



SPECTROSCOPY APPARATUS FOR THE MEASUREMENT OF THE HYPERFINE STRUCTURE OF ANTIHYDROGEN AT CERN

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On behalf of the **ASACUSA** Collaboration

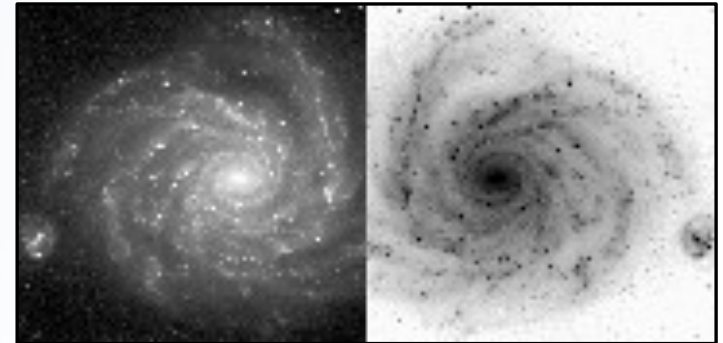
FLAIR Collaboration Workshop

May 16th 2014



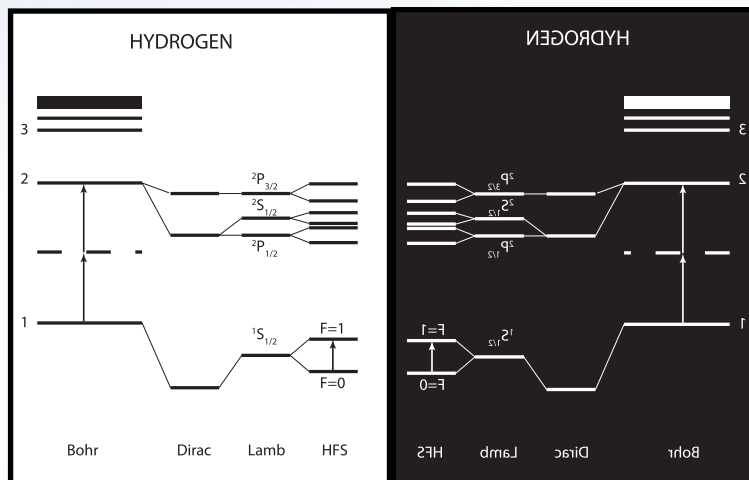
MOTIVATIONS

No observation of antimatter universe:
asymmetry at the cosmological scale

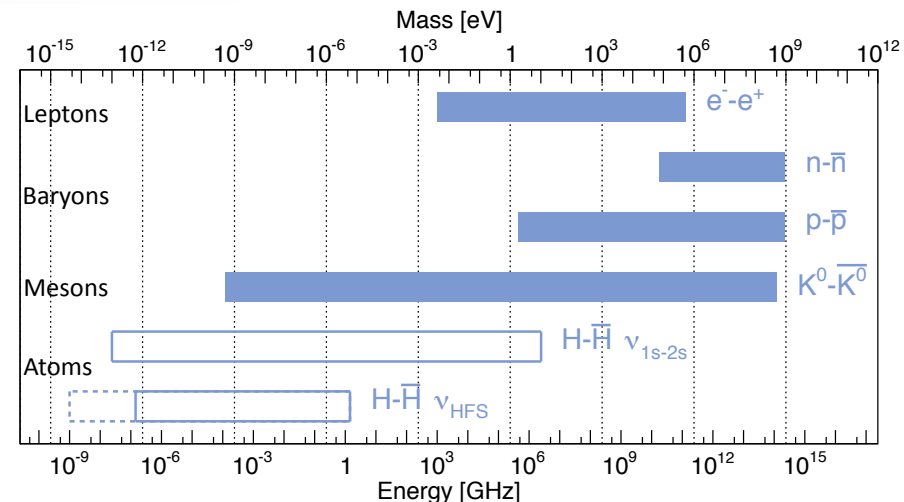


CPT Theorem

No violation of CPT observed to date:
symmetry at the microscopic scale



High absolute precision (potential high sensitivity: Standard Model Extension)



GROUND STATE HYPERFINE SPLITTING

$$\nu_F = 1.420\,405\,751\,766(9)\text{GHz}$$

Leading term: **Fermi contact term**

has been measured to 5ppm

DiSciacca et al, Phys. Rev. Lett. 110, 13 (2013)

$$\nu_F = \frac{16}{3} \left(\frac{M_p}{M_p + m_e} \right)^3 \frac{m_e}{M_p} \frac{\mu_p}{\mu_N} \alpha^2 c R_y$$

Finite electric and magnetic radius (**Zemach corrections**): ~41ppm

access to the electric and magnetic form factors of the antiproton

$$\Delta\nu(\text{Zemach}) = \nu_F \frac{2Z\alpha m_e}{\pi^2} \int \frac{d^3p}{p^4} \left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1 \right]$$

Polarizability of p(bar) < 4ppm

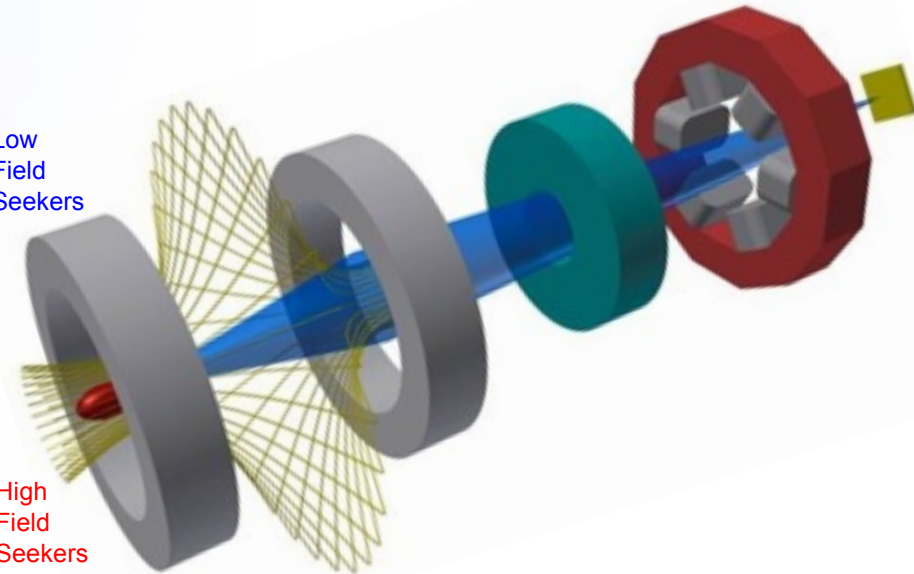
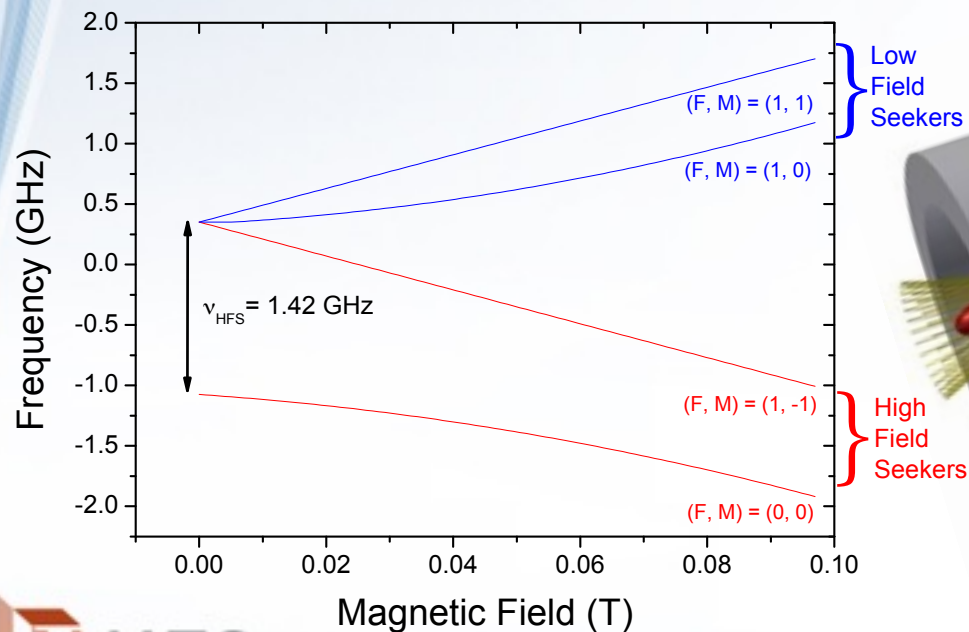
e.g Friar et al. Phys.Lett. B579 (2004)

