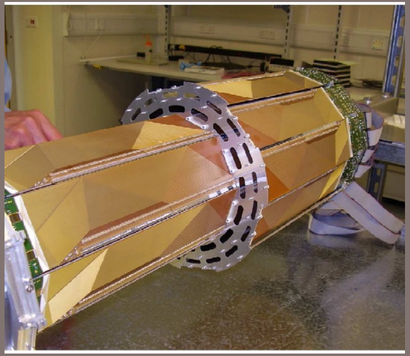
TRIUMF
Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

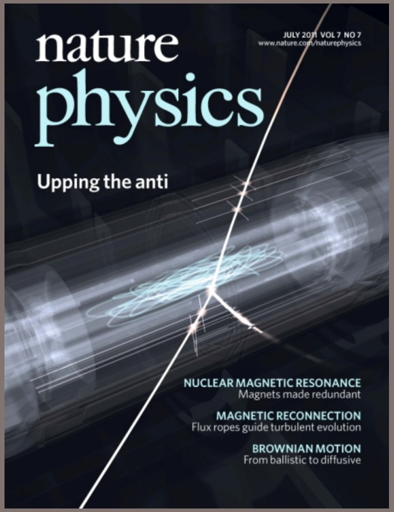
Entering the Precision Era: Antihydrogen Symmetry Tests with ALPHA

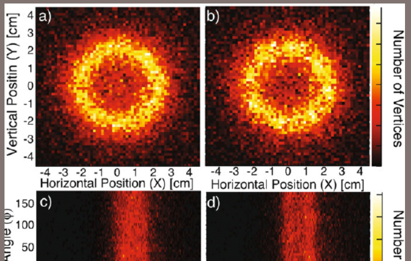
Physics of Fundamental Symmetries and Interaction
PSI 2016

Makoto C. Fujiwara

Head, Particle Physics Department
TRIUMF – Canada's National Lab. for Particle & Nuclear Physics







Outline

- Big questions
  - MCF: arXiv:1309.7468
- Brief overview
- First precision results with anti-H
  - Implications of recent charge neutrality tests
- Status and Prospects

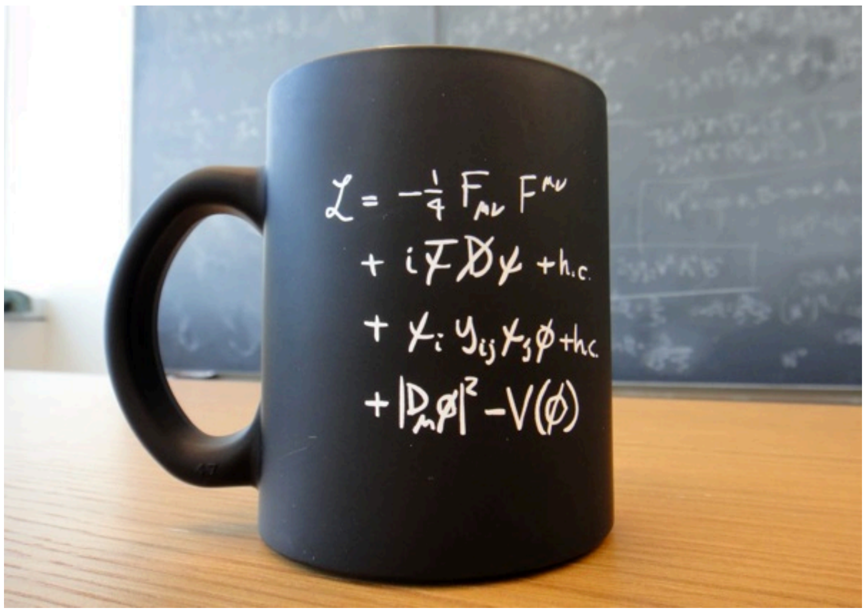
What is Particle Physics?

(e.g. Grossman)

$$\boxed{\mathcal{L} = \,?}$$

“Simple Answer”

The Standard Model! is (technically) unnatural …



- Fine tuning of Higgs mass
- Should be new physics at TeV scale, e.g SUSY
- Cosmological constant

Are we asking right question?

"L=?" really right question to ask?

Is Quantum Field Theory correct description of Nature?

Motivations: Symmetries

Quantum Field Theory ↔ CPT Symmetry ↔ H & anti-H Spectra

- CPT: Fundamental property of QFT
  - Theorem: atomic spectra of H & anti-H identical

General Relativity ↔ Equival. Principle ↔ H & anti-H Free fall

- Einstein's Equivalence Principle
  - Matter and Antimatter fall in same way

Any violation would force radical change in theory!

ALPHA Experiment

ALPHA brief history

- ATHENA: produced first cold Hbars (2002)
  (They were not trapped)
  Completed data taking in 2004
- Developed into new experiments (2005)
  – Trapping and Spectroscopy of Hbars

~~**ALE**~~

~~Antihydrogen Laser Experiment~~

$\overline{\forall}$LPHA

Antihydrogen Laser Physics Apparatus

Also Microwaves, Gravity, Charge…

TRIUMF

ALPHA Collaboration

University of Aarhus: G. Andersen, P.D. Bowe, J.S. Hangst

RIKEN: Y. Yamazaki

Federal University of Rio de Janeiro: C.L. Cesar, D. Miranda

University of Tokyo: R. Funakoshi, R.S. Hayano

University of Wales, Swansea: E. Butler, M. Charlton, A. Humphries, N. Madsen, L. V. Jørgensen, M. Jenkins, D.P. van der Werf

Auburn University: F. Robicheaux

University of California, Berkeley: W. Bertsche, S. Chapman, J. Fajans, A. Povilus, J. Wurtele

Nuclear Research Centre, Negev, Israel: E. Sarid

University of Liverpool: P. Nolan, P. Pusa

University of British Columbia: A. Gutierrez, S. Seif El Nasr, M. Michan, T. Momose, W.N. Hardy*

University of Calgary: R. Hydomako, C. Friesen, R.I. Thompson*

Université de Montréal: J.-P. Martin*

Simon Fraser University: M. Dehghani, M. Hayden*

TRIUMF: P. Amaudruz*, M. Barnes, M.C. Fujiwara*, D.R. Gill*, L. Kurchaninov*, K. Olchanski*, A. Olin*, S. Stracka J. Storey + Professional Support**

York University: S. Amole, A. Capra, H. Malik, S. Menary*

Canadian students & Postdocs

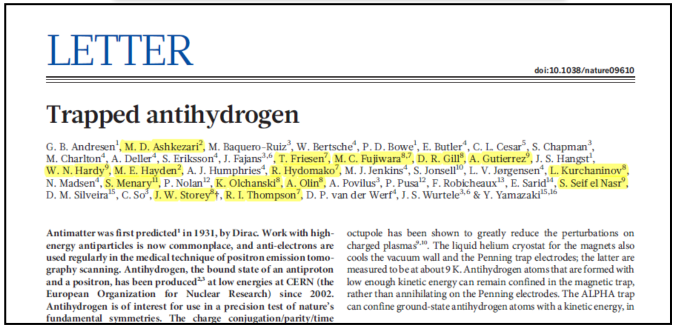
* Active faculty/staff in present phase

**P. Bennett, D. Bishop, R. Bula, S. Chan, B. Evans, D. Healey, T. Howland, H. Hui, K. Langton, C. Marshall, J. Nelson, D. Rowbotham, P. Vincent, T. Meyer, M. Pavan ++ Undergrads: W. Lai, L. Wasilenko, C. Kolbeck, N. Evetts

Great team effort!

Some ALPHA-1 Achievements

Nature 2010
Antihydrogen trapped


LETTER

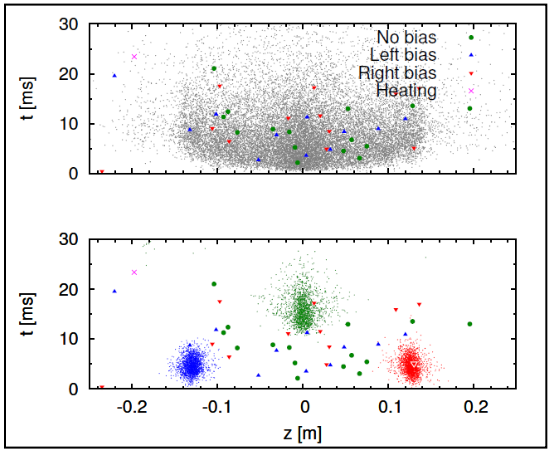
doi:10.1038/nature09610

Trapped antihydrogen

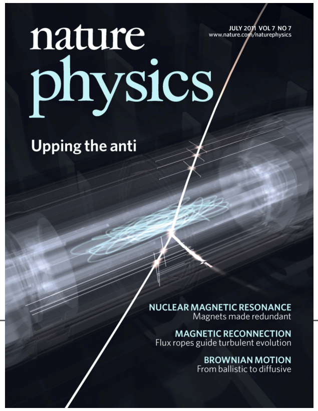
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

