ALPHA: Precision Measurements of Antihydrogen

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TRIUMF
on behalf of the ALPHA collaboration

Banff, WNPPC 2019, 14 February

Outline

ALPHA @ CERN/AD

ALPHA Collaboration

- 50 people
- 17 institutions
- 8 countries
- Canadian institutions represent about one third of the collaboration

A quick checklist for the ALPHA $\overline{\text{H}}$ experiment(s)

ALPHA-2

- Laser, Microwave, Atomic physics
- *Electromagnetic* interaction
- **CPT invariance** test
- First part of the talk

ALPHA-g

- Atomic physics $\Rightarrow$ Gravitational physics
- *Gravitational* interaction
- **Weak Equivalence Principle** test
- Second (shorter) part of the talk

Hydrogen vs. Antihydrogen

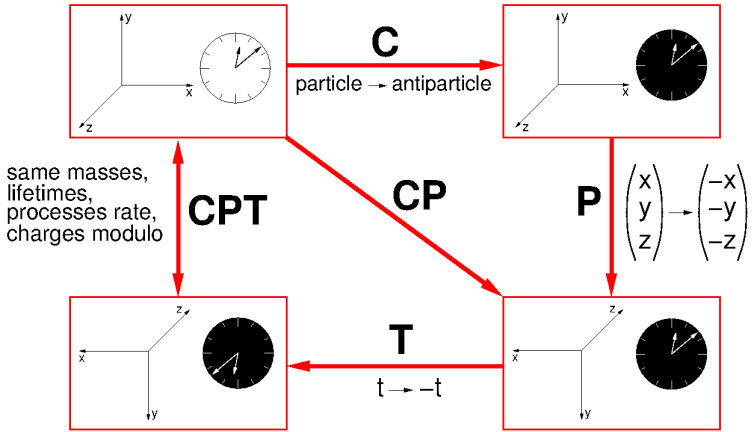
- Hydrogen is the best known physical system
  both theoretically,
  e.g., H. A. Bethe and E. E. Salpeter, *Quantum mechanics of one and two-electron atoms* (1977)
  and experimentally,
  e.g., Atomic Data and Nuclear Data Tables **96**, 586–644 (2010)

- $\overline{\text{H}}$ is the only anti-atomic system that can be, within reach of current technology,
  - shaped in a beam, like ASACUSA or AEGIS
  - trapped in a magnetic trap, like ATRAP and ALPHA (or GBAR)

- High-precision spectroscopy on hydrogen achieved $\mathbf{4 \times 10^{-15}}$
  Phys. Rev. Lett. **107** 203001 (2011)

- Natural linewidth is $\sim$ 0.001ppt of central frequency

What's CPT invariance?



What's CPT invariance?

Every theory with

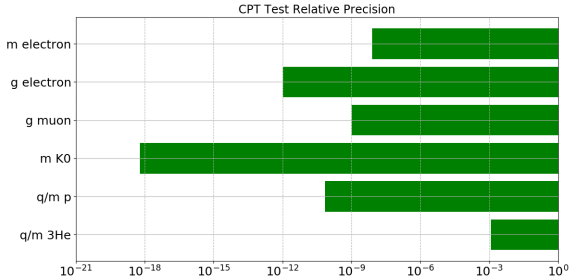
- an Hermitian Hamiltonian $\mathcal{H} = \mathcal{H}^\dagger$
- local operators $\mathcal{O} = \mathcal{O}(\mathbf{x}, t)$,
  constructed from spin zero, one-half and one fields
- usual connection between spin and statics is valid,
  i.e., fermion fields anticommute $\{\psi_i, \psi_j\} = \delta_{ij}$
- products are normally ordered, i.e., $\psi_1^\dagger \psi_2^\dagger \psi_1 \psi_2$

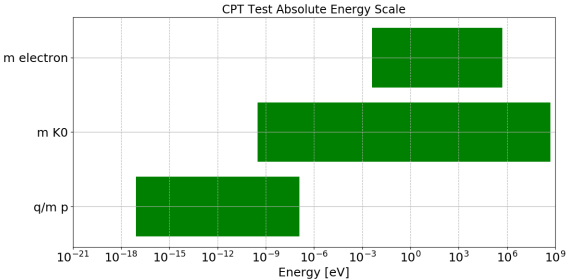
is **invariant** under the combined action of
parity reflection P, *time reversal* T and *charge conjugation* C

G. Lüders, Annals Phys. **2** 1-15 (1957)

Where *invariance* means that the action is unchanged, thus, the equations of motion, following from the variational method, remain unchanged.