MEASUREMENT PRINCIPLE

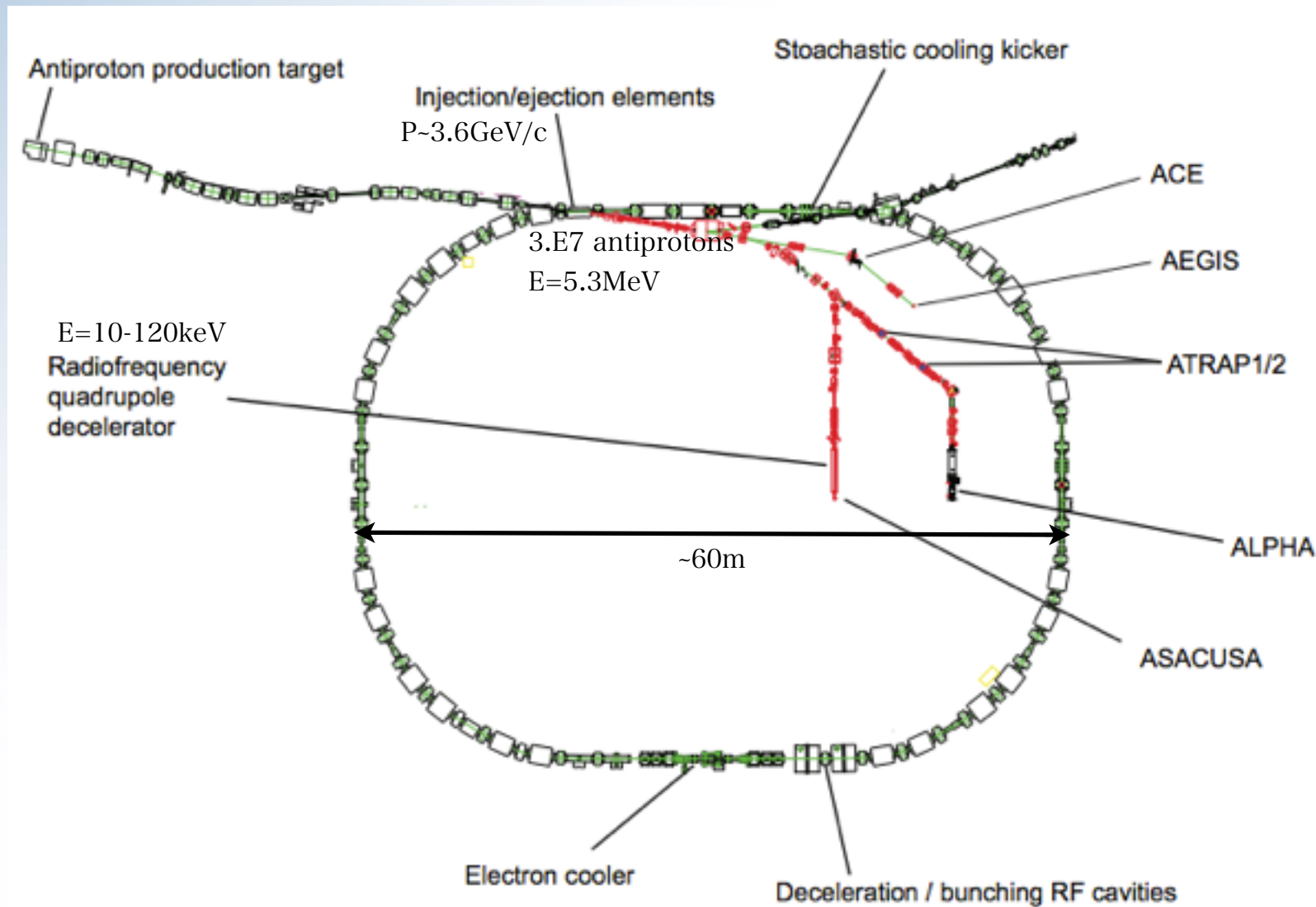
Spectroscopy with trapped antihydrogen: lower precision due to strong confining field

Good candidate: atomic beam with RF resonance

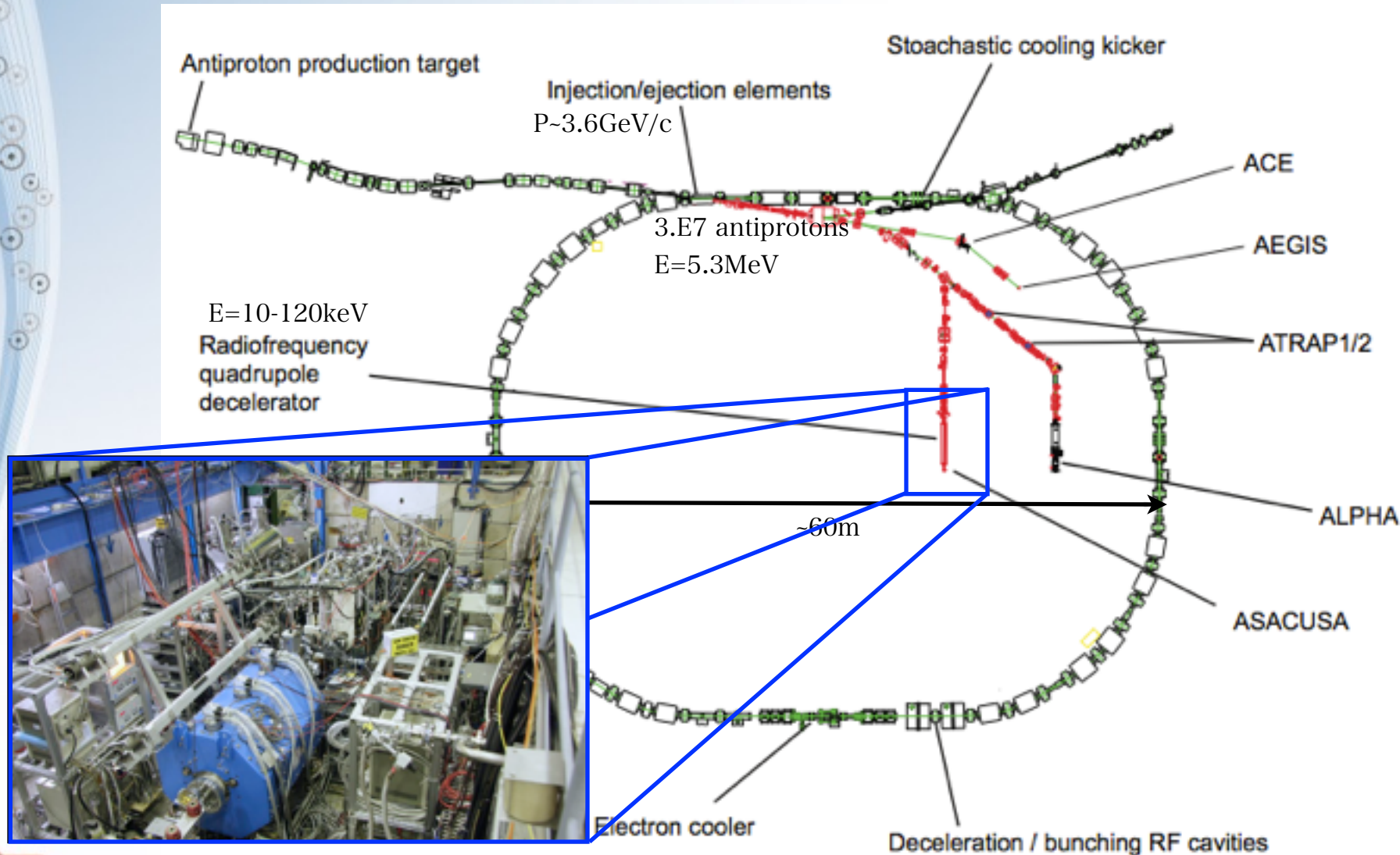
- 1) no $\bar{\text{H}}$ trapping needed $\rightarrow$ no need for ultra-cold (< 1 K) $\bar{\text{H}}$
- 2) atomic beam method can work up to 50-100 K
- 3) $\bar{\text{H}}$ atoms can be guided with inhomogeneous magnetic field