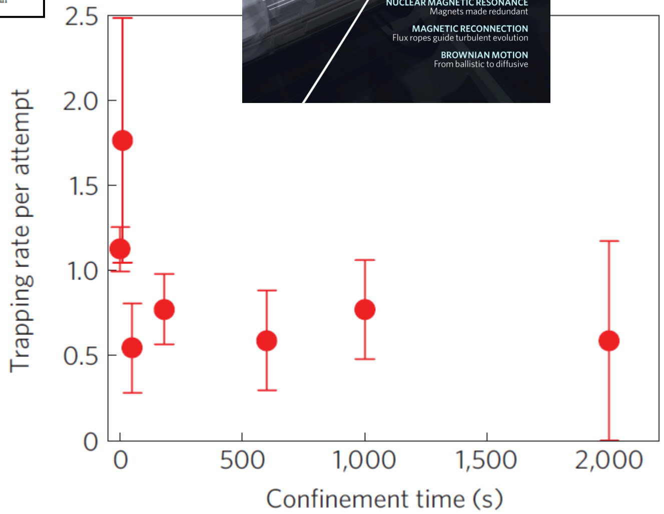
Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at low energies at CERN (the European Organization for Nuclear Research) since 2002. Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time

octupole has been shown to greatly reduce the perturbations on charged plasmas[9,10]. The liquid helium cryostat for the magnets also cools the vacuum wall and the Penning trap electrodes; the latter are measured to be at about 9 K. Antihydrogen atoms that are formed with low enough kinetic energy can remain confined in the magnetic trap, rather than annihilating on the Penning electrodes. The ALPHA trap can confine ground-state antihydrogen atoms with a kinetic energy, in

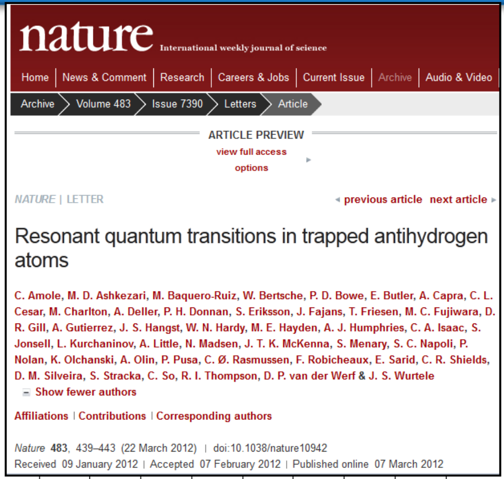


Nature physics 2011
1000 sec confinement





Nature 2012
Microwave "spectroscopy"


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video

Archive > Volume 483 > Issue 7390 > Letters > Article

ARTICLE PREVIEW
view full access options

NATURE | LETTER

previous article next article

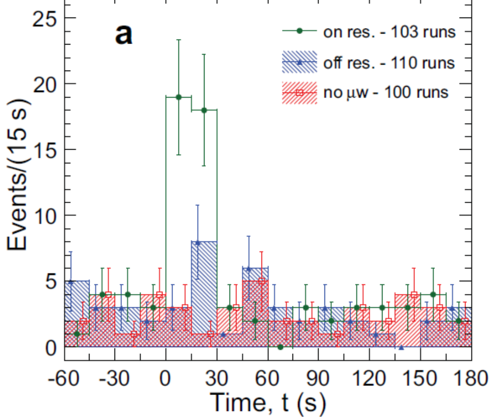
Resonant quantum transitions in trapped antihydrogen atoms

C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, P. H. Donnan, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac, S. Jonsell, L. Kurchaninov, A. Little, N. Madsen, J. T. K. McKenna, S. Menary, S. C. Napoli, P. Nolan, K. Olchanski, A. Olin, P. Pusa, C. Ø. Rasmussen, F. Robicheaux, E. Sarid, C. R. Shields, D. M. Silveira, S. Stracka, C. So, R. I. Thompson, D. P. van der Werf & J. S. Wurtele

Show fewer authors

Affiliations | Contributions | Corresponding authors

Nature **483**, 439–443 (22 March 2012) | doi:10.1038/nature10942
Received 09 January 2012 | Accepted 07 February 2012 | Published online 07 March 2012

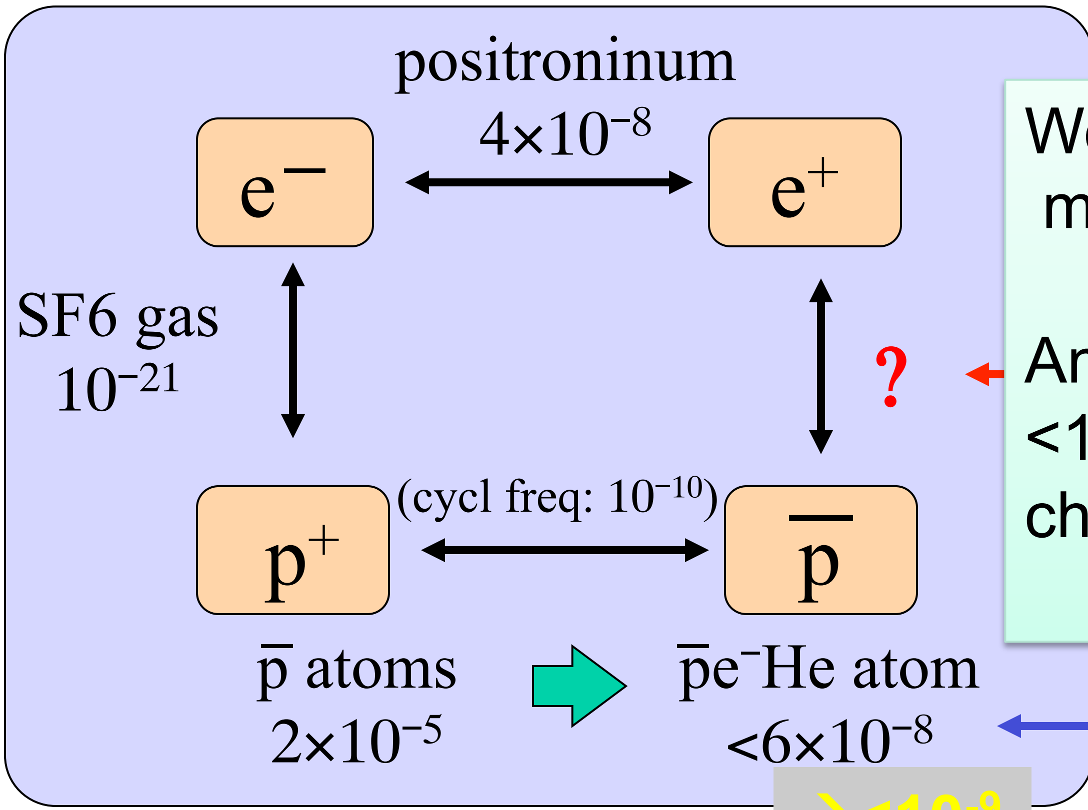


A side project

Anti-H Charge Neutrality Tests
(Nature Comm. 2014, Nature 2016)

Experimental Limits on $|\delta q/q|$

Slide from 2002!