CPT Tests





Phys. Rev. D **98** 030001 (2018)

Weak Equivalence Principle

Definition: $m_I = m_G$

First **direct** test of the *Universality of Free Fall* or WEP on antimatter system

- pure antimatter system

$\overline{\mathrm{H}}$ is a convenient tool to test WEP

- charge neutral

less experimental issues, more control over systematics. Nature 529, 373-376 (2016)

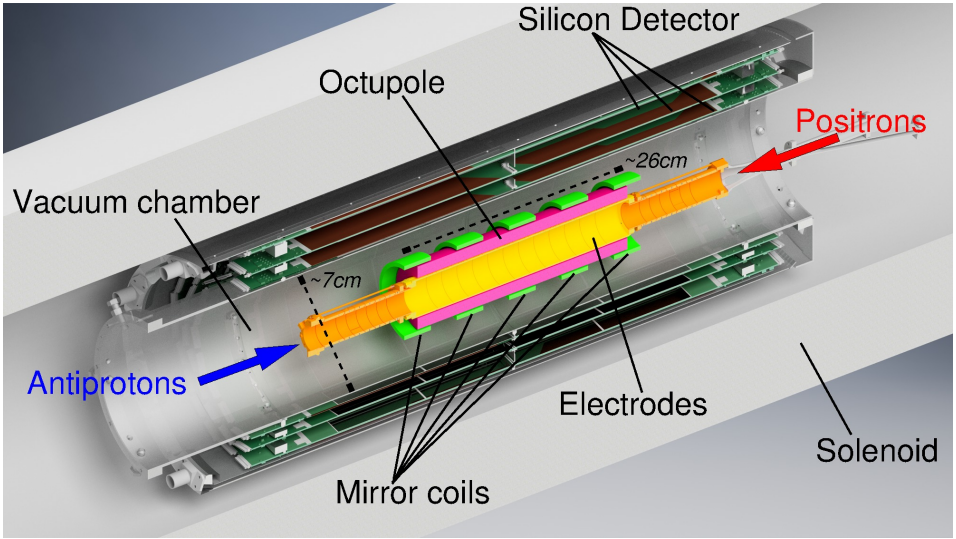
$$\text{The question:} \quad ? < \frac{\overline{m_G}}{\overline{m_I}} <?$$

While looking for new physics, check upon the core principle(s)

Test of GR and more generally of the *metric theories of gravity*
Cosmological implications, e.g., baryon/antibaryon asymmetry

Phys. Rep. **205** 221-281 (1991)

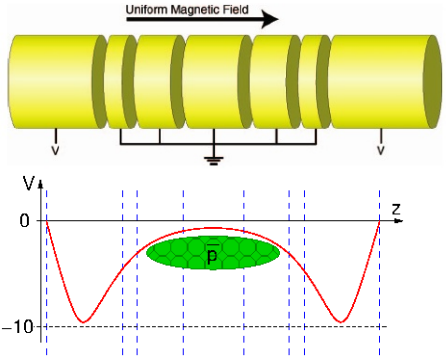
The ALPHA-2 Apparatus



A **Penning trap** holds **charged particles**.

Segmented electrodes provide the axial confinement.

