PRECISION MEASUREMENT OF THE MASS DIFFERENCE BETWEEN LIGHT NUCLEI AND ANTI-NUCLEI WITH ALICE AT THE LHC

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ALICE

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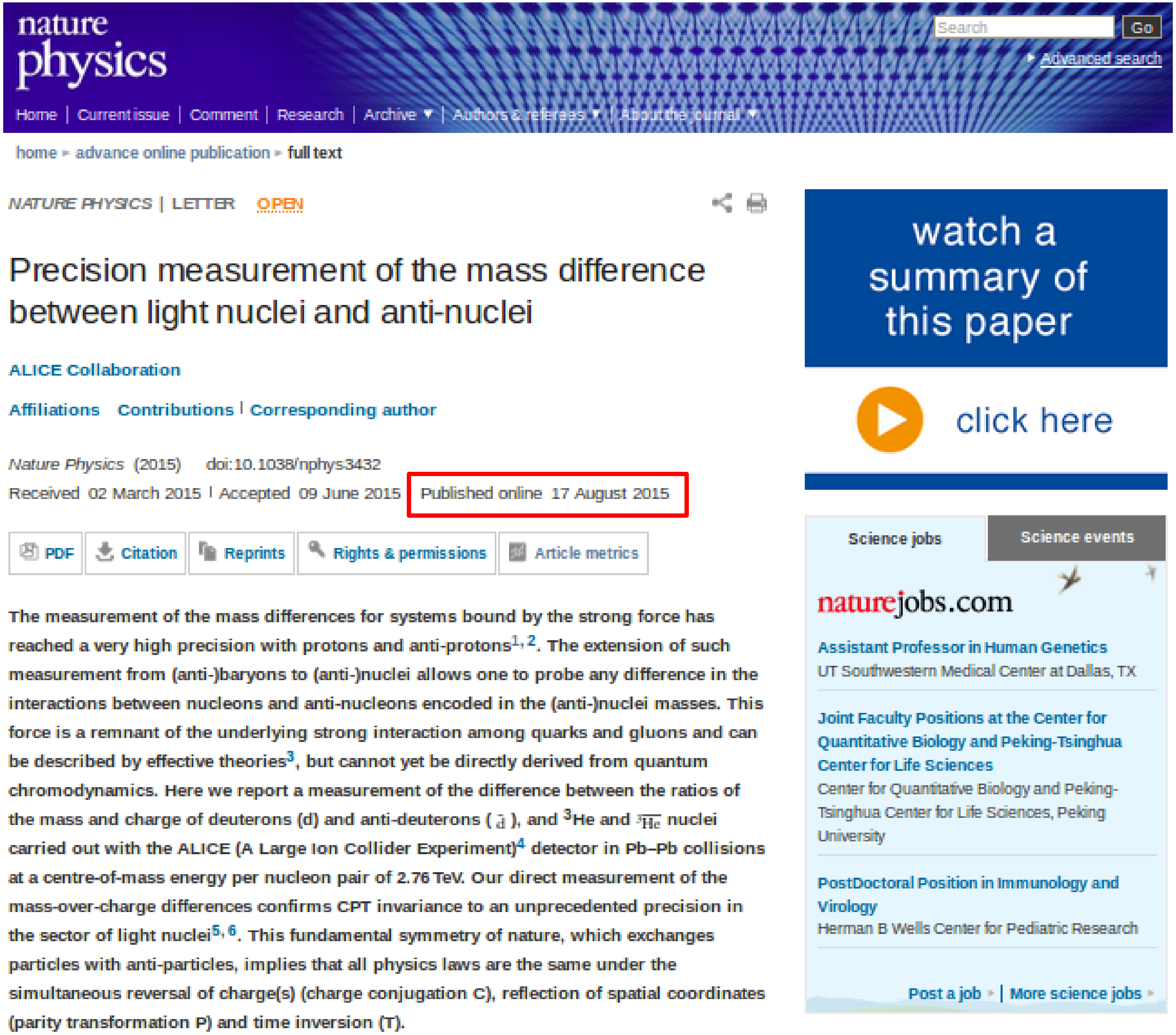

NATURE PHYSICS | LETTER OPEN

Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration

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The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons[1,2]. The extension of such 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. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories[3], but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\bar{d}$), and ^{3}He and $^3\overline{\mathrm{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)[4] detector in Pb–Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirms CPT invariance to an unprecedented precision in the sector of light nuclei[5,6]. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T).

Introduction

CPT invariance guaranteed within a QFT description of interactions* based on

① Lorentz invariance

② Locality of the interaction

J. Schwinger

W. Pauli

… but situation less clear combining the Standard Model with gravity. See e.g PRL 82 (1999) 11.

① **many efforts on experiments to detect any possible CPT violation** in various sectors looking for difference in fundamental properties of particles and antiparticles

② **SM Extension (SME) developed adding artificially CPT violating terms** to the SM Lagrangian constrained by experimental limits. See *Rev. Mod. Phys.* **83** (2011) 11

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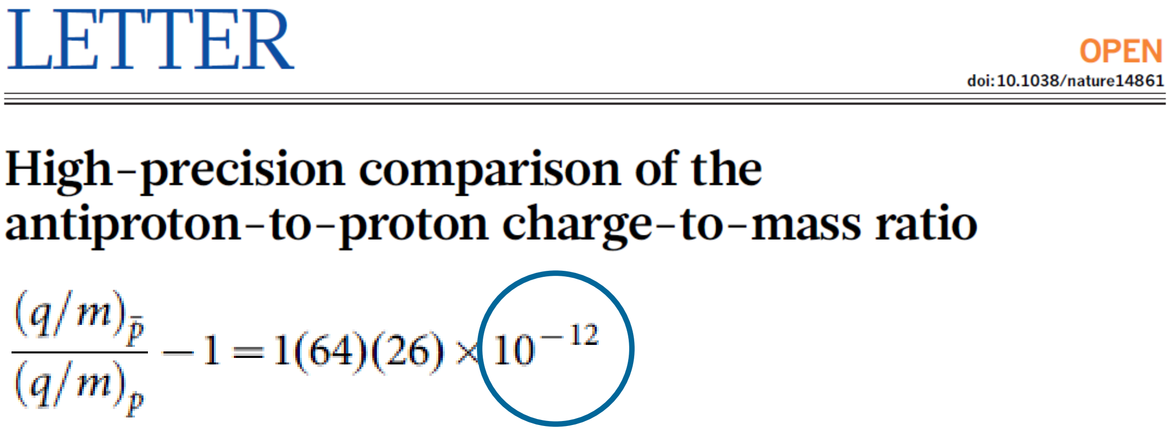
* J. Schwinger, *Phys. Rev.* **82** (1951) 914. G. Lüders, *Kong. Dan. Vid. Sel. Mat. Fys. Med.* **28N5** (1954) 1. W. Pauli in *Niels Bohr and the Development of Physics* (1955).

