Precision measurement of the mass difference between light nuclei and anti-nuclei with ALICE at the LHC

Francesco Noferini*

on behalf of the ALICE collaboration

* INFN Bologna and CNAF, E. Fermi Centre

14/07/2015

Outline

- CPT, anti-matter discovery and CPT tests
- Details about the ALICE analysis
- ALICE results
- Conclusions

More details in ALICE-PUBLIC-2015-002
https://cds.cern.ch/record/2033777

Matter and anti-matter

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0$$

The existence of anti-particle was predicted by Dirac (1928) with the discovery of the equation describing ½-spin particles.

Few years later (1932) Anderson discovered the positron opening the field to a new class of particles.

However, the existence of anti-matter has additional requirements with respect to anti-particles: the interaction has to be symmetric for particle and anti-particle → the existence of a fundamental symmetry in nature (C, P, T, CPT).

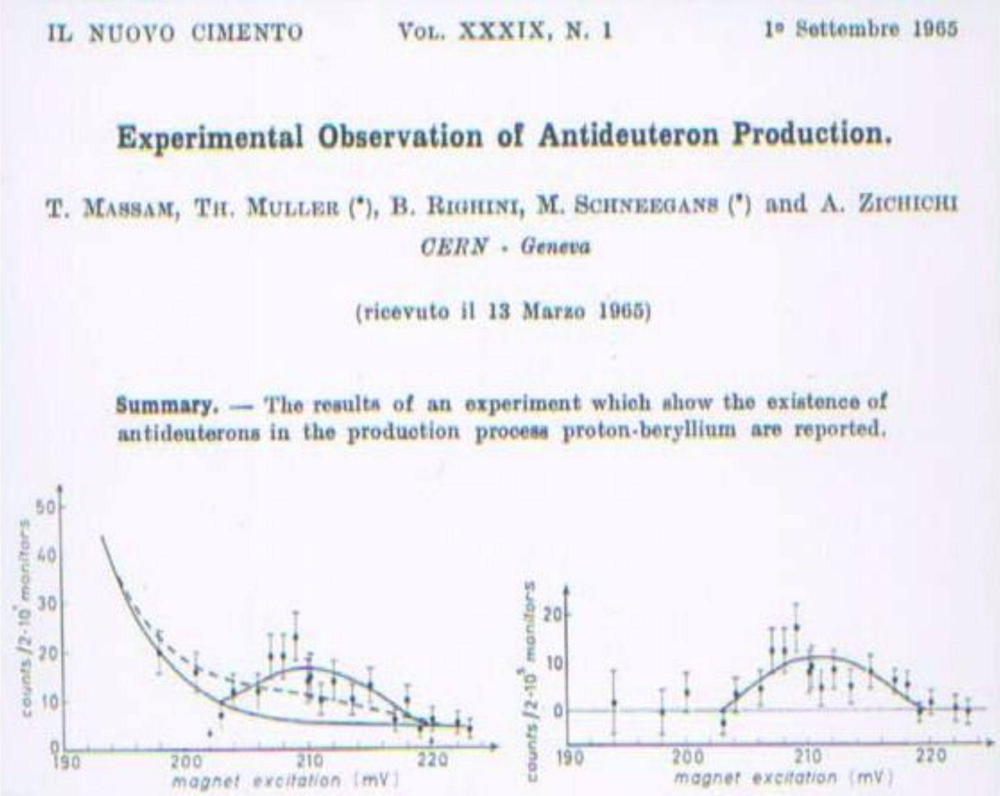
The fundamental symmetry: CPT

Lee and Yang proposed for the first time the P-violation which was experimentally discovered by C.S. Wu in 1956.

The study of the Neutral Kaon decay in 1964 (Cronin and Fitch) showed a violation of CP (and consequently of T)
→ the only remaining symmetry which is able to guarantee the existence of anti-matter is CPT.

The CPT theorem (Lueders and Pauli, 1954 and 1955) demonstrated that CPT symmetry is guaranteed in RQFT, once the Lorentz invariance and the locality of the interaction are requested.

Anti-nuclei discovery at CERN



IL NUOVO CIMENTO VOL. XXXIX, N. 1 1° Settembre 1965

Experimental Observation of Antideuteron Production.

T. MASSAM, TH. MULLER (*), B. RIGHINI, M. SCHNEEGANS (*) and A. ZICHICHI
CERN - Geneva

(ricevuto il 13 Marzo 1965)

Summary. — The results of an experiment which show the existence of antideuterons in the production process proton-beryllium are reported.

On March 1965 the group of A. Zichichi discovered the existence of an anti-nucleus state (anti-deuteron) at CERN, confirmed few months later by D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting (Phys. Rev. Lett 14 (1965) 1003)

At that time, such a measurement confirmed that anti-matter could exist as a bound state system (anti-nucleus) having the same properties of the ordinary matter, confirming the validity of the CPT symmetry expectation

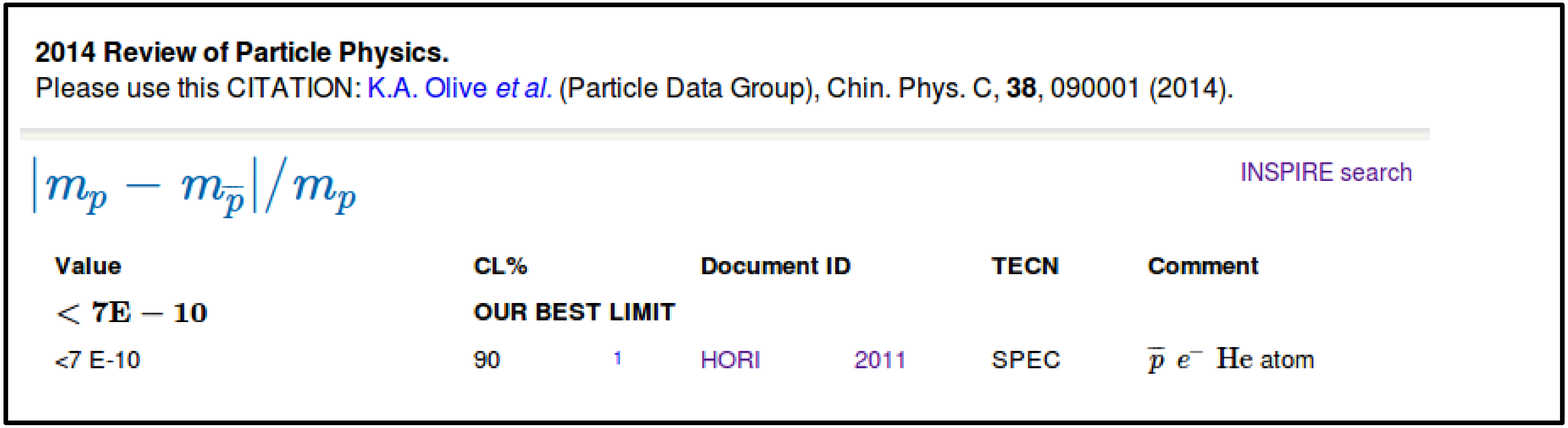
CPT violation is still under investigation

The CPT theorem is demonstrated in RQFT → At the Planck scale, close to the GUT scale where forces are supposed to be originated, the CPT symmetry is no longer guaranteed (string theory).

Experiments are still looking for a possible violation of CPT in several sectors, looking for differences in mass, width, charge (i.e. ALPHA experiment at CERN on the limit on the charge of the anti-hydrogen)

Theory: SM Extensions are developed to use the experimental limits to constrain, for different interactions, the parameters of effective field theories explicitly violating CPT (V.N. Kostelecky, N. Russel, Rev. Mod. Phys 83,11).

The best CPT limit for baryon/anti-baryon systems



2014 Review of Particle Physics.
Please use this CITATION: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

$\left| m_p - m_{\overline{p}} \right| / m_p$

INSPIRE search

Value	CL%	Document ID	TECN	Comment
$< 7\mathrm{E} - 10$	**OUR BEST LIMIT**			
<7 E-10	90	[1] HORI 2011	SPEC	$\overline{p}\ e^-$ He atom

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons (at the level of 7x10^{-10}).
Why do we need nuclei and anti-nuclei?

From (anti-)baryon to (anti-)nuclei

The extension of the measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses, a remnant of the underlying strong interaction among quarks and gluons not yet directly derived from quantum chromodynamics.

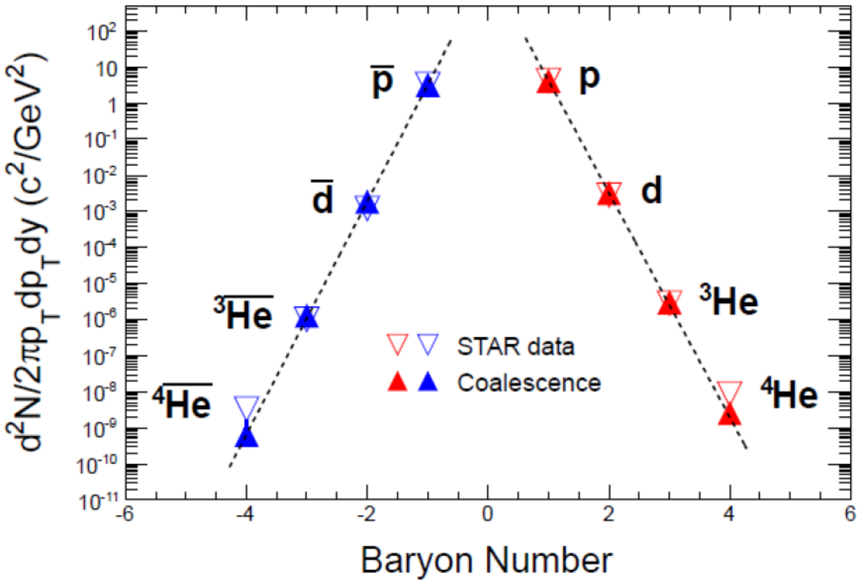
(anti-)baryons → (anti-)nuclei: binding energy ε_A

$$\boxed{m_A} = Zm_p + (A-Z)m_n - \boxed{\varepsilon_A}$$

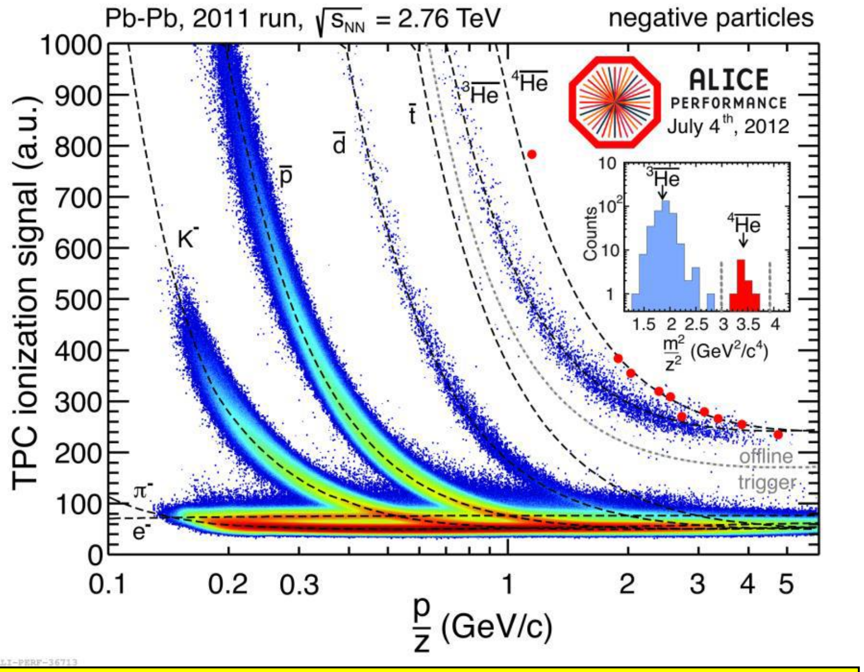
$$\boxed{m_{\overline{A}}} = Zm_{\overline{p}} + (A-Z)m_{\overline{n}} - \boxed{\varepsilon_{\overline{A}}}$$

