H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

In-beam hyperfine spectroscopy of (anti)hydrogen for test of CPT and Lorentz Invariance

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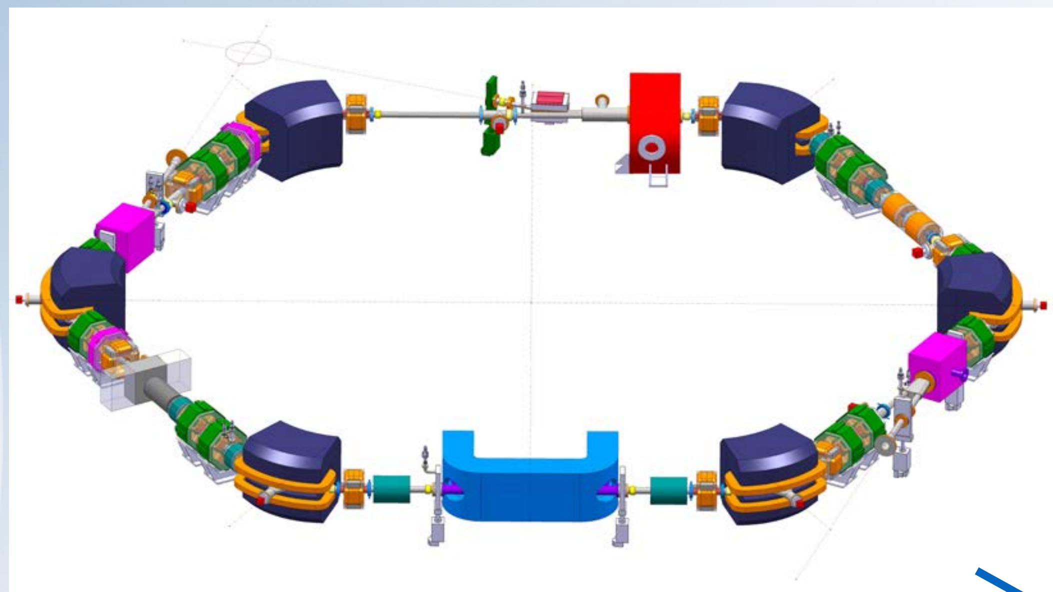
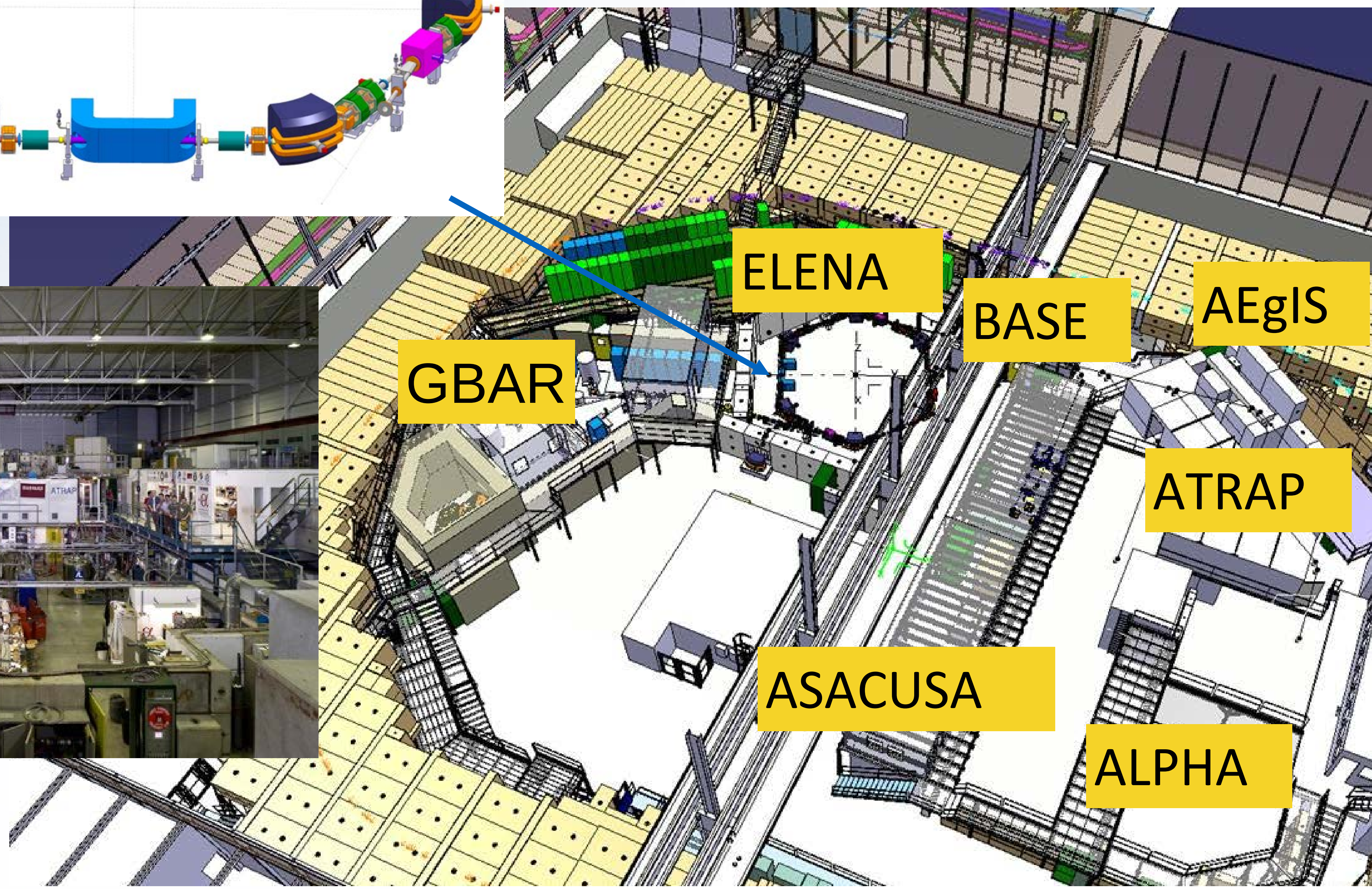
SMI erc ÖAW

Ginzburg Centennial Conference on Physics
Lebedev Institute, Moscow, 29 May 2017

Antiproton Delecerator & ELENA@CERN



AD: 5 MeV
ELENA: 5 MeV → 100 keV
Pulsed beam, $3\text{x}10^7$ $\bar{p}$ every ~ 100 s



ELENA operation from 2017

ASACUSA COLLABORATION

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

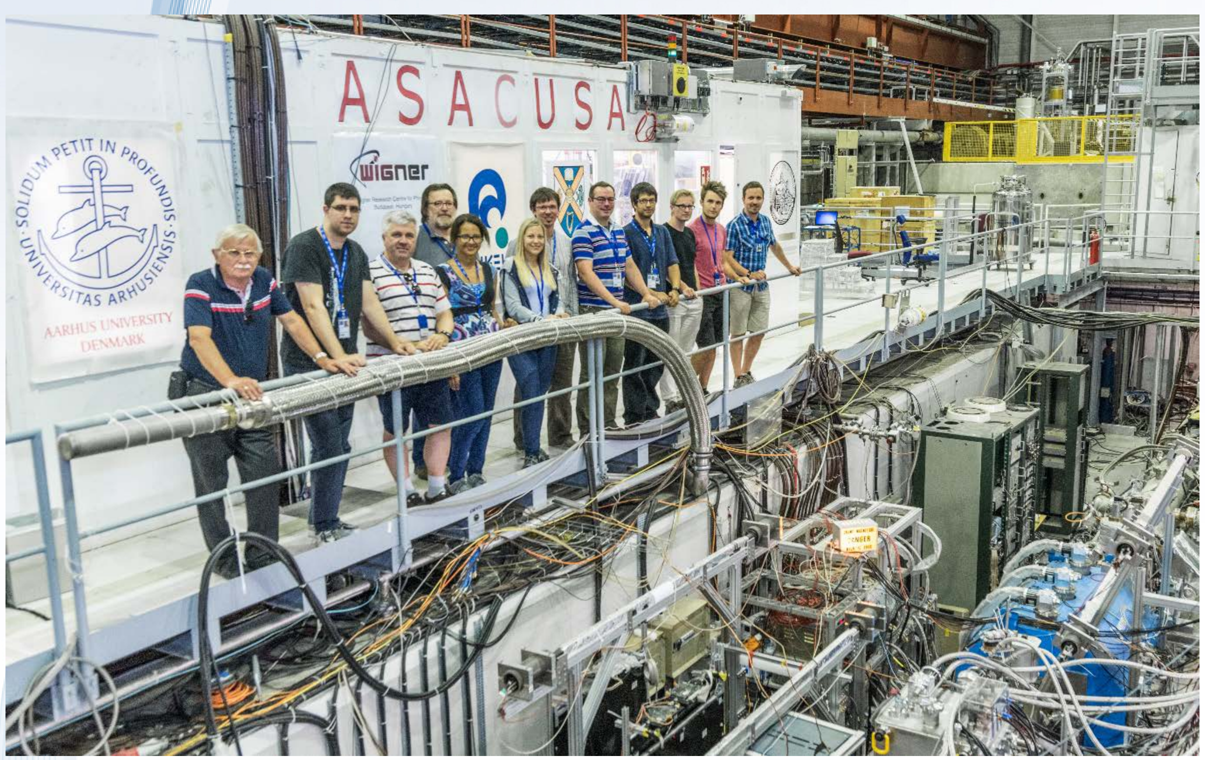
ASACUSA Scientific project

(1) Spectroscopy of $\bar{p}$He

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{H}$ production and spectroscopy

The Antihydrogen team



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

Stefan Meyer Institut für Subatomare Physik: A. Capon, S. Cuendis, M. Diermaier, M. Fleck, B. Kolbinger, O. Massiczek, C. Sauerzopf, M.C. Simon, H. Spitzer, K. Suzuki, S. Vamosi, E. Widmann, M. Wiesinger, J. Zmeskal

CERN: H. Breuker, C. Malbrunot

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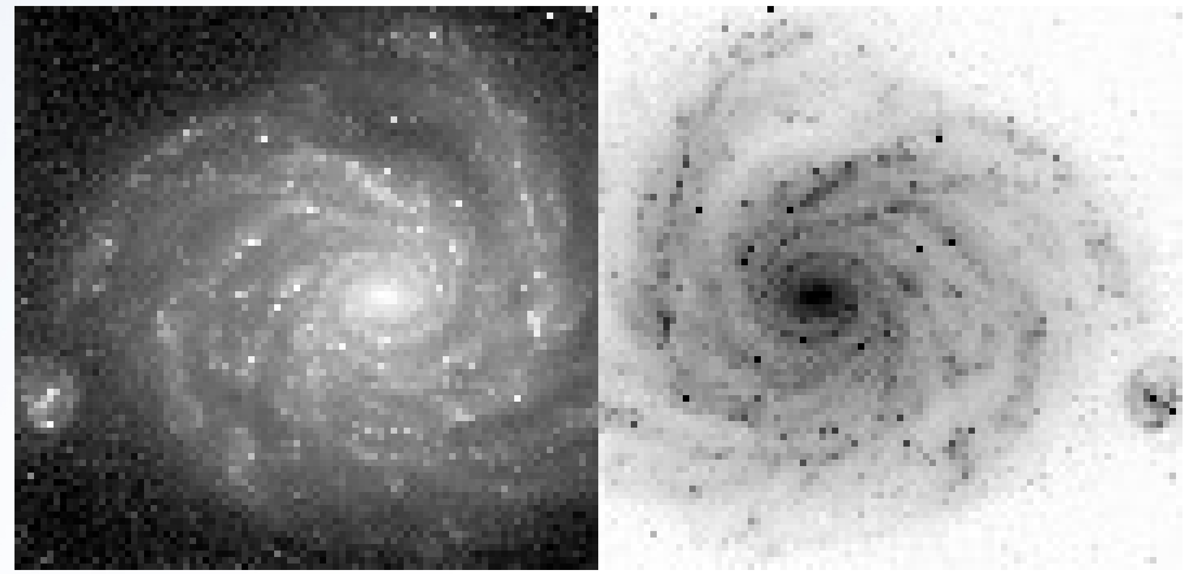
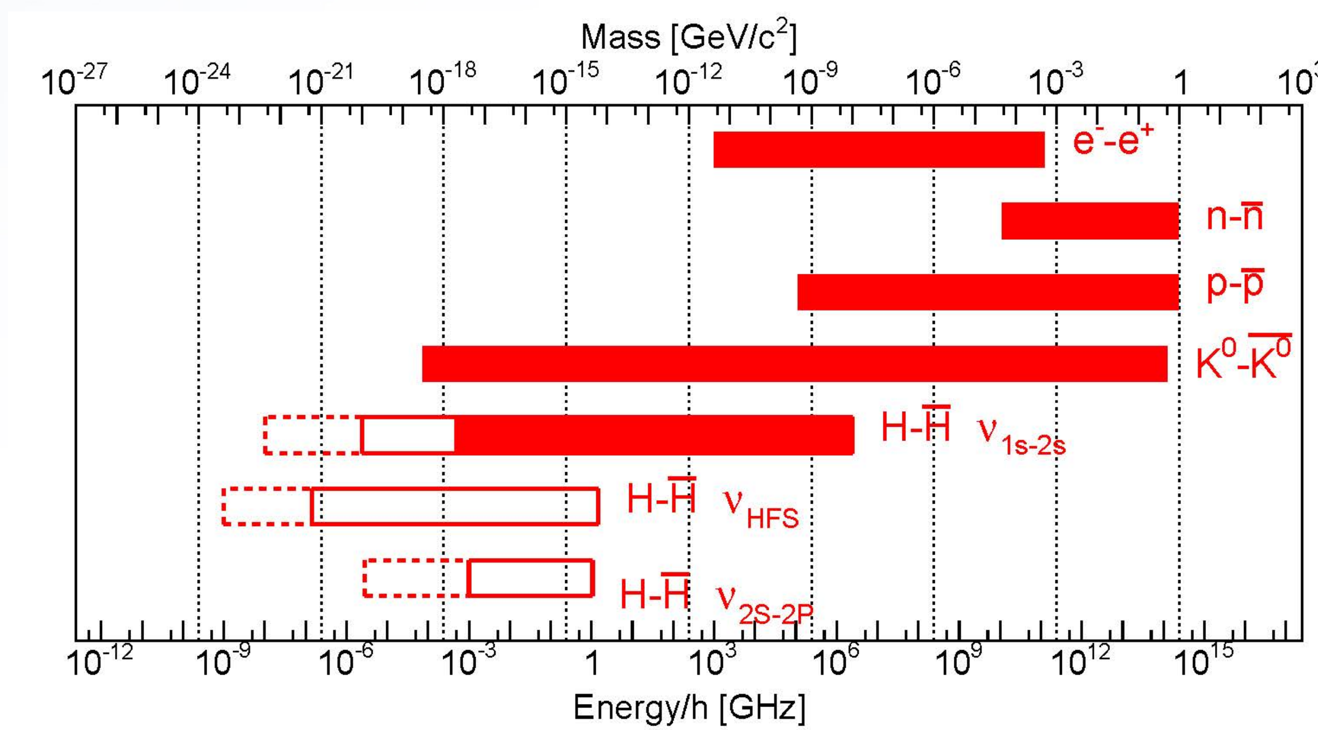
Matter-antimatter symmetry

- Cosmological scale:
  - Asymmetry
    - $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6x10^{-10}$

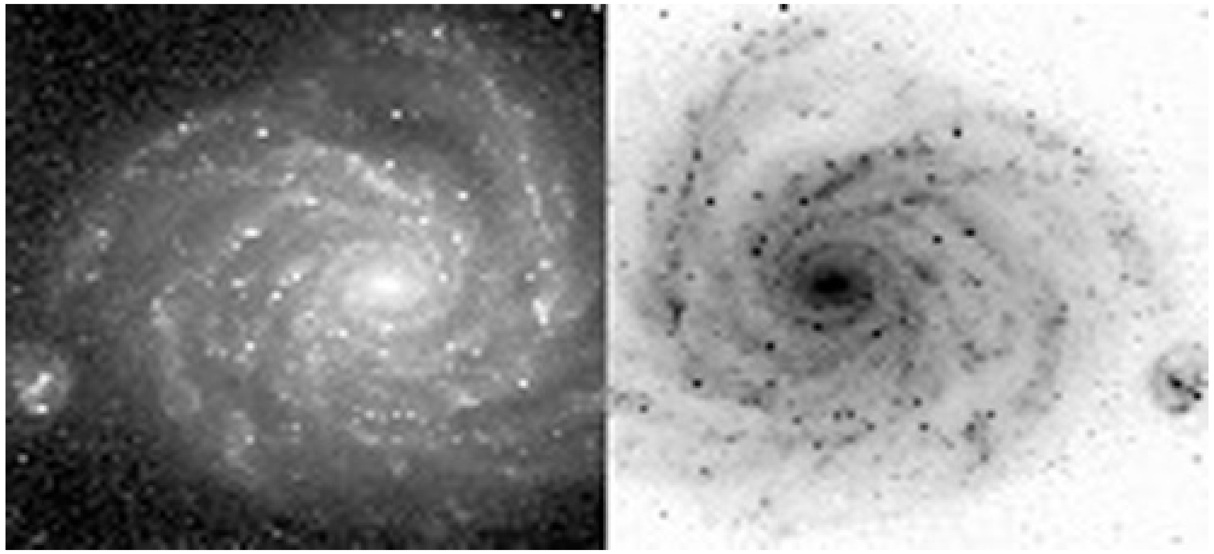


- CPT
  - Microscopic: symmetry?

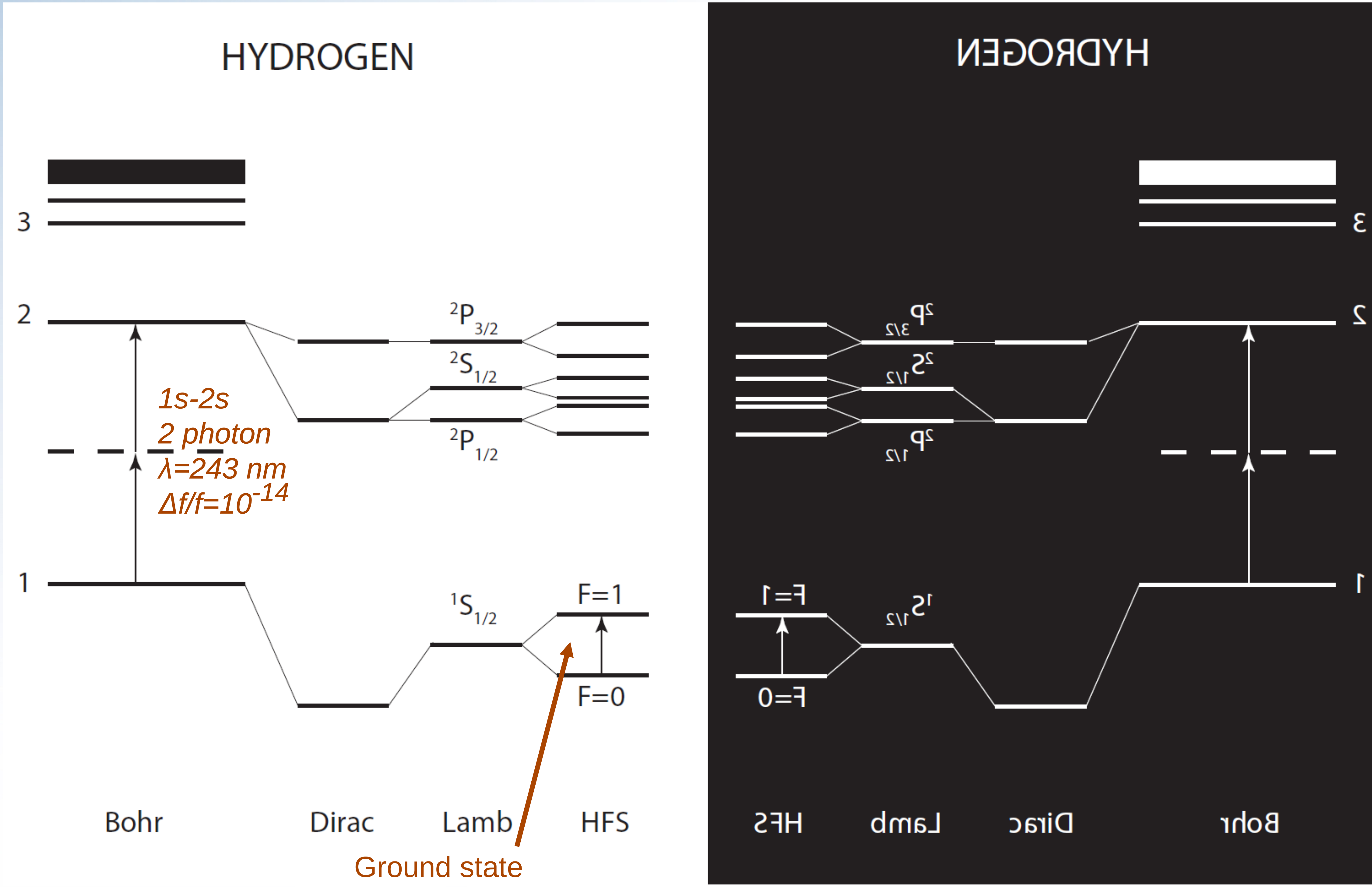


CPT symmetry & cosmology

- mathematical **theorem**, not valid e.g. in string theory, quantum gravity
- possible hint: antimatter *absence* in the universe
  - Big Bang -> if CPT holds: equal amounts matter/antimatter
  - Standard scenario for **Baryogenesis** (Sakharov 1967)
    - Baryon-number non-conservation
    - C and CP violation
    - Deviation from thermal equilibrium
- Currently known CPV **not** large enough
  - Other source of baryon asymmetry?
    CPT non-conservation?



