Measurement of the ground-state hyperfine splitting of antihydrogen

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Nordic Winter Meeting on FAIR
March 23, 2010
Björkliden, Sweden

Austrian Academy of Sciences

Stefan Meyer Institute

ASACUSA collaboration

CERN

Outline

(1) What is ground-state hyperfine splitting

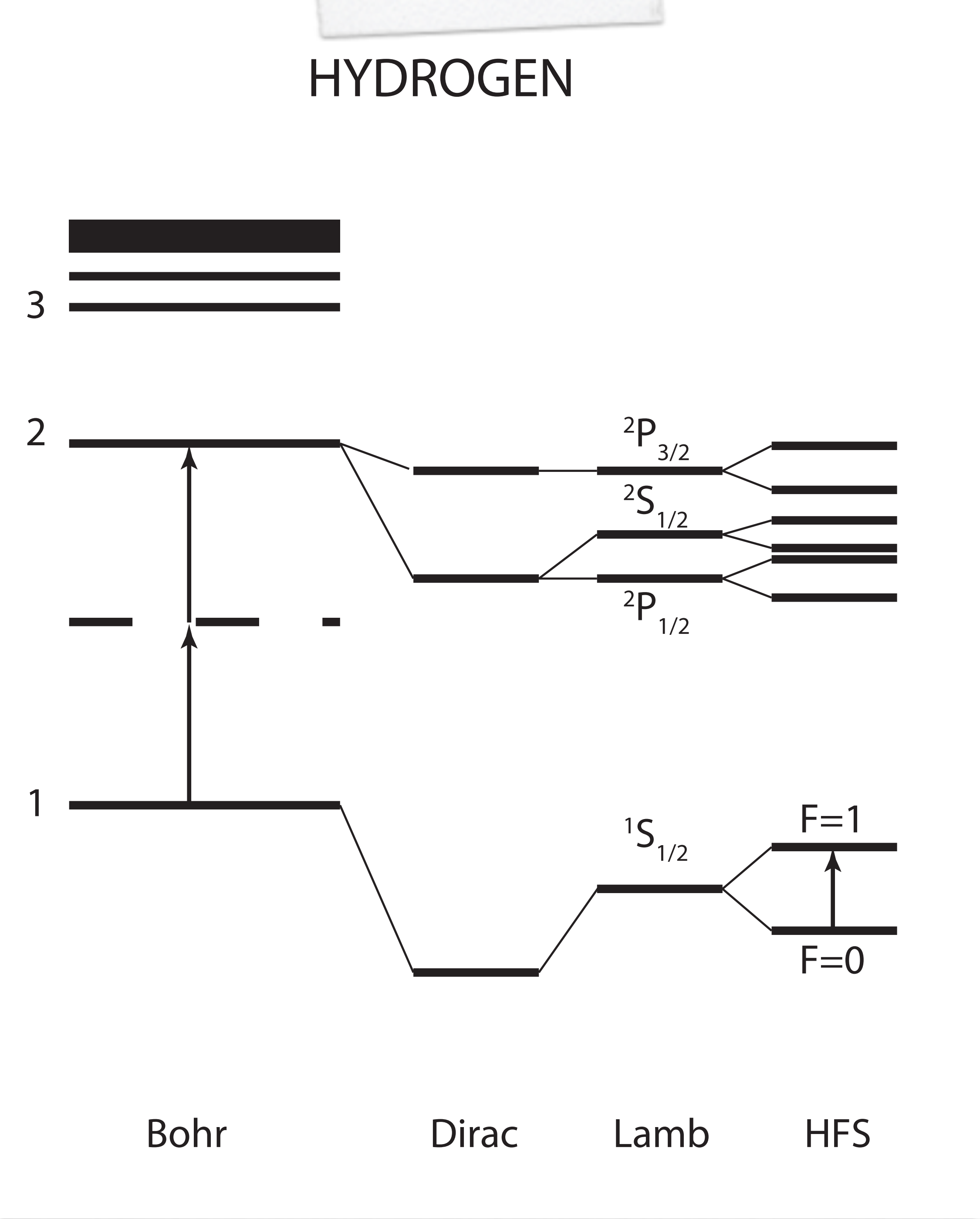
(2) Why we want to measure it

(3) How we want to measure it

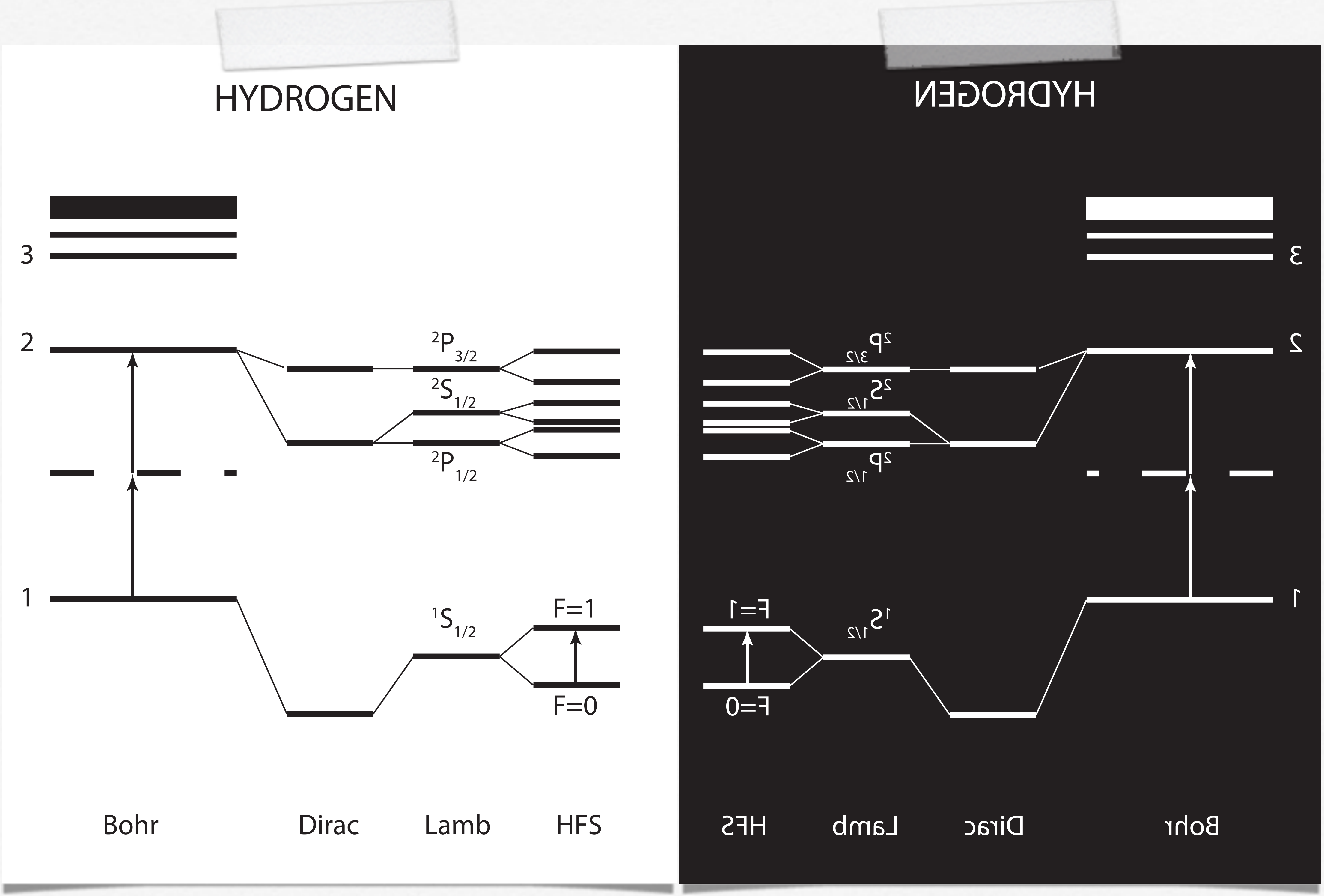
(4) MC simulations

(5) Future at FLAIR

(Anti)hydrogen energy levels

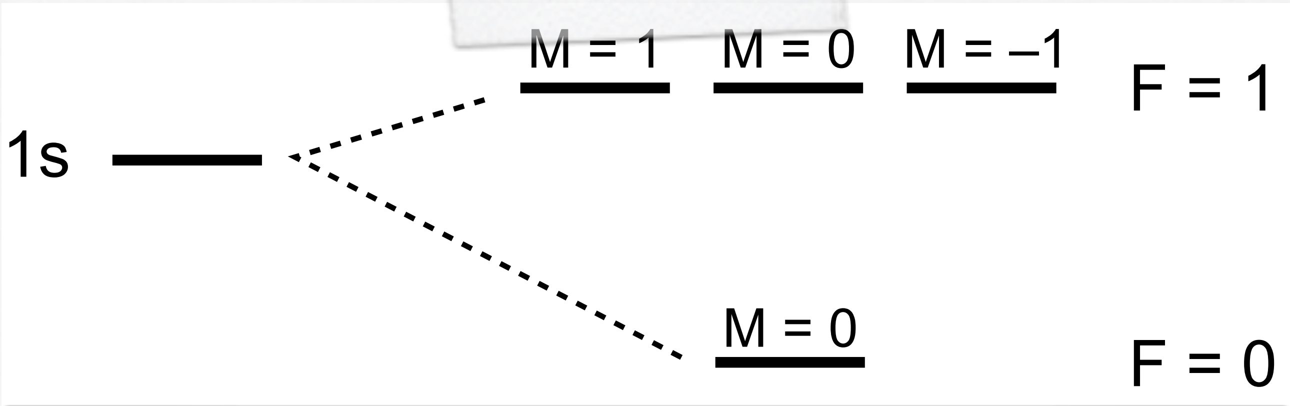


(Anti)hydrogen energy levels



(Anti)hydrogen ground-state hyperfine splitting

- Interaction between (anti)proton and electron (positron) spin magnetic moments
- Results in a triplet (*F* = 1) and a singlet (*F* = 0) sublevels