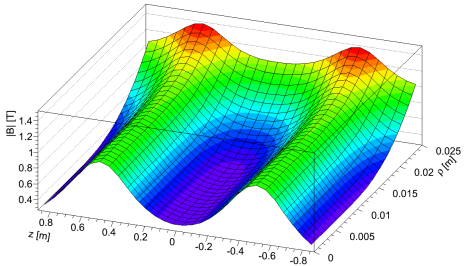
A uniform $\boldsymbol{B}$ provides the radial confinement.



Magnetic Field gradient confines neutral particles: *magnetic dipole moment* - $\mu_{\overline{H}}$.

Potential energy of $\mu_{\overline{H}}$ in a magnetic field is:
$U = -\mu_{\overline{H}} \cdot \boldsymbol{B} = -|\mu_{\overline{H}}||\boldsymbol{B}| \cos(\widehat{\mu_{\overline{H}}\boldsymbol{B}})$

If $\cos(\widehat{\mu_{\overline{H}}\boldsymbol{B}}) < 0$, i.e., $\mu_{\overline{H}}$ is anti-parallel to $\boldsymbol{B}$, $\overline{H}$ is confined by the U-minimum.



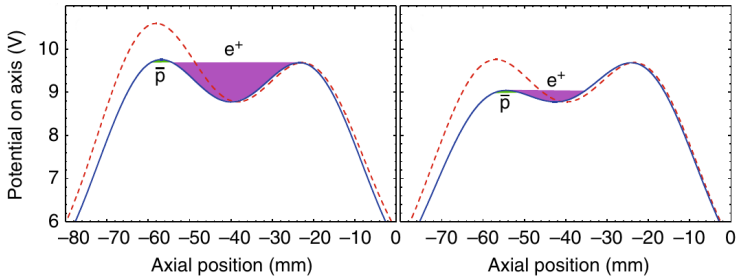
$\boldsymbol{\mu}_{\overline{\mathrm{H}}}$ for ground-state $\overline{\mathrm{H}}$ is dominated by the e^+ spin: $|\boldsymbol{\mu}_{\overline{\mathrm{H}}}| \sim \mu_B \approx 6 \times 10^{-11}\,\mathrm{MeV\,T^{-1}}$

Magnetic field gradient in ALPHA: $\boldsymbol{\nabla} B \sim \Delta B \approx 0.8\,\mathrm{T}$,

The typical trap depth is therefore $\Delta U \sim \mu_B \Delta B \approx 0.5\,\mathrm{K} \approx 50\,\mu\mathrm{eV}$

Only ultra-cold $\overline{\mathrm{H}}$ can be trapped!

Antihydrogen Synthesis



PhotoCredit: ALPHA

1. Morph potentials such that e^+ and $\overline{p}$ are in a nested well.
2. **Mixing** by overlapping the e^+ and $\overline{p}$ clouds.

$$e^+ + e^+ + \overline{p} \rightarrow \overline{H} + e^+$$

Three-body recombination

Phys. Rev. A **69** 010701 (2004)
Phys. Rev. A **70** 022510 (2004)
J. of Phys. B **41** 192001 (2008)

Antihydrogen Detection I

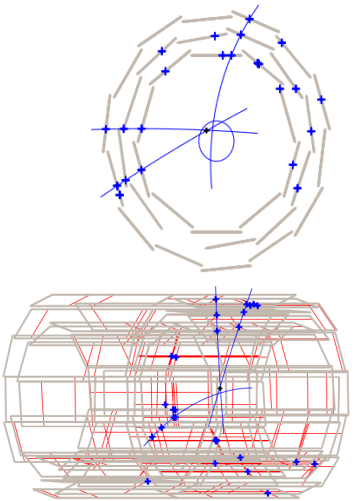
$\overline{H}$ annihilation with Penning trap electrode

$\pi^{\pm}$ from $\overline{p}$ annihilation are detected by the

- **Silicon Vertex Detector**
  - double-sided microstrip tracker

$\overline{H}$ annihilation position $\Longleftrightarrow$ the *vertex*:

1. hits position from clusters of strip,
2. reconstruction of *tracks* from hits,
3. tracks selection, $\pi^{\pm}$-like,
4. determine the point where the tracks pass closest to each other.