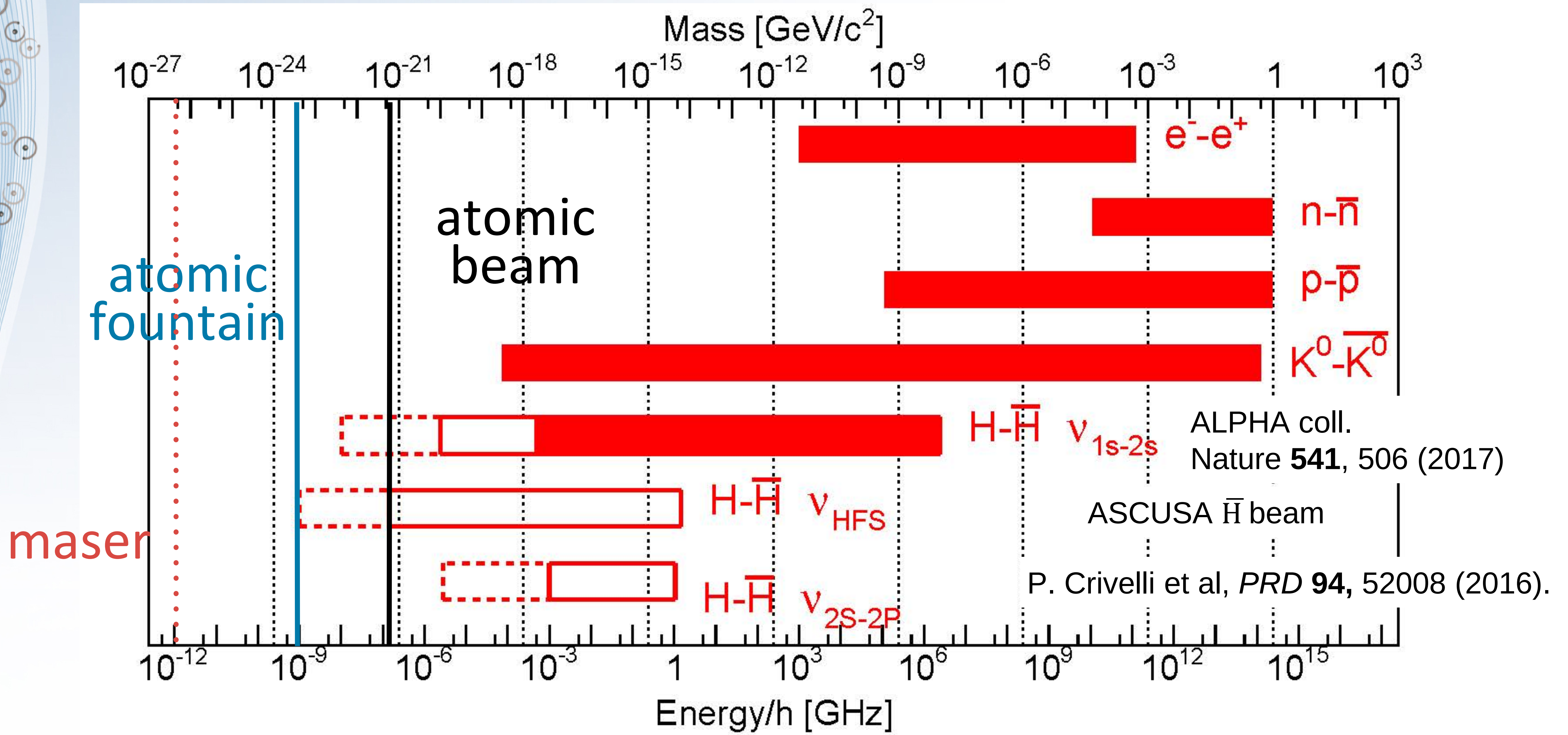
Antihydrogen spectroscopy



Ground state hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

CPT tests - relative & absolute precision

- Atomic physics experiments, especially antihydrogen offer the most sensitive experimental verifications of CPT



Minimal Standard Model Extension

Modified Dirac equation

CPT & LORENTZ VIOLATION

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0 .$$

LORENTZ VIOLATION

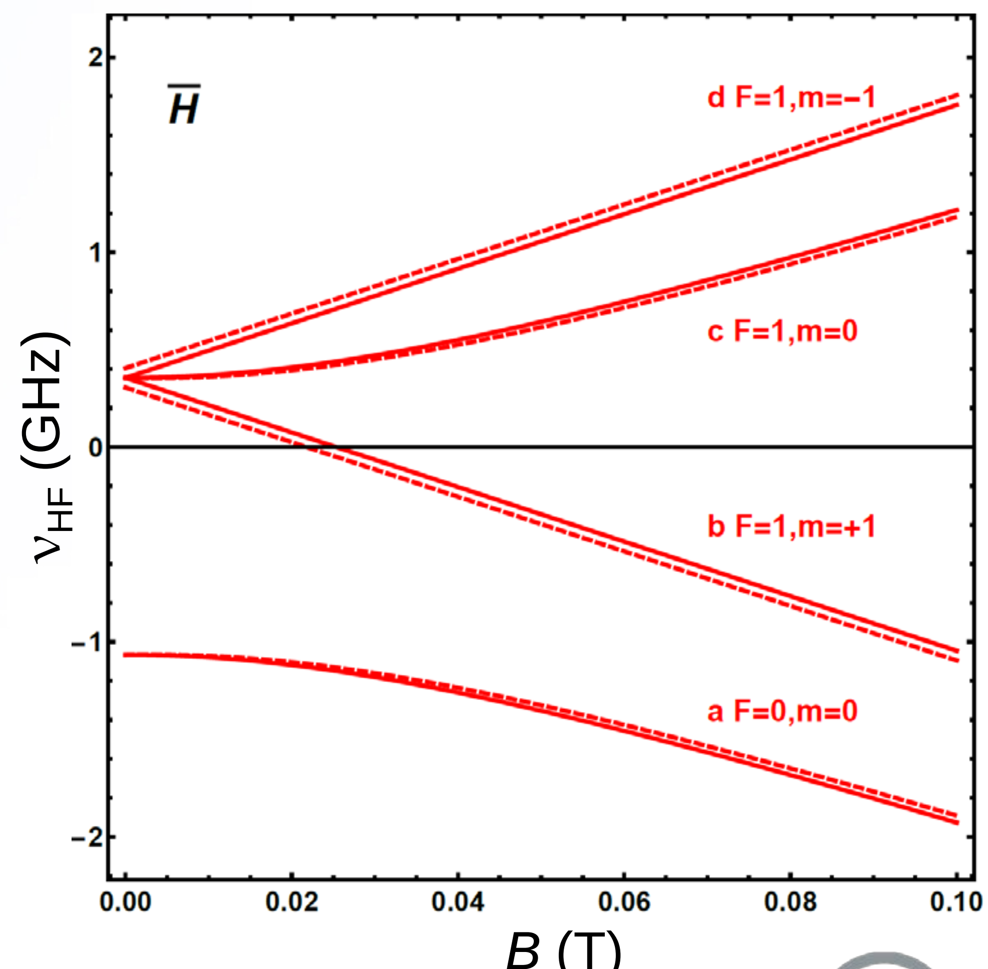
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

H HFS energy shift:

$$\begin{aligned}\Delta E^{\mathrm{H}}(m_J, m_I) &= a^e_0 + a^p_0 - c^e_{00} m_e - c^p_{00} m_p \\ &+ (-b^e_3 + d^e_{30} m_e + H^e_{12}) m_J/|m_J| \\ &+ (-b^p_3 + d^p_{30} m_p + H^p_{12}) m_I/|m_I| .\end{aligned}$$

H→$\overline{\mathrm{H}}$: a, d, H reverse sign

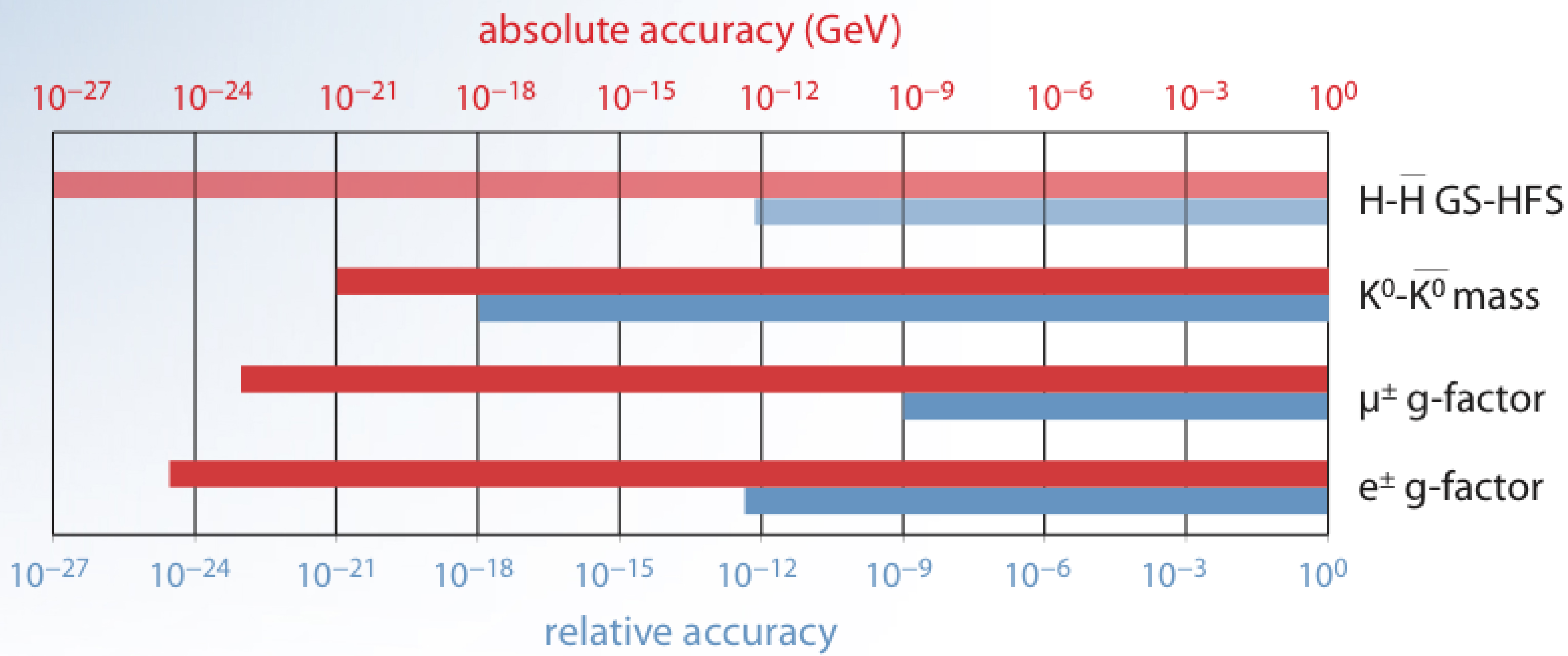
Only transitions with Δm≠0 show CPTV



Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

HFS and Standard Model Extension

- Minimal SME

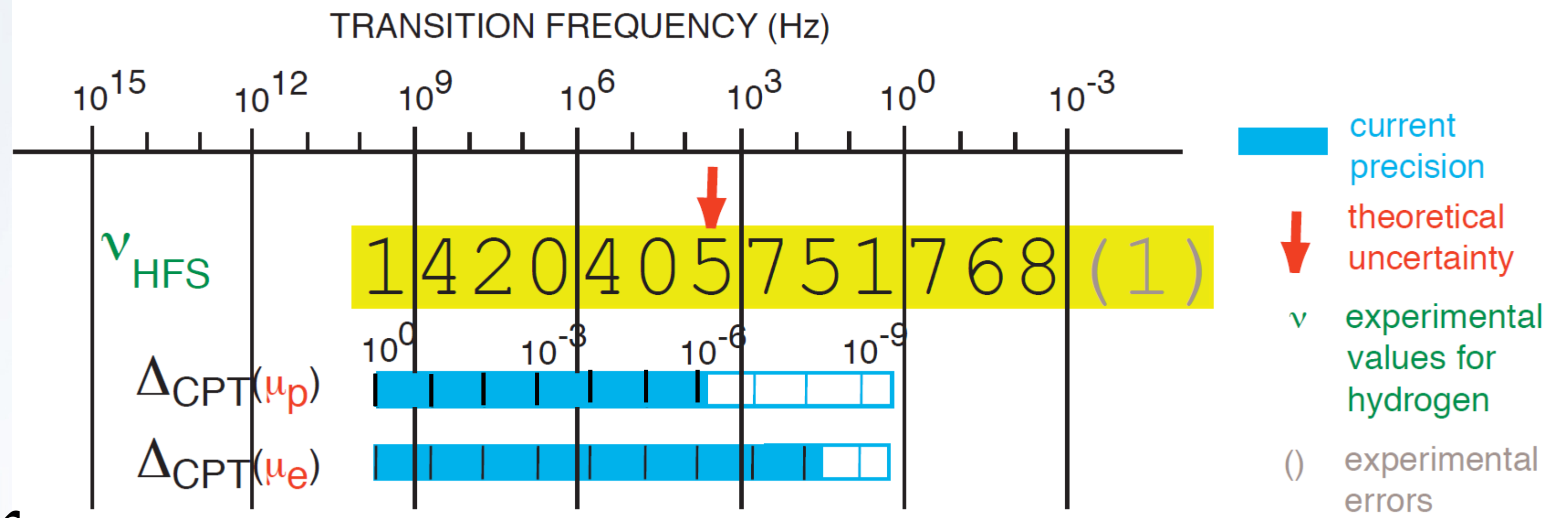


no CPT effect on 1S-2S transition *(changed in non-minimal SME)*
allows to compare different quantities in different sectors

Ground-State Hyperfine Splitting of H/$\bar{\text{H}}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

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



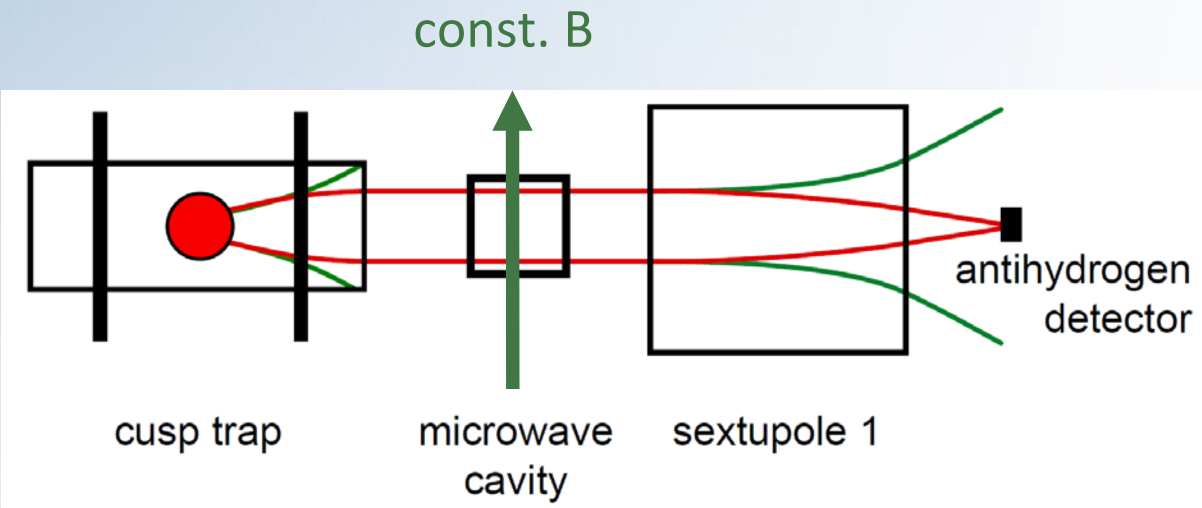
- magnetic moment of p̄
  - 2017 BASE Penning trap 0.8 ppm Nat.Comm. 8, 14084 (2017)

H: deviation from Fermi contact term:	–32.77(1) ppm
finite electric & magnetic radius (Zemach corrections):	–41.43(44) ppm
polarizability of p/p̄	+1.88(64) ppm
remaining deviation theory-experiment:	+0.86(78) ppm

C. E. Carlson et al., *PRA 78, 022517 (2008)*

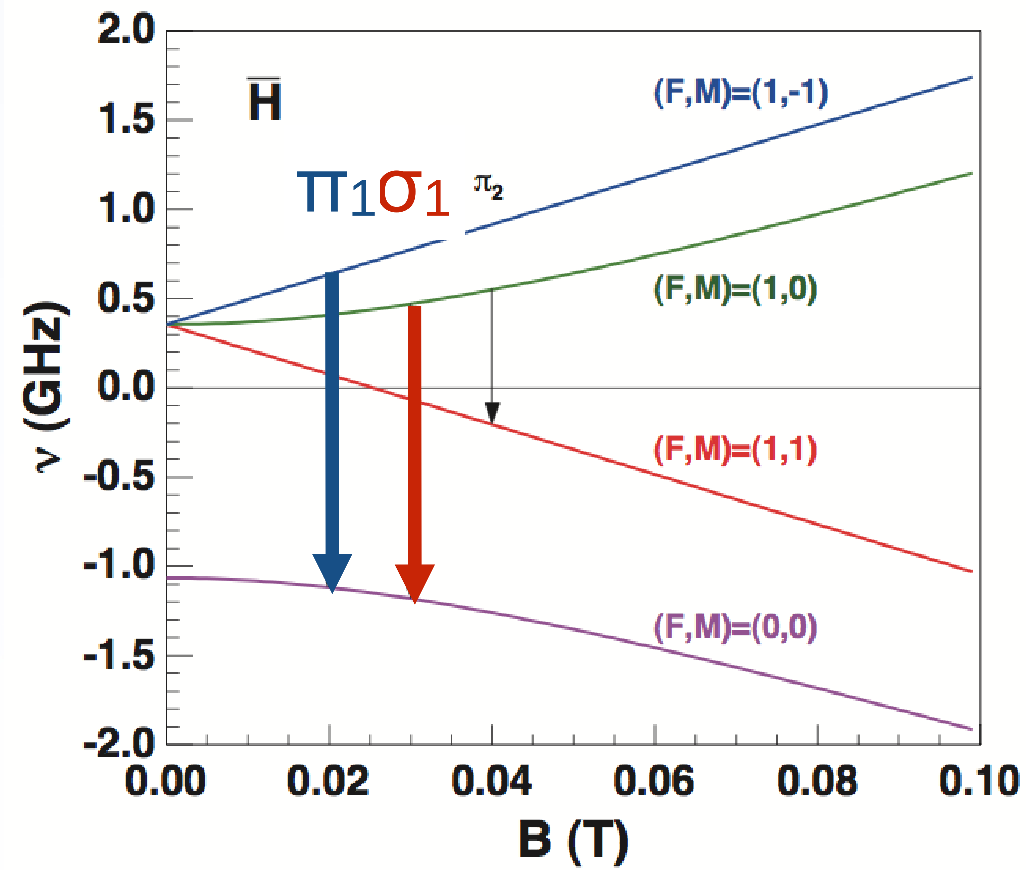
Finite size effect of proton/antiproton becomes visible < 1 ppm

HFS in an atomic beam



- atoms evaporate - no trapping needed
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

E.W. et al. ASACUSA proposal addendum CERN-SPSC 2005-002

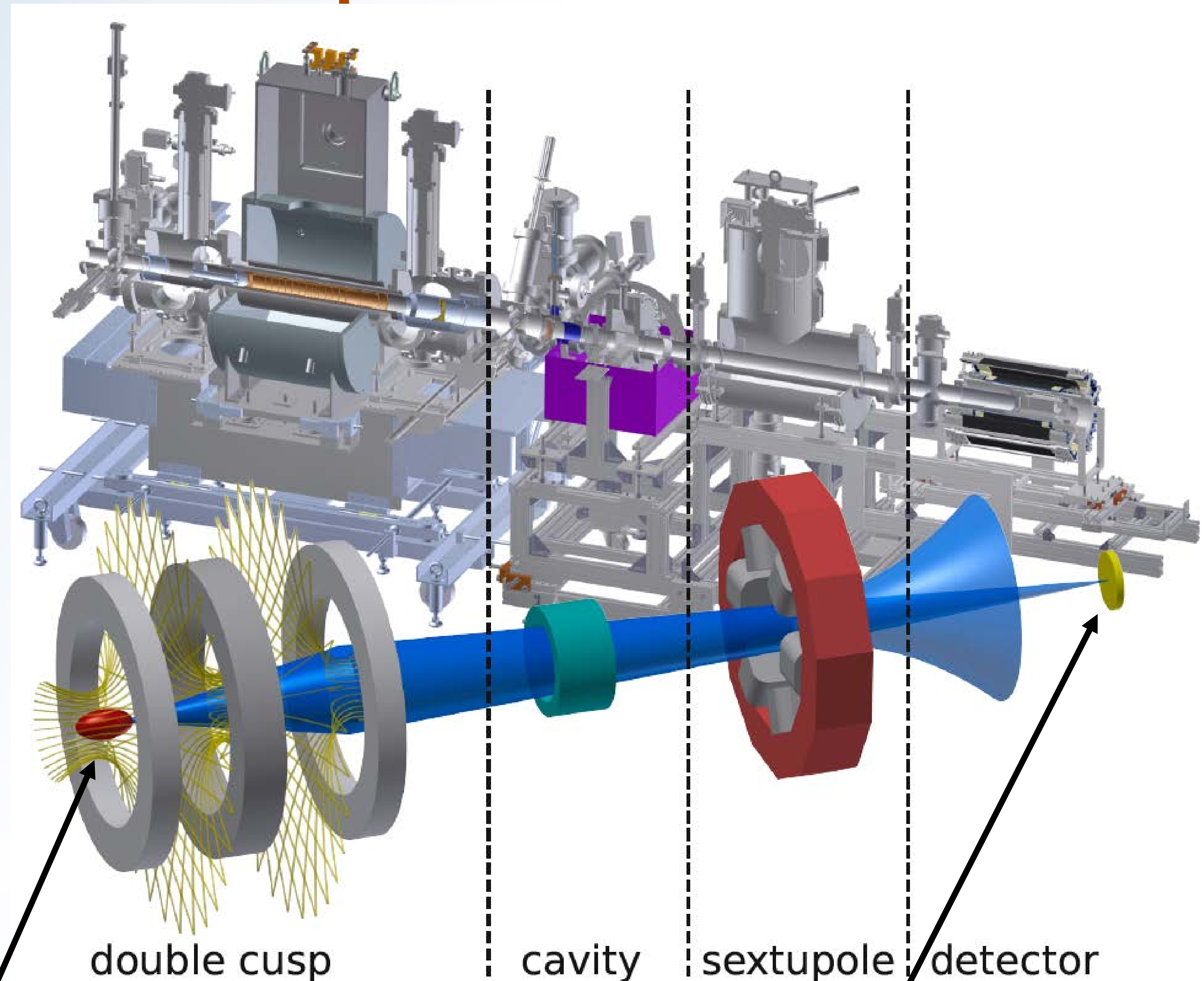


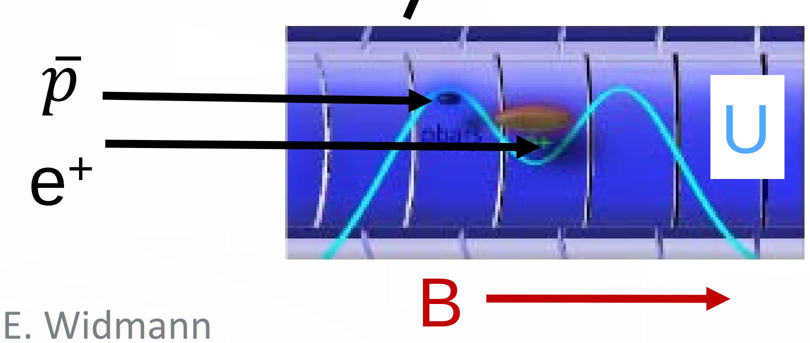
achievable resolution

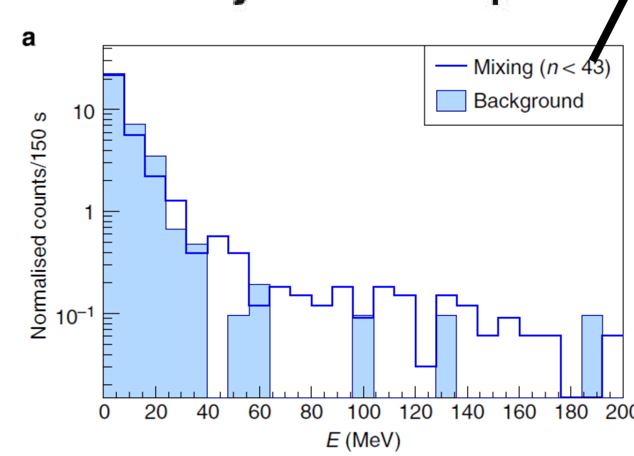
- better 10^{-6} for $T \leq 100$ K
- > 100 $\bar{H}$/s in 1S state into 4π needed
- event rate 1 / minute: background from cosmics, annihilations uptsreams