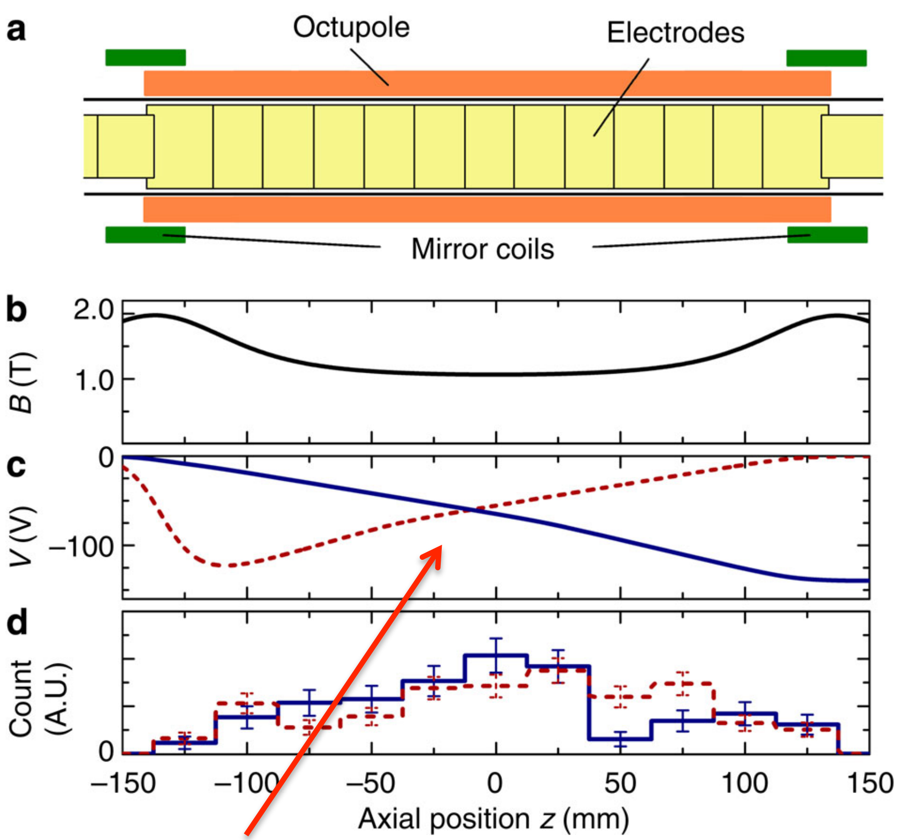
$\rightarrow <10^{-9}$ in 2014

We don’t know why matter is neutral

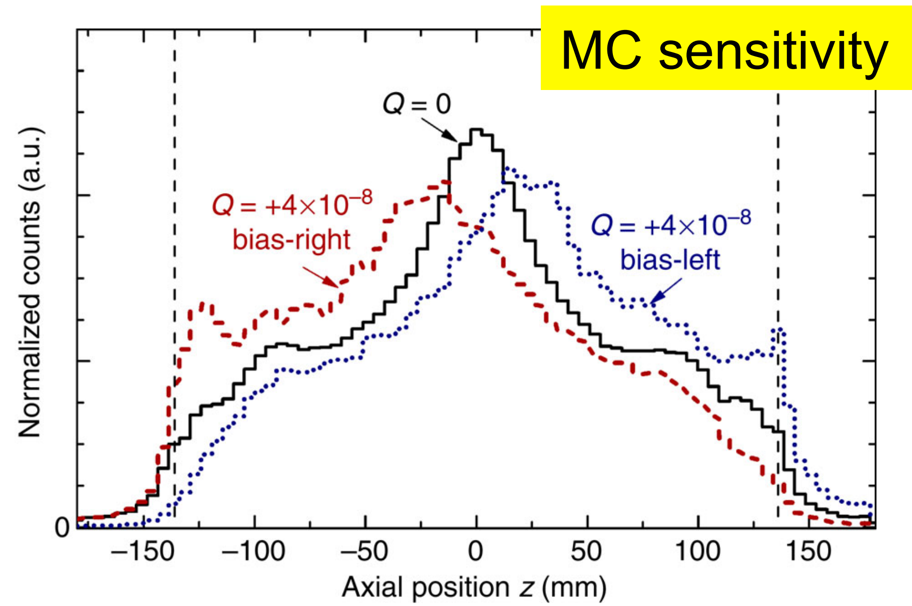
Anti-H neutrality meas. $<10^{-8}$ would improve e+ charge

3 body calc. needed

2014: Anti-H Charge Neutrality Test



Biasing E field



Key: position sensitive detection

Trapped Anti-H energy μΔB ~ 50 μV
<< applied potential ~100 V

2014 (ALPHA-1): $Q<1.3\times10^{-8}$
via DC fields

2016 (ALPHA-2): $Q<0.7\times10^{-9}$
via random pulses

ALPHA's first precision results!
(from side project)

Improved Limit on $|\delta Q/Q|$

(Nature 2016)

PDG 2014

$|q_{e^+} + q_{e^-}|/e$

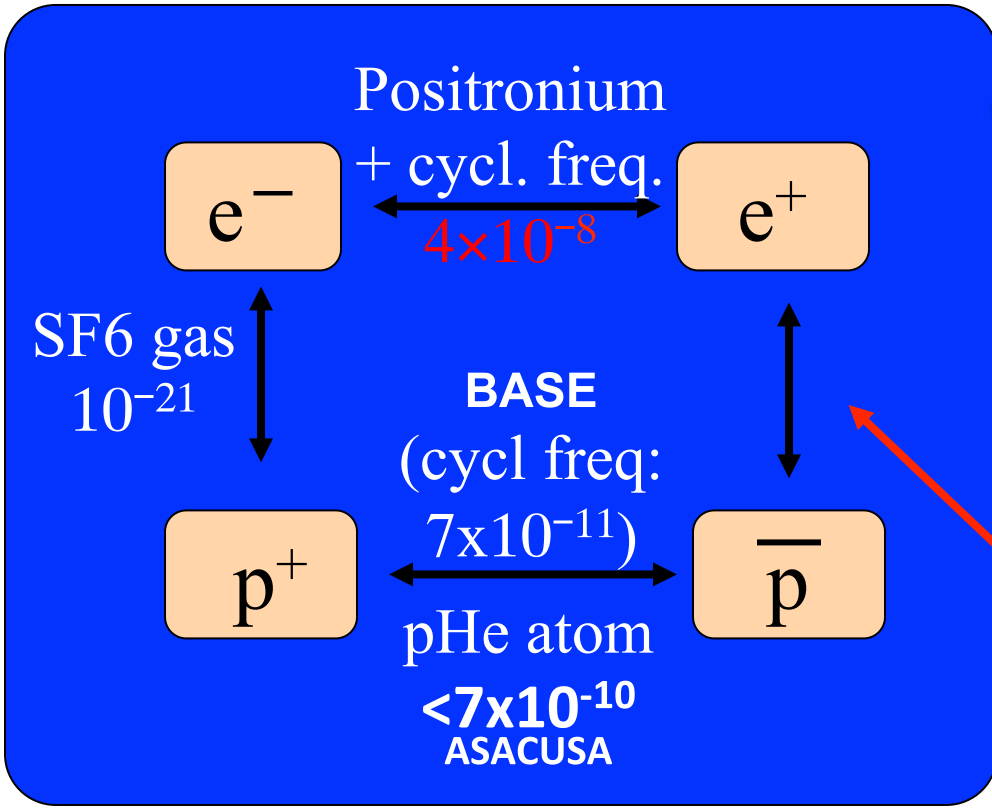
A test of *CPT* invariance. See also similar tests involving th

VALUE	DOCUMENT ID		TECN	CO
$<4 \times 10^{-8}$	[7] HUGHES	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc.				
$<2 \times 10^{-18}$	[8] SCHAEFER	95	THEO	V
$<1 \times 10^{-18}$	[9] MUELLER	92	THEO	V

[7] HUGHES 92 uses recent measurements of Rydberg-energy and c tios.

[8] SCHAEFER 95 removes model dependency of MUELLER 92.

[9] MUELLER 92 argues that an inequality of the charge magnitudes order vacuum polarization, contribute to the net charge of atoms



Anti-H neutrality tests:

2014 (ALPHA-1): $Q<\sim10^{-8}$

2016 (ALPHA-2): $Q<0.7\text{x}10^{-9}$

New e+ charge limit $\sim10^{-9}$

(40 fold improv't over PDG)

TRIUMF

What about e+ mass?

PDG 2014

$(m_{e^+} - m_{e^-}) / m_{average}$

$< 8 \times 10^{-9}$

A test of *CPT* invariance.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8 \times 10^{-9}$	90	[6] FEE	93	CNTR	Positronium spectroscopy
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-23}$	90	[7] DOLGOV	14		From photon mass limit
$<4 \times 10^{-8}$	90	CHU	84	CNTR	Positronium spectroscopy

[6] FEE 93 value is obtained under the assumption that the positronium Rydberg constant is exactly half the hydrogen one.

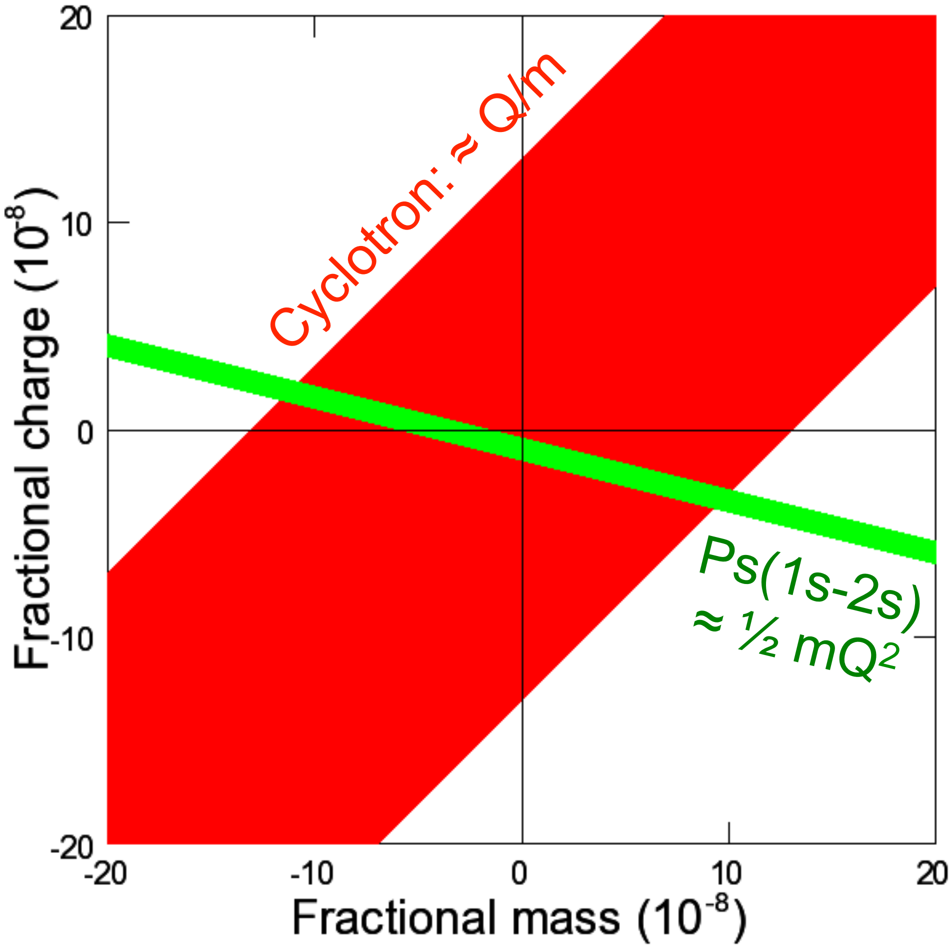
[7] DOLGOV 14 result is obtained under the assumption that any mass difference between electron and positron would lead to a non-zero photon mass. The PDG 12 limit of 1×10^{-18} eV on the photon mass is in turn used to derive the value quoted here.