Anti-alpha discovery

STAR Coll., *Nature 473 (2011) 353*



J. Phys. G: Nucl. Part. Phys. 38 (2011) 124073



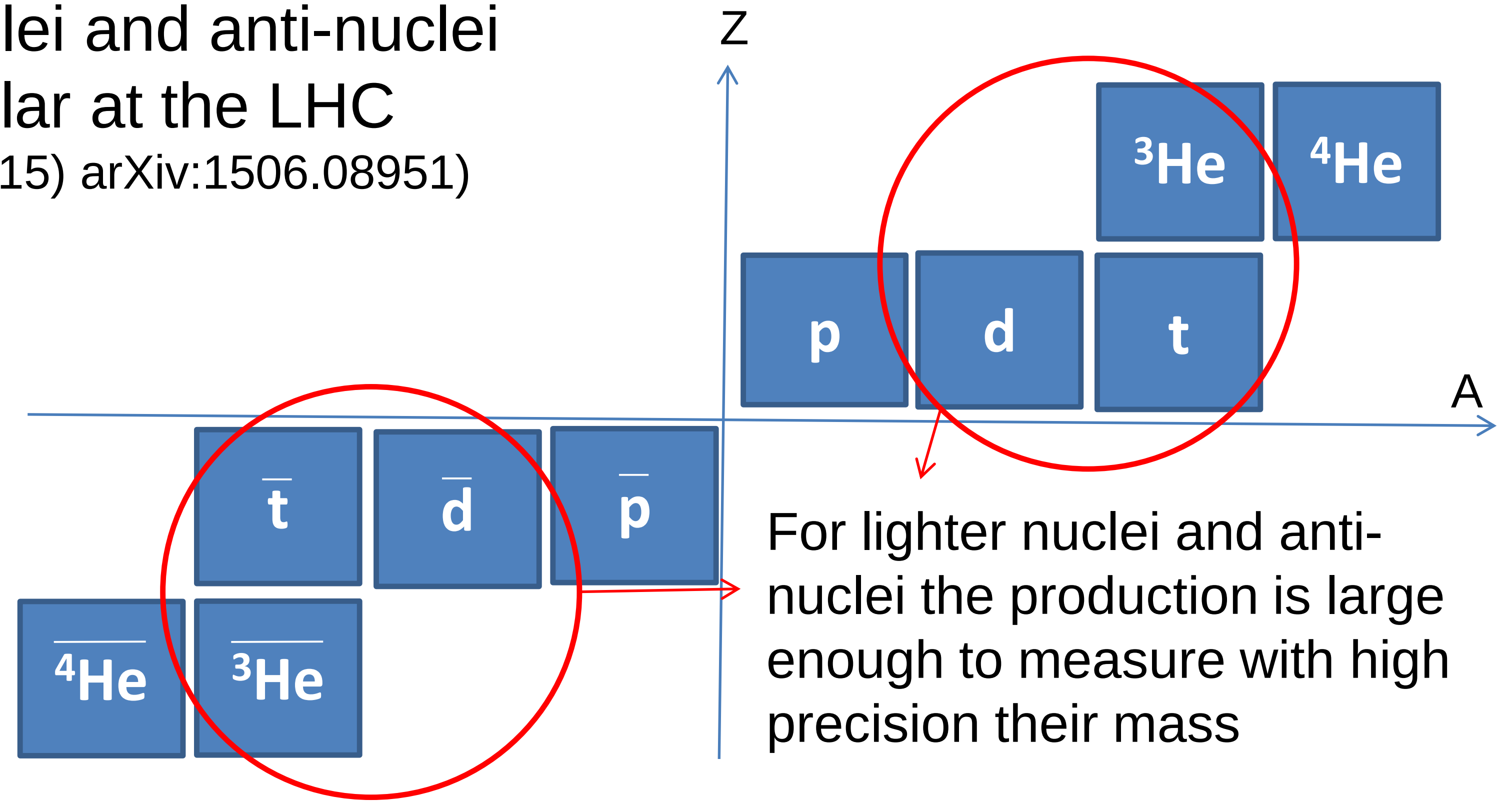
So far the heaviest anti-nucleus observed is the anti-alpha ($^4\overline{\text{He}}$). $^4\overline{\text{He}}$ was discovered for the first time by the STAR collaboration at RHIC and then observed also at the LHC by ALICE .

Anti-nuclei production in AA collisions

In high energy Pb-Pb collisions at the LHC a large amount of nuclei and anti-nuclei is produced.

Yields of nuclei and anti-nuclei are very similar at the LHC

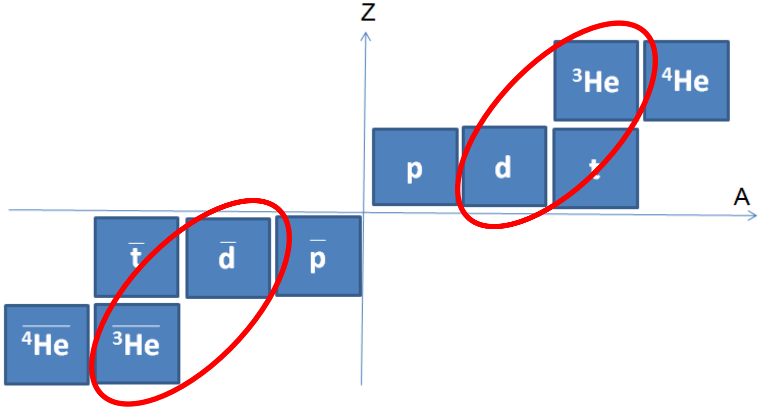
(ALICE Coll., (2015) arXiv:1506.08951)

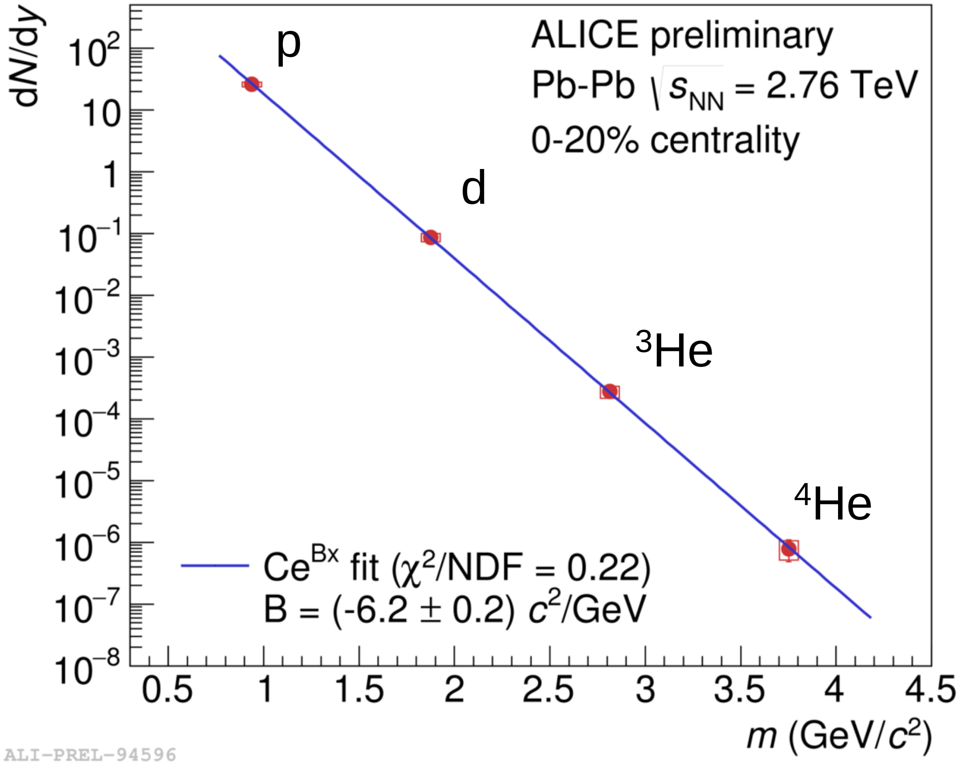


For lighter nuclei and anti-nuclei the production is large enough to measure with high precision their mass

Anti-nuclei production in AA collisions

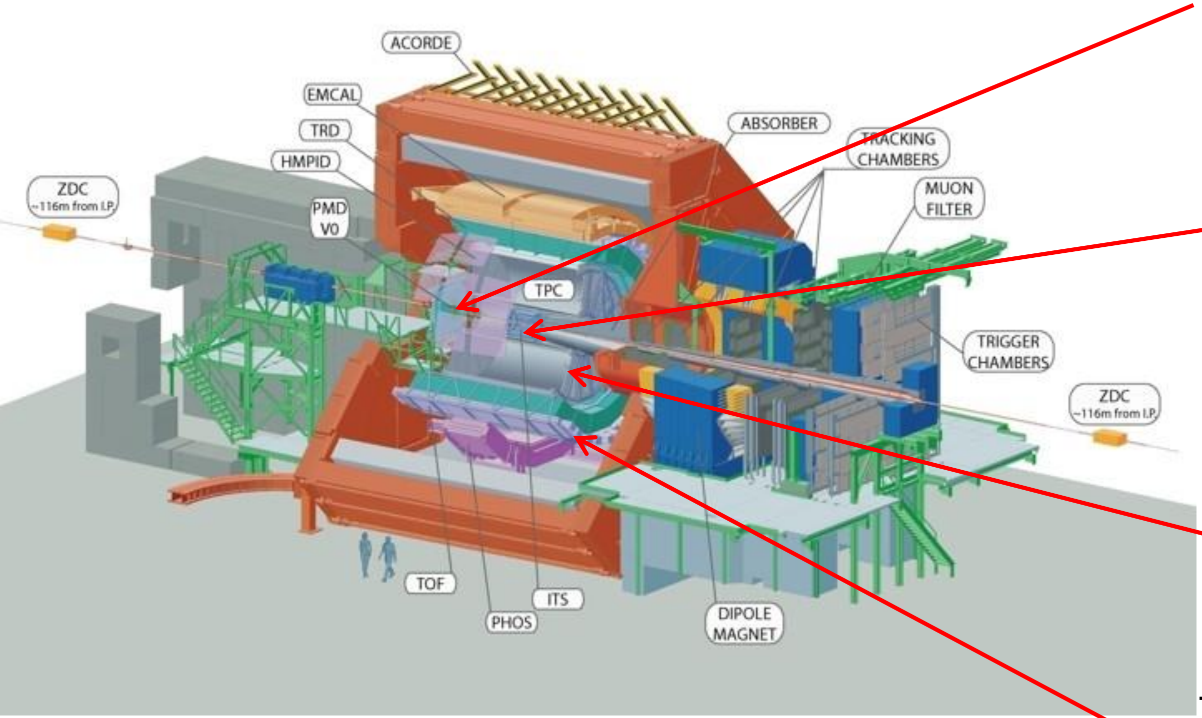
Double charged (anti-)nuclei (He and $\overline{\text{He}}$) are easier to be identified (see next slides)





The penalty factor, namely the reduction of the yield by adding one nucleon, is approximately 300 extracted by fitting the light nuclei yields.