Experimental setup $\bar{H}$-HFS line

- $\bar{H}$ production 1st time in 2010 in nested Penning trap
- Three body recombination expected to produce Rydberg states
- 1st observation of beam in field free region n>29







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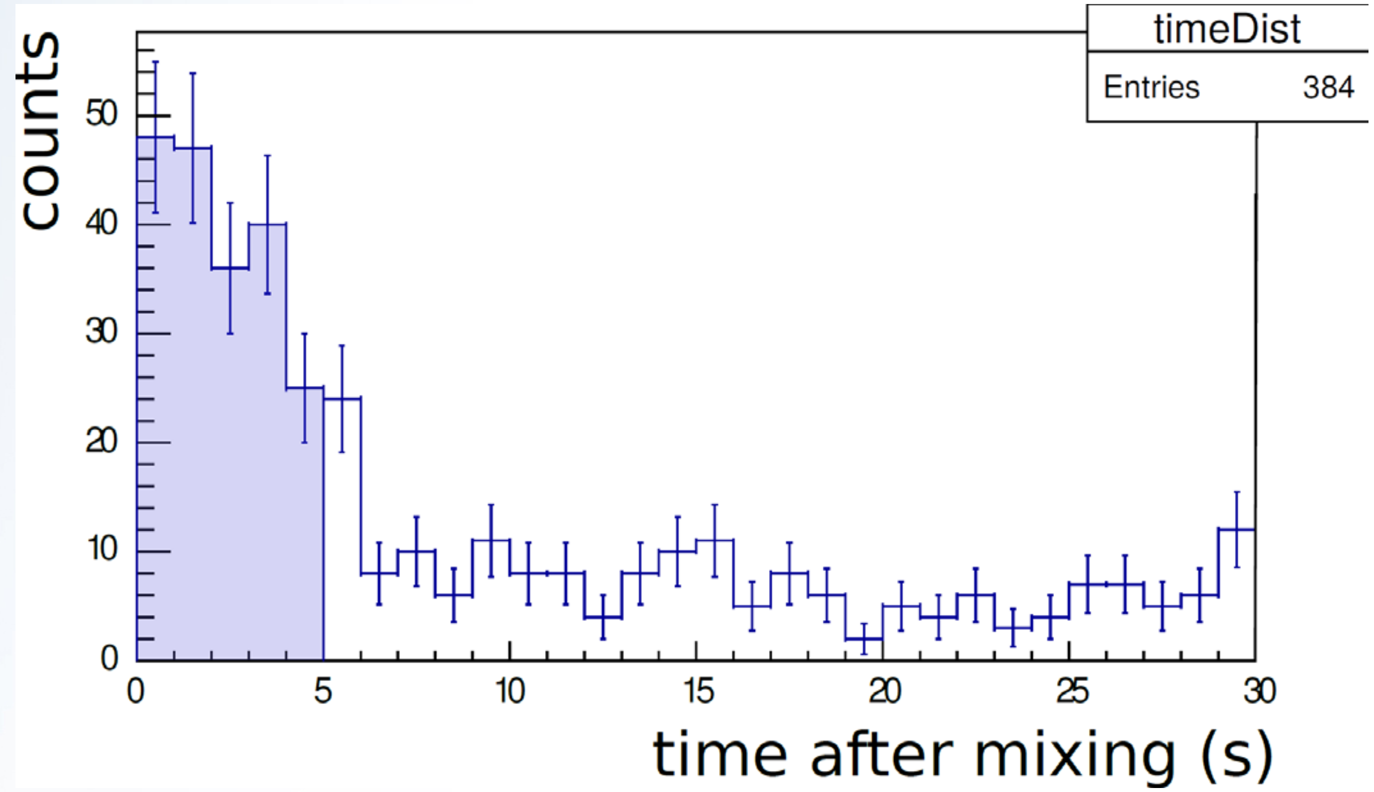
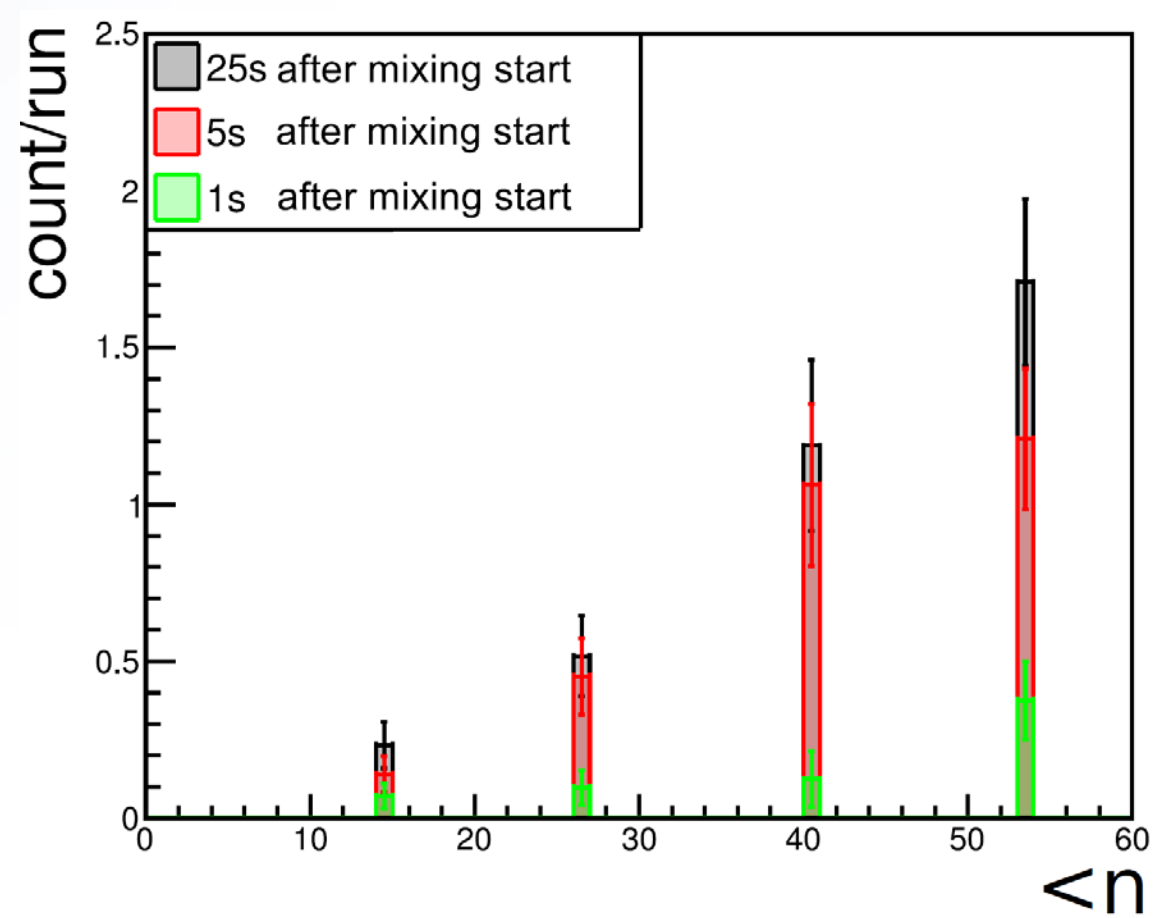
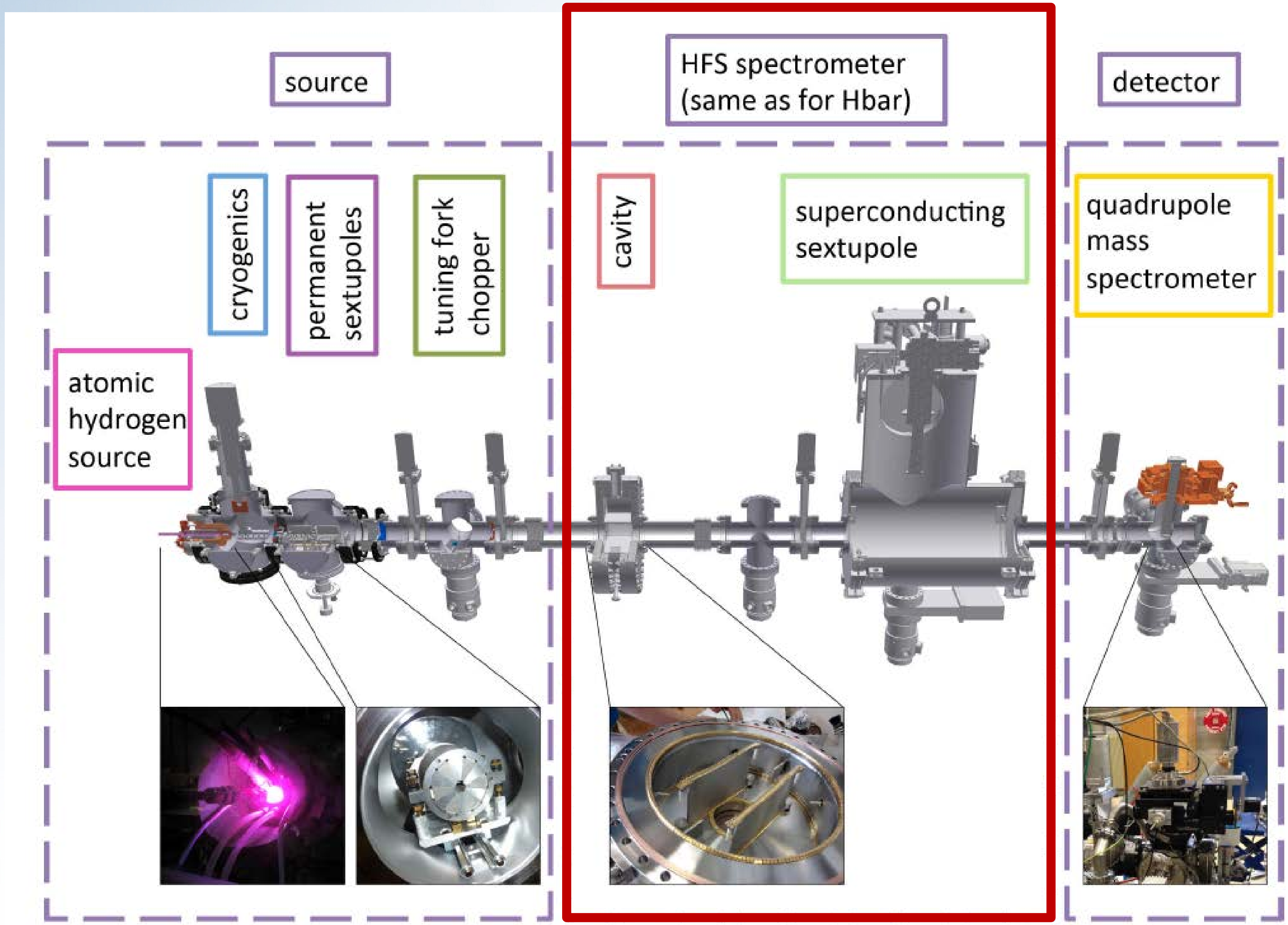
Results 2016

- Time distribution of $\overline{\mathrm{H}}$ within mixing cycle
  - At cavity position
- Principal quantum number by field ionization
  - 0.5 m upstream of cavity
  - n=14 significance <3σ
  - τ(n=14) ~ 50 μs



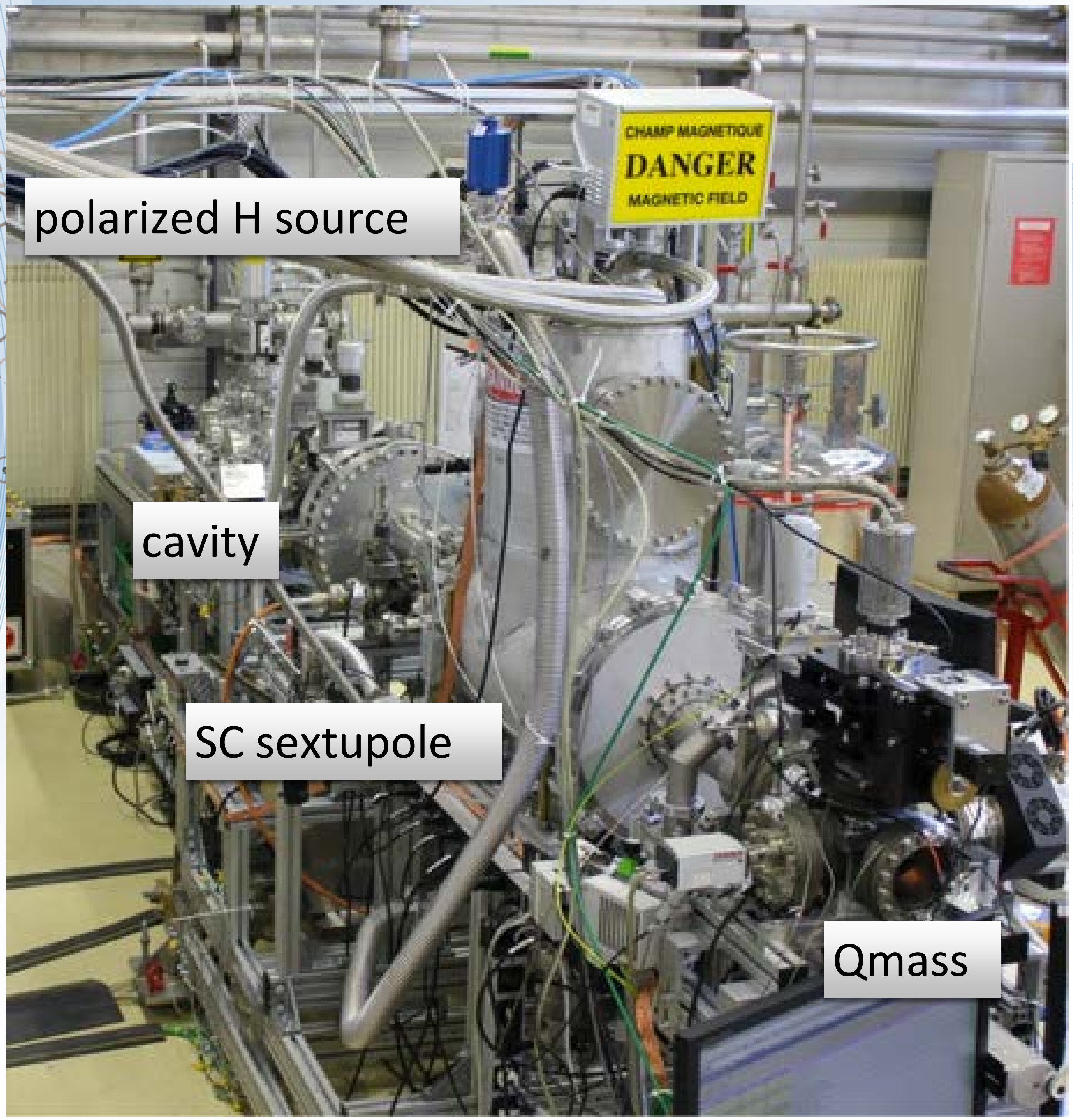


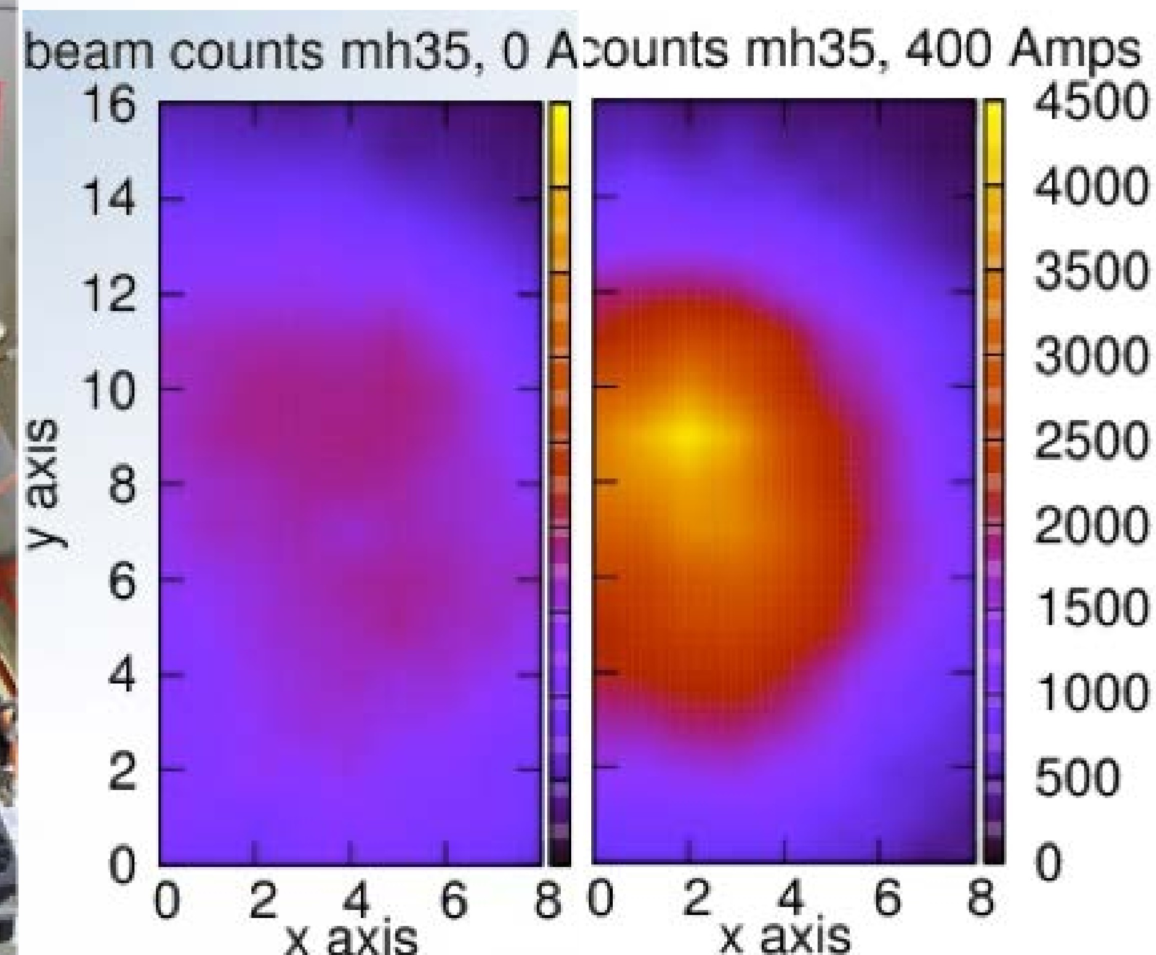
Hydrogen beam measurements



Primary goal: verify spectroscopy method:
reproduce expected antihydrogen beam parameters