I have issues with PDG and Fee, Chu et al.!

1. PDG "assumption that the Ps Rydberg is exactly half of the hydrogen one" does not make sense
2. It seems FEE93 assumed incorrect sensitivity between Δfreq(1s-2s) and $\Delta m_{e+}/m_e$
3. e+ mass & charge should be treated independently (as for Pbars)
4. Not clear if the limit is 90% CL rather than 1σ

Positron charge & mass before ALPHA

(MCF at LEAP 2016)



Before ALPHA

– $\Delta m_{e+}/m_{e+} \sim 10^{-7}$

– $\Delta Q_{e+}/Q_{e+} \sim 3\mathrm{x}10^{-8}$

(Pbar mass, charge anomaly negligible)

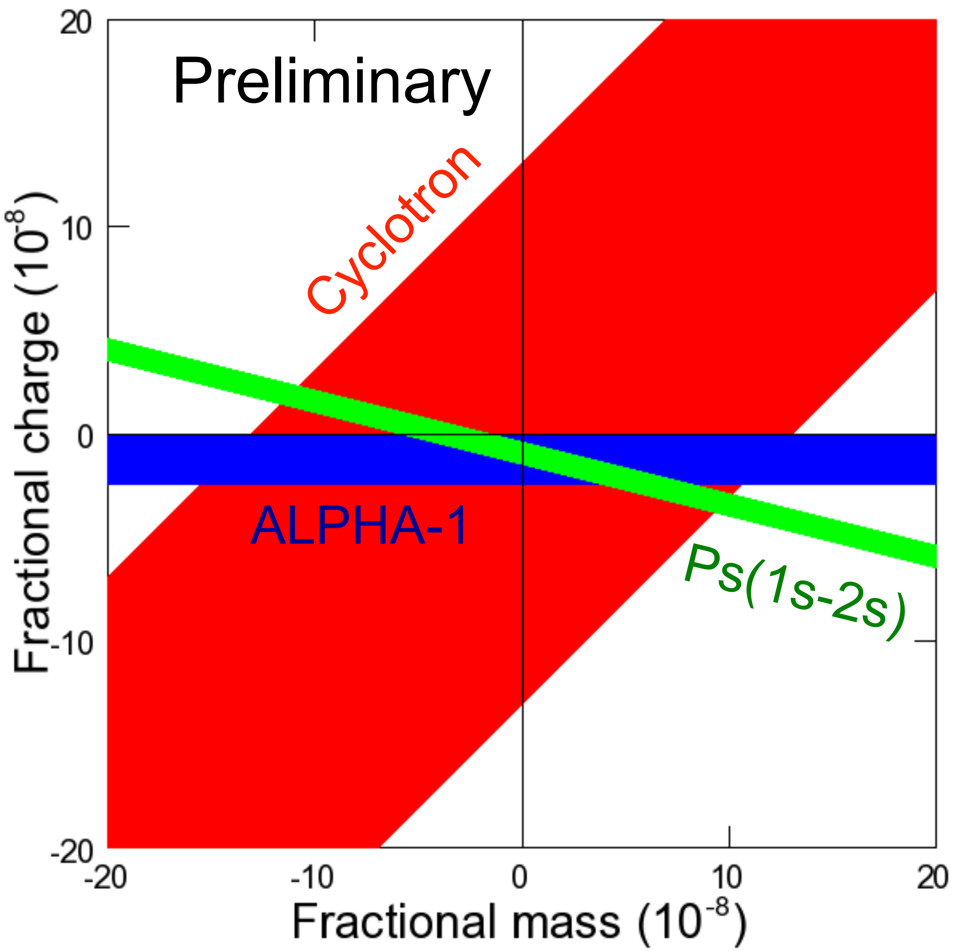
Cf: PDG 2014

– $\Delta m_{e+}/m_{e+}$: $8 \mathrm{x}10^{-9}$

(x 10 overestimate of precision!)

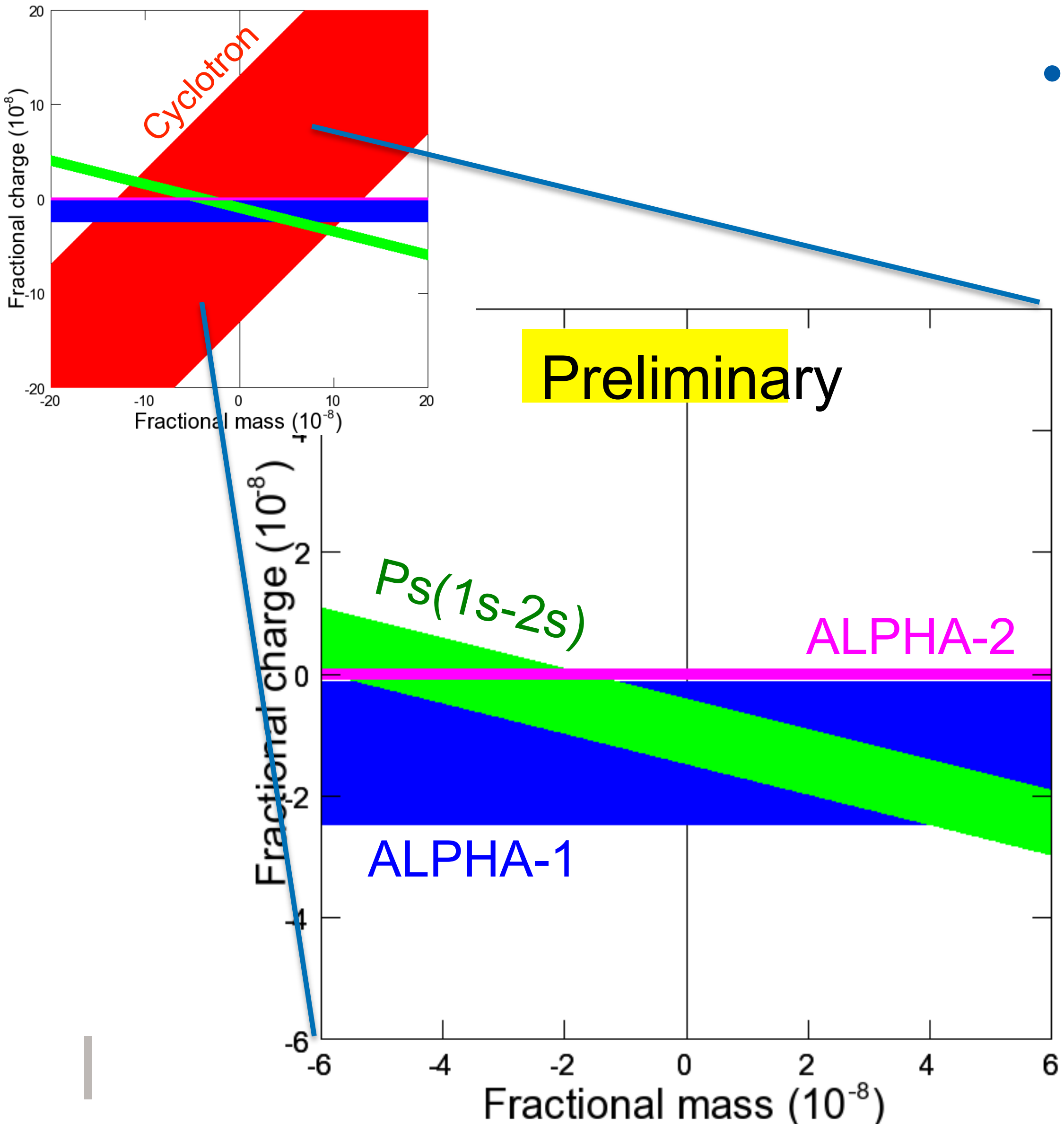
– $\Delta Q_{e+}/Q_{e+}$: 4×10^{-8}

Positron Charge & Mass after ALPHA-1



- After ALPHA-1 [3]
  - Both $\Delta m_{e+}/m_{e+}$ and $\Delta Q_{e+}/Q_{e+}$ improved marginally ~ x2

Positron Charge & Mass after ALPHA-2



- After ALPHA-2 [4]
  - Ignore pbar charge & mass anomaly (4×10^{-10})
  - $\Delta Q_{e+}/Q_{e+} \sim 7 \times 10^{-10}$ (1σ), 40-fold improvement over pre-ALPHA
  - $\Delta m_{e+}/m_{e+} \sim \pm 2 \times 10^{-8}$, ~5 fold improvement
  - But central value shifted due to disagreement between theory and exp in Ps(1s-2s)

Antiproton Mass & Charge

- Analysis so far assumed:

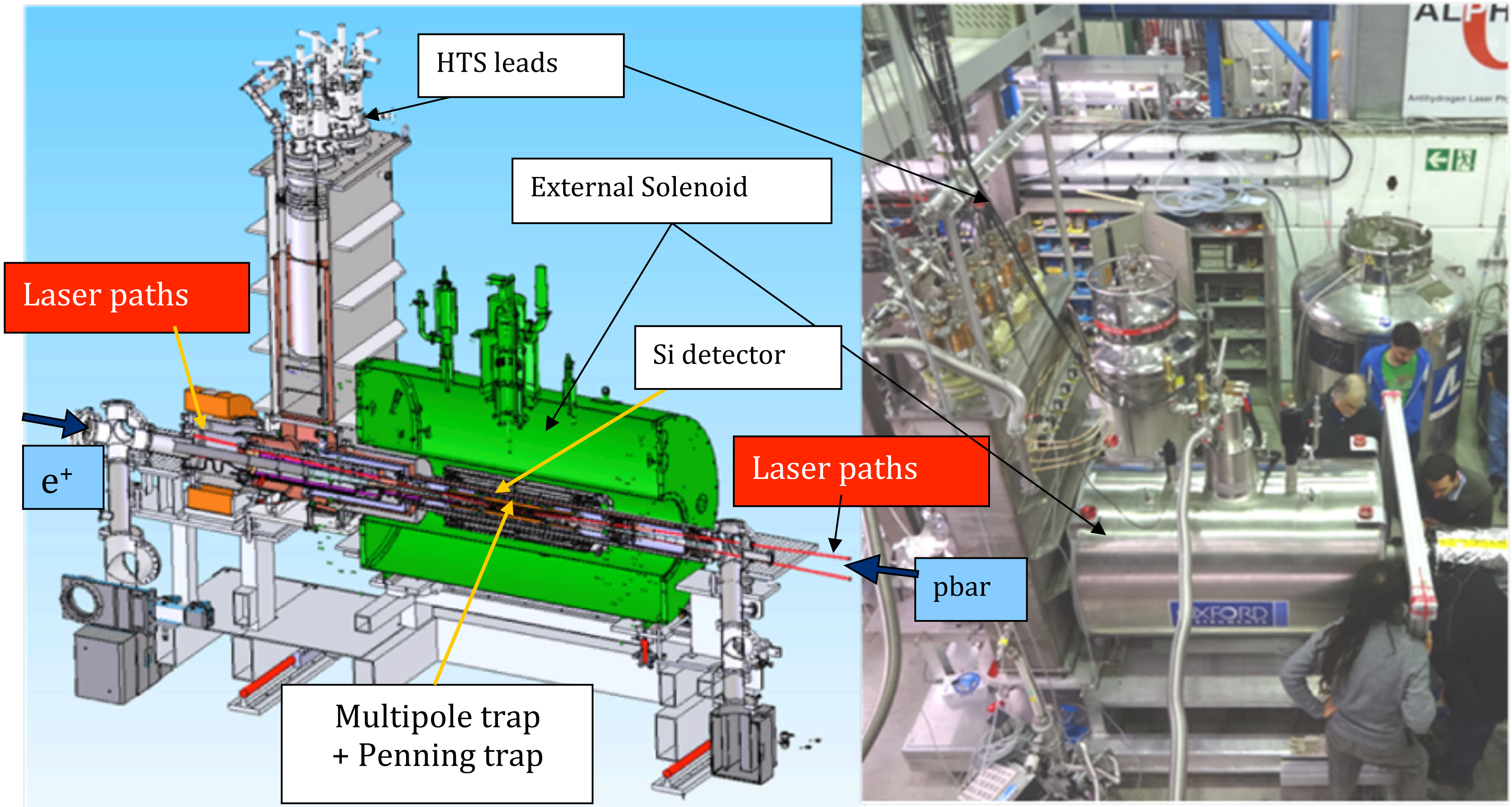
  $\delta m_{pbar}/m_{pbar}$, $\delta Q_{pbar}/Q_{pbar}$ << $\delta m_{e+}/m_{e+}$, $\delta Q_{e+}/Q_{e+}$
- Next generation Anti-H exp'ts can no longer assume this.
- In general, need 4 independent measurements to determine m_{pbar}, Q_{pbar}, m_{e+}, Q_{e+}. Possibilities:

Measurement	Leading order dependence	Current precision (1σ)	Near future prospects
Pbar/p cyclotron	Q_{pbar} / m_{pbar}	7×10^{-11}	Base: 10^{-11} ?
Pbar He	$m_{pbar}\ Q_{pbar}^2$	4×10^{-10}	ASACUSA: 10^{-10} ?
e+/e- cyclotron	Q_{e+}/m_{e+}	**1.3×10^{-7}**	Harvard ?
Ps(1s-2s)	$(m_{e+}/2)\ Q_{e+}^2$	5×10^{-9}	ETH: 5×10^{-10} ?
Anti-H (charge)	$Q_{pbar} + Q_{e+}$	7×10^{-10}	ALPHA: 10^{-12} ?
Anti-H (1s-2s)	$m_{e+}\ Q_{pbar}^2\ Q_{e+}^2$	-	ALPHA: 10^{-11} ?

Anti-H studies entering precision era!

Spectroscopy with ALPHA-2

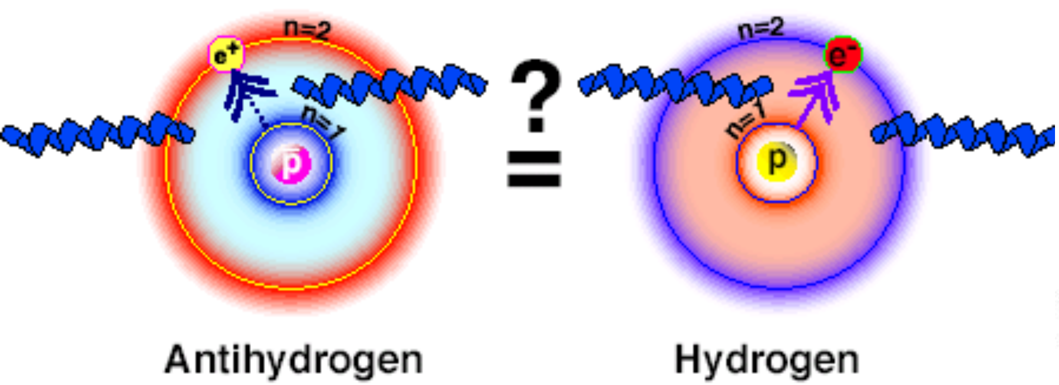
ALPHA-2: Precision Spectroscopy Machine



Laser access; Improved microwaves, 5 mirror coils
Getting ready for first laser spectroscopy in 2016