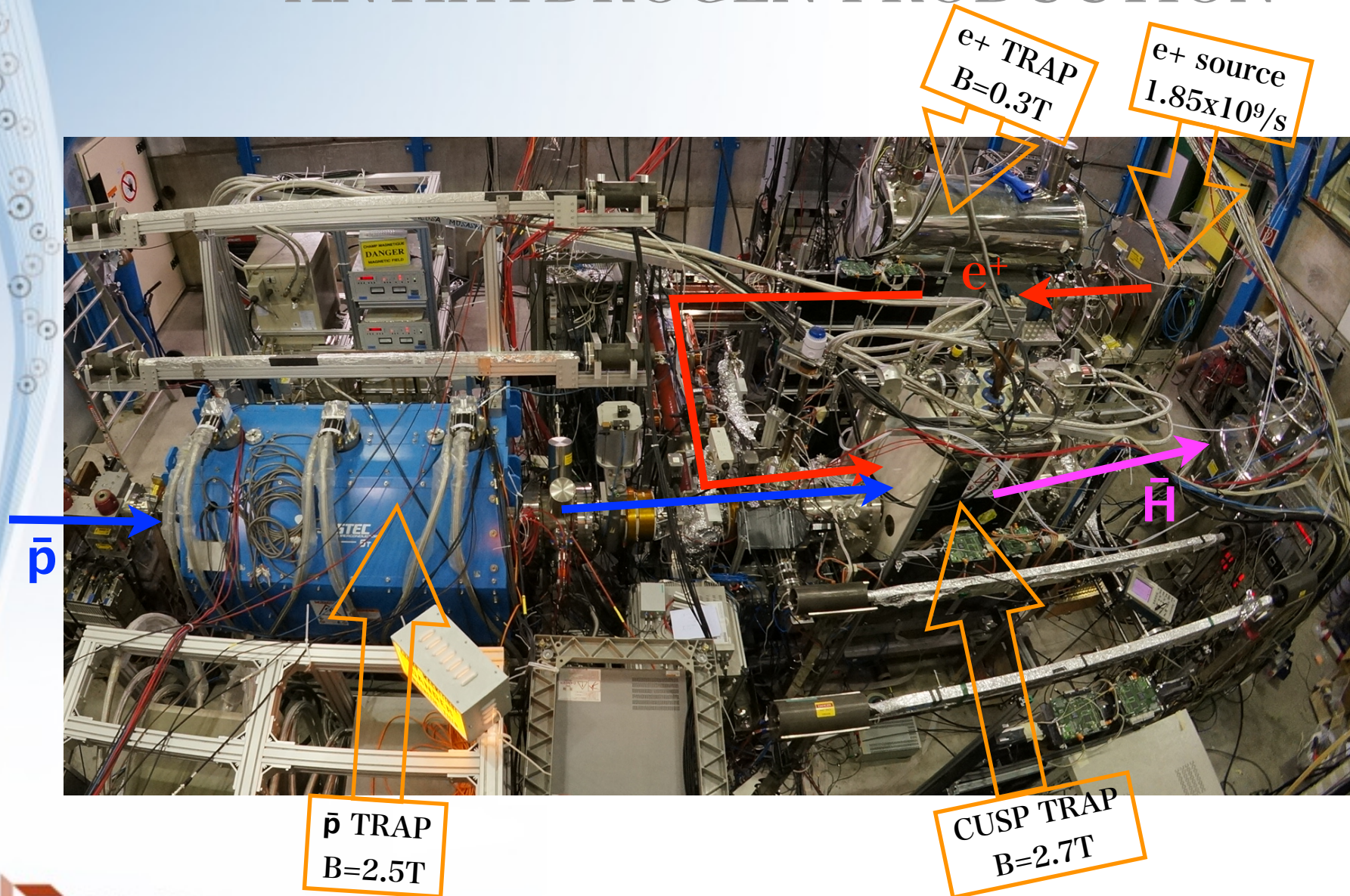
CERN'S ANTIPROTON DECELERATOR



CERN'S ANTIPROTON DECELERATOR



ANTIHYDROGEN PRODUCTION



ANTIHYDROGEN PROPERTIES

Ultra-low temperature antihydrogen are not necessary for a beam experiments (unlike trap experiments).

BUT cold antihydrogen is better for:

- 1) **Polarisation intensity**
- 2) Cascading time: **lower n state**
- 3) **Interaction time** with the microwave field in the cavity



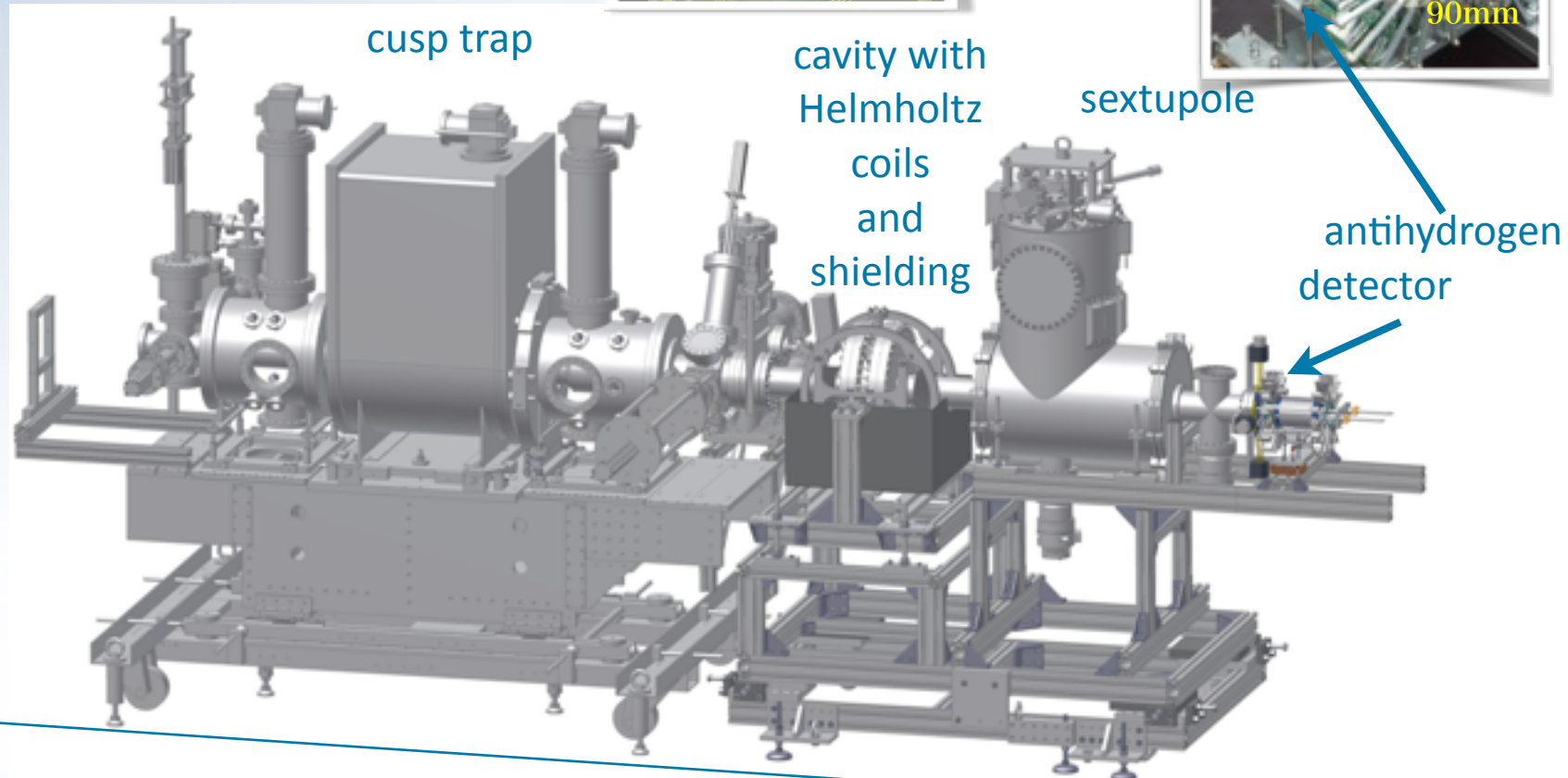
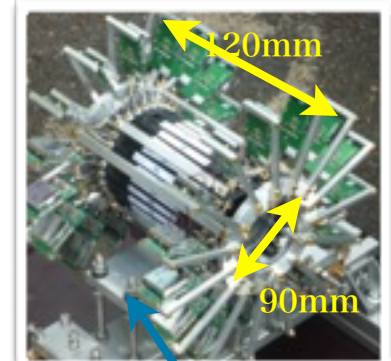
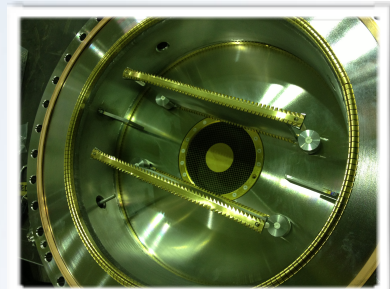
**SIMULATION
WITH GEANT 4**

Behaviour of antiproton and positron plasmas simulated using **SIMBUCA**

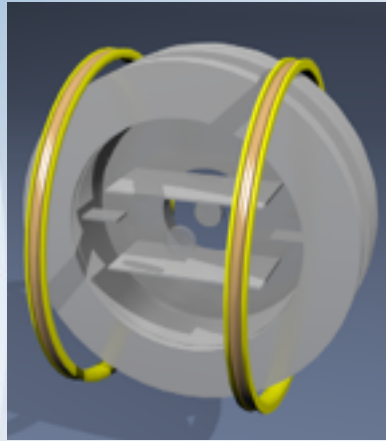
Formation of antihydrogen simulated CTMC

Pipeline between these simulations and Geant4

THE SPECTROMETER LINE



THE MICROWAVE CAVITY

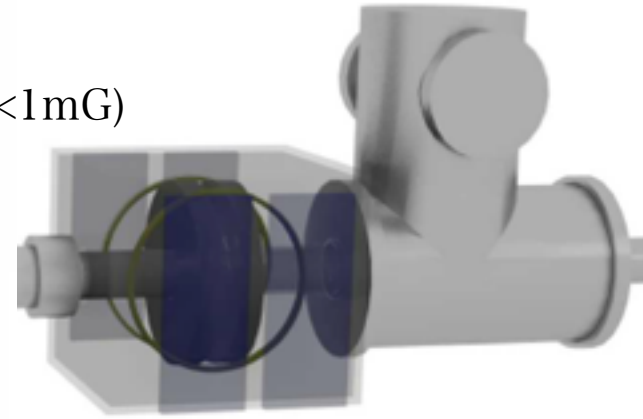


Helmholtz coils 0-10G static field
high stability power supply
Field Stability $<0.025\%$ @ 4G ($<1\text{mG}$)