- Between *F* = 1 and *F* = 0:

$$\nu_{\text{HF}} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c\, R_\infty (1+\delta) \simeq 1.42\ \text{GHz}$$

- ν_{HF} is appr. proportional to the (anti)proton magnetic moment $\mu_{\bar{p}}$
- δ: higher-order QED & strong interaction corrections: ~10^{-3}
- Theoretical uncertainty on δ: ~10^{-6}

SME including CPTV and LIV

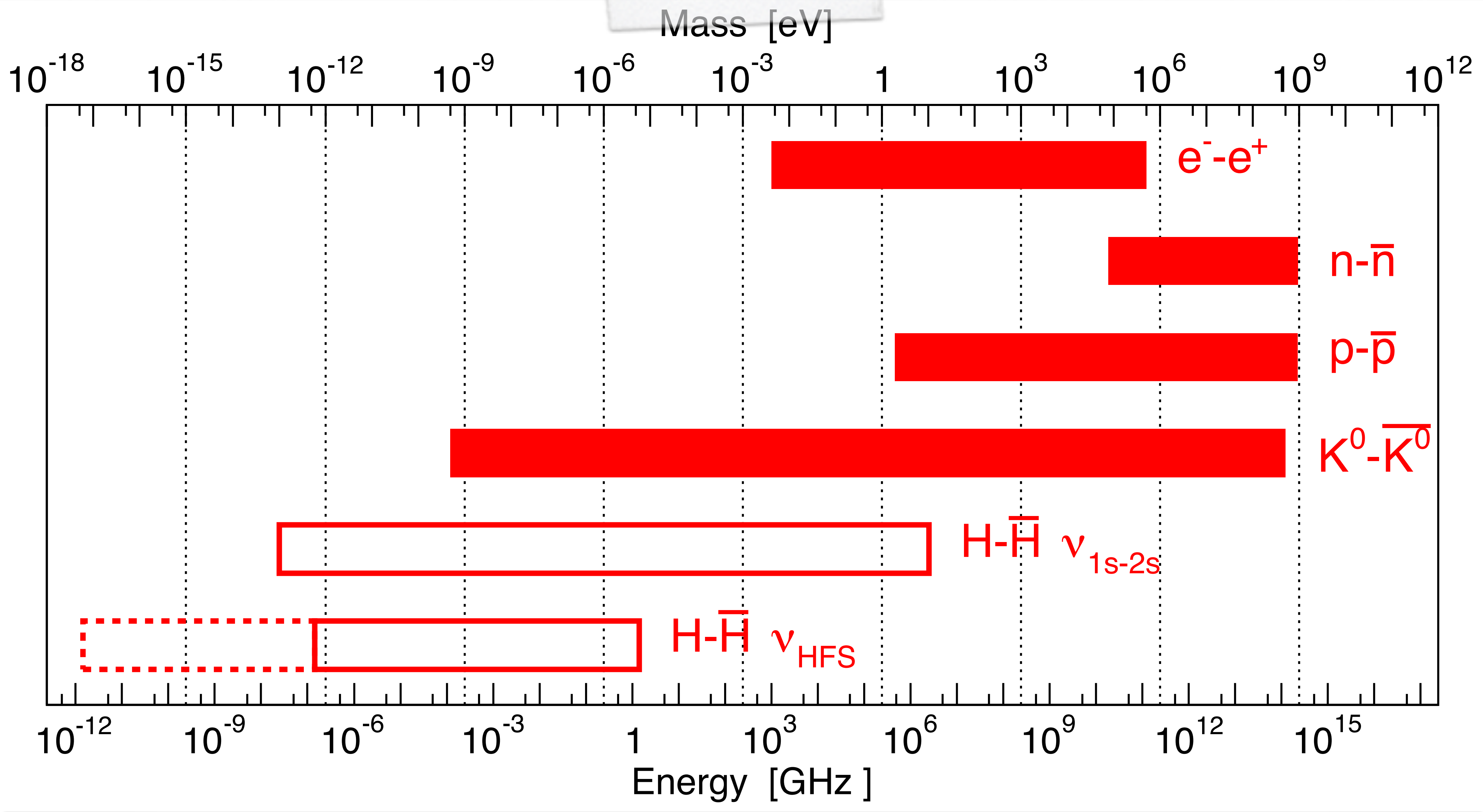
- Bluhm, Kostelecký, Russell, PRL 82: Standard Model extension (SME) including
  - Charge-Parity-Time invariance violating (CPTV), and
  - Lorentz invariance violating (LIV)

  terms in the Lagrangian
- Correction to the 1s (& 2s) hyperfine levels:

$$\begin{aligned}\Delta E^{\mathrm{H}}(m_J, m_I) \quad = \quad & a_0^e + a_0^p - c_{00}^e m_e - c_{00}^p m_p \\ & +(-b_3^e + d_{30}^e m_e + H_{12}^e) m_J/|m_J| \\ & +(-b_3^p + d_{30}^p m_p + H_{12}^p) m_I/|m_I|\end{aligned}$$

- Parameters a, d, and H reverse sign for antihydrogen
- Parameters a and b have a dimension of *energy*
  - Not relative, but *absolute* precision matters

Mass/energy CPT limits



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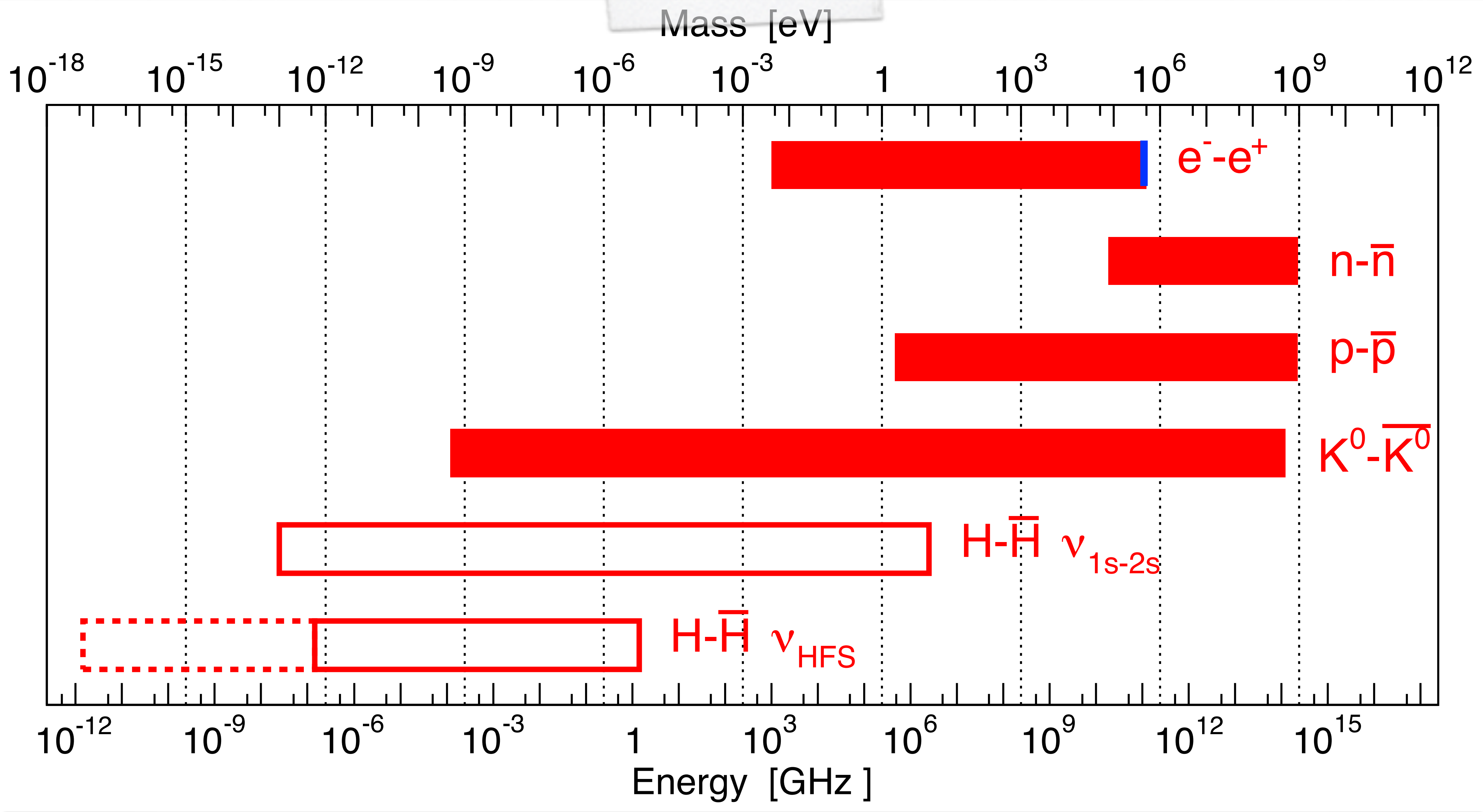
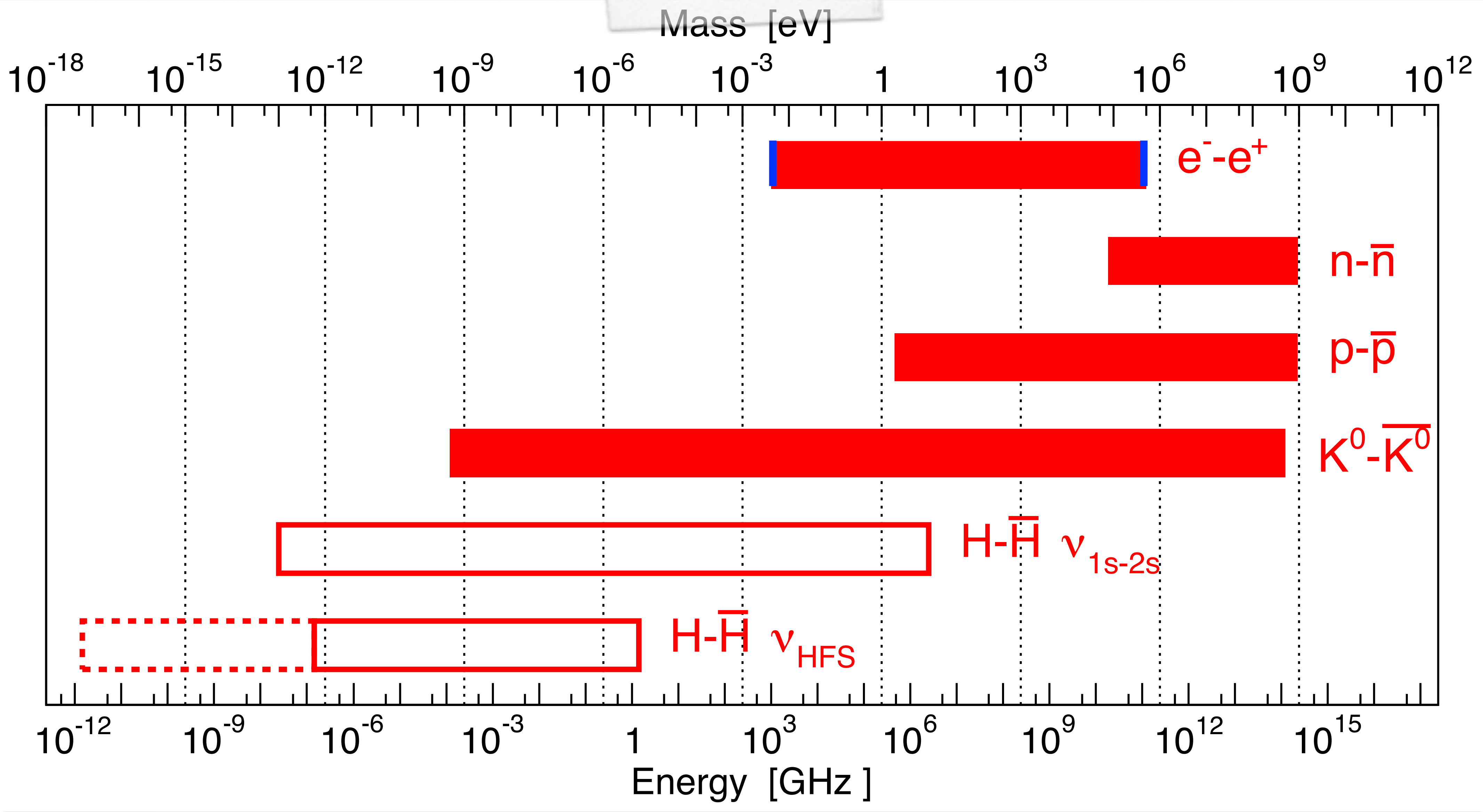