Introduction



LETTER

OPEN

doi:10.1038/nature14861

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = 1(64)(26) \times 10^{-12}$$

(anti-)baryons → (anti-)nuclei: **binding energy ε_{A}**

$$m_{\mathrm{A}} = Zm_{\mathrm{p}} + (A - Z)m_{\mathrm{N}} - \varepsilon_{\mathrm{A}}$$

$$m_{\bar{\mathrm{A}}} = Zm_{\bar{\mathrm{p}}} + (A - Z)m_{\bar{\mathrm{N}}} - \varepsilon_{\bar{\mathrm{A}}}$$

→ The extension of the measurement to (anti-)nuclei allows **to probe any asymmetry in the interactions between nucleons and anti-nucleons**, today described ***only by effective theories***

… but this requires a **factory of light nuclei and anti-nuclei: LHC!**

Introduction

In high energy **Pb-Pb collisions at LHC**

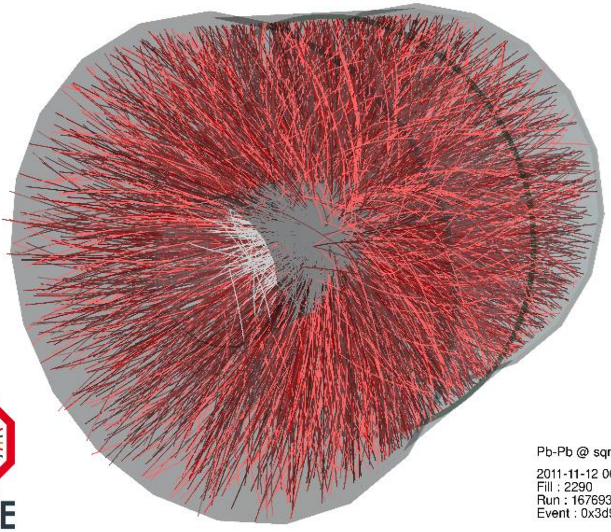
① large number of matter and anti-matter particles are produced: dN/dη~10^3 in central collisions

② high temperature (~156 MeV) and energy density (~1 GeV/fm^3) in the primary interaction

❖ **suitable environment for the production of nuclei and anti-nuclei**

❖ yield of nuclei and *corresponding* anti-nuclei are very similar at LHC energies
[ALICE Coll. arXiv : 1506.08951v1]

❖ $^4\overline{\mathrm{He}}$ is the heaviest anti-nucleus observed until today
[STAR Coll. *Nature* **473** (2011) 353]
[A. Kalweit (for the ALICE Coll.). *J. Phys. G: Nucl. Part. Phys.* **38** (2011) 124073]



Pb-Pb @ sqrt(s) = 2.76 ATeV
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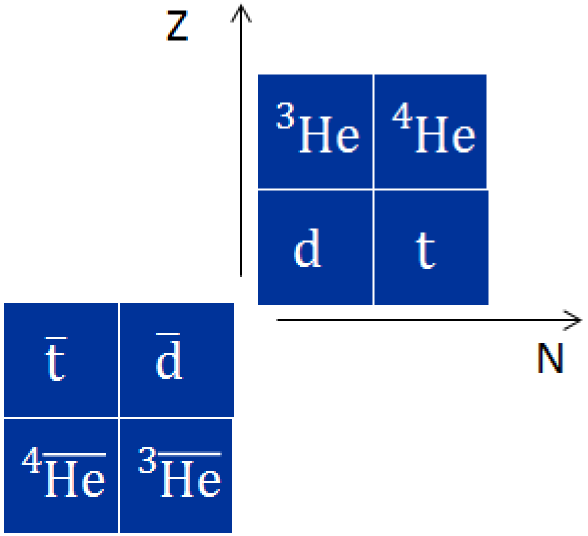
Event : 0x3d94315a



Introduction

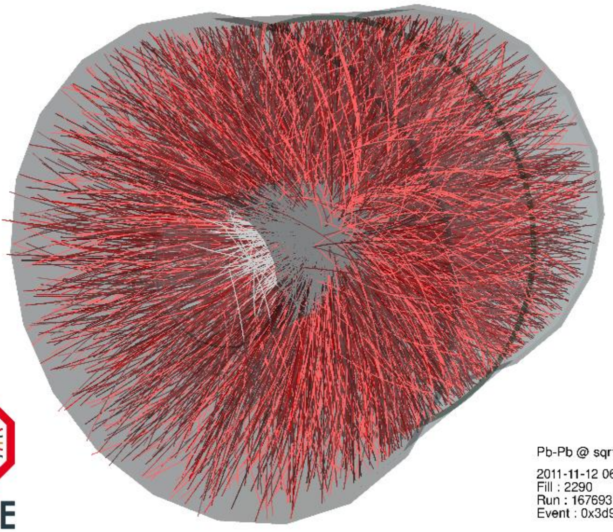
In high energy Pb-Pb collisions at LHC

① large number of matter and anti-matter particles are produced: $dN/d\eta \sim 10^3$ in central collisions

② high temperature (~156 MeV) and energy density (~1 GeV/fm^3) in the primary interaction

- ❖ suitable environment for the production of nuclei and anti-nuclei

→ Precision comparison of mass between nuclei and anti-nuclei is possible at LHC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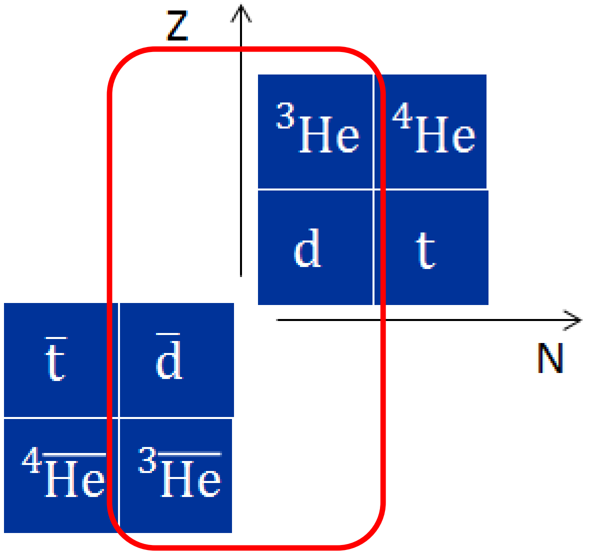


Experimental setup and data analysis

VZERO detector

for *triggering*

Inner Tracking System

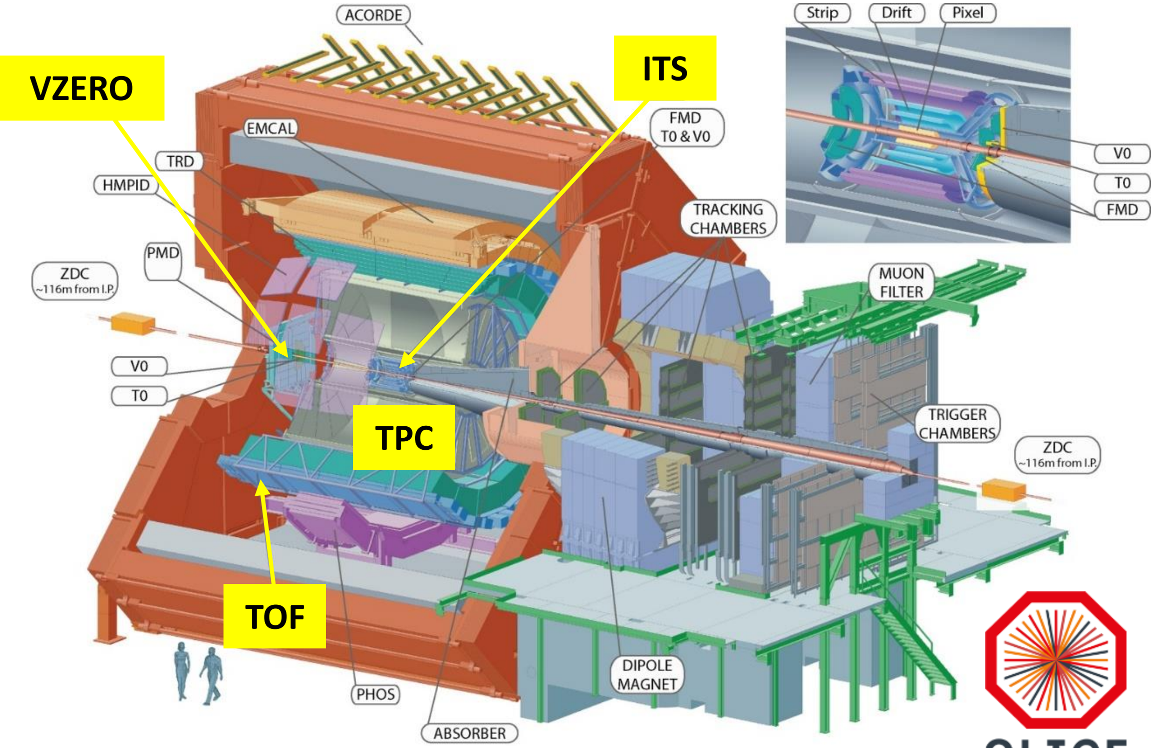
for *triggering* and charged particles *tracking*