Anti-H long term goal: Precision spectroscopy

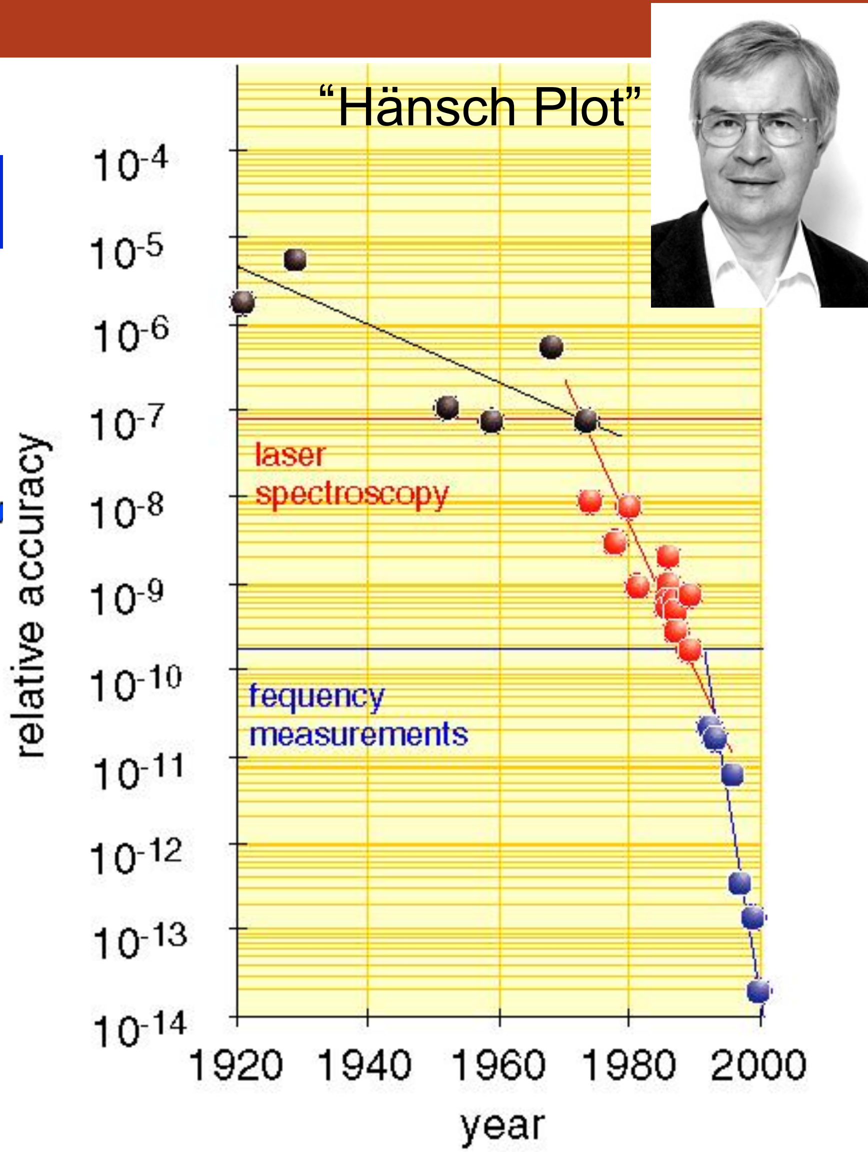
1s-2s two-photon spectroscopy



- "Lamp post"
- Doppler effect cancels
- High precision in matter sector

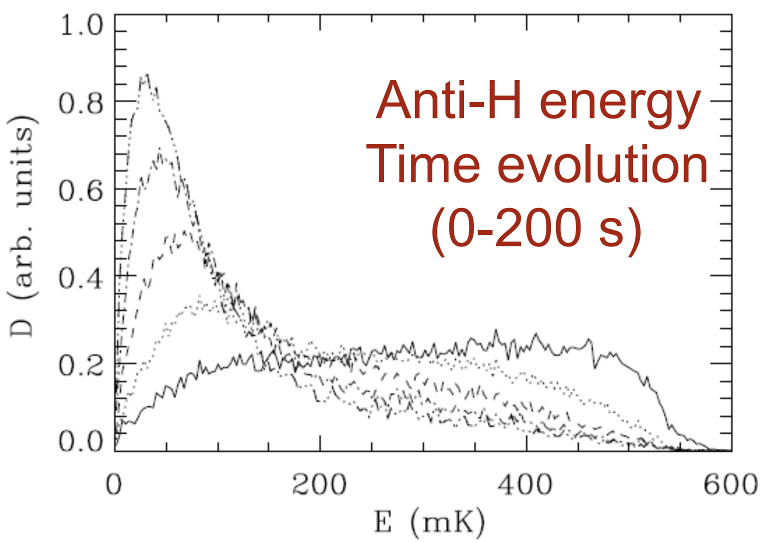
"Initial" anti-H precision ~10^{-11}

(Implications for proton radius puzzle)



Anti-H Laser Cooling

- Laser cooling
  - Provides cold, dense, spatially confined sample
  - Needed for high precision & gravity experiments
  - 122 nm (Lyman-alpha) laser challenging!



- Realistic proposal

[Donnan, MCF, Robicheaux, J. Phys. B. 46, 205302 (2013)]

  - Pulsed laser cooling
  - Cooling on 1 dimension
  - Use coupling of deg. of freedom for 3-D cooling
  - Cooling from ~500 mK to ~20 mK in few 100 s
- Laser built at UBC

First laser exp't attempts
Fall 2016

TRIUMF

ALPHA-g

Antimatter Gravity Measurement

- Gravity
  - Never measured with antimatter
- Very difficult experiment since gravity is so weak
- Now plausible due to long confinement time

nature physics

ARTICLES

PUBLISHED ONLINE: 5 JUNE 2011 | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here, we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.

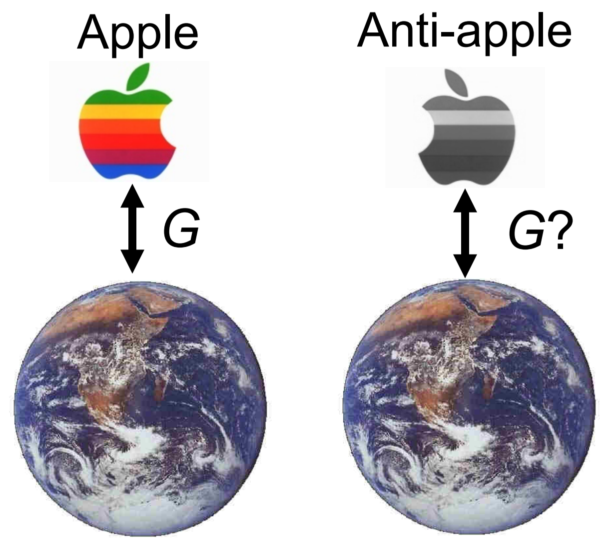
Antimatter Gravity Experiment

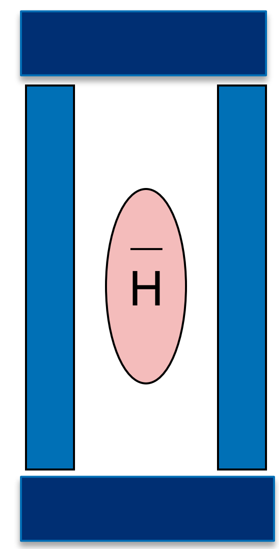
- Does antimatter fall down?
  - Many indirect constraints incl. EP tests
  - Experimental question!
    (e.g. Lykken et al, arXiv:0808.3929)
  - Anti-H "gas" will sag due to gravity
  - Need anti-H cooling to ~mK

    $$1/2kT = mgh$$

    $$\text{Vertical trap}: h \sim 1\ m$$

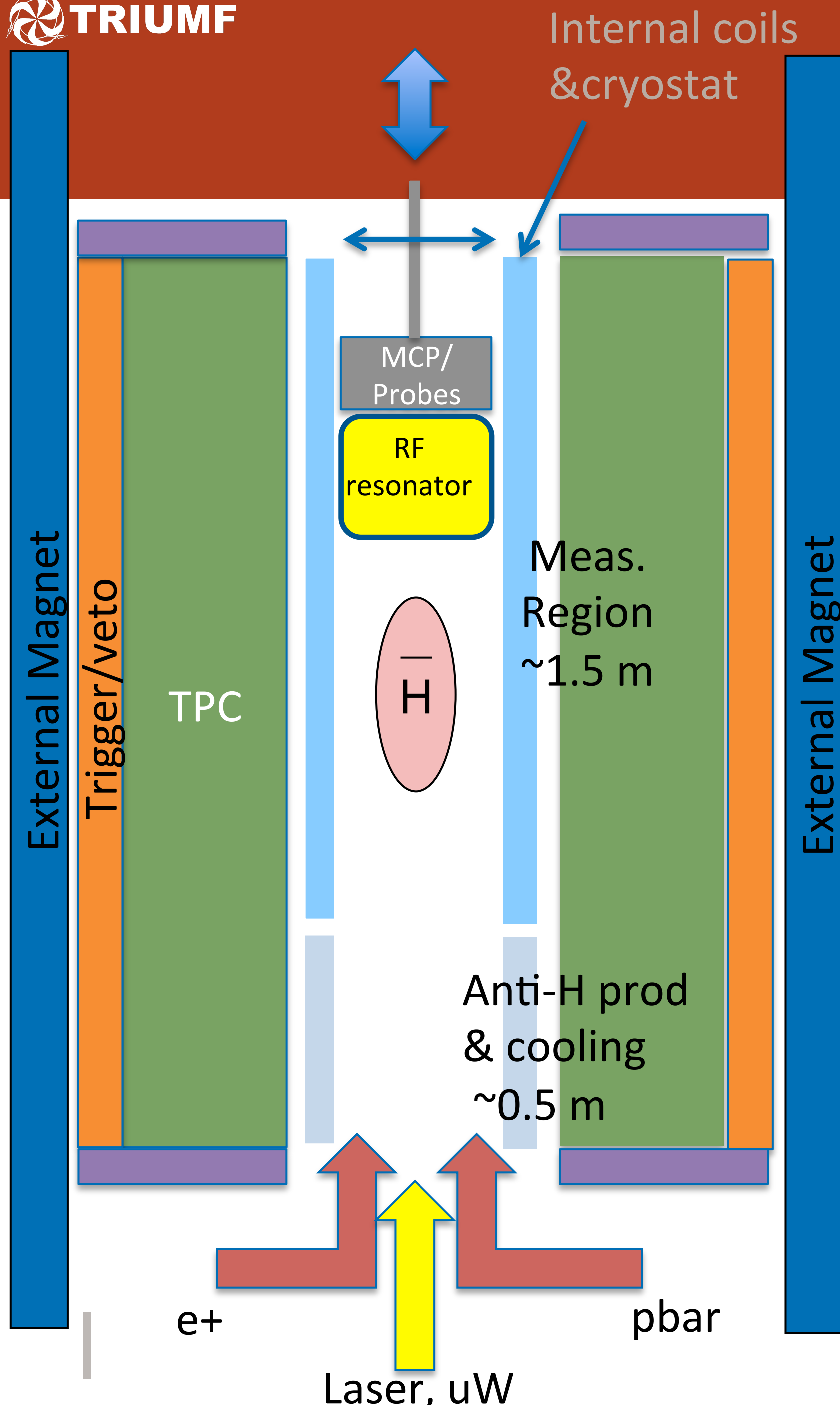
  - Position sensitive detection via annihilations
- Laser cooling essential step: development at UBC
  - NB: Cold atom tests of gravity: ~10^{-10}





