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ALPHA

Measurement of anti-hydrogen acceleration in Earth’s gravitational field

Marta Urioni on behalf of the ALPHA collaboration

Bormio Conference

60th International Winter Meeting on Nuclear Physics

22 - 26 January 2024
Bormio, Italy

Antimatter and gravity

- The theory of **General Relativity** has passed a number of stringent experimental tests *(Will, C.M. The confrontation between general relativity and experiment. Living Rev. Relativ. 2014, 17, 1–117)*
- One of the principles of GR is the **Weak Equivalence Principle (WEP)**: all objects fall at the same rate, regardless of their internal composition or structure.

WEP is **expected to hold for antimatter**

A **deviation from WEP** could signal:

- incompleteness in our interpretation of gravity
- or the presence of new interactions (fifth forces), vector and scalar mediated forces that couple to some combination of baryon and lepton number *(arXiv:0808.3929)*

Antimatter and gravity

Previous "free fall" experimental attempts:

- 1967: Fairbank and Witteborn tried to use positrons *(Phys. Rev. Lett. 19, 1049 (1967))*
- 1989: PS-200 experiment at CERN tried to use (4 K) antiprotons *(Nucl. Instr. and Meth. B, 485 (1989))*

Failed: charged particles are susceptible to electromagnetic fields that are stronger than gravity

ALPHA as well as **AEGIS** and **Gbar** study gravity on **anti-hydrogen** because of its neutrality

- How much of antiproton is antimatter? *(arXiv:1207.7358)*

most of the inertial mass of an (anti)proton comes from its binding energy. Quark mass is ~1%

Antihydrogen Laser PHysics Apparatus

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Pavia, Pisa) Italy

Stockholm University, Sweden

Simon Fraser University, Canada `

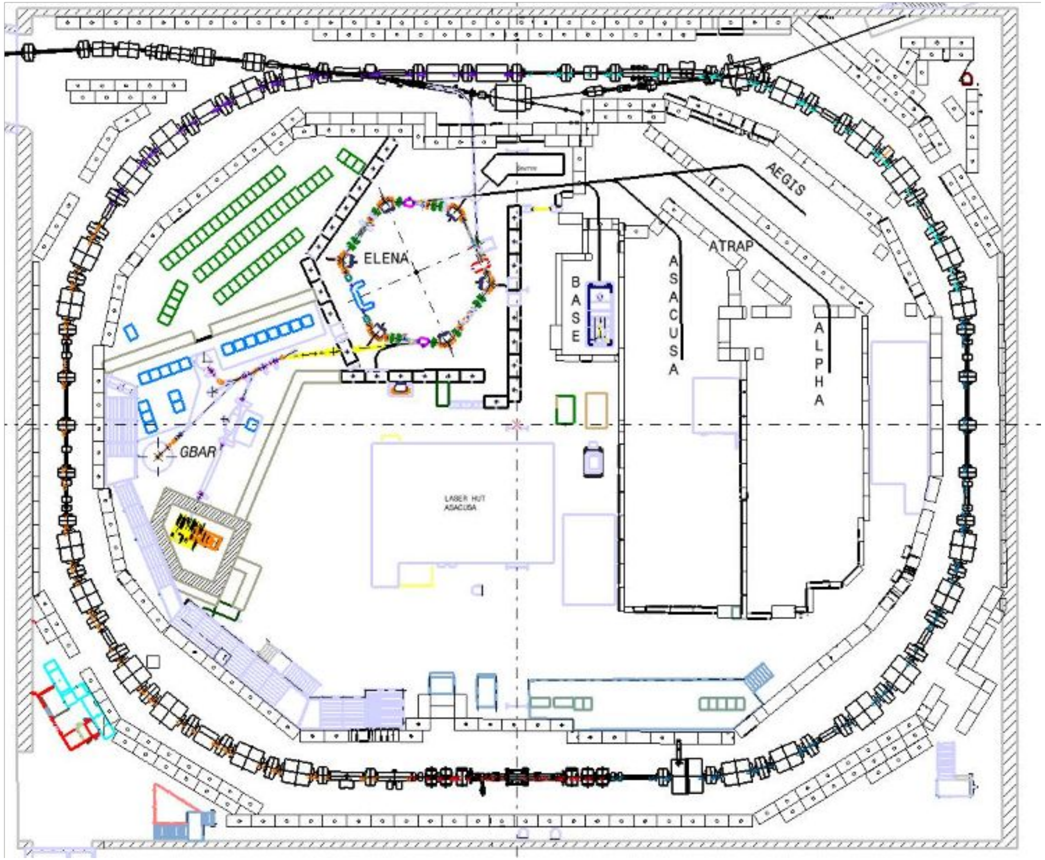
TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

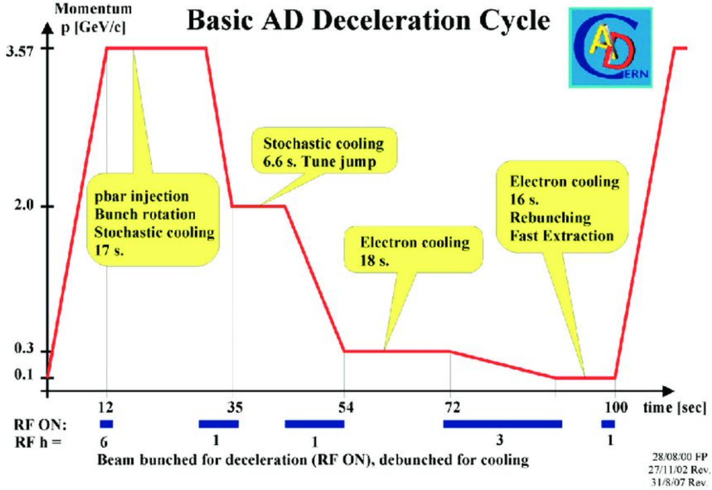
York University, Canada

The antimatter Factory



ALPHA (*Antihydrogen Laser PHysics Apparatus*) located in the antimatter factory where antiprotons produced in a proton beam-target collision are decelerated:

- The **AD**: pbar to an energy of **5.3 MeV**
- The **ELENA** ring 10^7 pbar at **100 keV**

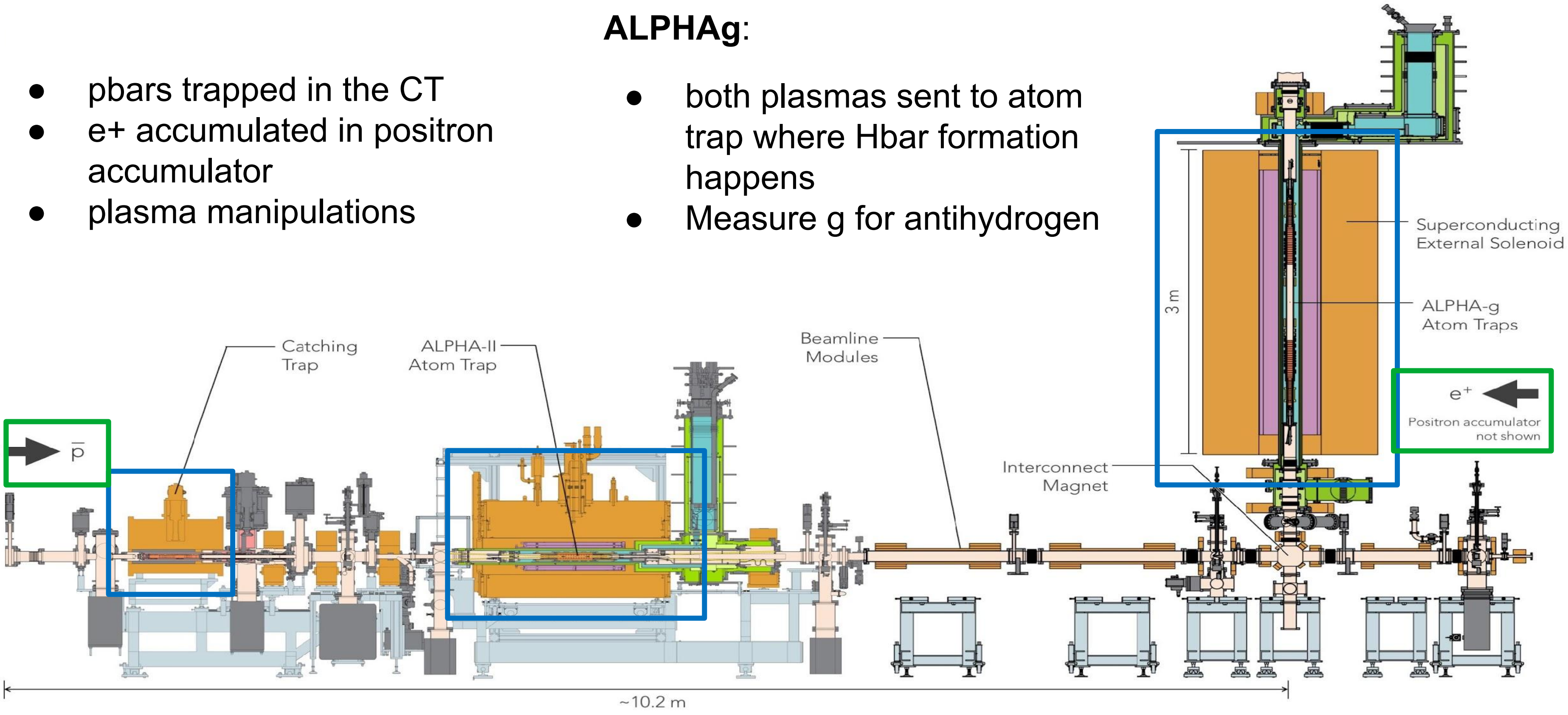


ALPHA Schematic

- pbars trapped in the CT
- e+ accumulated in positron accumulator
- plasma manipulations

