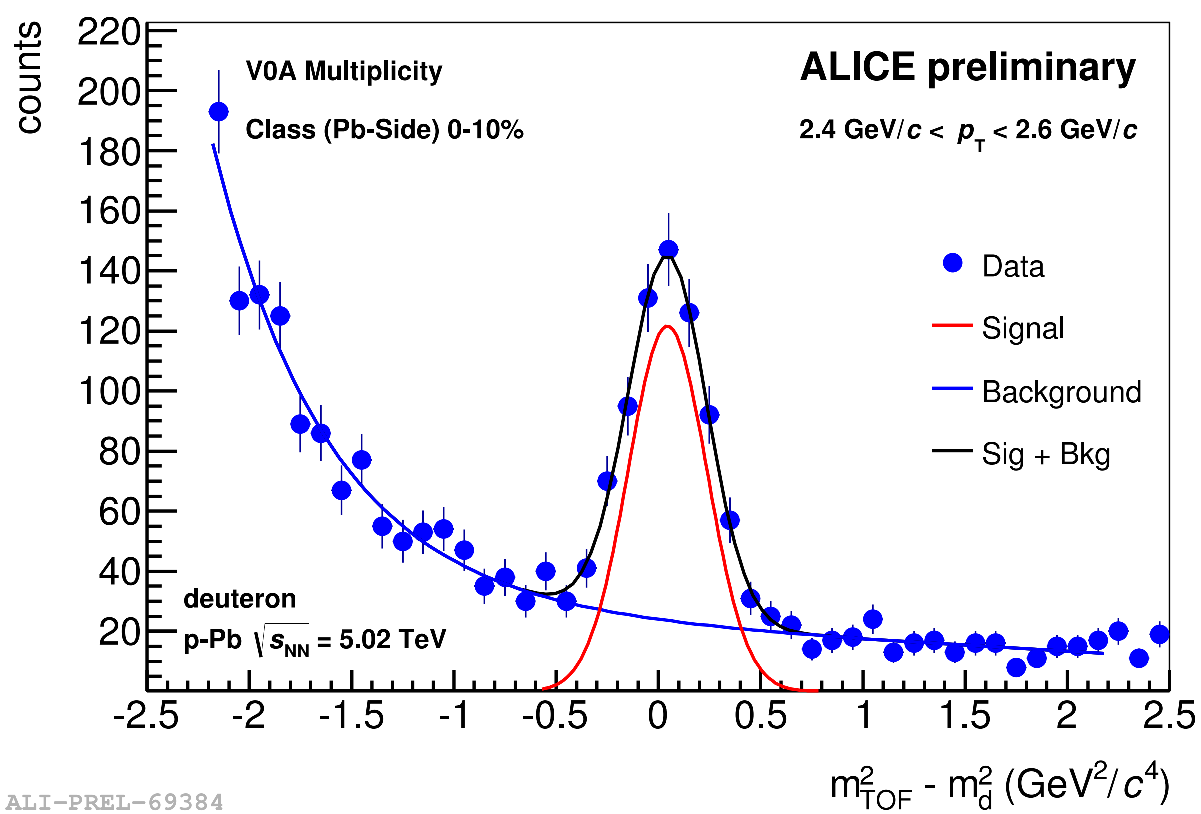
Coalescence models

- 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)

Analysis technique





Currently all the measurements of nuclei and hyper-nuclei at the LHC were performed by the **ALICE** experiment.

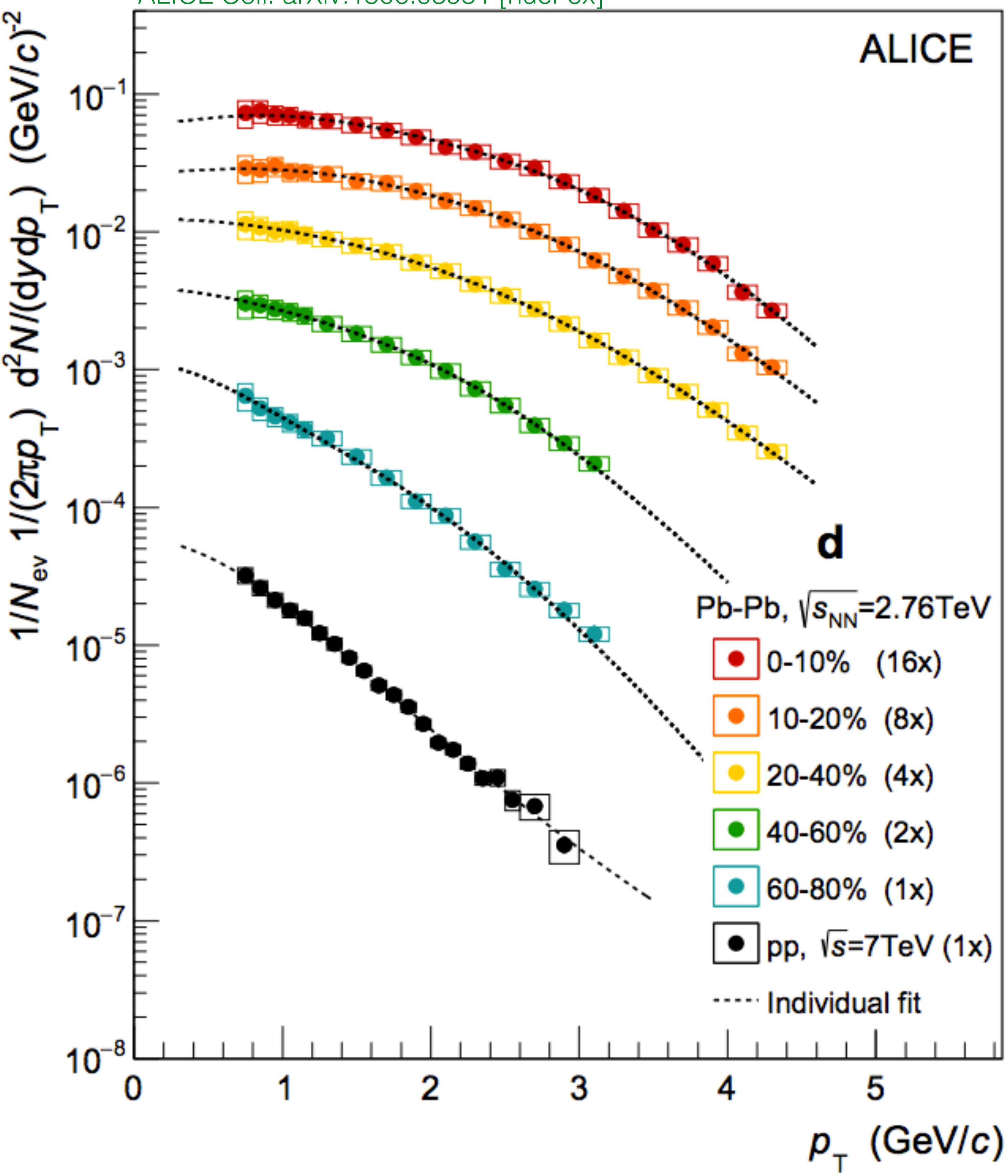
Main tools: particle identification detectors

- **T**ime **P**rojection **C**hamber: allows to identify particles looking at the specific energy loss in its volume
- **T**ime **O**f **F**light detector: allows to identify particles measuring their beta with the help of the tracking information.

See the talk of F. Noferini today

Deuteron production in pp and Pb-Pb

ALICE Coll. arXiv:1506.08951 [nucl-ex]



pp

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

$$\frac{d^2N}{dp_T dy} = p_T \frac{dN}{dy} \frac{(n-1)(n-2)}{nC(nC + m_0(n-2))} \left(1 + \frac{m_T - m_0}{nC}\right)^{-1}$$

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)

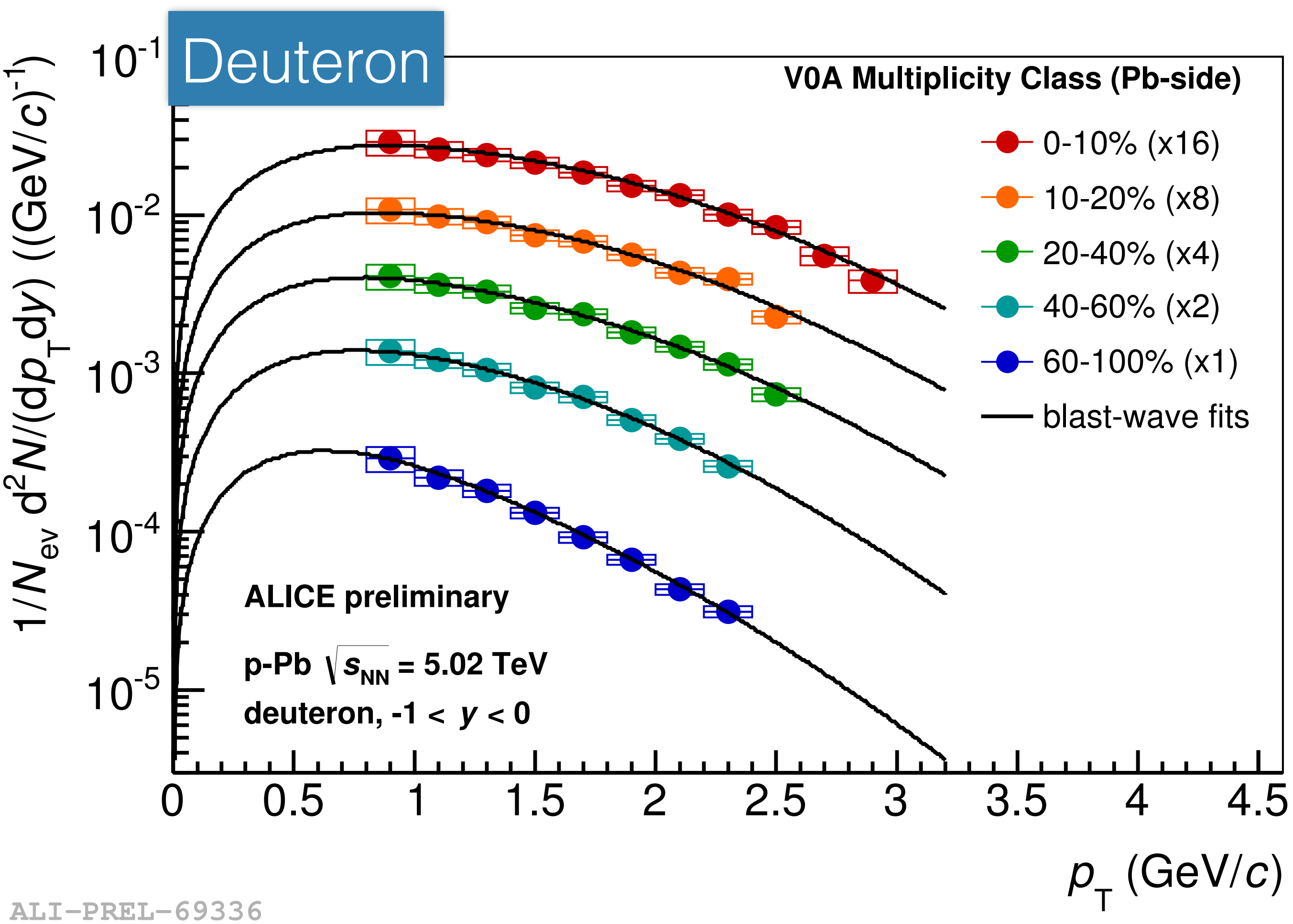
Pb-Pb

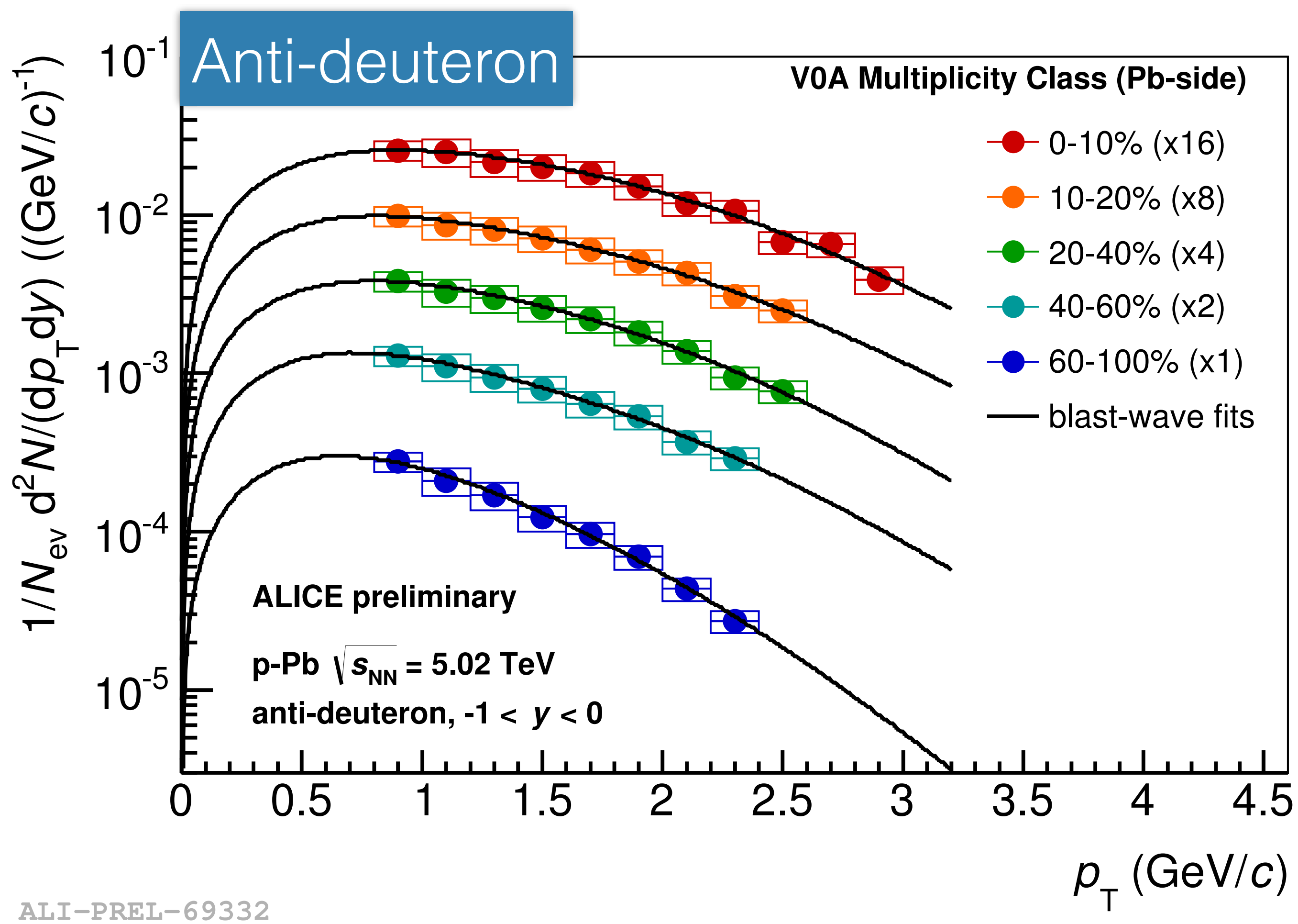
- The Blast-Wave (BW) function fits well the data.
- Characteristic hardening of the spectrum with increasing centrality.
- These fits are used for the extrapolation of the yield to the unmeasured region at low and high p_T.

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

(Anti-)deuteron production in p-Pb

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

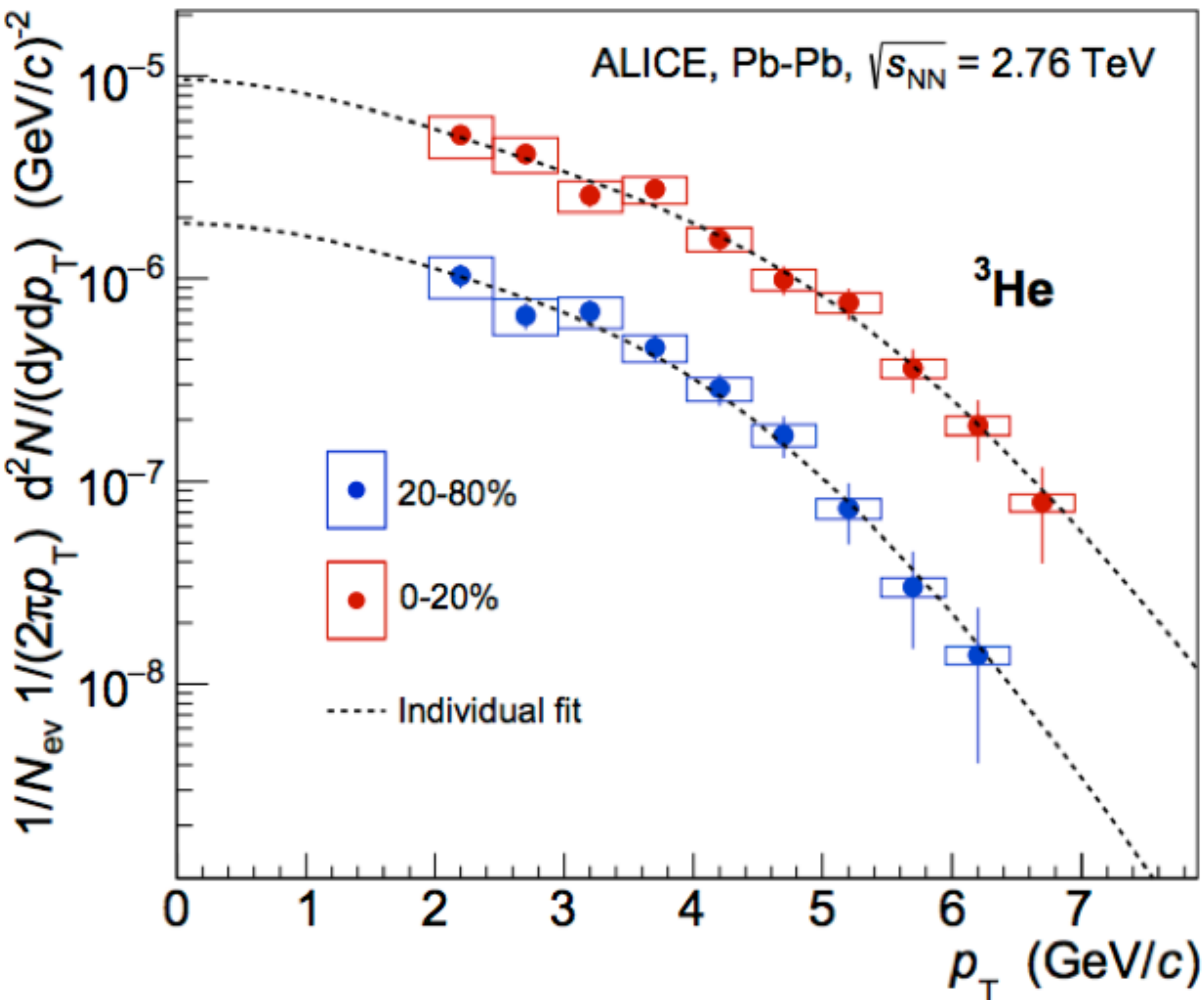




The spectra become harder with increasing multiplicity

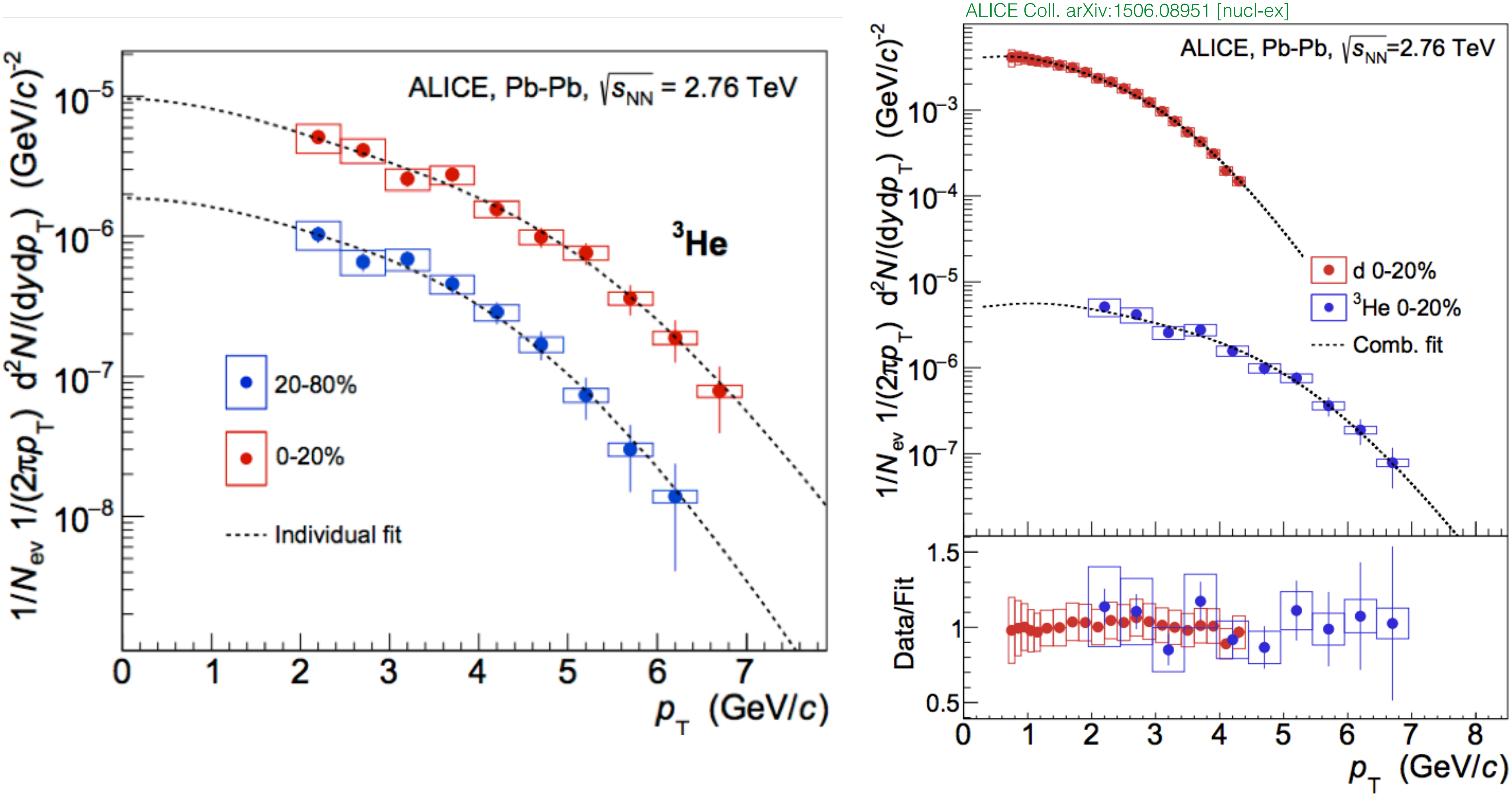
(Anti-)^{3}He production in Pb-Pb

The individual Blast-Wave fits describe well the data.