Hydrogen beam line test setup @ CERN

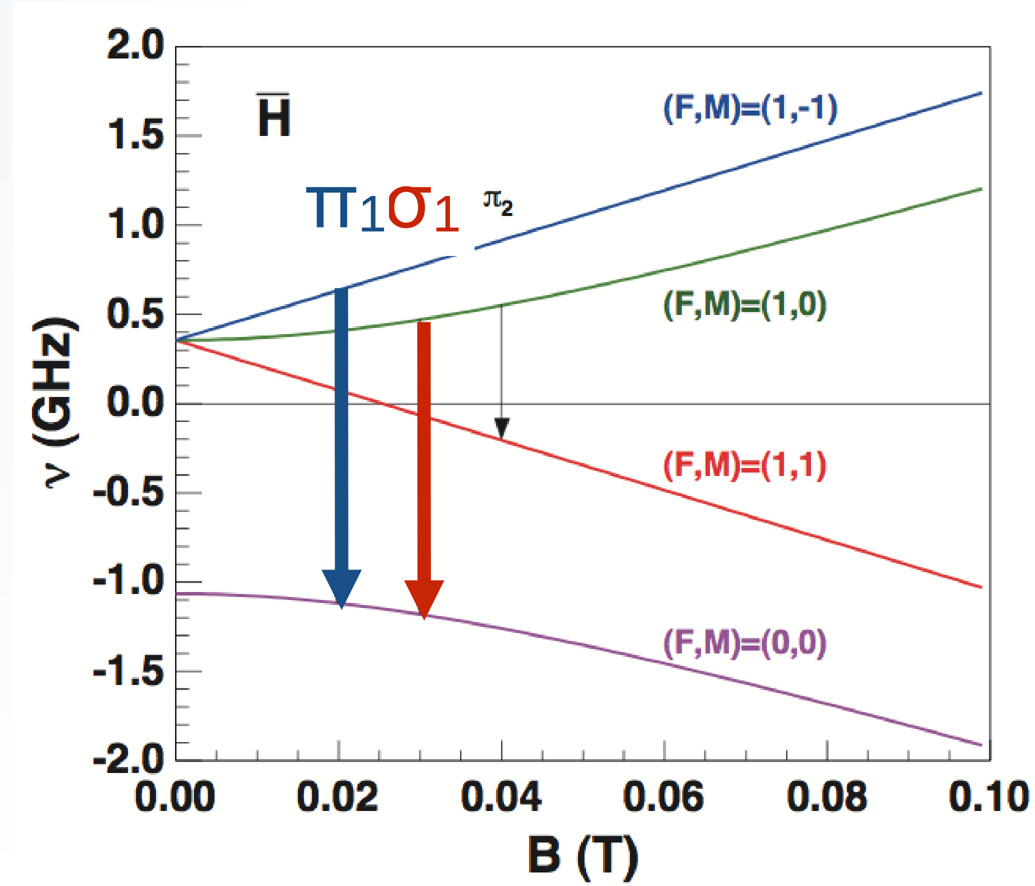




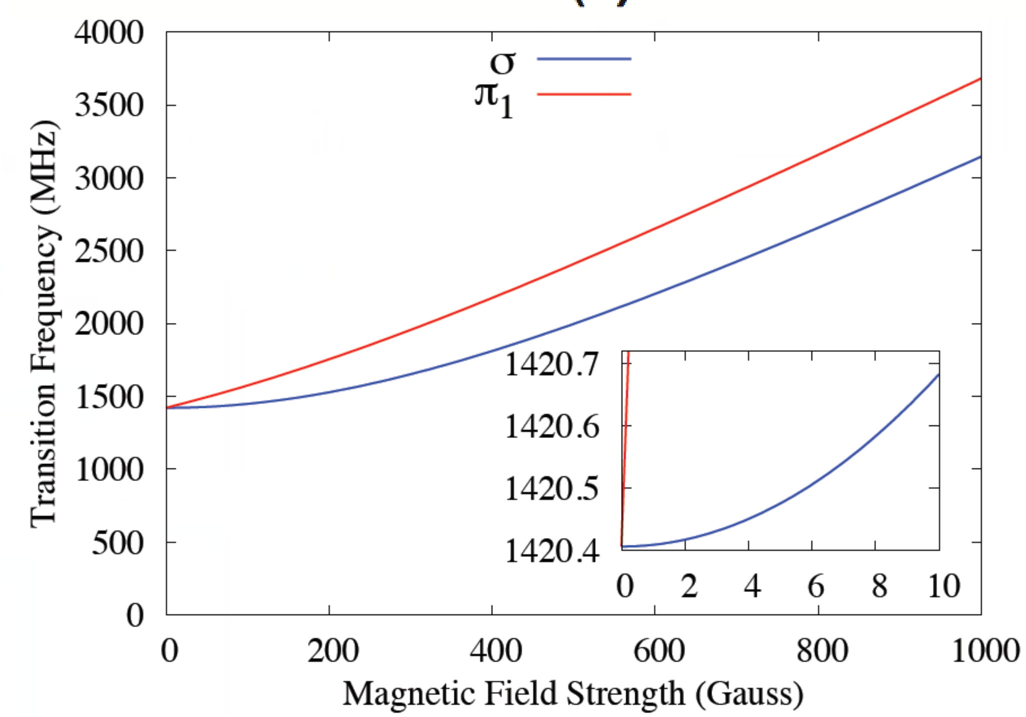
beam focusing by superconducting sextuple observed

σ_1 vs. π_1 transition

- Different B-field dependence
  - π_1 more sensitive to homogeneity

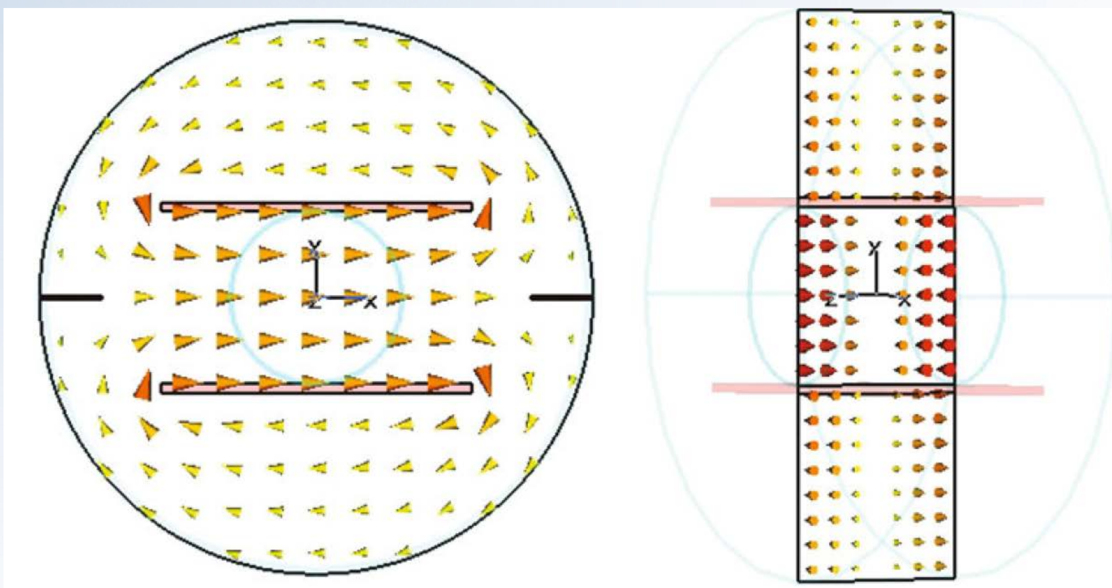


- Selection by orientation of $\vec{B}_{osc}, \vec{B}_{ext}$



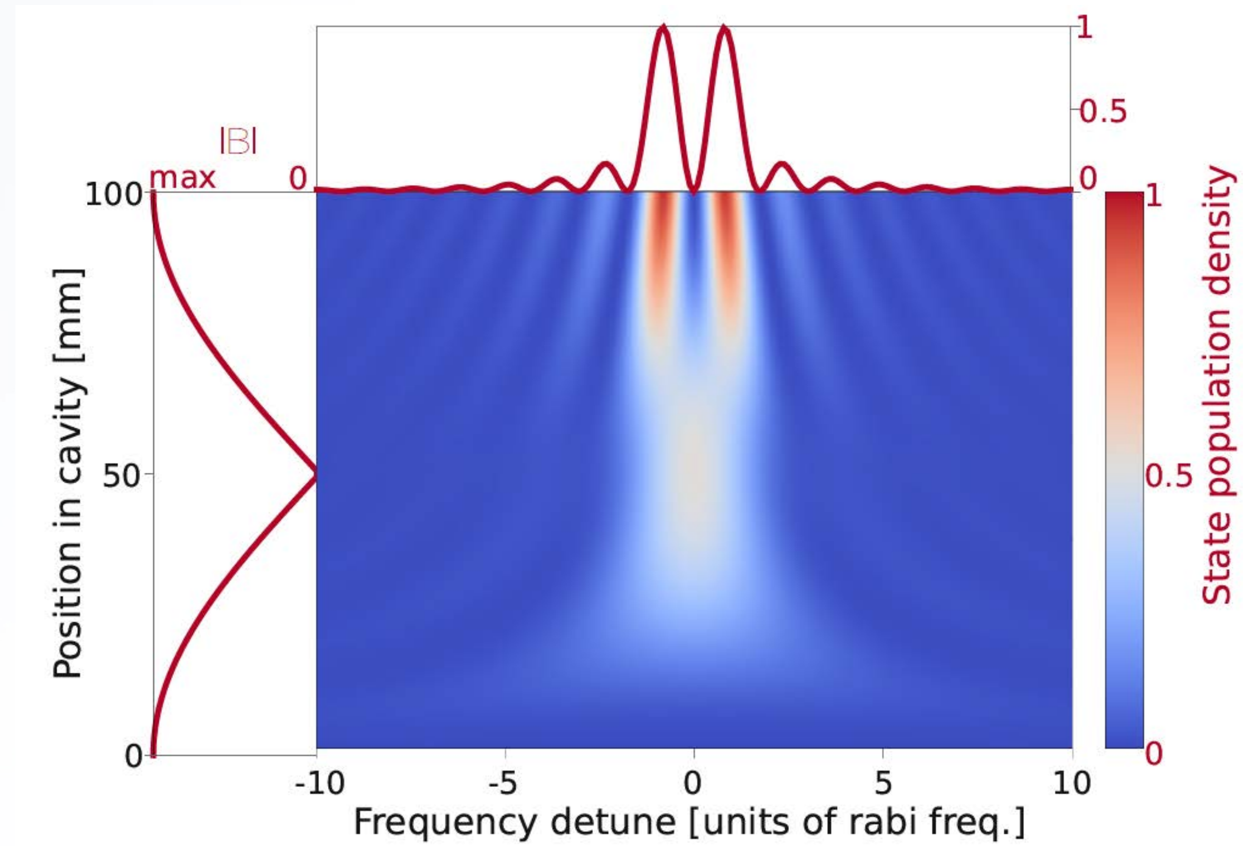
Spin-flip resonator

- f = 1.420 GHz, Δf = few MHz, ~ mW power
- challenge: homogeneity over 10x10x10cm^3@ λ=21cm
- solution: strip line



transverse field: homogeneous

longitudinal field: cos(z)



Line shape by optical Bloch equations for single velocity

- Full line shape: sum of simulated line shape for velocity distribution

H-HFS σ_1

$$\nu_{HF} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \text{Hz}$$

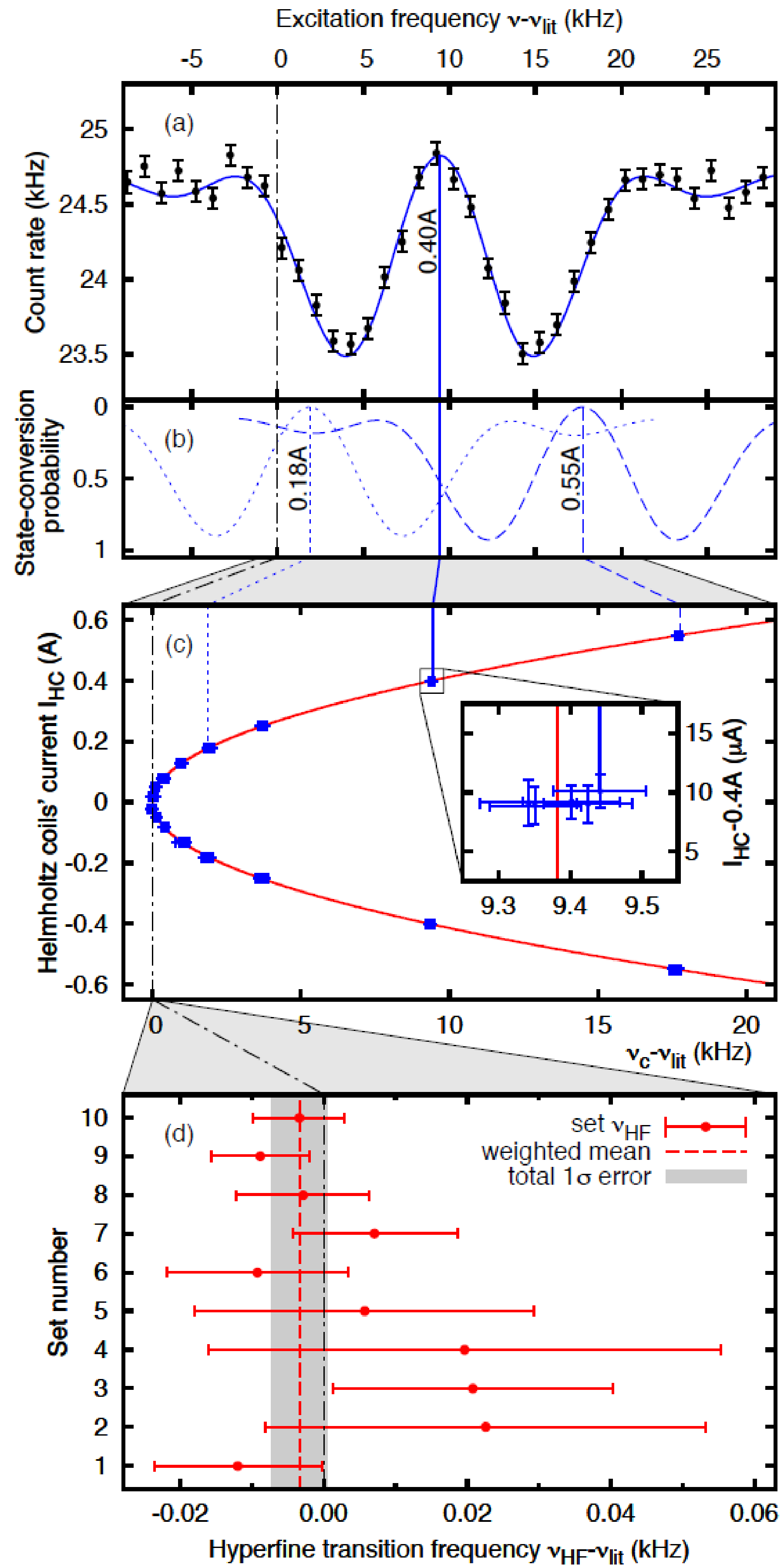
Error **2.7 ppb**: 18x improvement over *Kush, Phys. Rev. 100, 1188 (1955)*

Deviation from maser ($\Delta f/f \sim 10^{-12}$) :

3.4 Hz < 1σ error

Extrapolation to $\bar{\text{H}}$: **8000** atoms needed to achieve **1 ppm**

contribution	1σ st.dev. (Hz)
systematic error	
frequency standard	1.62
common fit parameters	
$\bar{v}_H$	0.05
σ_v	0.03
B_{osc}	0.02
systematic error total	1.62
statistical error	3.43
total error	3.79



arXiv:1610.06392, Nat. Comm., in print

Non-minimal SME

- Operators of arbitrary dimensions

$$\mathcal{L} \supset \frac{1}{2}\overline{\psi_w}(\gamma^\mu i\partial_\mu - m_w + \hat{\mathcal{Q}}_w)\psi_w + \mathrm{H}.$$

$$\delta h_{\mathrm{H}}^{\mathrm{NR}} = \delta h_e^{\mathrm{NR}} + \delta h_p^{\mathrm{NR}}$$

- Non-relativisitc spherical coefficients

$\mathcal{K}_{kjm}$	Mass-dimensions	CPT sign	Spin-dependence
c_{kjm}^{NR}	Even numbers	+1	Independent
a_{kjm}^{NR}	Odd numbers	−1	Independent
$g_{kjm}^{\mathrm{NR}(qP)}$	Even numbers	−1	Dependent
$H_{kjm}^{\mathrm{NR}(qP)}$	Odd numbers	+1	Dependent

$$a_{200}^{\mathrm{NR}} \supset a_{200}^{(5)} + a_{200}^{(7)} m_0^2 + a_{200}^{(9)} m_0^4 \ldots$$

Kostelecký, V. A., & Mewes, M.. *PRD 88*, 096006 (2013).

Non-minimal SME & H beam

- Shift only for π-transition ($\Delta m_F \neq 0$)

$$2\pi\delta\nu = -\frac{\Delta m_F}{2\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q} (1 + 4\delta_{q2}) \times \sum_{w} [g_{w(2q)10}^{\mathrm{NR}(0B)} - H_{w(2q)10}^{\mathrm{NR}(0B)} + 2g_{w(2q)10}^{\mathrm{NR}(1B)} - 2H_{w(2q)10}^{\mathrm{NR}(1B)}].$$

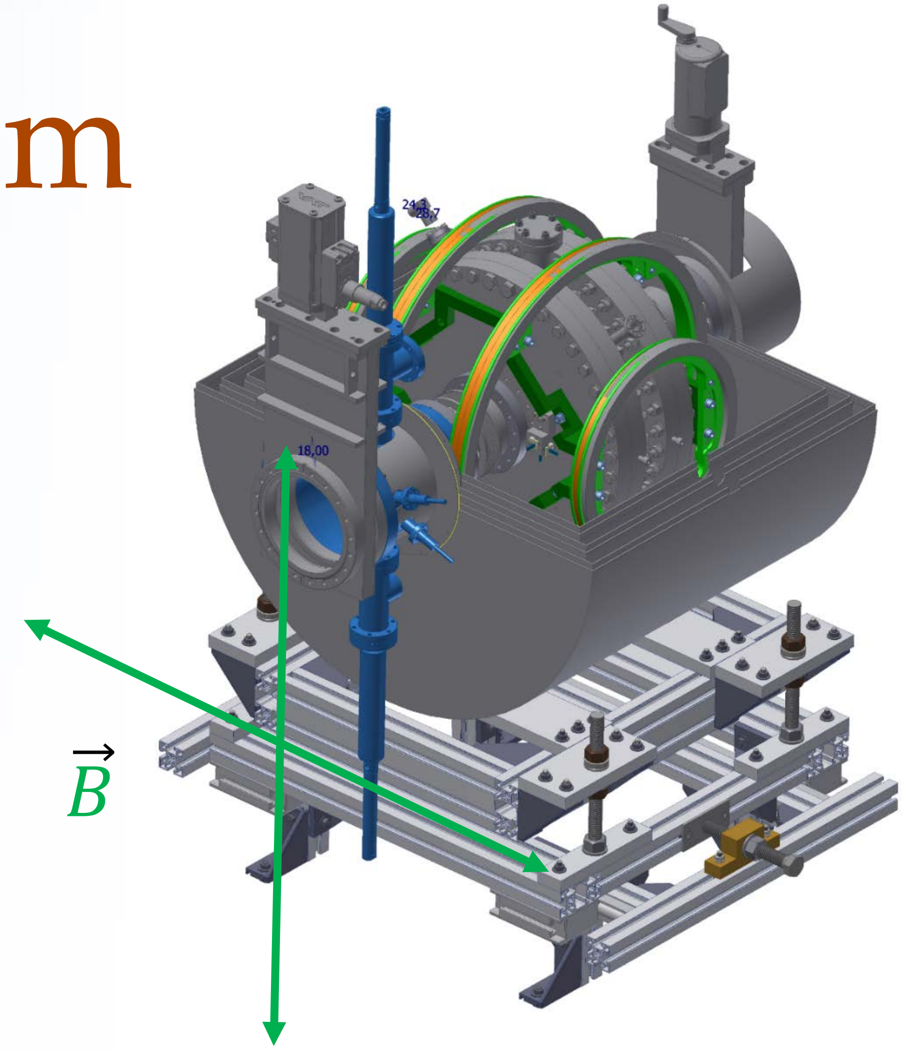
- B direction dependence

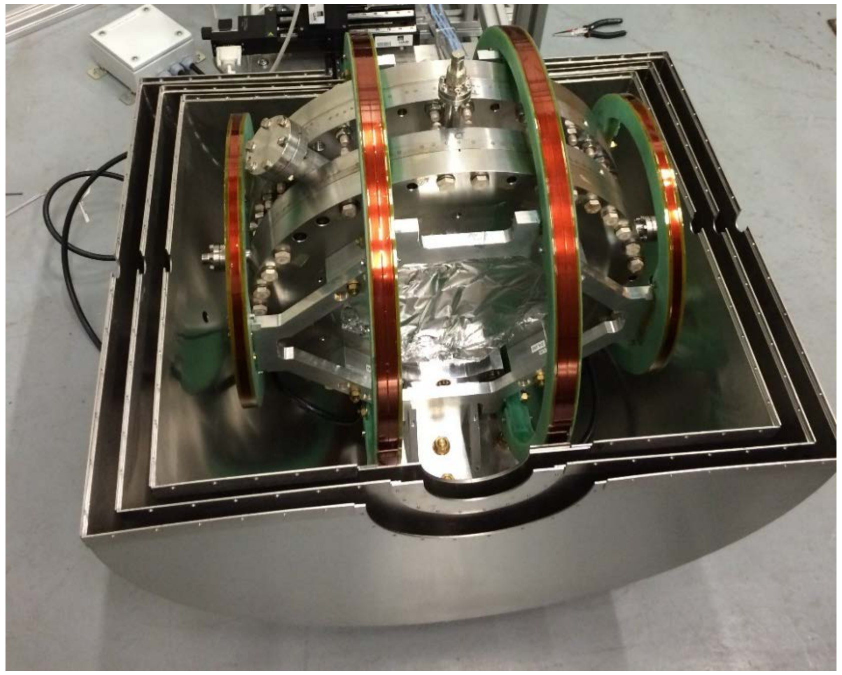
$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q} (1 + 4\delta_{q2}) \sum_{w} [g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)}]\end{aligned}$$

Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

Next steps for H-beam

- π_1 transition
  - Better field homogeneity
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam
- Conditions
  - Invert direction of B-field
  - Rotate B-field
  - Measure also σ_1 (no CPTV) as reference