ALPHAg:

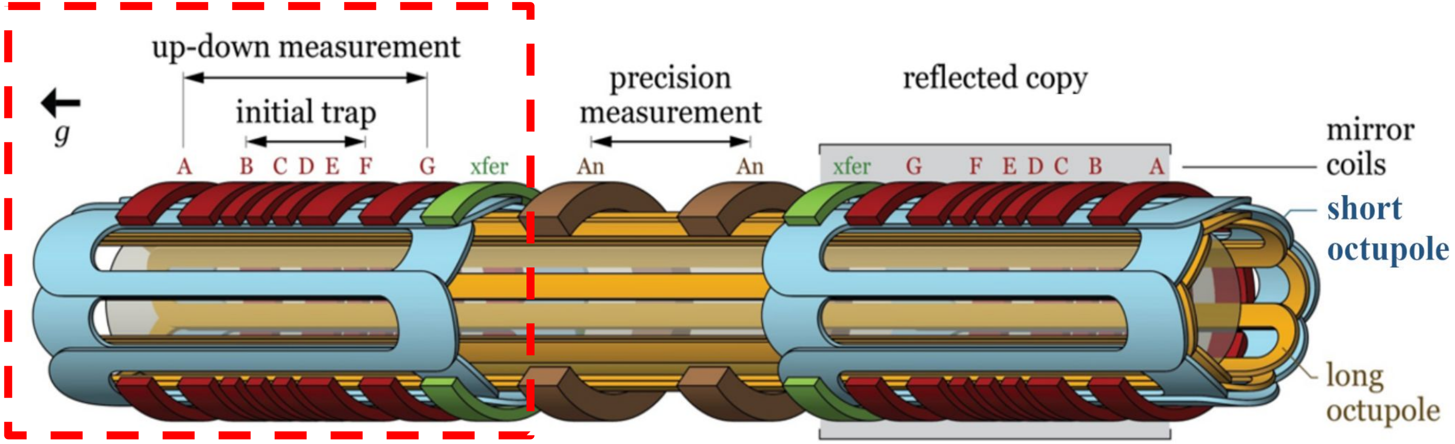
- both plasmas sent to atom trap where Hbar formation happens
- Measure g for antihydrogen



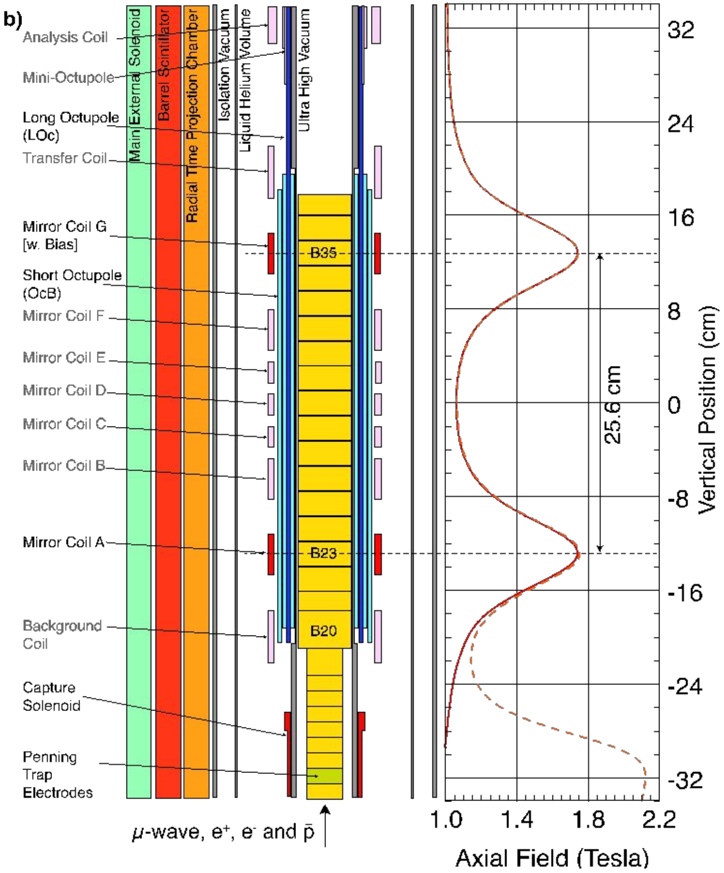
ALPHAg magnets

In ALPHAg:

- Three trapping regions
- **Long+short octupoles:** minimise field errors due to fabrication tolerance in central ("precision") region
- **Precision region:** designed to perform a 1% precision g measurement
- But in the 2022 measurement just the **long octupole** and the **bottom trap** were used



Hbar production and detection in the bottom trap



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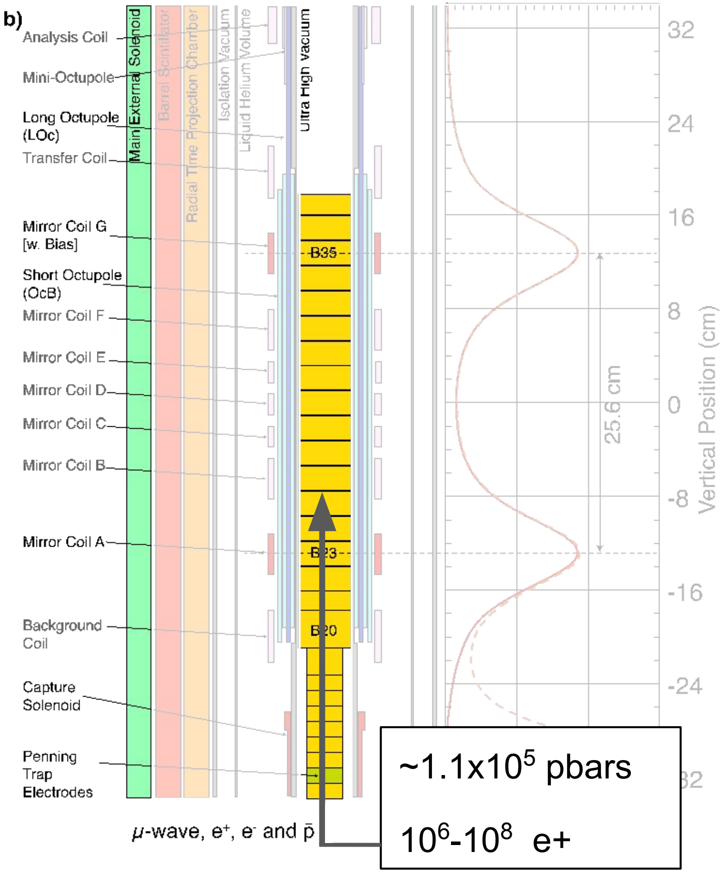

- antihydrogen is formed by gently **mixing** the clouds of **positrons** and **antiprotons**