(Anti-)^{3}He production in Pb-Pb

It is possible to fit simultaneously deuteron and ^{3}He to extract common parameters. The simultaneous fit describes well the data and the common kinetic freeze-out speed is $<\beta>= 0.617\pm0.009$



Combined BW fit

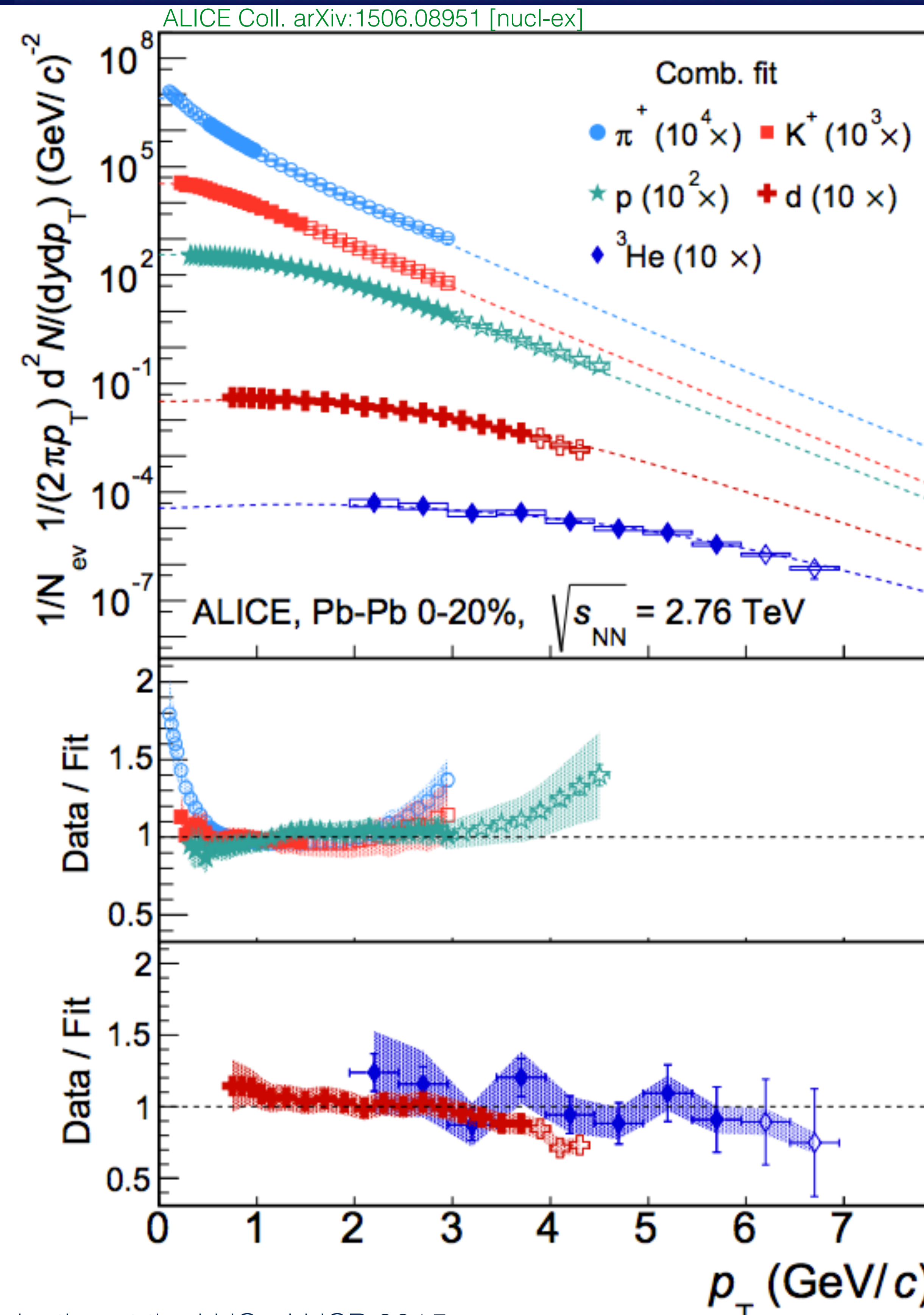
BW model fit:

- 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.

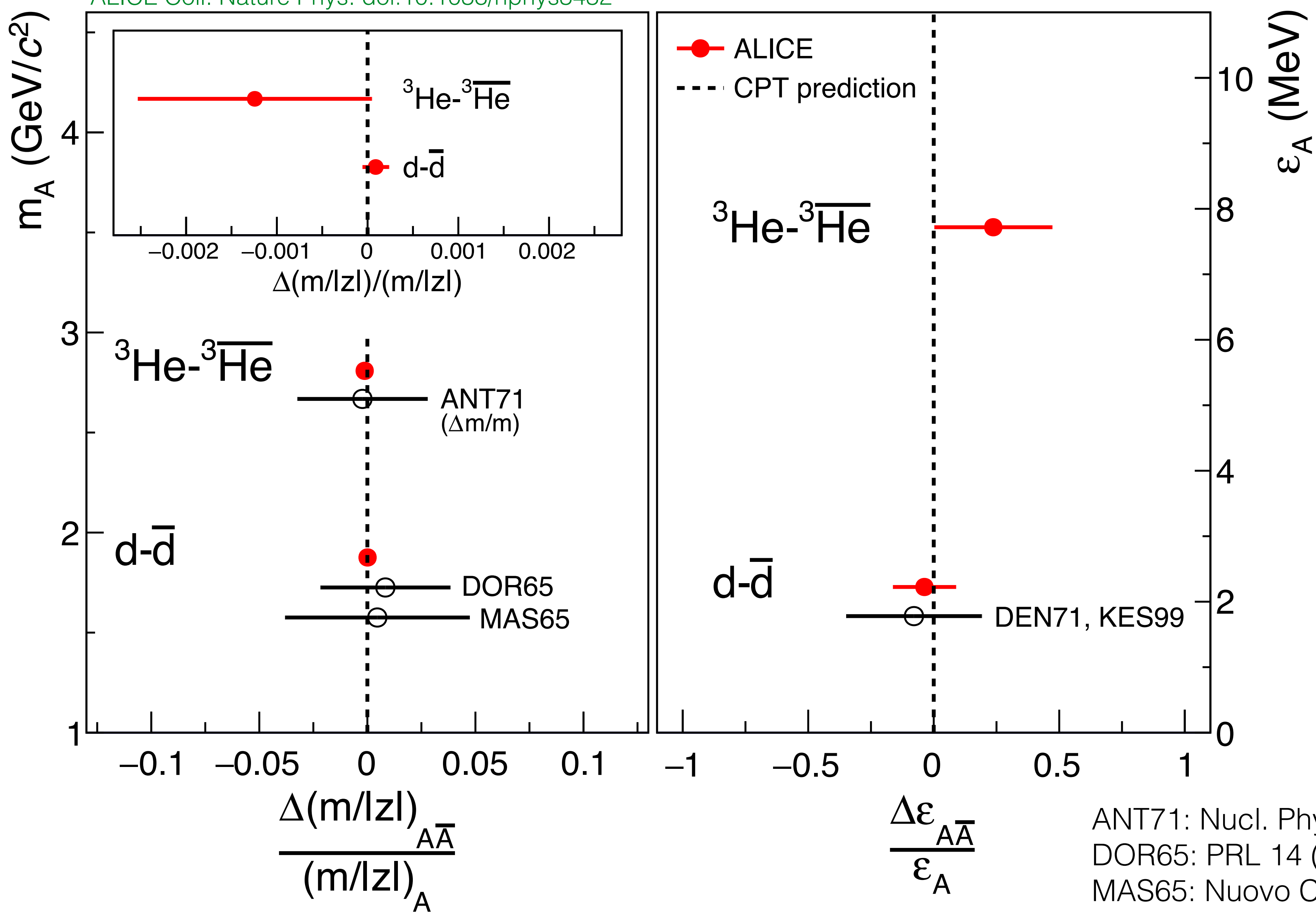
Solid symbols denote the spectra points used for the fit.



Mass difference nuclei/anti-nuclei

ALICE collaboration performed a test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei.

ALICE Coll. Nature Phys. doi:10.1038/nphys3432

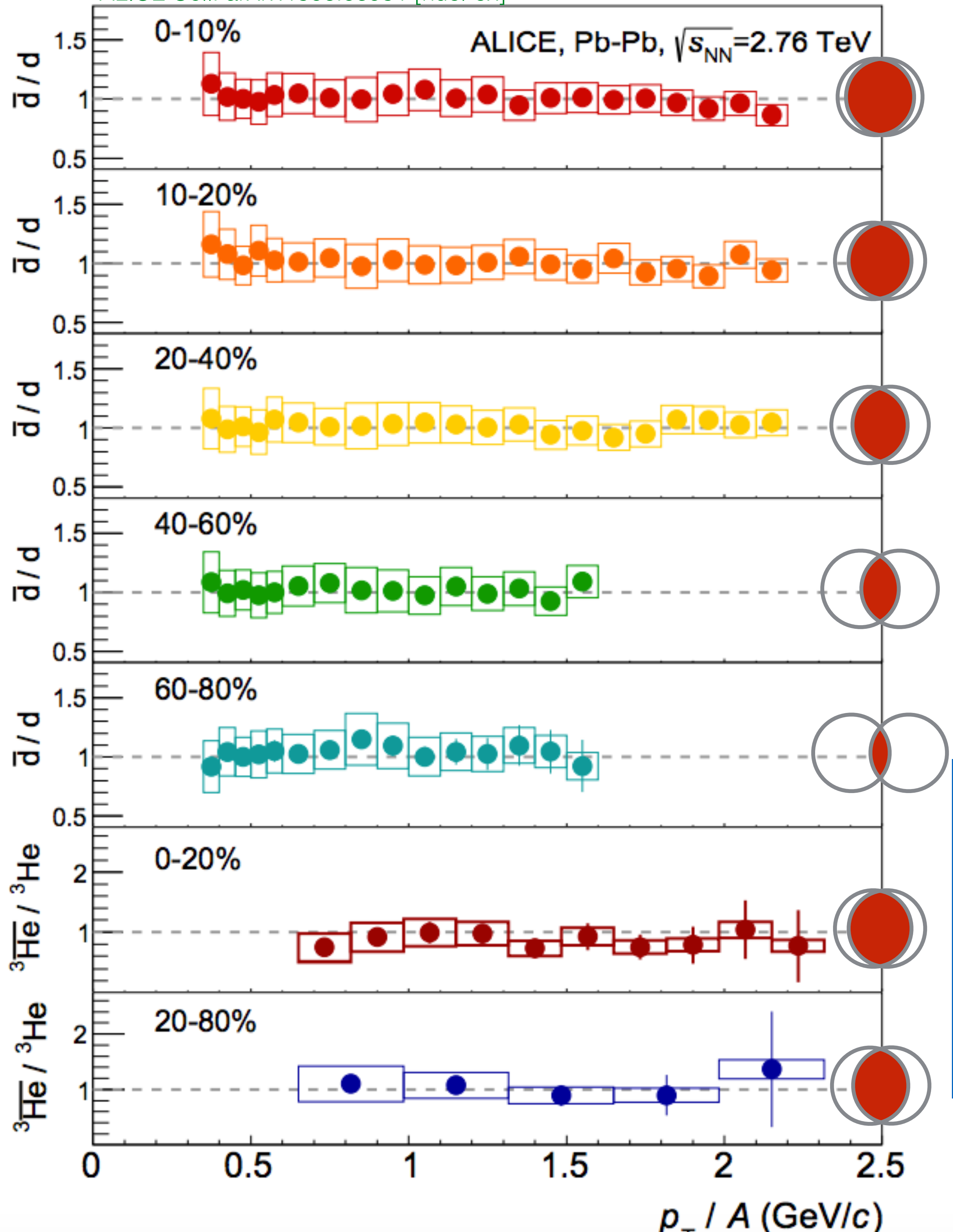


ANT71: Nucl. Phys. B31 (1971) 235
DOR65: PRL 14 (1965) 1003
MAS65: Nuovo Cim. 39 (1965) 10

This test shows that the **mass of nuclei and anti-nuclei are compatible** within the uncertainties. The binding energies are compatible in nuclei and anti-nuclei as well.

Ratio matter / anti-matter

ALICE Coll. arXiv:1506.08951 [nucl-ex]

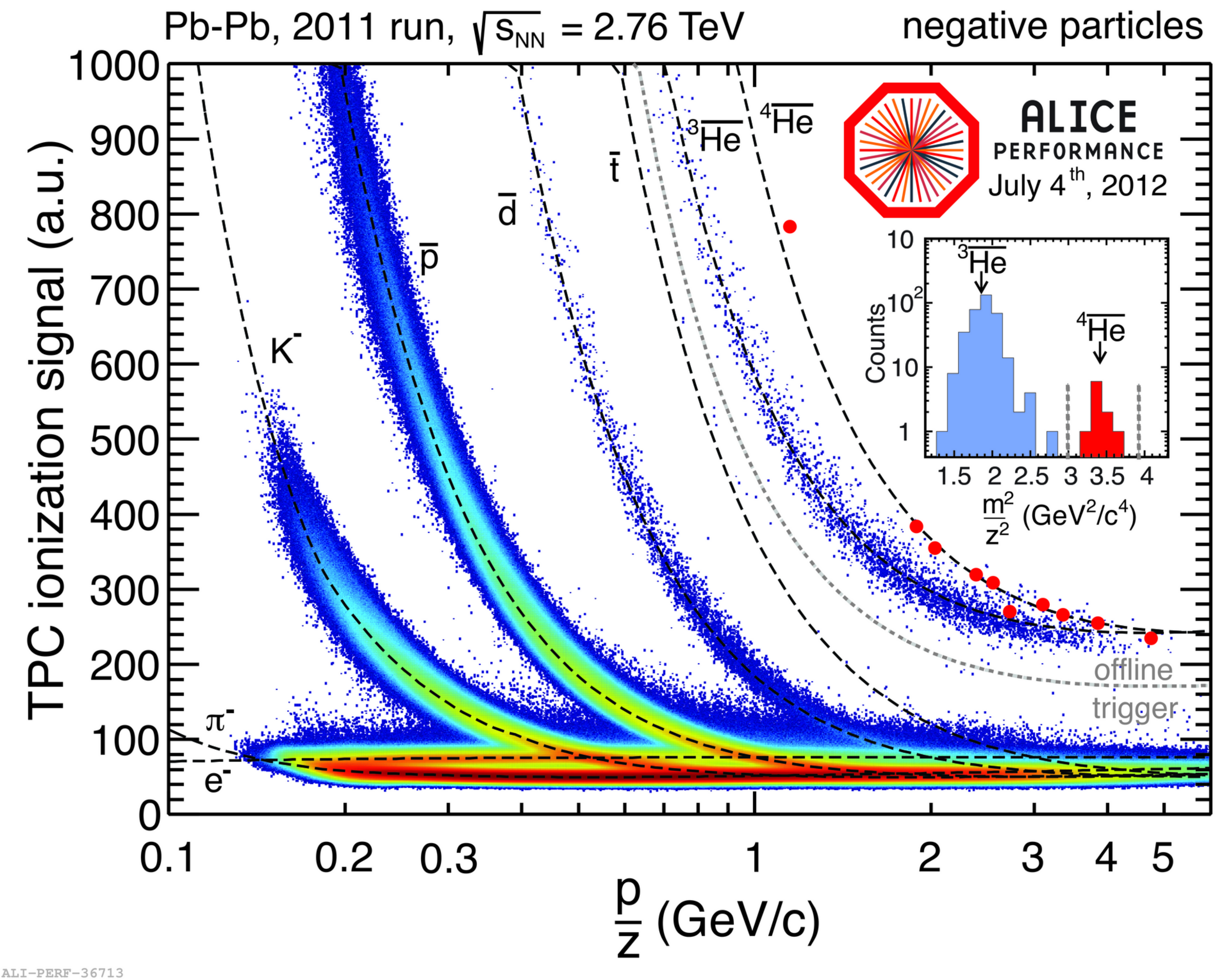


The ratio nuclei / anti-nuclei is compatible with one

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

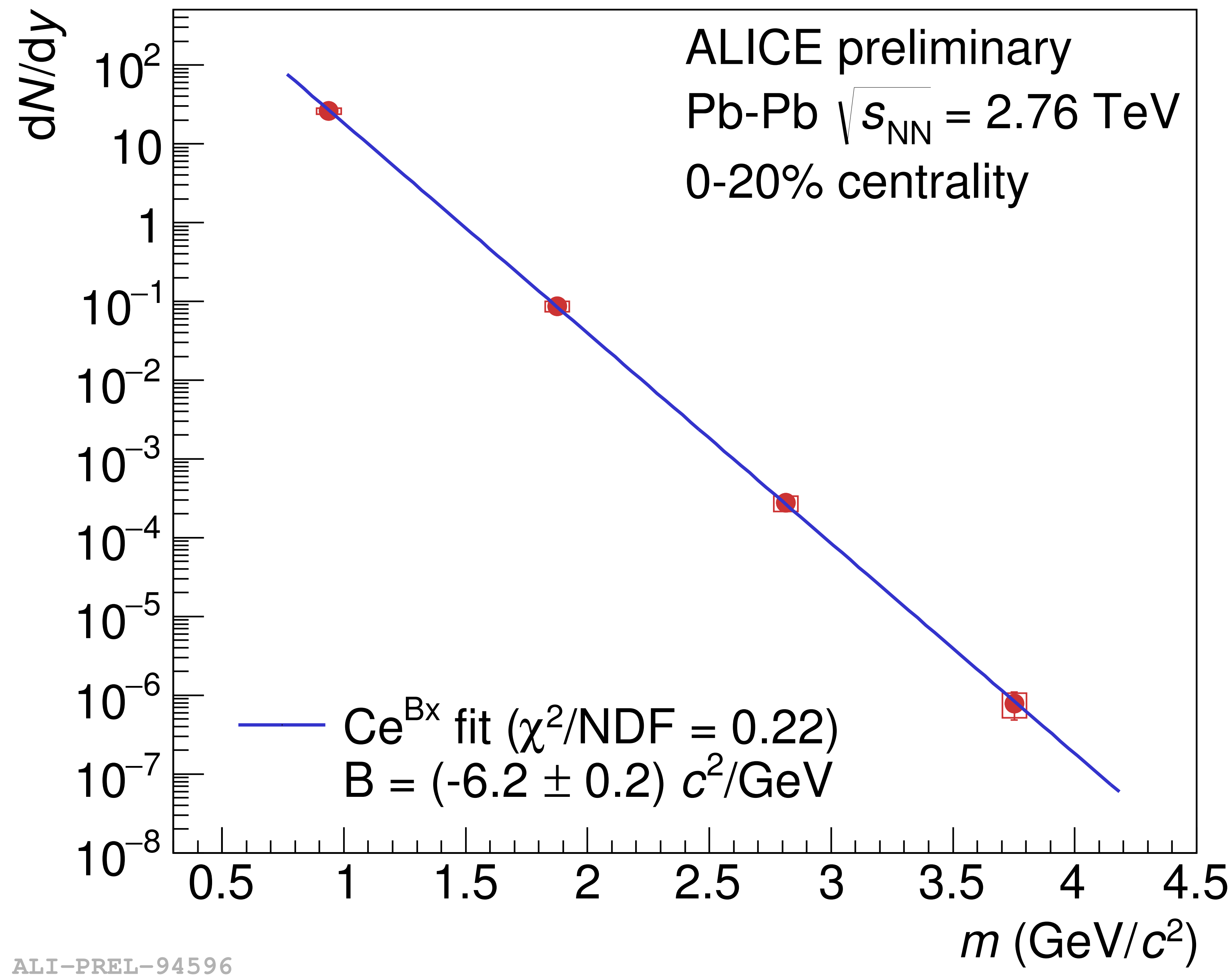
A large fraction of the systematic uncertainties on the determination of the ratios is due to the limited knowledge of the cross sections of anti-nuclei interacting with the material of the detector.