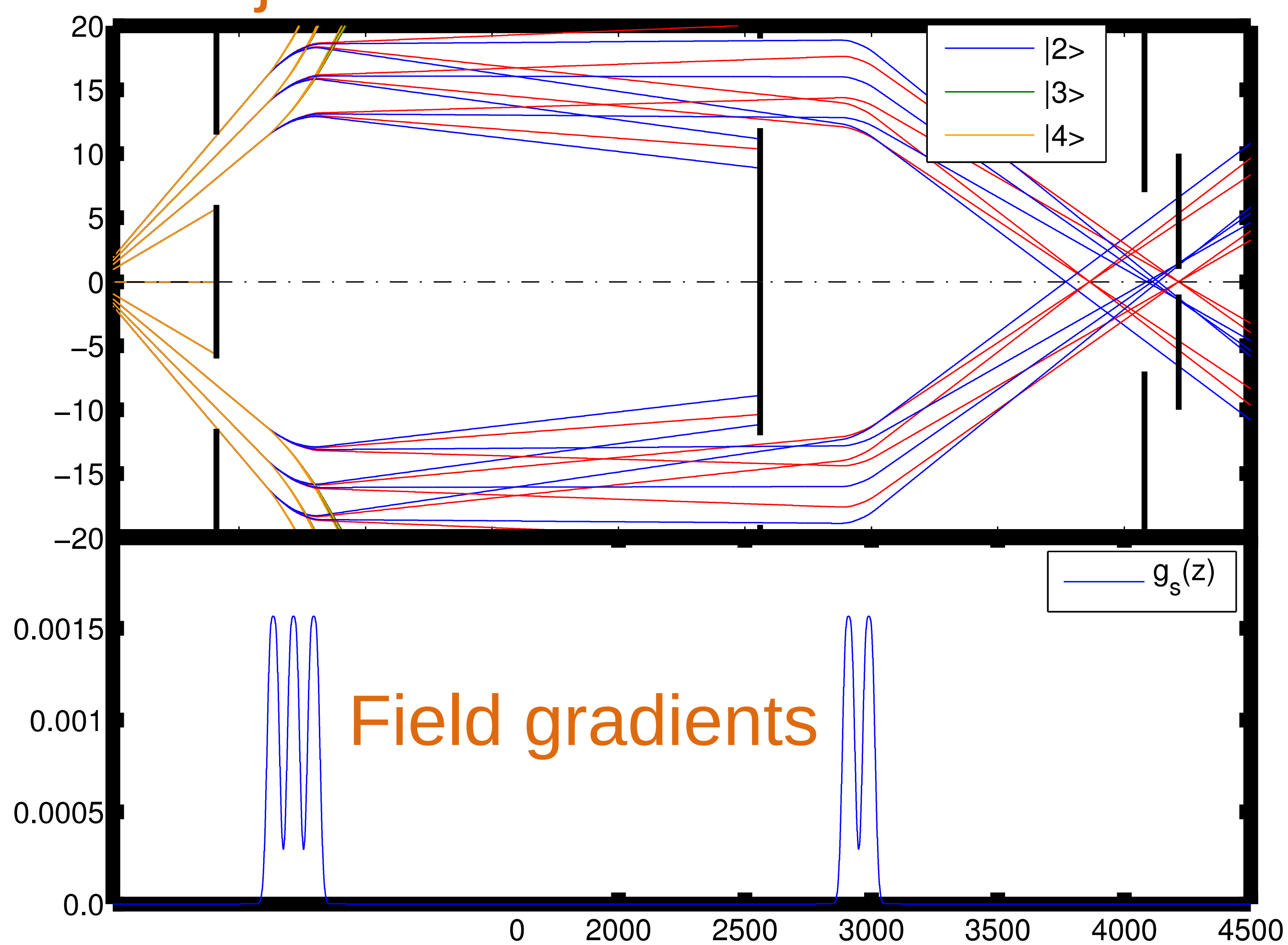




New beam optics

- Same focus for all HF states

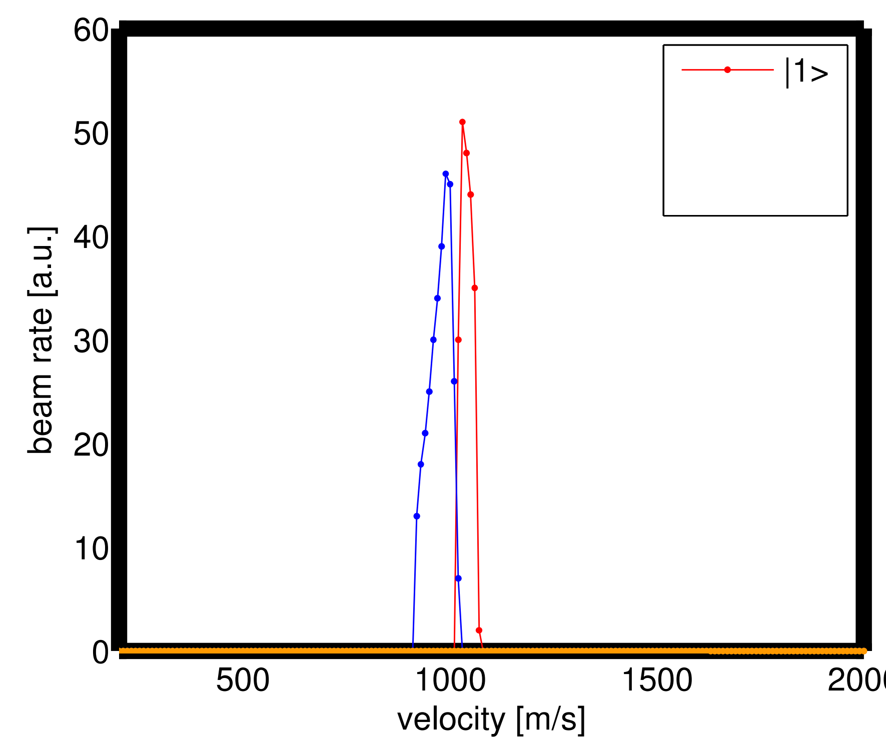
Trajectories



Beam direction

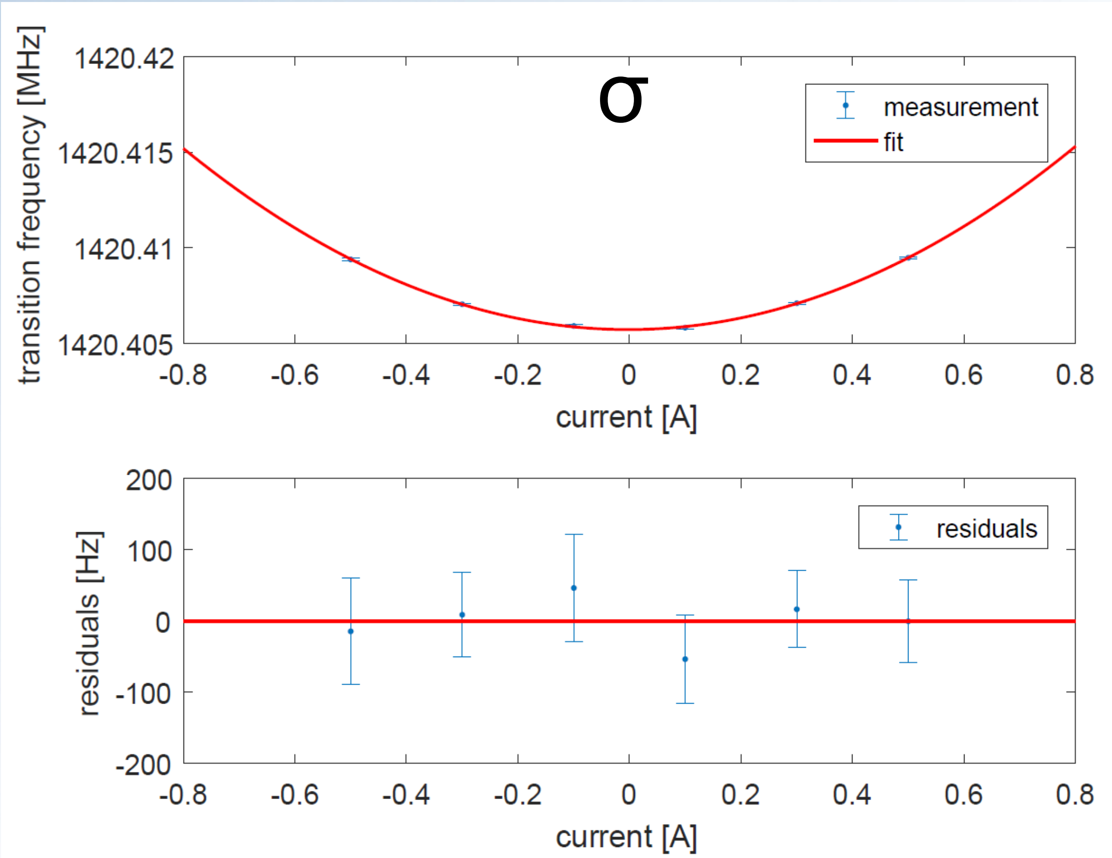
Ring aperture

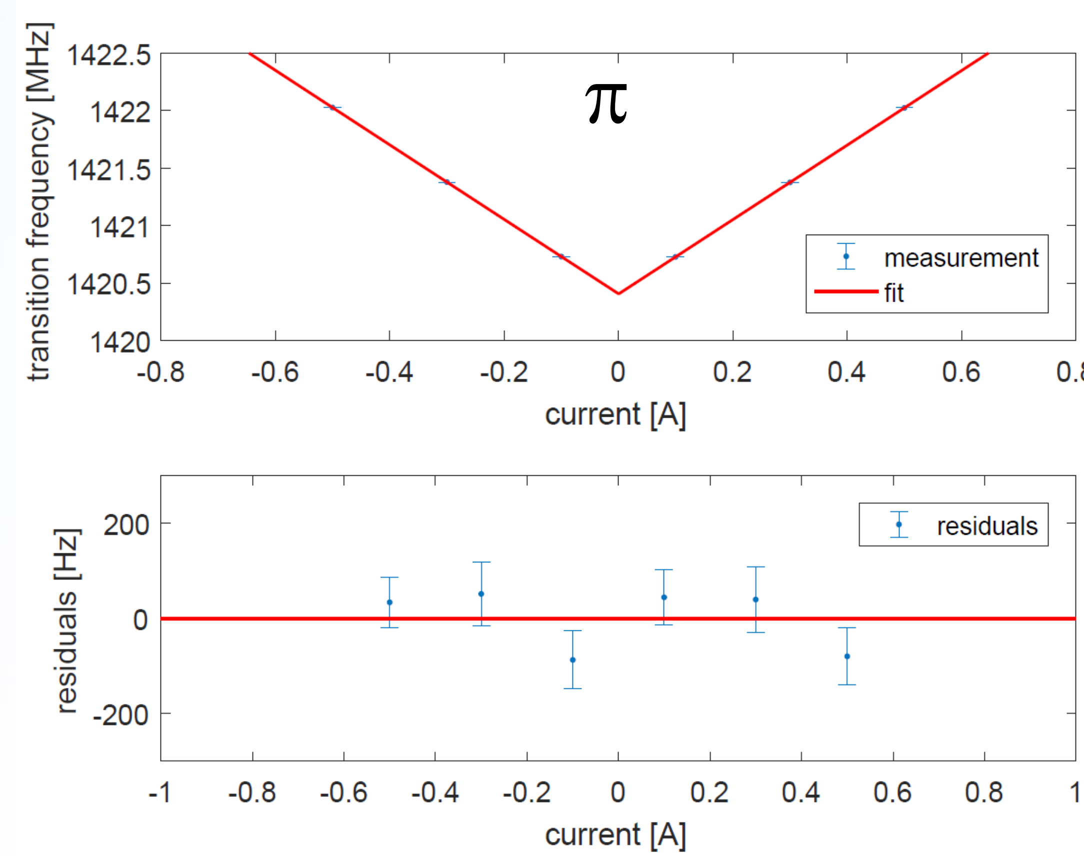
Velocities



Extrapolation B=0

PRELIMINARY

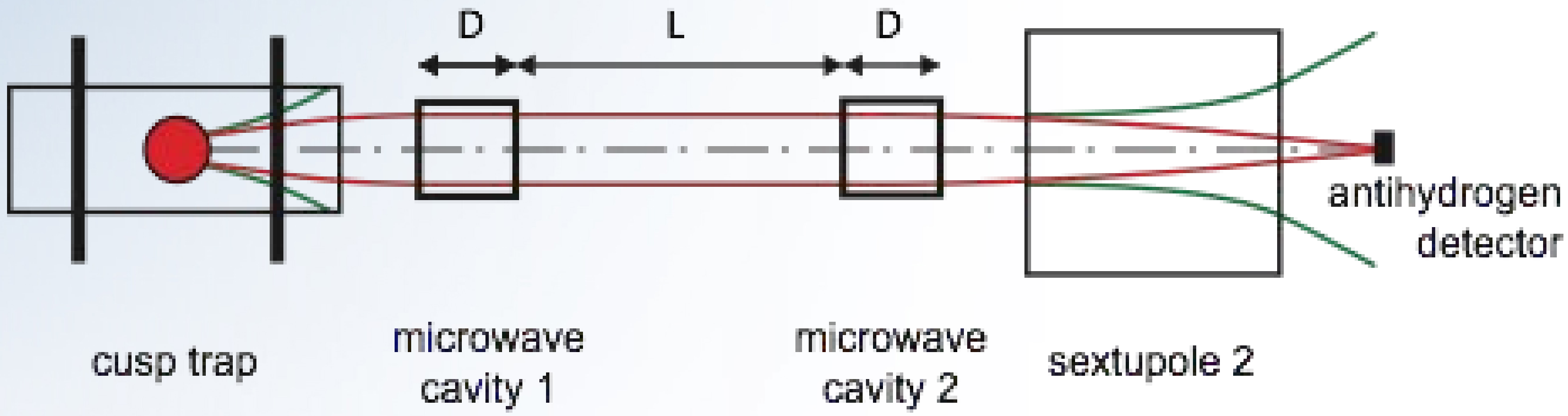




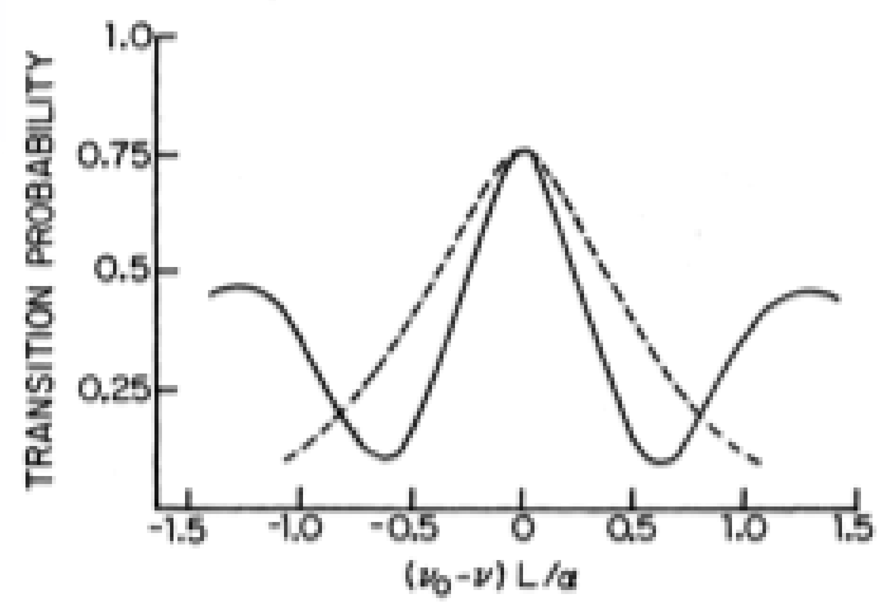
- Accuracy $\nu_{\mathrm{HF}}(B = 0) \sim 10$ Hz
  - ~ 100 hours of data taking
  - Measurement campaign to start

Experiments in an atomic beam

- Phase 2: Ramsey separated oscillatory fields

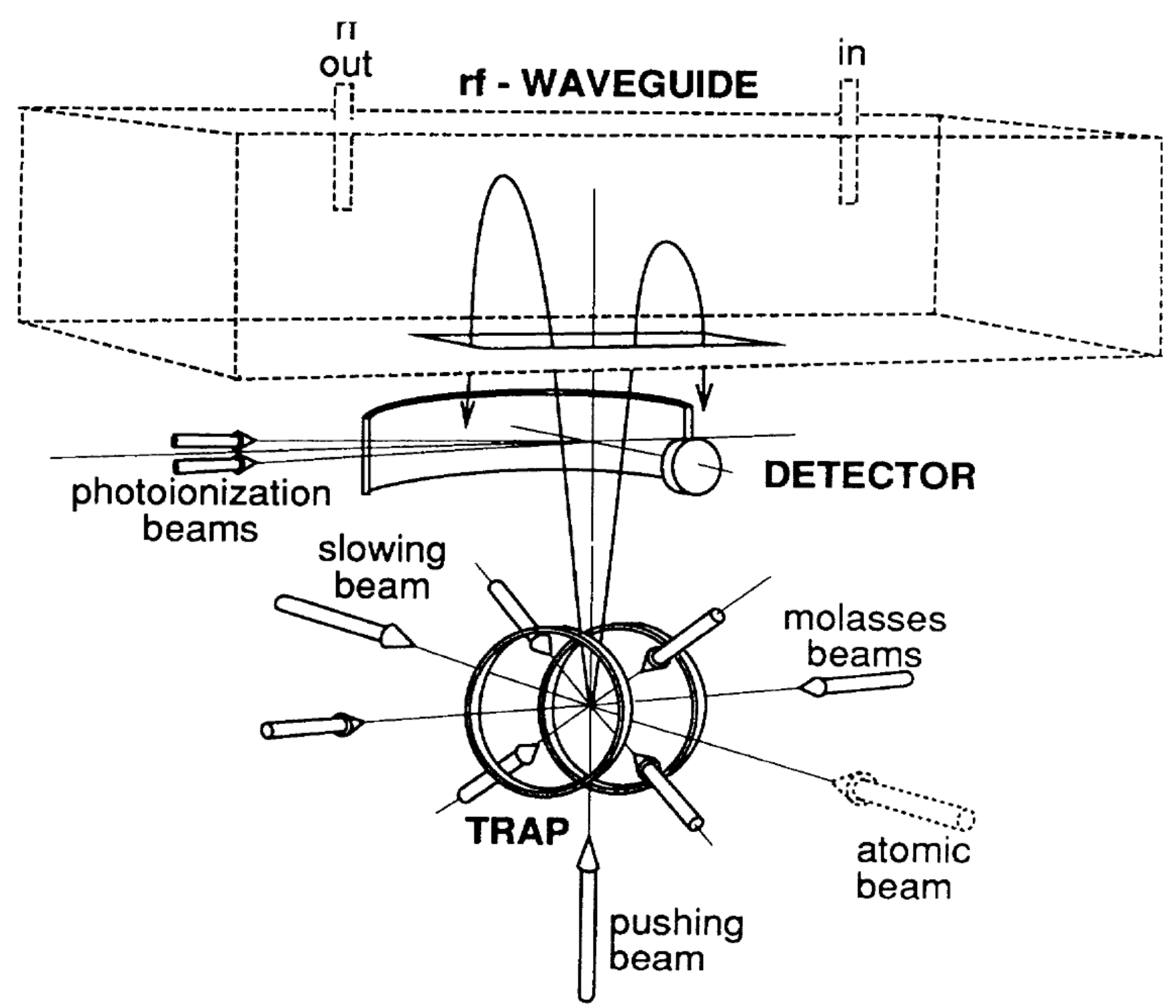


Linewidth reduced by D/L



(Far) future experiments

- Phase 3: trapped $\overline{\mathrm{H}}$
  - Hyperfine spectroscopy in an atomic fountain of antihydrogen
  - needs trapping and laser cooling outside of formation magnet
  - slow beam & capture in measurement trap
  - Ramsey method with d=1m
    - Δf ~3 Hz, $\Delta f/f$ ~ 2×10^{-9}



M. Kasevich, E. Riis, S. Chu, R. DeVoe, PRL 63, 612–615 (1989)

Summary

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
  - First "beam" of $\bar{H}$ observed in field-free region
  - Next steps: optimize rate, check polarization, velocity
- HFS measurement in H beam of 2.7 ppb achieved
  - Proof-of-principle for $\bar{H}$ measurement
  - Potential to measure non-minimal SME coefficients
  - Modifications to increase precision being studied
  - Other atoms: D looks feasible

ERC Advanced Grant 291242
HbarHFS
www.antimatter.at
PI EW

H·HFS

Hyperfine Structure of Antihydrogen

ERC Advanced Grant

PI: Prof. Dr. Eberhard Widmann

Thank you for your attention

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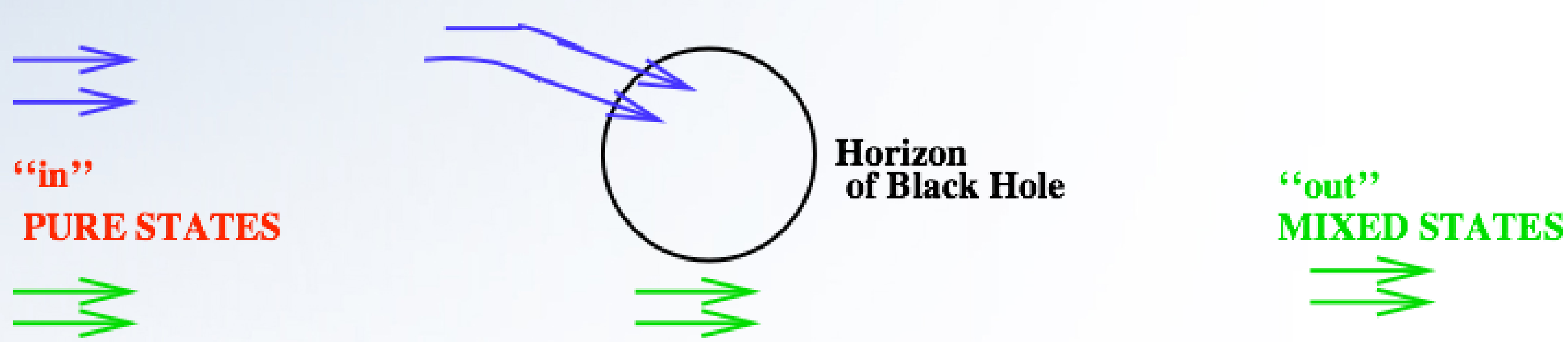
Other possibility: foam and unitarity violation