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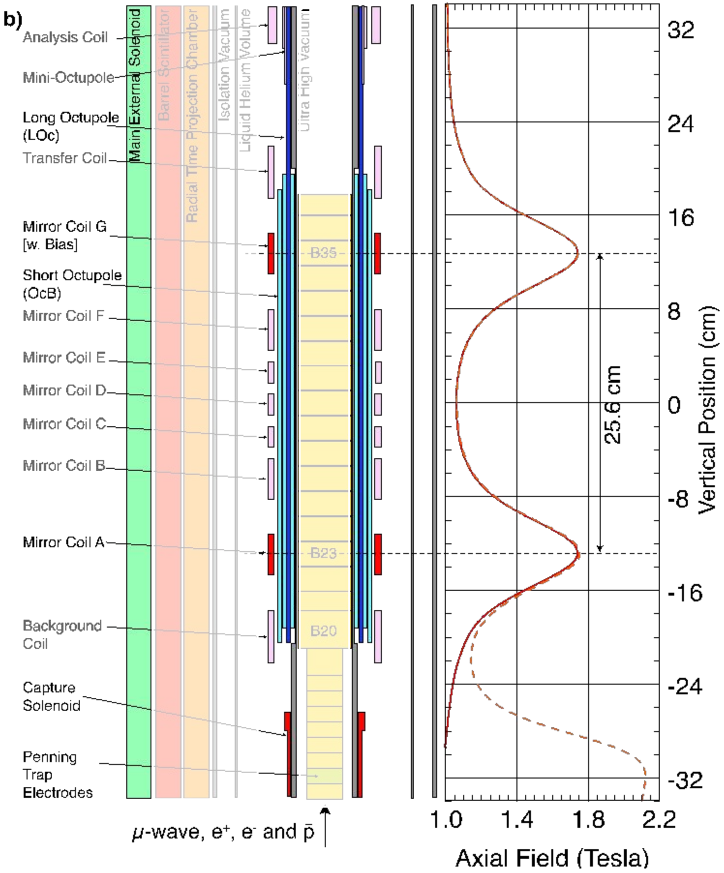
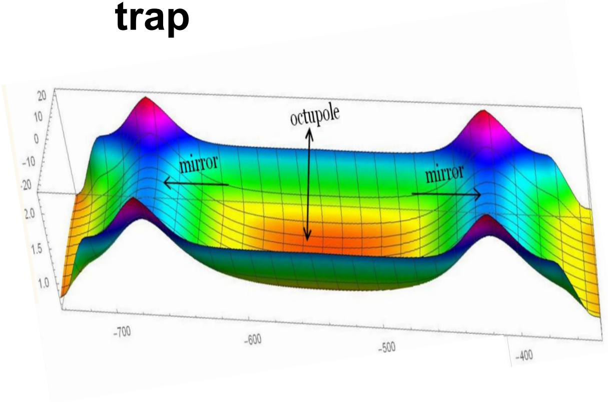


- antihydrogen is formed by gently **mixing** the clouds of **positrons** and **antiprotons**

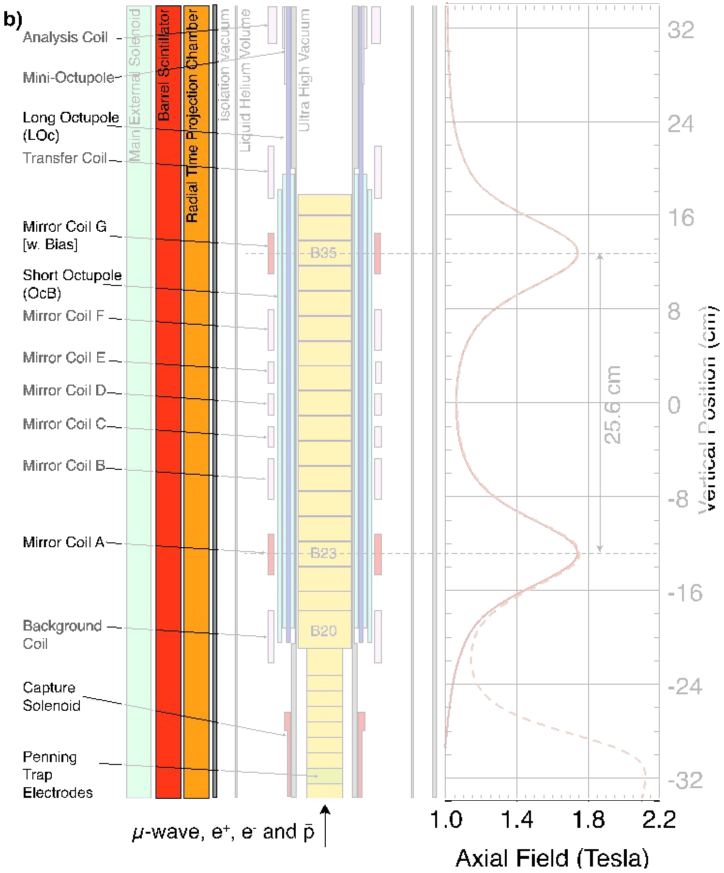
- Hbar is then **trapped in** the **ALPHAg atom trap**



confinement potential $U = -\boldsymbol{\mu}_{\bar{H}} \cdot \boldsymbol{B}$

$\mu^{\parallel}_{\bar{H}} = \pm\mu_B$

Hbar production and detection in the bottom trap



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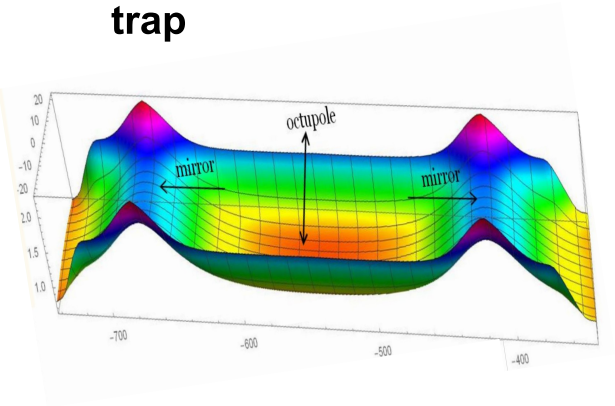

confinement potential $U = -\boldsymbol{\mu}_{\bar{H}} \cdot \boldsymbol{B}$

$\mu_{\bar{H}}^{\parallel} = \pm\mu_B$

- Hbar is **released** and annihilation vertex is reconstructed via:
    - **rTPC**
    - **Scintillators barrel veto**

ALPHAg measurement procedure

- **Magnetic fields and gravitational field** act on Hbars: $U = -\boldsymbol{\mu_H} \cdot \mathbf{B} + m_H g h$
- Goal: measure the **gravitational acceleration of Hbar**
- Assumptions: $\mu_{\bar{H}} = \mu_H$, $m_{\bar{H}} = m_H$ *(Phys. Rev. Lett. 59, 26 – 6 July 1987), (Nature **475**, 484–488 (2011))*

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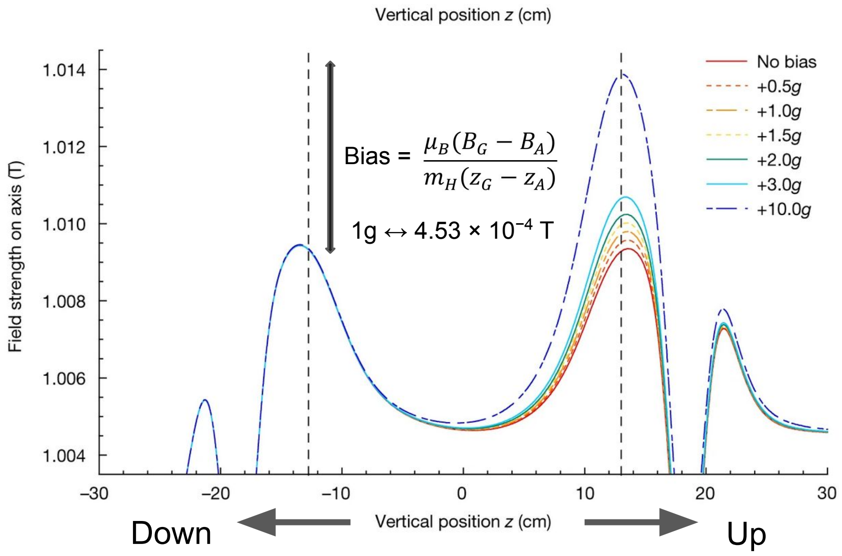
General concept:

- **measure total potential** via the **asymmetry *A*** between number of up annihilations and down annihilations when releasing vertically the Hbars

$$A_i^{raw} = (N_{u,i} - N_{d,i})/S_i$$



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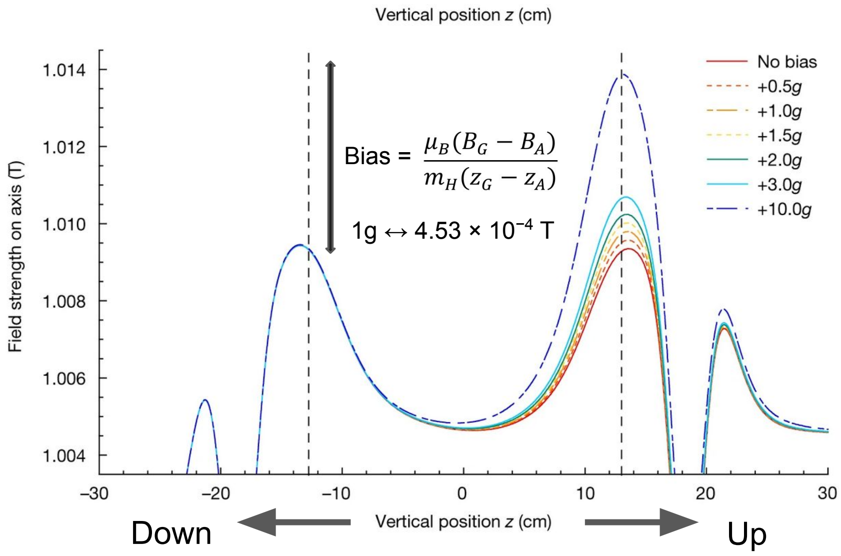
  - via ancillary B field measurements
- This is **repeated** at **different** magnetic field **configurations** (Biases)