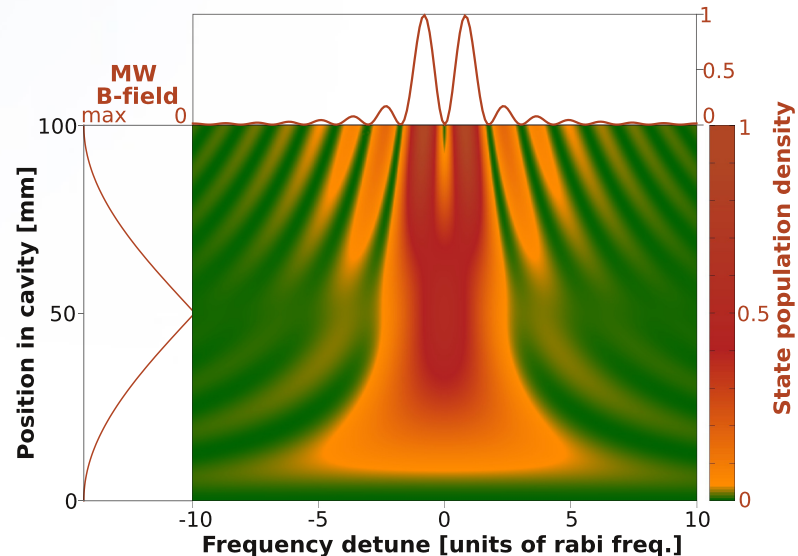
beam stopper: stop particles
coming from the center of the CUSP

cavity length 10 cm
MW frequency: 1.42GHz

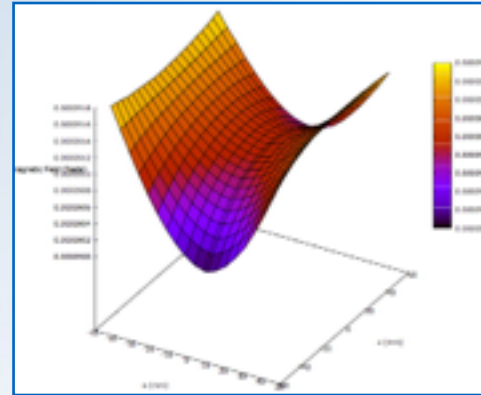
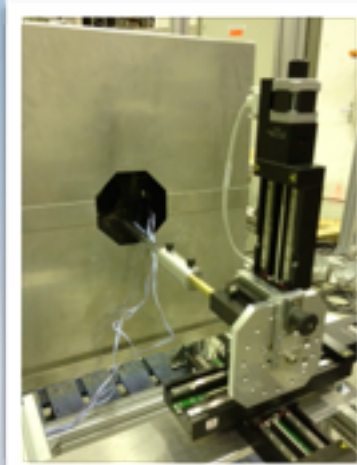
Q~100



shielding

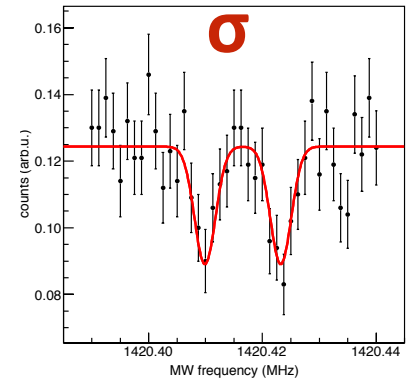


THE MICROWAVE CAVITY



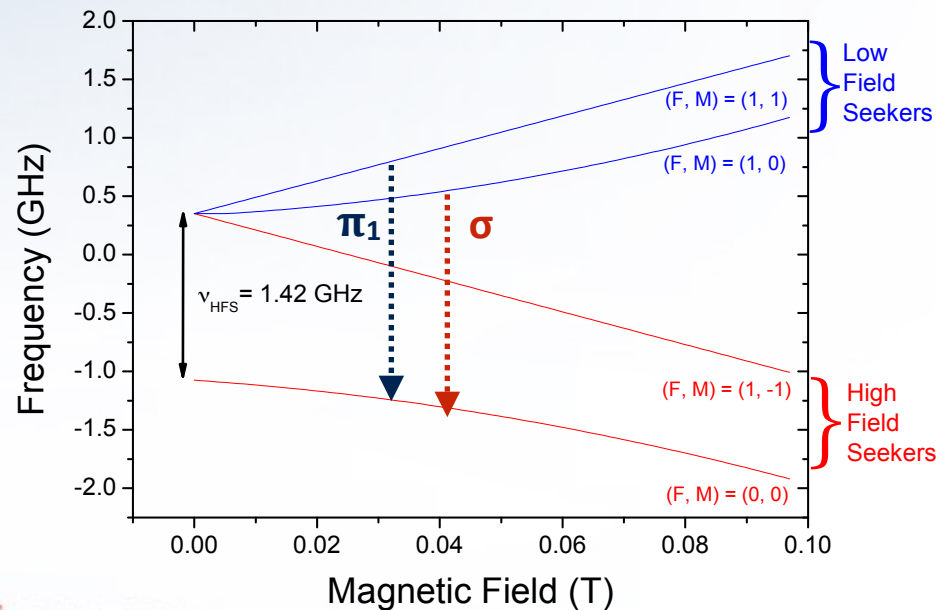
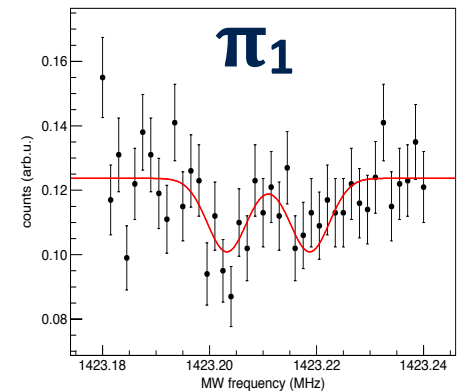
precise static field characterization

$$\frac{\Delta B}{B} = 1\%$$



simulation done at 2G, T=50K

$$\frac{\Delta B}{B} = 0.1\%$$



DETECTOR IMPROVEMENTS

Detector:

- combination of calorimeter (distinction between $\bar{H}$ and $\bar{H}$ annihilation products) and tracking detector
- addition of a 2nd layer of hodoscope (vertex reconstruction)

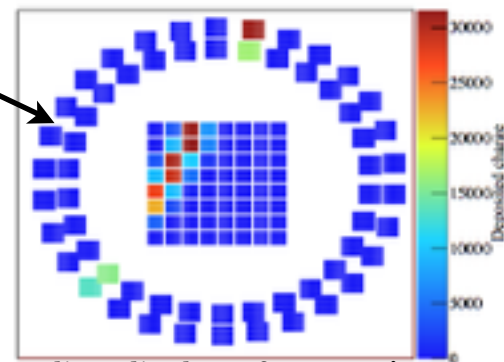
SIMULATION:

cosmics simulated with CRY 1.7 in G4

Assuming 2012 experimental conditions, S/N ratio of ~10
~50% detection efficiency

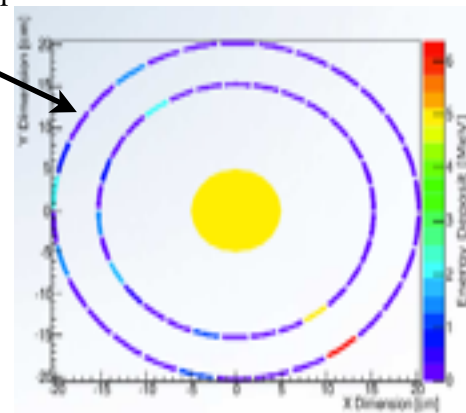
1 layer of hodoscope.