Analysis details



VZERO detector
Two forward scintillator arrays
($-3.7<\eta<-1.7$, $2.8<\eta<5.1$):
Triggering and beam-gas rejection

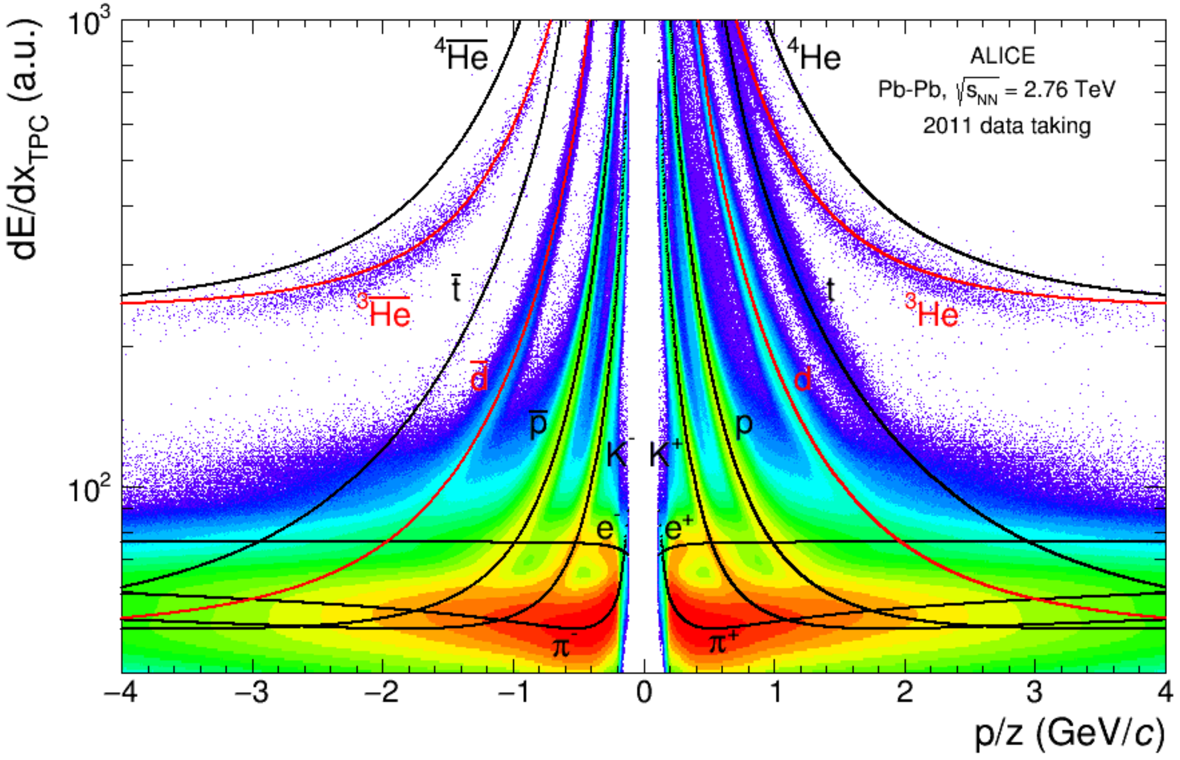
Inner Tracking System
(ITS)
($-0.8<\eta<0.8$)
Tracking + triggering

Time Projection Chamber
(TPC):
($-0.8<\eta<0.8$)
Tracking + particle identification(PID)

Time Of Flight (TOF):
($-0.8<\eta<0.8$)
Mass/Charge measurement

DATA sample:
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV **(2011 data, 67M events)**
Trigger selection: enriched in **central and semi-central collisions**, beam–gas interactions are rejected

Particle identification with the TPC

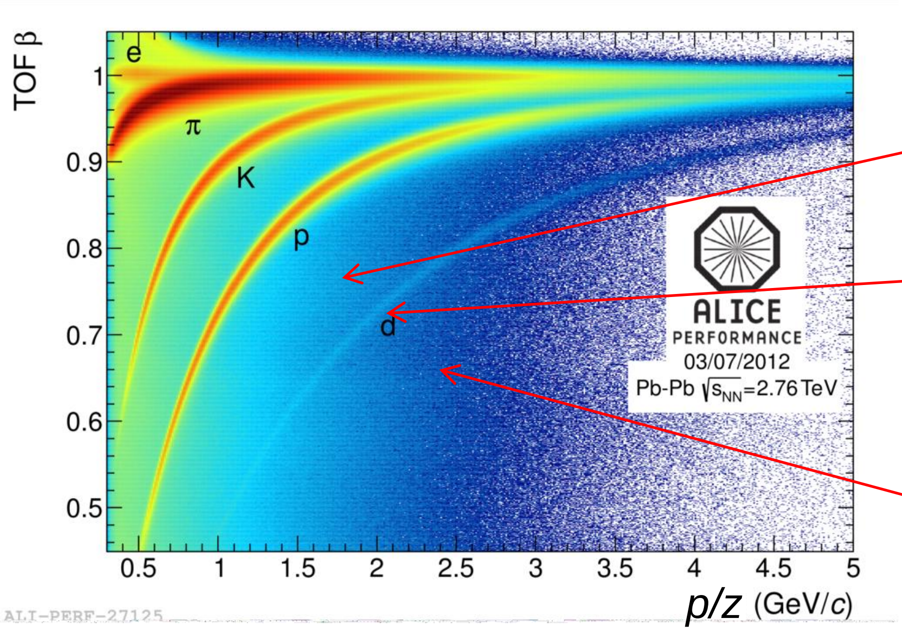


The TPC is able to identify (anti-)deuteron up to *p/z* ~ 2 GeV/*c.*

For the (anti-)He case the larger charge (*Z*=2) determines a larger energy loss (even in the MIP region) allowing to separate (anti-)He from hadrons in the full momentum region.

(anti-)^{3}He is a better candidate than (anti-)triton even if they have a similar mass → see also next slides.

Particle identification with the TOF



^{3}He is expected to be in the middle of p and d.

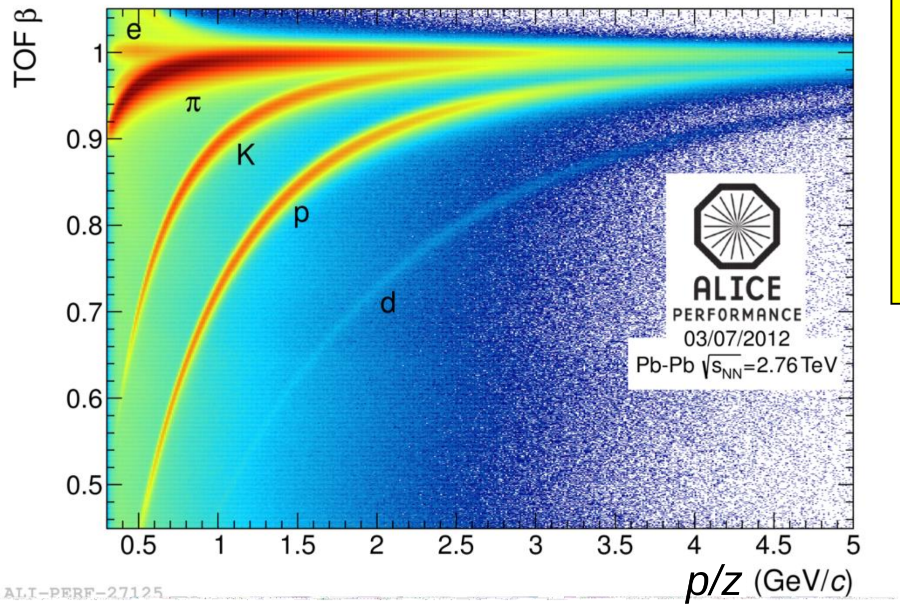
^{4}He is expected to reach the TOF at the same time as a deuteron (because of the same m/z ratio)

The background dominates in case of triton

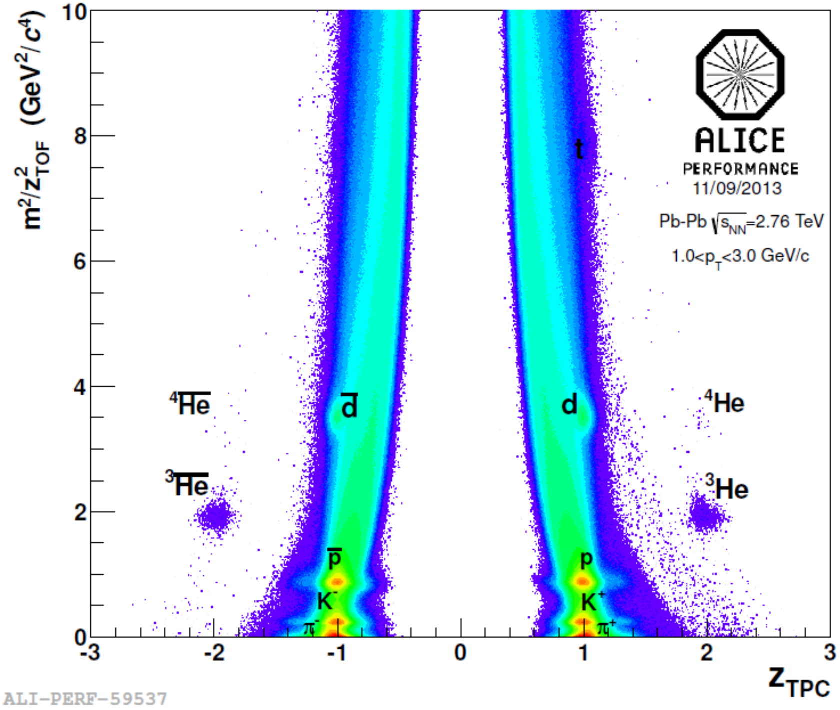
Light nuclei are well identified by TOF up to very high rigidities, thanks to a time resolution of 80 ps.