Time Projection Chamber

for charged particles *tracking* and PID based on d*E*/dx measurement

Time Of Flight

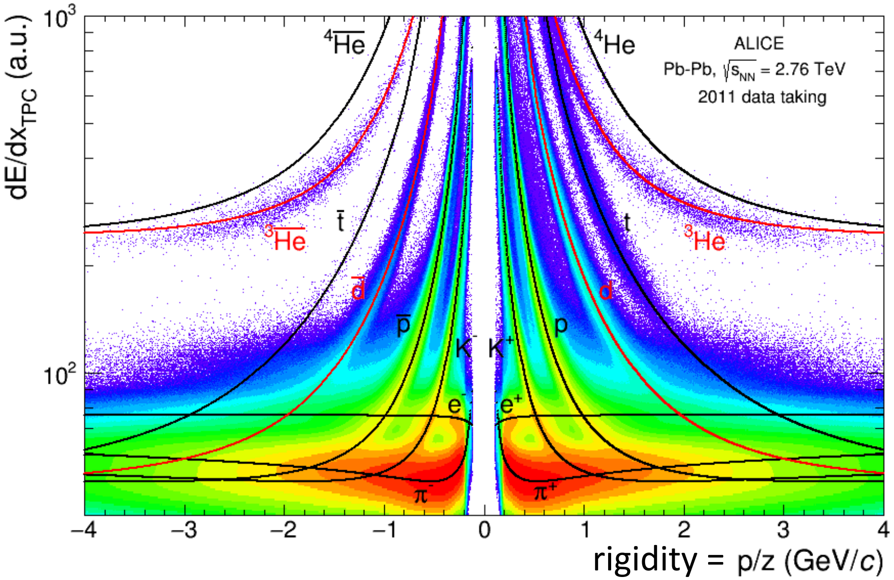
for the *mass* reconstruction based on time of flight measurement



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

2011 data taking (67 x 10^6 ev.)

Experimental setup and data analysis

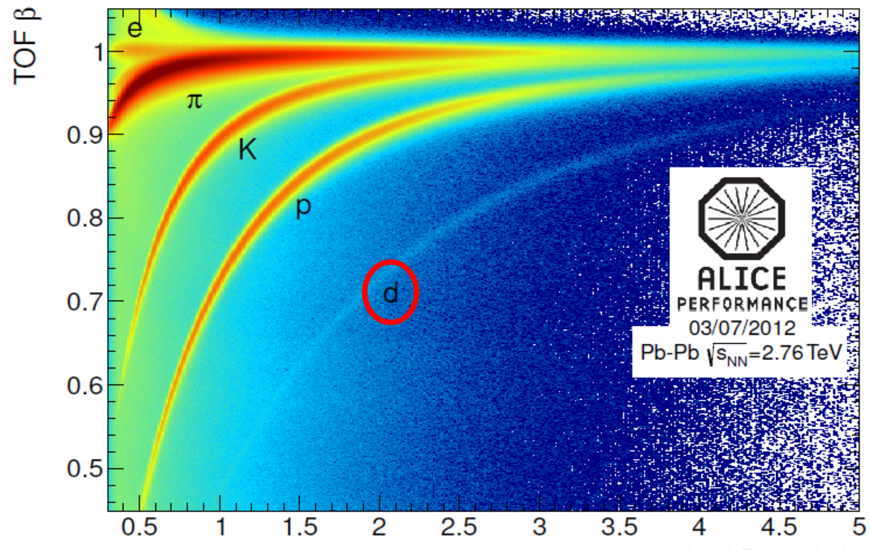


① **TPC dE/dx PID**

- identification of ^{3}**He nucleus** from other particles in the full rigidity range by virtue of its double charge
- identification of **deuteron** at rigidities below ~2 GeV/*c*

② **excellent TOF resolution (~80 ps)**

- it allows for the **deuteron** separation at higher rigidities
- … background from mismatched tracks significantly reduced by compatibility with TPC dE/dx PID



ALI-PERF-27125

Experimental setup and data analysis

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

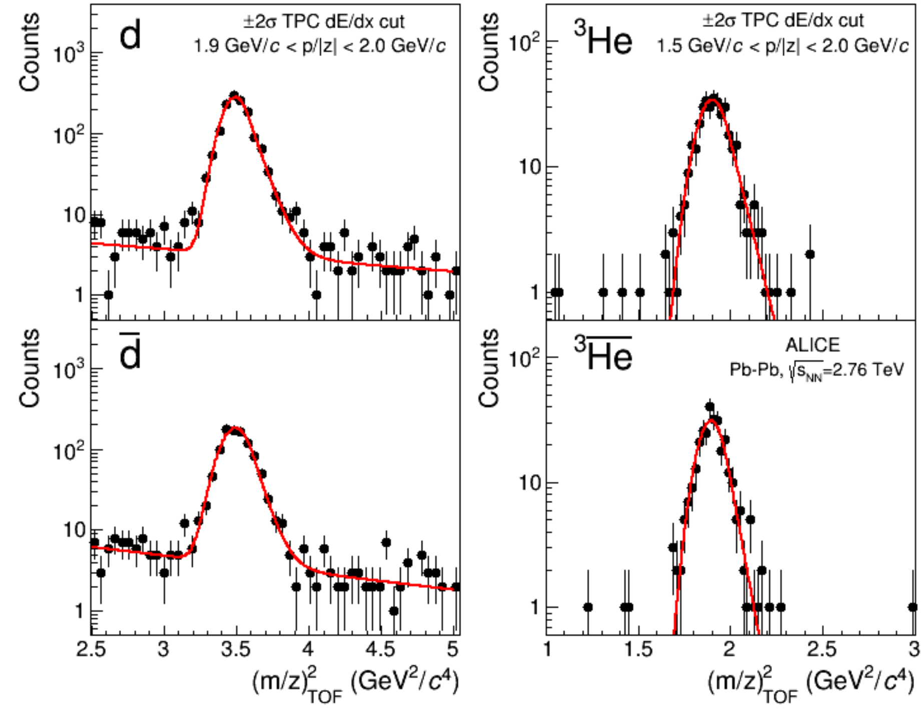
$$\mu^2_{\mathrm{TOF}} \equiv (m/z)^2_{\mathrm{TOF}}$$

① The *difference* of masses ($\Delta\mu_{\mathrm{TOF}}$) reduces significantly the syst. uncertainties affecting tracking and time calibration

② The mass independent residual effects are reabsorbed via correction based on *proton mass*:

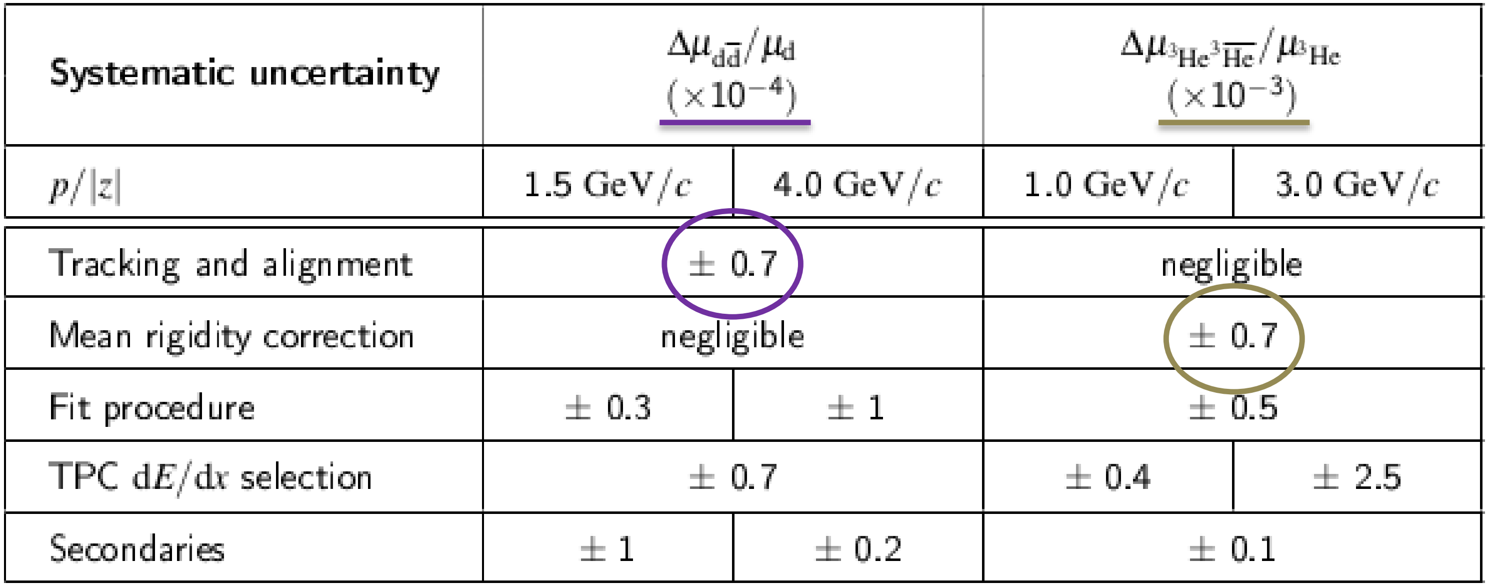
$$\mu_{\mathrm{A}(\bar{\mathrm{A}})} = \mu^{\mathrm{TOF}}_{\mathrm{A}(\bar{\mathrm{A}})} \times \frac{\mu^{\mathrm{PDG}}_{\mathrm{p}(\bar{\mathrm{p}})}}{\mu^{\mathrm{TOF}}_{\mathrm{p}(\bar{\mathrm{p}})}}$$

③ remaining uncertainty estimated inverting the polarity of the magnetic field $\vec{B}$



μ^2_{TOF} peak position of fitting curves

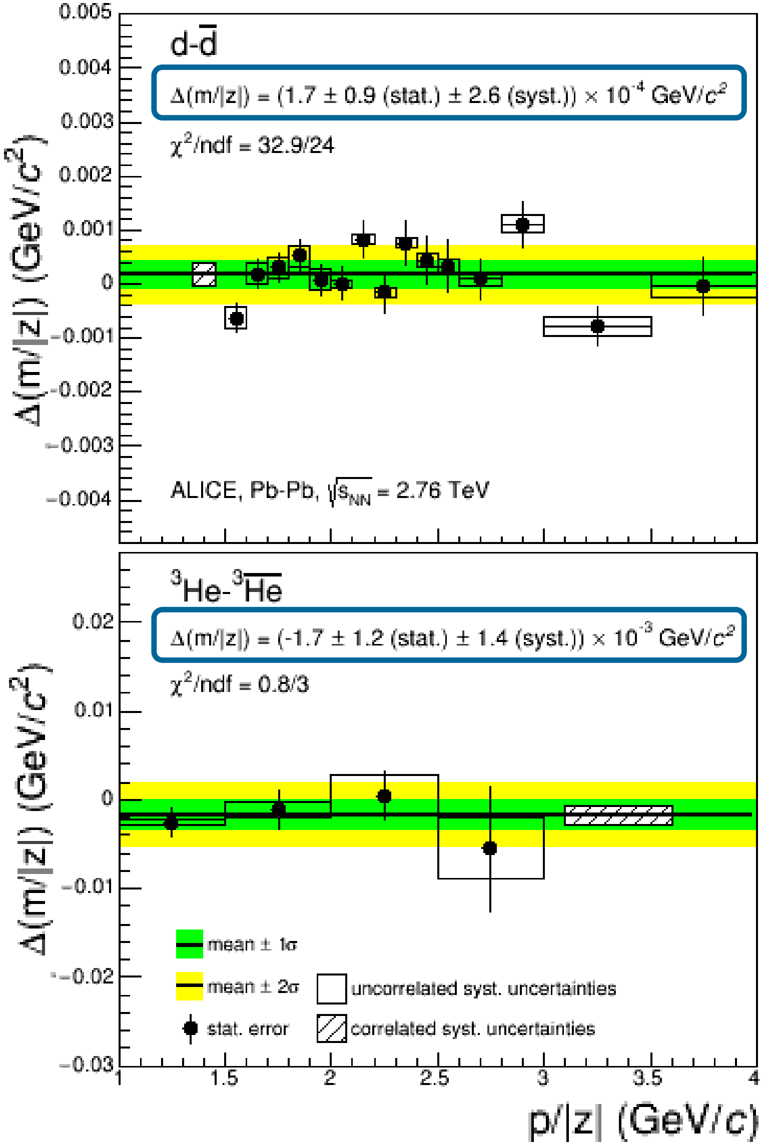
Experimental setup and data analysis



Systematic uncertainty	$\Delta\mu_{d\bar{d}}/\mu_{d}$ ($\times 10^{-4}$)		$\Delta\mu_{^{3}He\,^{3}\overline{He}}/\mu_{^{3}He}$ ($\times 10^{-3}$)	
$p/\lvert z\rvert$	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 dE/dx selection	± 0.7		± 0.4	± 2.5
Secondaries	± 1	± 0.2	± 0.1	

- **Tracking and alignment**: see previous slide
- **Mean rigidity correction** accounting for ionization energy loss in the detector material in the measurement of the rigidity
- **Fit procedure** uncertainty estimated varying the shape and the range chose to fit the mass-over-charge distributions
- **TPC dE/dx selection** varied to probe the sensitivity of the fit result on the background
- **Secondary** *nuclei* produced in secondary interactions in the detector material…

