INTERNATIONAL CONFERENCE ON EXOTIC ATOMS AND RELATED TOPICS – EXA2017

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AUSTRIAN ACADEMY OF SCIENCES, THEATERSAAL, SONNENFELSGASSE 19, 1010 WIEN, AUSTRIA

PRECISION COMPARISON OF LIGHT NUCLEI AND ANTI-NUCLEI MASS-TO-CHARGE RATIO WITH ALICE AT THE LHC

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Outline

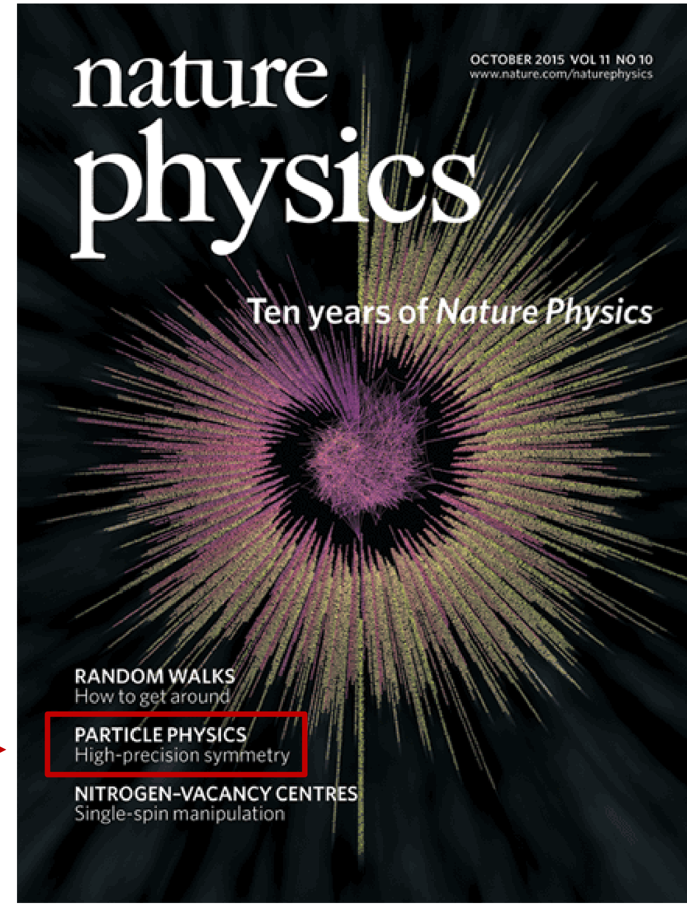
- Physics motivations
- The ALICE experiment
- Analysis strategy
- Results
- Conclusions and outlook

Results published in *Nature Phys.* 11 (2015) 811

http://www.nature.com/nphys/journal/v11/n10/full/nphys3432.html

more details can be found in ALICE-PUBLIC-2015-002

https://cds.cern.ch/record/2033777



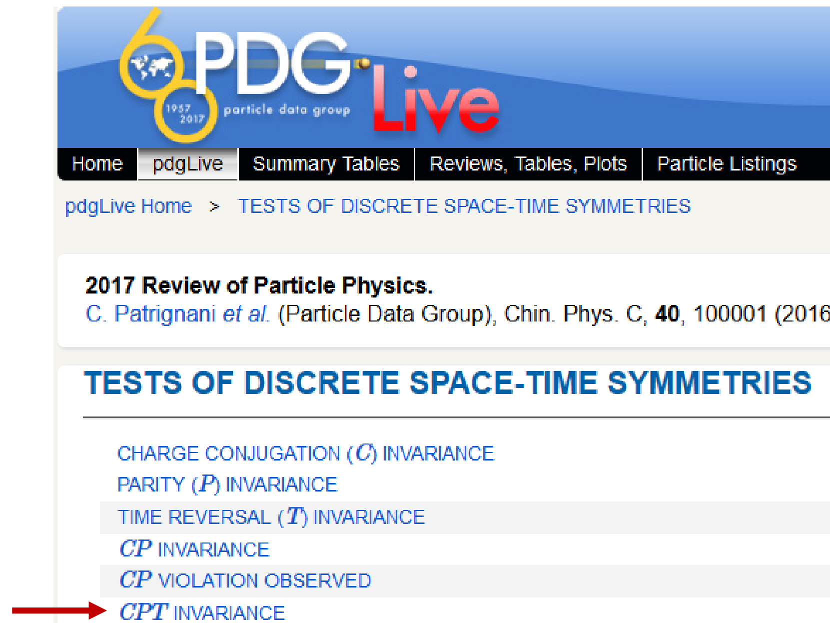
Introduction

- In the today's Universe we observe only ordinary matter but… the Standard Model predicts that in the primordial Universe there should have been equal amounts of matter and anti-matter
→ CPT violation? See e.g. *Rev. Mod. Phys.* 53 (1981) 141, *Phys. Lett.* B 725 (2013) 407

- The CPT theorem demonstrates that CPT symmetry is guaranteed within a RQFT description of interactions constructed in a flat space-time (1), based on Lorentz invariance (2) and on the locality of the interactions (3)

→ if some of the conditions which back-up the CPT theorem are not satisfied, the symmetry is no longer guaranteed
(see e.g. *Phys. Rev.* D 92 (2015) 056002)

- Many experimental tests based on one important consequence of CPT symmetry: mass, lifetime, charge, magnetic moment of a particle equal to those of the corresponding anti-particle



From (anti-)baryons to (anti-)nuclei

- Δ(q/m) for systems bound by the strong force has reached a very high precision with protons and anti-protons

LETTER [BASE Coll. *Nature* 524 (2015) 126] 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**

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

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

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

→ The extension of such measurement to (anti-)nuclei allows **to probe any matter/anti-matter asymmetry in nucleus-nucleus interactions**, today described only by effective theories

LHC as an (anti-)nuclei factory

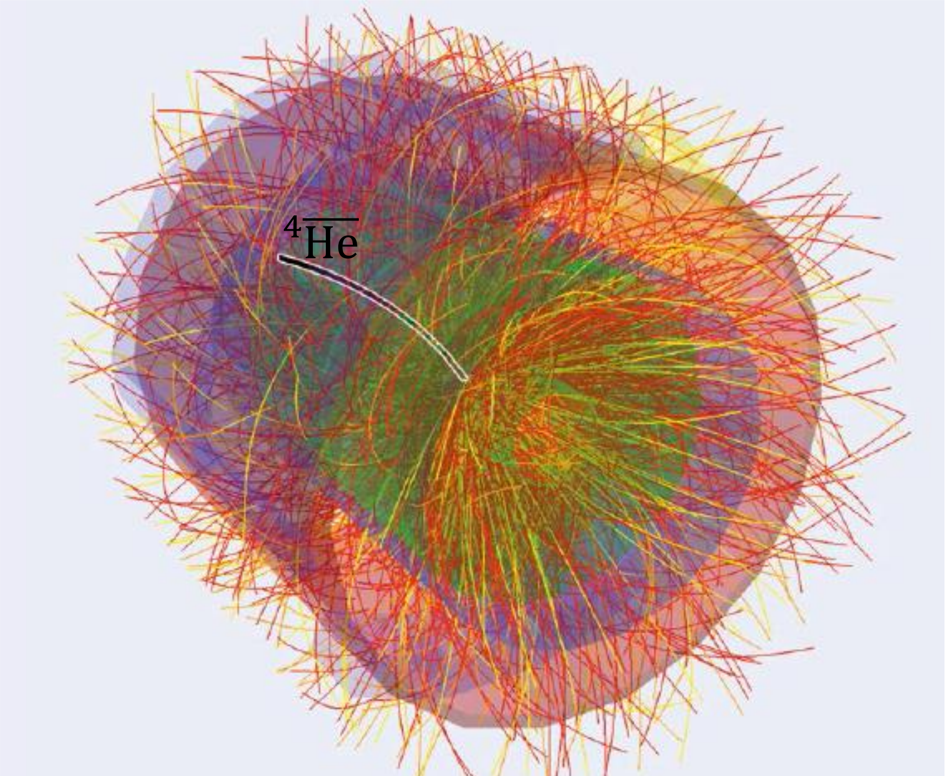
Central Pb-Pb collision in ALICE at LHC

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 → (anti-)nuclei production via coalescence of (anti-)nucleons

② high temperature (~156 MeV) and energy density (~1 GeV/fm^3) in the primary interaction → thermal production of (anti-)nuclei

→ Pb-Pb collisions are an abundant source of nuclei and anti-nuclei allowing to study their properties