SPACE–TIME FOAMY SITUATIONS
NON UNITARY (CPT VIOLATING) EVOLUTION OF PURE STATES TO MIXED ONES



10^{-35} m

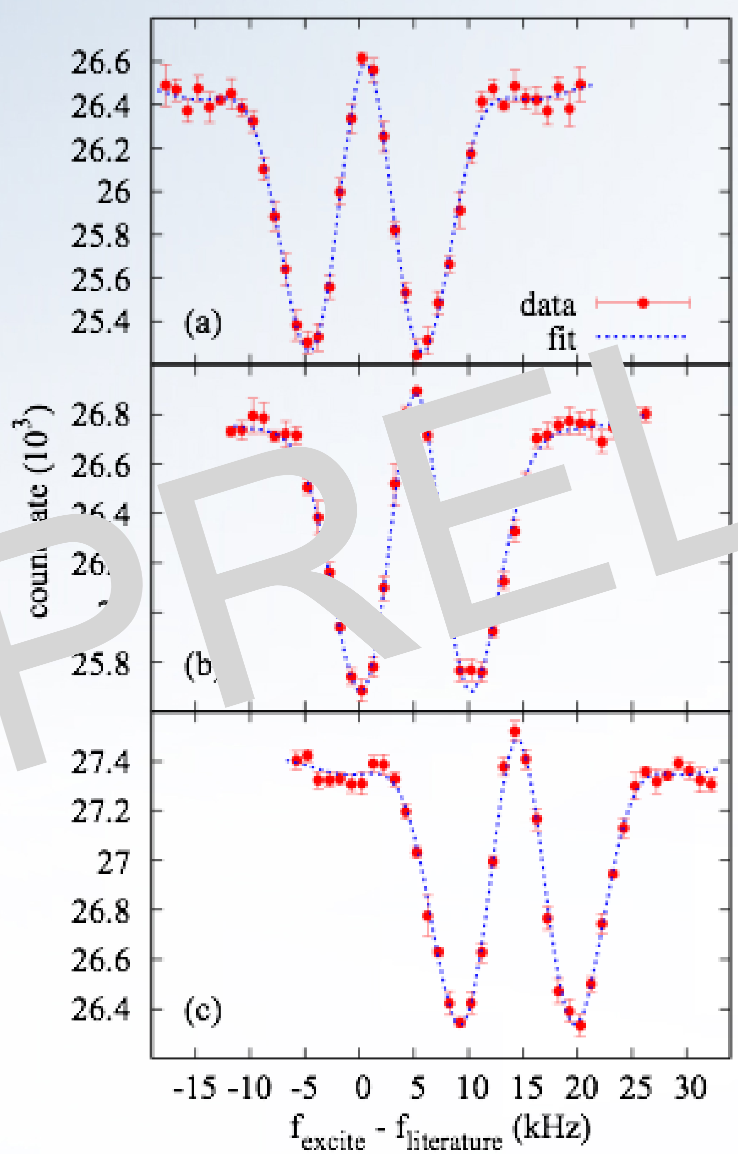
After Weinberg 99

$$\frac{d}{dt}\rho = i\,[\,\rho\,,H\,] + \Delta H(\rho)\,\rho$$

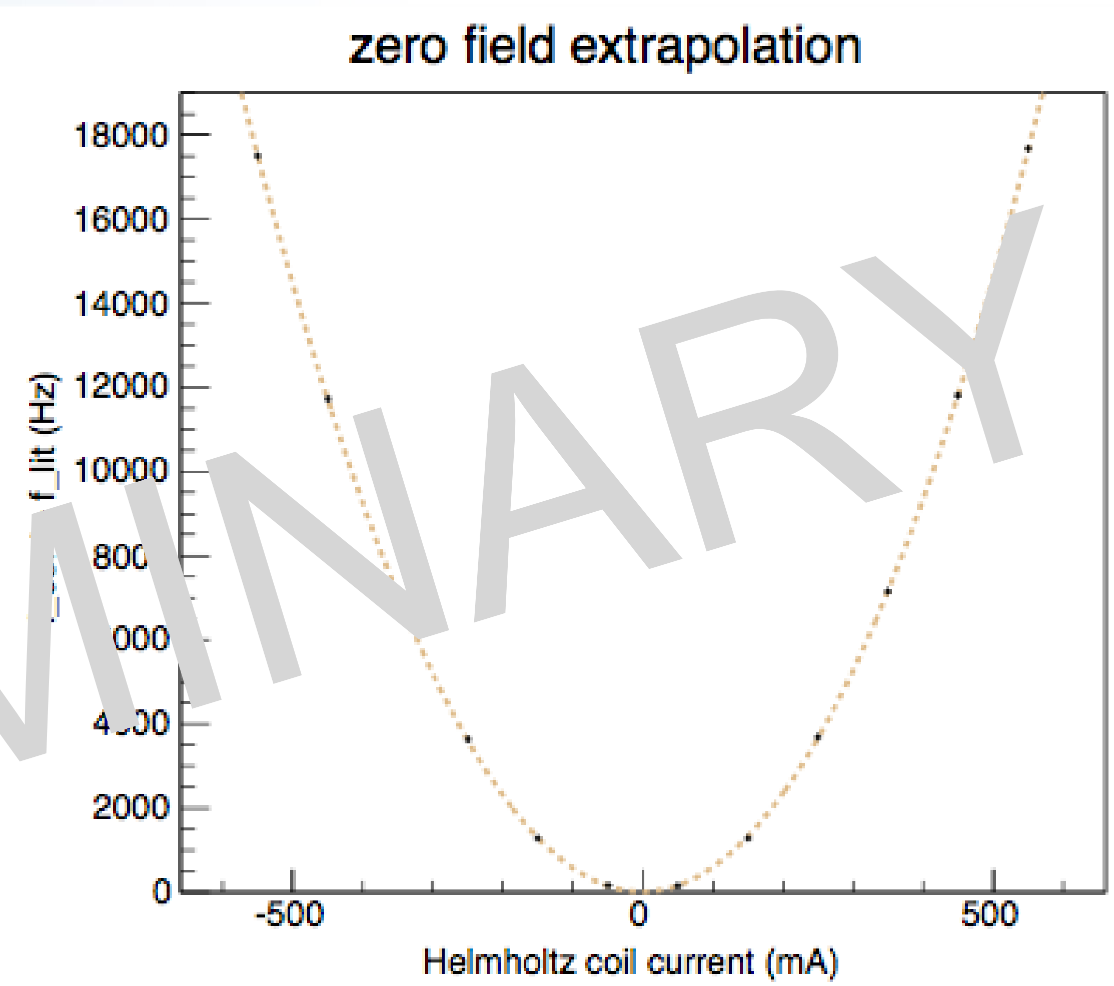
quantum mecha–nical terms — **quantum mechanics violating term**

H beam HFS result

- σ_1 transitions
- Fit the data with numerical simulated Bloch equations data



shift of resonances in magn. field
(a) 100 mA (b) 300 mA (c) 500 mA



$$\nu = 1420.405757(9)\,\mathrm{MHz}$$

$$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$$

$$\nu_{hyp} - \nu_{lit} = 6.06 \pm 9.26\,\mathrm{Hz}$$

H maser: $\Delta\nu/\nu \sim 10^{-12}$

H·HFS

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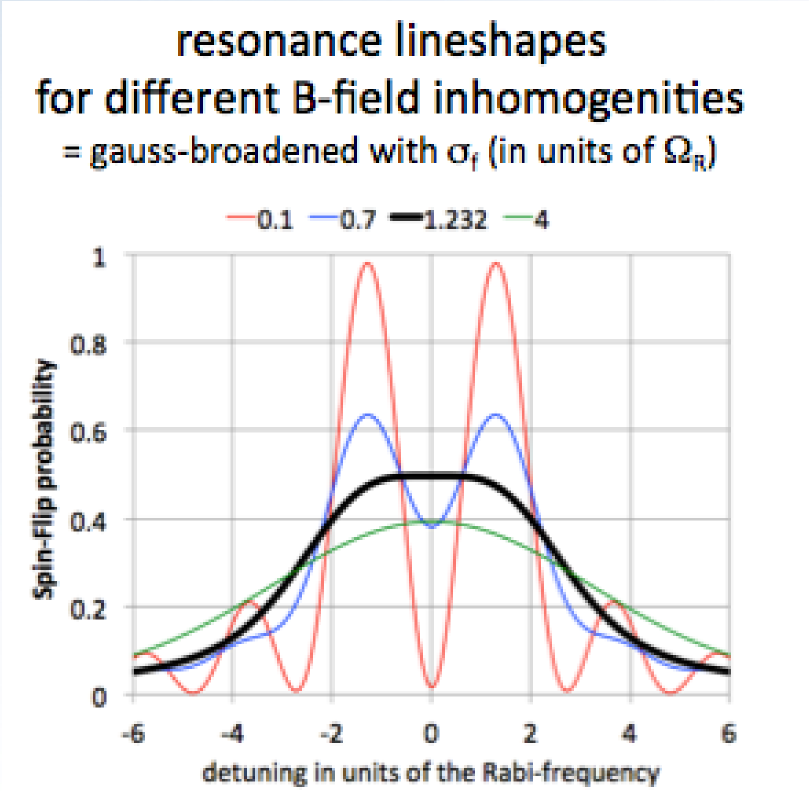
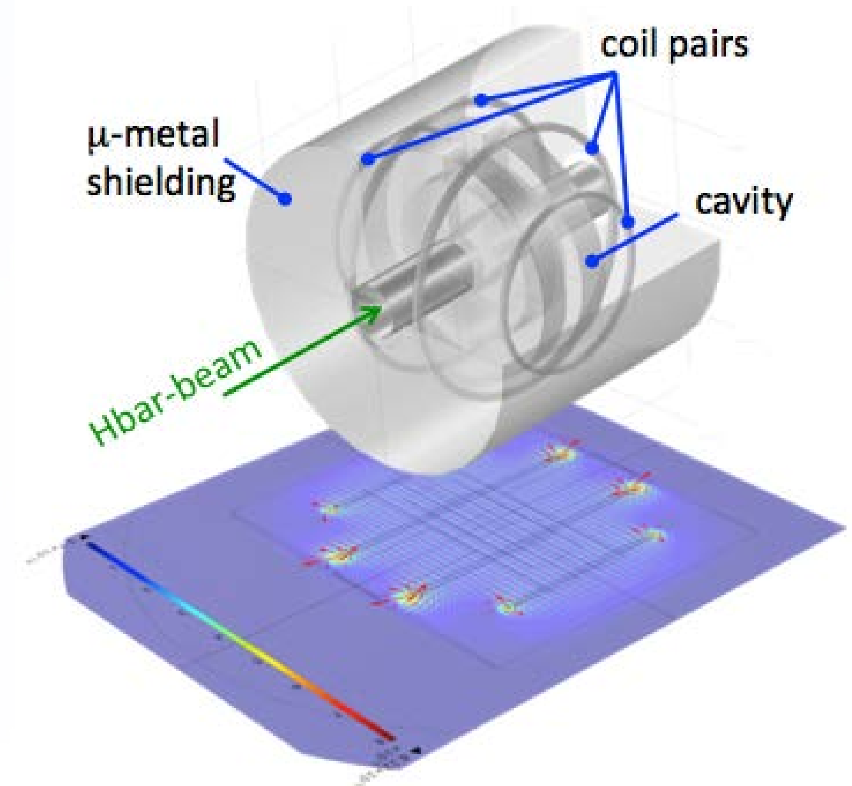
PREPARATIONS FOR π_1 MEASUREMENT

- SME: sensitive to CPTV
- better field homogeneity needed



Rabi frequency Ω_R typically 7kHz
7kHz frequency shift caused by 2.5mG

requirement → **better 0.1%**

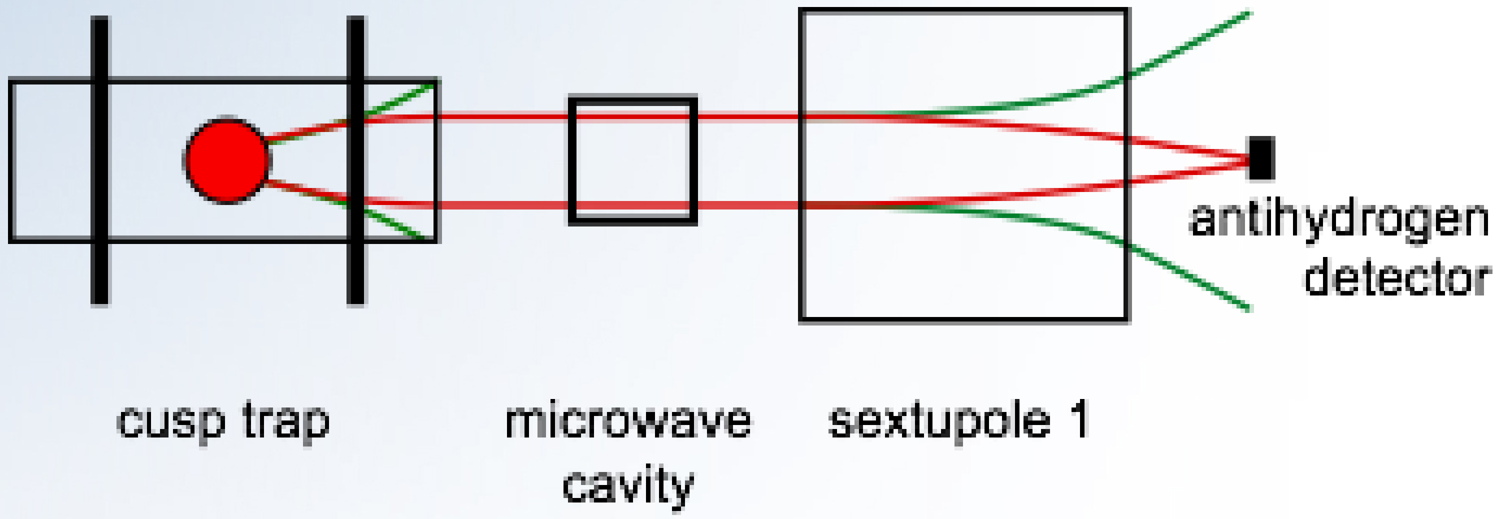


coils & shielding geometry optimized in COMSOL
(starting from McKeehan configuration)

theoretically achieved: **< 0.02%**

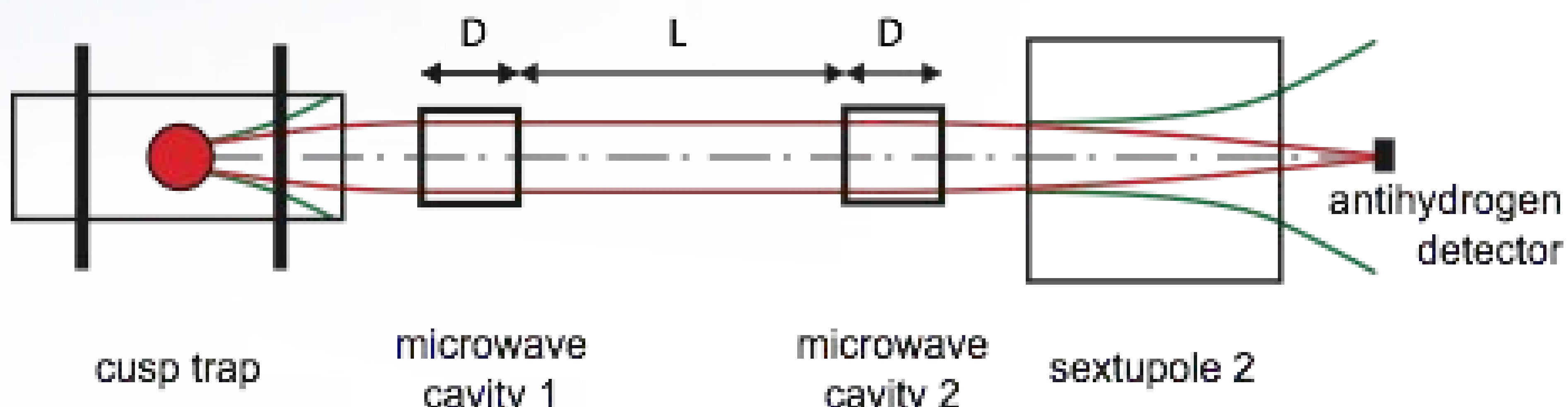
Experiments in an atomic beam

- Phase 1 (ongoing): Rabi method



$\Delta\nu/\nu \sim 10^{-7}$

- Phase 2: Ramsey separated oscillatory fields



Linewidth reduced by D/L

Standard Model Extension SME

CPT violation and the standard model

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Modified Dirac eq. in SME

CPT & LORENTZ VIOLATION

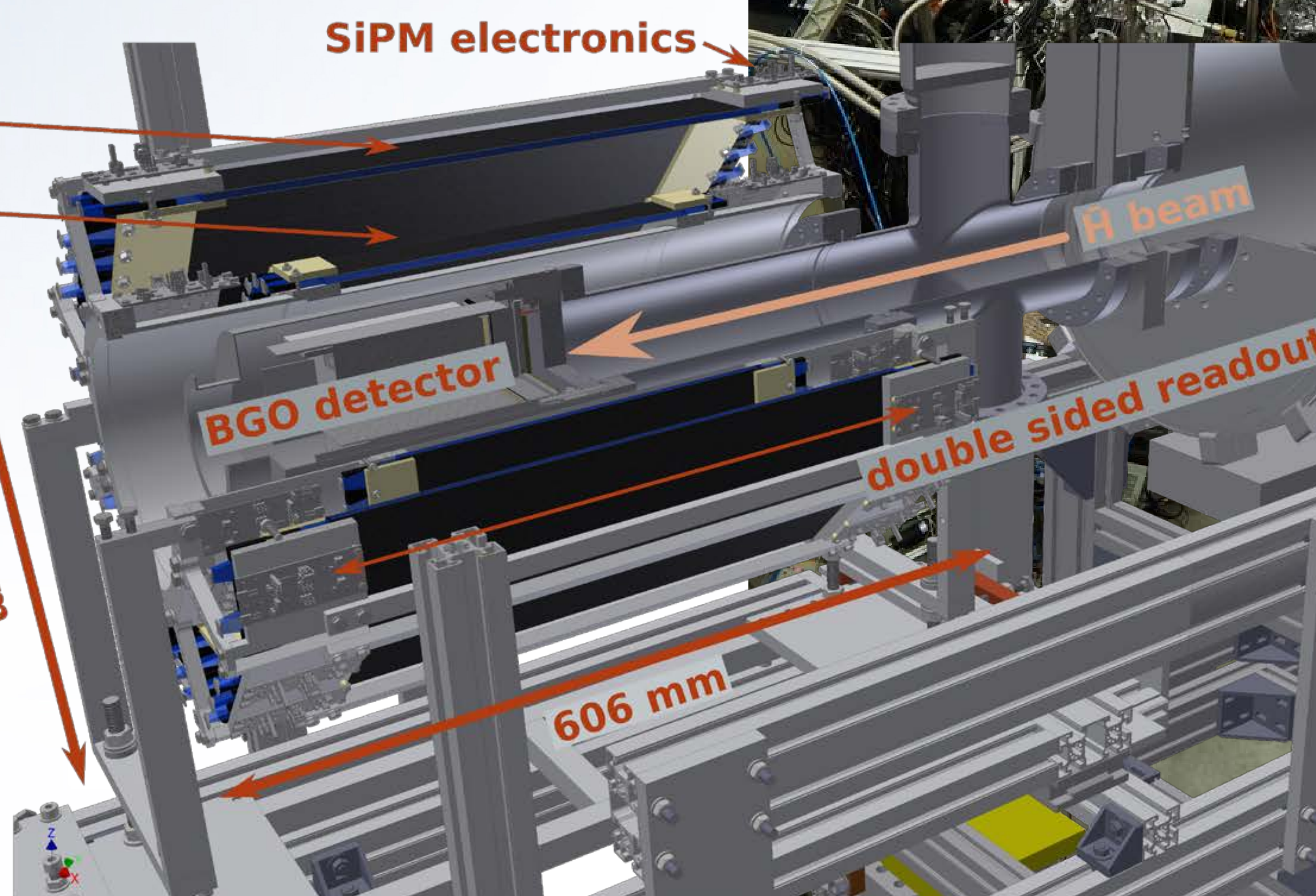
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + ic^e_{\mu\nu} \gamma^\mu D^\nu + id^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0\,.$$

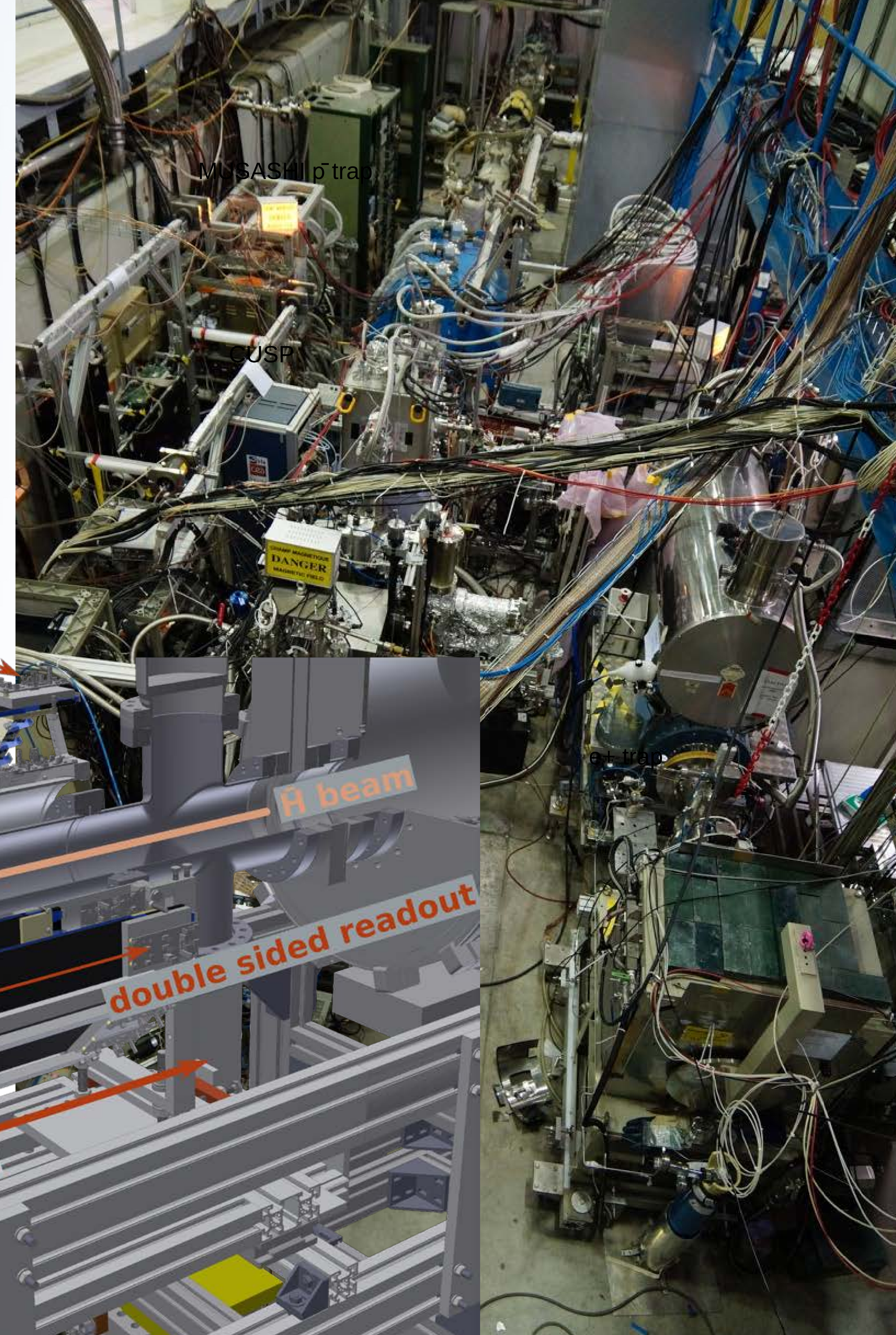
LORENTZ VIOLATION

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: there is a preferred frame, sidereal variation due to earth rotation may be detectable