Observation of the anti-^{4}He



- First time observed at RHIC by STAR collaboration
- ALICE TPC allows to separate particles with Z=2 from those with Z=1 over the full momentum range.
- Using also the ALICE TOF it is possible to identify about 10 anti-^{4}He

Mass ordering in Pb-Pb



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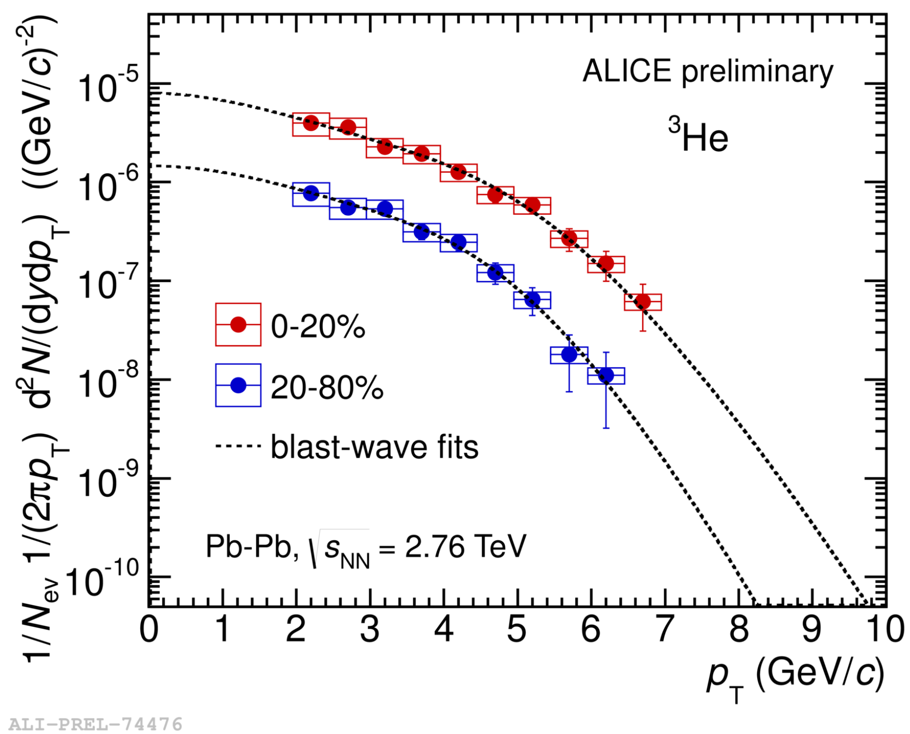
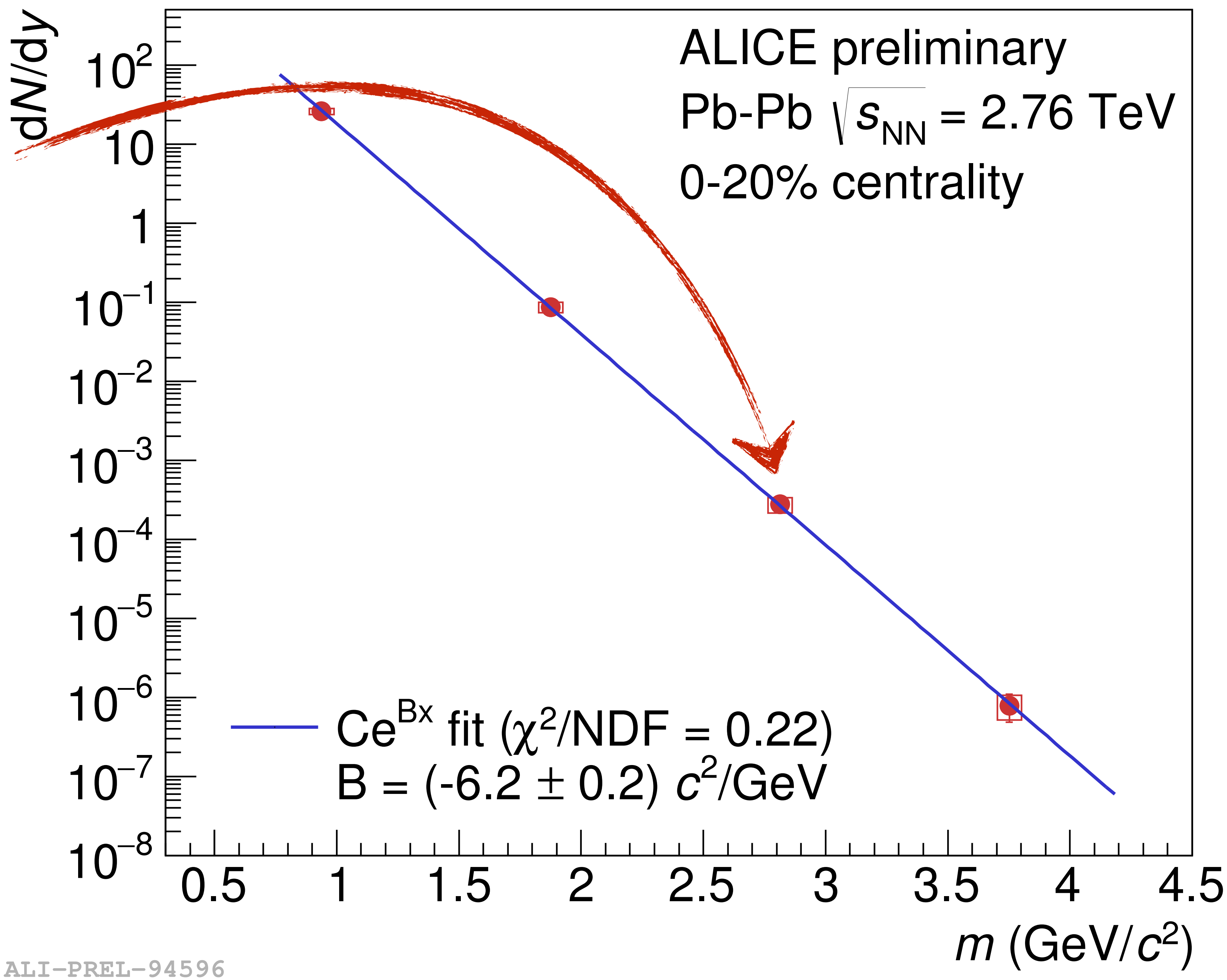


Both ^{3}He and anti-^{4}He integrated yields have been measured and compared to deuteron and proton integrated yields



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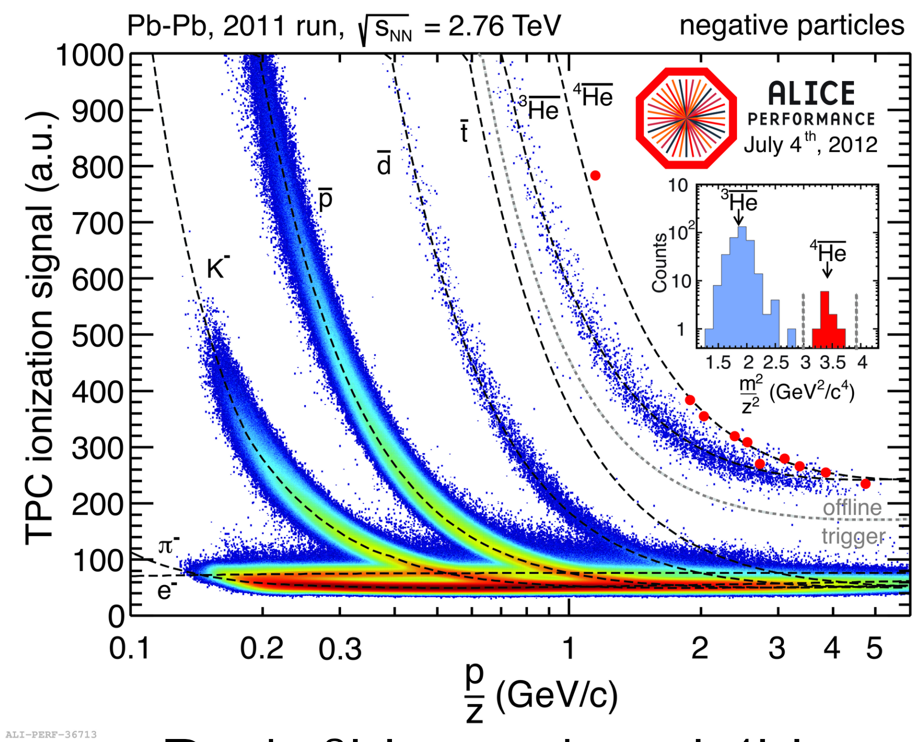

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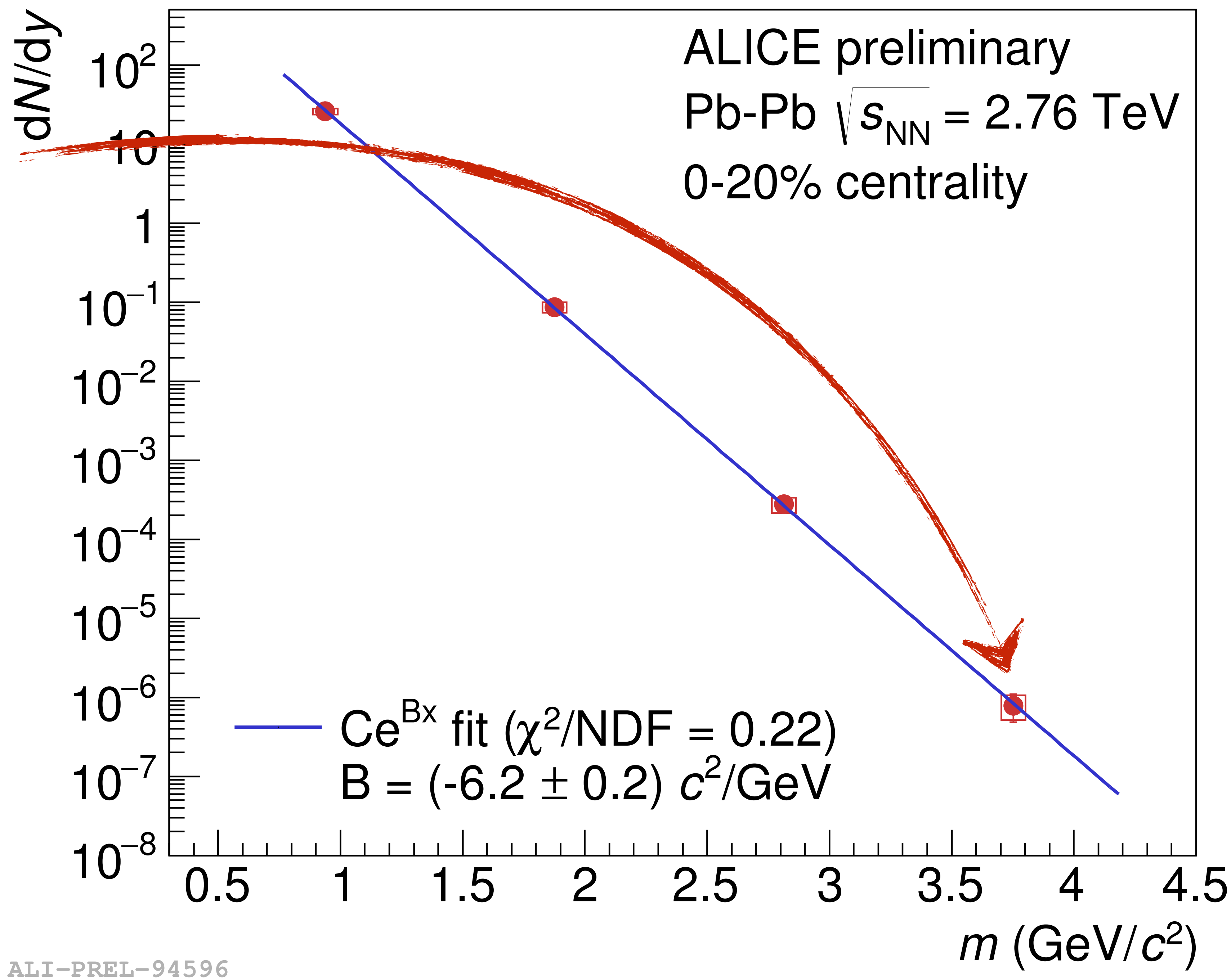
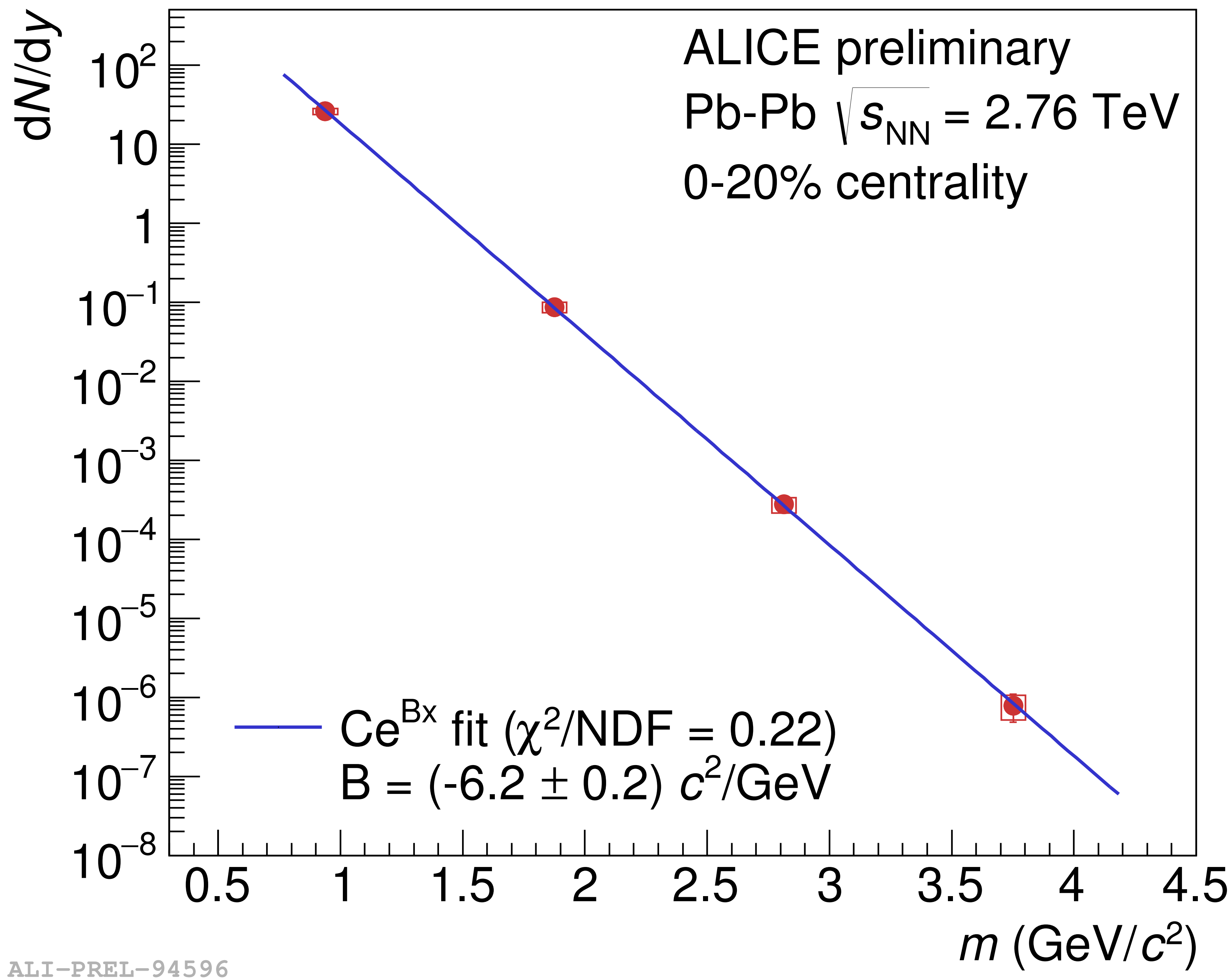


Mass ordering in Pb-Pb

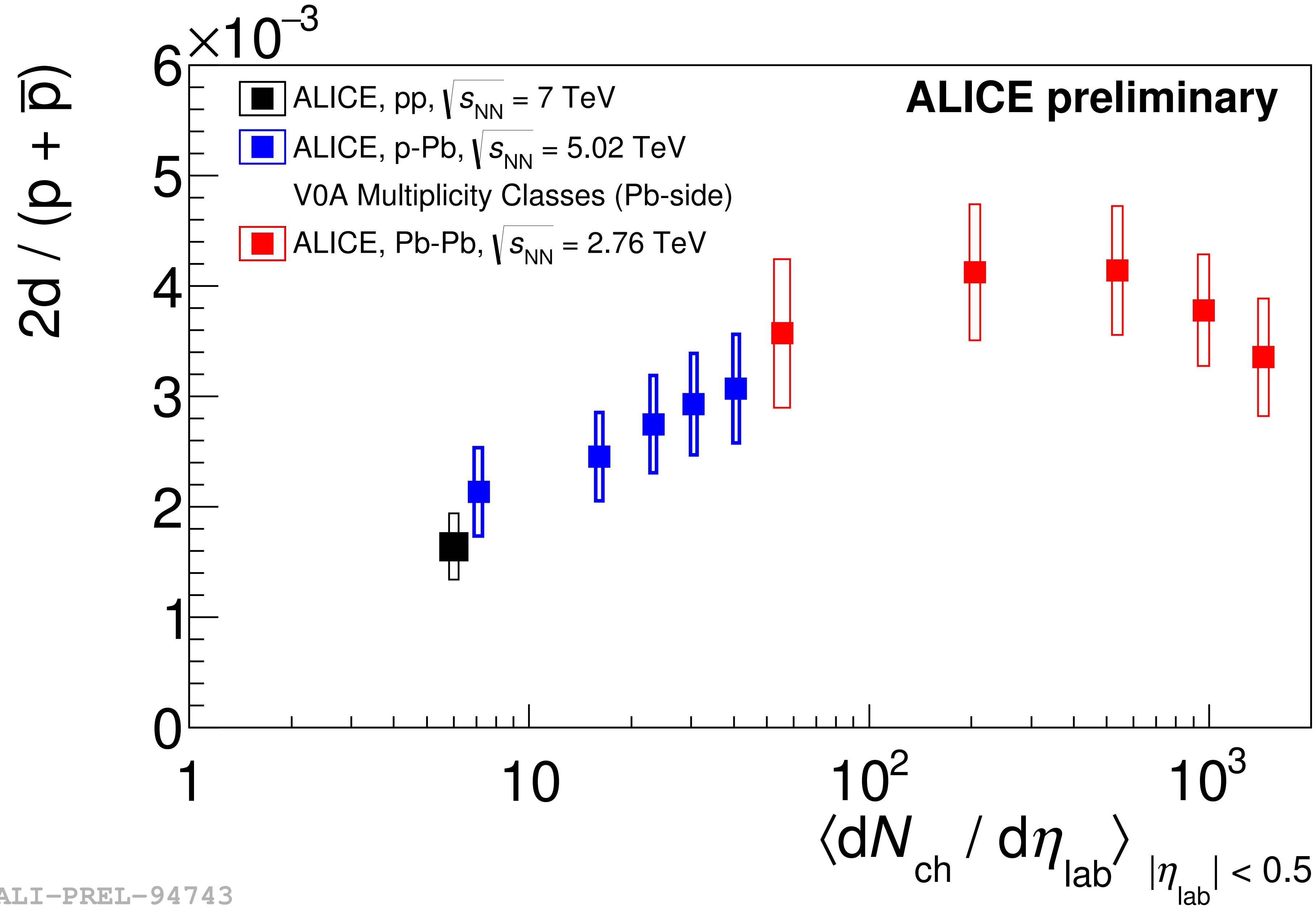
Thermal model predicts:

$$\frac{dN}{dy} \propto exp\left(-\frac{m}{T_{chem}}\right)$$

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



d / p ratio



- 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

Coalescence parameter B_2

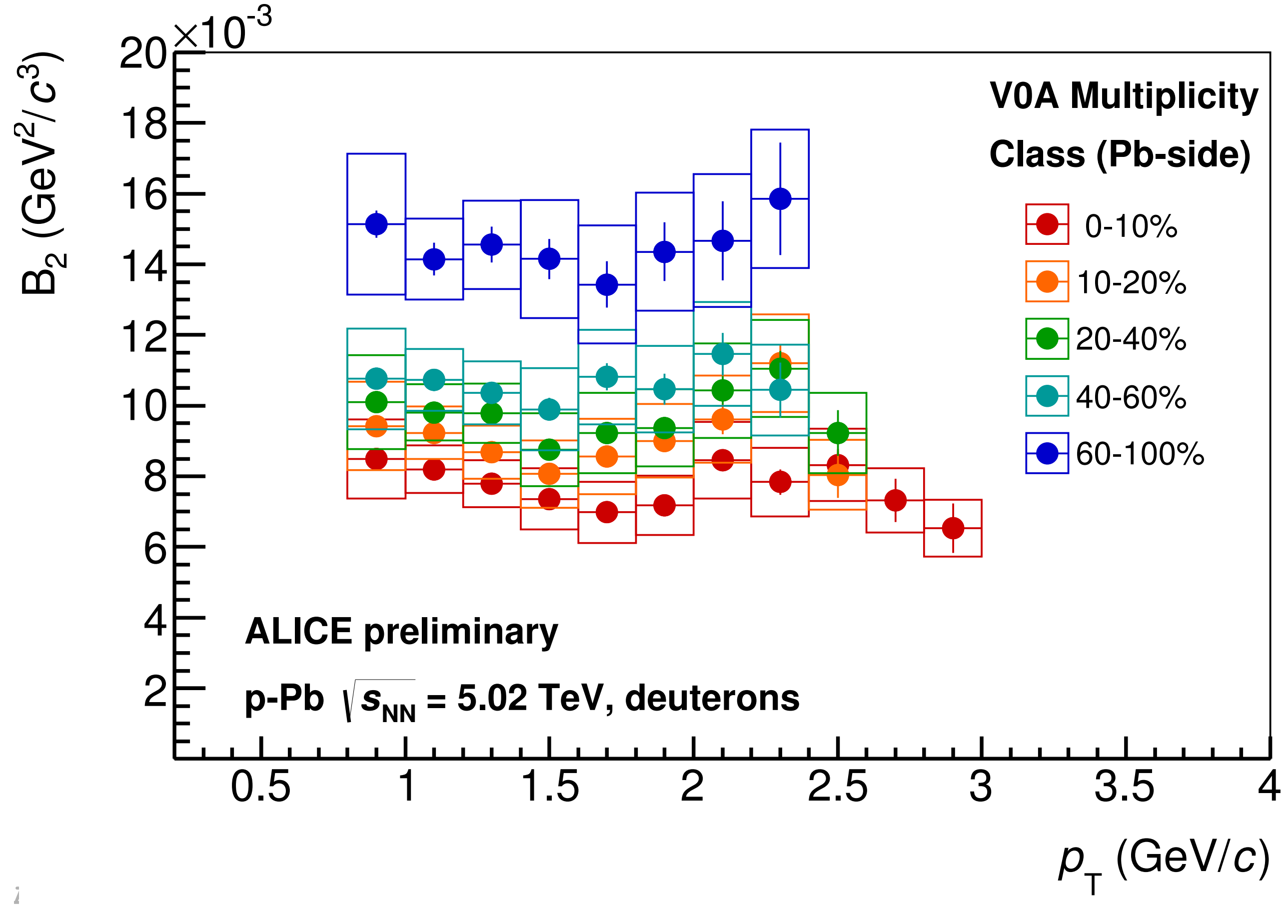
B_2 parameter: R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

The coalescence parameter, defined as:

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

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

This is observed in p-Pb collisions.