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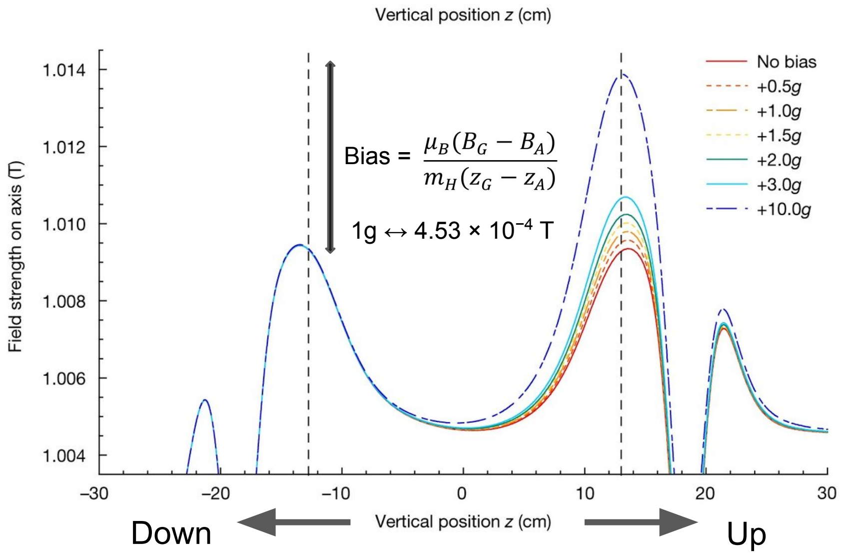
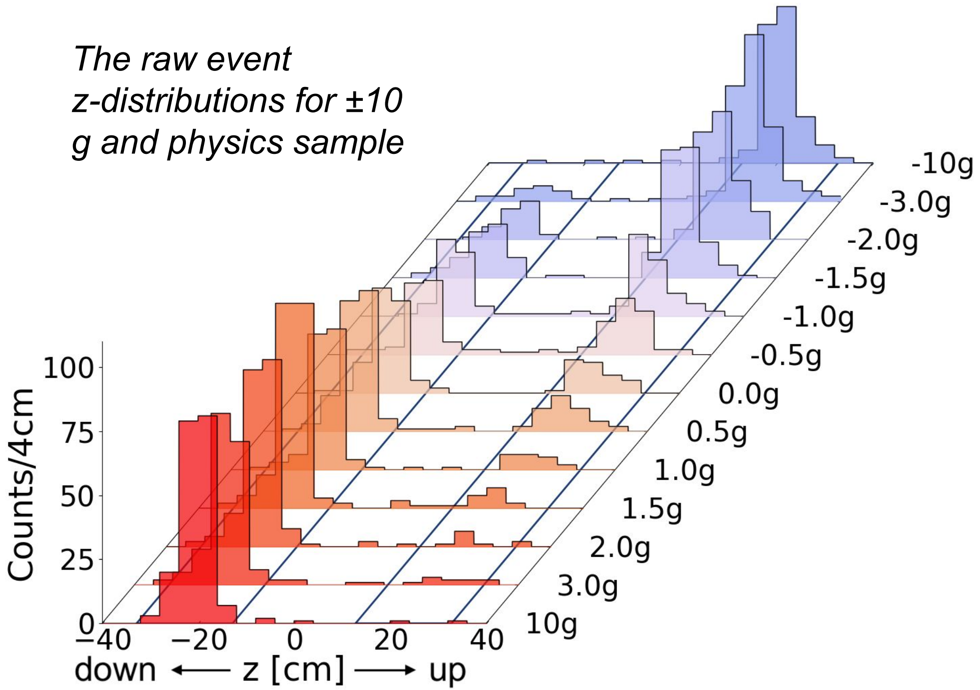
- **measure magnetic potential**:
  - via ancillary B field measurements
- This is **repeated** at **different** magnetic field **configurations** (Biases)
- subtraction of the effect of magnetic potential in order to **obtain the gravitational one**
  - in practice relation between potentials and asymmetry is obtained **from simulation**



Analysed data

The raw event z-distributions for ±10 g and physics sample



- **±10 g** *calibration sample*, collected with a fast MAGB ramp-down of the upper/lower gate
- **Background** enriched *calibration sample* (with no antip in the experiment)
- **±3 g, ±2 g, ±1.5 g, ±1 g, ±0.5 g, 0 g**: *physics sample*, with fast (20 s) ramp of the MAGB.

- *Calibration samples* and *LoC ramp-down*: to determine the detector response
- *Physics sample*: for the determination of the up-down annihilation asymmetries (A^{raw}) for each bias

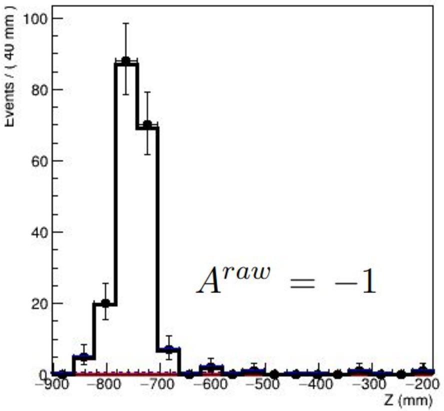
Model definition and calibration

- Likelihood for the release ramp annihilation positions Z in a given bias configuration (*i* bias label):

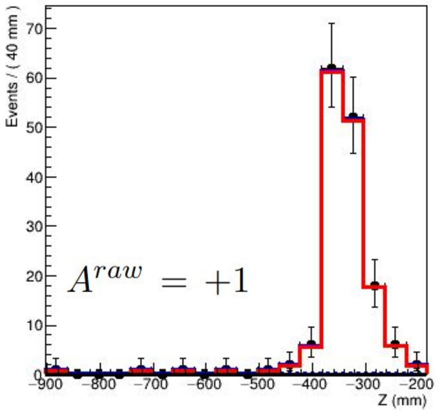
$$\mathcal{L}_i(\mathbf{Z}_i|A_i^{raw}, S_i) \propto e^{-(S_i+B_i)} \prod_{z_e \in \mathbf{Z}_i} [\frac{1}{2}S_i(1-A_i^{raw})f_d(z_e)+\frac{1}{2}S_i(1+A_i^{raw})f_u(z_e)+B_i f_b(z_e)]$$

PDF in z for upwards, downwards released Hbar, and background fixed by fitting

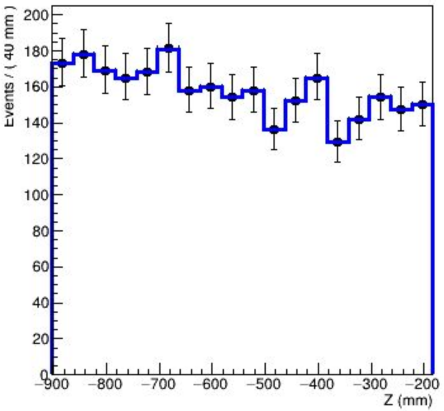
down release template
+10g calibration sample



up release template
-10g calibration sample



background template
cosmic ray data



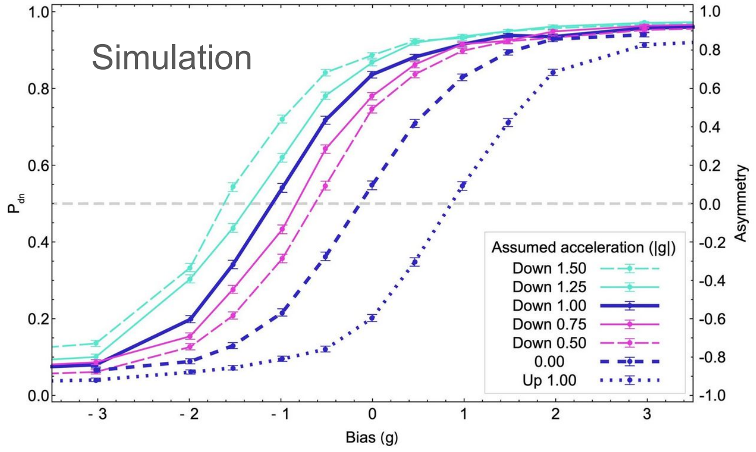
The release asymmetry

- Likelihood for the release ramp annihilation positions Z in a given bias configuration (*i* bias label):

$$\mathcal{L}_i(\mathbf{Z}_i|A_i^{raw}, S_i) \propto e^{-(S_i+B_i)} \prod_{z_e \in \mathbf{Z}_i} [\frac{1}{2}S_i(1-A_i^{raw})f_d(z_e)+\frac{1}{2}S_i(1+A_i^{raw})f_u(z_e)+B_i f_b(z_e)]$$

The MAGB likelihood on the *physics samples* depends on the number of signal events S_i and the raw asymmetry A^{raw}.