Antihydrogen trapped 2018! 1 of 3965

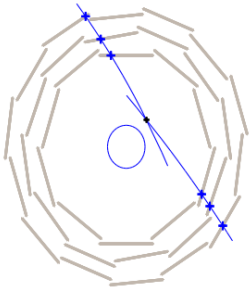
Antihydrogen Detection II

Events unrelated to $\overline{H}$ annihilation are background:

- Un-bound $\overline{p}$, since e^+ annihilation is not detected.
- Cosmic rays, mainly $\mu^{\pm}$, occur at all times.

Two methods used for cosmic ray rejection

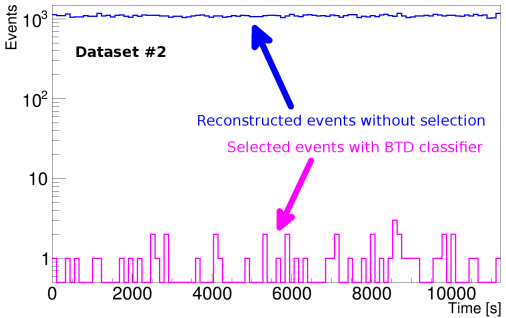
- Cuts on reconstructed vertex radius and on "straightness" of tracks
  - Efficiency: 68%
  - False-positive rate: 47mHz
    Nucl. Instrum. Meth. **A684** 73 (2012)
- Machine Learning - *Boosted Decision Trees*
  - Efficiency: 40%
  - False-positive rate: 4mHz
    J. of Phys. **1085** 042007 (2018)



Application of ML to $\overline{H}$ Detection

Lifetime of Trapped $\overline{H}$: $>$ **66 hours** Hyper. Int. **240** (2019)

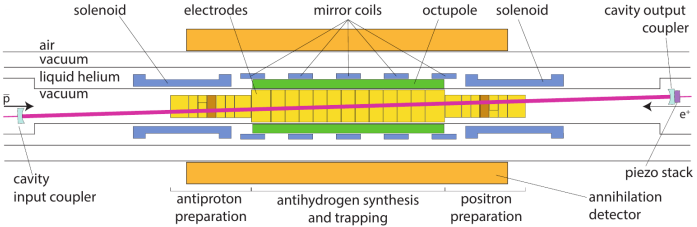
- more than 7 hours of $\overline{H}$ confinement
- more than 1000 $\overline{H}$ trapped
- stacking more than 100 $\overline{H}$ mixing



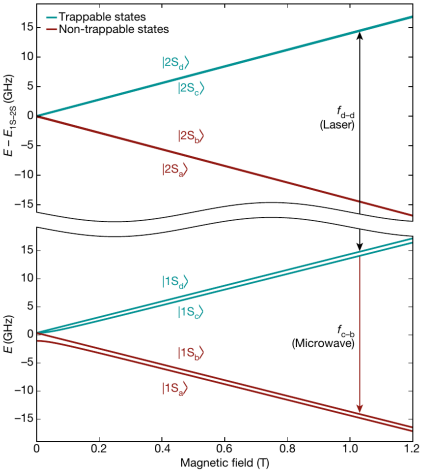
A quick checklist for the ALPHA-2 experiment

1. Ground-State Hyperfine splitting Nature **561** 211 (2018)
2. 1S-2S, in the next few slides
3. 1S-2P Nature **561** 211 (2018), see *Lamb shift in Antihydrogen* by Andrew Evans