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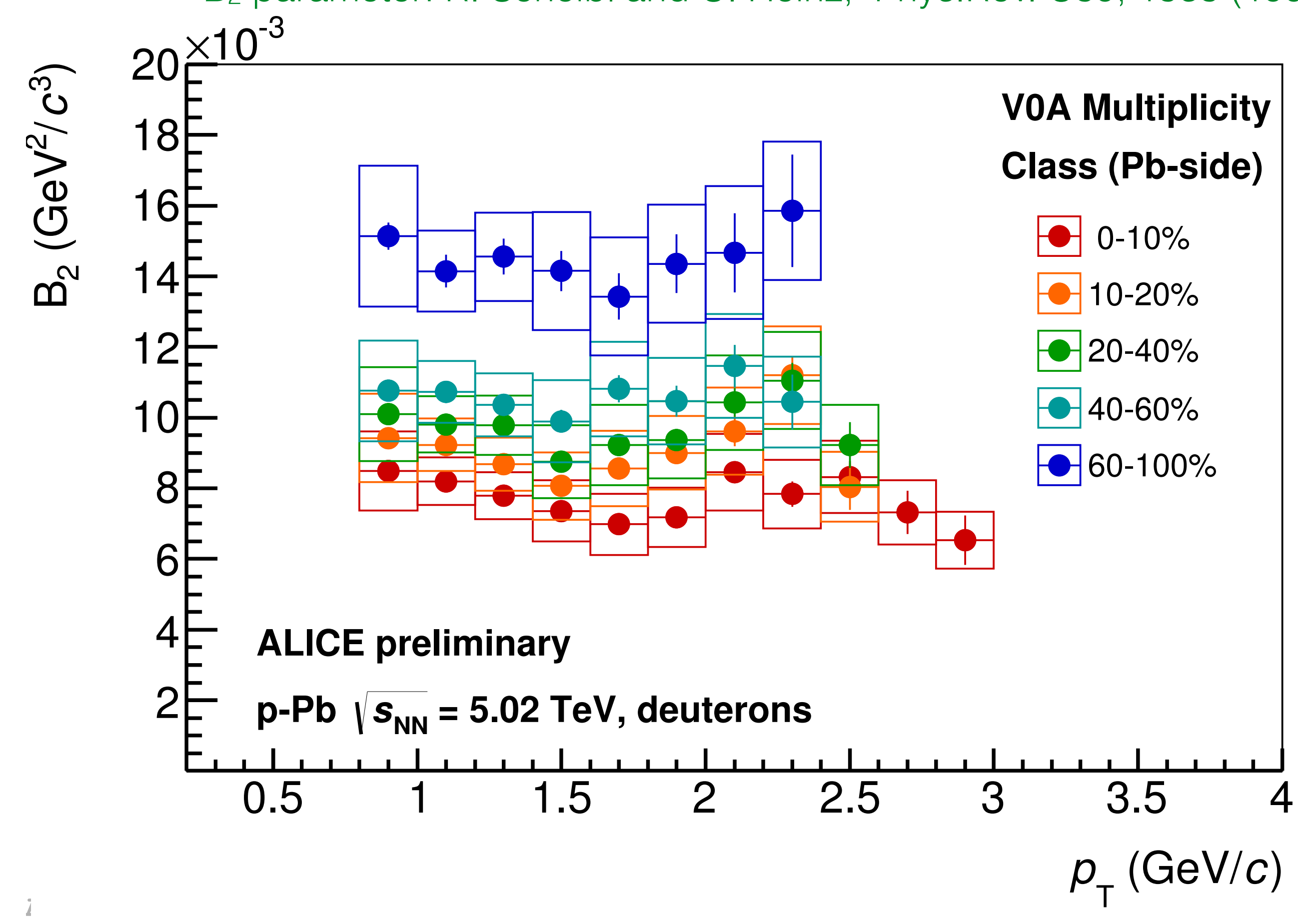
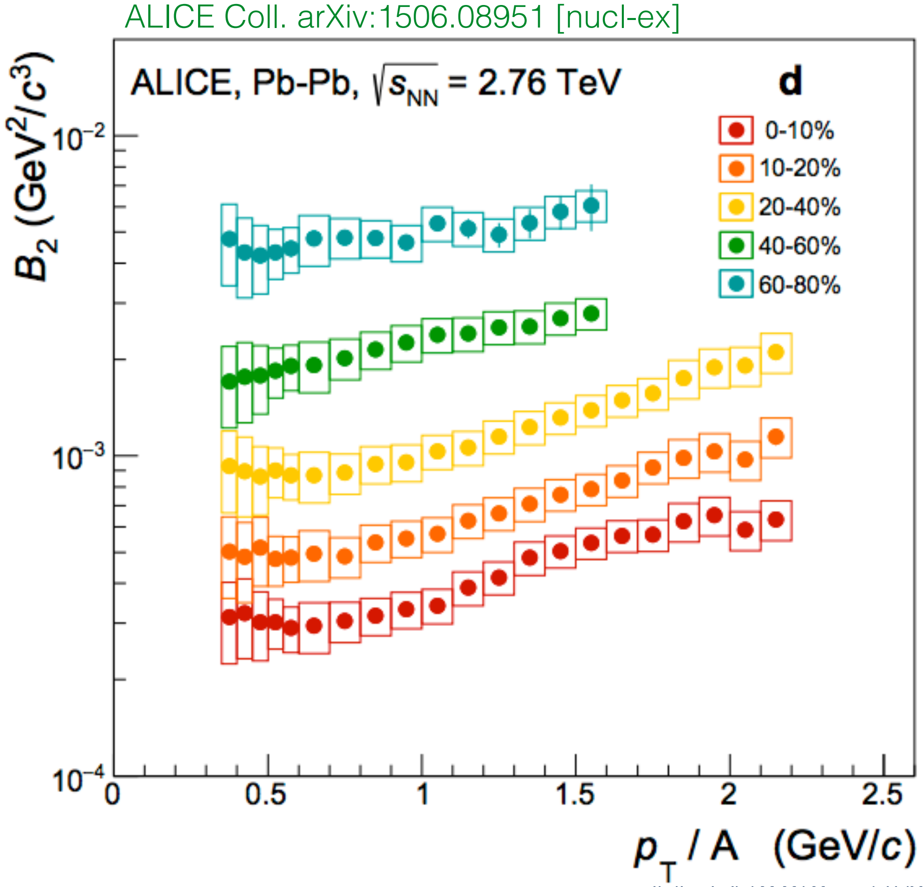


ALICE Coll. arXiv:1506.08951 [nucl-ex]



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.

(Anti-)Hyper-triton in Pb-Pb

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

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

Decay modes

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

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

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

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

+ anti-hypertriton counterpart

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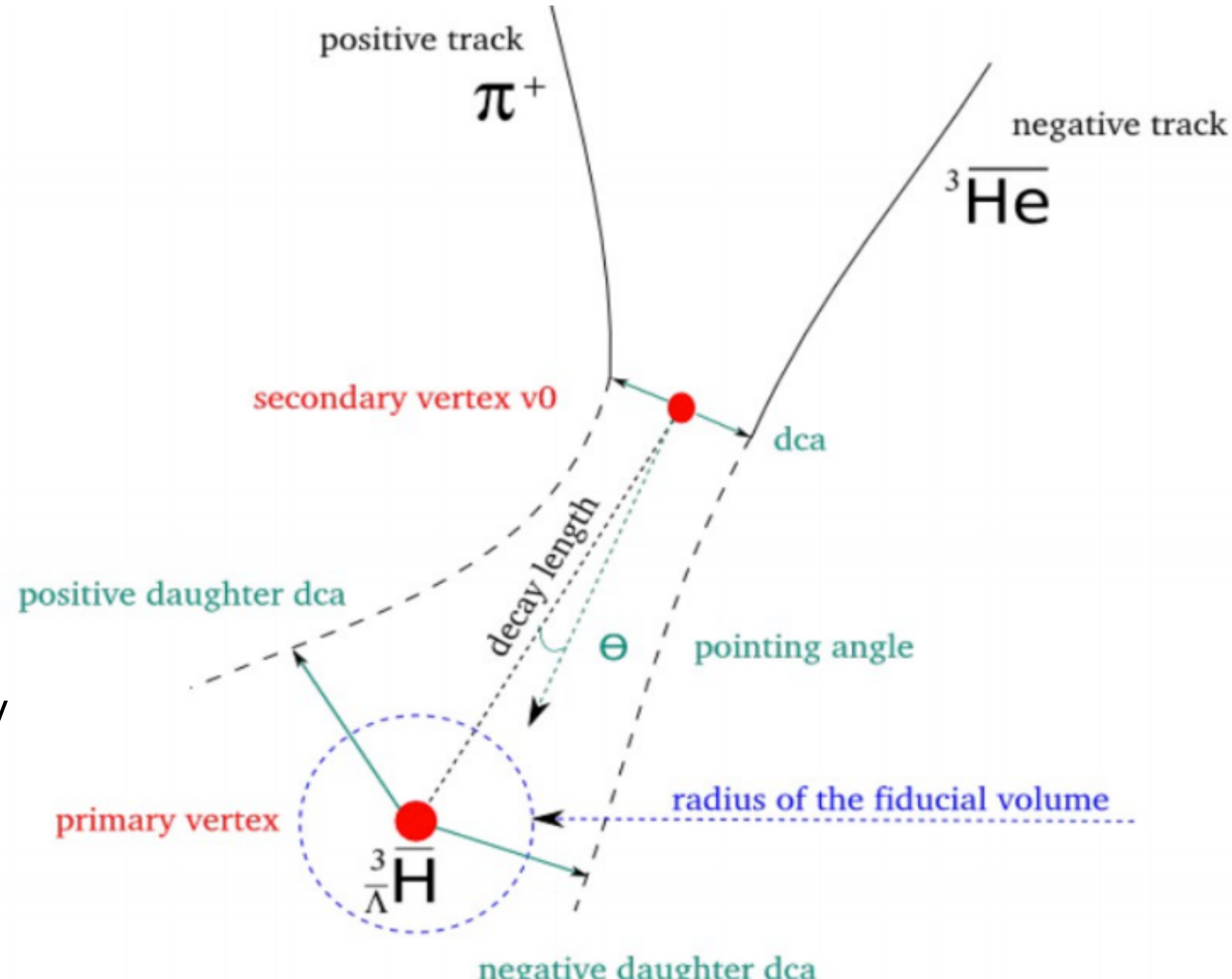

Image not in scale

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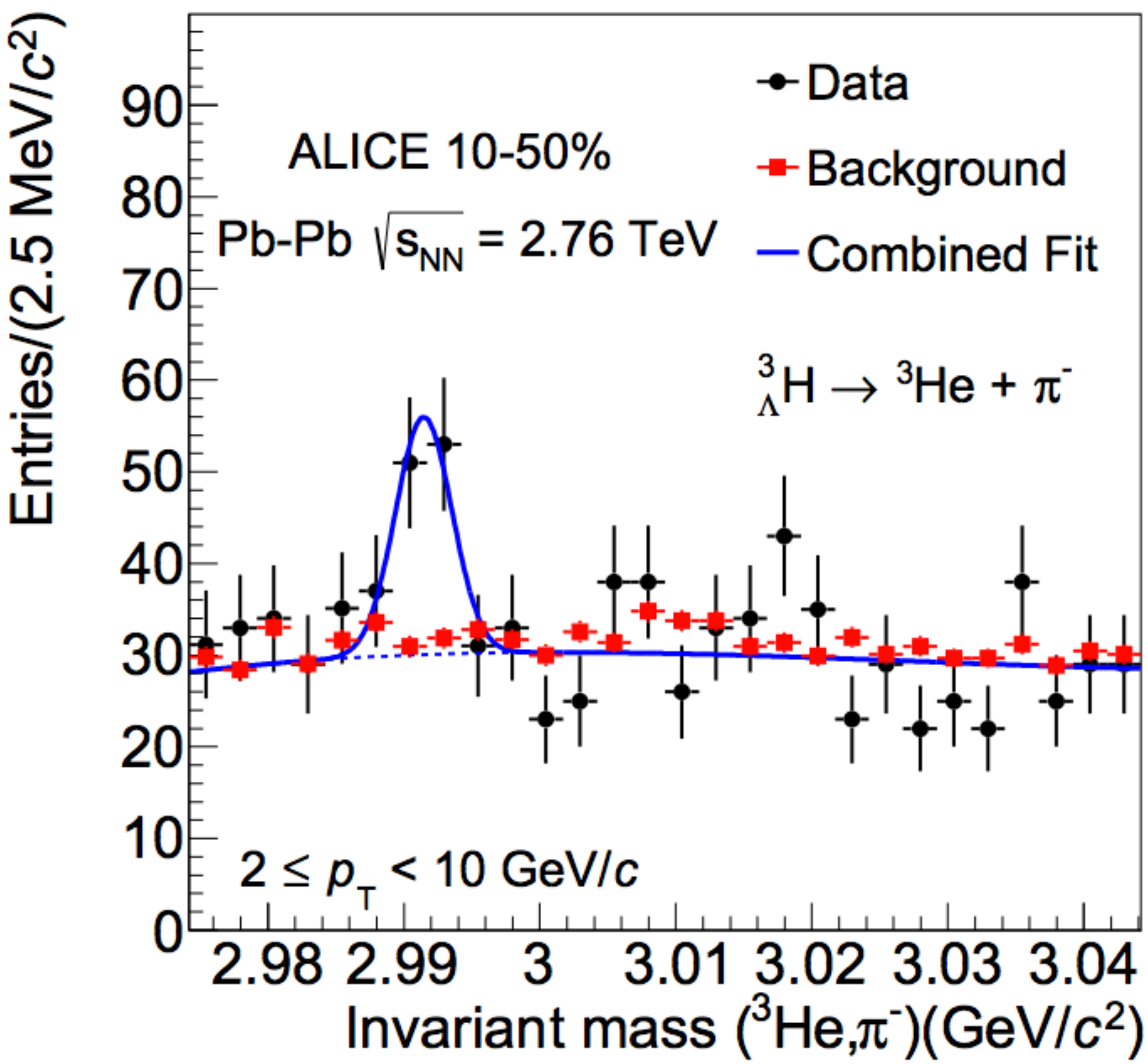

ALICE Coll. arXiv:1506.08453 [nucl-ex]

(Anti-)Hyper-triton in Pb-Pb

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

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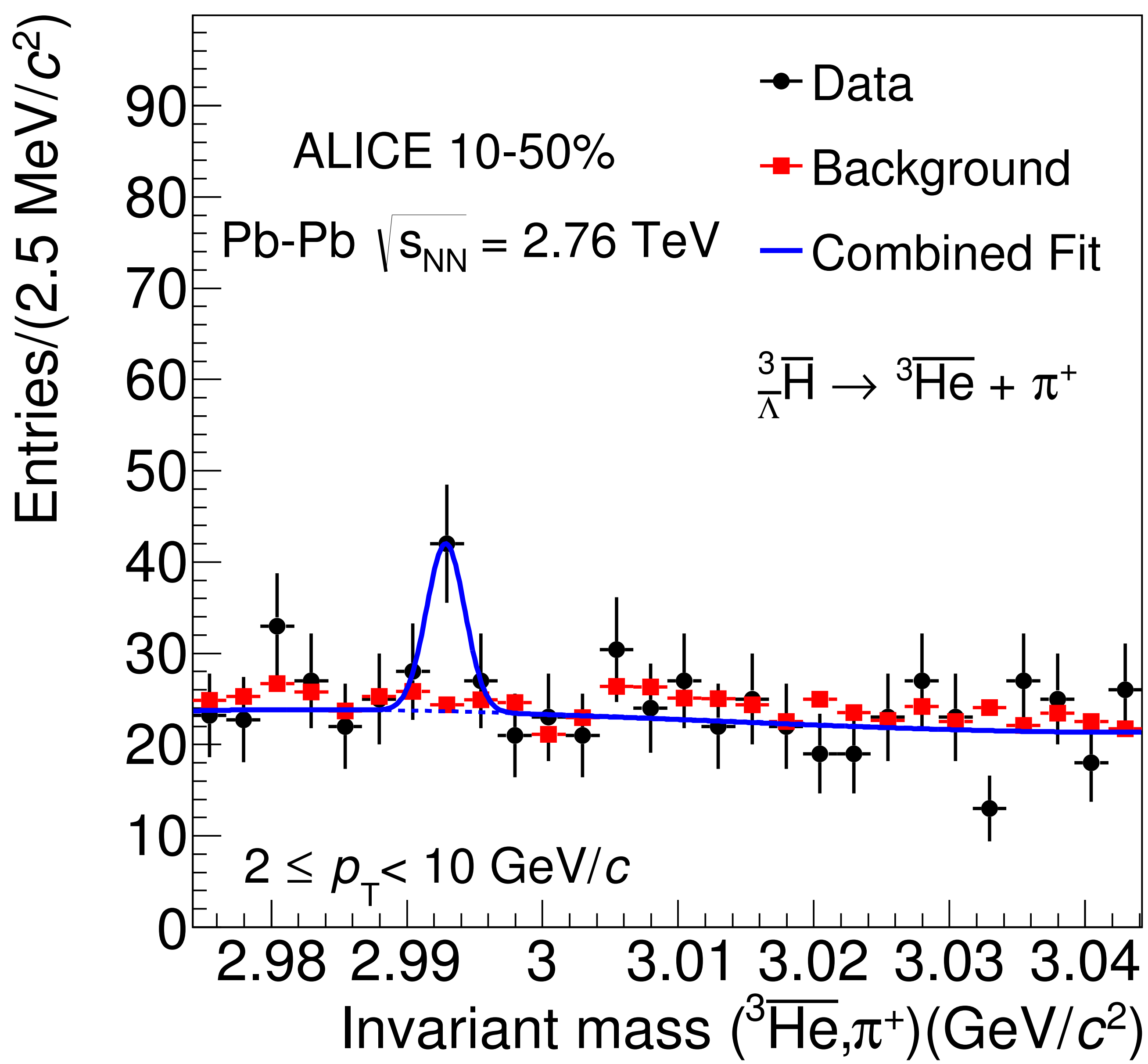
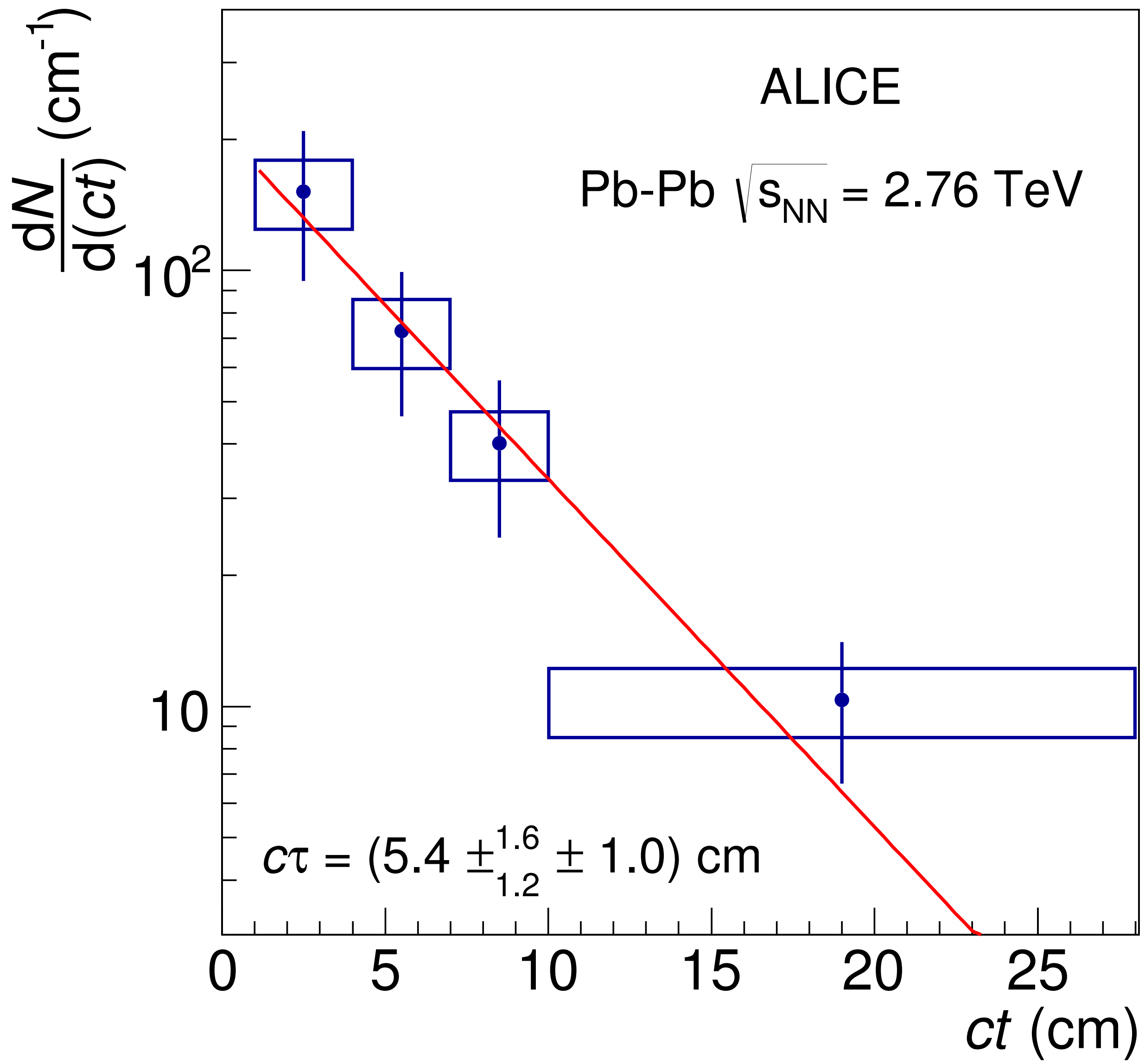


ALICE Coll. arXiv:1506.08453 [nucl-ex]

Measurement of the hyper-triton lifetime

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

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

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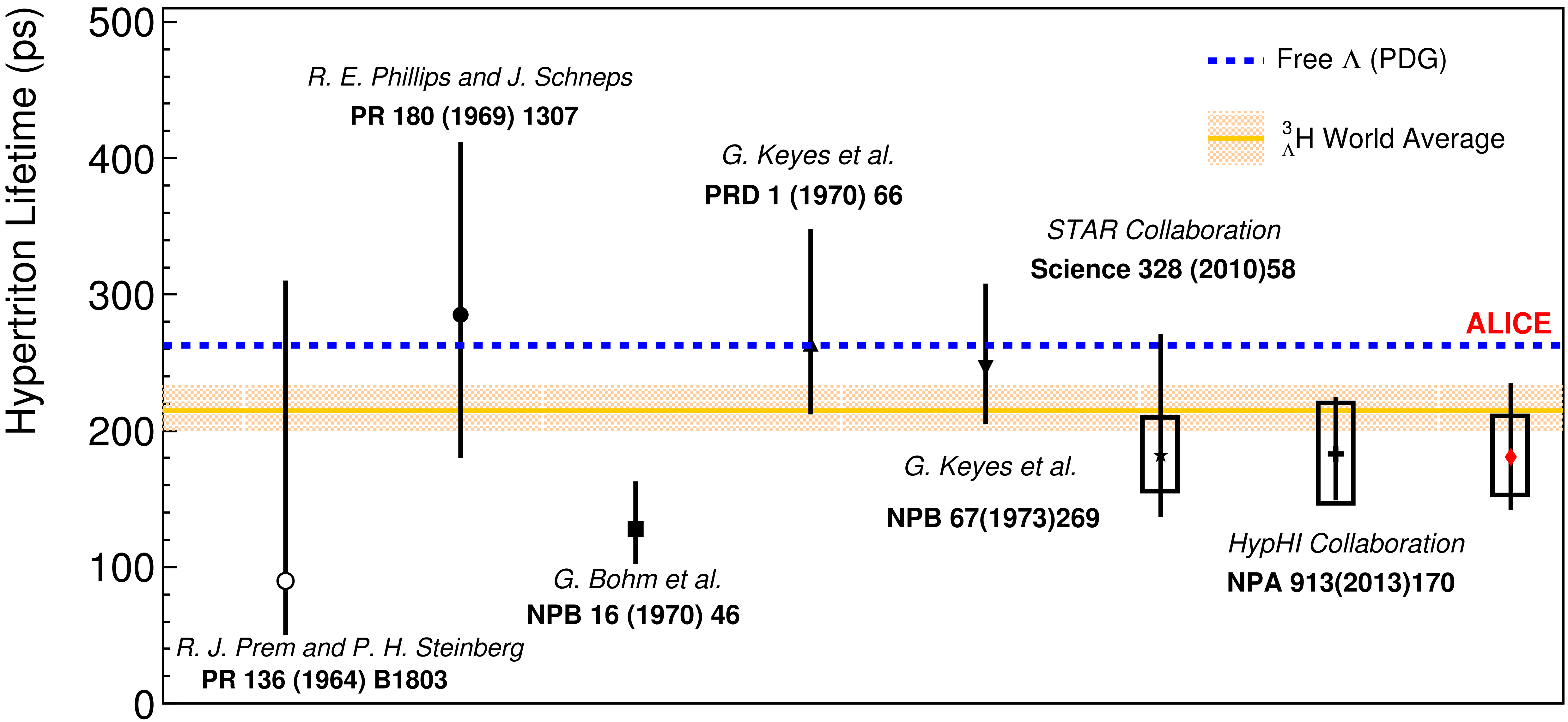