- To derive the release asymmetry *A*, A^{raw} is corrected by the **detector efficiency asymmetry *D***.
- To obtain the gravitational acceleration of Hbar (a_g) a **model of the Hbar release asymmetry *A* vs *bias*** is needed:
  - From simulation as field measurements are done in 1d and not in real time during the Hbar release



Systematic uncertainties

- From the maximum of the **total likelihood**

$$\mathcal{L}(\mathbf{Z}|a_g, D, \mathbf{S}) = \prod_i \mathcal{L}_i[\mathbf{Z}_i|A_i^{raw}(a_g, D), \mathbf{S}]$$

Obtained a_g estimate with statistical uncertainty:
$a_g = 0.75 \pm 0.06$ g

- Different sources of **systematic uncertainty**, the most relevant are:
  - uncertainty **on *D*** evaluated by setting a gaussian constraint:

$$\mathcal{L}' = \mathcal{L} \cdot \frac{1}{\sqrt{2\pi\sigma_D^2}} \exp\left\{-\frac{(D-\mu_D)^2}{2\sigma_D^2}\right\}.$$

  - uncertainty **on the simulation** quoted separately and included in the final result

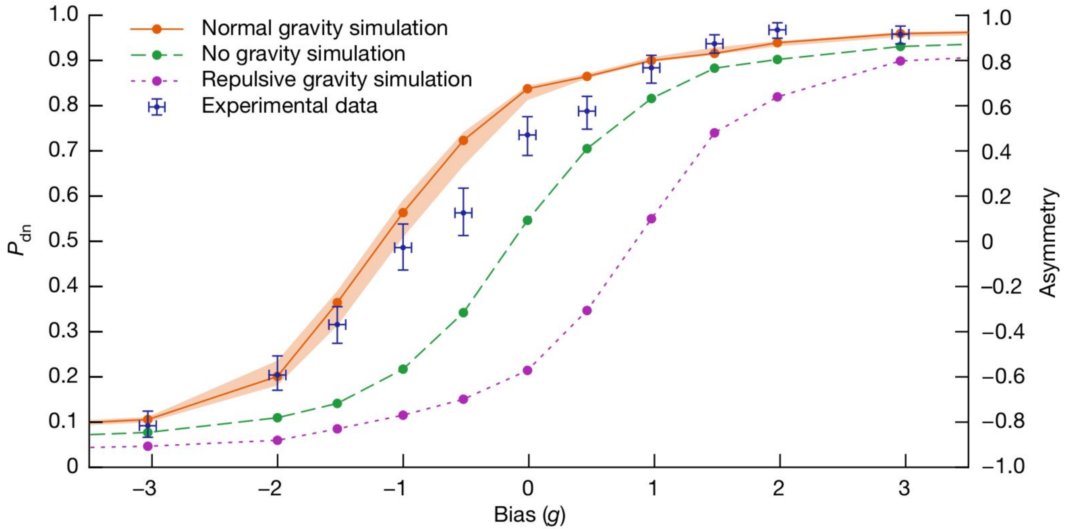
	Source	Fast ramp $\sigma(g)$
	Statistical	0.06
	Systematics	
a)	Efficiency correction	0.11
b)	Calibration sample size	0.03
c)	Calibration sample purity	0.00
d)	Simulation sample size	0.02
e)	Simulation interpolation	0.03
f)	Calibration/physics	0.00
g)	Fit bias (for $a_g < 0.5$)	0.01
	$\bar{H}$ simulation	
h)	Energy distribution (A_i^{sim} slope)	0.03
i)	Simulation B-field on-axis tuning	0.06
l)	Simulation off-axis model - 8-fold	$0.15 = 0.26/\sqrt{3}$

Results

- After having treated properly the *systematic uncertainties* the local acceleration of Hbar towards the Earth is estimated to be:

$$a_g = [-0.75 \pm 0.06(stat.) \pm 0.12(syst.) \pm 0.16(model)] \ \ g.$$

- **Compatible** with what is expected from General Relativity



Nature 621, 716–722 (2023). https://doi.org/10.1038/s41586-023-06527-1

Conclusions

- **ALPHAg** has the goal of testing the **weak equivalence principle** on **anti-H**

- **Result:**
  - **Compatible** with what is expected from General Relativity
  - Demonstrated **sensitivity to gravity effects** on antihydrogen in the magnetic trap

- **Outlook:**
  - **reach 1% precision** via systematic uncertainty reduction, use of laser cooling and the precision trap
  - 10^{-6} precision goal probably not possible with this technique (other more precise techniques could be implemented in ALPHAg: atomic fountain and interferometry)

Backup

Antimatter and gravity

Previous "red shift" based experiments:

- K0 − anti-K0 oscillation rate *(Physics Letters B Volume 452, Issues 3–4, 22 April 1999, Pages 425-433)*
- measurements of cyclotron frequencies for the proton and the antiproton *(Phys. Rev. Lett. 66, 854 (1991))*

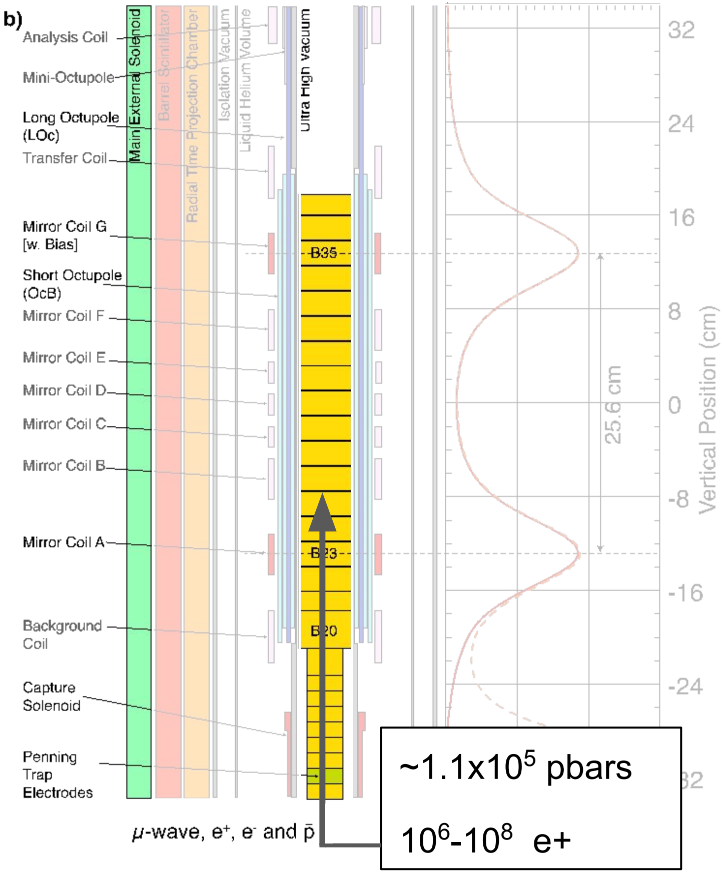
- Haven't deviations from WEP on antimatter already been ruled out by previous experiments?

even considering a photon as an e+ e- pair a 5th force effect can appear in Hbar because it has baryon number unlike the photon *(arXiv:1207.7358)*

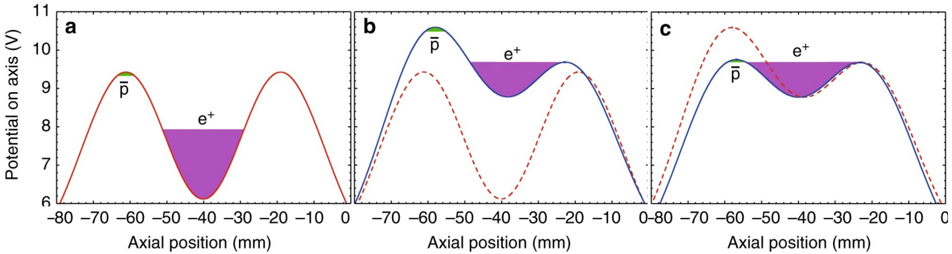
- How much of antiproton is antimatter? *(arXiv:1207.7358)*

most of the inertial mass of an (anti)proton comes from its binding energy. Quark mass is ~1%