Read out on both side

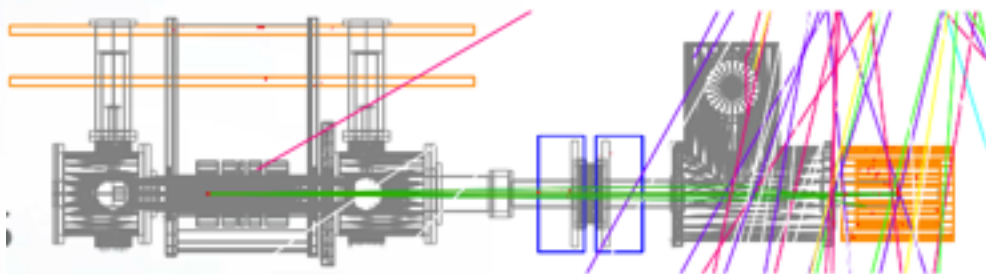


online display of a cosmic events in the detector (2012)

2 layers of hodoscope

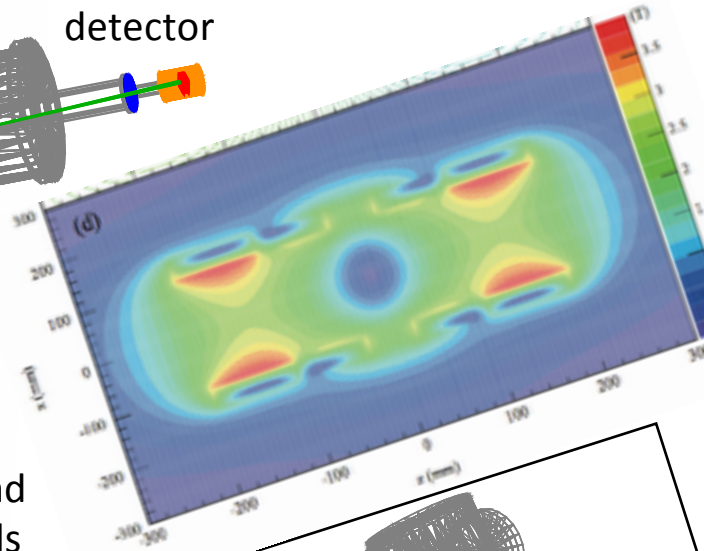
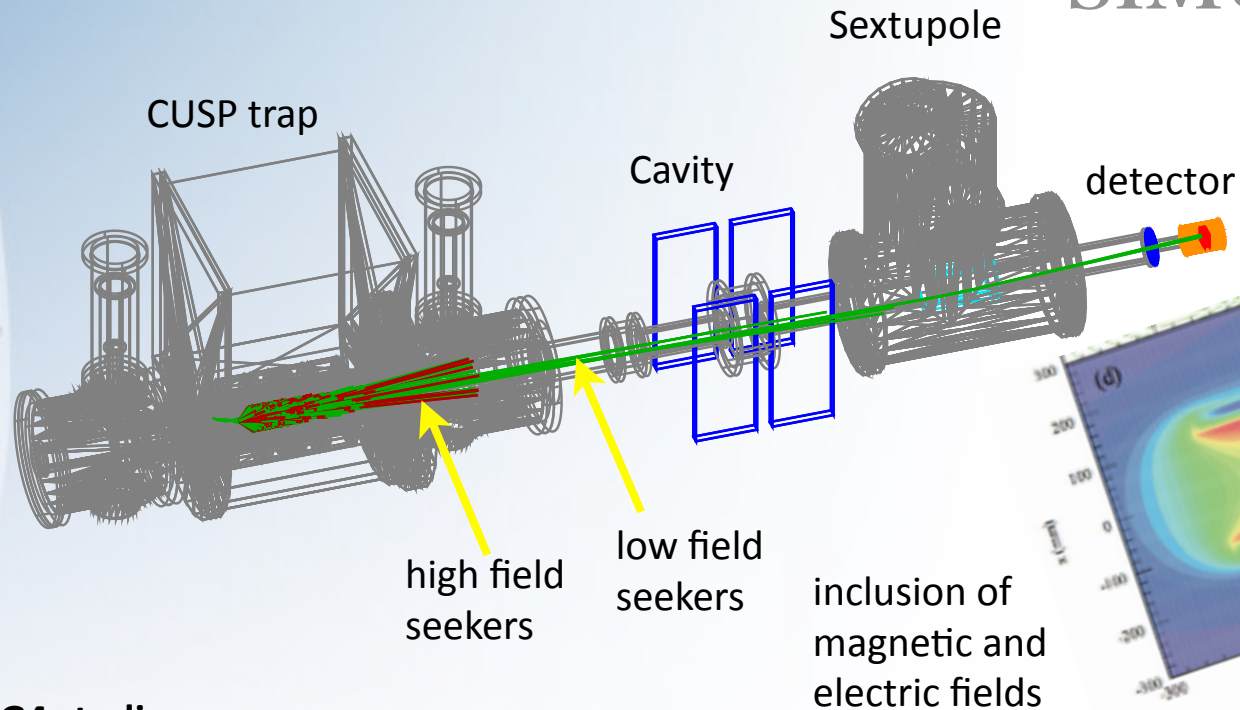


simulation of an $\bar{H}$ annihilation



12

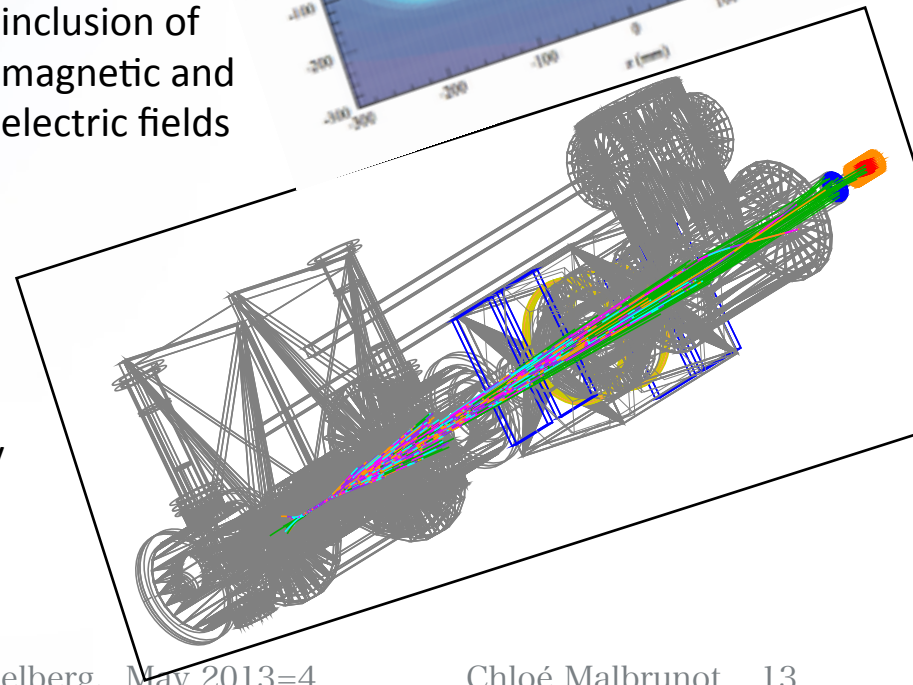
SIMULATION



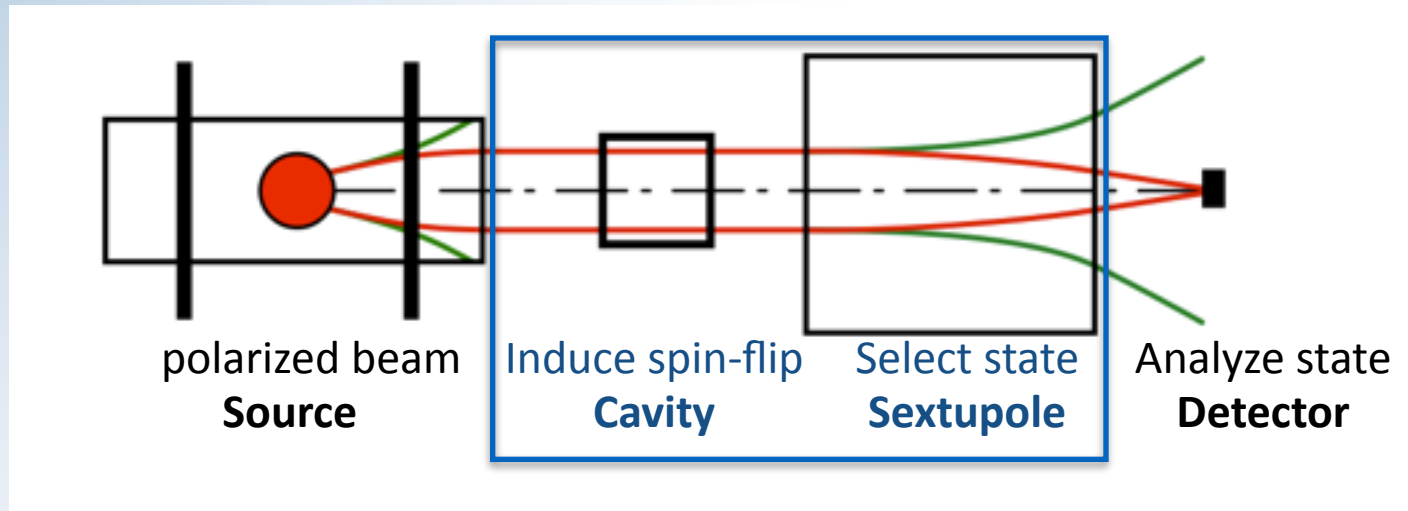
G4 studies:

- simulation of $\bar{H}$ trajectories in field (tracking neutral particle)
- inclusion of radiative decay
- background simulation
- cosmics
- estimation of transition probabilities in cavity
- effect of inhomogeneities of static field
- benchmarking of physics lists

inclusion of
magnetic and
electric fields



TEST SETUP WITH HYDROGEN BEAM (LS1)



	$\bar{\text{H}}$ beam	H beam
Beam rate at production (4π)	small (≈ 10)	high (≈ 10)
Quantum state	broad distribution	GS
Detection efficiency	detector 0.4 to 0.6 solide angle (≈ 10)	detector (≈ 10) solide angle (≈ 10)
Detection method	Energy deposit, tracking	ionization and single ion counting
Background	cosmics, upstream annihilation	residual gas background $\gg$ signal (LIA)