Full setup 2014

- double cusp
- field ioniser
- H^{bar} detector





new 2-layer hodoscope
with central BGO detector

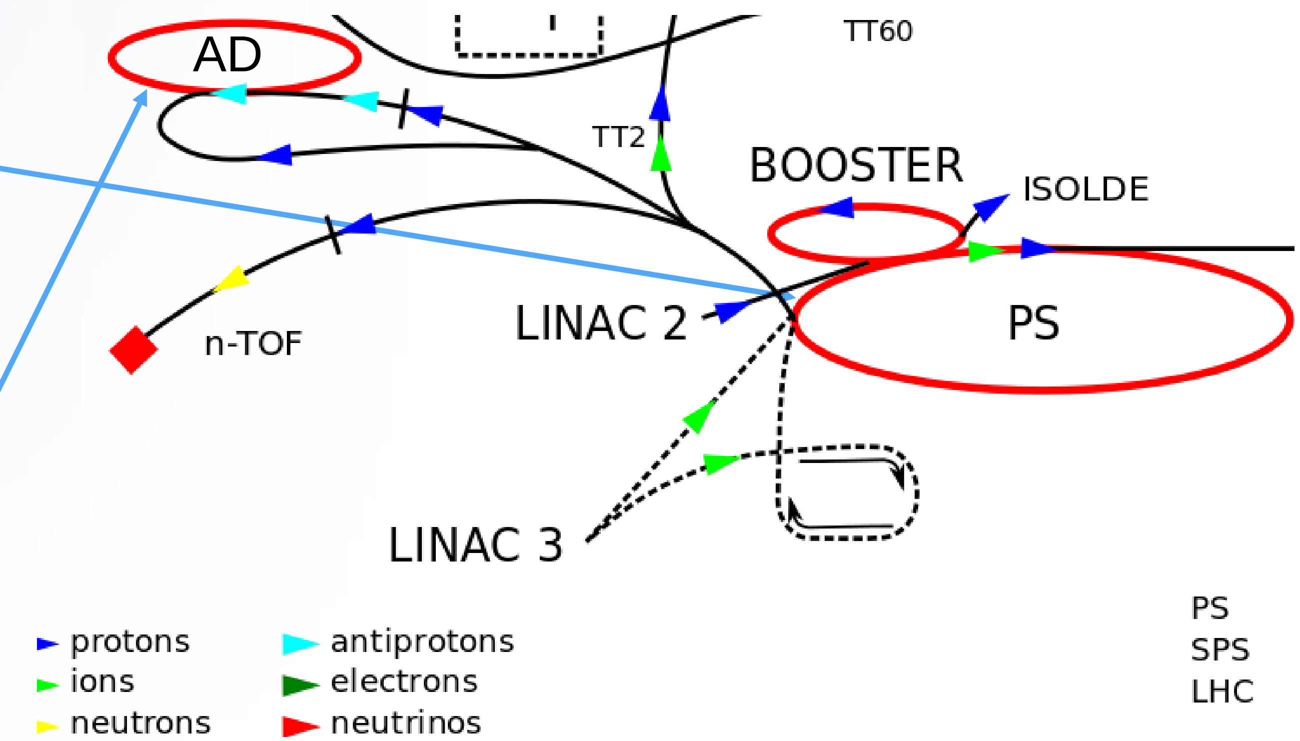
Antiproton production @ CERN

$$p + p \rightarrow p + p + \boxed{p + \bar{p}}$$

beam target

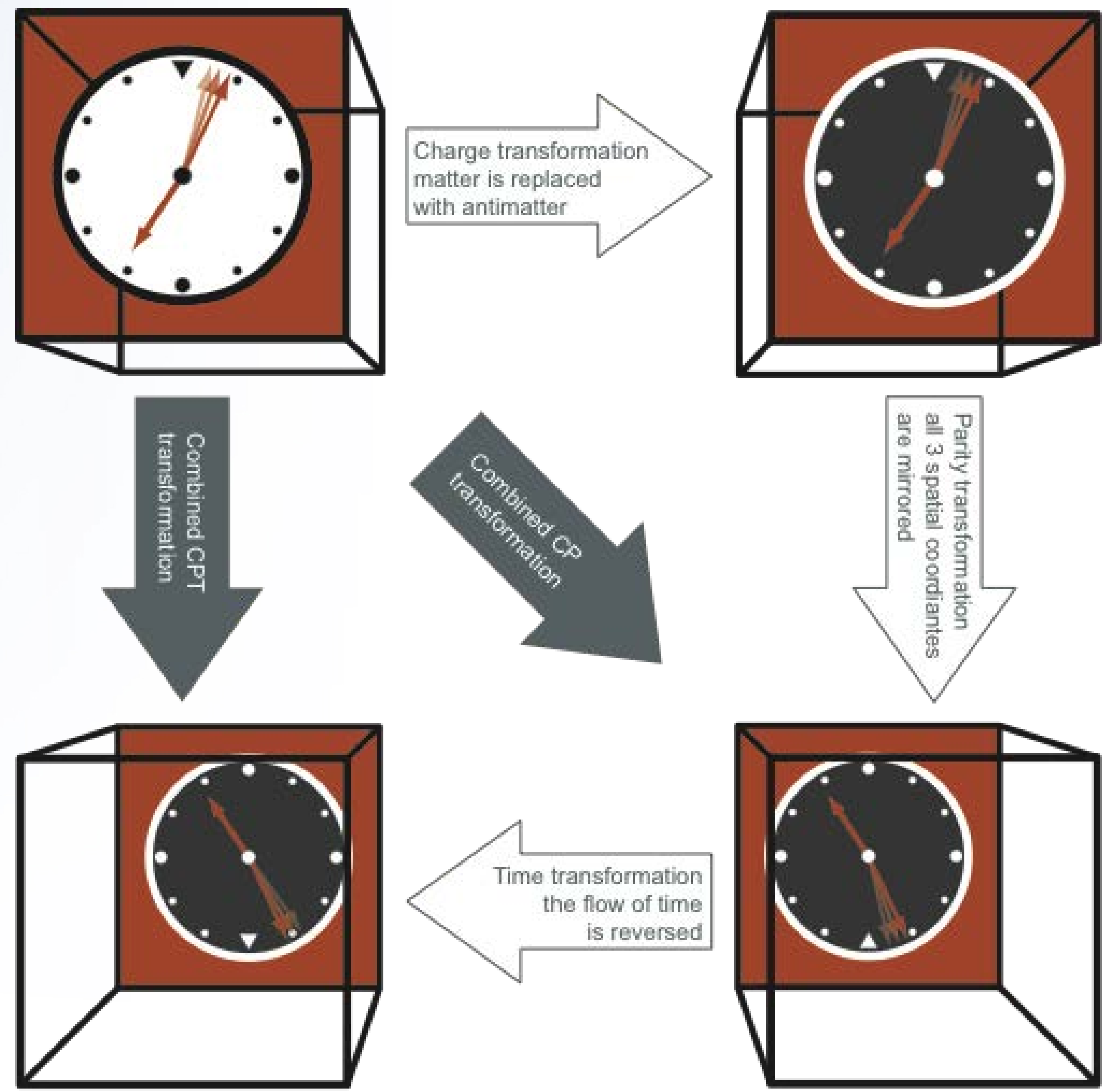
pair creation from vacuum

- Threshold 6 m_p (5.6 GeV)
- PS: 26 GeV
- Antiprotons of 3.7 GeV/c
- Low-energy beam
  - Accumulation
  - Deceleration
  - Cooling (stochastic, electron)
- Since 2000
  - All-in-one machine: AD



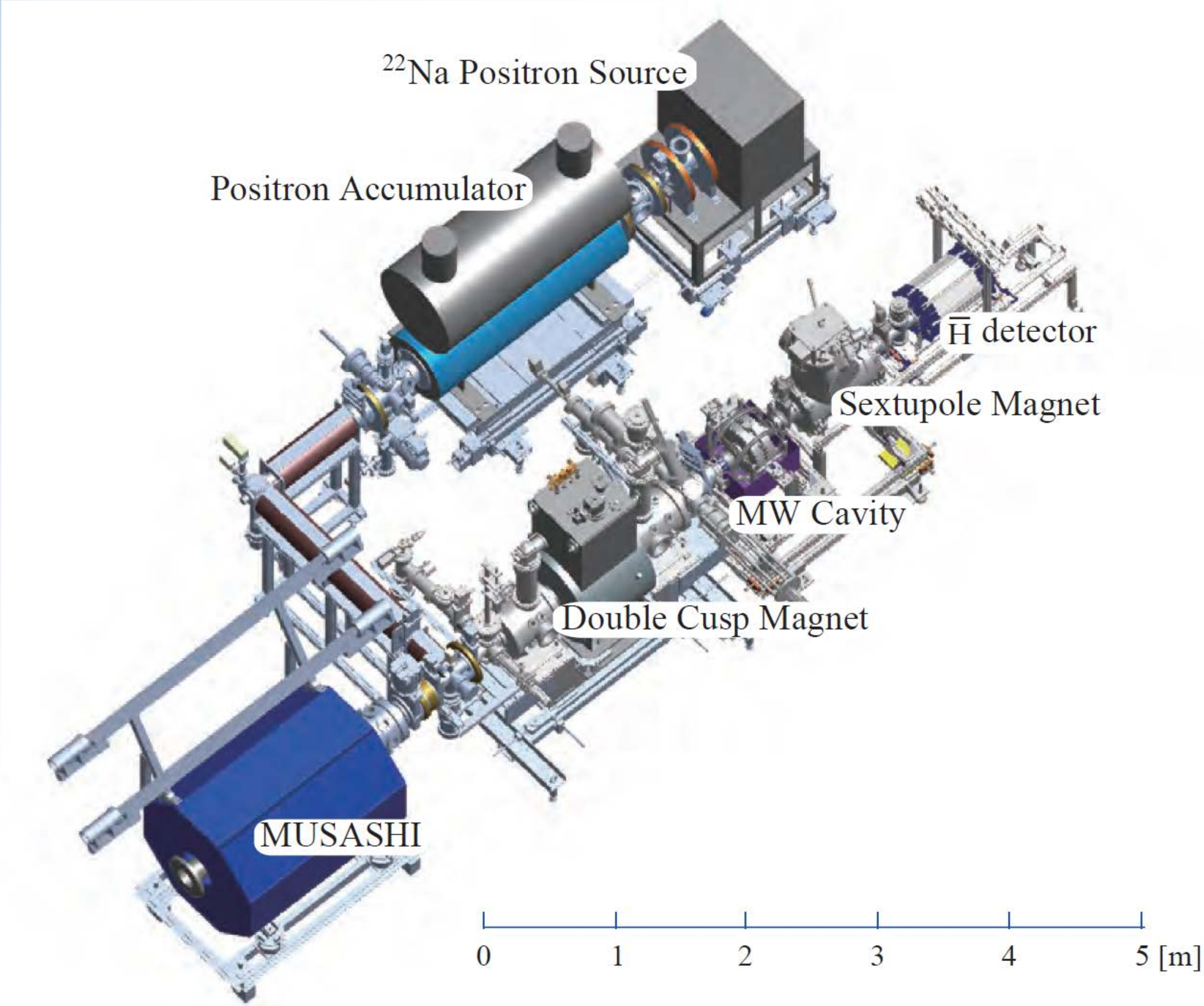
Fundamental symmetries C,P,T

- C: charge conjugation particle ↔ antiparticle
- P: parity: spatial mirror
- T: time reversal
- CPT theorem: consequence of
  - Lorentz-invariance
  - local interactions
  - unitarity
    - *Lüders, Pauli, Bell, Jost 1955*
- all QFT of SM obey CPT
- not necessarily true for string theory



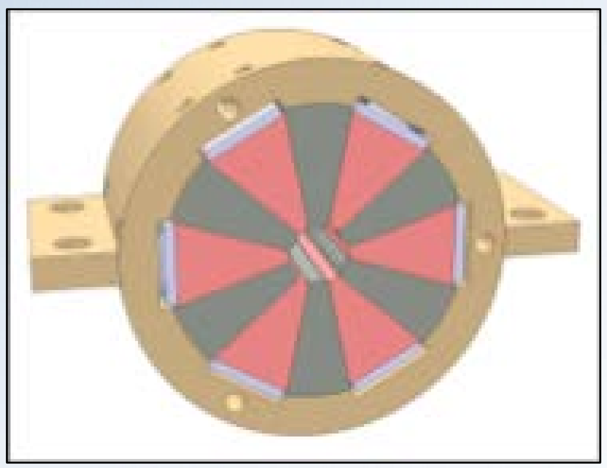
CPT → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

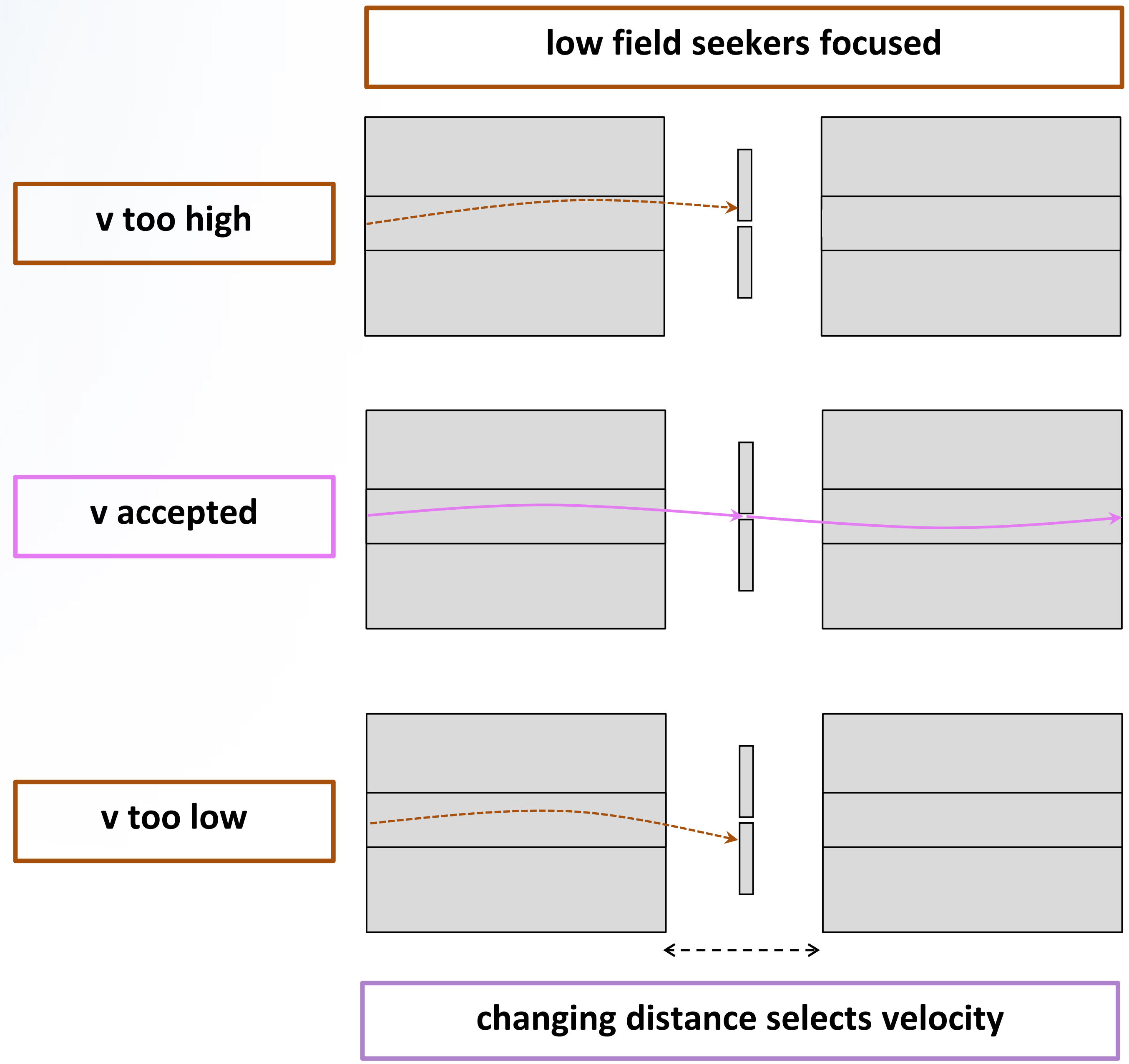
ASACUSA $\bar{H}$ production 2014~

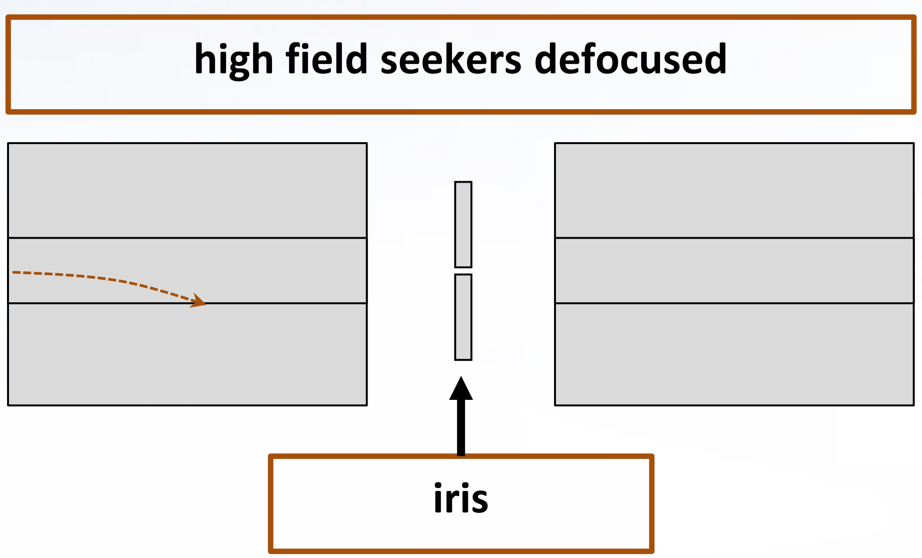


Polarisaton: permanent sextupoles

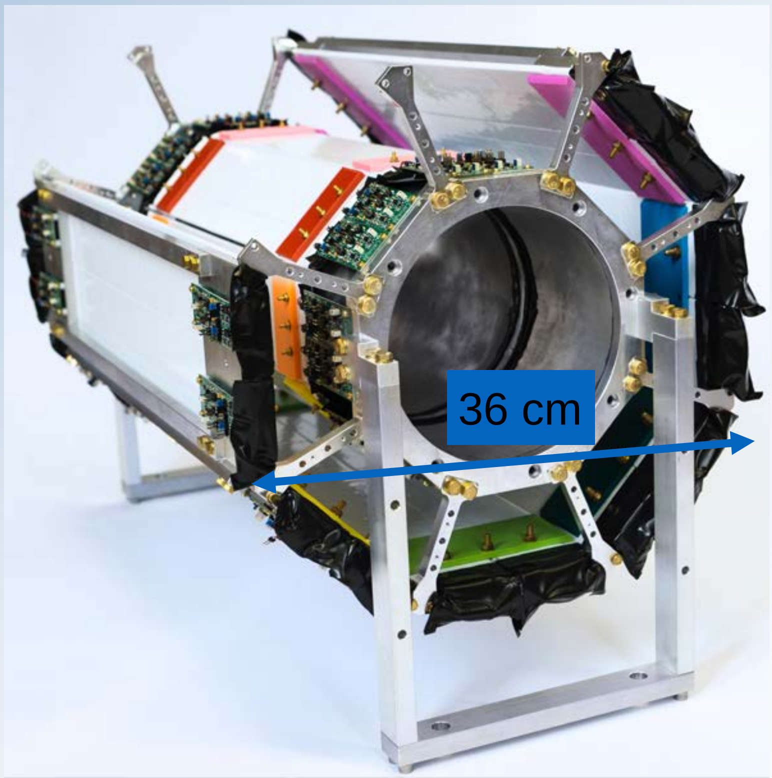
- 2 Halbach magnets B_{max}=1.3 T, L=6 cm, r=1 cm