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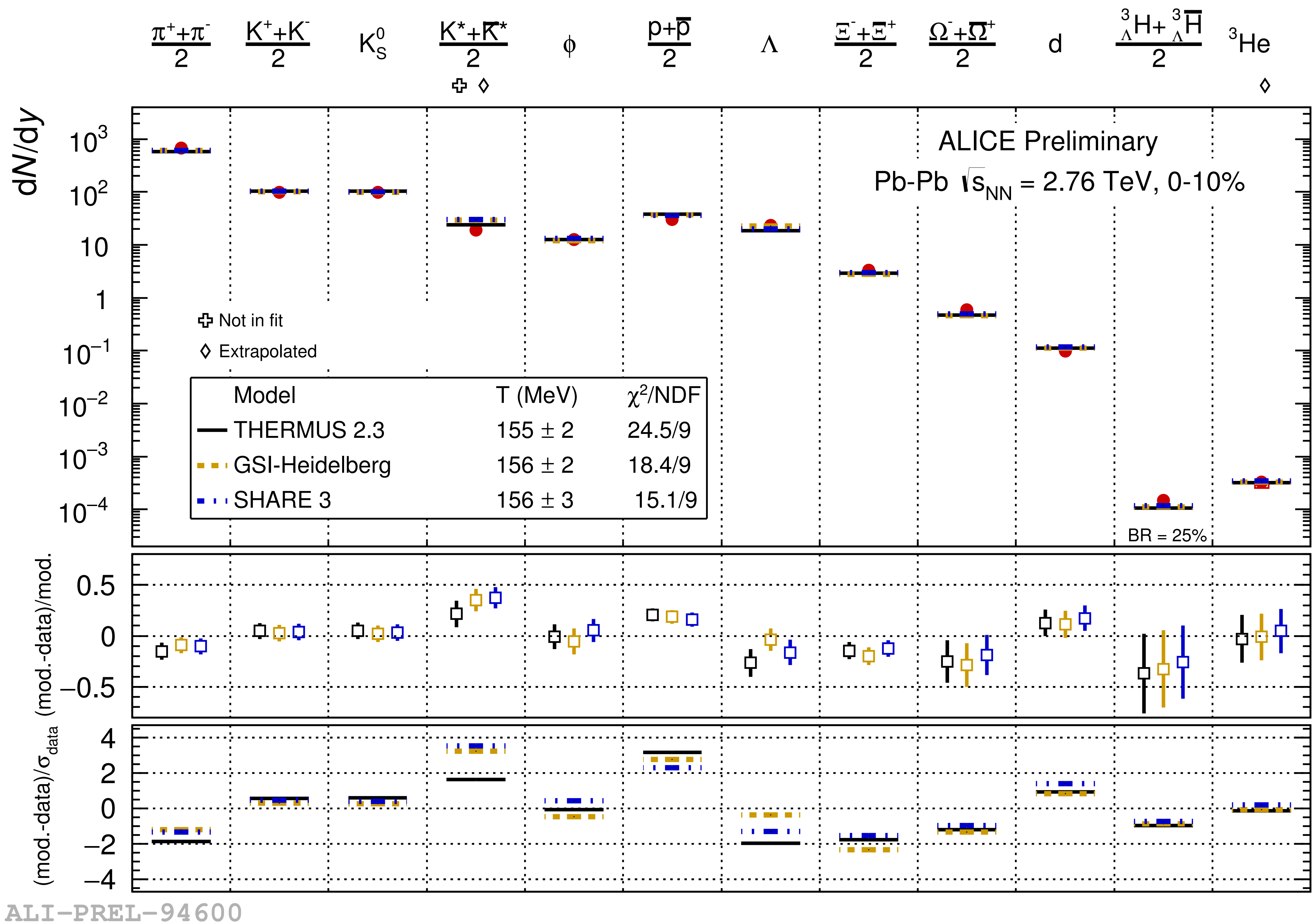
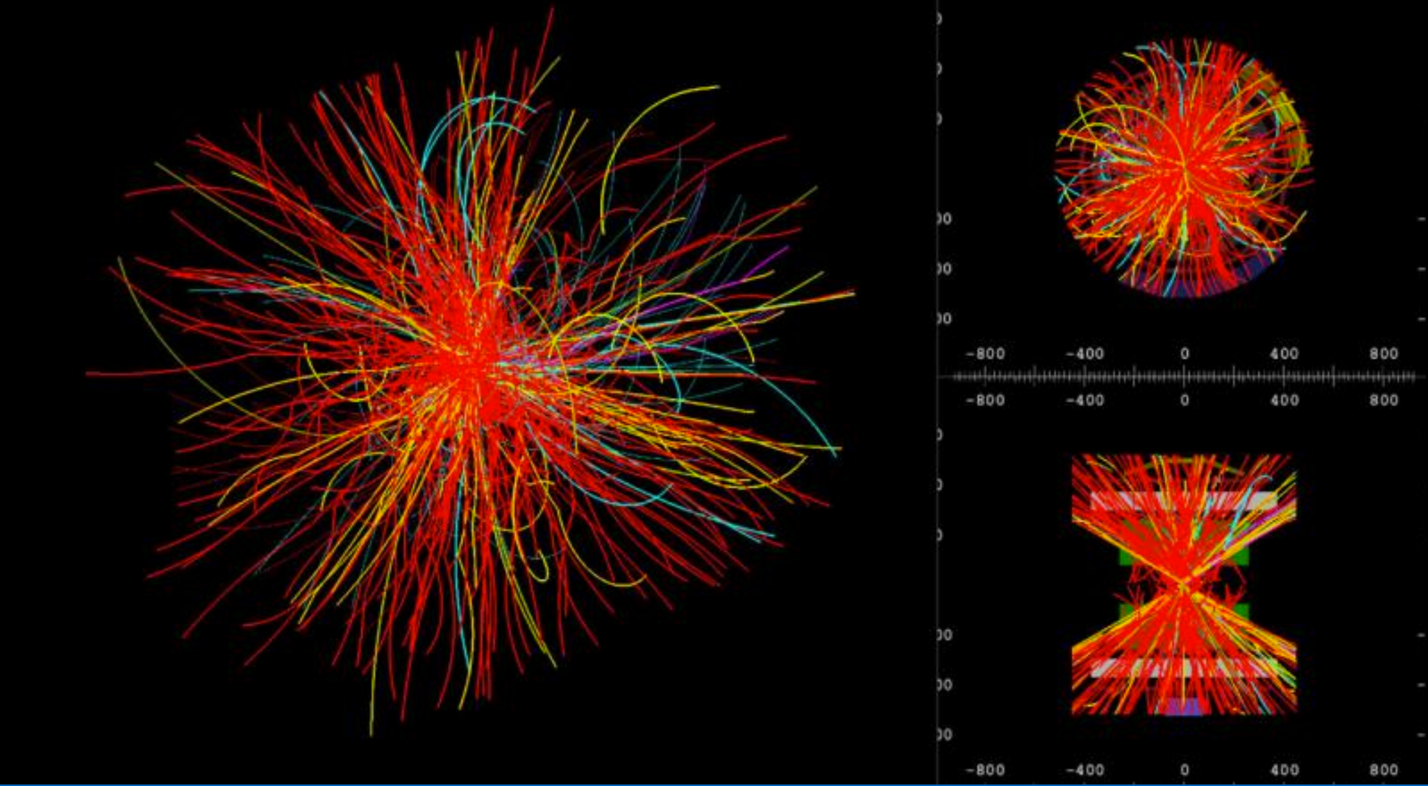
Thermal model fits



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*.

Conclusions and perspectives

- Nuclei production at the LHC has been measured up to A=4
- 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 measurements confirm the puzzle of its short lifetime
- LHC Run 2 will give the opportunity to extend the current measurements and put tighter constraints on theoretical models.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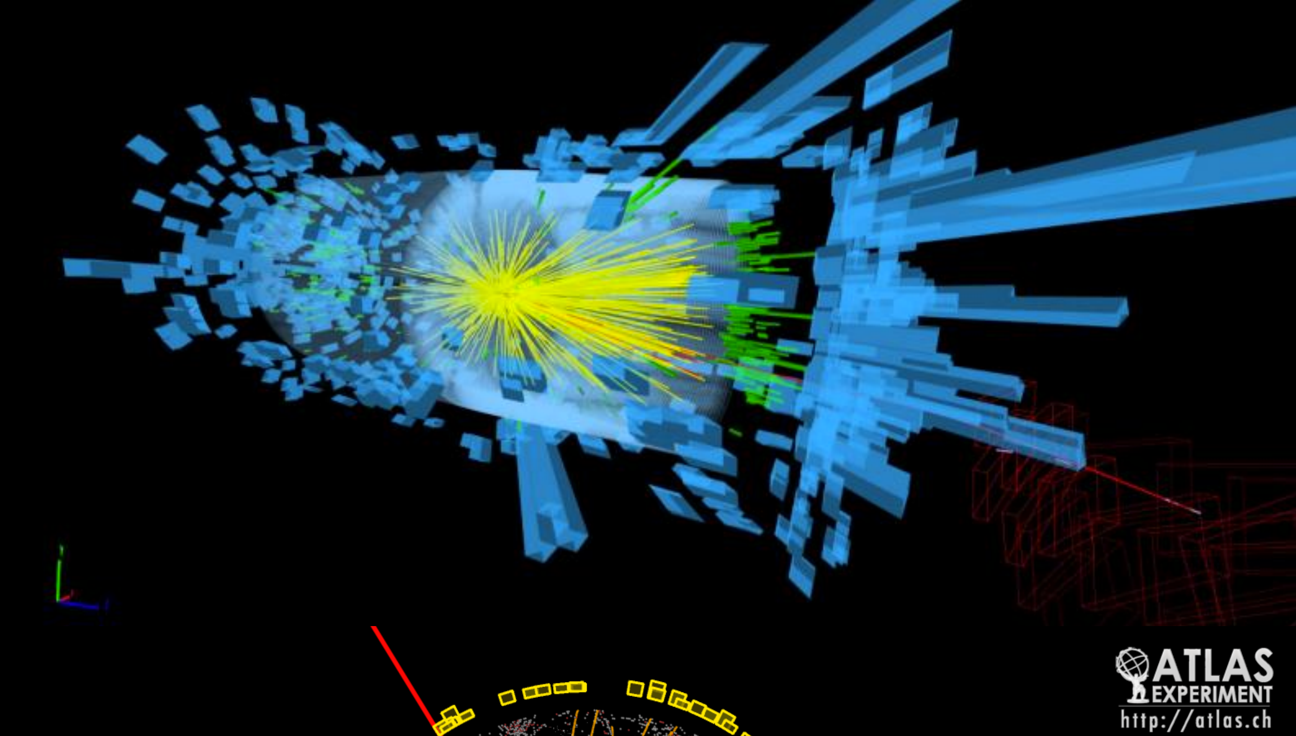
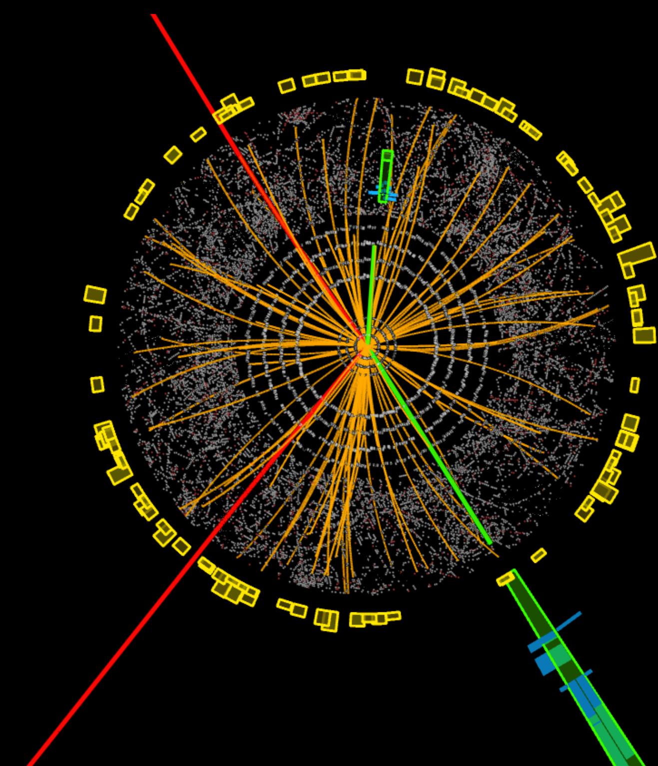
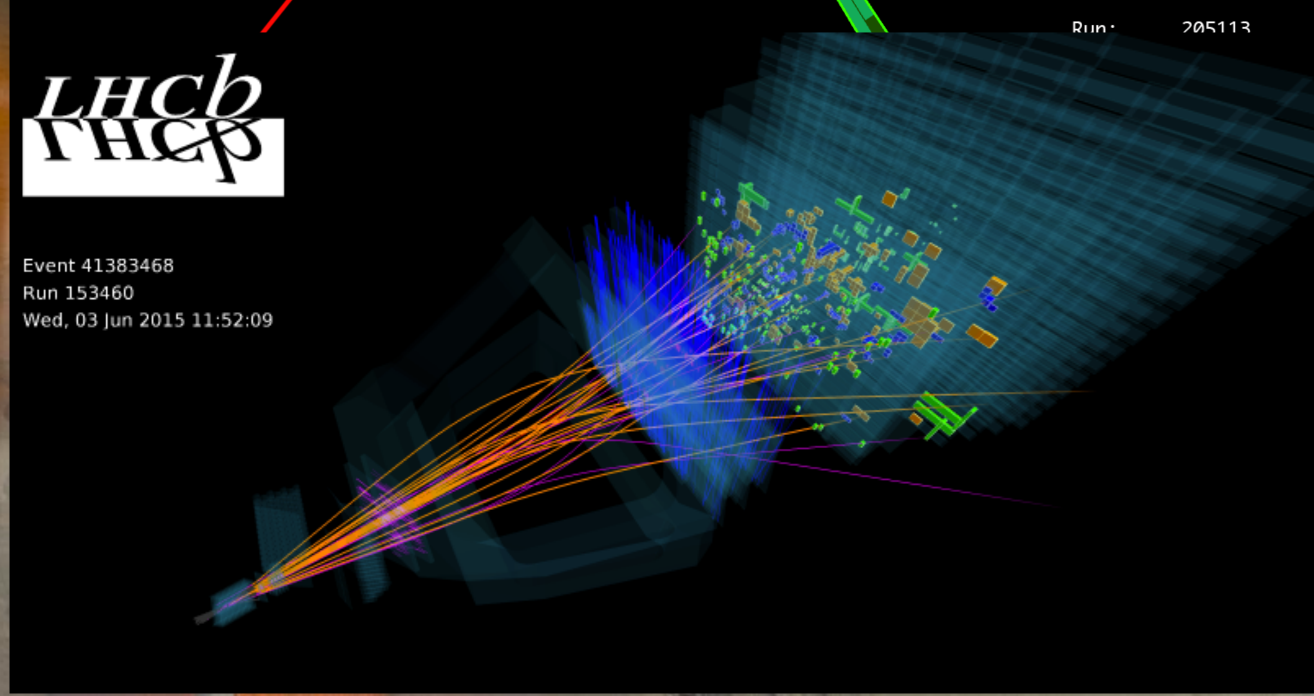
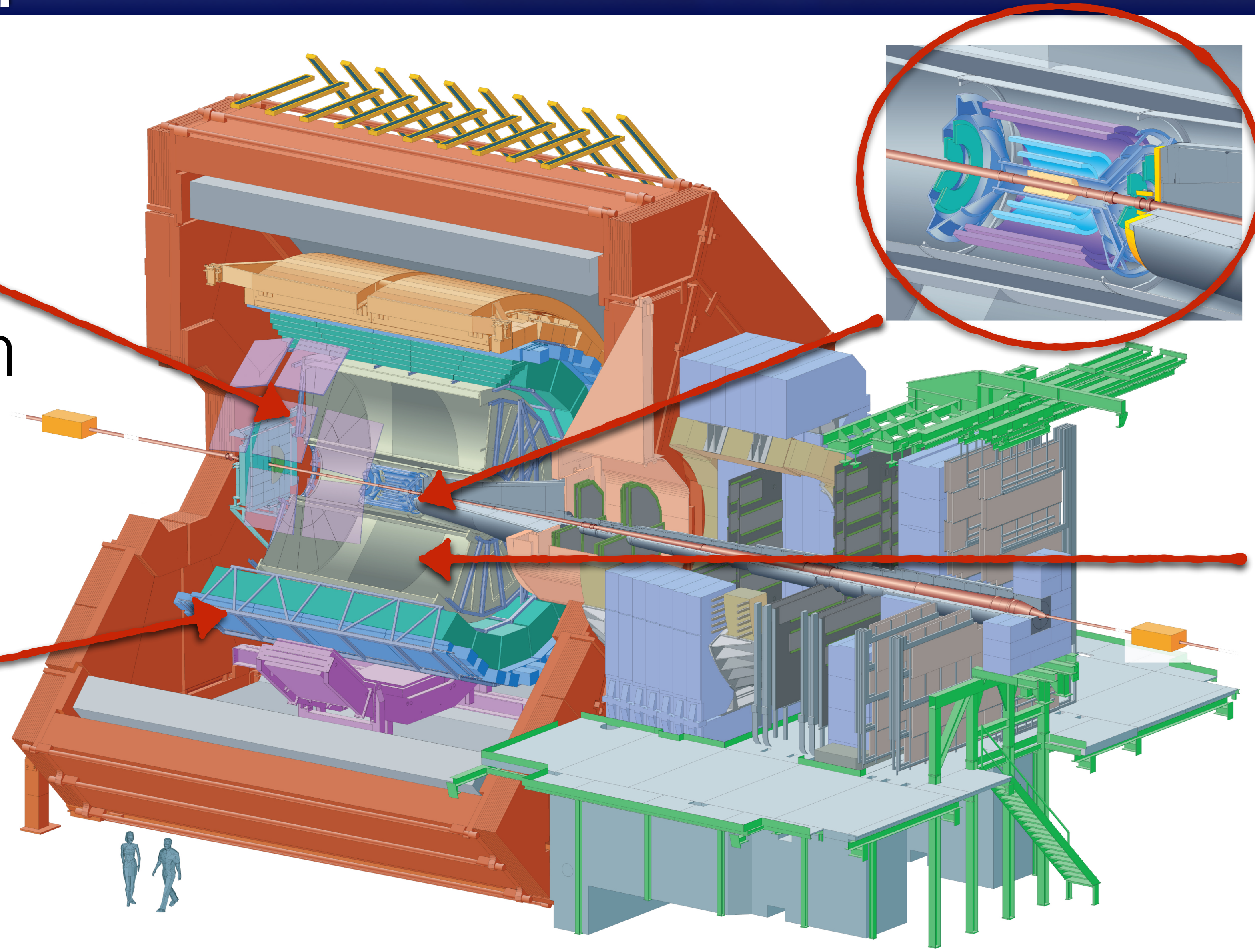