TEST SETUP WITH HYDROGEN BEAM (LS1)

atomic H source

ON $\rightarrow$ H and H₂
OFF $\rightarrow$ H₂ only

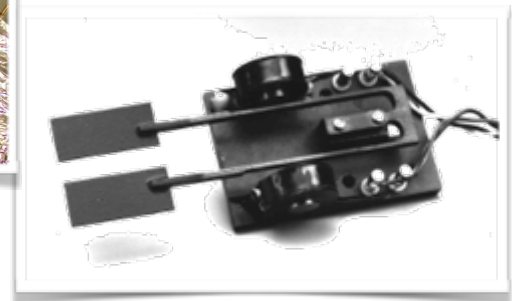
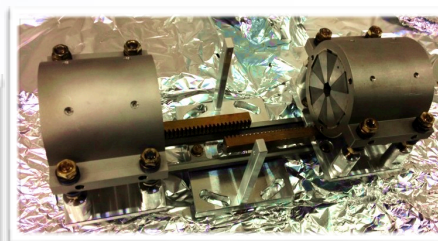
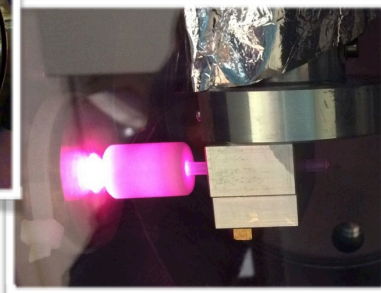
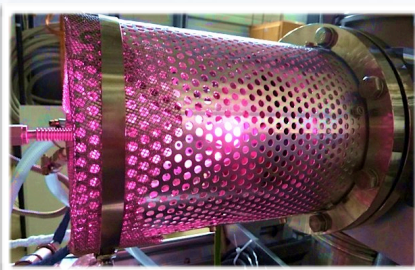
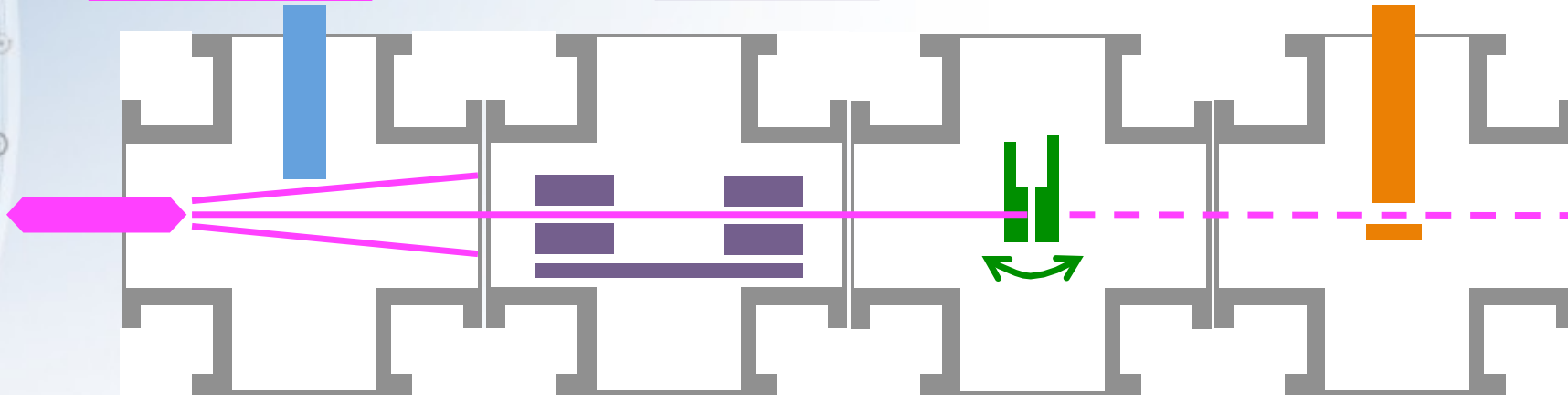
Cryogenic
(cold head)
for 50-100K
beam

Sextupole
for polarized
beam

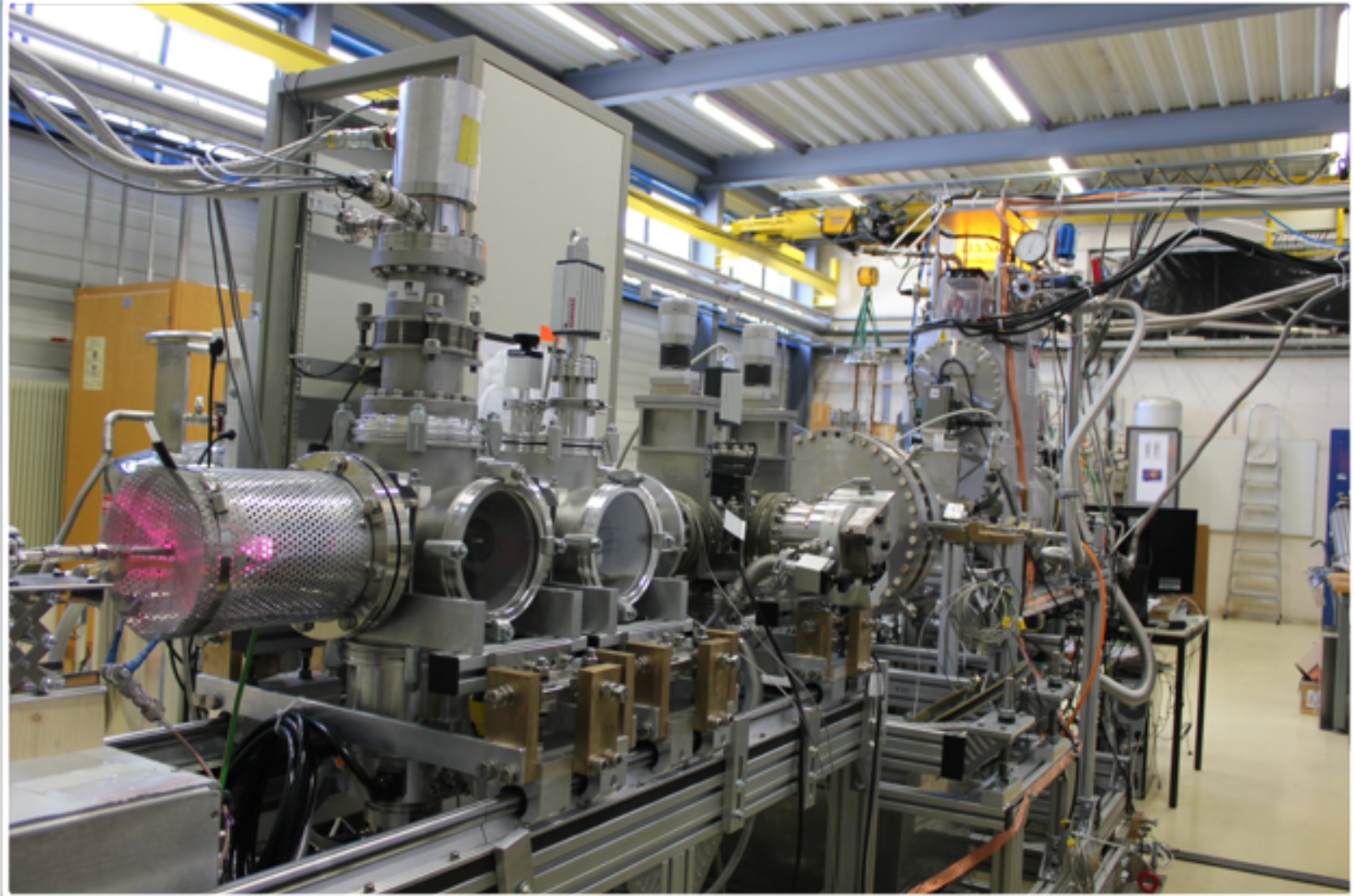
Fork-Chopper
 $f \approx 178$ Hz
50% duty cycle

Quadrup. Mass Spec.