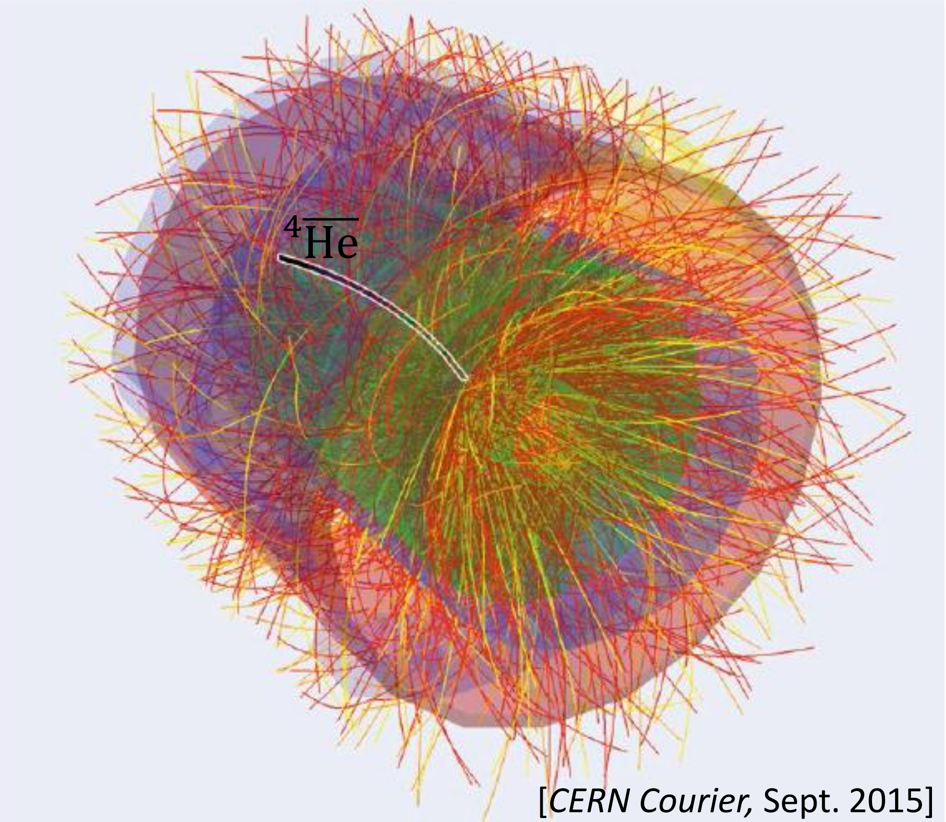
[*CERN Courier*, Sept. 2015]

LHC as an (anti-)nuclei factory

Many results at LHC *exclusively* by ALICE
During this conference:

- Production of (anti-)nuclei in pp, p-Pb, Pb-Pb
  → for small systems, **see B. Dönigus's Talk**
- (Anti-)hypernuclei production in Pb-Pb
  → **see S. Piano's Talk**
- Searches for exotic QCD bound states
  → **see A. Mastroserio's Talk**
- CPT test with light (anti-)nuclei
  → **this contribution**

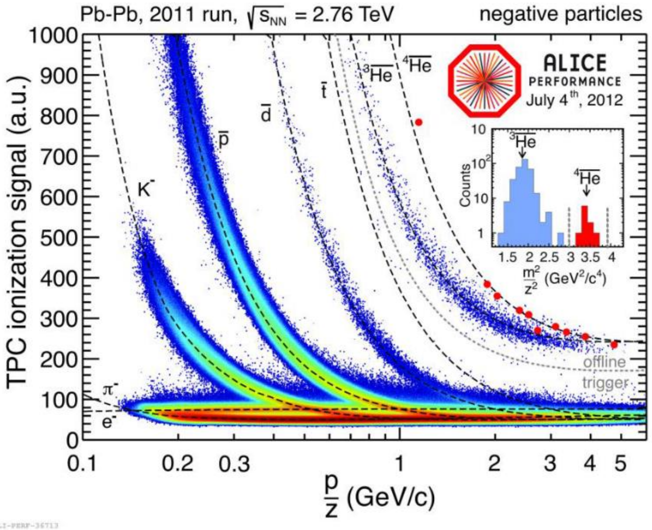
Central Pb-Pb collision in ALICE at LHC



[*CERN Courier,* Sept. 2015]

LHC as an (anti-)nuclei factory

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



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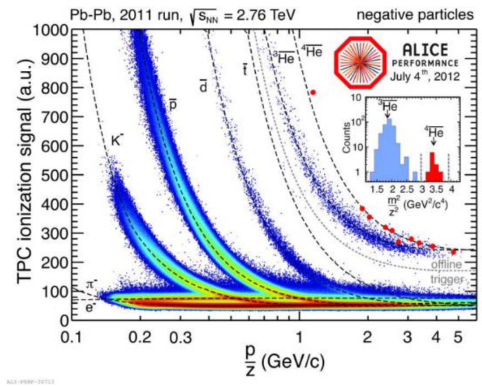
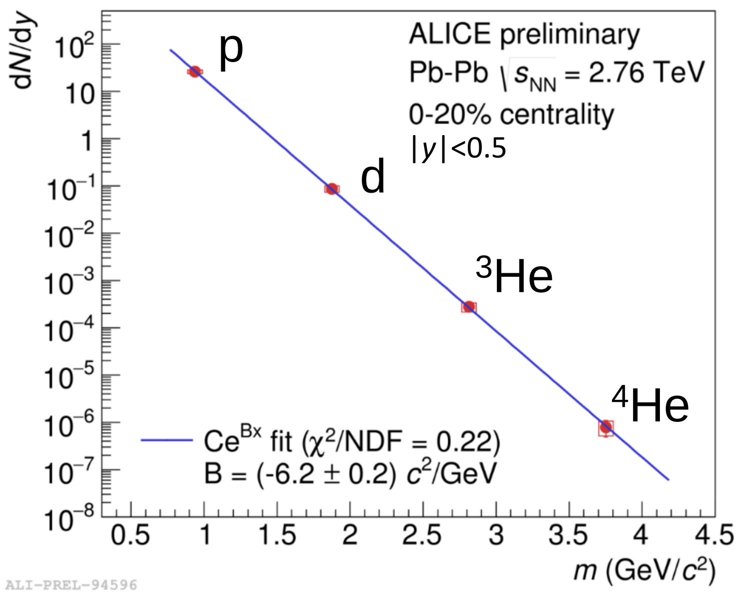
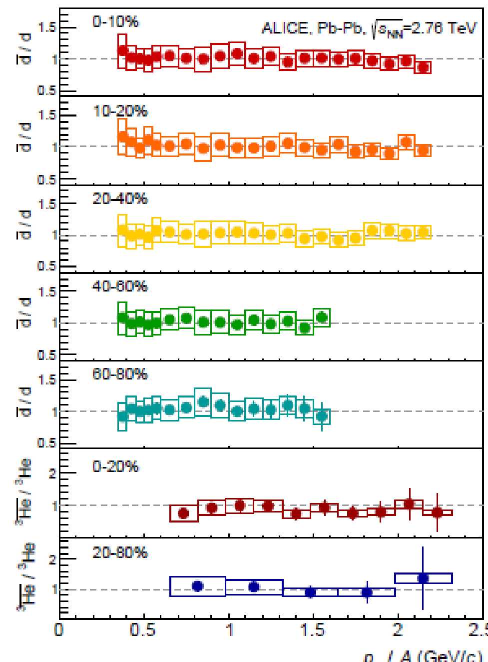


[ALICE Coll. PRC 93 (2015) 024917]

- Lighter (anti-)nuclei more abundantly produced
  The yield is reduced by a factor ≈300 by adding one nucleon, as extracted by fitting the experimental data:





(yields of nuclei and *corresponding* anti-nuclei are very similar at LHC energies [ALICE Coll. PRC 93 (2015) 024917])

LHC as an (anti-)nuclei factory

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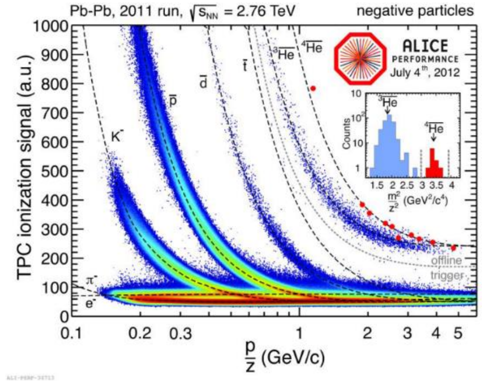