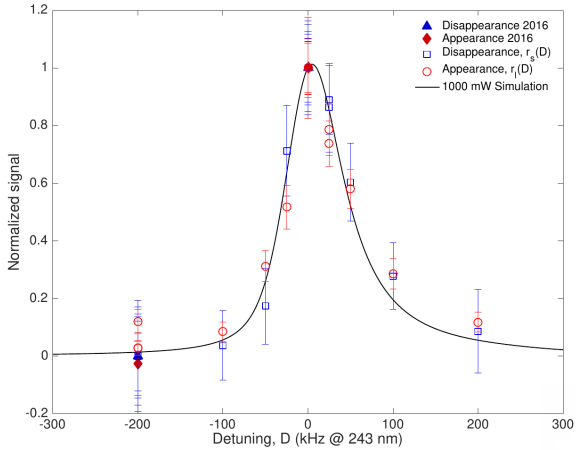
Spectroscopy 1S-2S I



1. Trap antihydrogen (3 mixing cycles, $\sim$40 atoms)
2. Clear out any remaining charged particles
3. 300s laser exposure at fixed frequency near $|1S,d\rangle \rightarrow |2S,d\rangle$ transition
4. 32s microwave sweep to eject $|1S,c\rangle$
5. Ramp down magnets to detect remaining atoms



Nature **557** 71 (2018)



Credit: C. Ø. Rasmussen

Observational channels:

- Appearance - during laser illumination: **1991** $\overline{\text{H}}$ detected
- Disappearance - during trap shutdown: **6137** $\overline{\text{H}}$ detected

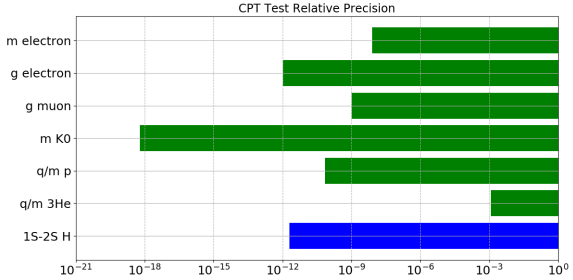
$\gtrsim$ **15000** $\overline{\text{H}}$ trapped

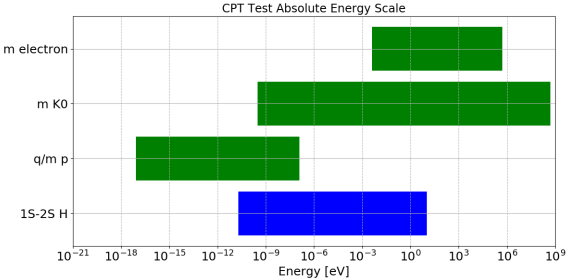
Lineshape predicted by simulation, assuming CPT conservation

Fit of the experimental data

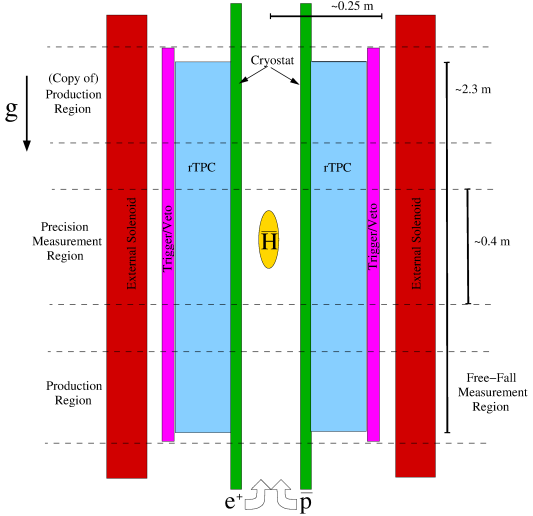
$f_{\text{d-d}} = 2\,466\,061\,103\,079.4(5.4)\,\text{kHz}$

CPT Tests - Updated





ALPHA-g



- Vertical $\overline{H}$ trap for gravity measurement
- Two identical ALPHA-2-like production regions at either ends
- Central region to perform the measurement

Goals:

- Unambiguous observation of $\overline{H}$ free-fall
- Measurement of $\overline{H}$ gravitational mass to 1%

Planned Measurement of the $\overline{H}$ Gravitational Mass

- Slow (≥ 10 s) release of $\overline{H}$ by ramping down only mirror coils
- Detection of $\overline{H}$ annihilation with tracking detector
- With equal currents in the mirror coils