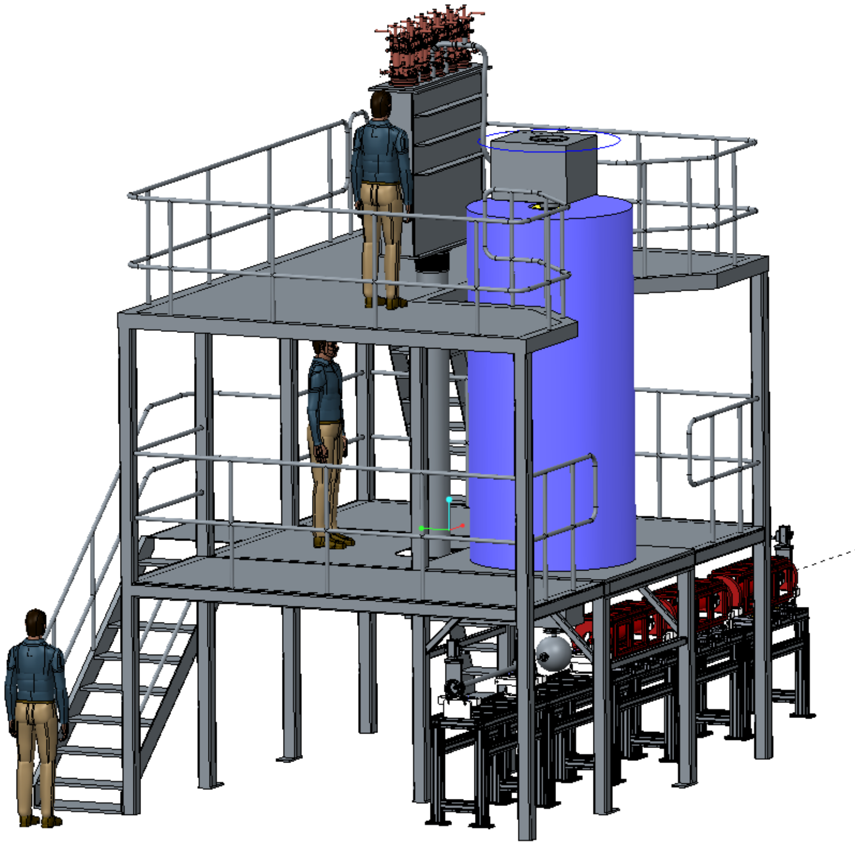
Vertical trap

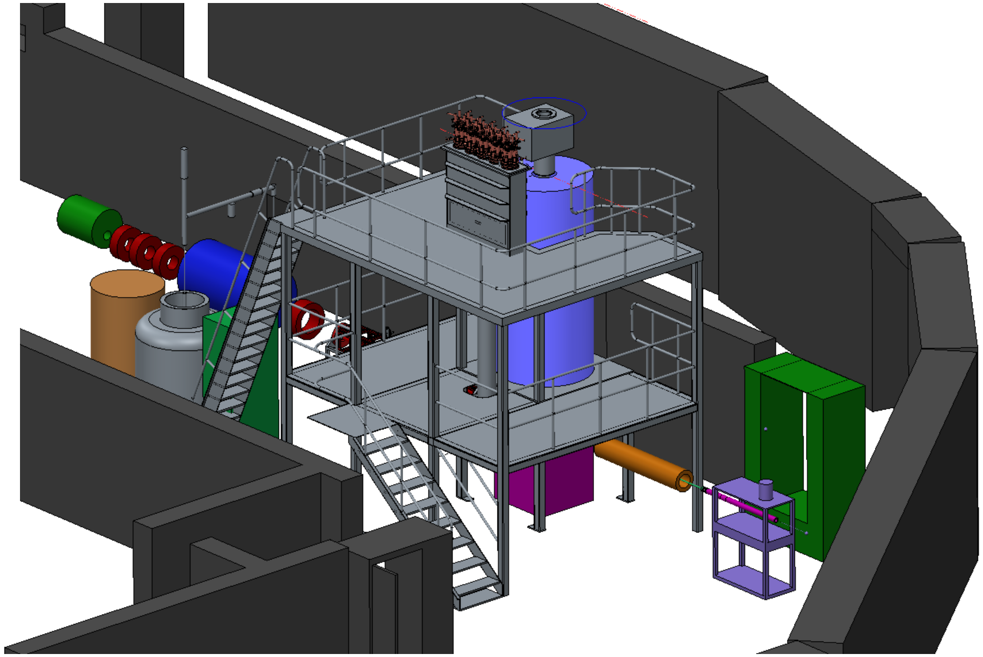
ALPHA-g Experimental Concept



- A long (~ 2m) vertical trap
  - Anti-H production region
    Production, trapping, & cooling
  - Measurement region
    - Sagging of anti-H "gas"
    - Anti-atomic "fountain"
    - Anti-atomic interferometry
    - uW spectroscopy
- Major Canadian funding
  (thank you, referees!)

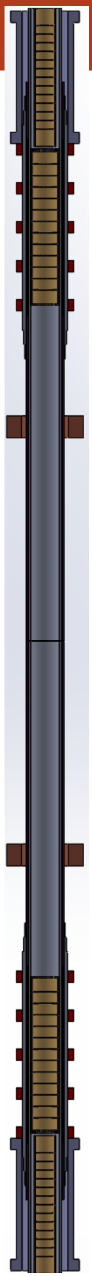
ALPHA-g in AD zone



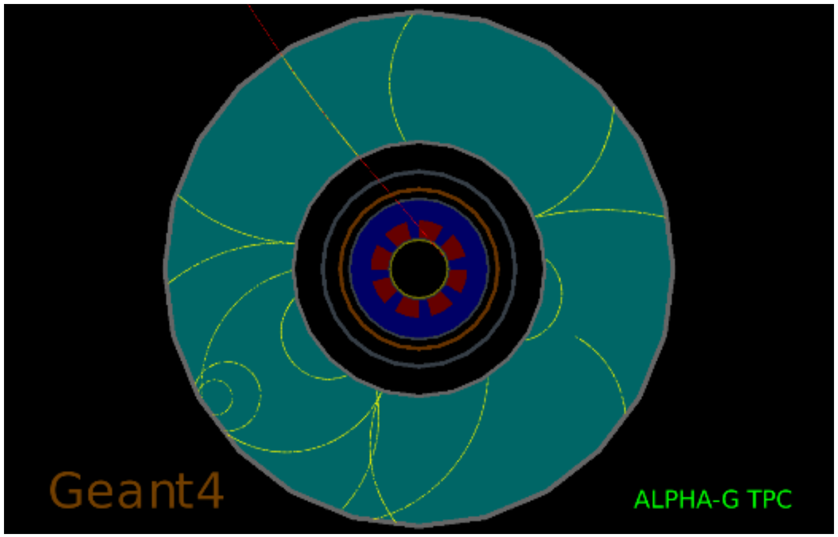


Aiming for commissioning in 2017!