TPC track–TOF time mis-association is the bigger source of background (especially at low rigidities).

Particle identification with the TOF & TPC



By combining TPC and TOF information the background around the TOF (anti-)He bands is removed (thanks to Z=2)



$$\mu^2_{TOF} = \left(\frac{m}{z}\right)^2_{TOF} = \left(\frac{p}{z}\right)^2\left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

$$z^2_{TPC} = \frac{(dE/dx)_{TPC}}{(dE/dx)_{\mathrm{expected\ \ for\ \ m_{TOF},}\ \ z=1}}$$

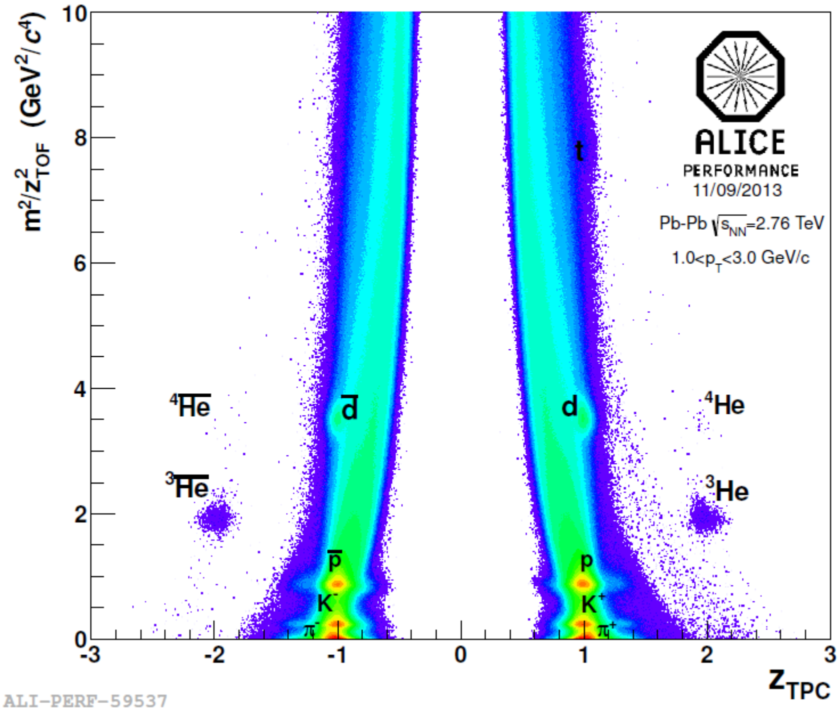
Particle identification with the TOF & TPC

$$\mu_{TOF}^2 = \left(\frac{m}{z}\right)_{TOF}^2 = \left(\frac{p}{z}\right)^2 \left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

$$z_{TPC}^2 = \frac{(dE/dx)_{TPC}}{(dE/dx)_{\text{expected for } m_{TOF},\ z=1}}$$

A cut on TPC signal within 2σ from the expected Bethe-Bloch value of the species under investigation is applied before fitting the TOF square mass distribution of light (anti-)nuclei.

A sample of about 10^6 anti-deuterons and 2000 $^3\overline{\text{He}}$ is selected by these cuts.



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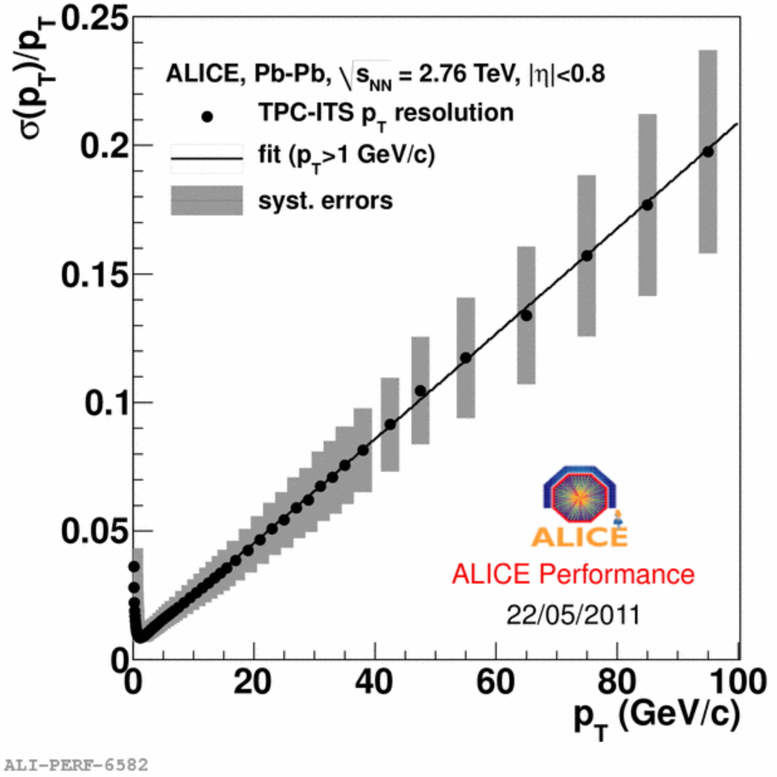
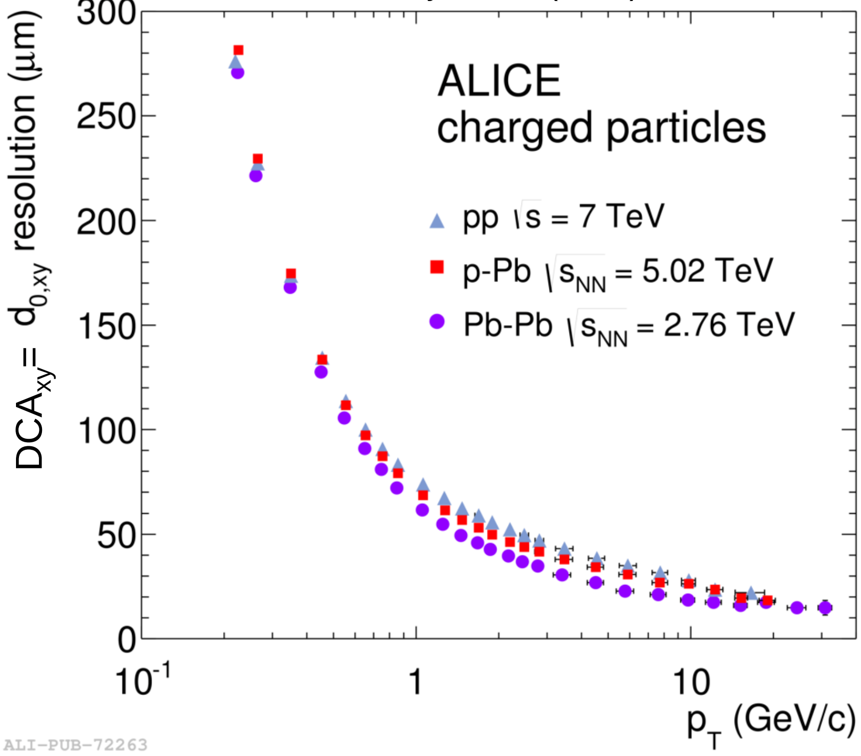
Tracking performance and track selection



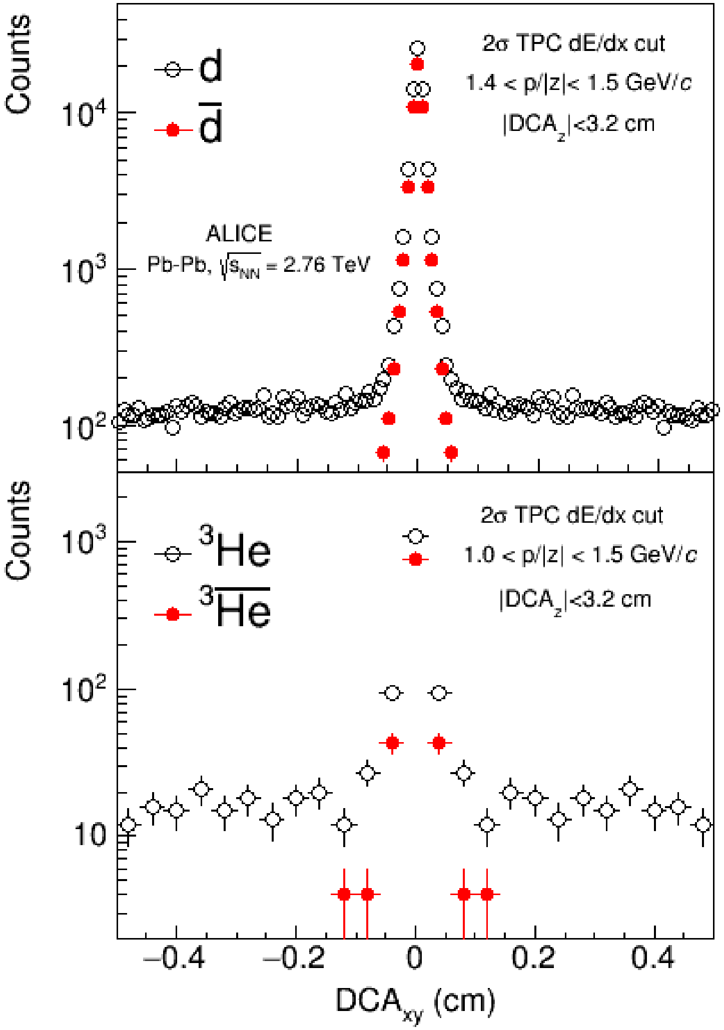
Int. J. Mod. Phys. A 29 (2014) 1430044



Tracks are selected requiring ITS-TPC standard cuts and a TOF time signal associated to the track.