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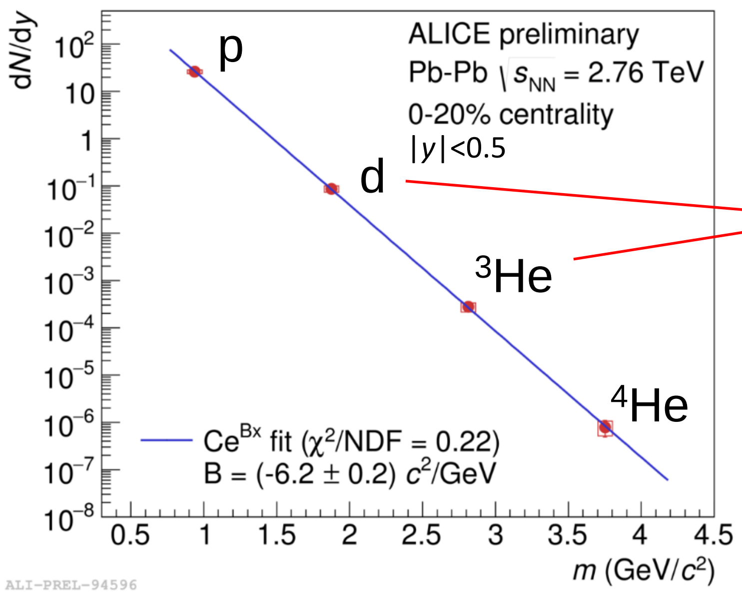
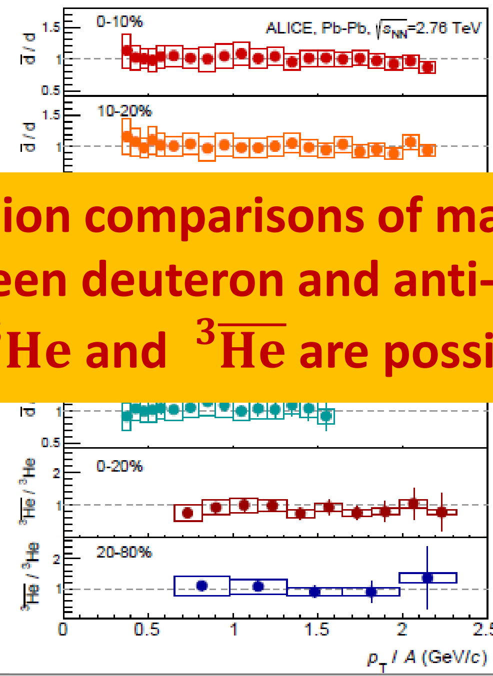
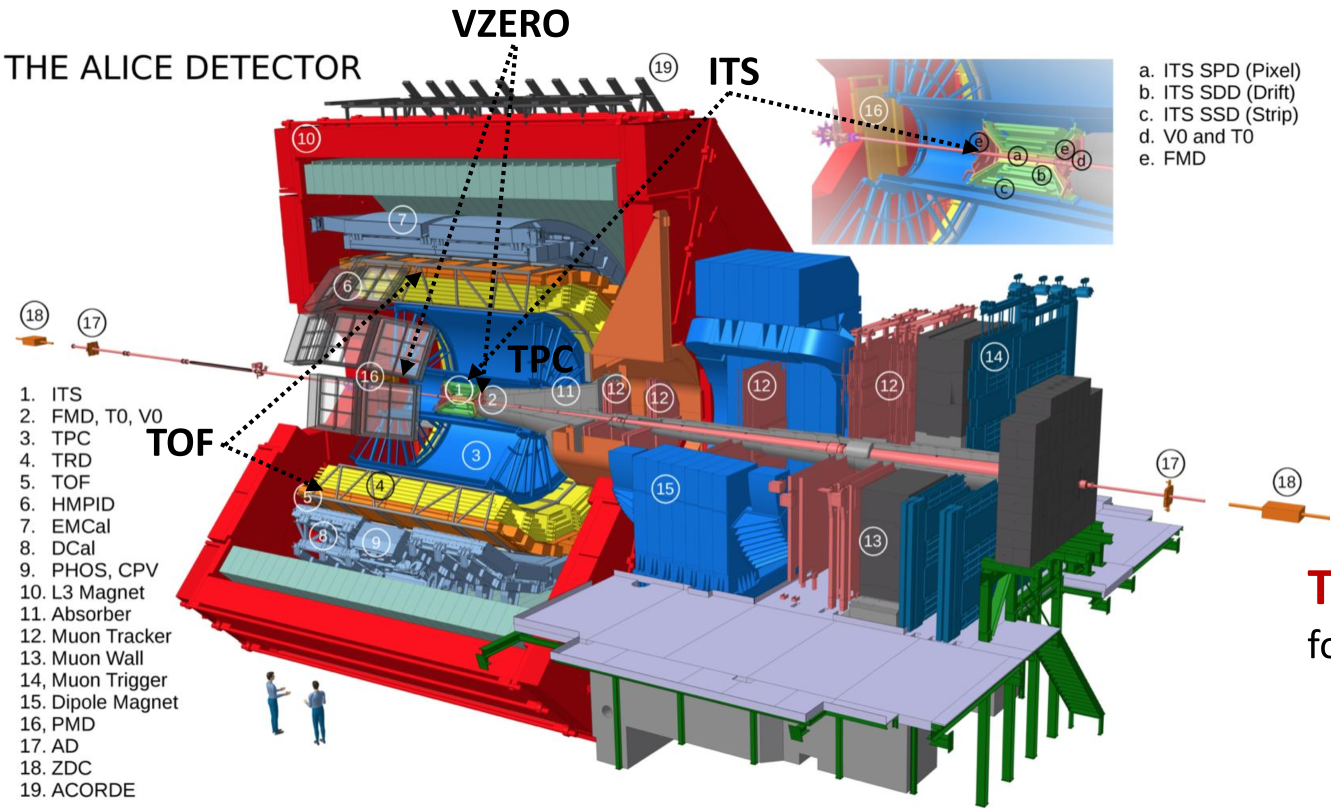




Precision comparisons of mass/charge between deuteron and anti-deuteron, and ^{3}He and $^{3}\overline{He}$ are possible at LHC

(yields of nuclei and *corresponding* anti-nuclei are very similar at LHC energies [ALICE Coll. PRC 93 (2015) 024917])

Detectors involved in the analysis



VZERO
for *triggering*

Inner Tracking System
for *triggering* and charged particles *tracking*

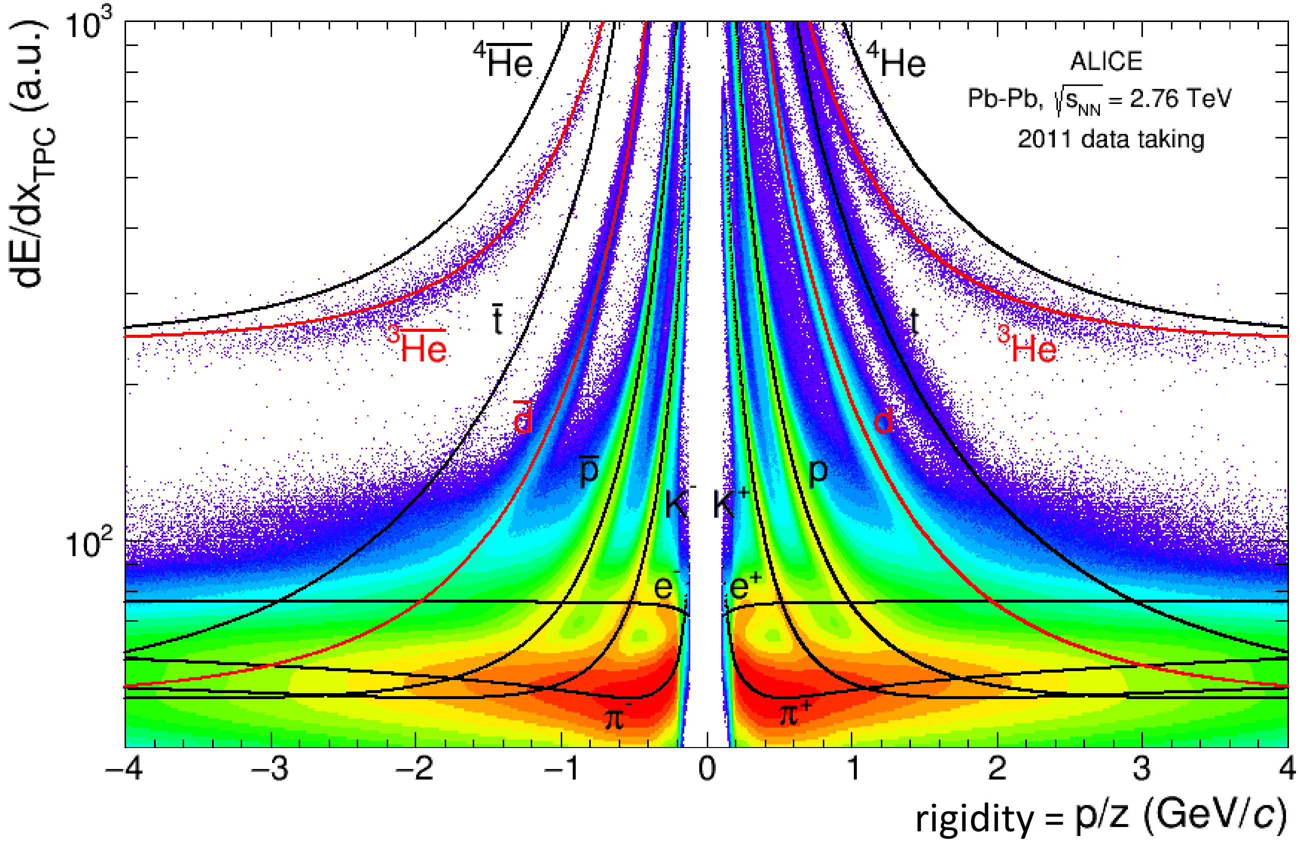
Time Projection Chamber
for charged particles *tracking* and PID based on dE/dx measurement

Time Of Flight
for the mass/charge reconstruction based on time of flight measurement

DATA set:
Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV (2011 data taking: 67M events)
Trigger selection: enriched in central and semi-central collisions

Particle Identification with TPC

- **(anti-)d** identified at rigidities **p/z<2 GeV/*c***
- **(anti-)^{3}He** well separated from lighter particles in the **full p/z range** thanks to its double charge (z=2)
- $\bar{t}$ is is much more difficult to measure than $^3\overline{He}$ even if they have a similar mass