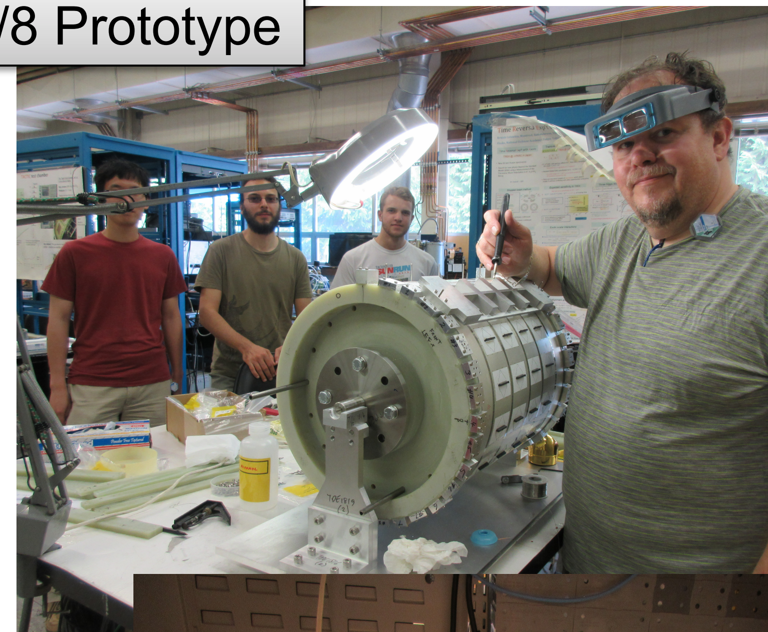
Radial TPC Construction at TRIUMF

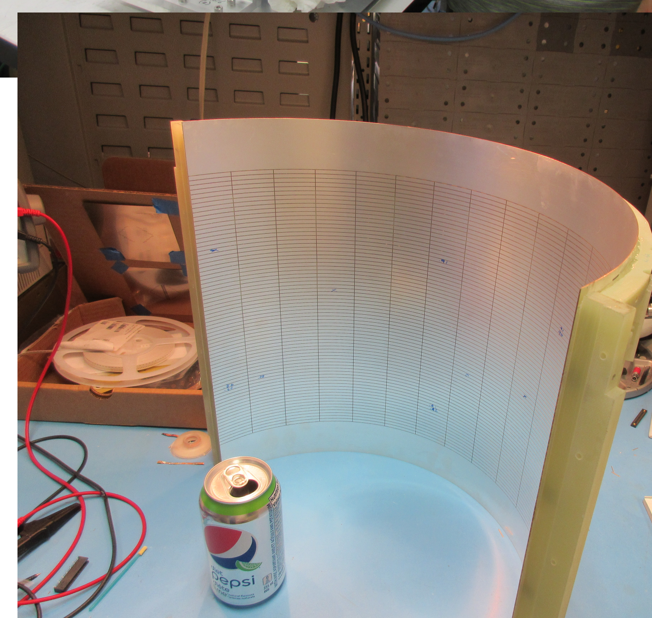


GEANT simulation



1/8 Prototype



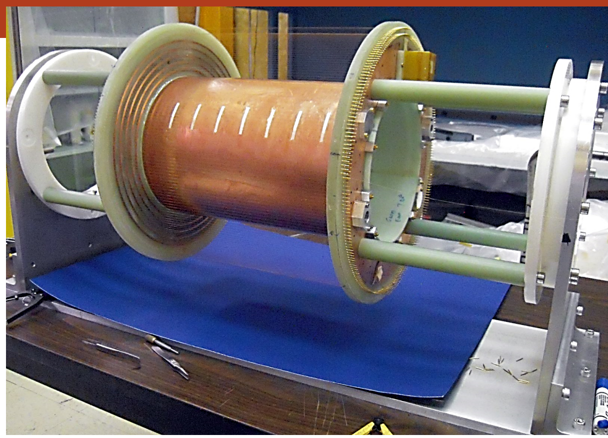


2.3 m long, Radial thickness: 8 cm
Unusual magnetic fields

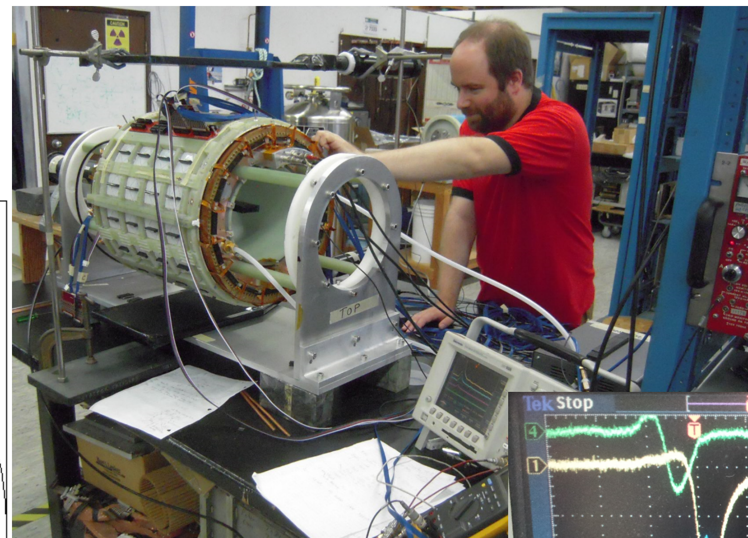
→ Radial-drift TPC

TRIUMF

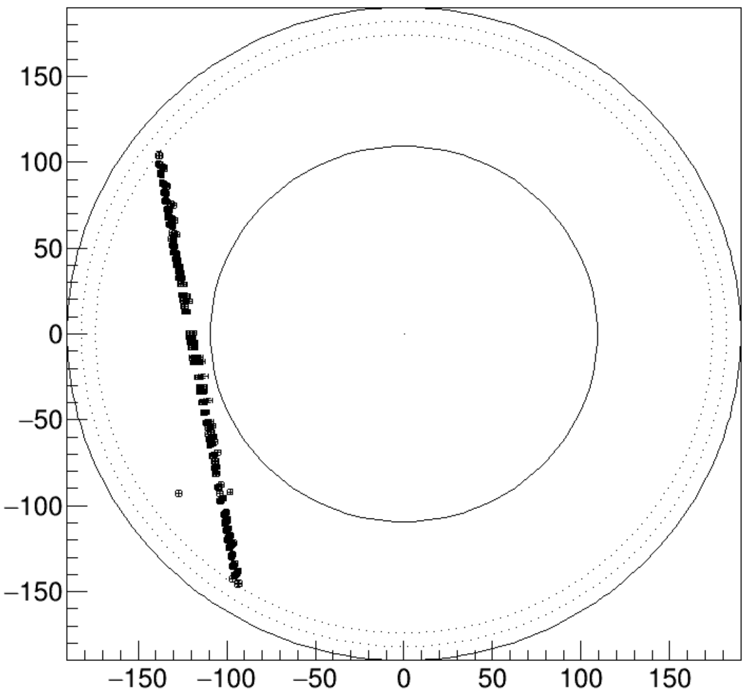
Radial TPC Prototype, Cosmic Test



- Prototype: 1/8 length, full radial size
- Cosmic test: anode RO partially instrumente
- Cathode RO firmware under development



Anode signa



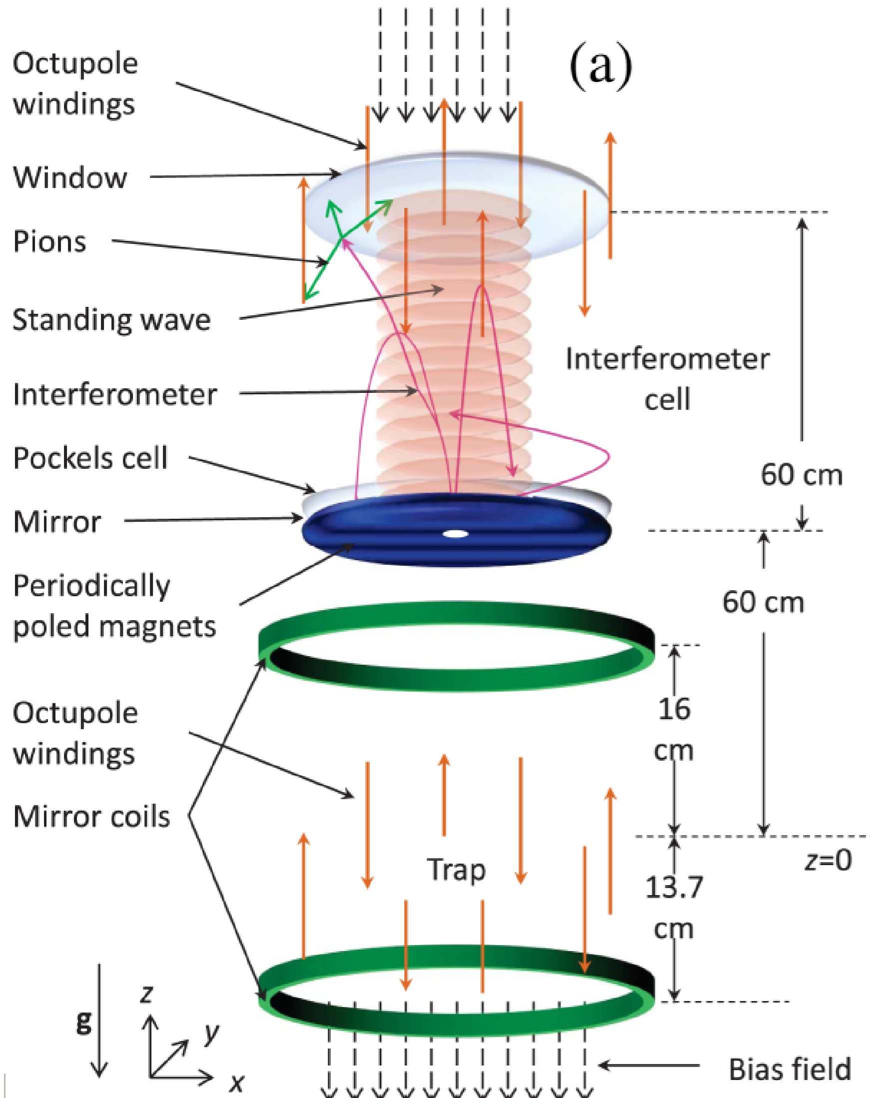
Reconstructed Cosmic Rays (no B field)

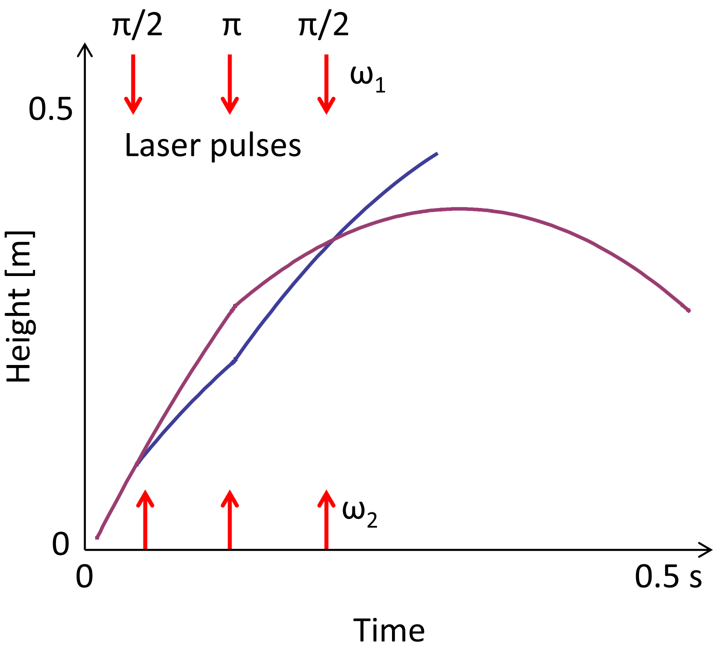
Future?

TRIUMF

Future: Anti-atomic fountain & interforometry

Hamilton et al, Phys. Rev. Lett. (2014)





$$\Delta\varphi = (k_{eff}\cdot g)\, T^2$$

Ultimately 10^{-6}?

Summary

- We hope to address some of most fundamental questions in physics with Anti-H
- After many years of efforts, anti-H studies finally entering precision era!
  - Improving the knowledge of positron charge and mass
  - First laser, and improved microwave spectroscopy
- Many exciting opportunities to come!
  - Anti-H gravity
  - Fountain, Interferometer, etc.

Thank you!
Merci!

4004 Wesbrook Mall | Vancouver BC | Canada V6T 2A3 | Tel 604.222.1047 | Fax 604.222.1074 | www.triumf.ca