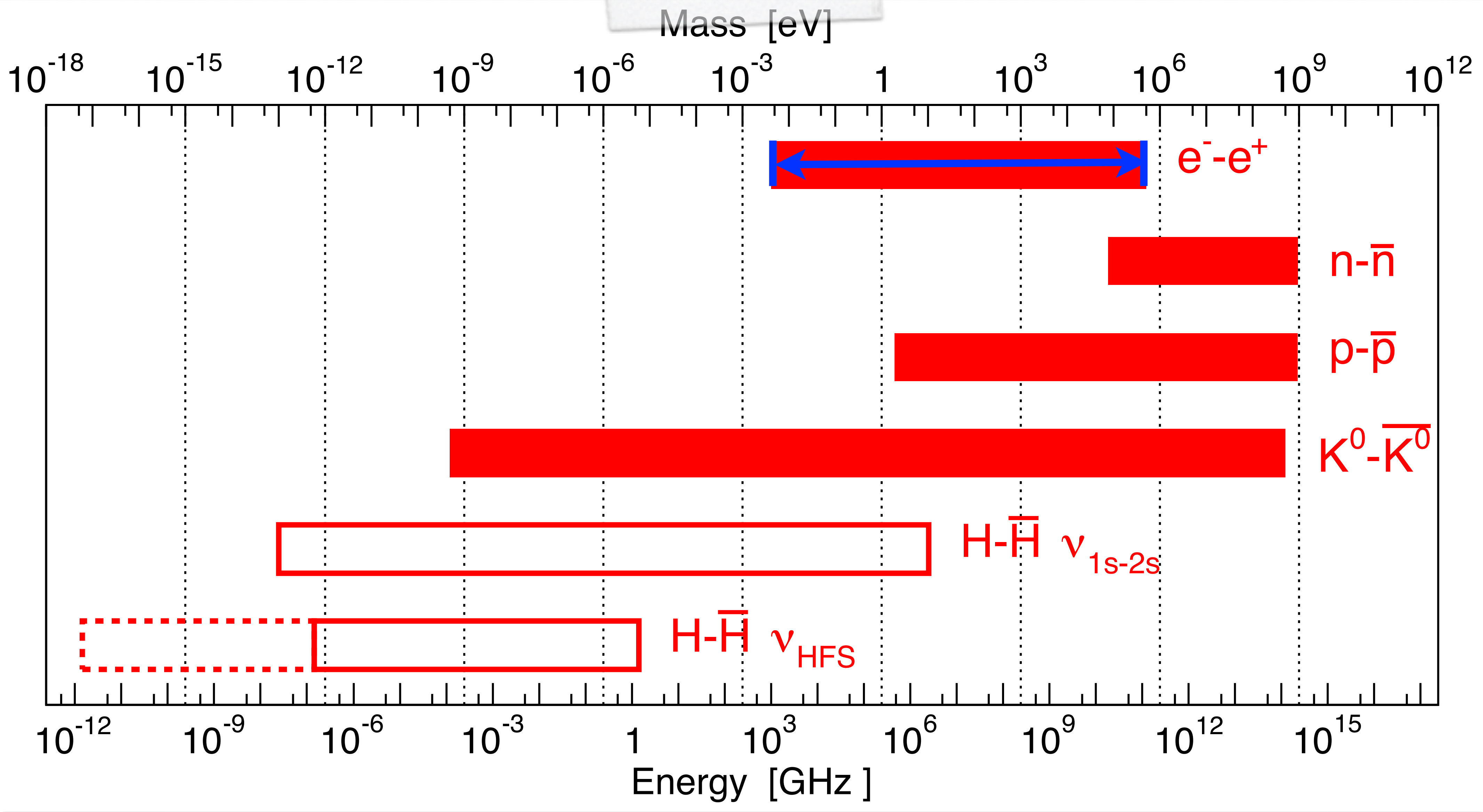
measured quantity (right edge)

Mass/energy CPT limits



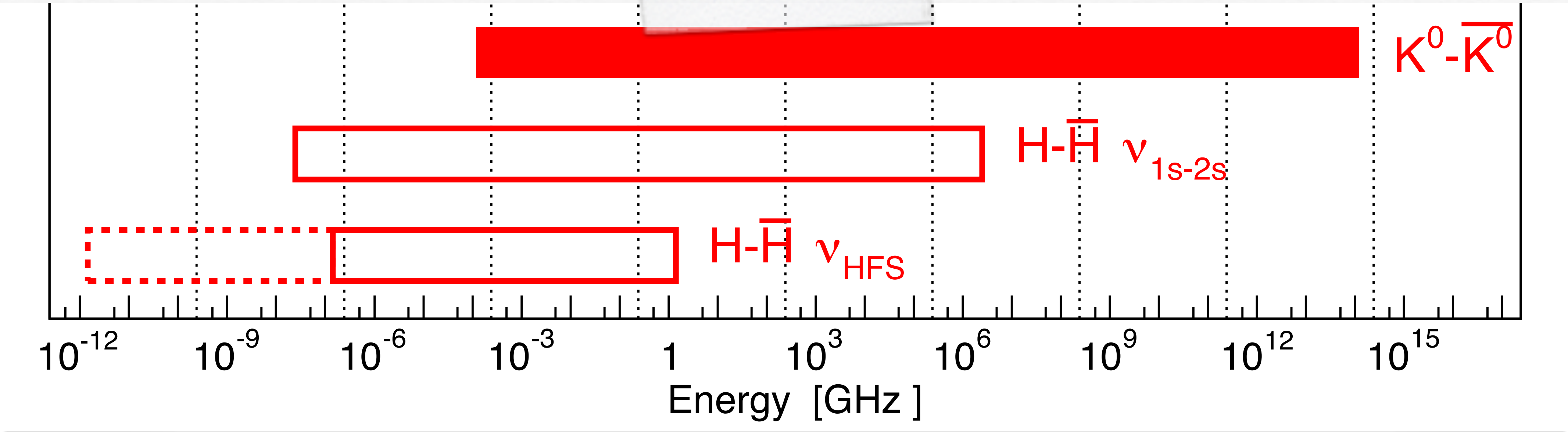
$$\frac{\text{absolute precision (left edge)}}{\text{measured quantity (right edge)}}$$