Results



final measurement: weighted mean over all rigidity intervals

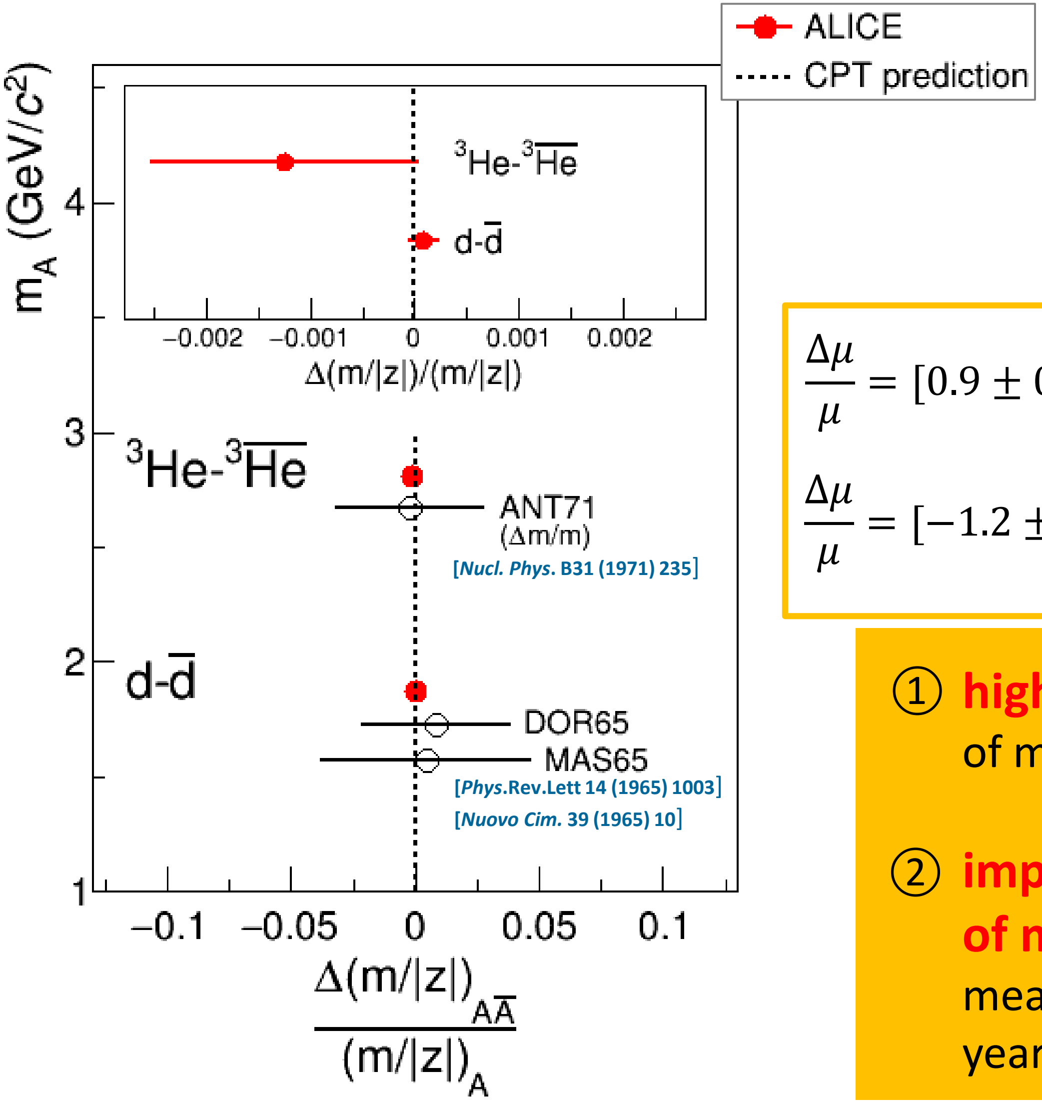
$$\frac{\Delta\mu}{\mu} = [0.9 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})] \times 10^{-4}$$

d-$\bar{\text{d}}$

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

^{3}He- $^3\overline{\text{He}}$

Results



[*Nucl. Phys.* B31 (1971) 235]

[*Phys.*Rev.Lett 14 (1965) 1003]

[*Nuovo Cim.* 39 (1965) 10]

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

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

① **highest precision** direct measurements of mass difference in the sector of nuclei

② **improvement by one to two orders of magnitude** compared to previous measurements obtained more than 40 years ago

Results

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

$\Delta m_{\mathrm{p\bar{p}}} < 7 \times 10^{-10}$ GeV (CL=90%)
[*Nature*, **475** (2011) 484]

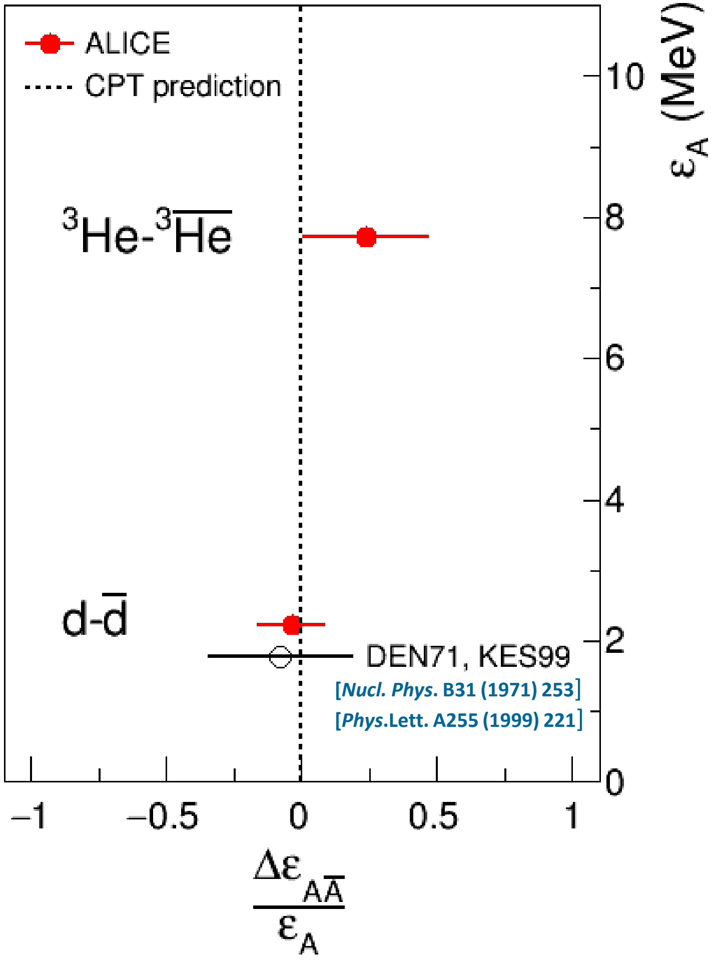
$\Delta m_{\mathrm{n\bar{n}}} = [0.85 \pm 0.51\ (\text{stat.}) \pm 0.29\ (\text{syst.})] \times 10^{-4}$ GeV
[*Phys.Lett.* **B177** (1986) 206, *erratum* **B200** (1988) 587]