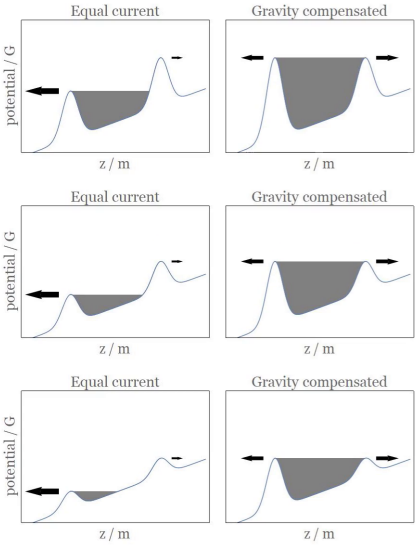
$\Rightarrow$ Larger amount of $\overline{H}$ escapes downward

- With larger current in bottom coil

$\Rightarrow$ Equal amount of $\overline{H}$ annihilate upwards and downwards

$\Rightarrow$ Gravity compensation: Targeted precision 1%

Credit: C. So



Experimental Challenges

Gravitational potential energy $U_g = mg\Delta z$, if $m = m_{\overline{\mathrm{H}}}$ and $\Delta z = 40\,\mathrm{cm}$

$$U_g \approx 4 \times 10^{-8}\,\mathrm{eV}$$

This corresponds to a magnetic field of

$$\frac{U_g}{\mu_B} \approx 0.7\,\mathrm{mT}$$

and to a temperature of

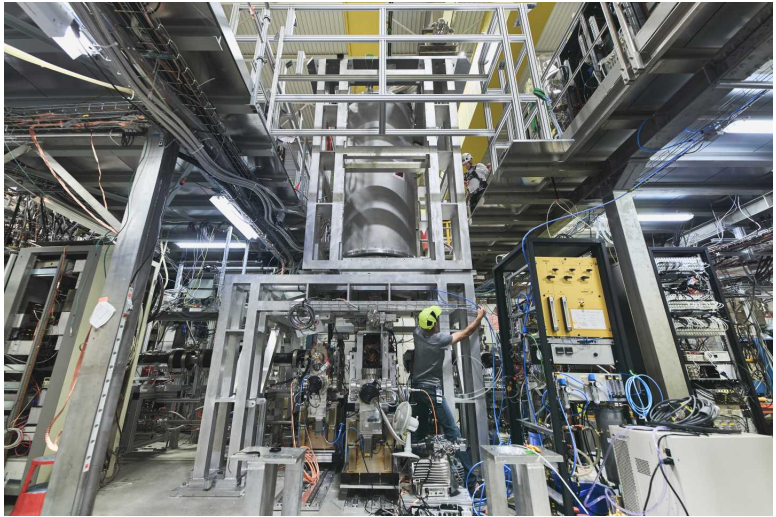
$$\frac{U_g}{k_B} \approx 0.5\,\mathrm{mK}$$

- Controlling magnetic fields to $\sim 10^{-4}\,\mathrm{T}$ is required.
- For 1% measurement magnetic environment must be controlled to $10^{-6}\,\mathrm{T}$.
- Using cooled $\overline{\mathrm{H}}$ is highly desirable, given that $\overline{\mathrm{H}}$ temperature could be 10^3 higher

Detection Challenges

- Detection over large volume
- Uniform efficiency, e.g., “top” vs “bottom”
- Annihilation position axial resolution
- Background rejection

ALPHA-g apparatus built in 2018



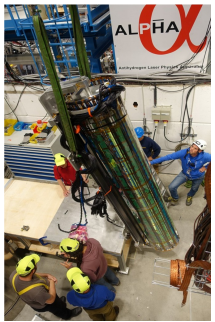
see *Commissioning the ALPHA-g Experiment at CERN* by Adam Powell