Mass/energy CPT limits



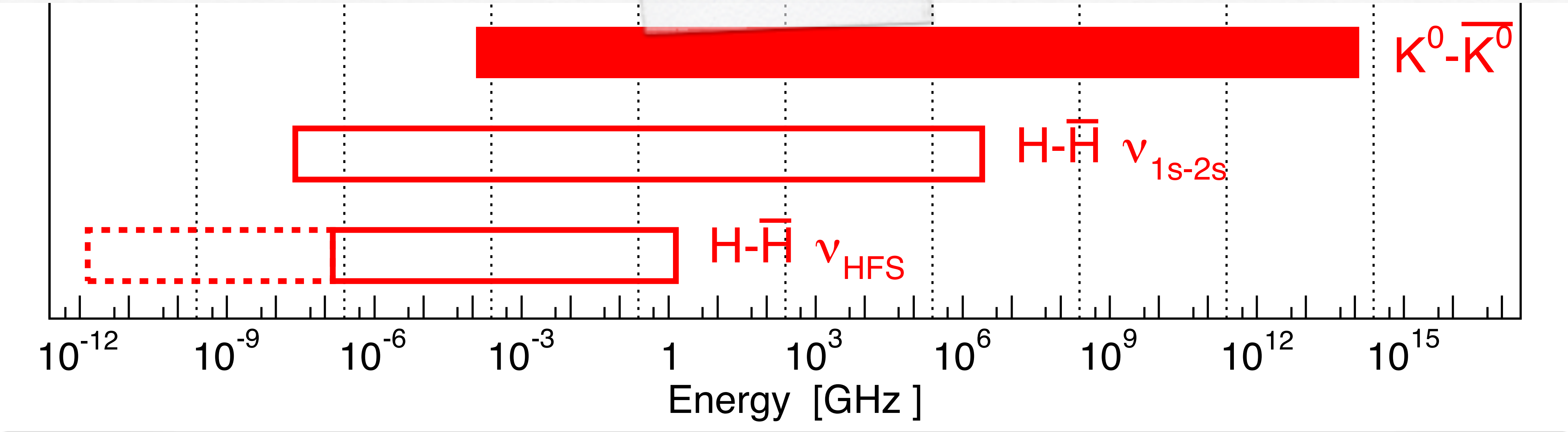
$$\frac{\text{absolute precision (left edge)}}{\text{measured quantity (right edge)}} = \text{relative precision (length)}$$

$\overline{H}$ GS-HFS vs. K^0-$\overline{K}^0$ $\Delta m/m$



- "Best CPT test": K^0-$\overline{K}^0$ $\Delta m/m \sim 10^{-18} \Leftrightarrow 10^5$ Hz
- Relatively accuracy of 10^{-4} of $\overline{H}$ GS-HFS ($\sim$ 1 GHz × $10^{-4} = 10^5$ Hz) can already be competitive
- But: K^0-$\overline{K}^0$ is sensitive to a, $\overline{H}$ GS-HFS is sensitive to b
  - The two measurements cannot be compared directly
- CPT violation might appear in one physical system, but not in another

$\bar{H}$ GS-HFS vs. $\bar{H}$ 1s-2s



- ☐ 1*s*-2*s* frequency mainly determined by electron (positron) mass
- ☐ (Anti)proton mass only comes at 4th digit
- ☐ This doesn’t mean 1*s*-2*s* is not worthwhile to measure;
  GS-HFS and 1*s*-2*s* complement each other

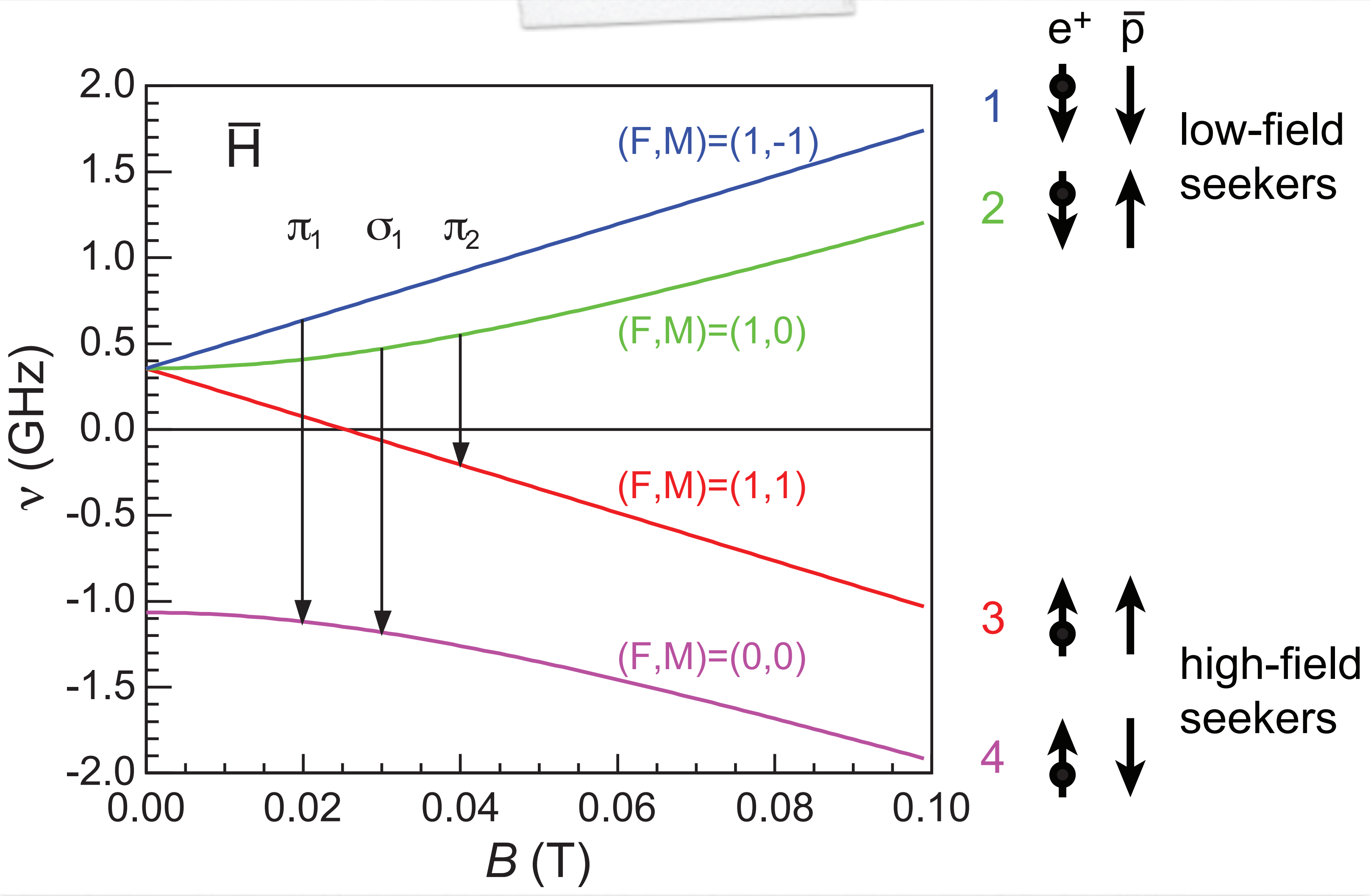
Measurement of the $\overline{\mathrm{H}}$ GS-HFS

- Highest precision for hydrogen: 10^{-12} with hydrogen maser
- But: maser is not possible for antihydrogen
- Spectroscopy with trapped antihydrogen: low precision due to strong confining field
- Good candidate: atomic beam with RF resonance
    - no $\overline{\mathrm{H}}$ trapping needed → no need for ultra-cold (< 1 K) $\overline{\mathrm{H}}$
    - atomic beam method can work up to 50-100 K
    - $\overline{\mathrm{H}}$ atoms can be guided with inhomogeneous magnetic field
- Measurement at the Antiproton Decelerator (AD) of CERN from ~2011

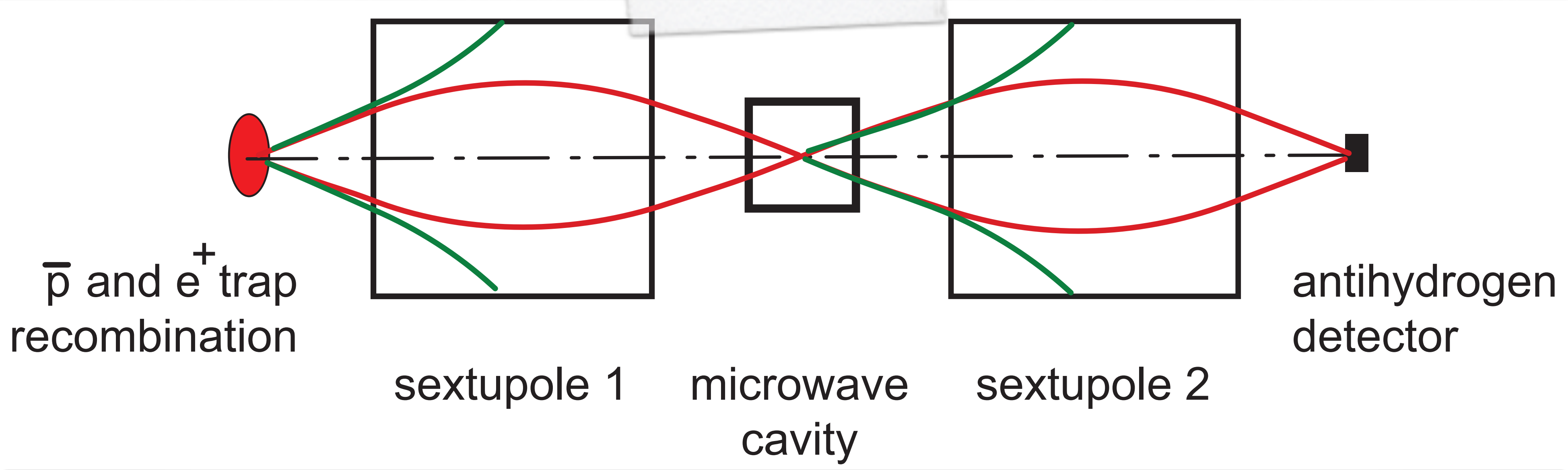
Ground-state antihydrogen in magnetic field

Energies of hyperfine states change in magnetic field:

- Increase for $(F, M) = (1, -1)$ and $(1, 0)$: low-field seekers ($\mu < 0$)
- Decrease for $(F, M) = (1, 1)$ and $(0, 0)$: high-field seekers ($\mu > 0$)



Measurement principle

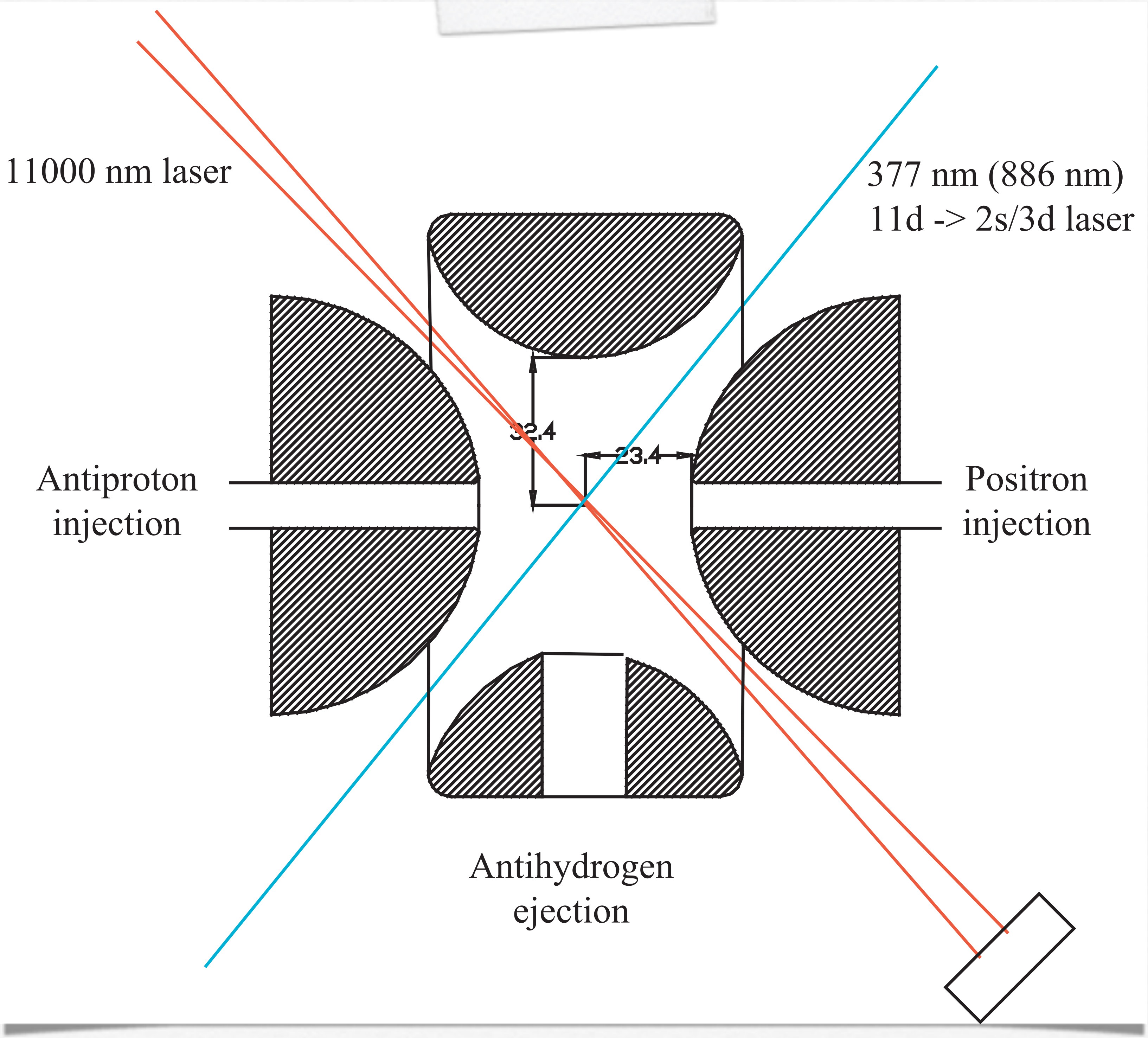


- $\bar{H}$ atoms from superconducting Paul trap
- Sextupole #1 polarizes beam: only low-field seekers pass through; high-field seekers are defocused
- Radio frequency resonator at 1.42 GHz to flip the e^+ spin
    - Conversion from low-field seeker to high-field seeker
- Sextupole #2 analyzes spin: only low-field seekers pass through
- Counts in antihydrogen detector will vary with RF frequency

Antihydrogen source

- “Conventional” way to make antihydrogen: nested Penning trap
  - Source too large for atomic beam method
  - Laser access is difficult
  - Too small extraction solid angle
- Superconducting two-frequency Paul trap
  - 2 superimposed RF fields to confine e^+ and $\bar{p}$
  - under development at CERN
- Cusp trap (anti-Helmholtz coils)
  - larger source size, but could provide (partially) polarized $\bar{H}$ beam
  - developed at RIKEN, already working at CERN, but no $\bar{H}$ yet

Superconducting two-frequency Paul trap



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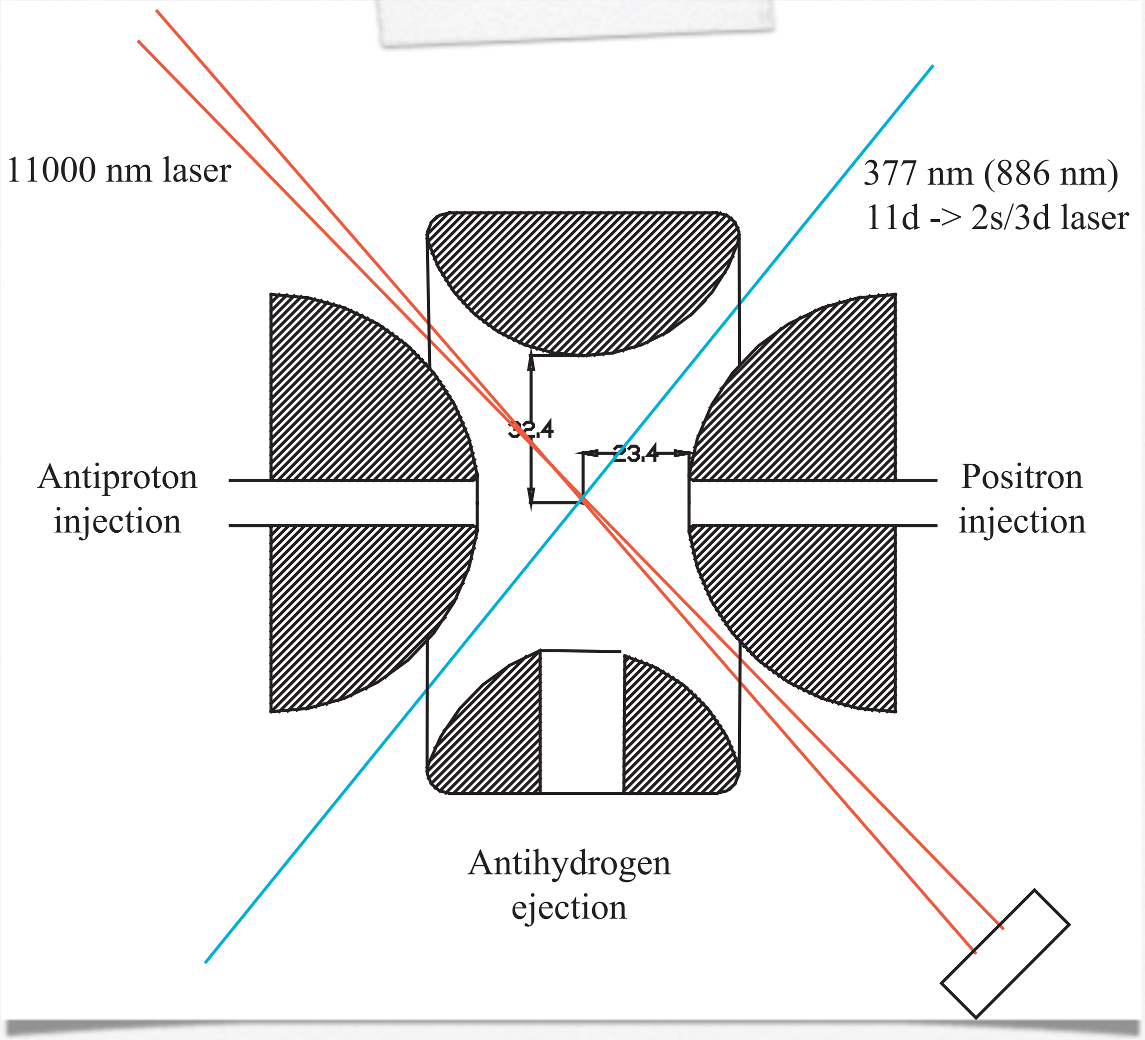
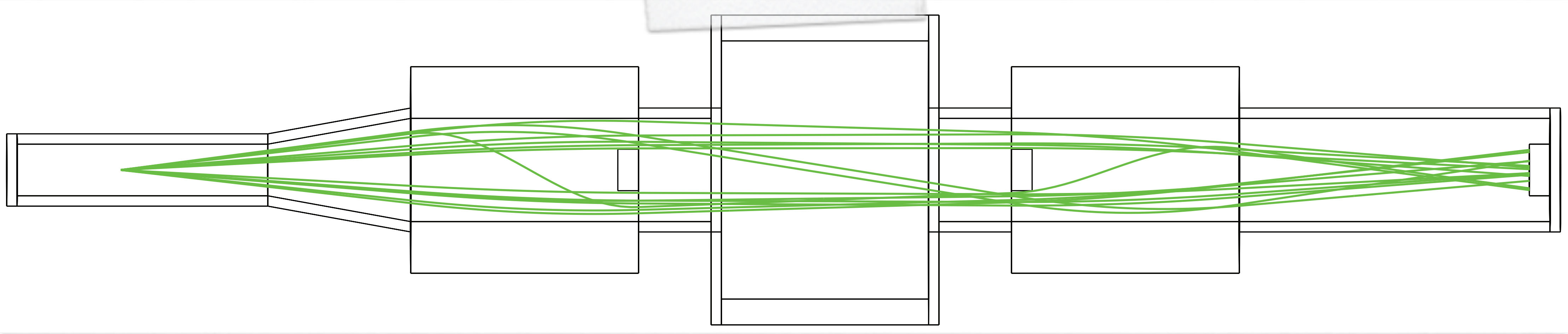