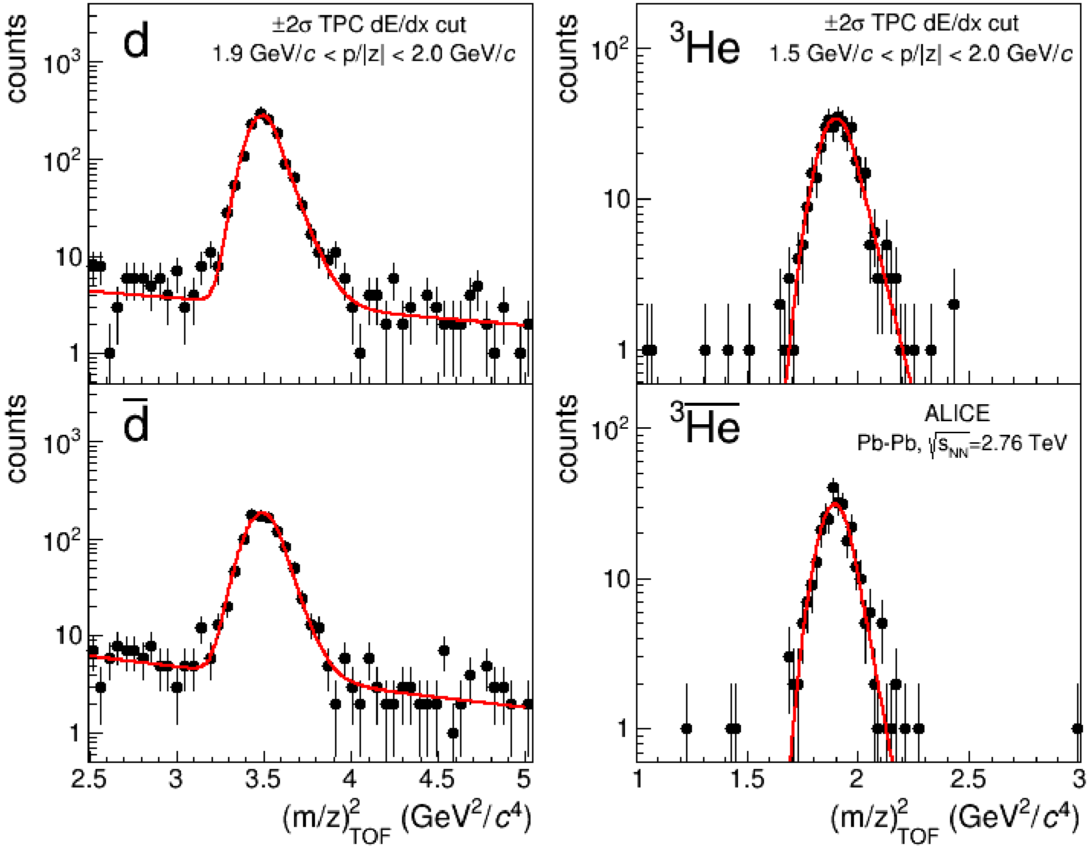
Additional cuts on the distance of closest approach (DCA) from the IP are applied to reject secondary particles

Secondaries rejection



Secondaries from material (only for nuclei) can be biased because they don't come from the the primary vertex.
A tight cut on DCA_{xy} was applied (< 1 mm) to reduce their influence.

Fit to square mass distribution



$$\mu^2_{TOF} = \left(\frac{m}{z}\right)^2_{TOF} = \left(\frac{p}{z}\right)^2\left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

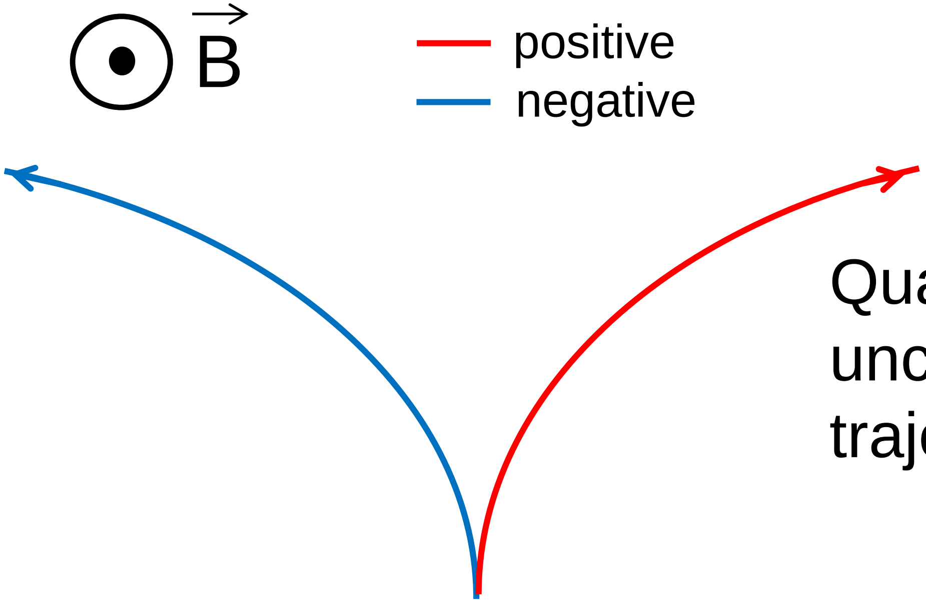
Fits were performed in rigidity (*p/z*) and pseudorapidity intervals.

The **fit function** used has two terms: **signal** + **background**

Signal = **Gaussian** distribution **with a small exponential tail** on the right to describe the **TOF time response**.

Background = **Exponential distribution** to fit residual background (in the deuteron case only)

Charge-dependent systematics



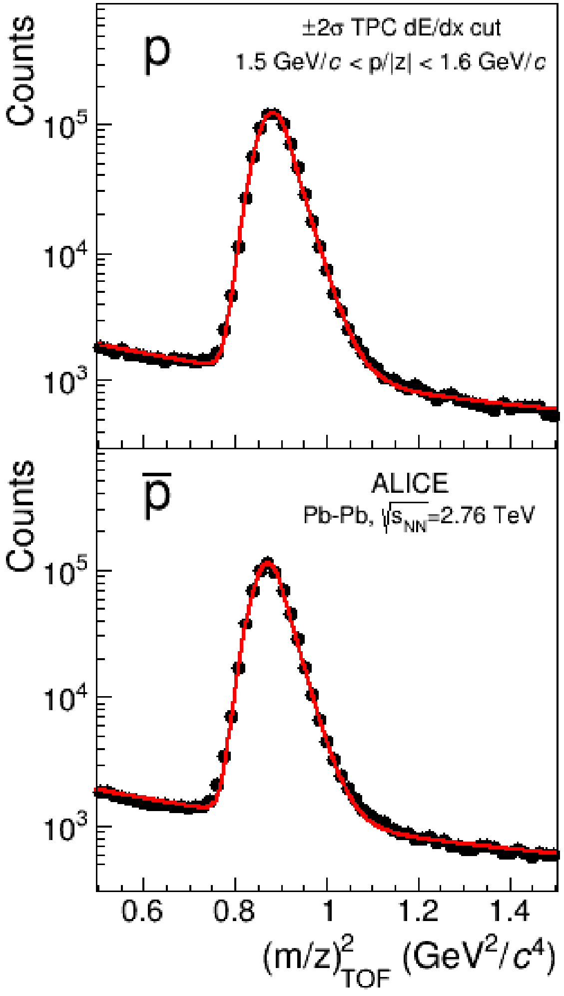
$$\mu_{TOF}^2 = \left(\frac{m}{z}\right)_{TOF}^2 = \left(\frac{p}{z}\right)^2\left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

Quantities sensitive to different uncertainties because of different trajectories.

Two ways to keep these systematics under control:

1. The main effect is mass independent and can be corrected for proton (+) and anti-proton (-) masses used as a reference.
2. The residual uncertainties can be estimated inverting the magnetic field (swapping positive/negative trajectories)

Correction using the (anti-)proton mass



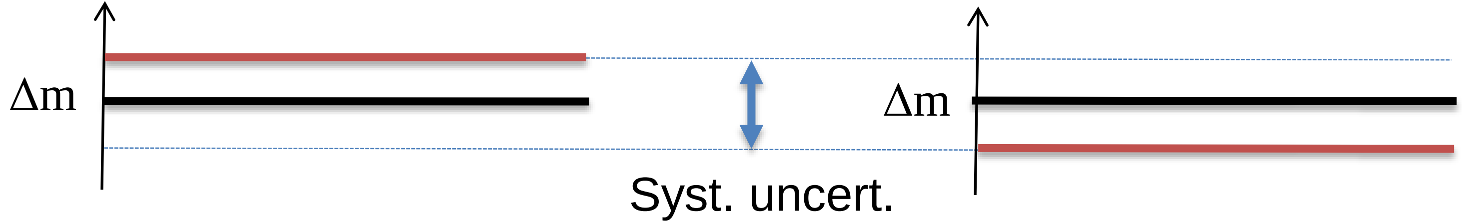
Protons and anti-protons mass distributions are fitted as well and used to correct for charge-dependent systematics assuming $m_p = m_{\bar{p}}$.

$$\mu_{A(\bar{A})} = \mu^{TOF}_{A(\bar{A})} \times \frac{\mu^{PDG}_{p(\bar{p})}}{\mu^{TOF}_{p(\bar{p})}}$$

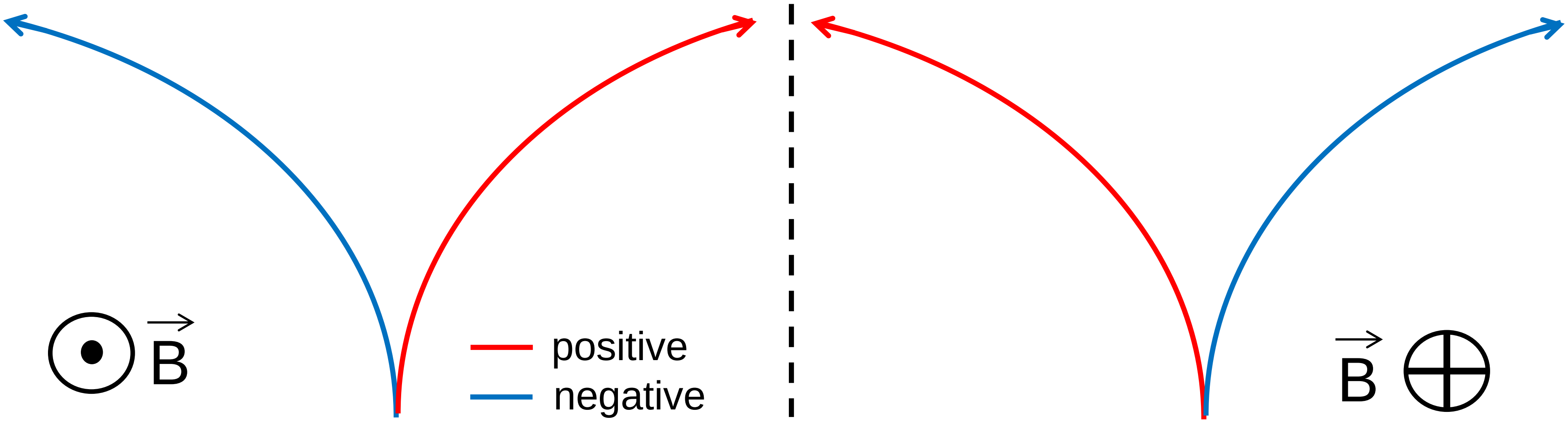
This variable allows to cancel all the contributions which are mass independent.