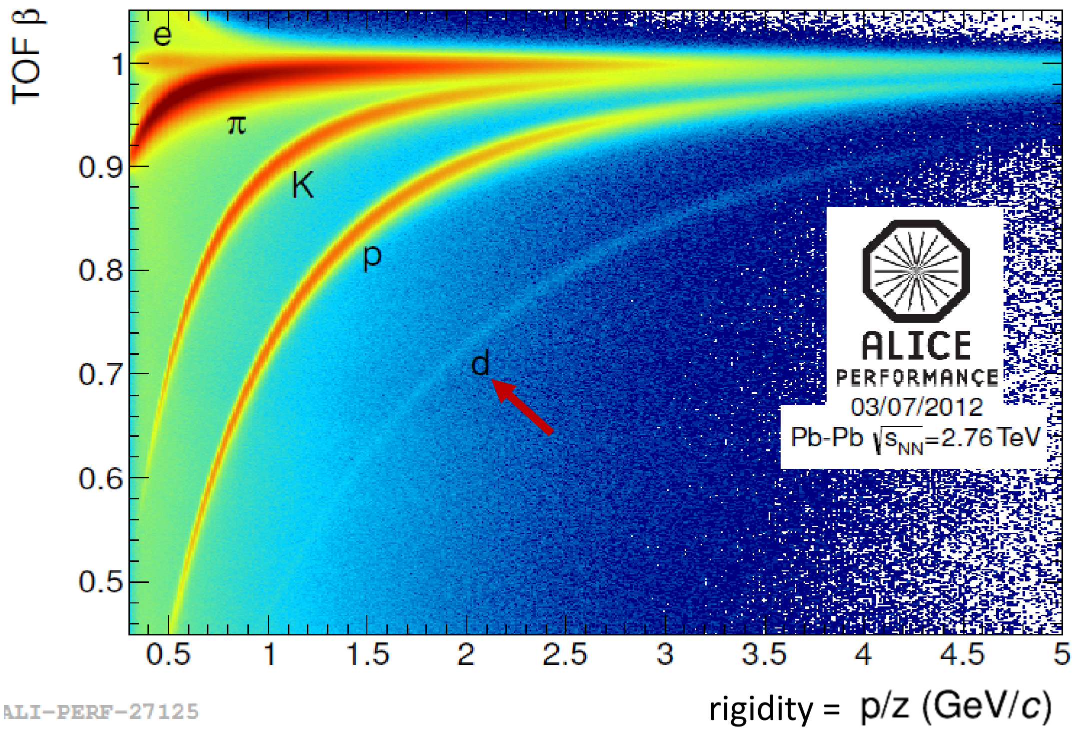


All nuclei, secondaries included

Particle Identification with TOF

- **(anti-)d** identification until **higher p/z** thanks to a time resolution of 80 ps [EPJ Plus 128 (2013) 44]
- **(anti-)^{3}He** also **well separated** (*between proton/deuteron band*) but under the background coming from track-TOF hit time mis-association (see the next slide too)
- The background (B) is significantly reduced requiring:

$$n_\sigma^{\mathrm{TPC}} = \frac{\left| \left(\frac{dE}{dx}\right) - \left(\frac{dE}{dx}\right)_{exp} \right|}{\sigma_{\mathrm{TPC}}} < 2$$



→ B/S < 4% at p/z<2 GeV/*c* (for deuteron) and B/S < 1% (for ^{3}He)

→ ≈ 10^6 (anti-)deuterons and ≈ 2 x 10^3 (anti-)^{3}He are selected for the analysis

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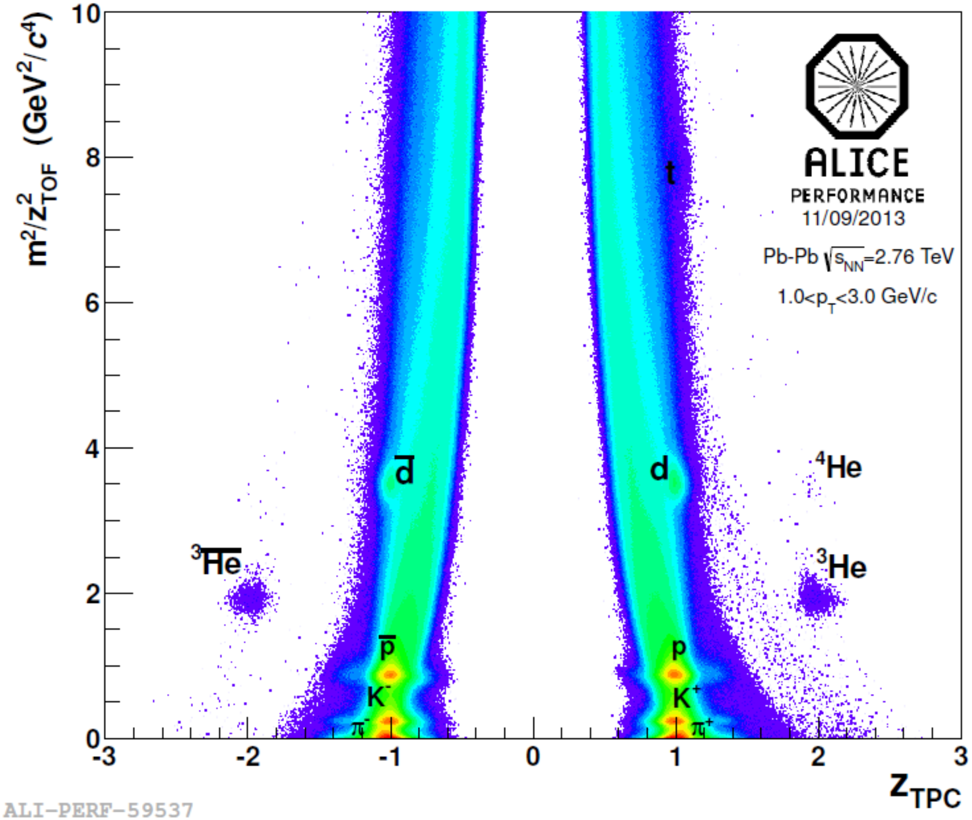

$$z^2_{TPC} = \frac{dE/dx^{TPC}}{dE/dx^{\exp,\, m_{TOF}}_{z=1}}$$

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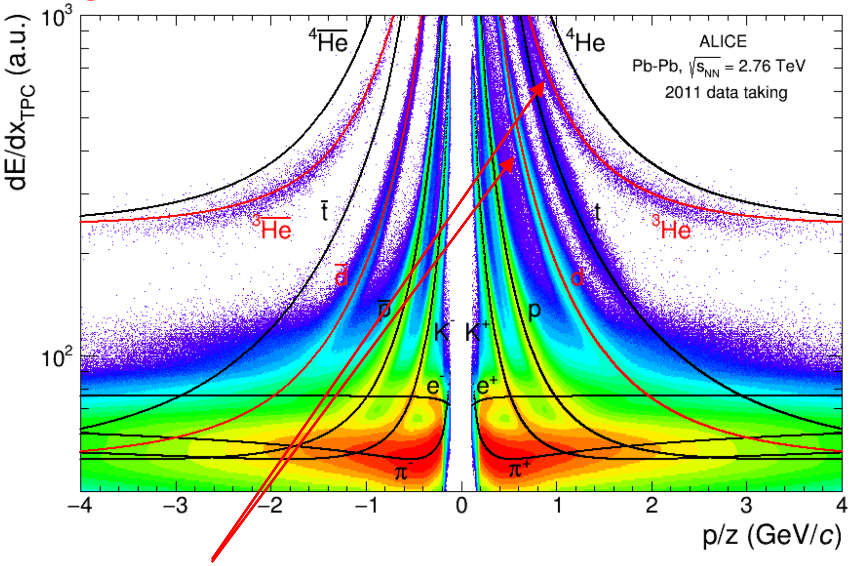
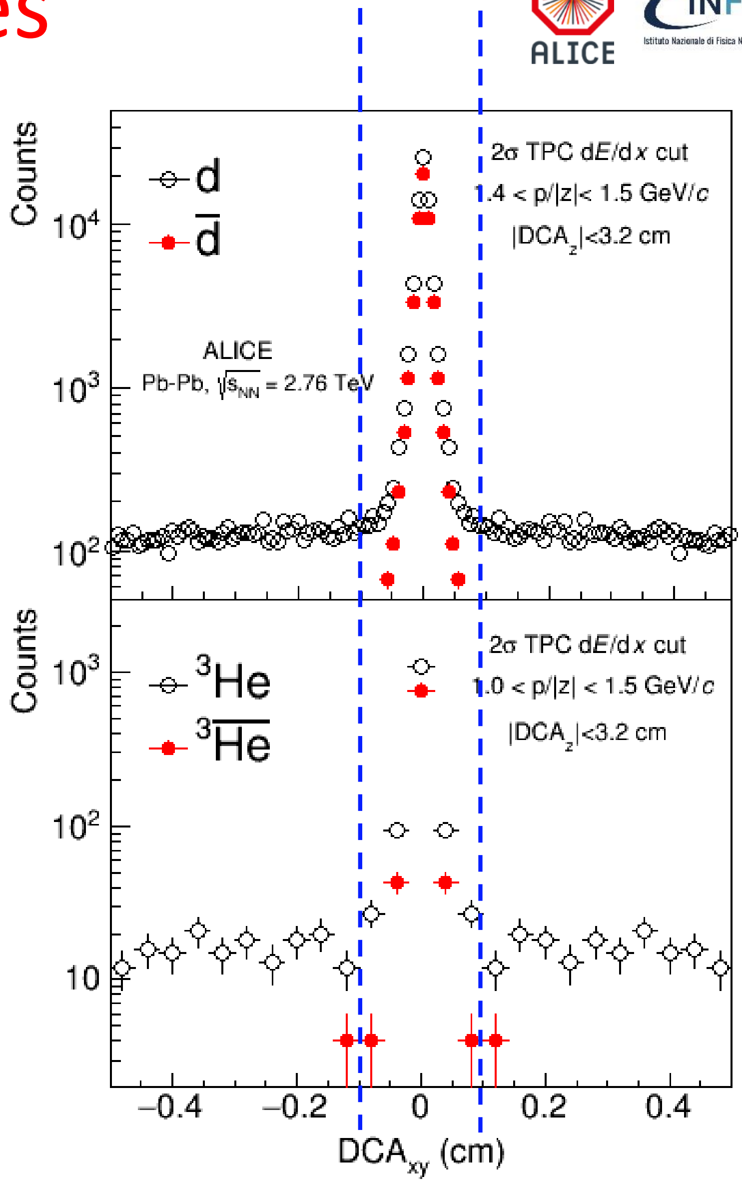
Rejection of secondaries