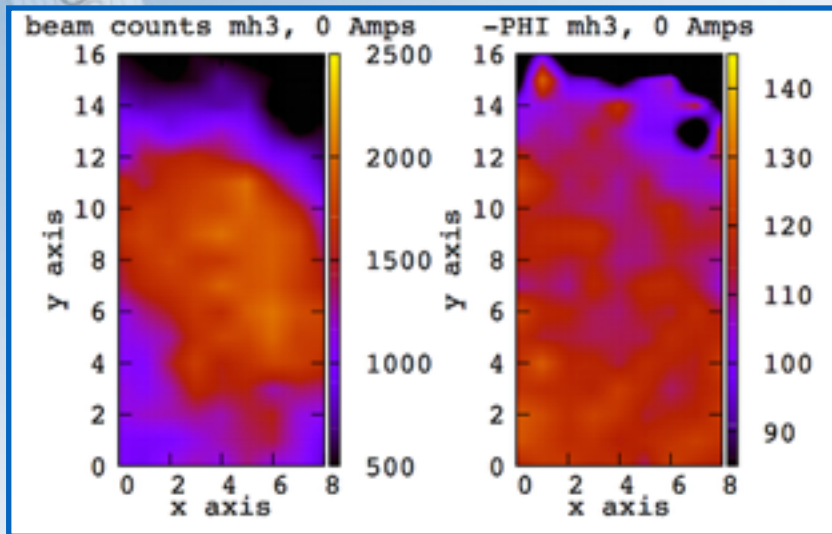
detects mass=1 H₁⁺
or mass=2 H₂⁺



TEST SETUP WITH HYDROGEN BEAM (LS1)



LATEST RESULT WITH HYDROGEN BEAM



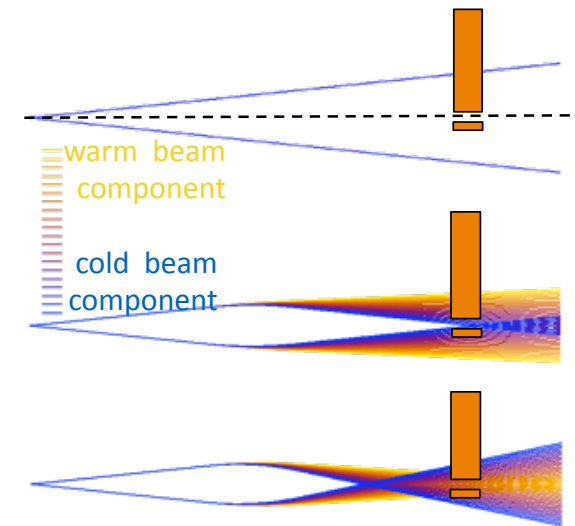
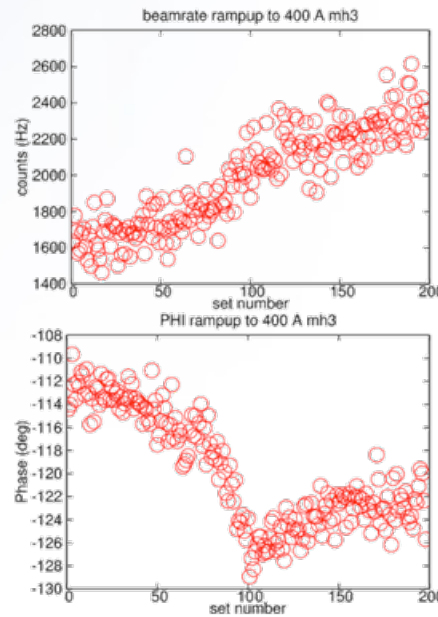
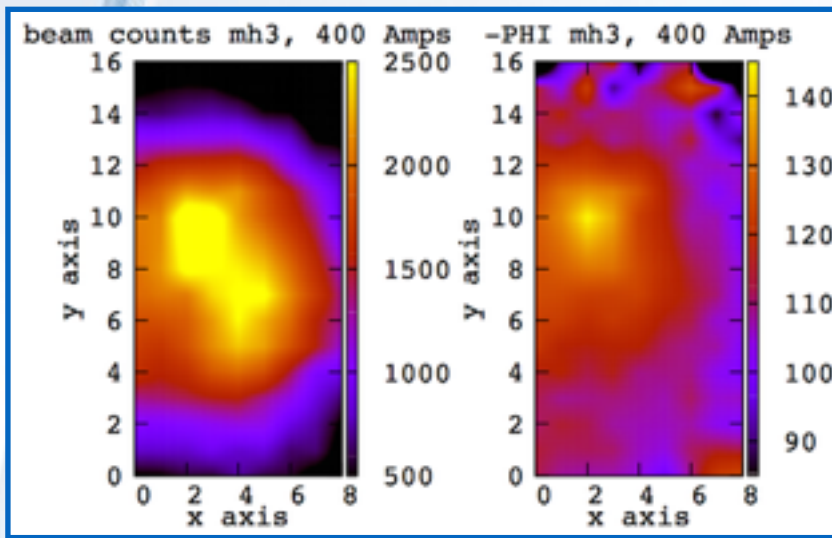
Polarized beam:

focusing effect of cold atoms

Phase can be compared to a laser beam

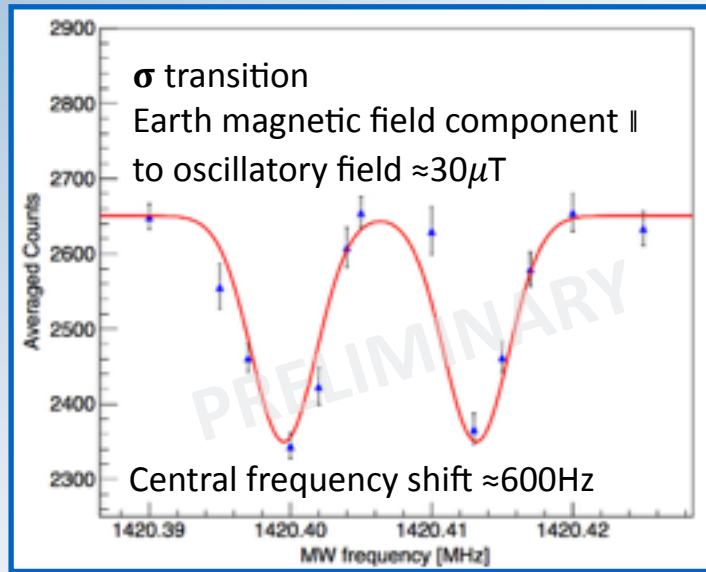
Estimation of the temperature of the beam 50-100K

large Parameter space



increasing sup. cond. sext. current

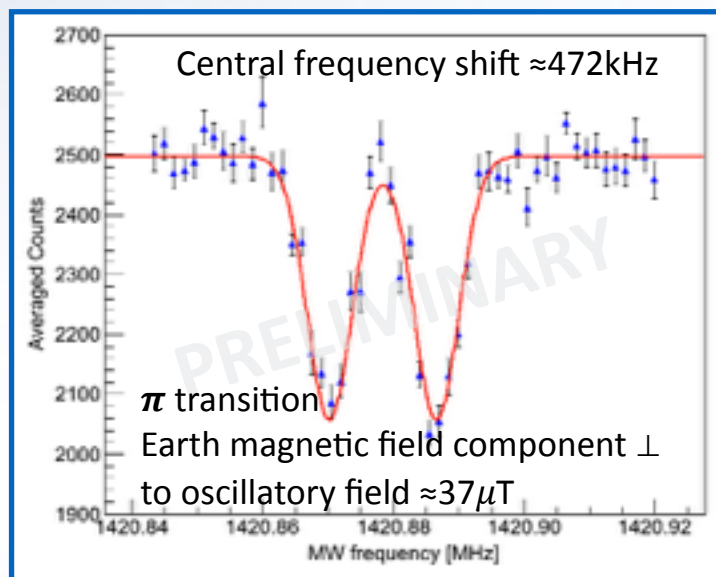
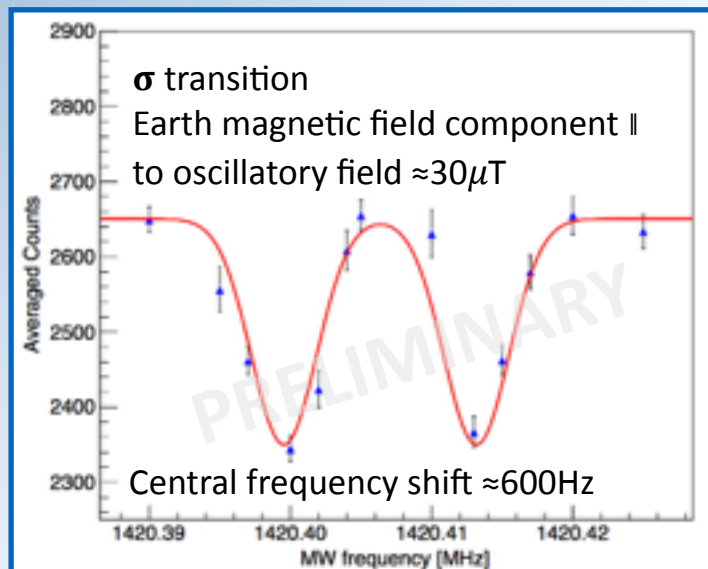
LATEST RESULT WITH HYDROGEN BEAM



Fit parameter	results
resonance σ [MHz]	0.0023
ν_0	1420.4063
err (	0.00013
Relative err (	9.3E-08

- small broadening (low temperature)
- Relatively large signal (high polarization, small temperature distribution)