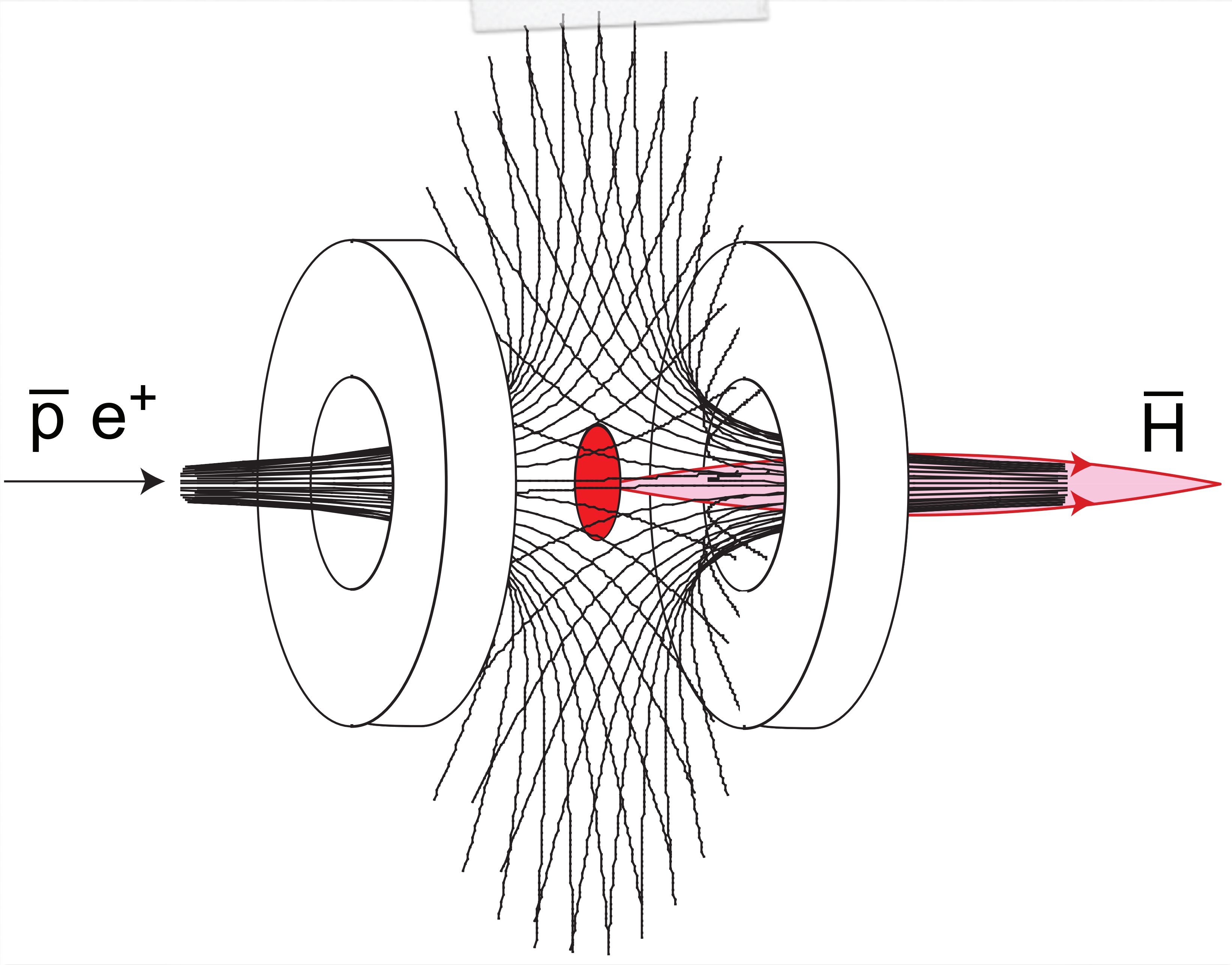
- Electrodes: 2 end caps, 1 ring
- e^+ from positron source,
  $\bar{p}$ from SC linear Paul trap
- RF: 350 MHz for e^+, 1 MHz for $\bar{p}$
- Laser-assisted de-excitation
- Good laser access
- Point-like $\bar{H}$ source
- Large $\bar{H}$ extraction solid angle
- Only 1s or 2s atoms are emitted
- Expected production rate:
  ~200 $\bar{H}$/s

MC simulations with the Paul trap



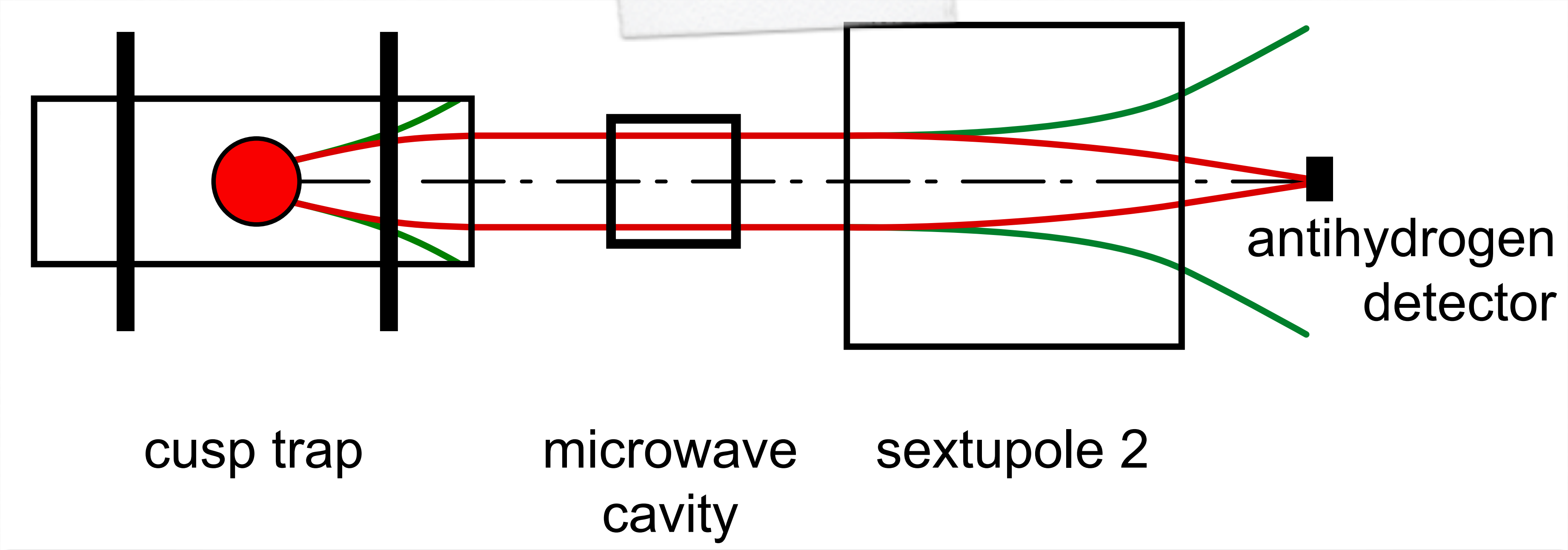
- Sextupole magnet parameters for 50 K $\bar{H}$:
  - internal diameter: 10 cm
  - field at the inner wall: 3 tesla
  - effective length (field FWHM): 22 cm
- Superconducting magnet is the best solution
- Total beam line length: ~150 cm
- Total efficiency: ~10^{-3}
- Expected count rate: ~10 $\bar{H}$/min