- The **nuclei** sample at *low* p/z may include secondaries originating from the interactions of primary particles with the detector material

- This source of background is strongly suppressed:
  - $|DCA_{xy}| < 0.1$ cm
  - restricting the analysis to p/z >1.5 GeV/*c* (deuteron) and p/z>1 GeV/*c* (^{3}He)

→ contamination from secondary nuclei reduced to a level below 3%



Mass/charge reconstruction

- **Squared mass-over-charge ratio** reconstructed following:

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

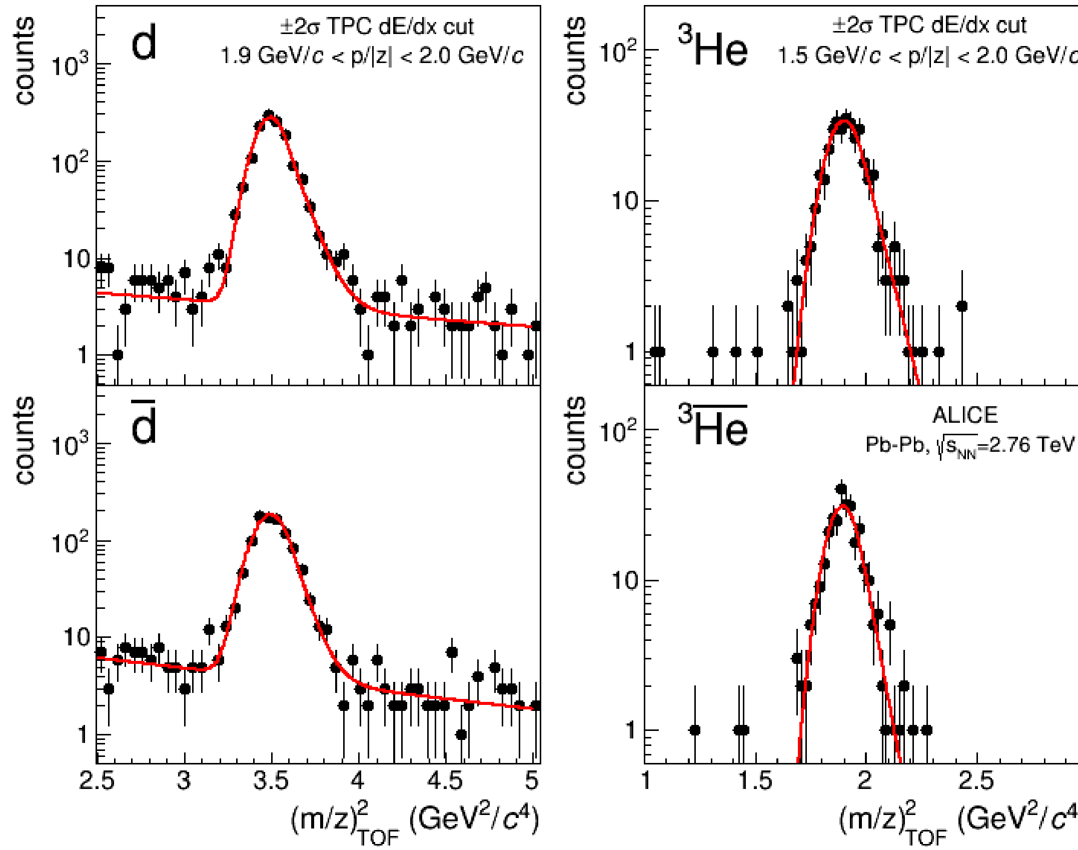
$$\mu^2_{\mathrm{TOF}} \equiv (m/z)^2_{\mathrm{TOF}}$$

- For each particle species the corresponding distribution is fitted in **each p/z and η interval**

- The fit function has two terms, signal + background:

  - signal: **gaussian** distribution **with an exponential tail** (right) according to the TOF time response

  - background: **exponential distribution** (in the deuteron case only)

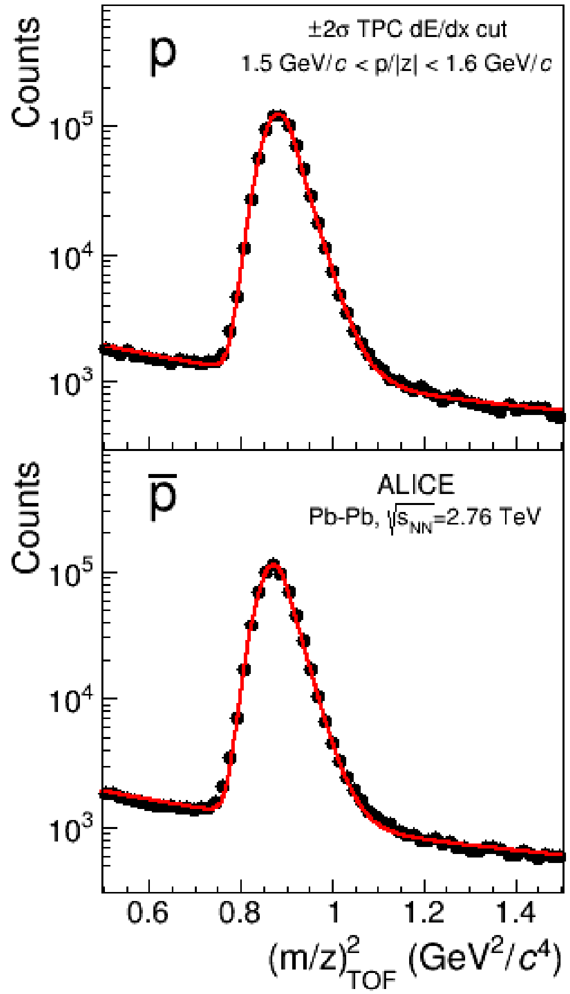


Improving the mass difference determination

- The *difference* of masses ($\Delta\mu_{TOF}$) reduces significantly the syst. uncertainties affecting tracking and time calibration
- The mass independent residual effects (mainly affecting the measurement of the rigidity) are significantly reduced via a correction based on the *(anti-)proton mass*:

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

- Upon inversion of the magnetic field $\vec{B}$ of the experiment the remaining effects (mainly affecting the precision on the determination of the track length) are inverted
  - the average of the two $\vec{B}$ polarities ($\pm$0.5 T) is the best estimate
  - the half-difference represents the corresponding systematic uncertainty on $\Delta\mu$ (see also Tab. next slides)
    - 7 x 10^{-5} for (anti)-deuteron
    - 7 x 10^{-4} for (anti)-^{3}He



Other sources of syst. uncertainties

- **TPC dE/dx cut** (n_{σ}^{TPC})
  - other cuts (tighter and looser: from 1 to 4) scanned to probe the sensitivity of the fit result on the residual background

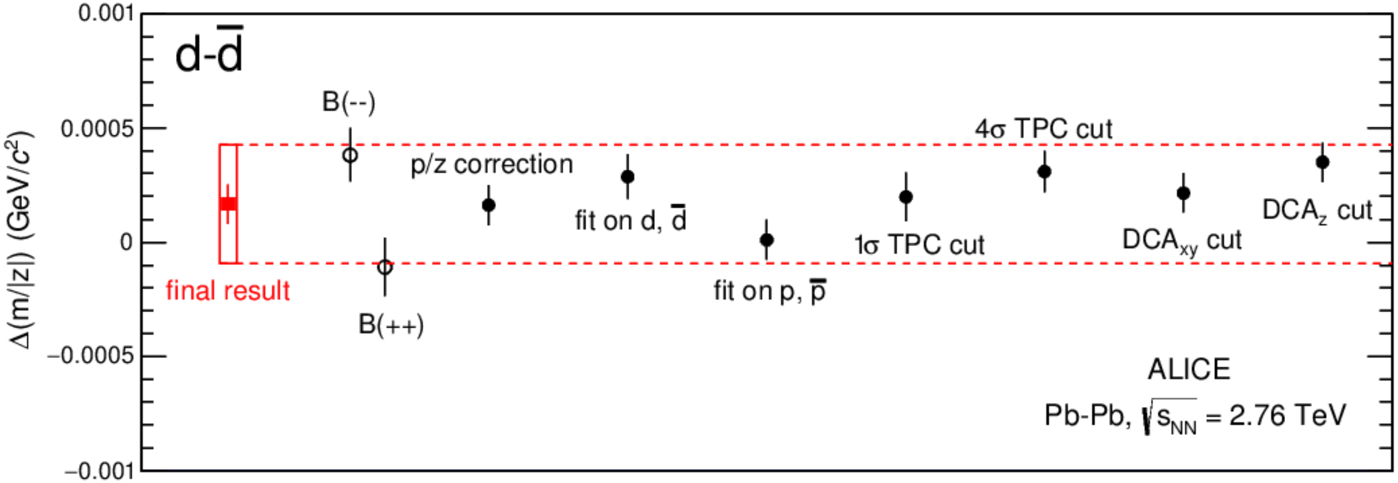
- **Fit of μ^2_{TOF} distributions**
  - assumptions on the fit functions and the range of the fit varied