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

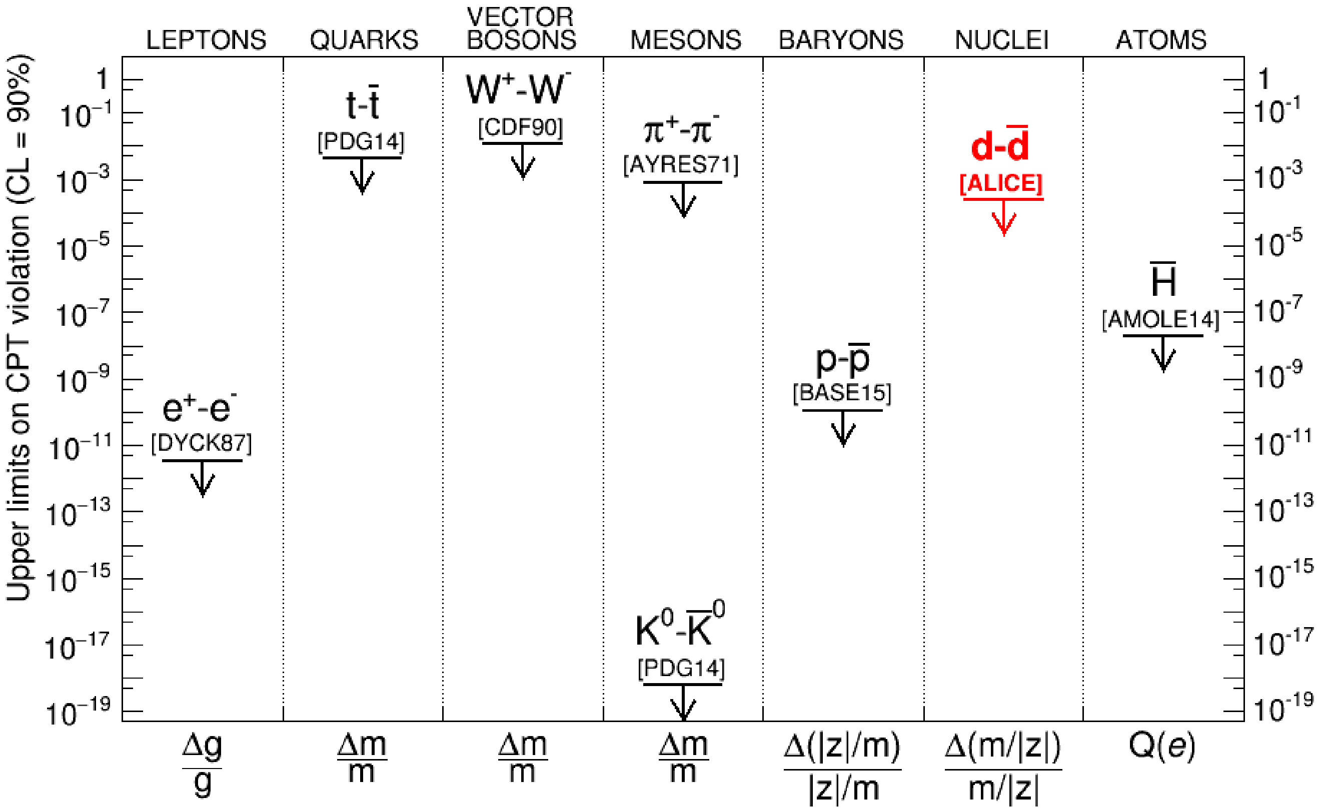
$$\frac{\Delta\varepsilon}{\varepsilon} = 0.24 \pm 0.16\ (\text{stat.}) \pm 0.18\ (\text{syst.}) \quad \mathbf{{}^{3}He\text{-}\,{}^{3}\overline{He}}$$

① constraint on CPT invariance improved by a **factor 2** for (anti-)deuteron case

② $\Delta\varepsilon$ determined for the **first time** in (anti-)^{3}He case



Results



…used also 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, arXiv:0801.0287]

Summary

① The production of (anti-)nuclei in relativistic Pb-Pb collisions at LHC represents a unique opportunity **to test the CPT invariance of nucleon-nucleon interactions** using light nuclei

② The measurements of $\Delta\mu$ between d and $\overline{\mathrm{d}}$, and $^{3}\mathrm{He}$ and $^{3}\overline{\mathrm{He}}$ have been extracted, **improving by one to two orders of magnitude** existing results

③ The results are also expressed in terms of Δε:

- for the (anti-)deuteron it improves by a **factor** two the constraints on CPT invariance inferred by existing measurements
- for the (anti-)^{3}He it has been **determined for the first time**, with a relative precision comparable to the one obtained in the (anti-)deuteron system

④ Remarkably, these improvements are reached in an experiment **not specifically dedicated** to test the CPT invariance in nuclear systems

"The measurements by ALICE and by BASE have taken place at the highest and lowest energies available at CERN, at the LHC and the Antiproton Decelerator, respectively. […] *This is a perfect illustration of the diversity in the laboratory's research programme*." CERN Director-General Rolf Heuer, 17 August 2015.

Grazie dell’attenzione!

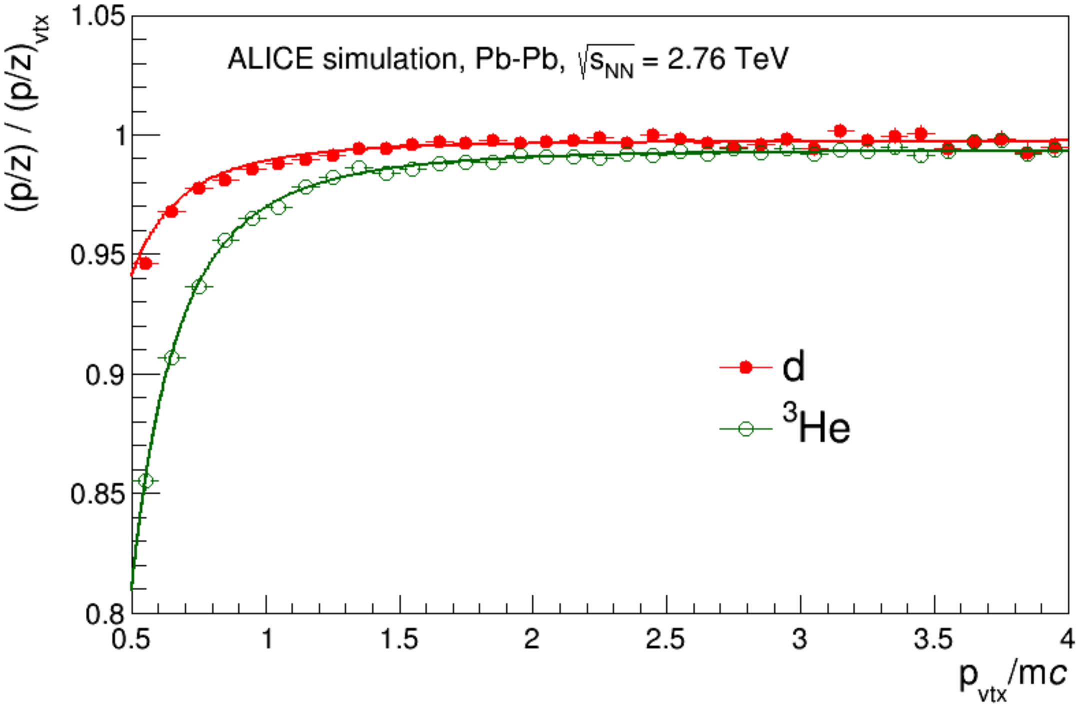
Backup

Mean rigidity correction

$$\mu_{\mathrm{TOF}}^2 = \underbrace{\left(\frac{p}{z}\right)^2}_{\textit{mean}\ \text{rigidity}} \left[\left(\frac{t_{\mathrm{TOF}}}{L}\right)^2 - \frac{1}{c^2}\right]$$

rigidity at the primary vertex $(p/z)_{vtx}$ provided by track reconstruction

→ $(p/z)_{vtx}$ adjusted to the mean one (p/z) by a correction calculated via a Monte Carlo simulation



on the tracking and alignment uncertainties

Opposite charges experience different syst. uncert. (e.g. from the alignment and the description of the magnetic field) because of their different trajectories.
→ they correspond to an error **on the rigidity (1)** and on the track length (2):

$$\frac{\delta\mu_{\mathrm{TOF}}}{\mu_{\mathrm{TOF}}} = \boxed{\frac{\delta(p/z)}{p/z}} \oplus \gamma^2 \frac{\delta L}{L} \qquad \oplus\, L - p/z \text{ corr. term (negl.)}$$

(1) is the largest one ($\leq 1\%$) and mass independent in a p/z interval

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

(1) **now negligible**; indeed it propagates in $\Delta\mu/\mu$ as

$$\frac{\Delta\mu}{\mu} \times \left[\frac{\delta(p/z)}{p/z}\right]^2$$

where the 1° term can be consider a
suppression factor and the 2° term is O(10^{-4})

on the tracking and alignment uncertainties

Opposite charges experience different syst. uncert. (e.g. from the alignment and the description of the magnetic field) because of their different trajectories.
→ they correspond to an error on the rigidity (1) and **on the track length (2)**:

$$\frac{\delta\mu_{\mathrm{TOF}}}{\mu_{\mathrm{TOF}}} = \frac{\delta(p/z)}{p/z} \oplus \boxed{\gamma^2 \frac{\delta L}{L}} \qquad \oplus\, L - p/z \text{ corr. term (negl.)}$$