TOF → measured values
PDG → values provided by the Particle Data Group

The magnetic field configurations



Upon inversion of the magnetic field the residual effects due to mis-alignments and mis-calibrations are inverted.
The average in the two configurations is taken as the final result and the difference is used to give a systematic uncertainty.



Other checks/sources of systematic uncertainties

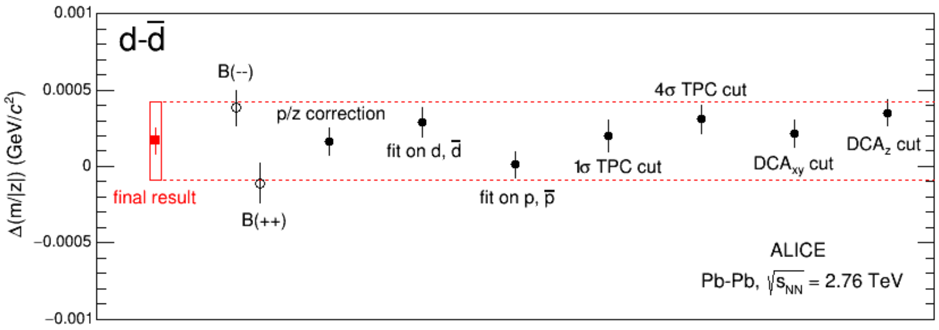
- The rigidity entering the mass formula is a **mean rigidity** (due to energy losses during the propagation). A parameterization from MC was used to derive it from the rigidity at the IP. The measurement was repeated with and w/o such a correction.

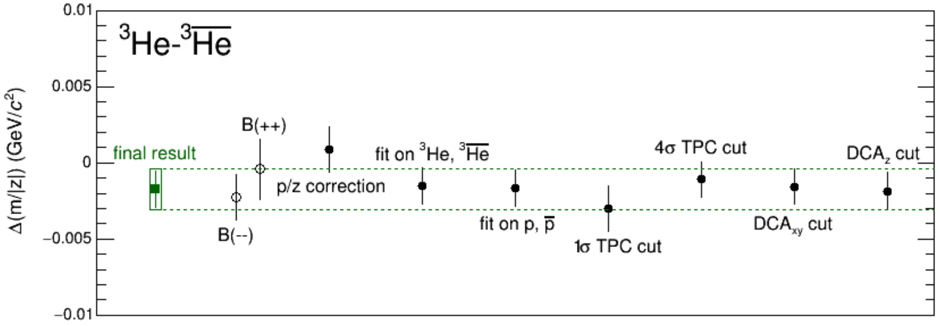
- **Fit procedure**: the assumptions on the fit function and the range of the fit were varied.

- **TPC dE/dx selection**: other cuts (tighter or looser: from 1σ to 4σ) were tested.

- Sensitivity to the **DCA cuts** (contamination from **secondaries**): a tight cut on the DCA_{xy} from the IP (< 1 mm) is applied. The cut is varied to estimate its influence on the final measurement.

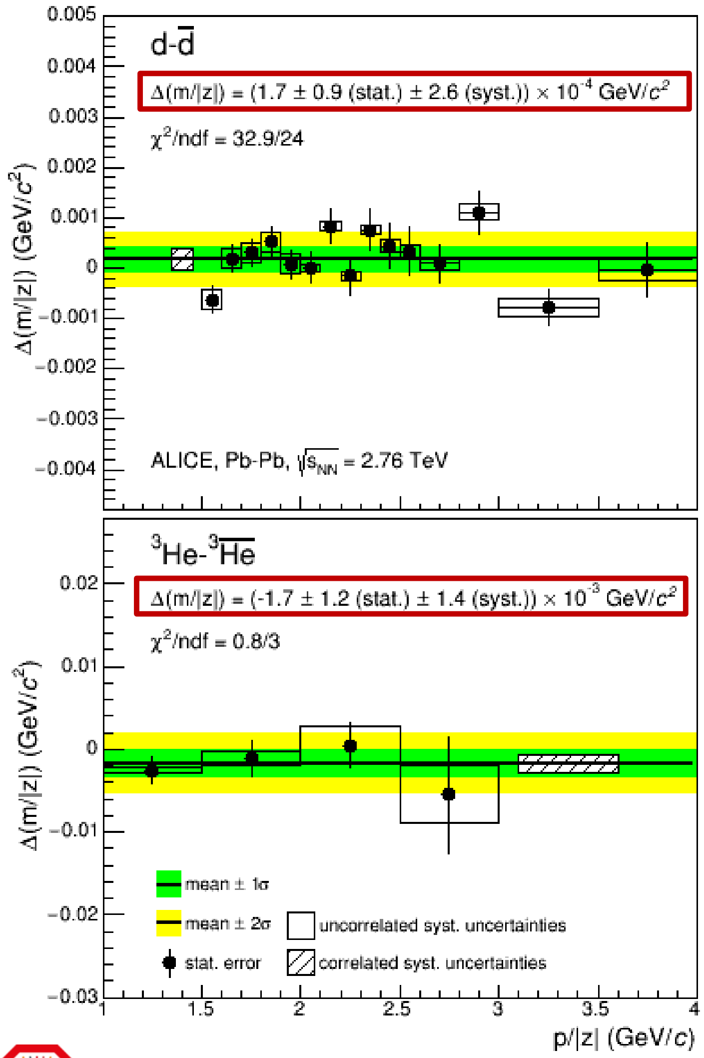
Summary of systematic uncertainties





Systematic uncertainty	$\Delta\mu_{d\bar{d}}/\mu_{d}$ $(\times 10^{-4})$		$\Delta\mu_{^3\mathrm{He}^3\overline{\mathrm{He}}}/\mu_{^3\mathrm{He}}$ $(\times 10^{-3})$	
$p/\vert z\vert$	1.5 GeV/c	4.0 GeV/c	1.0 GeV/c	3.0 GeV/c
Tracking and alignment	± 0.7		negligible	
Mean rigidity correction	negligible		± 0.7	
Fit procedure	± 0.3	± 1	± 0.5	
TPC $\mathrm{d}E/\mathrm{d}x$ selection	± 0.7		± 0.4	± 2.5
Secondaries	± 1	± 0.2	± 0.1	

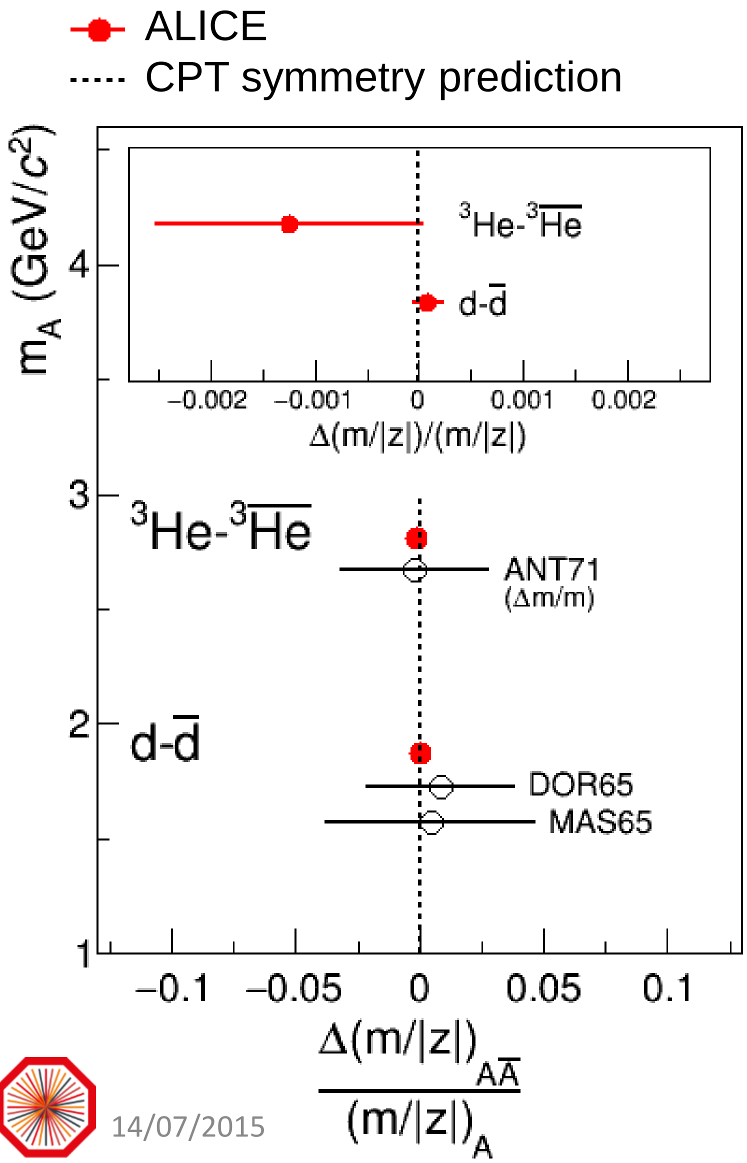
The ALICE measurement



d-$\bar{d}$ (top) and ^{3}He-$^{3}\overline{\text{He}}$ (bottom) mass-over-charge ratio difference measurements as a function of the particle rigidity.

The **final measurement** is obtained from a weighted average over all rigidity bins.