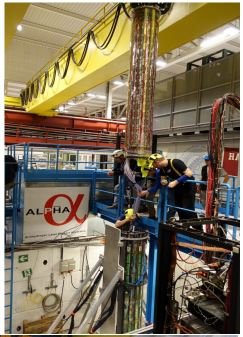
Radial Time Projection Chamber

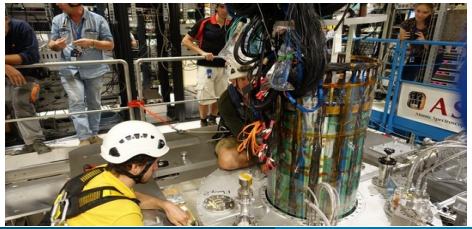
Gas detector to track charged particles produced by $\overline{\mathrm{H}}$ annihilation.
rTPC was entirely built at TRIUMF

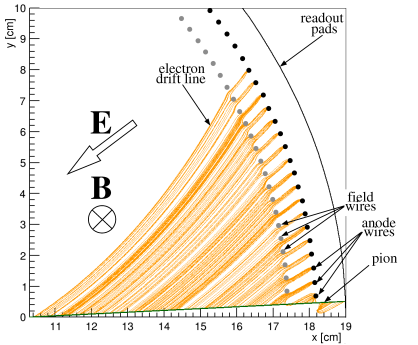
- 2.3 m active length
- 8 cm drift path
- 180 litres of Ar-CO_2 70:30
- 256 anodes (sensing wires)
- 576 $\times$ 32 pads = 18432 channels
- cathode -4 kV, anodes 3.1 kV

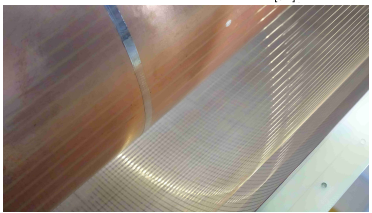
rTPC Installation - Summer 2018





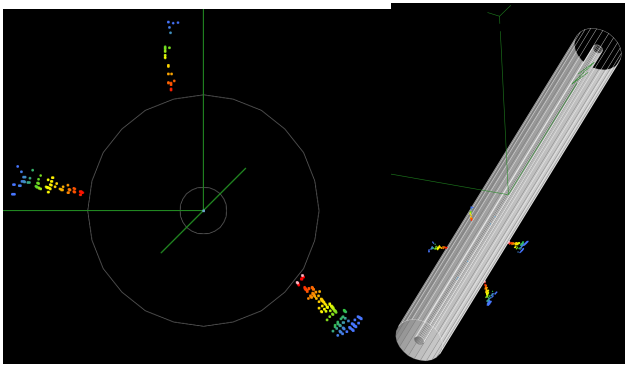






Spacepoints Reconstruction:

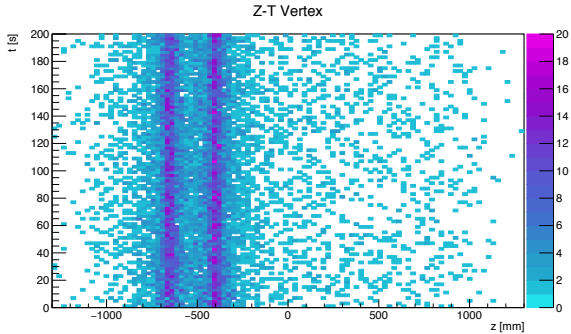
- e^- *drift time* $\Rightarrow$ Radial coordinate
- Anode position $\Rightarrow$ Azimuthal coordinate
- Charge induced on pads $\Rightarrow$ Axial coordinate