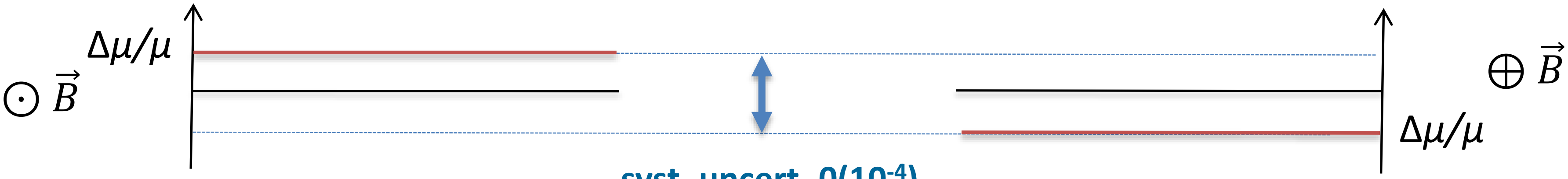
(2) is mass dependent via γ^2 factor.

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

(2) propagates in $\Delta\mu/\mu$ as

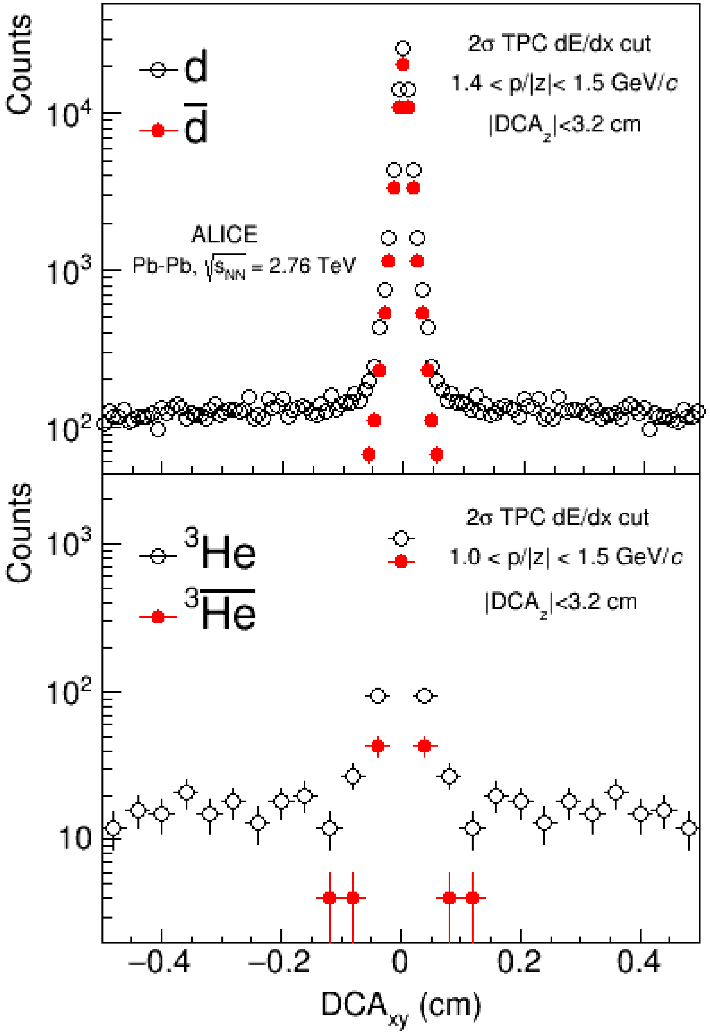
$$\left(\frac{\delta L}{L} - \frac{\delta \bar{L}}{\bar{L}}\right) \times \left(\gamma_{\mathrm{A}}^2 - \gamma_{\mathrm{p}}^2\right)$$

then inverting the magnetic field polarity $\delta L/L \leftrightarrow \delta\bar{L}/\bar{L}$…

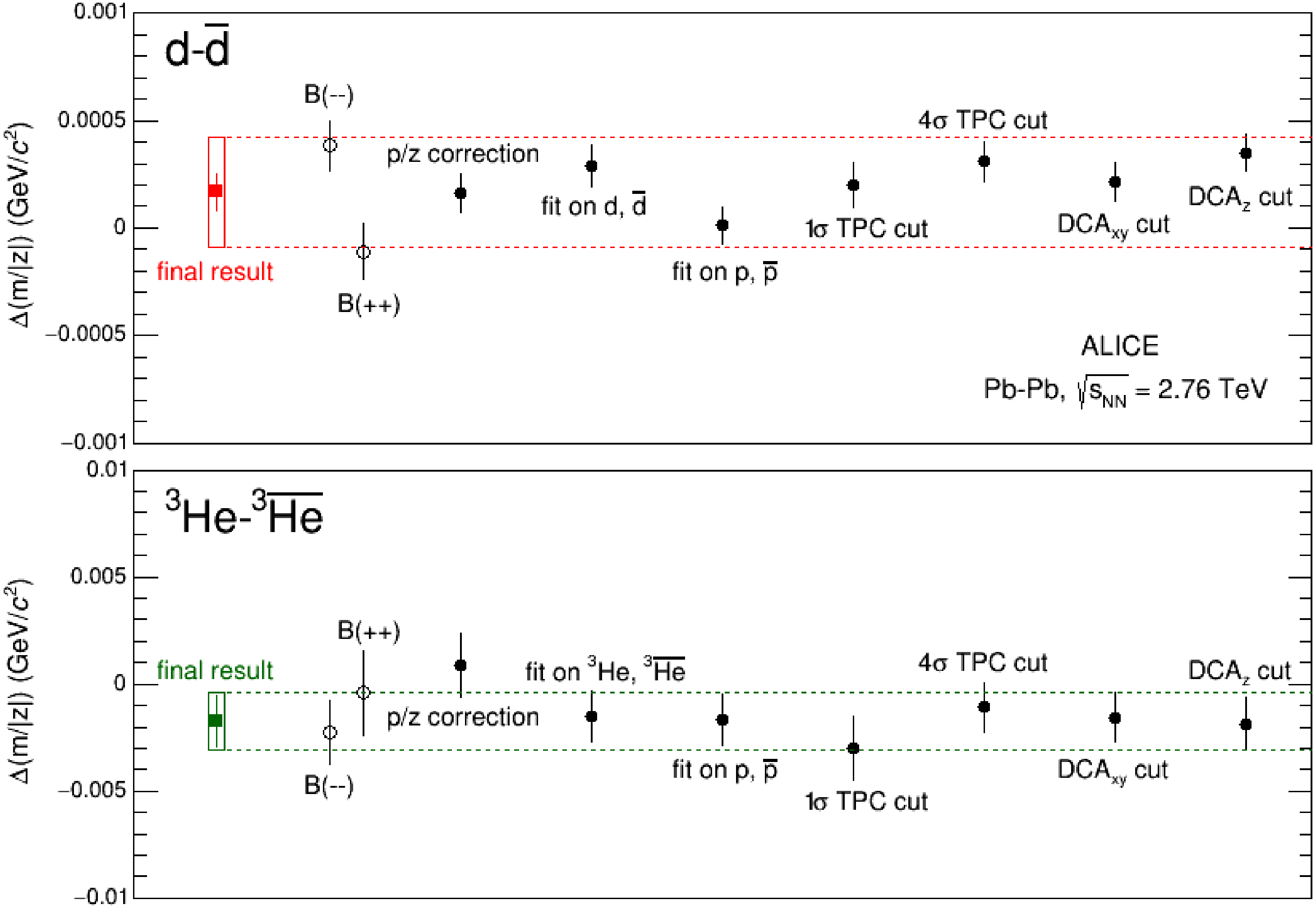


syst. uncert. 0(10^{-4})