Result (I): mass differences



$$\frac{\Delta\mu}{\mu} = [0.9 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})] \times 10^{-4} \qquad \mathbf{d\text{-}\bar{d}}$$

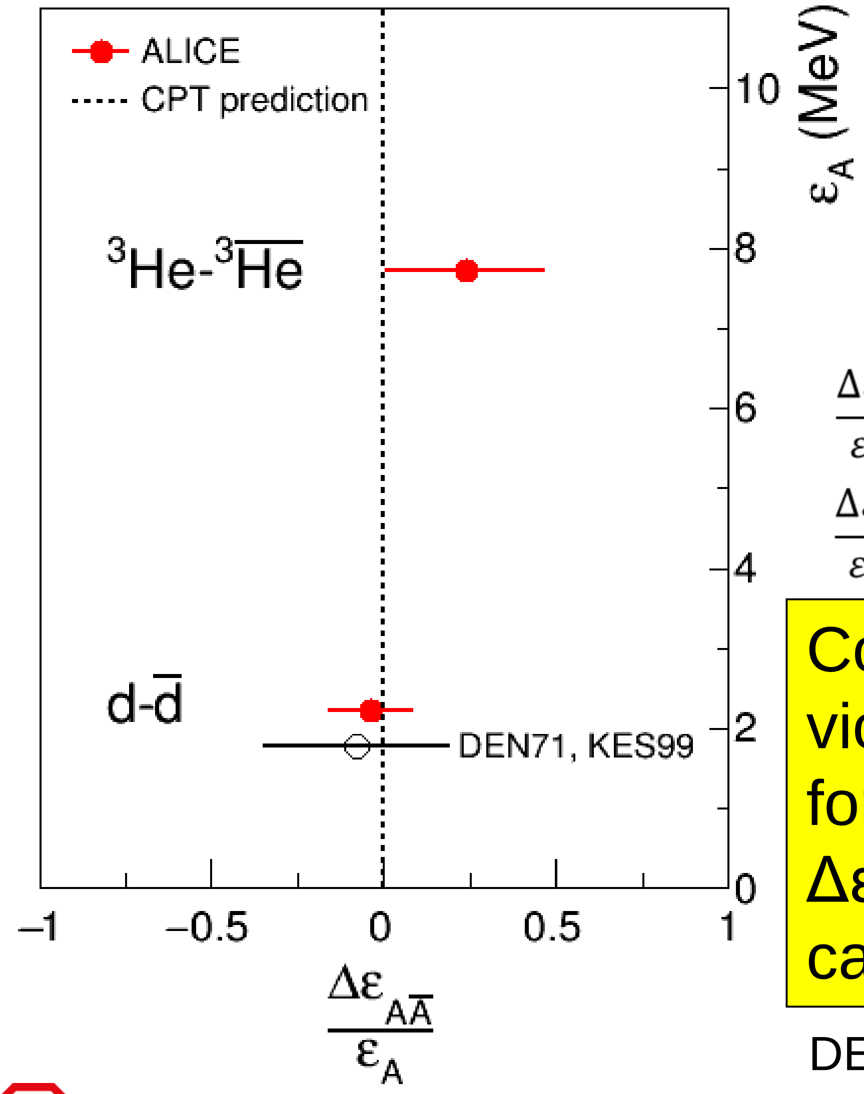
$$\frac{\Delta\mu}{\mu} = [-1.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.})] \times 10^{-3} \qquad \mathbf{{}^3He\text{-}{}^3\overline{He}}$$

Highest precision direct measurements of mass difference in the sector of nuclei

Improvement by one to two orders of magnitude compared to previous measurements obtained more than 40 years ago

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

Result (II): binding energy differences



$$\Delta\varepsilon_{A\bar{A}} = Z\Delta m_{p\bar{p}} + (A - Z)\Delta m_{n\bar{n}} - \Delta m_{A\bar{A}}$$

$$\Delta m_{p\bar{p}} < 7\times10^{-10}\,\mathrm{GeV}/c^2 \quad (\mathrm{CL} = 90\%)$$

Nature, 574 (2011) 484

$$\Delta m_{n\bar{n}} = \left(0.85 \pm 0.51(\mathrm{stat.}) \pm 0.29(\mathrm{syst.})\right)\times10^{-4}\,\mathrm{GeV}/c^2$$

Phys.Lett. B177 (1986) 206

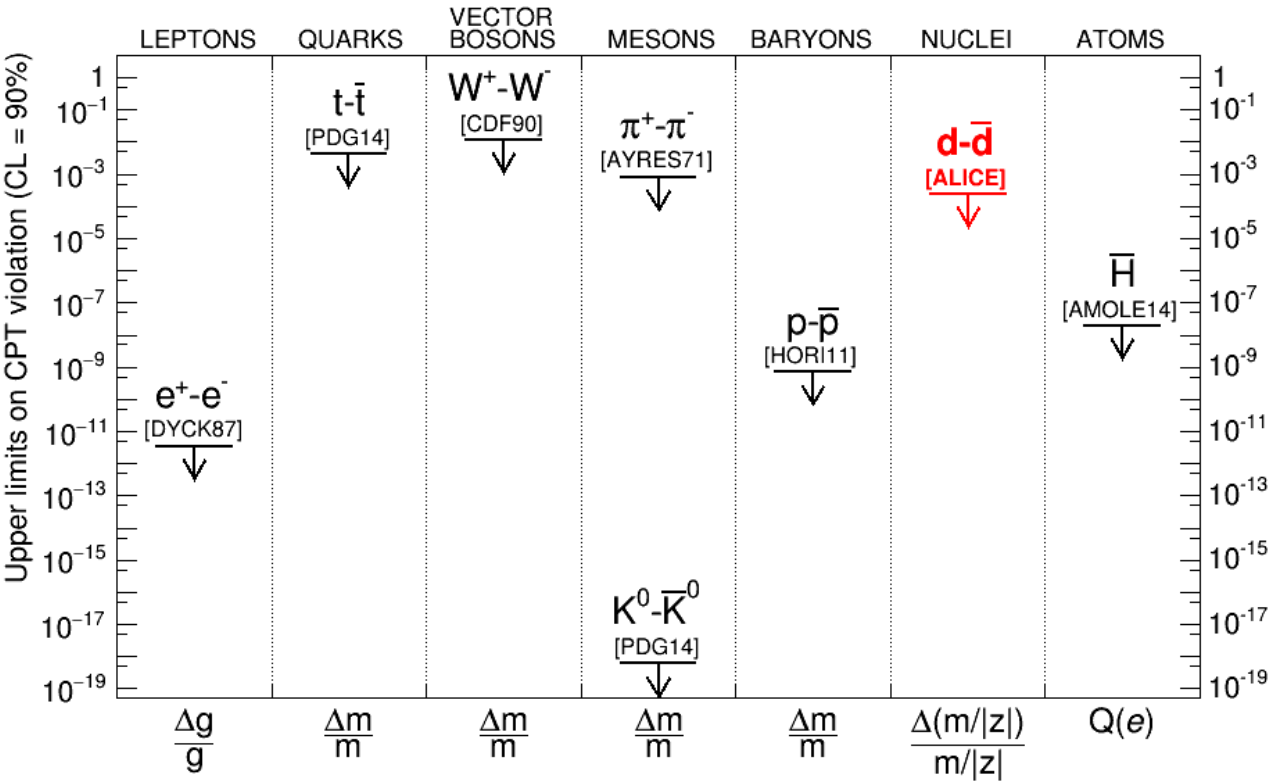
$$\frac{\Delta\varepsilon}{\varepsilon} = -0.04 \pm 0.05\ (\mathrm{stat.}) \pm 0.12\ (\mathrm{syst.}) \quad \mathbf{d\text{-}\bar{d}}$$

$$\frac{\Delta\varepsilon}{\varepsilon} = 0.24 \pm 0.16\ (\mathrm{stat.}) \pm 0.18\ (\mathrm{syst.}) \quad \mathbf{^3He\text{-}\,^3\overline{He}}$$

Constraint on CPT symmetry violation improved **by a factor two** for (anti-)deuteron case.
Δε determined for the first time in case of (anti-)^{3}He.

DEN71: Nucl. Phys. B31 (1971) 253
KES99: Phys.Lett. A255 (1999) 221

CPT invariance tests



Experimental limits are also used to constrain, for different interactions, CPT violating terms added to the SM Lagrangian in the Standard Model Extension (SME)

(Rev. Mod. Phys. 83 (2011) 11)

Conclusions

1. The abundant production rate of (anti-)nuclei in ultrarelativistic heavy-ion collisions combined with the unique **PID capability of the ALICE experiment** allows one to test the CPT invariance in nucleon-nucleon interactions.

2. The measurements of the difference of the mass-over-charge ratio between d and $\bar{d}$, and ^{3}He and $^{3}\overline{\text{He}}$ have been performed, improving by **one to two orders of magnitude** previous results obtained more than 40 years ago.

3. The results are also expressed in terms of binding energy differences. The value obtained for the (anti-)deuteron case improves by a **factor two** the constraints inferred by existing measurements. In the case of (anti-)^{3}He the binding energy difference has been determined for the first time, with a precision comparable to the (anti-)deuteron case.

Outlook

1. We are in touch with colleagues at the Indiana University Center for Spacetime Symmetries (IUCSS) to verify the **sensitivity of the SME parameters** to CPT invariance violation in the nuclei sector.
2. Remarkably, these improvements are reached in an experiment which is not specifically dedicated to CPT test and which will continue to take data in the next years, with an expected **increase in luminosity up to a factor 100**.

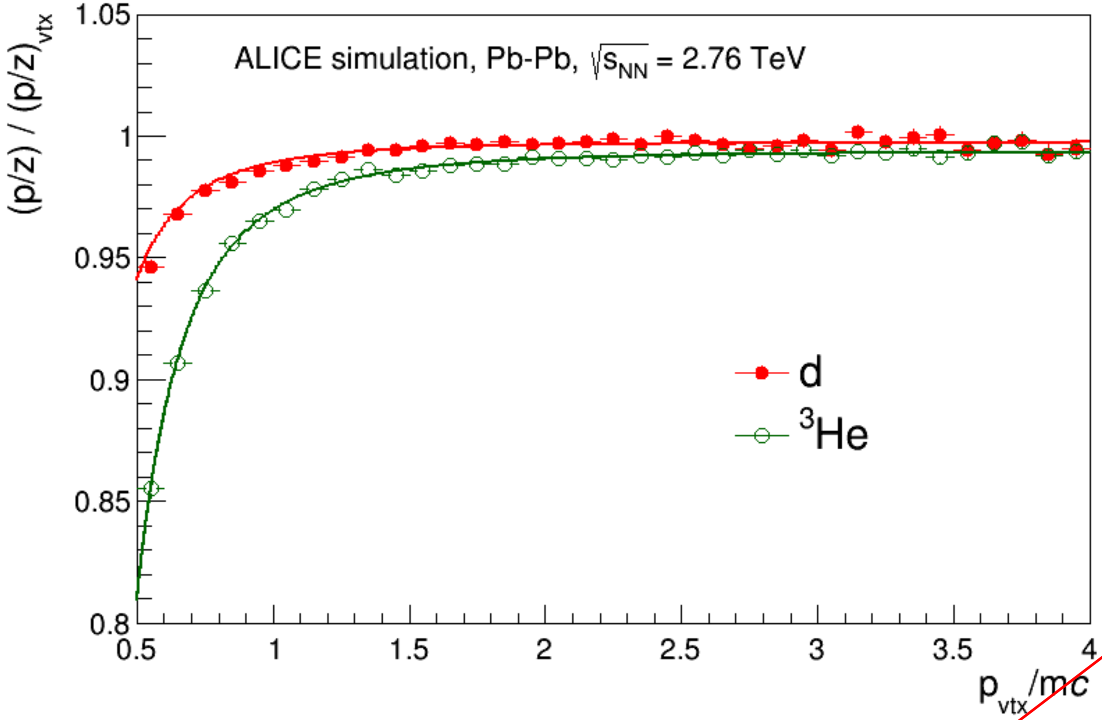
Thank you for your attention!