- The rigidity entering the mass formula is a **mean rigidity** (the particles slow down due to ionization energy loss during their propagation) → dedicated parameterization from Monte Carlo simulations is used to derive it from the rigidity at the IP
  - measurements repeated with/without such correction

- From the **contamination from secondary nuclei**
  - tighter and looser DCA_{xy} cuts varied to evaluate its impact on the final measurement

Summary of syst. uncertainties

Systematic uncertainty	$\Delta\mu_{d\bar{d}}/\mu_d$ ($\times10^{-4}$)		$\Delta\mu_{^3He^3\overline{He}}/\mu_{^3He}$ ($\times10^{-3}$)	
$p/\lvert z\rvert$	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	



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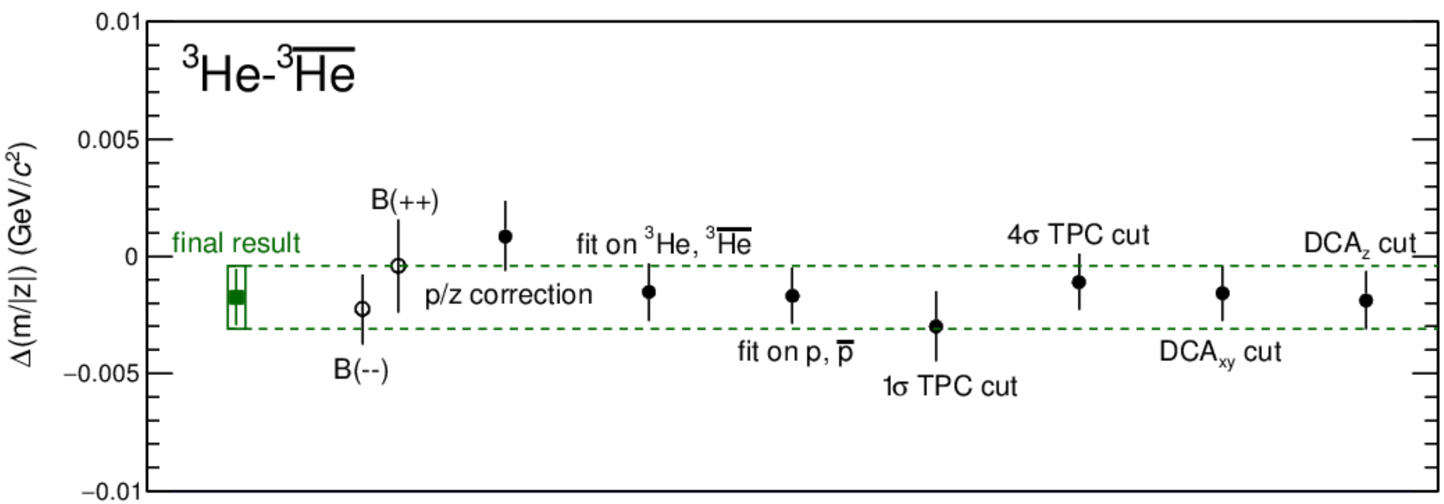
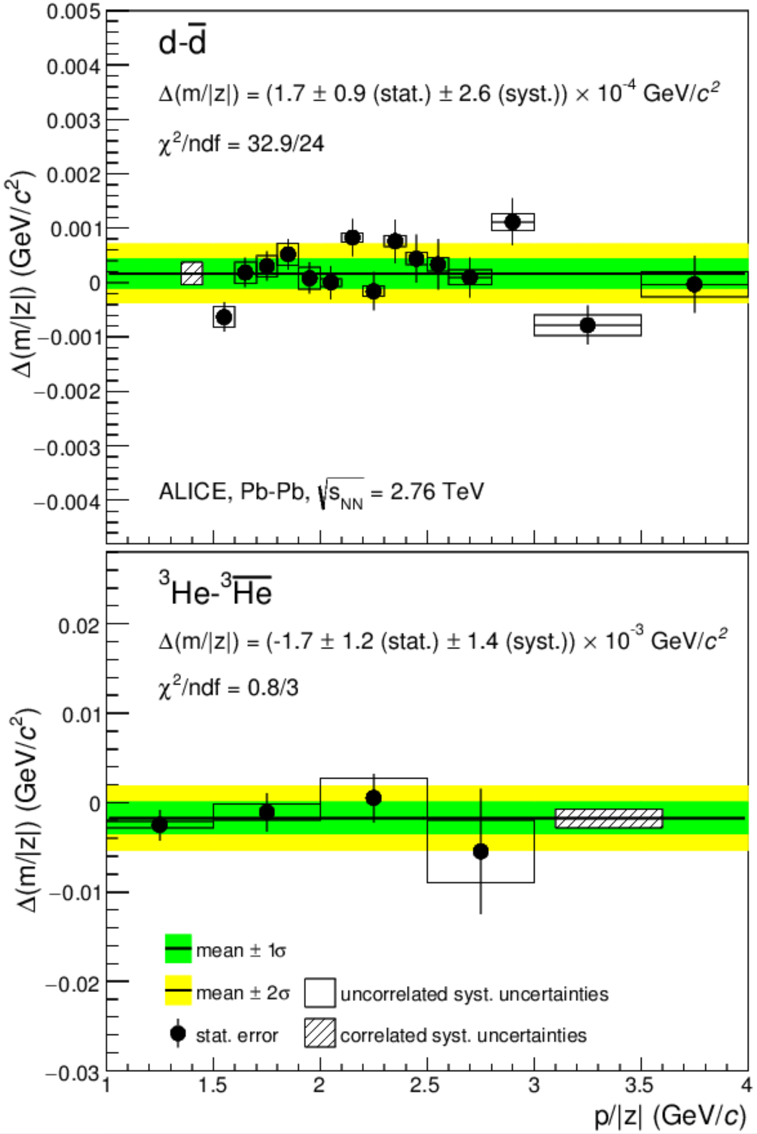
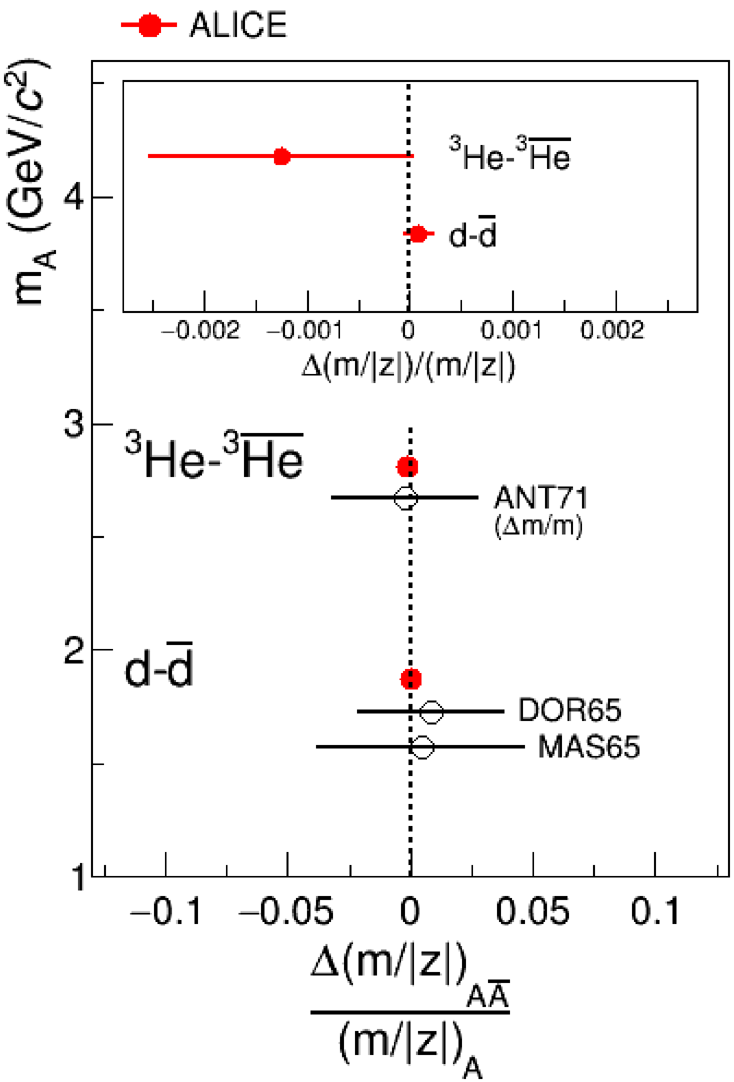


Results



The final measurement is obtained from the weighted average over all rigidity intervals