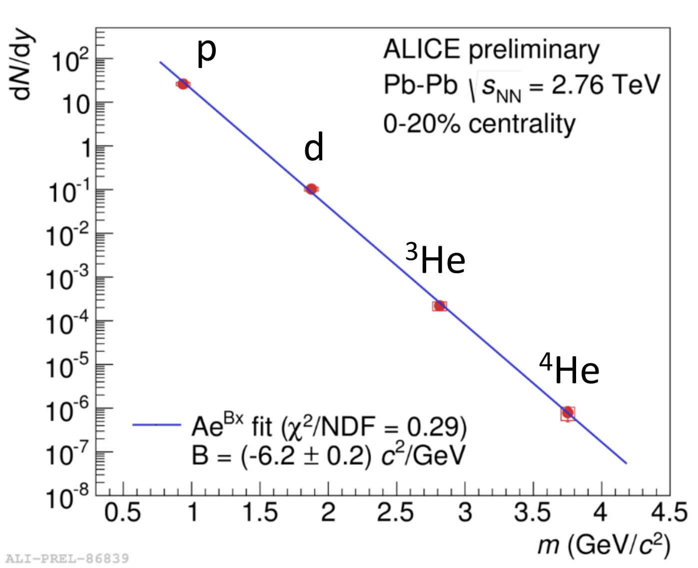
Distance of Closest Approach (DCA) to the primary vertex



Syst. uncertainties

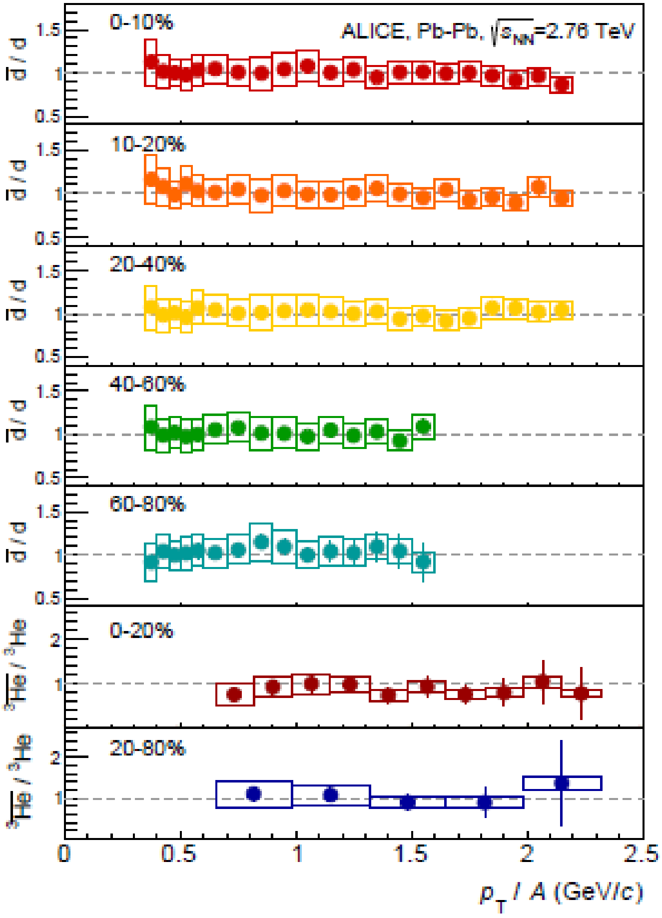


(anti-)nuclei production rate



The penalty factor, namely the reduction of the yield by adding one nucleon, is ~300

ALICE Coll. arXiv : 1506.08951v1



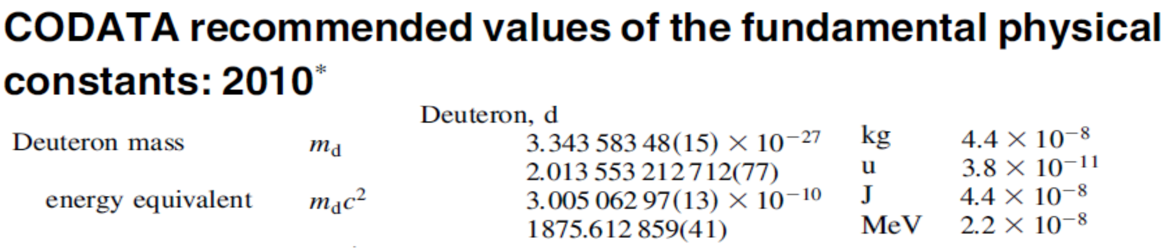
(anti-)nuclei production rate for Run-II (Pb-Pb)

Species	Minimum Bias (trigger)	Central collisions (trigger)
p	1.2×10^{9}	1.9×10^{9}
d	3.6×10^{6}	5.4×10^{6}
$^{3}\mathrm{He}$	1.06×10^{4}	1.6×10^{4}
t	52	79
$^{4}\mathrm{He}$	22	33
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi$	169	256
$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \mathrm{t}$	41	61

Rough estimates derived from dN/dy predicted by thermal models, the efficiency measured in Run-I and the expected number of Minimum Bias (10^{8}) and central collisions (6×10^{7}) for Run-II

deuteron and anti-deuteron mass

①

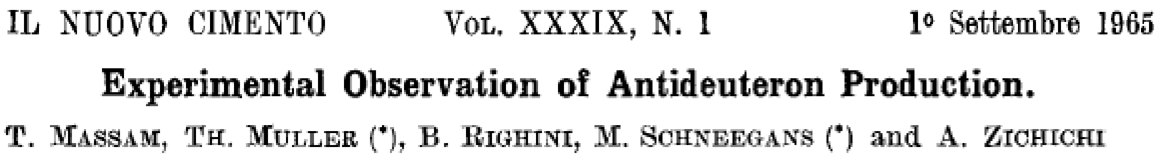


CODATA recommended values of the fundamental physical constants: 2010*

		Deuteron, d		
Deuteron mass	m_d	$3.343\,583\,48(15) \times 10^{-27}$	kg	4.4×10^{-8}
		$2.013\,553\,212\,712(77)$	u	3.8×10^{-11}
energy equivalent	m_dc^2	$3.005\,062\,97(13) \times 10^{-10}$	J	4.4×10^{-8}
		$1875.612\,859(41)$	MeV	2.2×10^{-8}

Very high precision ($\sim 10^{-8}$) reached for NUCLEI masses

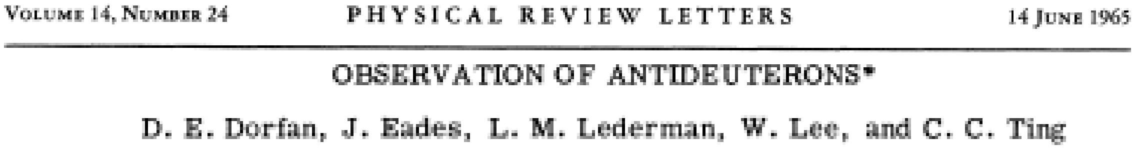
②



IL NUOVO CIMENTO Vol. XXXIX, N. 1 1º Settembre 1965

Experimental Observation of Antideuteron Production.

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



VOLUME 14, NUMBER 24 PHYSICAL REVIEW LETTERS 14 JUNE 1965

OBSERVATION OF ANTIDEUTERONS*

D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting

ANTI-NUCLEI masses come from their firsts observations