Backup

Precision measurement of the mass difference between light nuclei and anti-nuclei with ALICE at the LHC

Abstract: In ultrarelativistic heavy-ion collisions a large and equal amount of nuclei and anti-nuclei is produced in the central pseudorapidity region allowing for a precise investigation of their properties. Mass and binding energy are expected to be the same in nuclei and anti-nuclei as long as the CPT invariance holds for the nuclear force, a remnant of the underlying strong interaction between quarks and gluons. The measurements of the difference in mass-to-charge ratio between deuteron and anti-deuteron, and ^{3}He and $^{3}\overline{\text{He}}$ nuclei performed with the ALICE detector at the LHC is presented. The ALICE measurements improve by one to two orders of magnitude previous analogous direct measurements. Given the equivalence between mass and energy, the results improve by a factor two the constraints on CPT invariance inferred from measurements in the (anti-)deuteron system. The binding energy difference has been determined for the first time in the case of (anti-)^{3}He, with a precision comparable to the one obtained in the (anti-)deuteron system.

Mean rigidity parameterization



Due to energy loss the measured mass depends on the mean rigidity.
A MC parameterization was used to derive mean rigidity from the one measured at the interaction point .

$$\mu_{TOF}^2 = \left(\frac{m}{z}\right)_{TOF}^2 = \left(\frac{\langle p \rangle}{z}\right)^2 \left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

On the correction based on (anti-)proton mass

$$\mu_{TOF}^{2} = \left(\frac{m}{z}\right)_{TOF}^{2} = \left(\frac{p}{z}\right)^{2}\left[\left(\frac{t_{TOF}}{L}\right)^{2} - \frac{1}{c^{2}}\right]$$

$$\frac{1}{\mu}\frac{\partial\mu}{\partial p} = \frac{1}{p}$$

$$\frac{1}{\mu}\frac{\partial\mu}{\partial L} = \frac{1}{L}\gamma^{2}$$

$$\frac{\Delta\mu}{\mu} = \frac{\Delta p}{p}$$

$$\frac{\Delta\mu}{\mu} = \frac{\Delta L}{L}\gamma^{2}$$

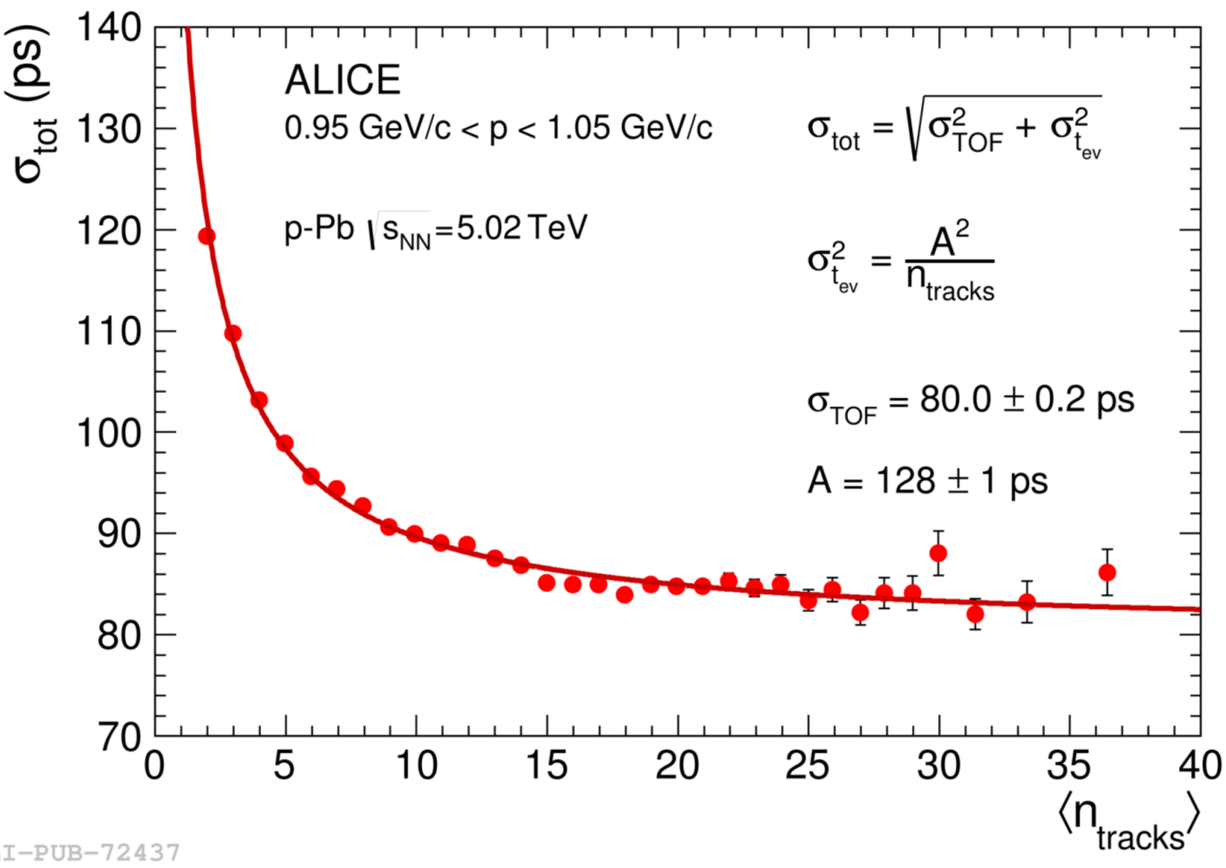
+ *L-p* correlation term

$$\boxed{\begin{aligned} &\frac{\Delta\mu}{\mu} = 0 \\ &\frac{\Delta\mu}{\mu} = \frac{\Delta L}{L}\left(\gamma_{A(\bar{A})}^{2} - \gamma_{p(\bar{p})}^{2}\right) \end{aligned}}$$

$$\mu_{A(\bar{A})} = \mu_{A(\bar{A})}^{TOF} \times \frac{\mu_{p(\bar{p})}^{PDG}}{\mu_{p(\bar{p})}^{TOF}}$$

The Start Time (t_{ev}) provided by TOF

Int. J. Mod. Phys. A 29 (2014) 1430044



In Pb-Pb collisions the start time is provided by TOF, while in p-p collisions the TZERO detector is also used.

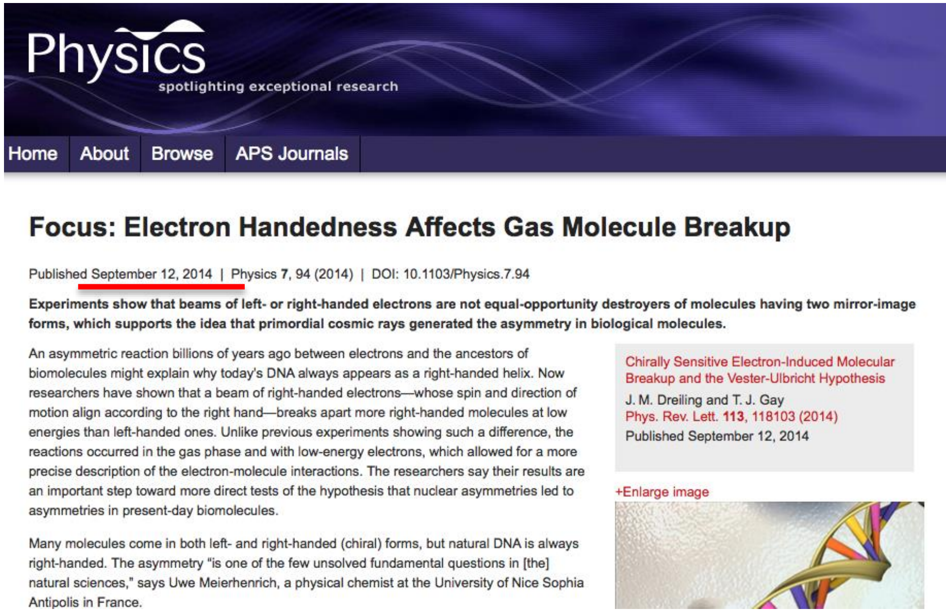
CPT invariance is confirmed with high precision for p–$\bar{p}$ system.
Why investigate light nuclei?

In light nuclei (“baryon molecules”) the nuclear force binding the nuclei is a remnant of QCD

Similarly in chemistry atoms within molecules are bound via forces derived from QED (P invariant). A big unresolved question in science is that bio-molecules in nature do have preferred chirality (DNA realized right-handed, etc.).
→ extremely active research field (origin of bio-homochirality). Weak interaction involved? How?

This analogy shows the importance of making CPT tests in different systems and in light nuclei in particular.

http://physics.aps.org/articles/v7/94



Focus: Electron Handedness Affects Gas Molecule Breakup

Published September 12, 2014 | Physics 7, 94 (2014) | DOI: 10.1103/Physics.7.94

Experiments show that beams of left- or right-handed electrons are not equal-opportunity destroyers of molecules having two mirror-image forms, which supports the idea that primordial cosmic rays generated the asymmetry in biological molecules.

An asymmetric reaction billions of years ago between electrons and the ancestors of biomolecules might explain why today's DNA always appears as a right-handed helix. Now researchers have shown that a beam of right-handed electrons—whose spin and direction of motion align according to the right hand—breaks apart more right-handed molecules at low energies than left-handed ones. Unlike previous experiments showing such a difference, the reactions occurred in the gas phase and with low-energy electrons, which allowed for a more precise description of the electron-molecule interactions. The researchers say their results are an important step toward more direct tests of the hypothesis that nuclear asymmetries led to asymmetries in present-day biomolecules.

Many molecules come in both left- and right-handed (chiral) forms, but natural DNA is always right-handed. The asymmetry "is one of the few unsolved fundamental questions in [the] natural sciences," says Uwe Meierhenrich, a physical chemist at the University of Nice Sophia Antipolis in France.

Chirally Sensitive Electron-Induced Molecular Breakup and the Vester-Ulbricht Hypothesis
J. M. Dreiling and T. J. Gay
Phys. Rev. Lett. **113**, 118103 (2014)
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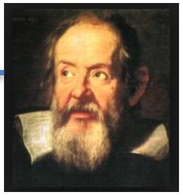
A. Salam, Chirality, phase transitions and their induction in amino acids, Phys Lett B. 288:153-160 (1992)
A. Salam, The role of chirality in the origin of life”, J.Mol.Evol. 33:105-113 (1991)



“But, irrespective of all these theoretical considerations, one has to follow the advice of Galileo and measure everything that can be measured.”
L. Okun (1996) discussing if it is worth to search for the particle-antiparticle mass differences in sectors others than K^0-$\bar{K}^0$ (arXiv:hep-ph/9612247)

ALICE