Results



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

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

- **Highest precision** direct measurements of mass differences in the sector of nuclei
- **Improvement by 1 to 2 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]

Results

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

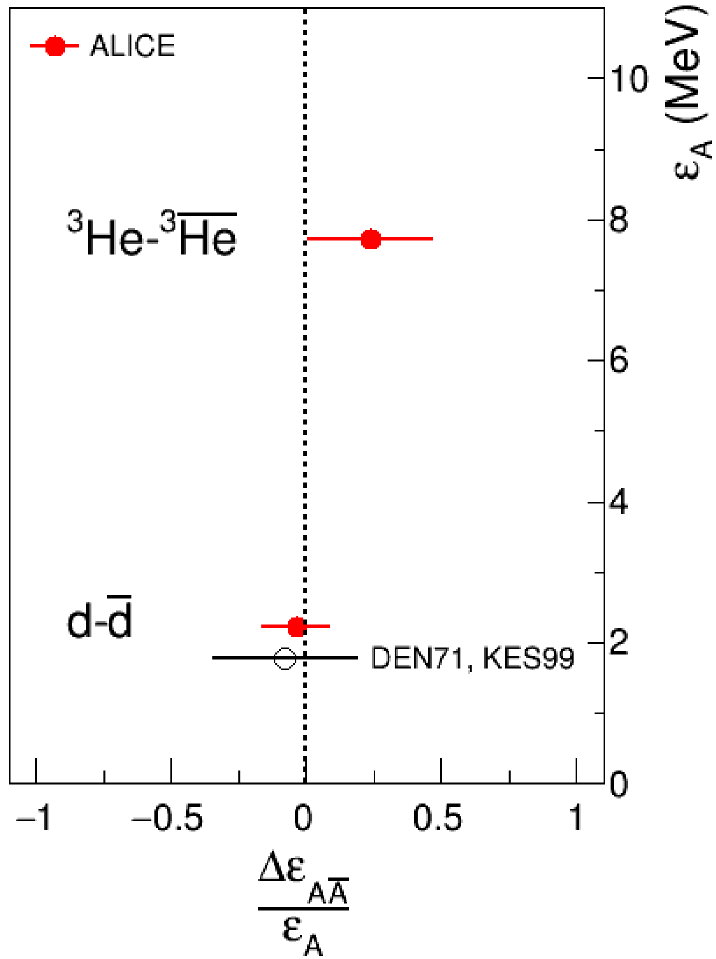
$\Delta m_{\mathrm{p\bar{p}}} < 7 \times 10^{-10}$ GeV (CL=90%)
[*Nature*, **475** (2011) 484]

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

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

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

- Constraint improved by a **factor 2** for (anti-)deuteron case
- $\Delta\varepsilon$ determined for the **first time** in (anti-)^{3}He case

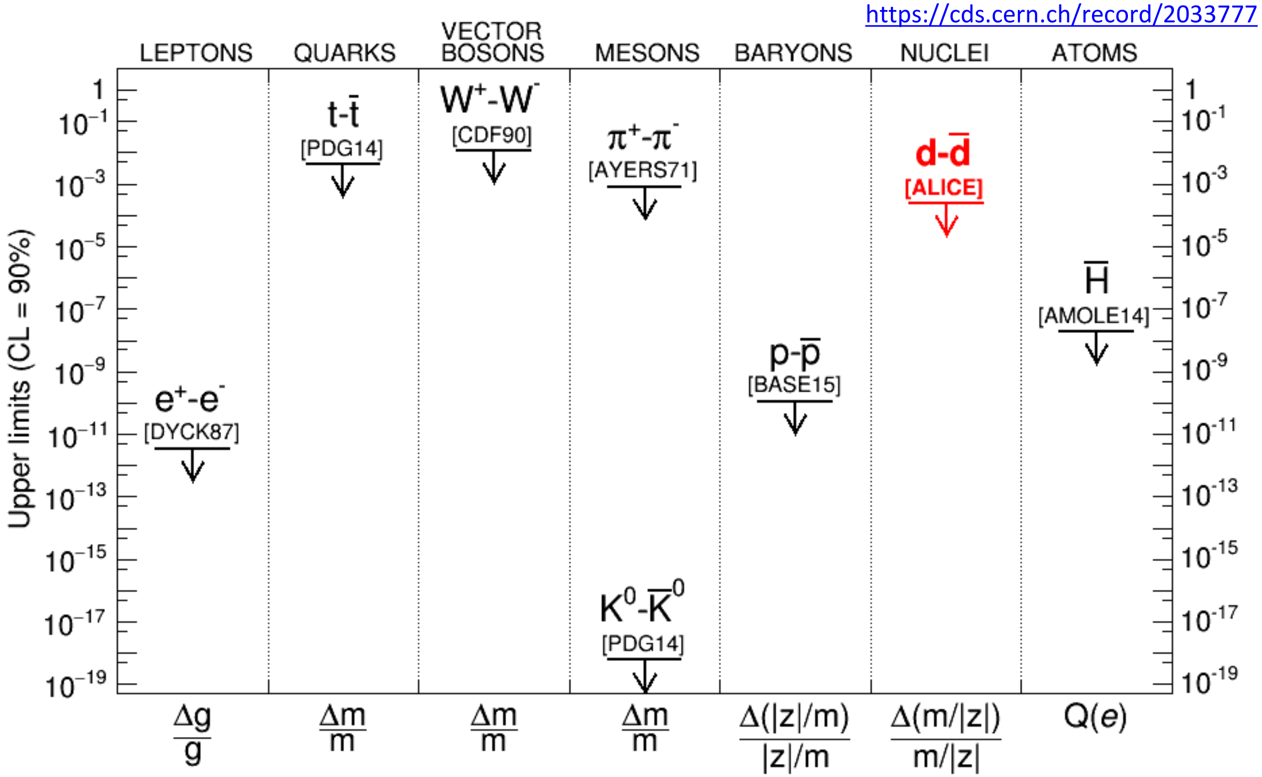


DEN71 [*Nucl. Phys*. B31 (1971) 253]

KES99 [*Phys*.Lett. A255 (1999) 221]

CPT experimental tests

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



- Experimental limits are also used to constrain some CPT violating terms added to the SM lagrangian in the Standard Model Extension (SME)

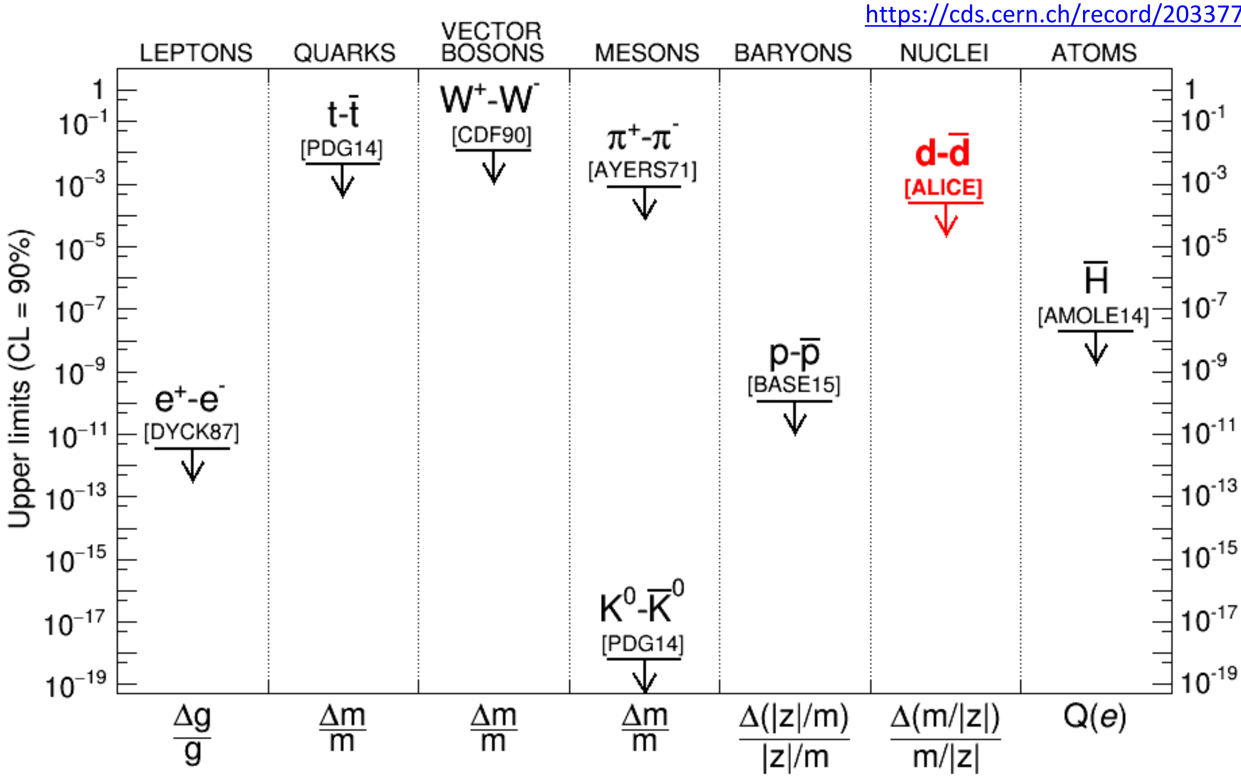
  [*Rev. Mod. Phys.* **83** (2011) 11, arXiv:0801.0287]