Measurement principle with the cusp trap



- Expected production rate: ~10^5 $\bar{H}$/s

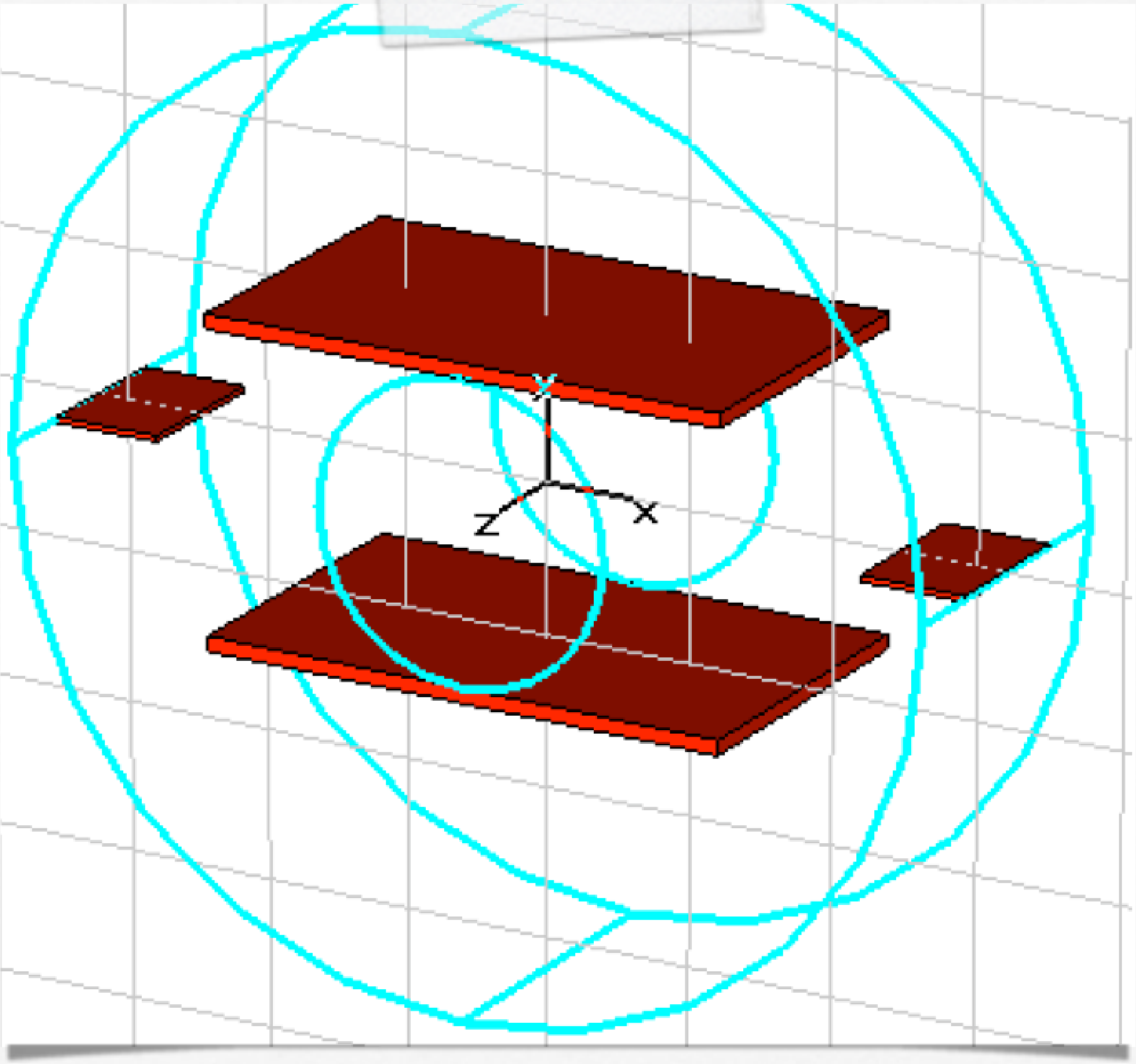
Measurement principle with the cusp trap



- ☐ Inhomogeneous field can focus low-field seekers, while it can defocus high-field seekers
- ☐ Rest of the system is the same as with the Paul trap
- ☐ Many unknowns
  - ☐ Temperature (5 K?) - “magnetically induced radiative cooling”
  - ☐ Polarization degree (4:1?) - depends on *T*
  - ☐ Fraction of ground-state atoms
  - ☐ Ground-state low-field seekers might be trapped forever?

Radiofrequency resonator

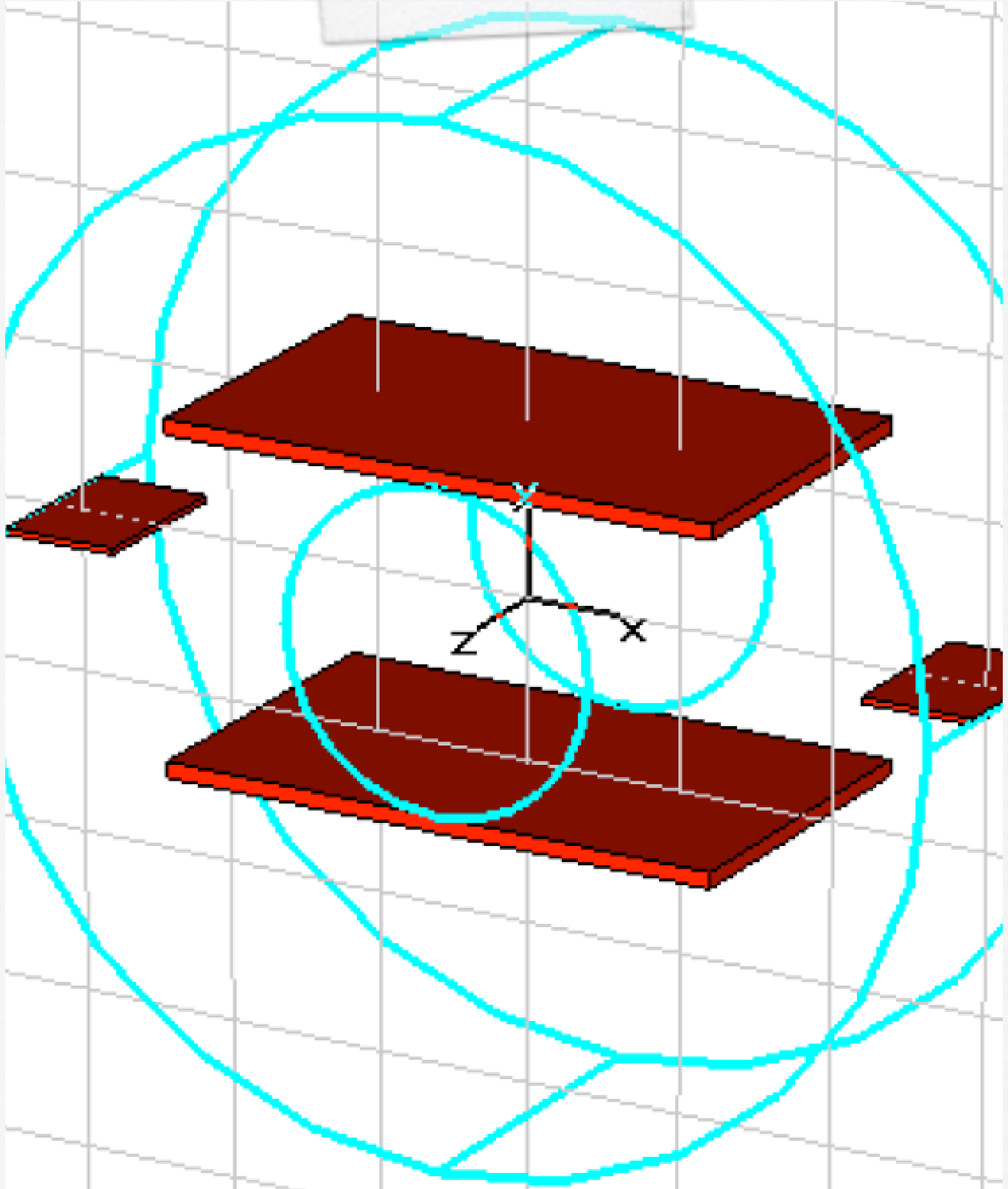
- Ideal resonator would have a perfect *B*-field homogeneity in *X*-*Y*-*Z*
  - But: volume size is comparable to half-wavelength → perfect homogeneity is impossible
- Preferred solution: double stripline resonator



by Tom Kroyer, CERN

Radiofrequency resonator

- Meshes on the front & back planes
- Stripline length in *Z*: λ/2, λ, 3λ/2, ...
- Width & stripline distance: arbitrary
- Low Q (500-1000)
  - Frequency can be changed by 1-2 MHz without external tuning
- Homogeneity in *X*-*Y* plane is quite good
- Longitudinal: *B* ~ sin(*Z*)
  - Zero field at the center plane
  - Front & back halves of the resonator are in opposite phase
  - Their effects cancel each other when $\nu_{\text{field}} = \nu_{\text{HF}}$ independently of velocity



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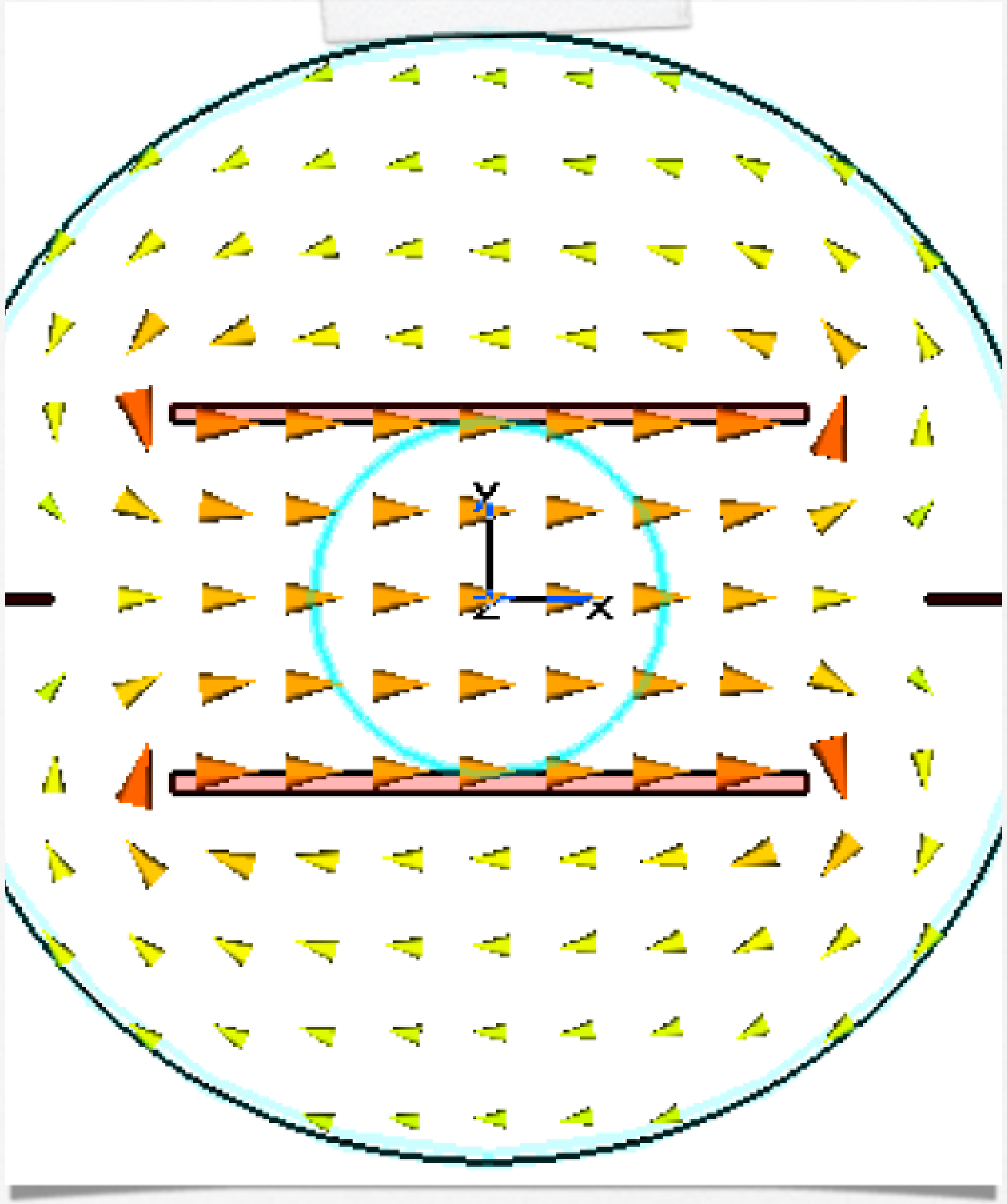