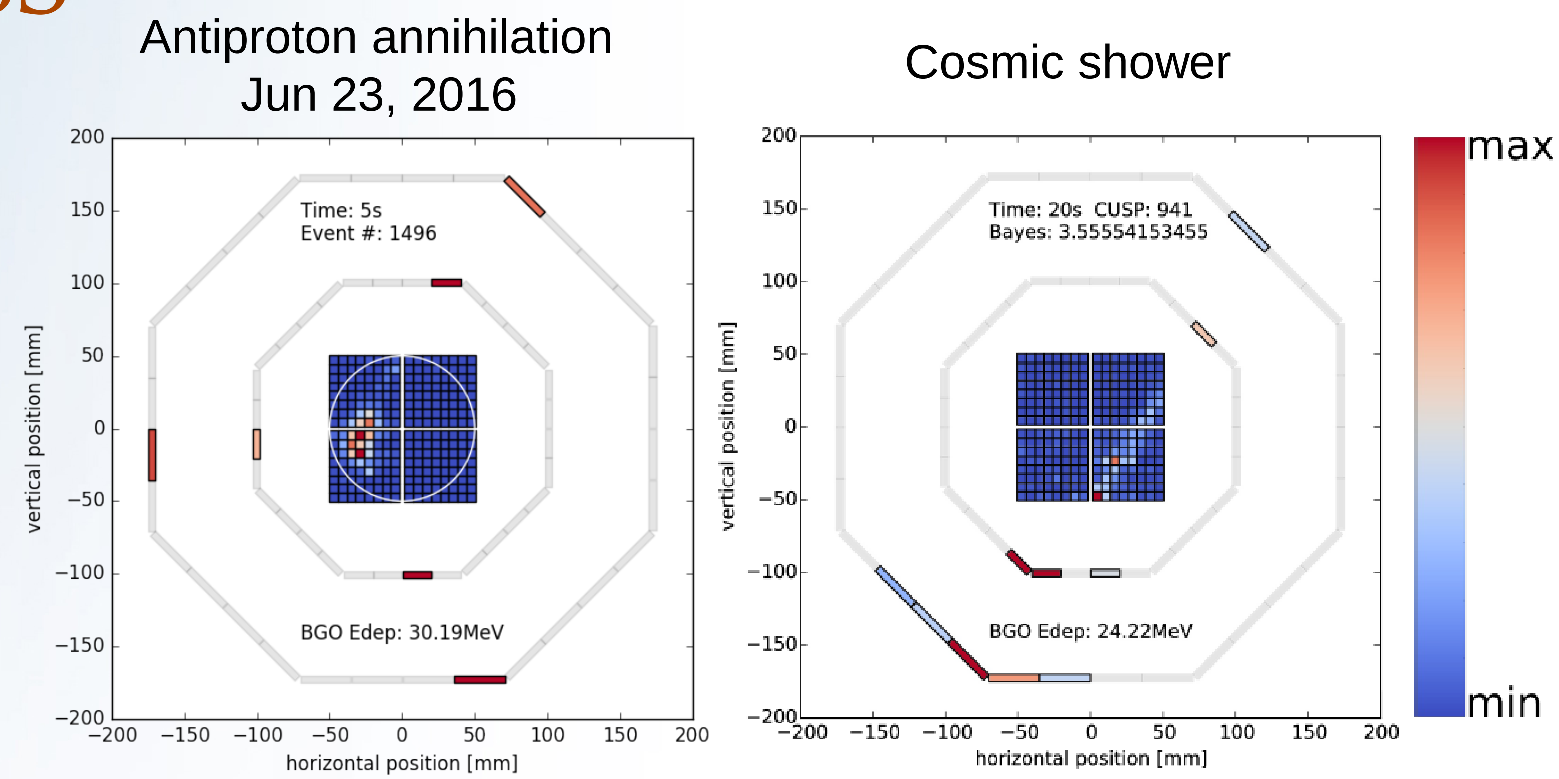




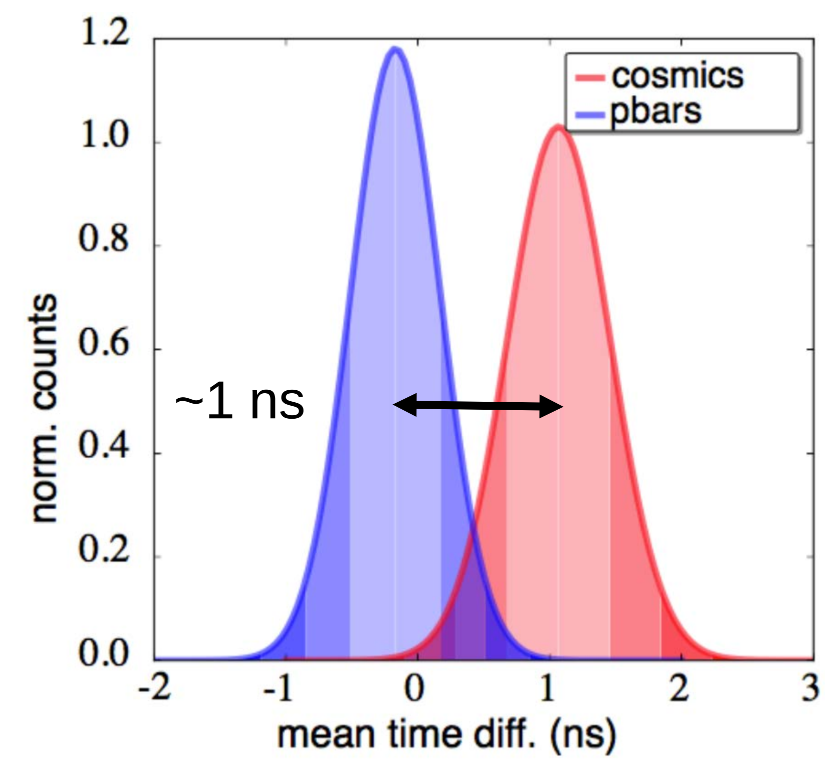


Recent progress



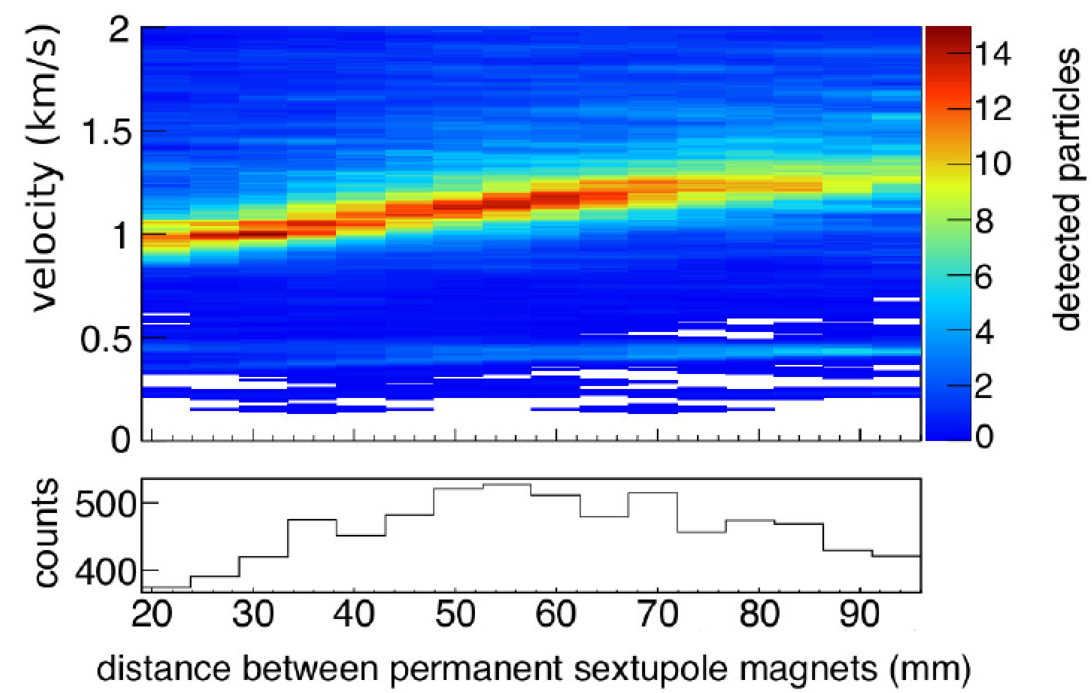


- BGO calorimeter + 2 layer hodoscope
- Optimize $\overline{\mathrm{H}}$ rate
- Measure n-state distribution
  - 1st results under analysis
- Polarisation
- Velocity

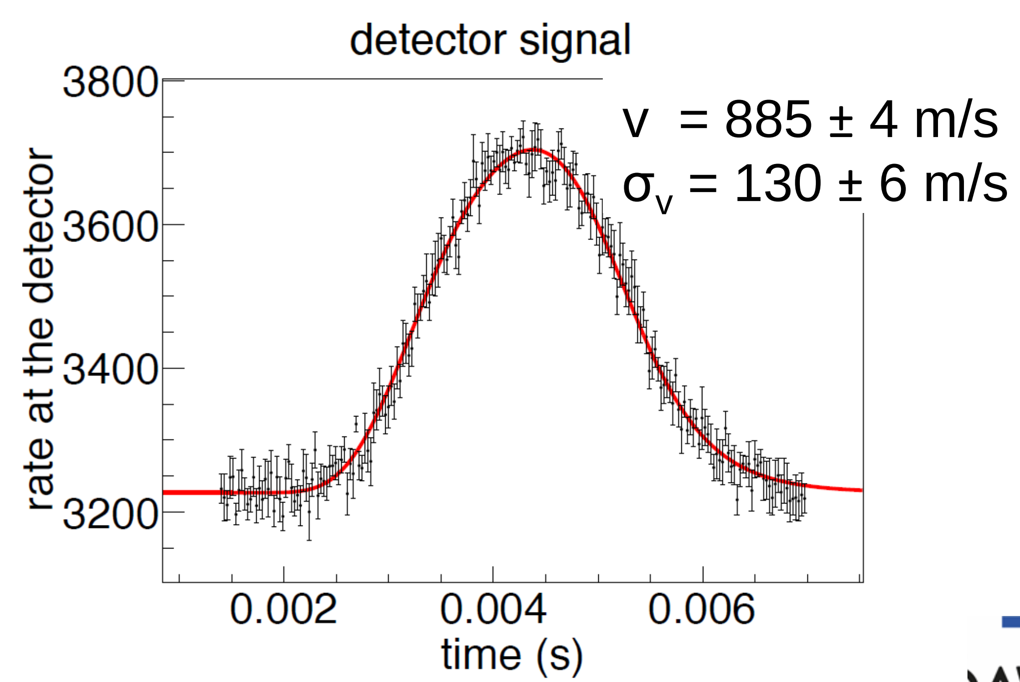


Current H-beam parameters

- similar to expected $\bar{\mathrm{H}}$ values
  - Determined by sextupoles
  - velocity: 1 km/s ÷ 50 K
  - Tunable by 10%



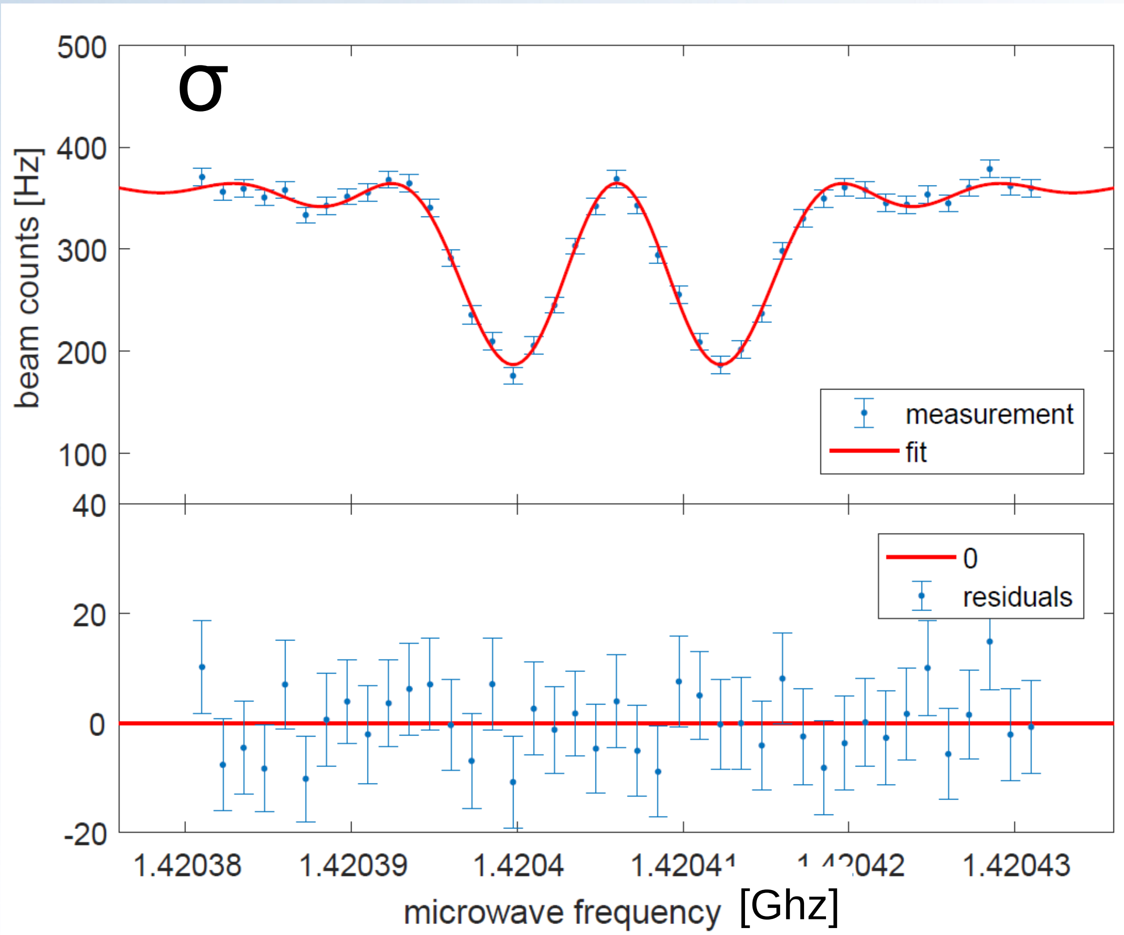
  - Velocity distribution

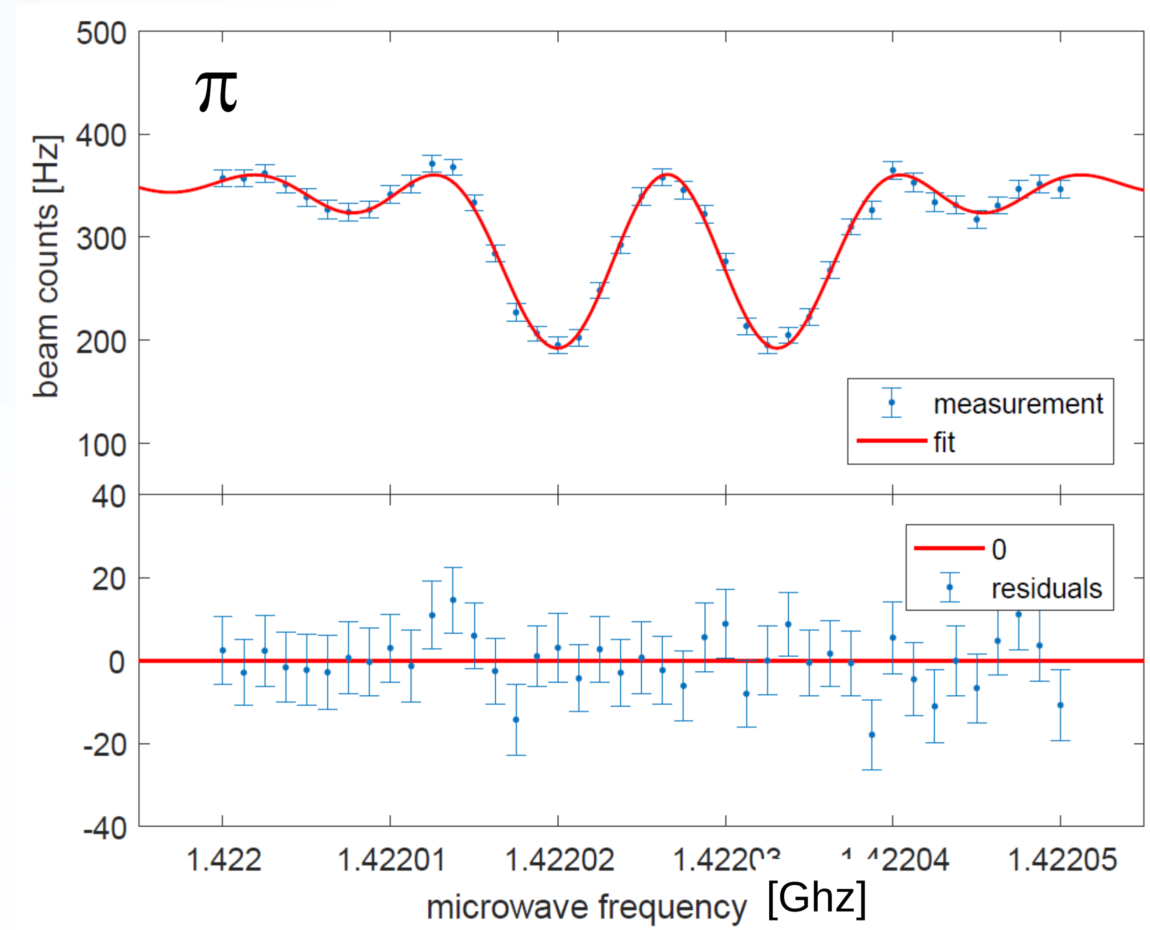


- Possible modifications
  - Shorter sext., lower fields
  - New geometry

First σ and π resoances Feb. 2017

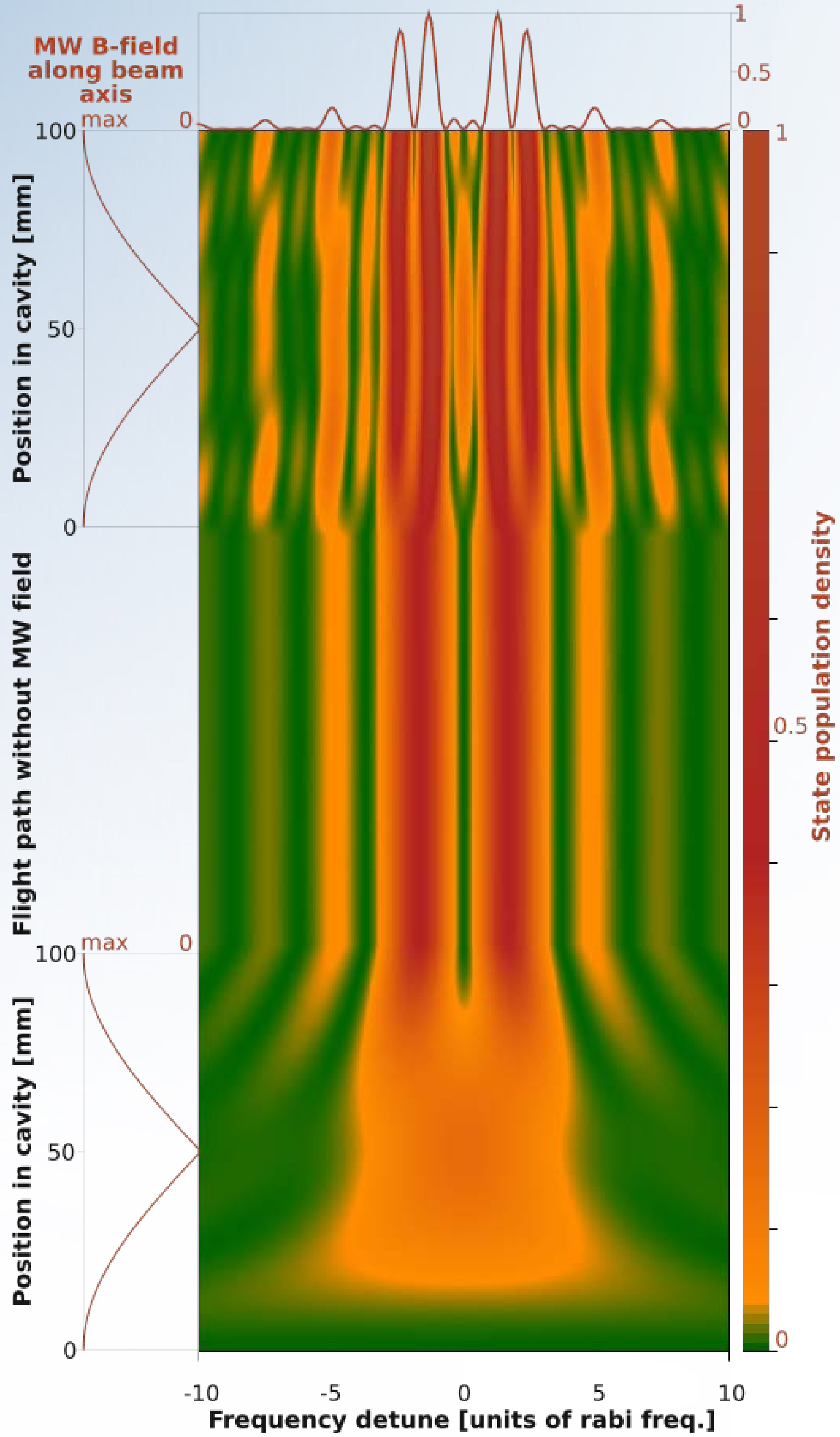
- Same amplitude at same beam line settings

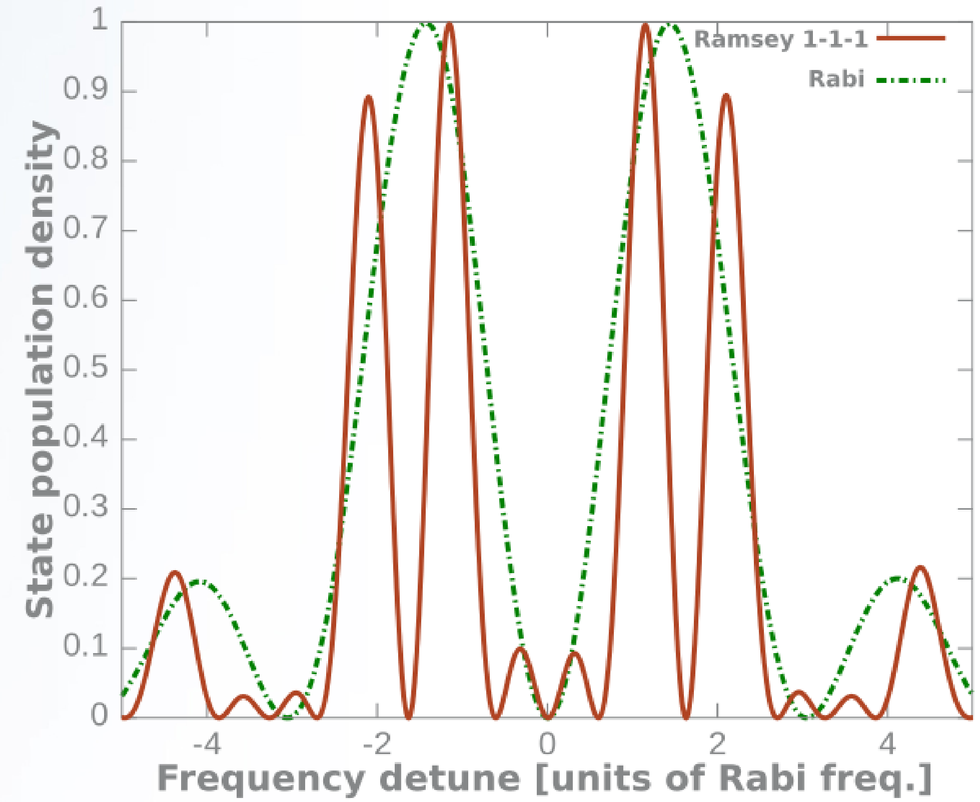




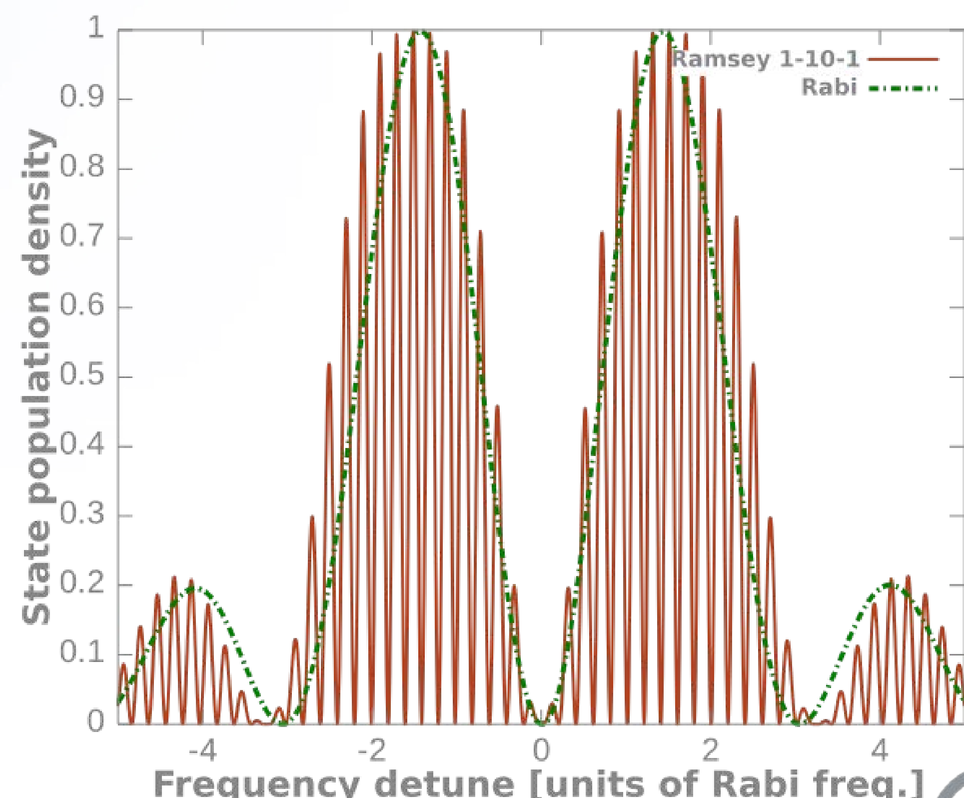
PRELIMINARY

Optical Bloch Equation solution





10cm RF
10cm free
10cm RF



10cm RF
1 m free
10cm RF