ATLAS EXPERIMENT
http://atlas.ch

Backup




LHCb
Event 41383468
Run 153460
Wed, 03 Jun 2015 11:52:09

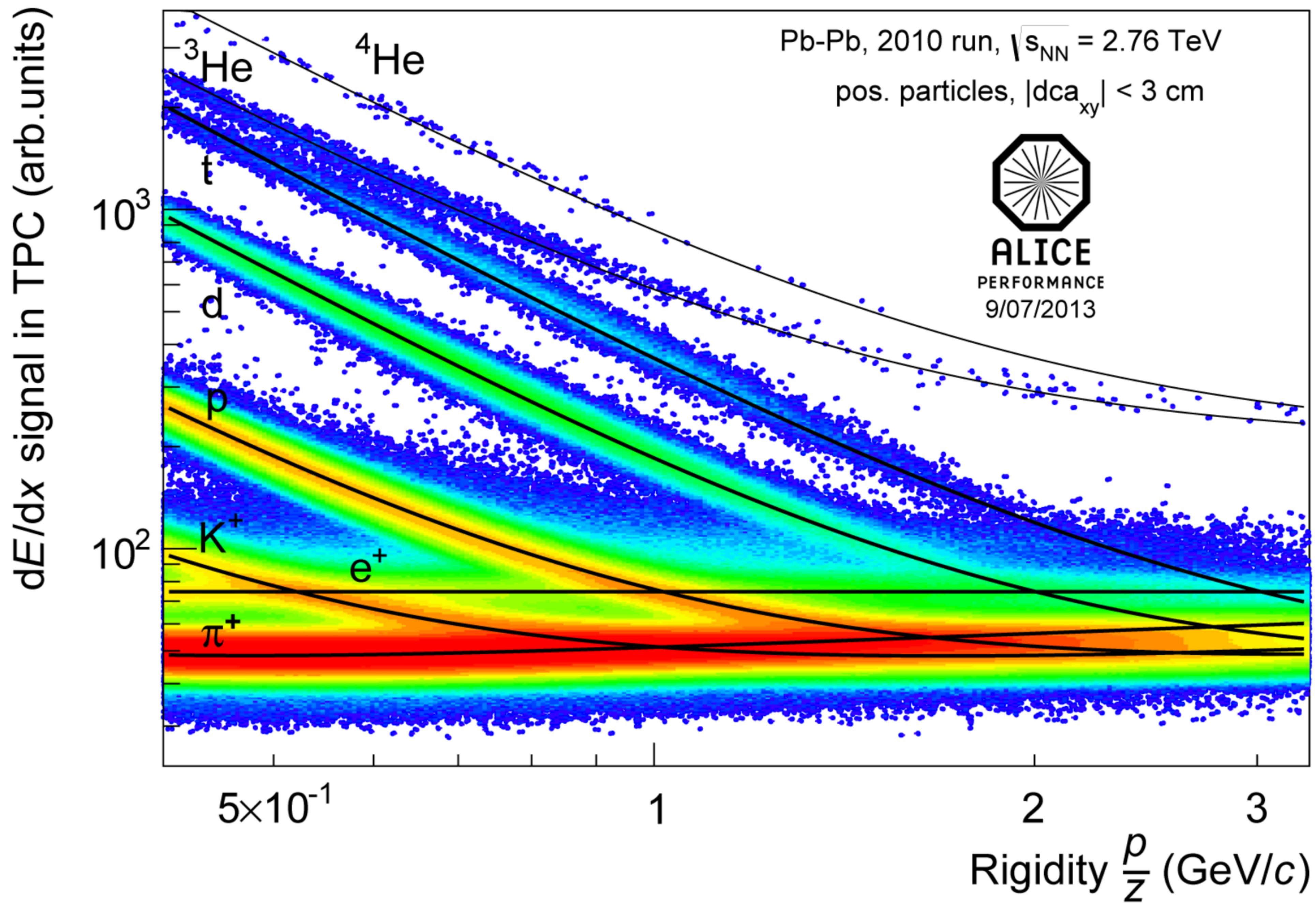
ALICE experiment



- 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

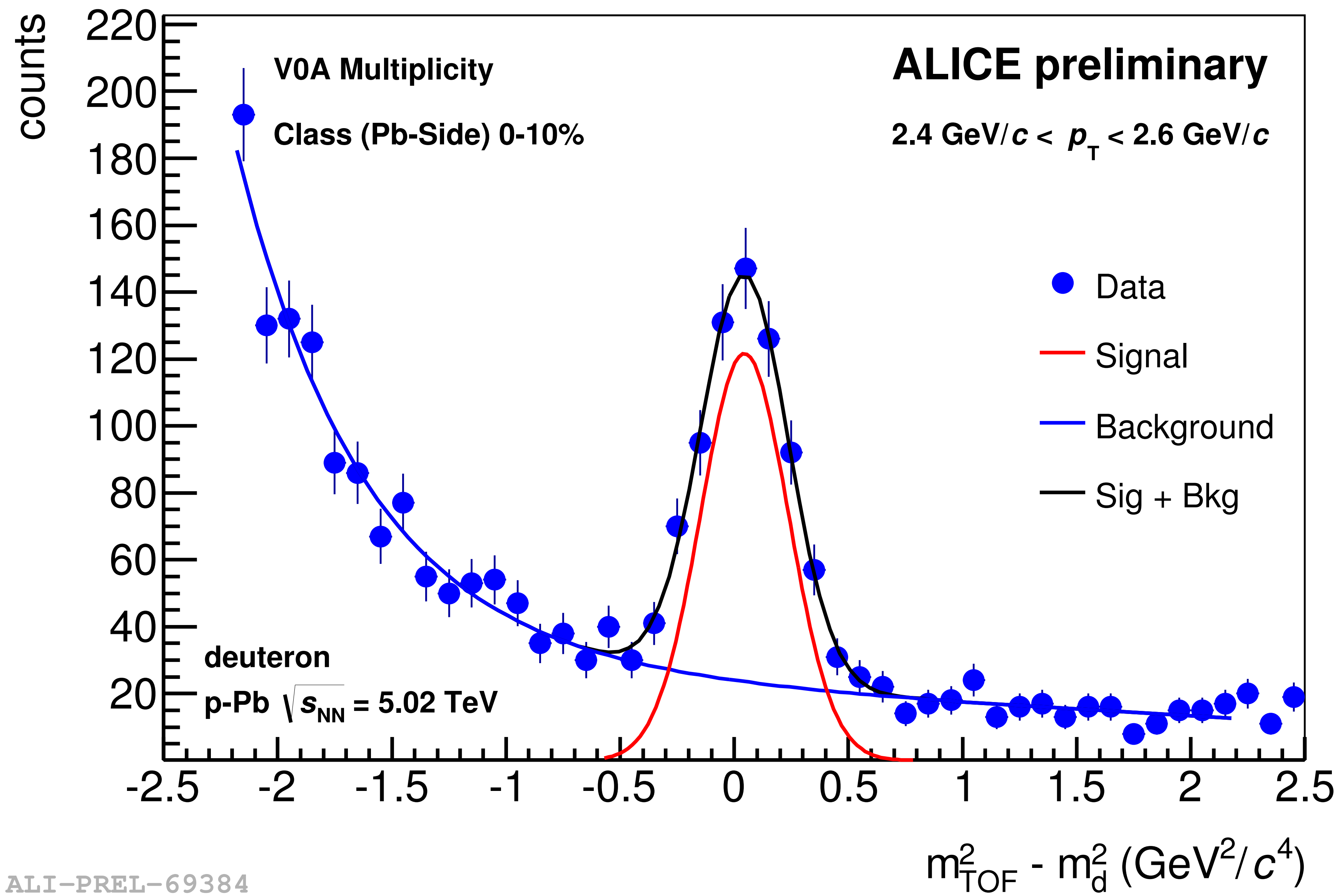
ALICE PID performance: TPC



Specific energy loss in the **T**ime **P**rojection **C**hamber volume provides PID information for light nuclei.

➡ $\sigma_{dE/dx}$~7% (in Pb-Pb collisions)

ALICE PID performance: TOF

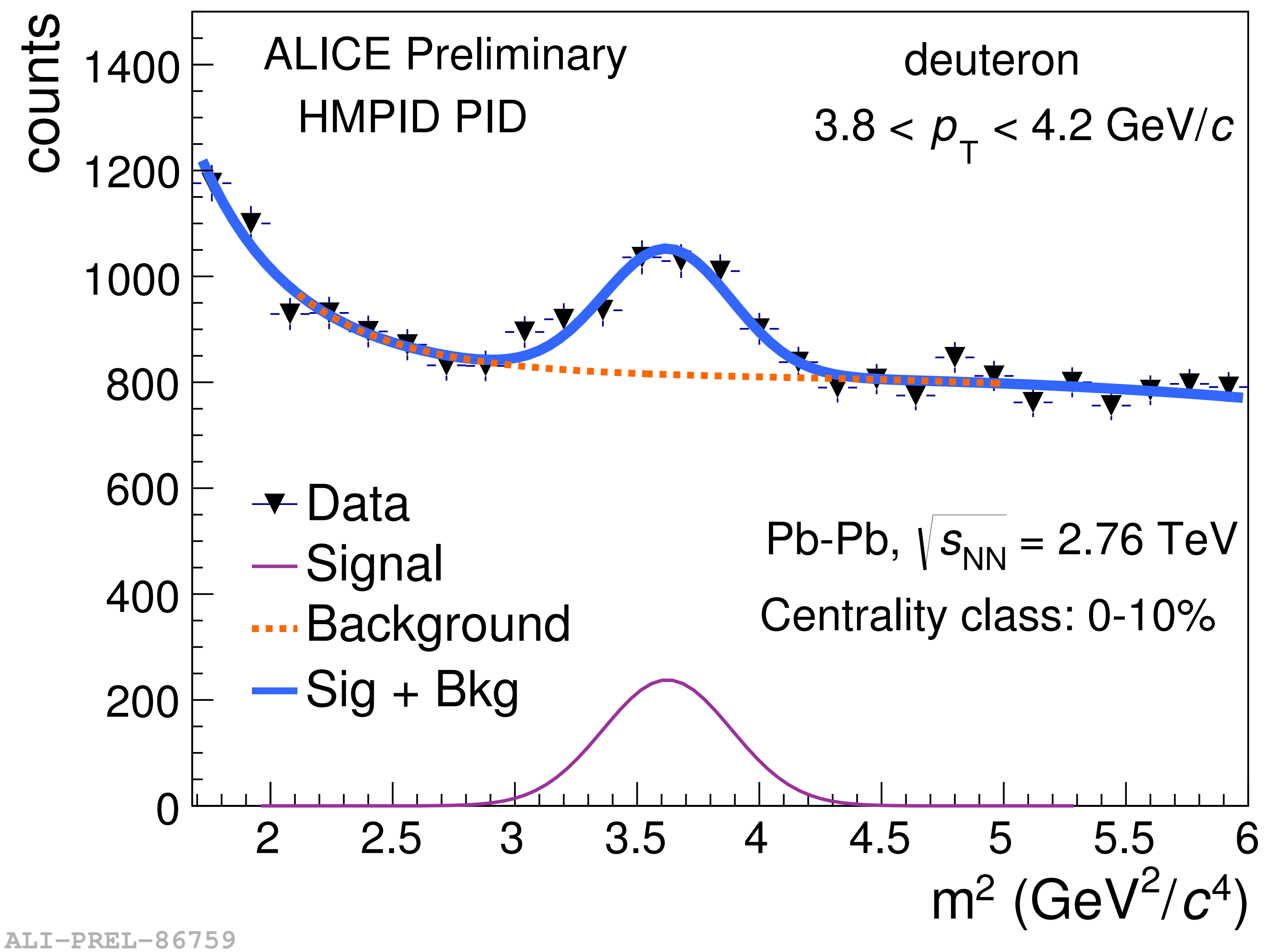


$$m_{\mathrm{TOF}} = \frac{p}{\beta\gamma} \quad \text{where} \quad \beta = \frac{l_{\mathrm{track}}}{c \cdot t_{\mathrm{TOF}}}$$

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)

ALICE PID performance: HMPID



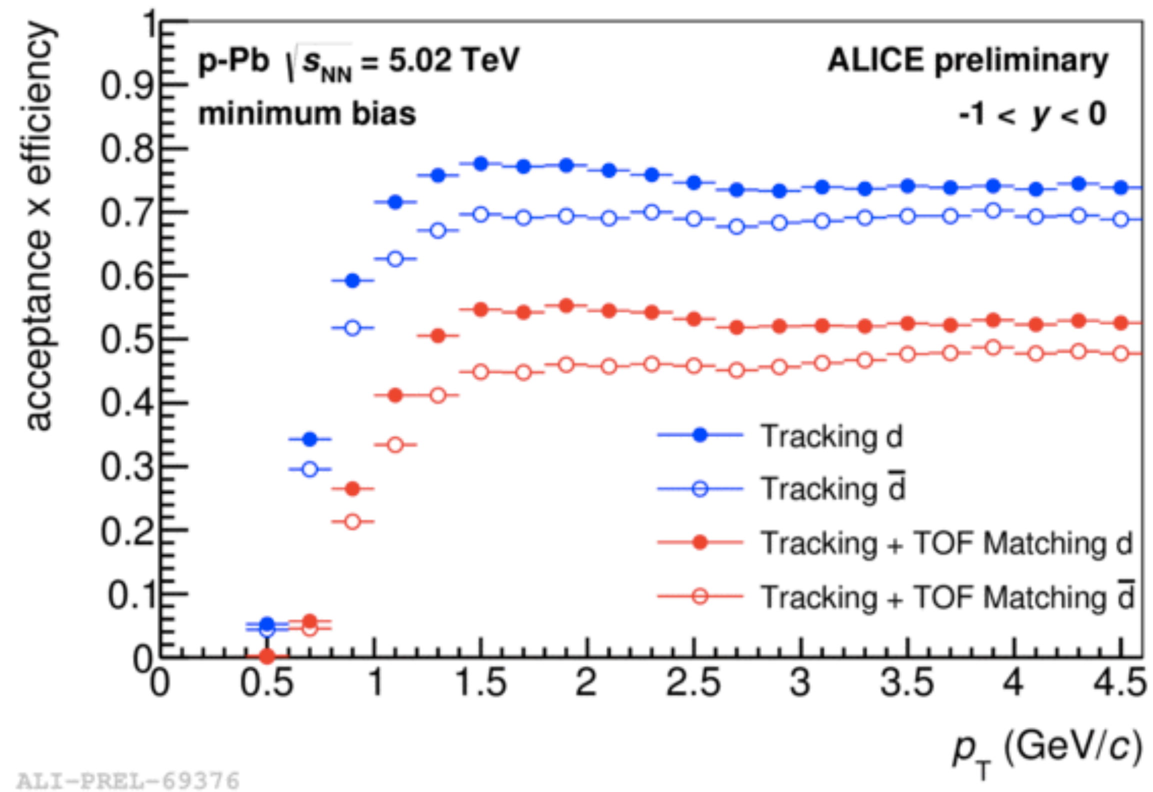
$$m_{\mathrm{HMPID}} = \frac{p}{\beta\gamma} \quad \text{where} \quad \beta = \frac{1}{n \cdot cos\theta_c}$$

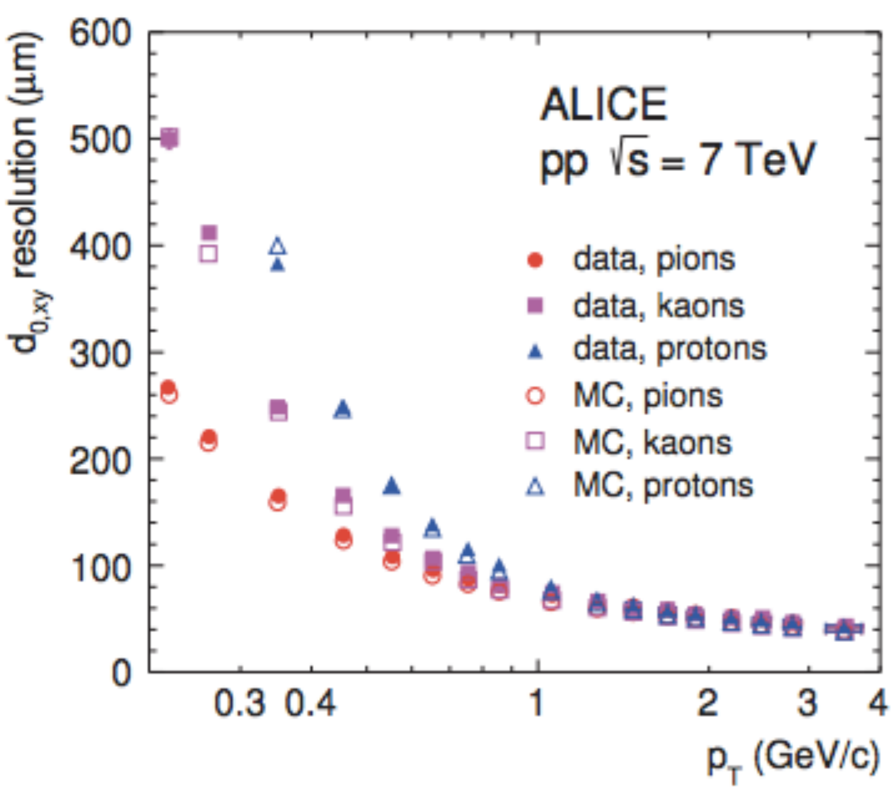
Tracking information + **H**igh **M**omentum **P**article **ID**entification detector (Cherenkov light detector) signal

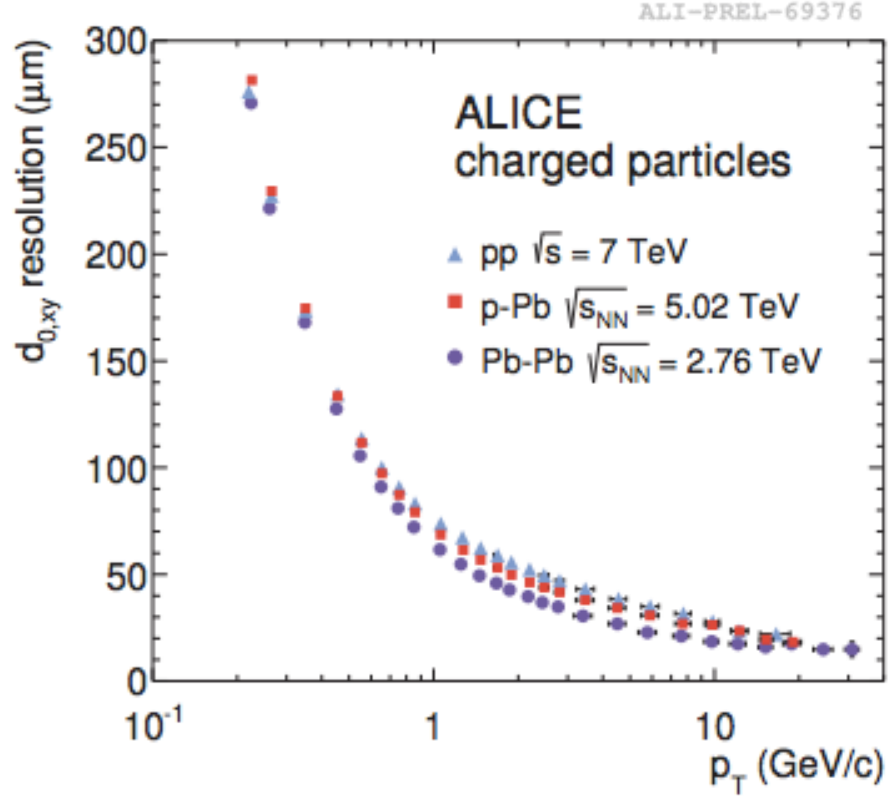
→ *m* of the particle

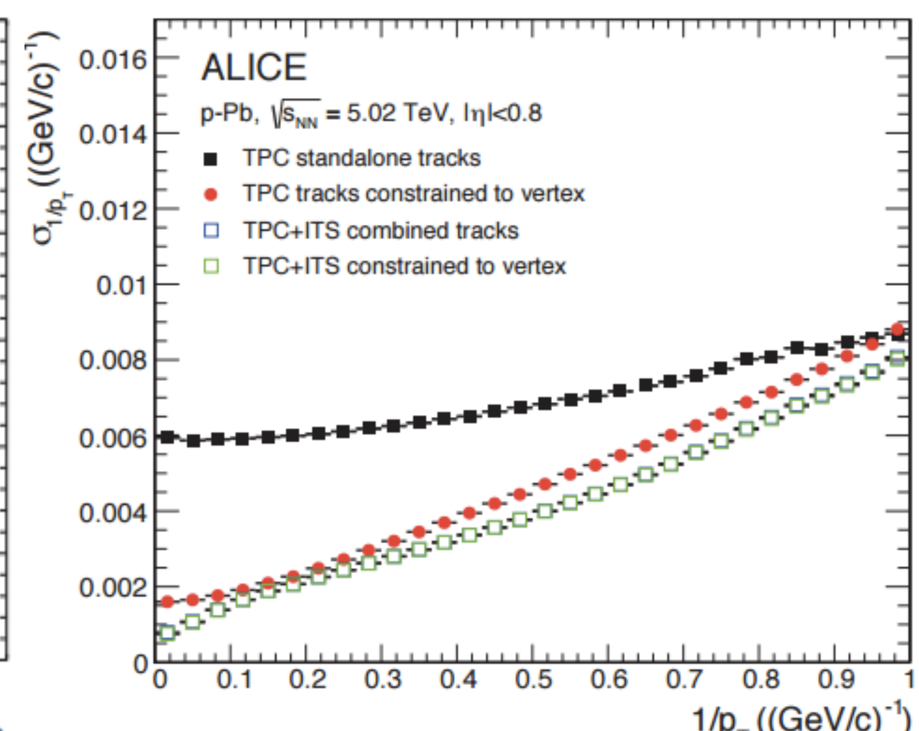
ALICE tracking efficiency

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



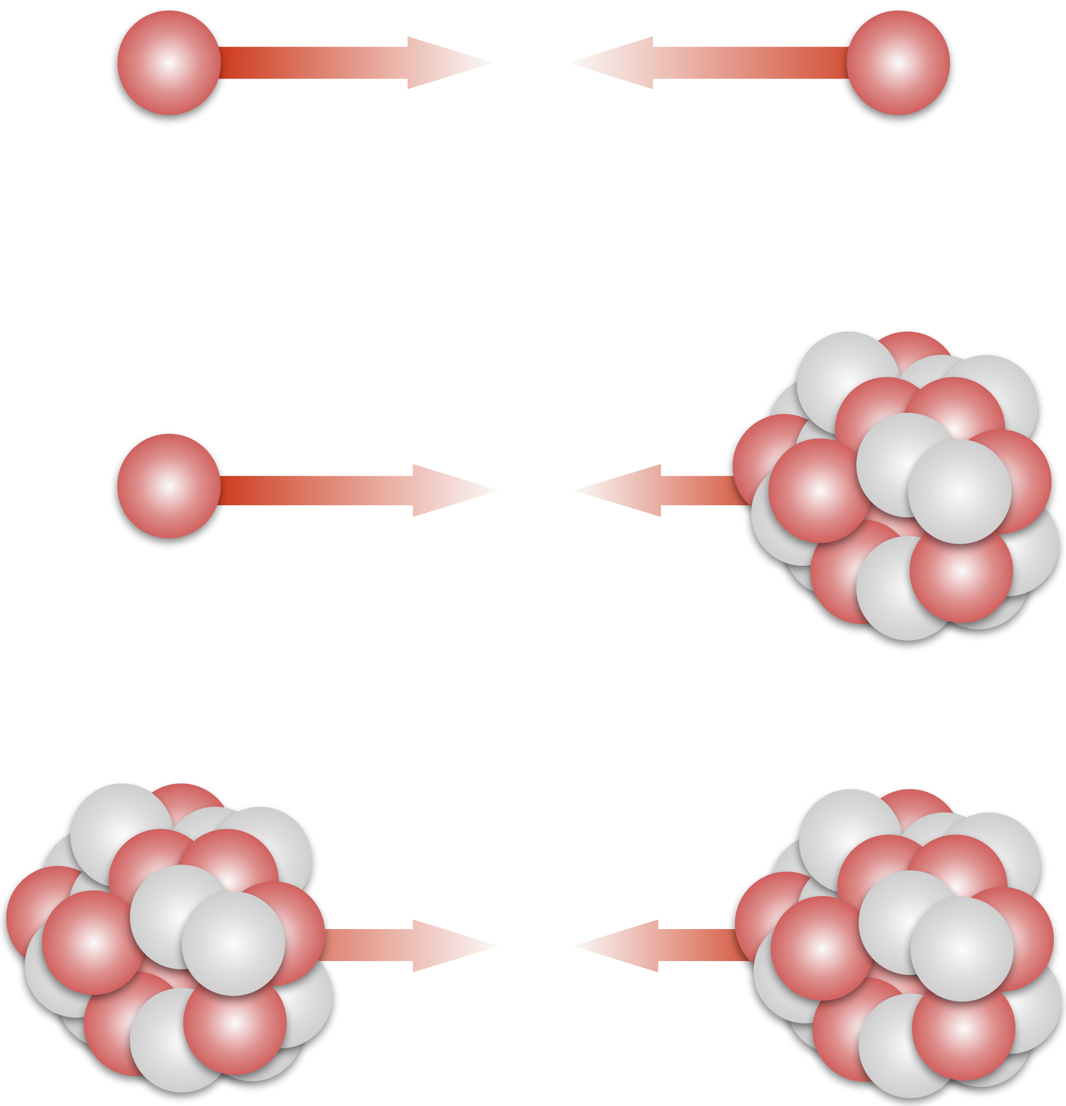






ALICE Coll. Int. J. Mod. Phys. A 29, 1430044 (2014)

Collision systems at the LHC



	$\sqrt{s}$	
pp	0.9 TeV 2.76 TeV **7 TeV** 8 TeV	Reference for measurement in other systems
	$\sqrt{s_{\mathrm{NN}}}$	
p-Pb Pb-p	**5.02 TeV** **5.02 TeV**	Study of nuclear matter effects
	$\sqrt{s_{\mathrm{NN}}}$	
Pb-Pb	**2.76 TeV**	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