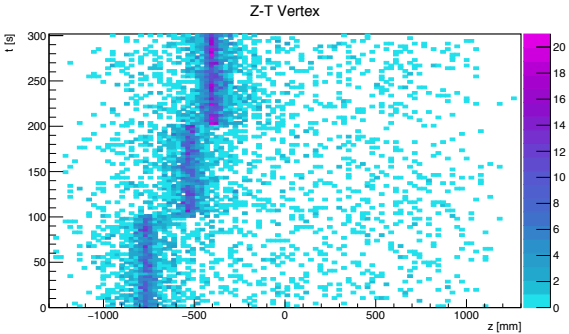


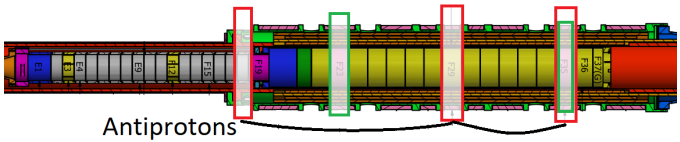
rTPC Commissioning - Fall 2018

Confine $\bar{p}$ in different electrodes $\Rightarrow$ Z resolution

Hold them for few minutes $\Rightarrow$ Commissioning of Penning trap





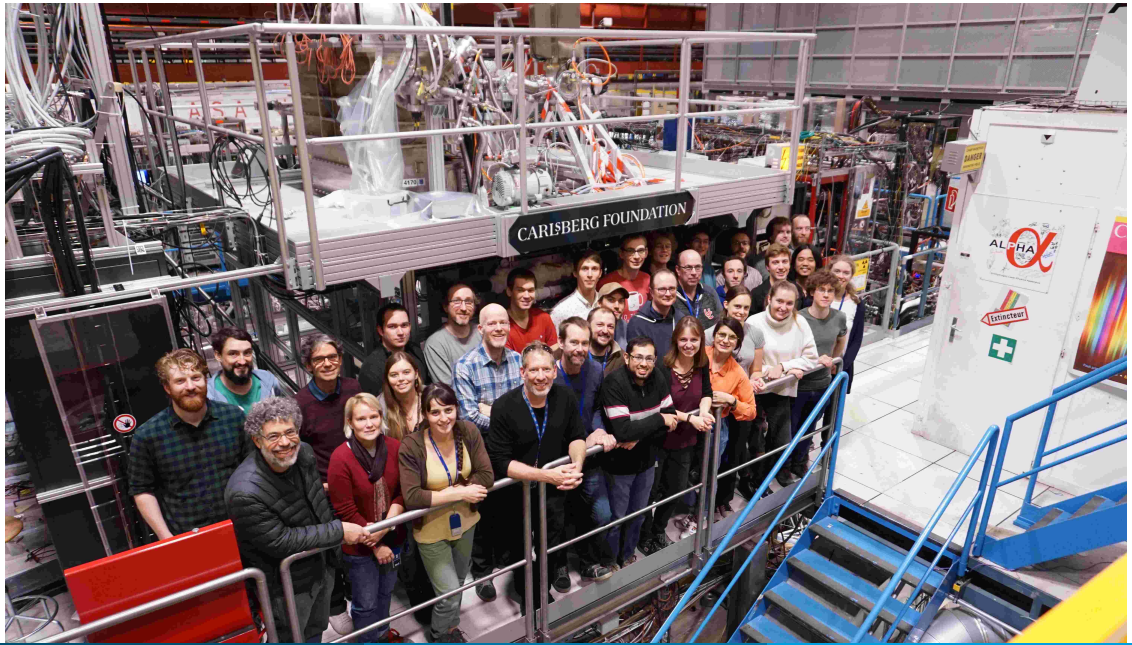


Outlook

- Increase precision of the 1S-2S measurement
- 1S-2S at different magnetic field to extract the “zero-field” limit
- Improve GS-HFS splitting measurement
- 2S-nS and 2S-nP
- Laser cooling
- Observe $\overline{\mathrm{H}}$ free-fall
- Determine its gravitational mass to 1%

Conclusions

- $\overline{H}$ is a portal to study CPT invariance violation
- The ALPHA antimatter apparatus is designed to perform precision spectroscopy of $\overline{H}$
  - 1S-2S transition measured at ppt level
  - ground state hyperfine splitting
  - 1S-2P to open the door for laser cooling of $\overline{H}$
- $\overline{H}$ is a tool to study post-Newtonian gravity
- ALPHA is gearing towards a measurement of the $\overline{H}$ gravitational mass with the ALPHA-g apparatus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