LATEST RESULT WITH HYDROGEN BEAM



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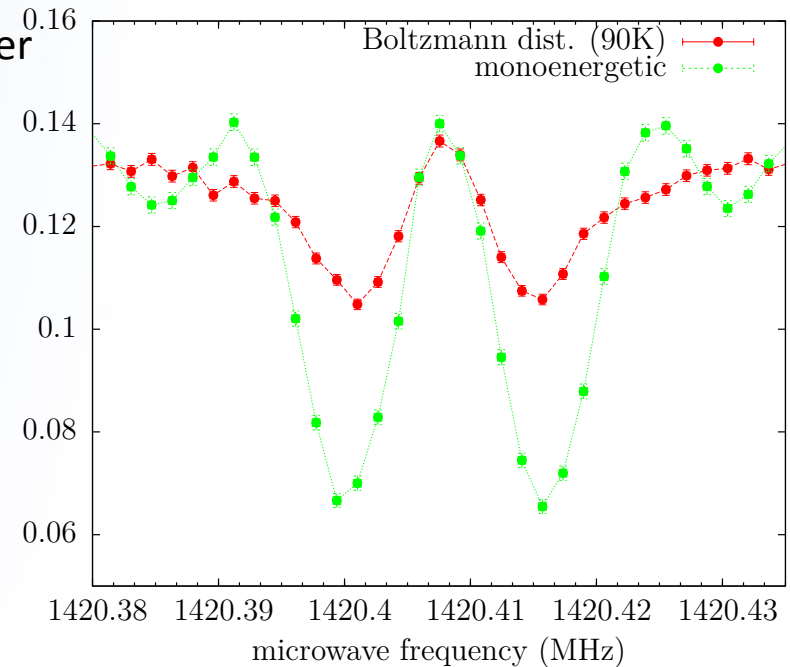
Fit parameter	results
resonance σ [MHz]	0.0034
ν_0	1420.878
err (	0.00010
Relative err (	7.2E-08

LATEST RESULT WITH HYDROGEN BEAM

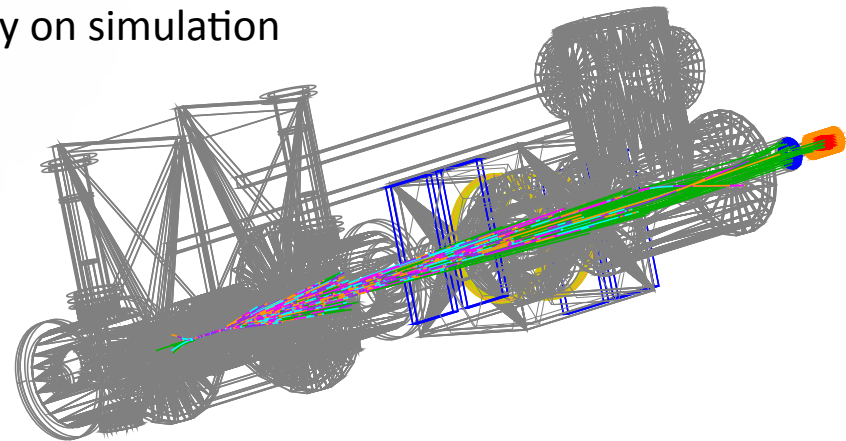
Study the resonance line shape in large parameter space

Systematics studies

- Vary polarization
- temperature distribution
- Velocity mean
- static field value
- static field inhomogeneities
- larger beam size
- shielding effect on Majorana spin flip



Cannot vary the quantum state distribution -> rely on simulation

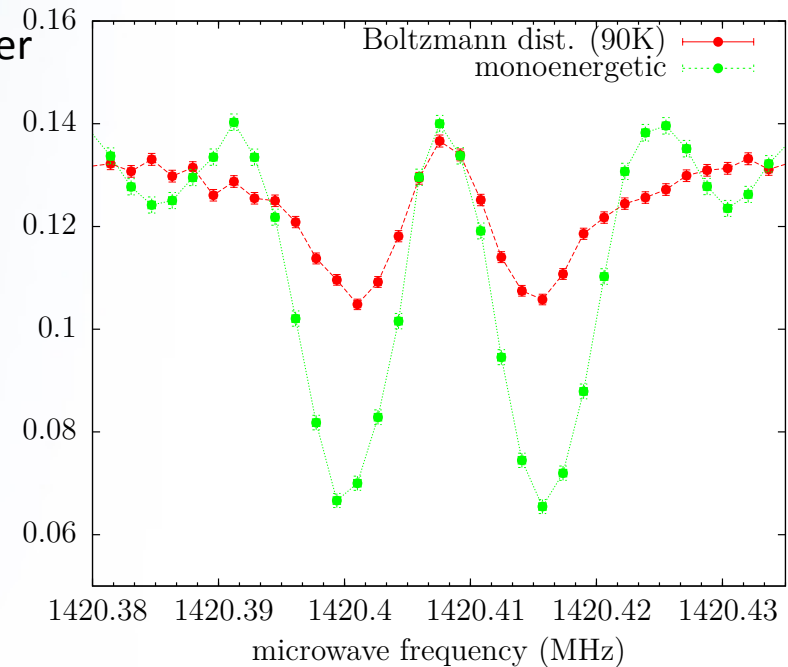


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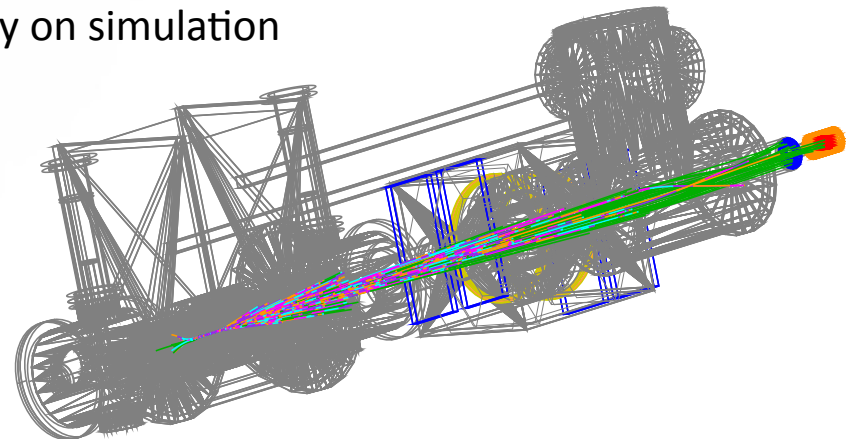
Systematics studies

- Vary polarization
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Cannot vary the quantum state distribution -> rely on simulation

- “cold” beam
- Ground state at the cavity
- Factor ≈ 10 more statistics



SUMMARY AND OUTLOOK

- Design and construction of a antihydrogen detector ongoing.
- Full spectroscopy beamline will be ready for the beamtime this year
- Extensive Monte Carlo simulation done/ongoing
- First Resonance in Hydrogen observed with part of the $\bar{H}$ spectroscopy setup
 - Adiabatic Transitions within the Earth Magnetic Field are small
 - Resonance width is small.
- Spectroscopy beamline systematics study ongoing
- Potential for a ppm precision measurement in sight

ACKNOWLEDGEMENTS



A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons

ASACUSA Scientific project

- (1) Spectroscopy of $\bar{p}\text{He}$
- (2) $\bar{p}$ annihilation cross-section
- (3) $\bar{H}$ production and spectroscopy

The $\bar{H}$ team

University of Tokyo, Komaba: K. Fujii, N. Kuroda, Y. Matsuda, M. Ohtsuka, S. Takaki, K. Tanaka, H.A. Torii

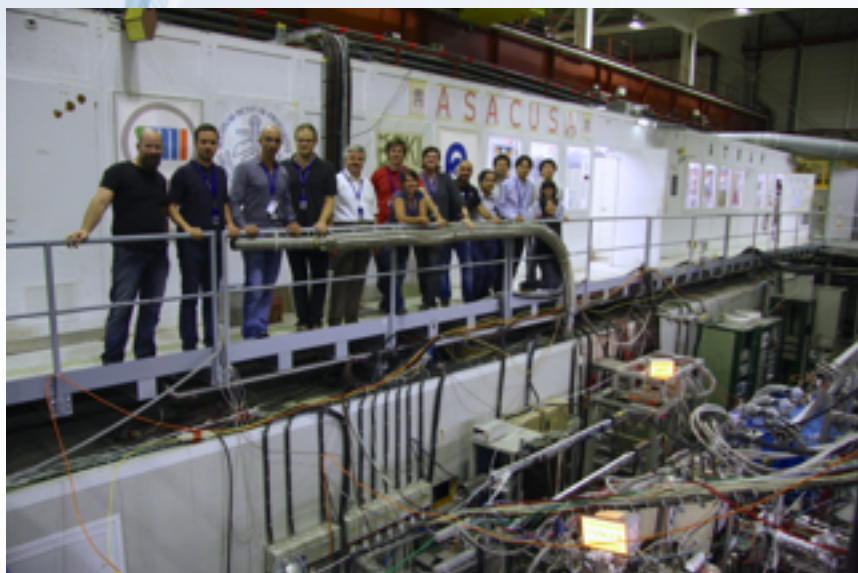
RIKEN: Y. Kanai, A. Mohri, D. Murtagh, Y. Nagata, B. Radics, S. Ulmer, S. Van Gorp, Y. Yamazaki

Tokyo University of Science: K. Michishio, Y. Nagashima

Hiroshima University: H. Higaki, S. Sakurai

Univerita di Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli, N. Zurlo

Stefan Meyer Institut für Subatomare Physik: P. Caradonna, M. Diermaier, C. Malbrunot, O. Massiczek, C. Sauerzopf, M. Simon, K. Suzuki, E. Widmann, M. Wolf, J. Zmeskal





THANK YOU FOR YOUR ATTENTION