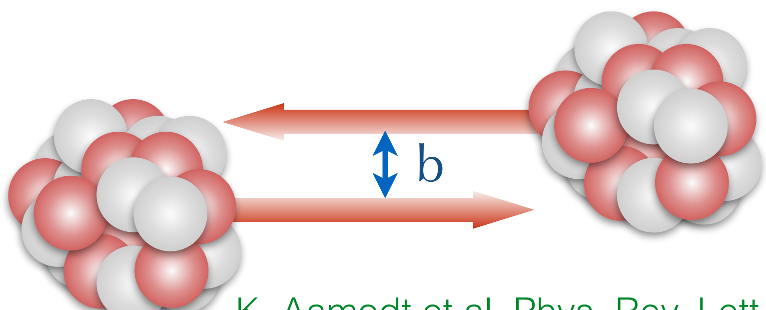
Centrality of a collision

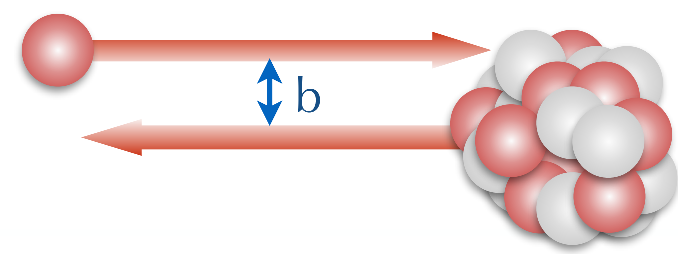
The centrality of a collision is defined by the impact parameter *b*:

Most central collision ⇔ Smallest b

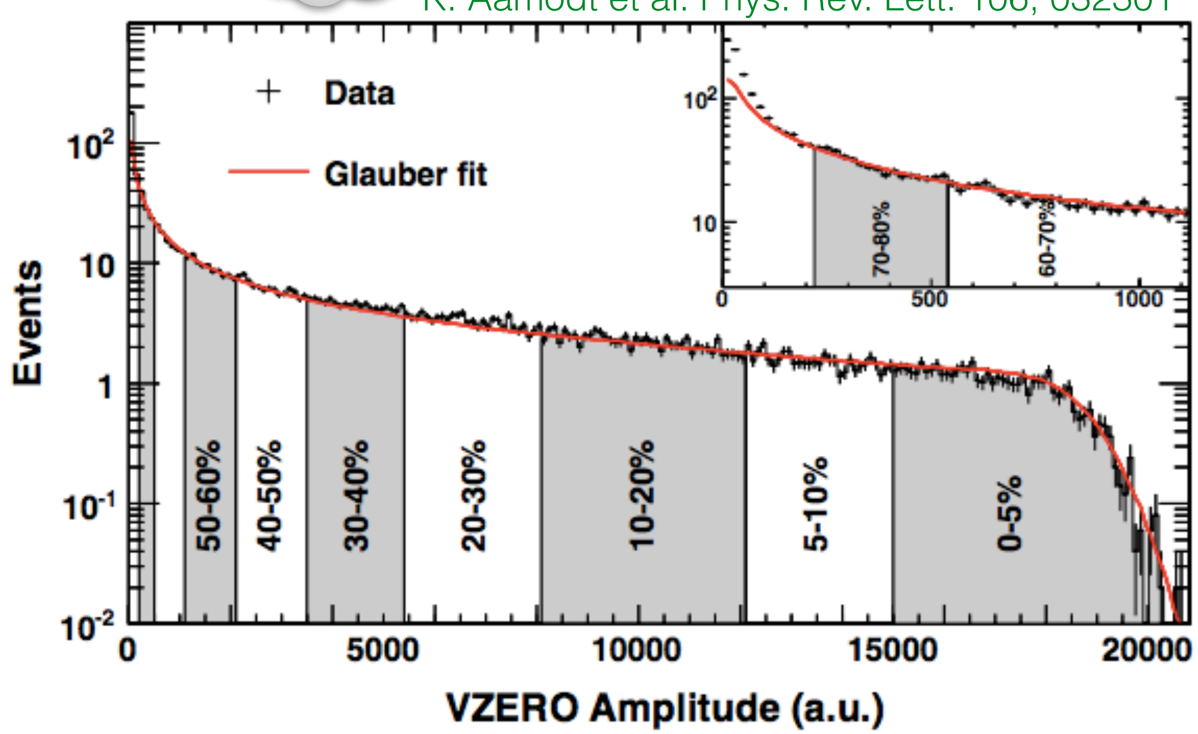
Experimentally it is possible to correlate the charged particle multiplicity to *b* by fitting data with the function shape predicted by the Glauber model.

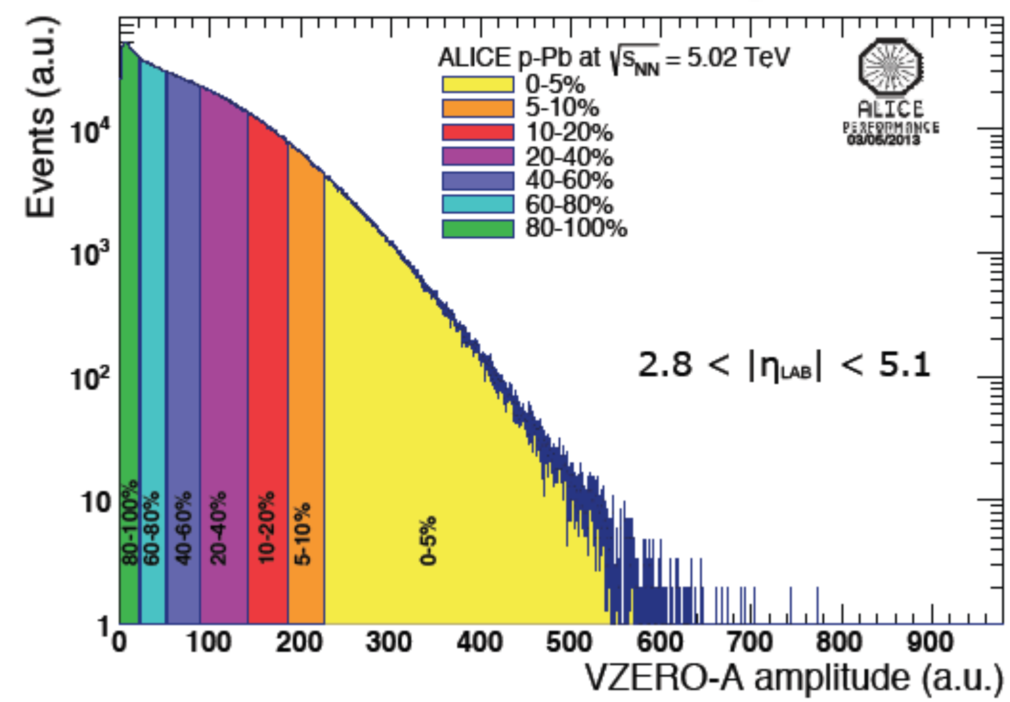
The correlation between charged particle mult. and impact parameter in p-Pb is broader.





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



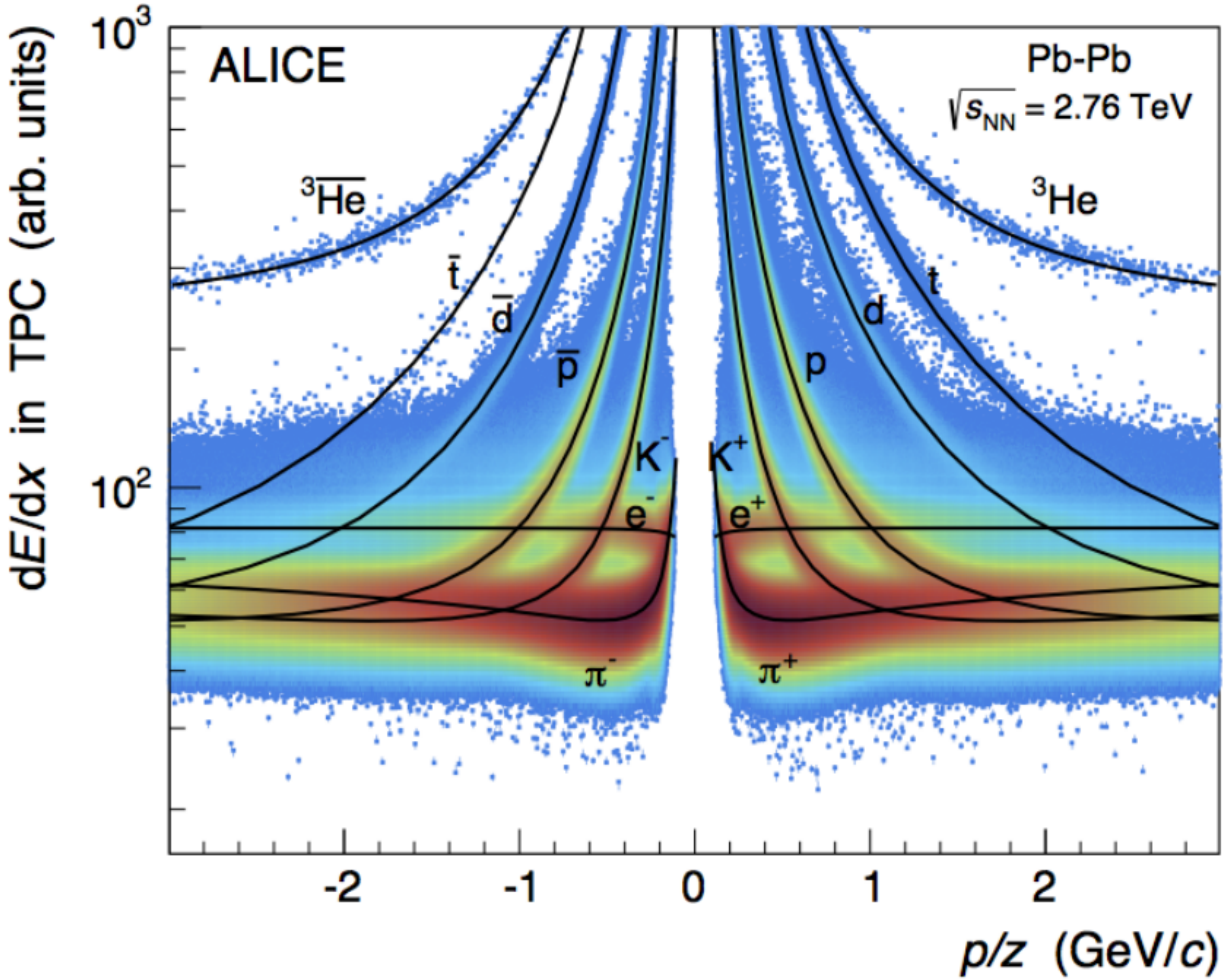


V-ZERO is a scintillator hodoscope used for centrality estimation and for the trigger.

Observation of the anti-triton

ALICE Coll. arXiv:1506.08951 [nucl-ex]

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.



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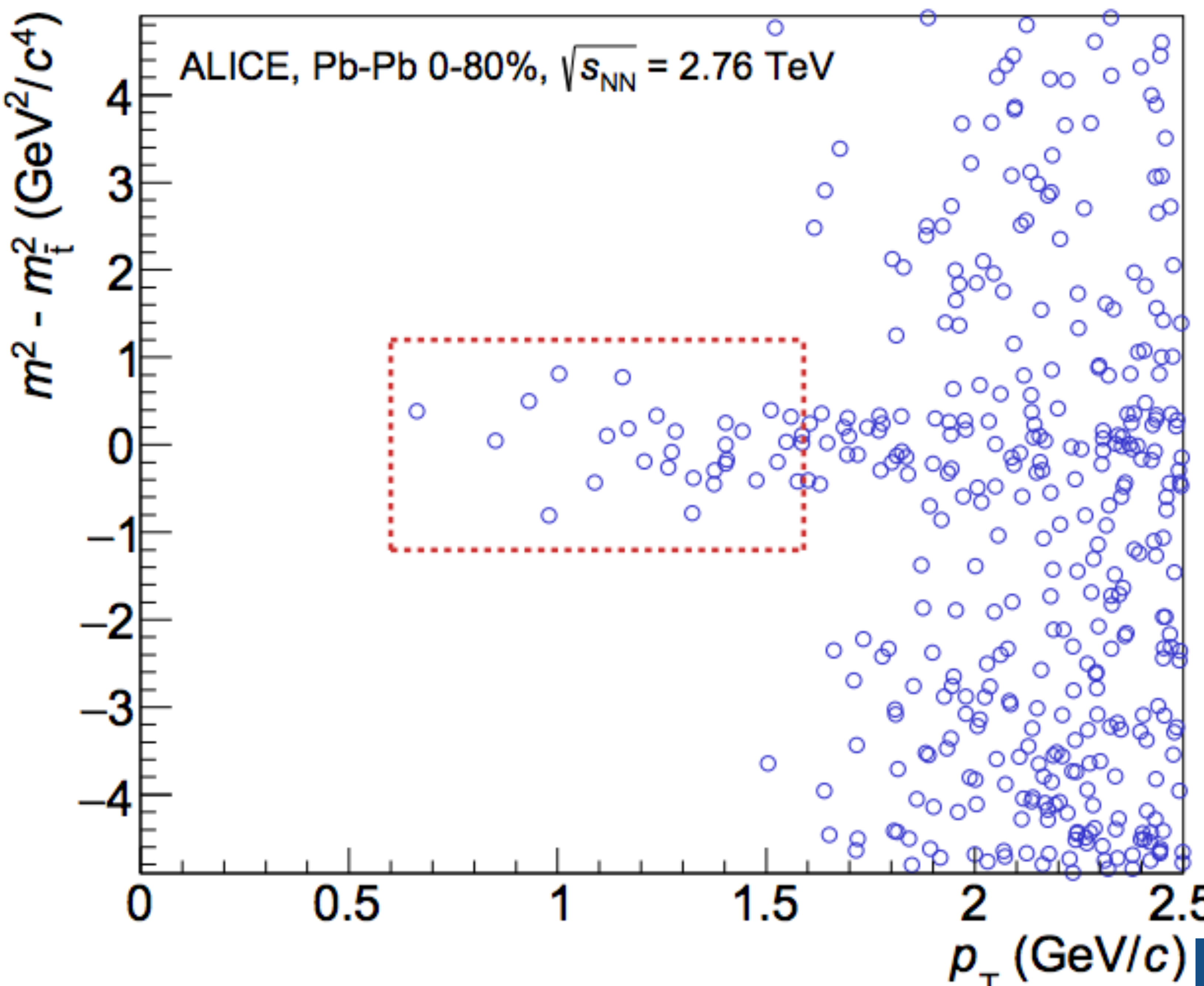
- 31 anti-tritons can be identified unambiguously
- In this kinematic range, extrapolations place the expected anti-triton yield somewhere between 11 and 40 particles



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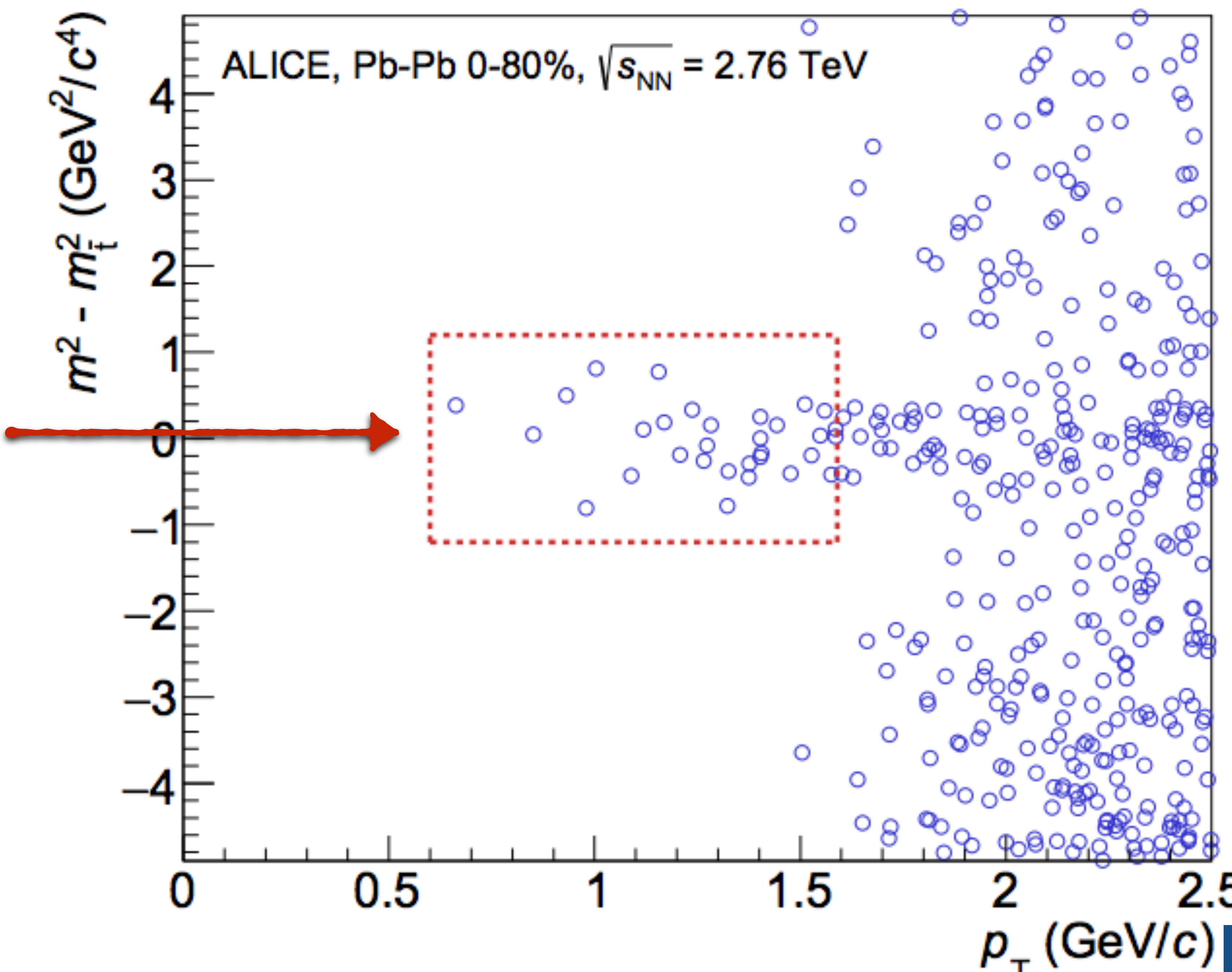


B_2 as a function of HBT radii

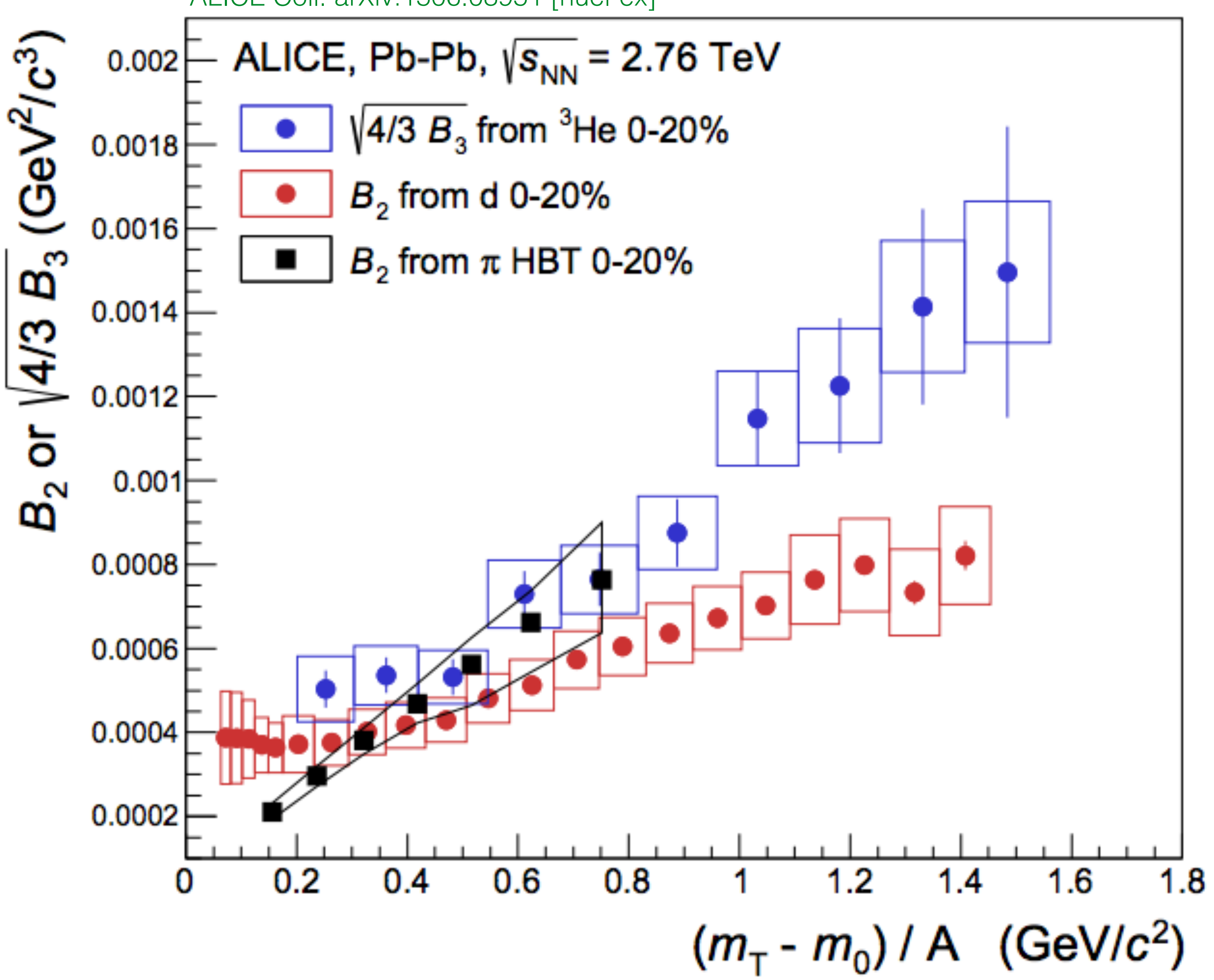
The coalescence parameter can be expressed as a function of the HBT radii:

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

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]