These tests *independently* verify each *distinct* prediction of CPT symmetry
[*Chin. Phys.* C 40 (2016) 100001]

- *More recent CPT tests*
  - An improved limit on the charge of antihydrogen from stochastic acceleration [ALPHA Coll. *Nature* 529 (2016) 373]
    → experimental bound on the antihydrogen charge, Qe, of $|Q| < 0.71 \times 10^{-9}$
  - Observation of the 1S–2S transition in trapped antihydrogen [ALPHA Coll., *Nature* 541 (2017) 506]
    → result consistent with CPT invariance at a relative precision of about 2×10^{-10}

CPT experimental tests

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



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[*Chin. Phys.* C 40 (2016) 100001]

- *More recent CPT tests*
  - Measurement of interaction between antiprotons [STAR Coll., *Nature* 527 (2015) 345]

    → scattering length f_0 and effective range d_0 of antiproton-antiproton interaction consistent with antiparticle counterpart at a relative precision of 5×10^{-2} and 6×10^{-1}, respectively

Looking forward: Run 3+4

More statistics is a necessary condition to increase the precision of our measurements:

- 25 Nov.-13 Dec. 2015: 1st period where we successfully collected Pb-Pb collisions at the top energy in the Run 2 of LHC (2015-2018)

→ very significant improvement of the int. luminosity (**100 times more than RUN 1 i.e. L_{int}=10 nb^{-1}**) expected for the **Run 3+4** of LHC (2020-2028) + **ALICE upgrade**

Table 3: Expected yields for light (hyper)nuclear states (and their antiparticles) for central Pb–Pb collisions (0–10%) at $\sqrt{s_{NN}} = 5.5$ TeV. From left to right: (hyper)nuclear species, production yield from the statistical hadronization model [396], branching ratio (only for hypernuclei and exotica states), rapidity interval, and number of expected reconstructed particles for $L_{int} = 10\ nb^{-1}$ [245] and reference for the estimation of the average acceptance-times-efficiency $\langle Acc. \times \epsilon \rangle$ for $p_T > 0$.

State	dN/dy	B.R.	$\|y\| <$	Yield	Ref.
d (TPC)	5×10^{-2}	–	0.5	3.1×10^{8}	[388]
d (TPC+TOF)	5×10^{-2}	–	0.5	1.4×10^{8}	[388]
^{3}He (TOF)	3.5×10^{-4}	–	0.5	2.2×10^{6}	[388]
^{4}He (TPC+TOF)	7.0×10^{-7}	–	0.5	1.5×10^{3}	[388]
$^3_\Lambda$H	1.0×10^{-4}	0.25	1	4.4×10^{3}	[396]
$^4_\Lambda$H	2.0×10^{-7}	0.50	1	1.1×10^{2}	[396]
$^4_\Lambda$He	2.0×10^{-7}	0.54	1	1.3×10^{2}	[396]
Λn	3.0×10^{-2}	0.35	1	2.9×10^{7}	[397]
$\Lambda\Lambda$	5.0×10^{-3}	0.064	1	1.9×10^{5}	[397]
$\Lambda\Lambda$	5.0×10^{-3}	0.41	1	1.2×10^{6}	[397]

[arXiv:1602.04120v1, February 2016]

Summary

- The abundant production of (anti-)nuclei in ultra relativistic heavy-ion collisions combined with the unique **tracking/PID capability of the ALICE experiment** allowed to report on ***rare* quantitative verification of the matter/anti-matter symmetry in the context of the nuclear forces**

- The measurements of $\Delta\mu$ between d and $\overline{\mathrm{d}}$, and $^{3}\mathrm{He}$ and $^{3}\overline{\mathrm{He}}$ have been obtained, **improving by 1 to 2 orders of magnitude** existing results

- The results are also expressed in terms of $\Delta\varepsilon$; for the (anti-)d it improves by a **factor 2** 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

- Remarkably, these improvements are reached in an high energy experiment not specifically designed/built for that

- Significant improved precisions are expected at Run 3+4 of LHC with the upgraded ALICE detector

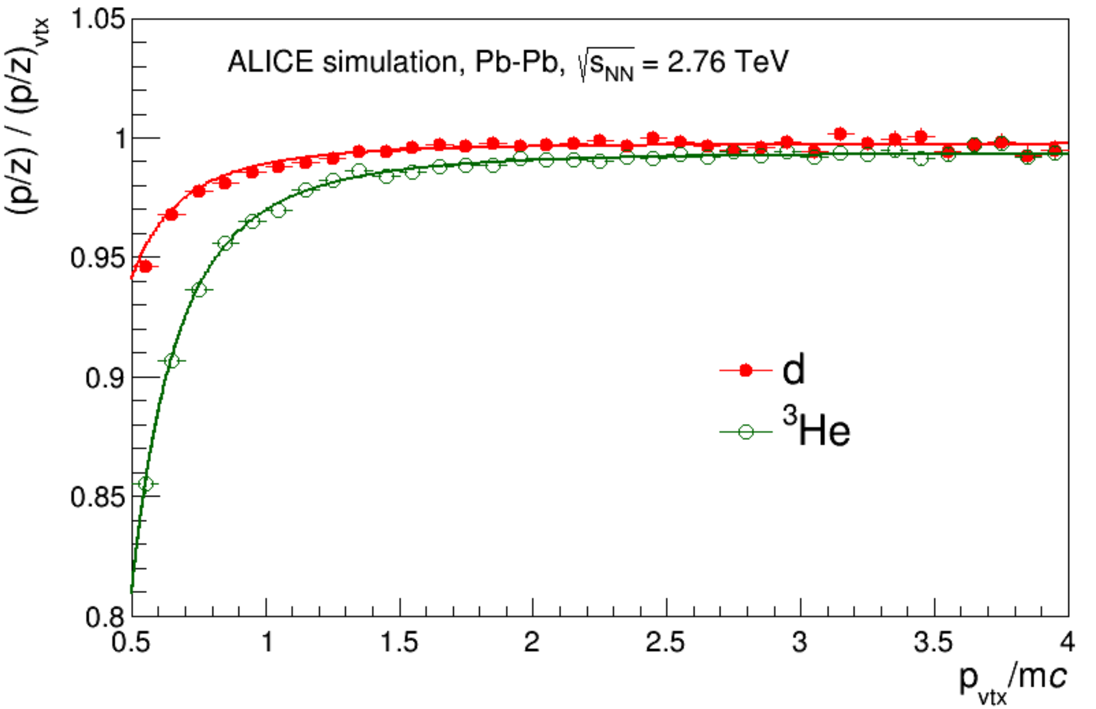
Backup

Thanks for the attention !!

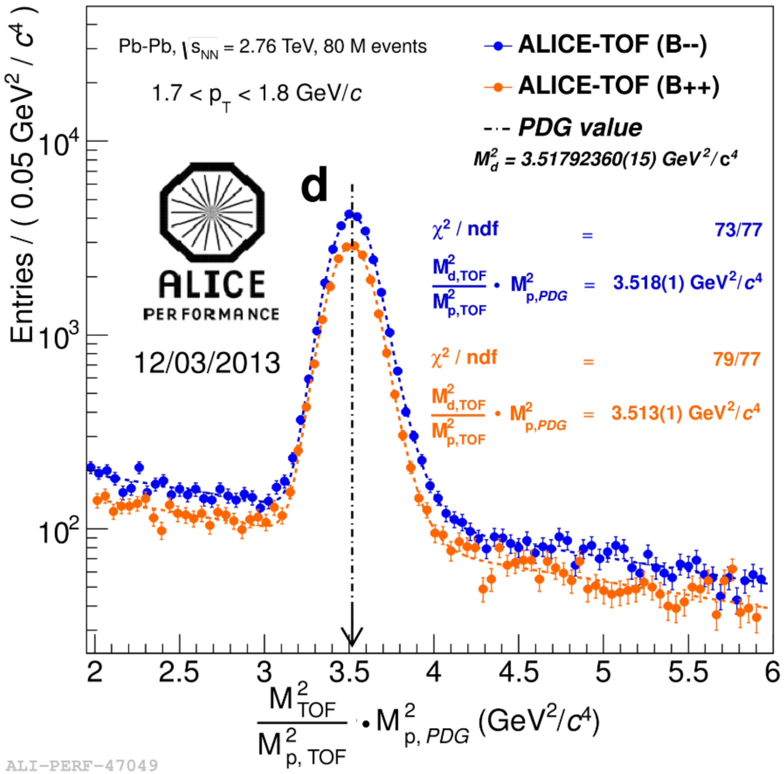
Mean rigidity correction

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

- 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



About the absolute deuteron mass



- After correcting the deuteron mass for the proton one we are able to measure even the absolute mass with an unexpected good precision for a high energy experiment (with other purposes e.g. tracking, PID, …)
- Caveat: in the mass difference most of the syst. uncertainties cancel !

on the tracking uncertainties

On the mass difference the uncertainties related to the particle tracking have to be accounted for.
→ they correspond to an error **on the rigidity (1)** and on the track length (2):

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

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

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

(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 uncertainties

On the mass difference the uncertainties related to the particle tracking have to be accounted for.
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(2) is mass dependent via γ^2 factor.

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

(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 $\delta L/L \leftrightarrow \delta\bar{L}/\bar{L}$...