Mixing plasmas



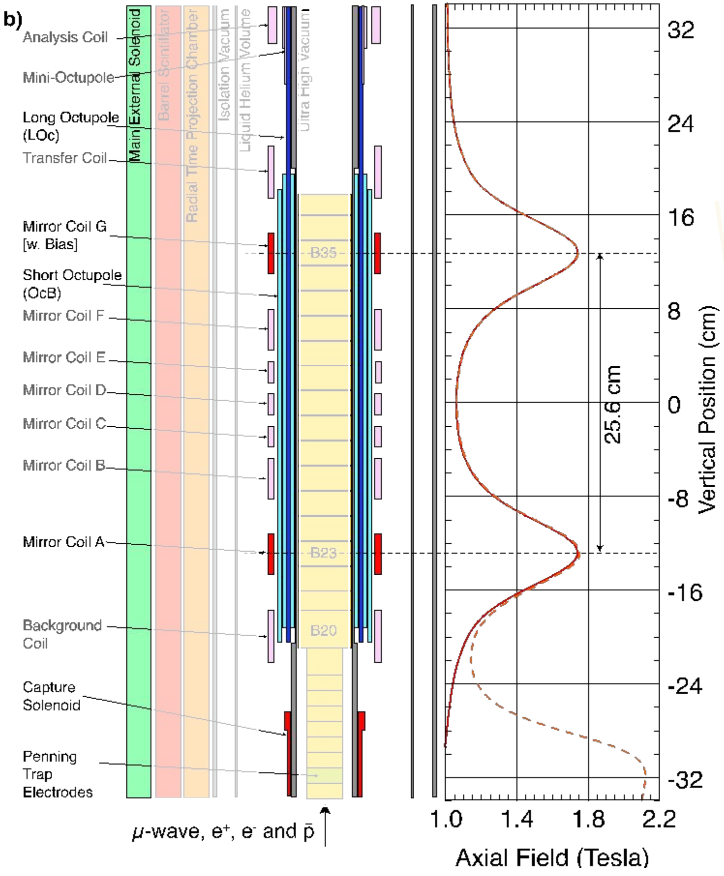
- Mixing charged plasmas in the Penning-Malmberg trap:
  - **electrodes:** plasma manipulations
  - **external solenoid** (1T field): radial confinement



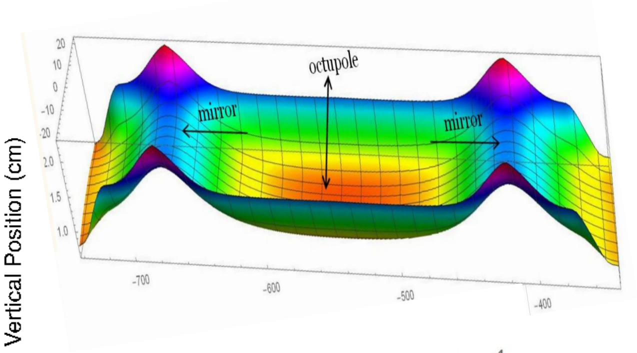
pbars and e+ in separated wells	Evaporative cooling on e+	pbar well decrease

Anti-hydrogen is formed in a three-body recombination process (1 s mixing), then quickly cascade to the ground state (τ < 0.5 s)

Trapping Hbar



- Hbar Trapping in the Ioffe-Pritchard trap:
  - Magnets: **octupoles and mirrors**
  - external solenoid: background field

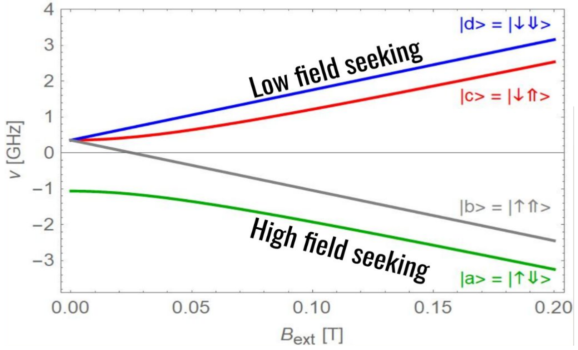


confinement potential $U = -\boldsymbol{\mu}_{\bar{H}} \cdot \boldsymbol{B}$

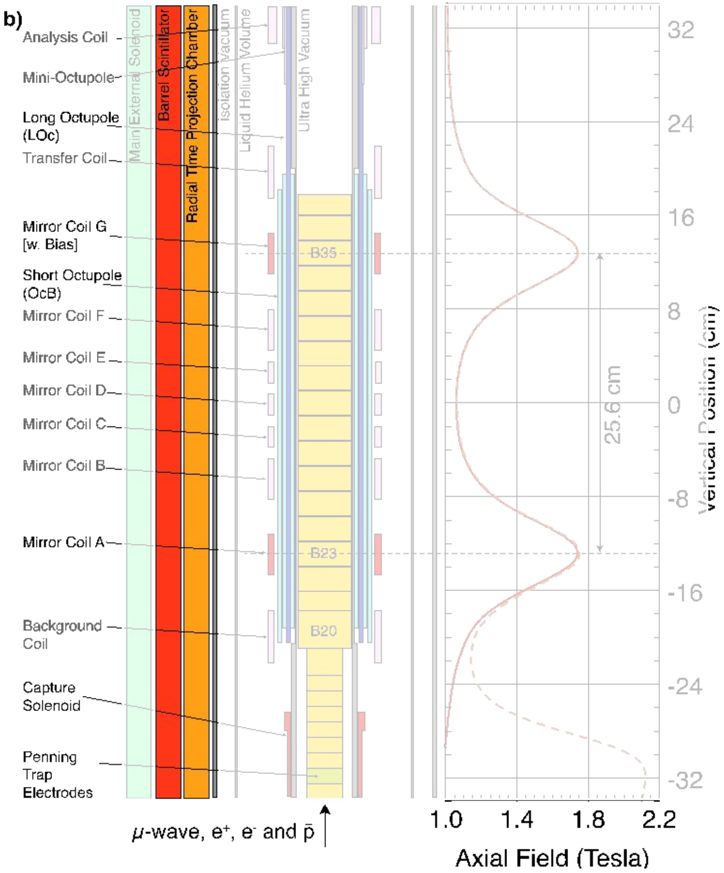
$$\mu^{\parallel}_{\bar{H}} = \pm\mu_B$$

Trappable Hbars:

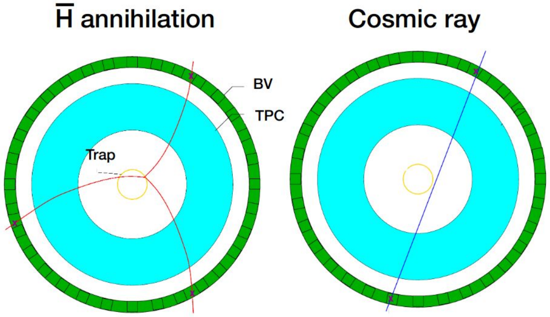
- E_{kin}<0.54 K
- Low field seeking states



Hbar detection

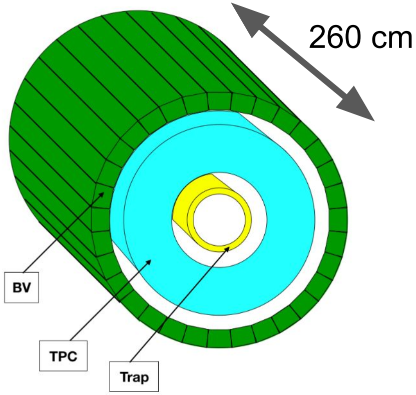


- Hbars can be **released by lowering the confining** magnetic **fields**
- Annihilation happens: products mostly pions
- Detectors:
  - **Radial field time-projection-chamber** (rTPC) filled with an Argon/CO2 mixture: vertex reconstruction
  - **Scintillators Barrel Veto**: cosmic background suppression



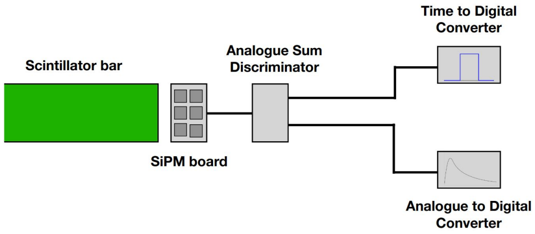
Diameter ~49 cm
Total height ~260 cm

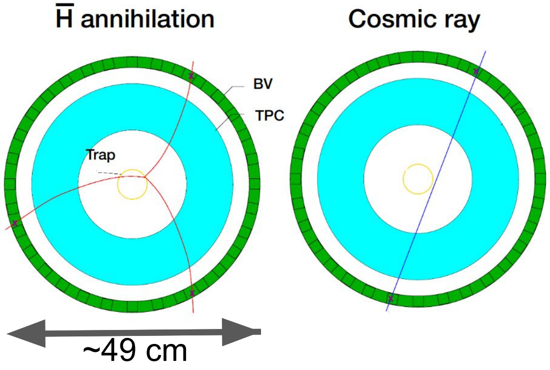
ALPHA-g detectors



Main detectors of the ALPHA-g apparatus:

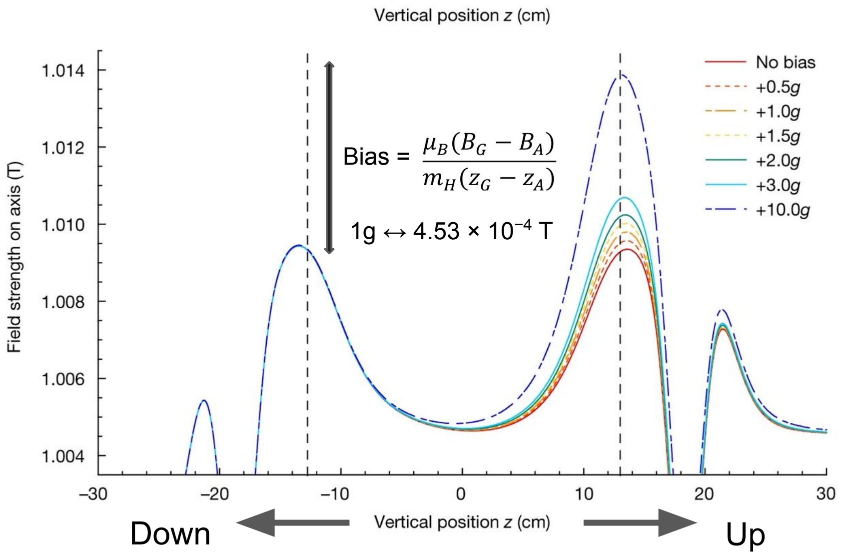
- **Radial Time Projection Chamber (TPC)**
- **Barrel Veto detector (BV):** 64 bars of plastic scintillator, each scintillator bar has a SiPM and is read out at both ends



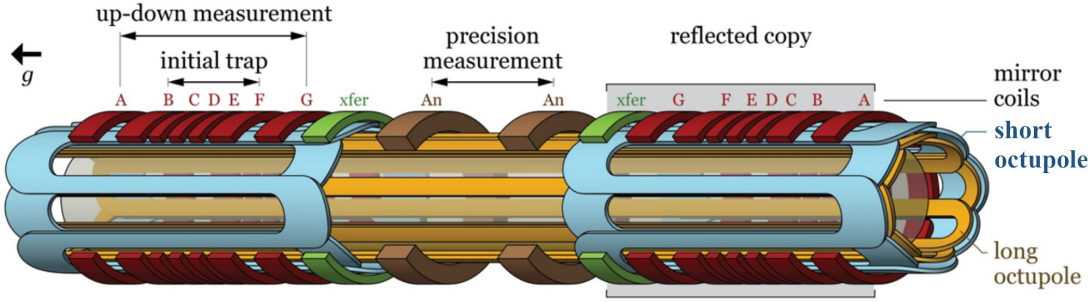


- The main **source of background** in this measurement is given by the **cosmic rays**
- The barrel veto was built with the purpose of reducing this background
- Background suppression: with a BDT classifier which is given as input 20 selection variables sensitive to the topological differences between annihilation events and cosmic ray events

ALPHA-g magnets release sequence



- antiH accumulation in the bottom trap
- Long octupole for transverse confinement is released
- Magnetometry
- axial release during the Mirror A and G ramp-down (MAGB)
- Magnetometry
- short octupole for transverse confinement is released
- effect of gravity: difference between the number of top and bottom released atoms



Model definition

- Likelihood for the release ramp annihilation positions Z in a given bias configuration (*i* bias label):

$$\mathcal{L}_i(\mathbf{Z}_i|A_i^{raw}, S_i) \propto e^{-(S_i+B_i)} \prod_{z_e \in \mathbf{Z}_i} [\frac{1}{2}S_i(1-A_i^{raw})f_d(z_e)+\frac{1}{2}S_i(1+A_i^{raw})f_u(z_e)+B_i f_b(z_e)]$$

For each bias (*i* bias label)

Model definition

- Likelihood for the release ramp annihilation positions Z in a given bias configuration (*i* bias label):

(1) (2) (3)

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		Expected yields	**Probability density functions**
(1)	Downwards released Hbar	$N_{d,i}=\frac{1}{2}S_i(1-A_i^{raw})$	$f_d(z_e)$
(2)	Upwards released Hbar	$N_{u,i}=\frac{1}{2}S_i(1+A_i^{raw})$	$f_u(z_e)$
(3)	Cosmic ray background	B_i	$f_b(z_e)$

In two z bins:
[-32.8,-12.8] U [12.8,32.8] cm

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		Expected yields
(1)	Downwards released Hbar	$N_{d,i} = \frac{1}{2}S_i(1-A_i^{raw})$
(2)	Upwards released Hbar	$N_{u,i} = \frac{1}{2}S_i(1+A_i^{raw})$
(3)	Cosmic ray background	B_i

Parameters

- $S_i = N^u_i + N^d_i$: total number of signal events (Hbar annihilations)
- A^{raw} asymmetry between upwards and downwards released Hbar:

$$A_i^{raw} = (N_{u,i} - N_{d,i})/S_i$$

Not corrected by detector efficiency

Model definition

- Likelihood for the release ramp annihilation positions Z in a given bias configuration (*i* bias label):

(1) (2) (3)

$$\mathcal{L}_i(\mathbf{Z}_i|A_i^{raw}, S_i) \propto e^{-(S_i+B_i)} \prod_{z_e \in \mathbf{Z}_i} \left[\frac{1}{2}S_i(1-A_i^{raw})f_d(z_e) + \frac{1}{2}S_i(1+A_i^{raw})f_u(z_e) + B_i f_b(z_e)\right]$$

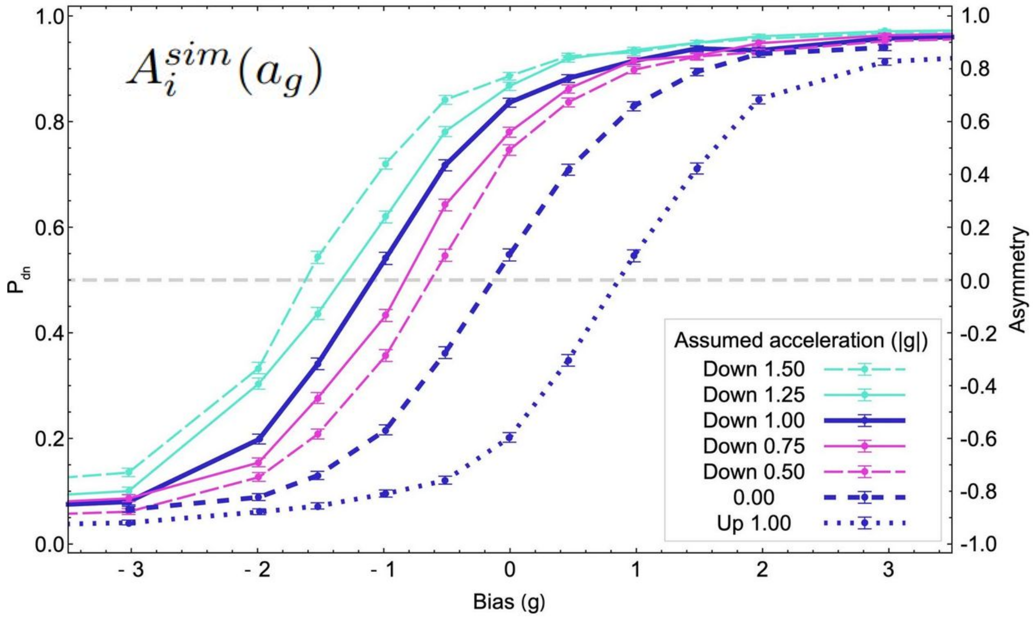
		Expected yields	Probability density functions
(1)	Downwards released Hbar	$N_{d,i} = \frac{1}{2}S_i(1-A_i^{raw})$	$f_d(z_e)$
(2)	Upwards released Hbar	$N_{u,i} = \frac{1}{2}S_i(1+A_i^{raw})$	$f_u(z_e)$
(3)	Cosmic ray background	B_i	$f_b(z_e)$

Fixed from fit to ±10 g *calibration samples* (for $f_d(z_e)$, $f_u(z_e)$)

From *background enriched samples* (for B_i, $f_b(z_e)$)

Regression with simulated model (S-curves)

- A model for the relation between the asymmetry and the total potential difference at the mirrors A and G is obtained via simulation:



- Modelling Initial energy distribution
- Modelling of magnetic fields
- Simulation of the trajectories of Hbar

GPR fitting used to extract the S-curves at intermediate a_g values

- Then, via simulation, it is possible to write the total likelihood in terms of a_g:

$$\mathcal{L}(\mathbf{Z}|a_g, D, \mathbf{S}) = \prod_i \mathcal{L}_i[\mathbf{Z}_i|A_i^{raw}(a_g, D), \mathbf{S}]$$