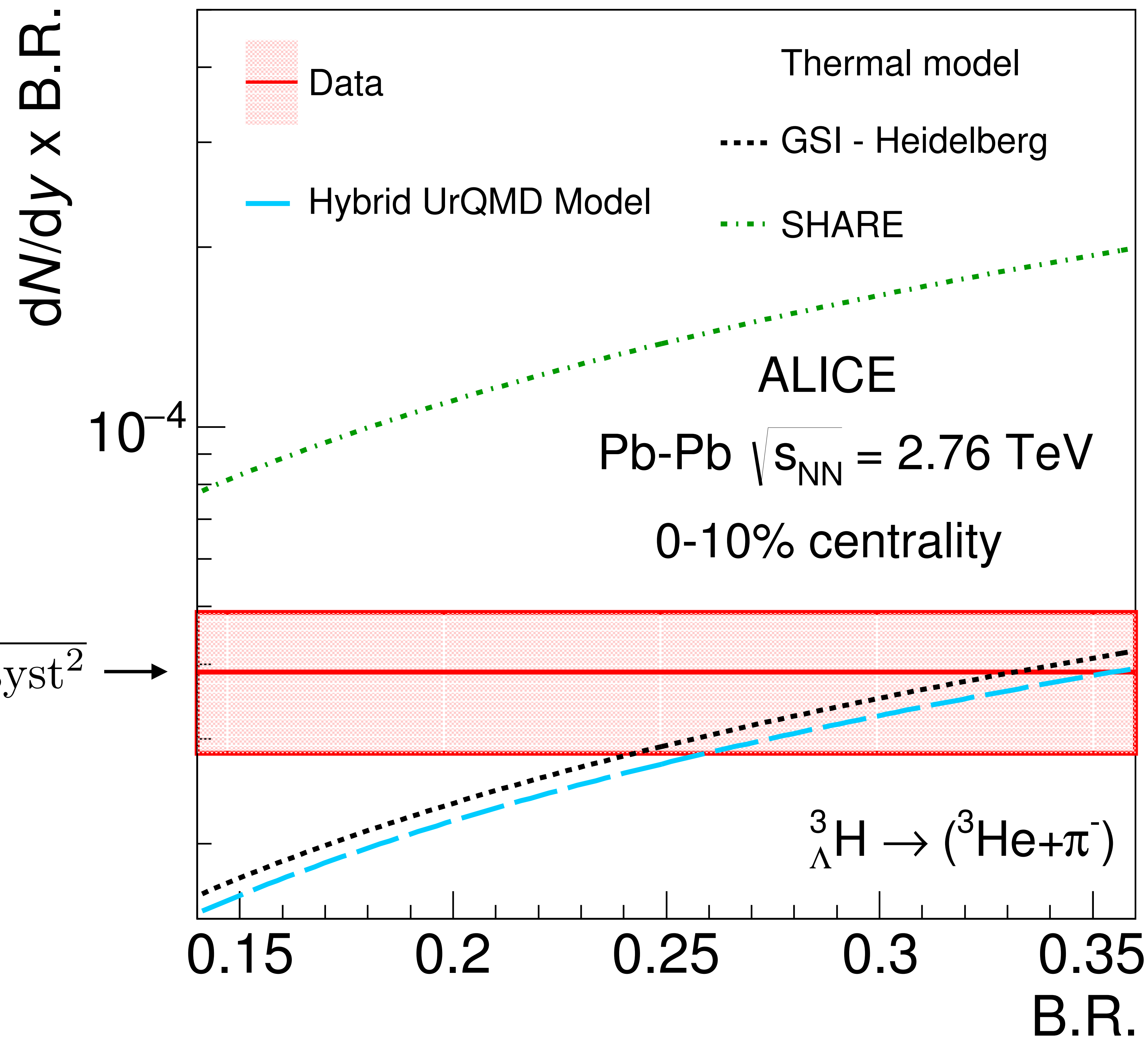
The coalescence parameter for a nucleus *i* with A nucleons is defined as:

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

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

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

Hyper-triton yield compared to thermal models



$\text{Measure} \pm \sqrt{\text{stat.}^2 + \text{syst}^2} \longrightarrow$

Search for ΛΛ and Λn

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:

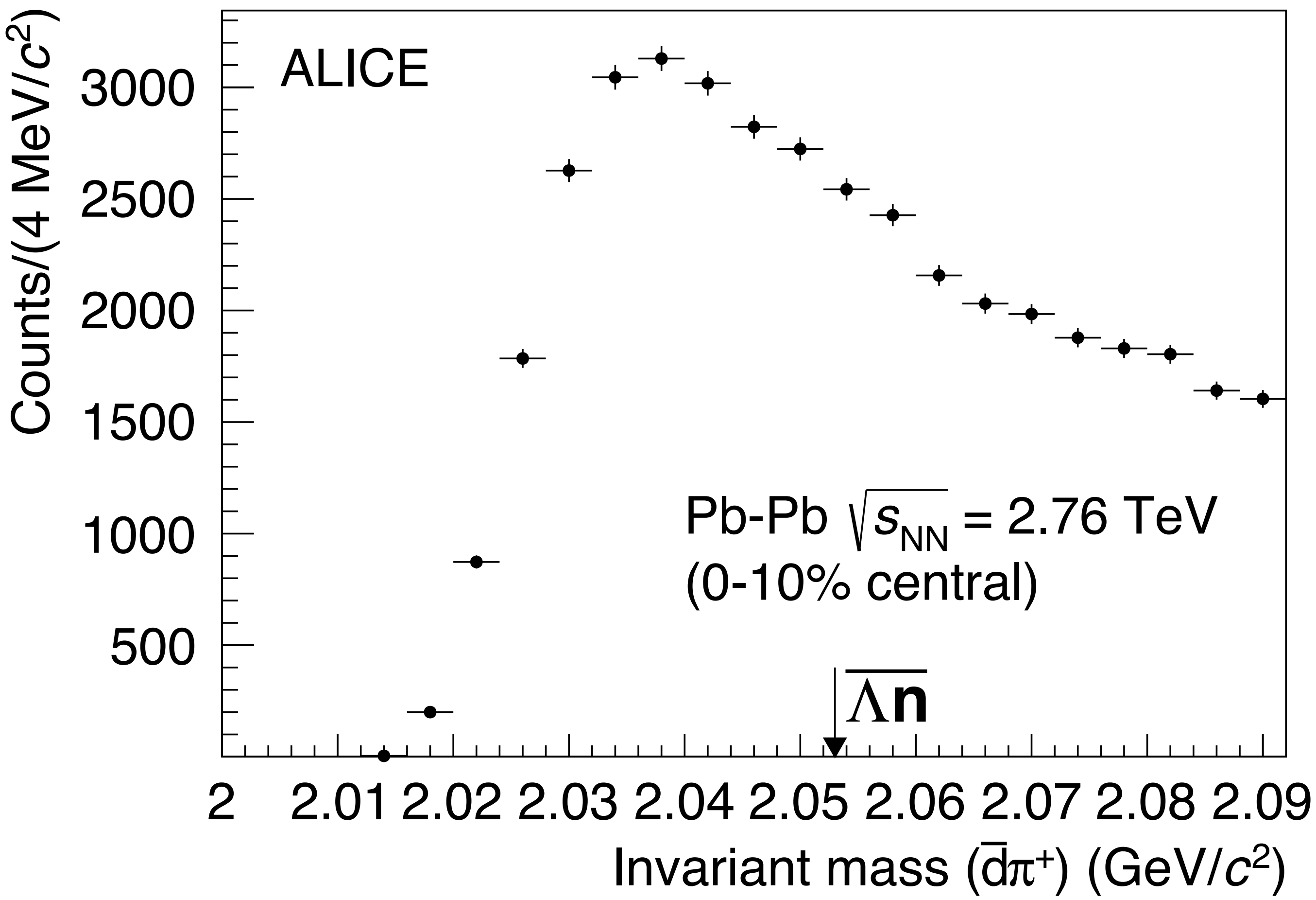
- ΛΛ (H-dibaryon):
  - predicted by Jaffe in bag model calculations
    R. L. Jaffe, PRL 38, 195 (1977)
  - lattice calculations suggest a lightly bound state or resonance close to Ξp threshold
    T. Inoue et al., PRL 106, 162001 (2011) and S. R. Beane et al., PRL 106, 162002 (2011)
  - **Predicted yield:** 211 - 2110 (in 14M events)
- Λn-bar bound state
  - **Predicted yield:** ~4000 (in 14M events)

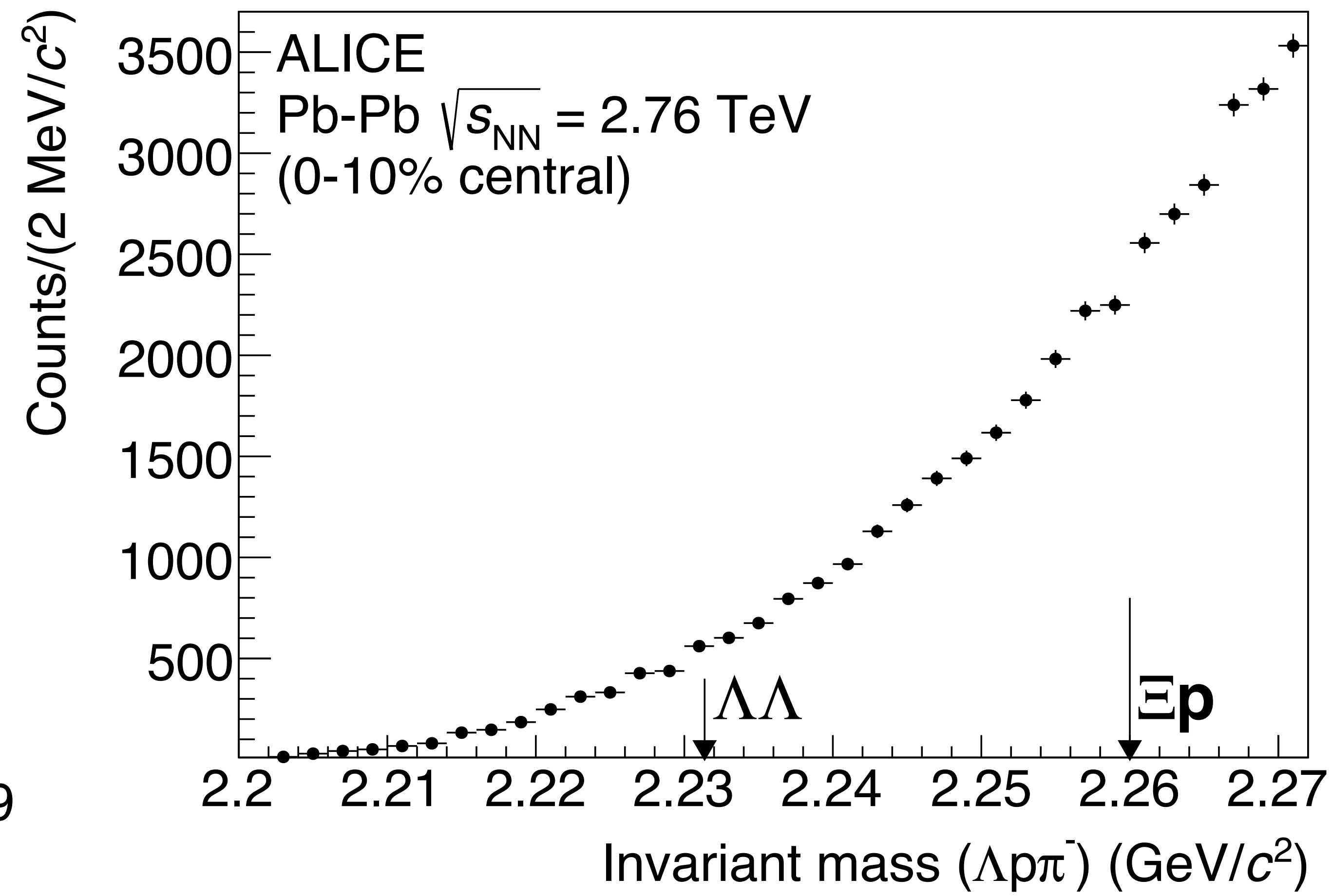
Both ΛΛ and Λn-bar should be measurable with the statistics available in ALICE according to the thermal models predictions.

Invariant mass spectra for ΛΛ and Λn-bar

ALICE Coll. arXiv:1506.07499 [nucl-ex]

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

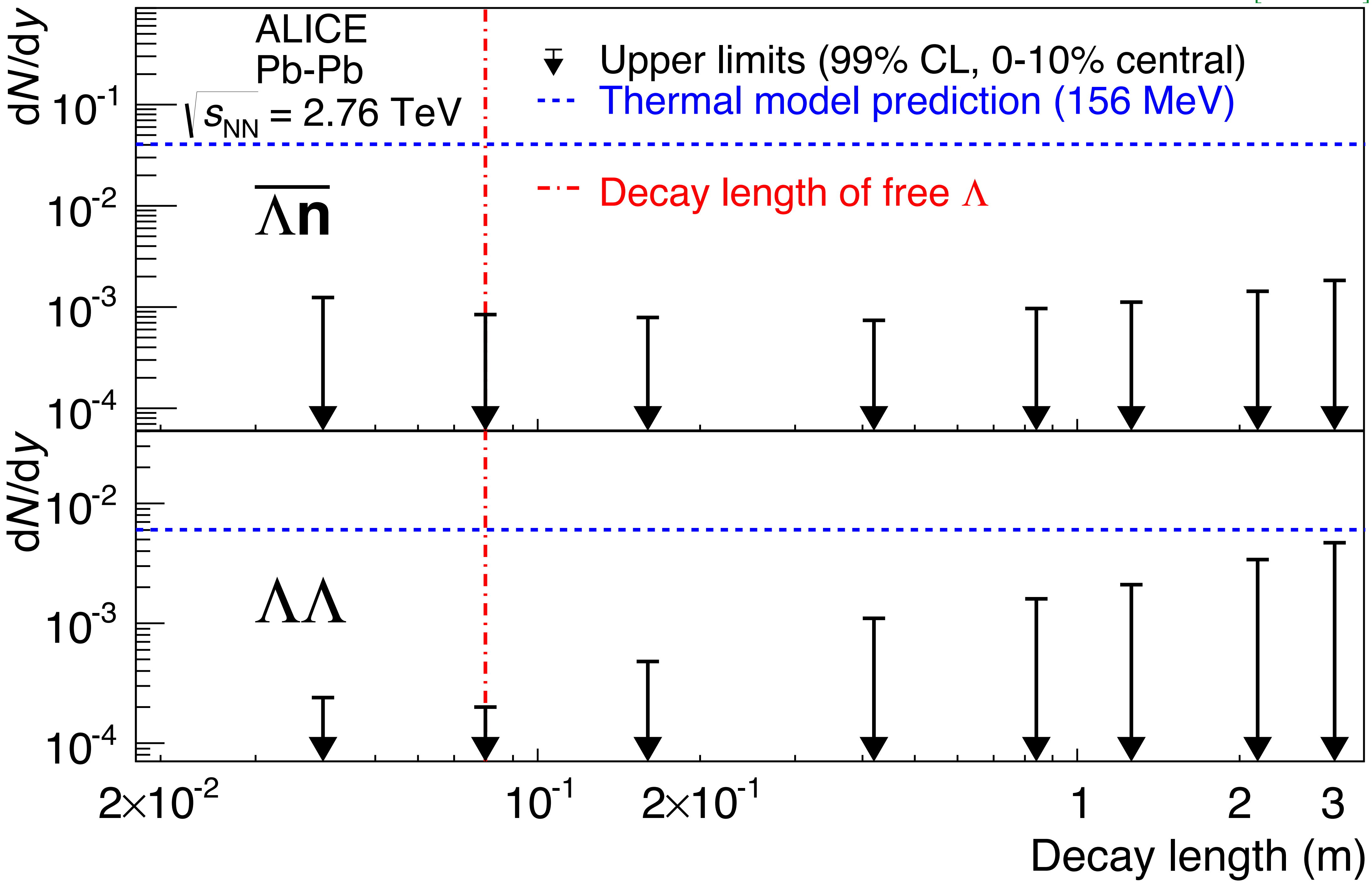




No signal visible in the invariant mass spectra. From the non-observation it is possible to compute the upper limits for the production rates.

Upper limits

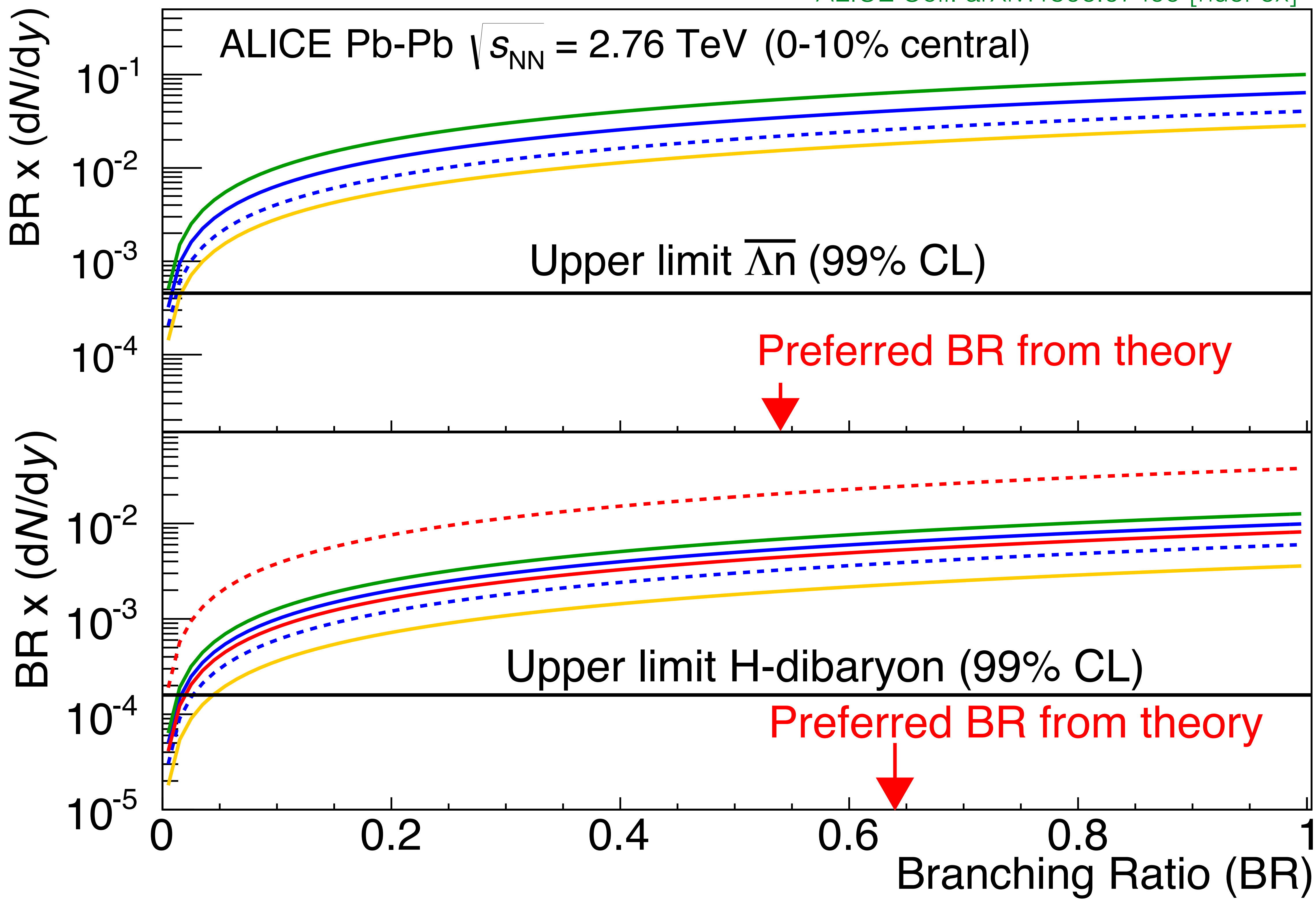
ALICE Coll. arXiv:1506.07499 [nucl-ex]



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.

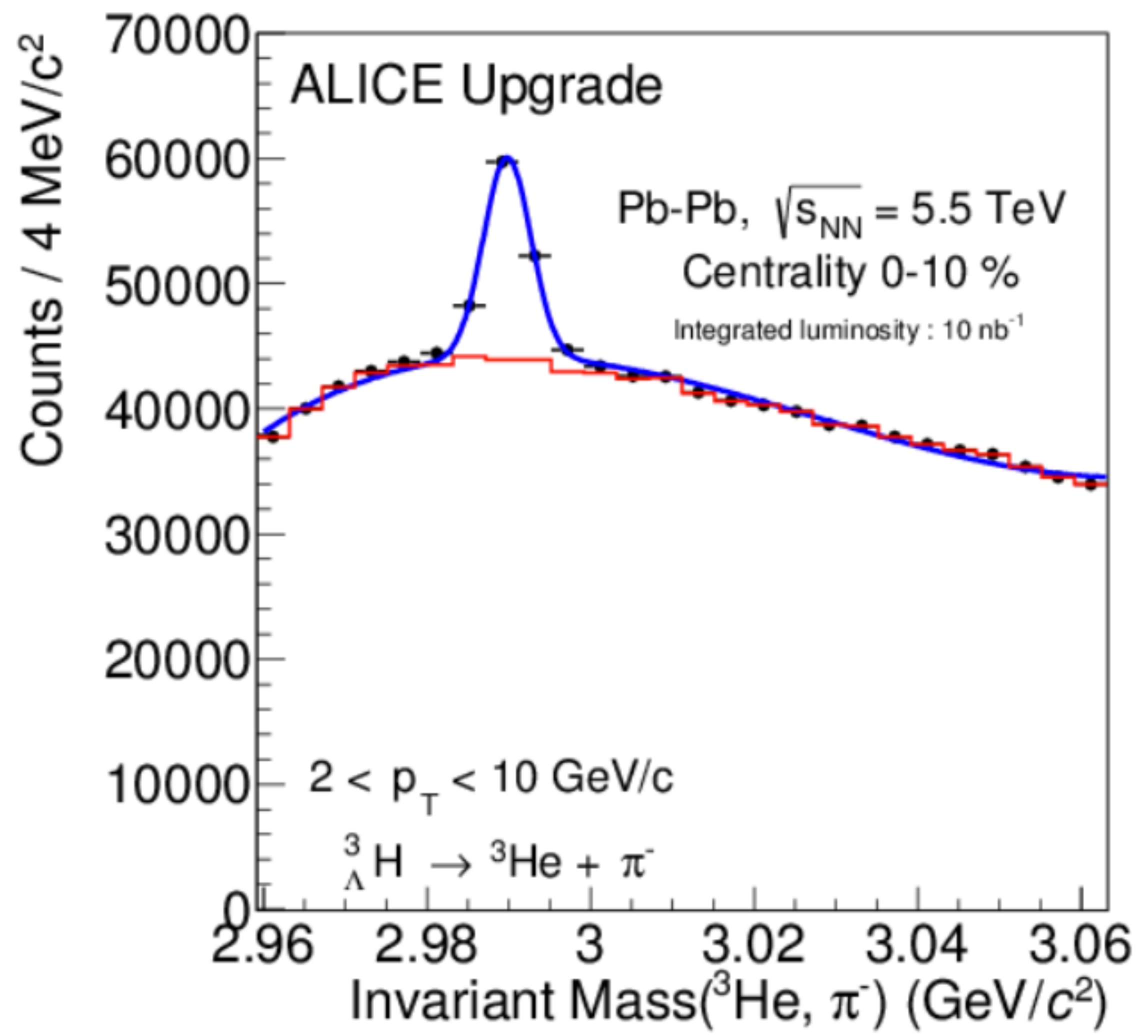
Upper limits to ΛΛ and Λn-bar production

ALICE Coll. arXiv:1506.07499 [nucl-ex]



ALICE Upgrade

- 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 Coll. J. Phys. G 41 (2014)

Numbers for L_{int} = 10 nb^{-1}

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