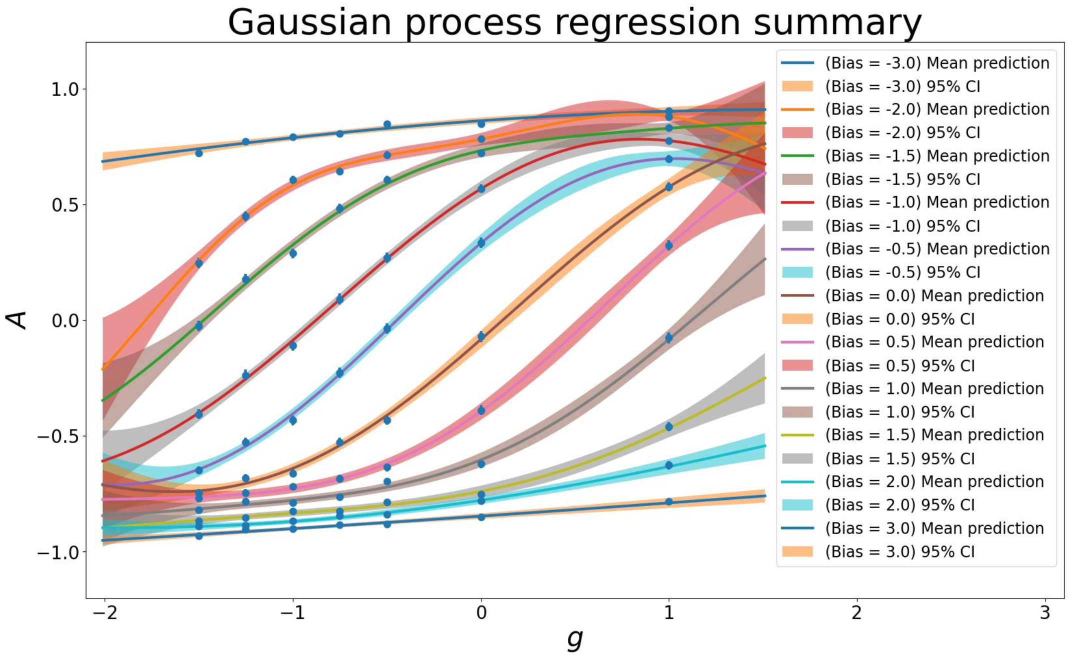
where $$A_i^{raw}(a_g, D) = \frac{A_i^{sim}(a_g) - D}{1 - A_i^{sim}(a_g)D}$$

Simulated model systematic uncertainties

- Off-axis:
  -studying the impact of possible magnet misalignment on the S-curves.
  -effect of this misalignment on the S-curve intercept with A=0 was evaluated.
  -The maximum shifts from the unperturbed configuration are found to be
  ±0.26 g (corresponding to the “octupole 8-fold” configurations). interpreted here as a worst-case scenario

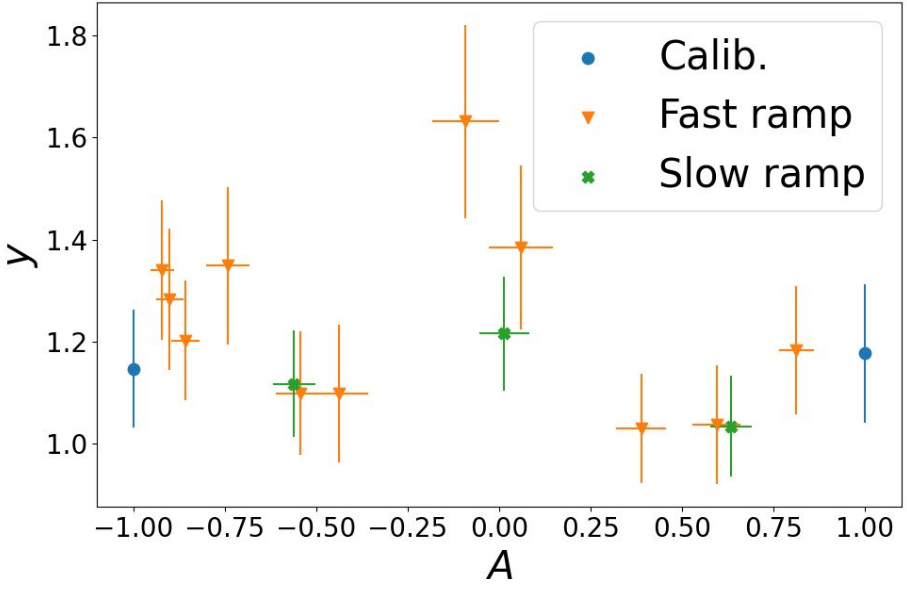
GPR fitting of simulated S-curves

- Points: from simulation, error 1 sigma
- Lines: mean prediction from GPR
- Bands: 95 % confidence interval from GPR



Efficiency asymmetry

Being η_u and η_d the efficiencies in detecting respectively *up* and *down* annihilations, D is defined as $\frac{\eta_d - \eta_u}{\eta_u + \eta_d}$.



Estimated assuming the proportionality between the LOc counts and the MAGB counts: LOc counts is proportional to the number of anti-H that were trapped

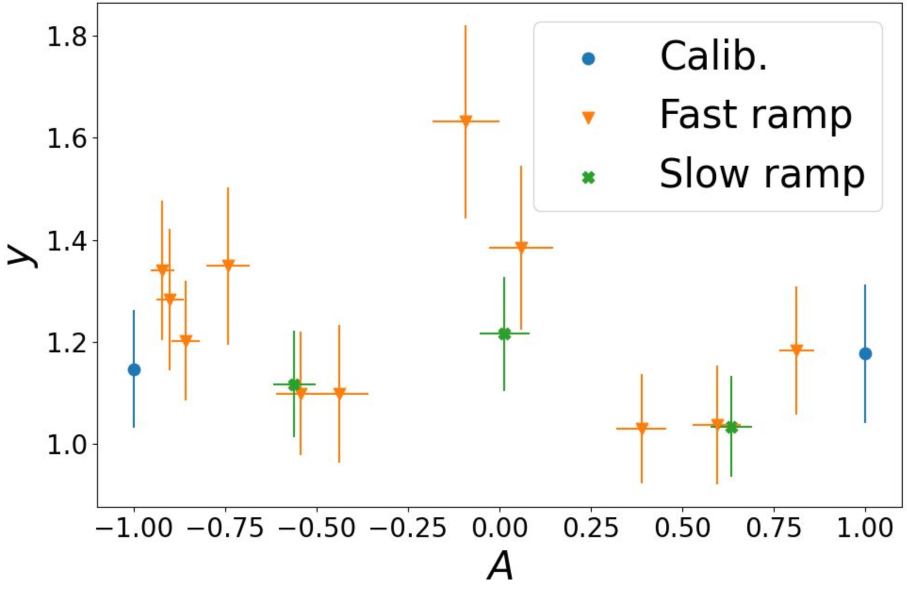
$$\frac{S_{i,o}}{S_i} = \kappa_i(1 + D_i A_i^{raw})$$

The different datasets highlighted in the plot were fitted with a linear model.

$$y = mx + q \qquad \begin{aligned} y &= S_{i,o}/S_i \\ x &= A_i^{raw} \end{aligned}$$

The obtained efficiency asymmetry is $$D = -0.03 \pm 0.06$$

Efficiency asymmetry



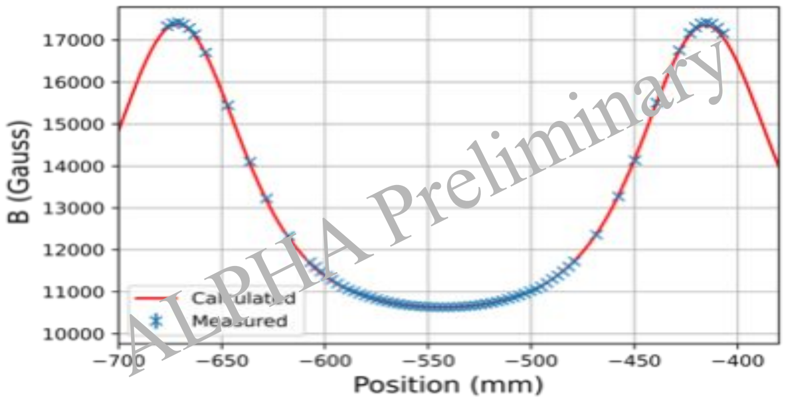
assumption of proportionality between LoC and the Hbar population before the MAGB ramp might not hold due to Hbar losses occurring between the two ramps

Systematic uncertainty on *D* is evaluated by varying the numerator of $y = \frac{S_{i,o}}{S_i}$

and repeating the fit again for each variation.

Cyst uncertainty found to be 0.02, to be added in quadrature to the statistical uncertainty of 0.06

Magnetometry



Electron Cyclotron Resonance:

- Microwave heating of electron plasmas when microwave freq ~ cyclotron freq
- precision of the measurement: ~10^{-2} Gauss
- Slow measurement (~ min)

(Phys. Plasmas 27, 032106 (2020); https://doi.org/10.1063/1.5141999)

Magnetron-based magnetic field measurement:

- Measurement of magnetron frequency of electrons in Penning-Trap
- For understanding dynamic evolution of the fields
- precision of the measurement: ~1 Gauss
- Fast measurement