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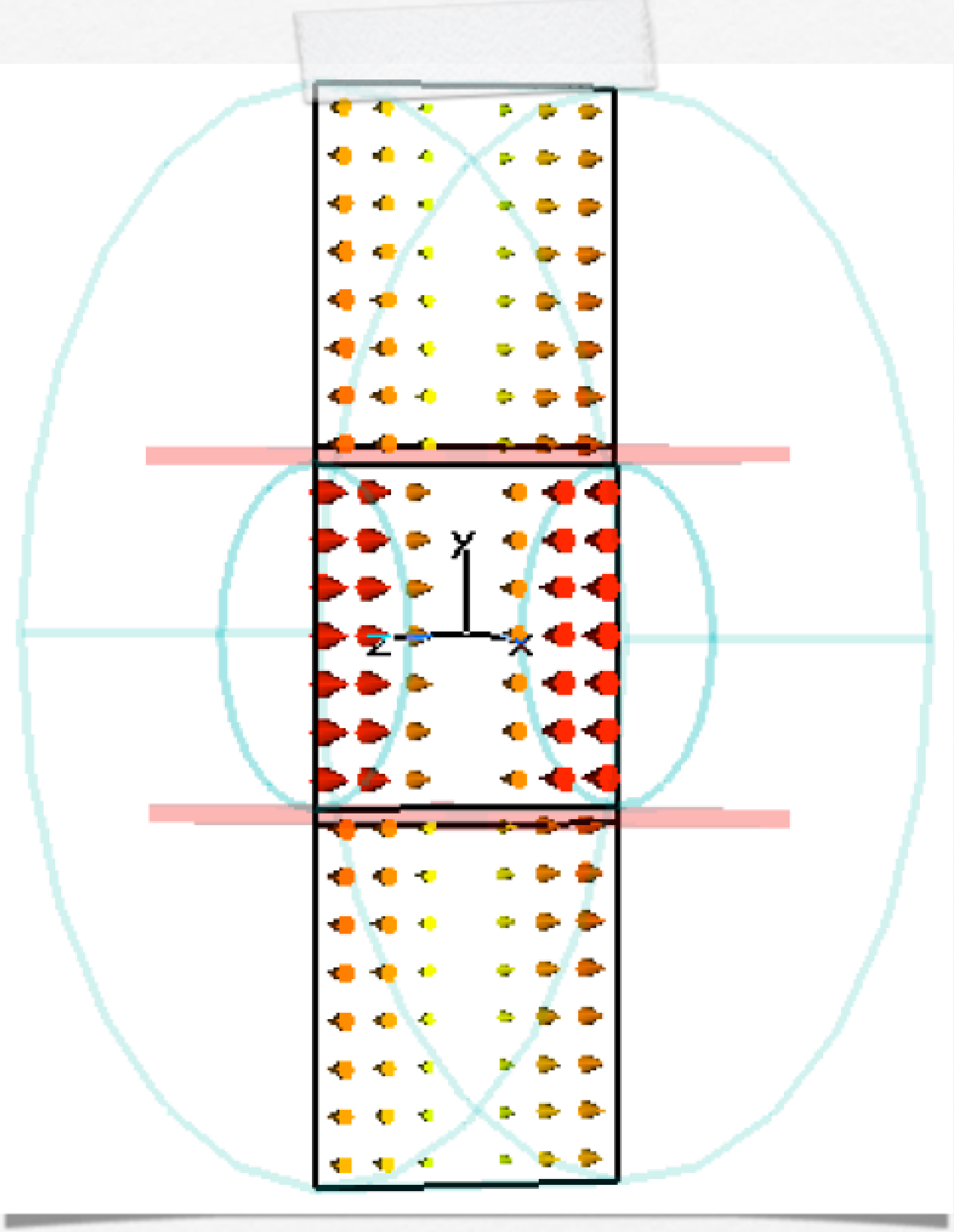

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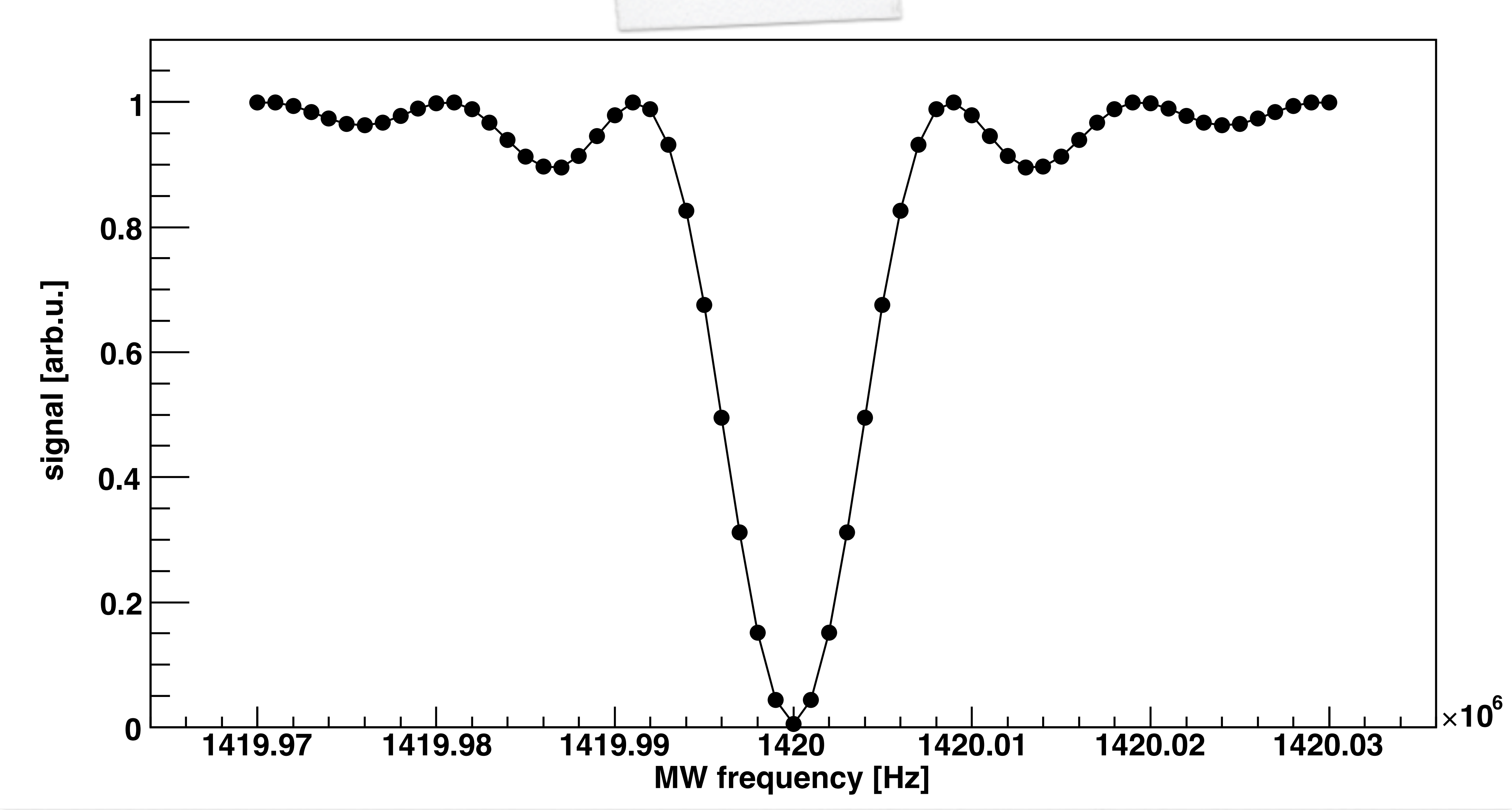
Resonance profile

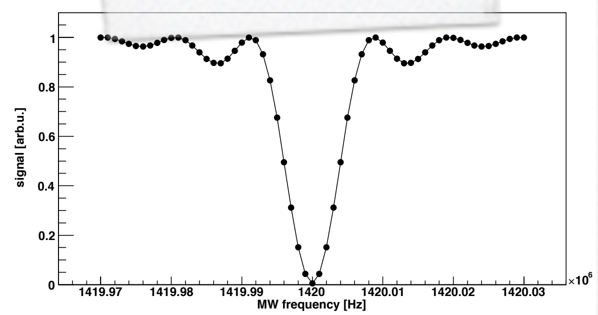
Resonance profile

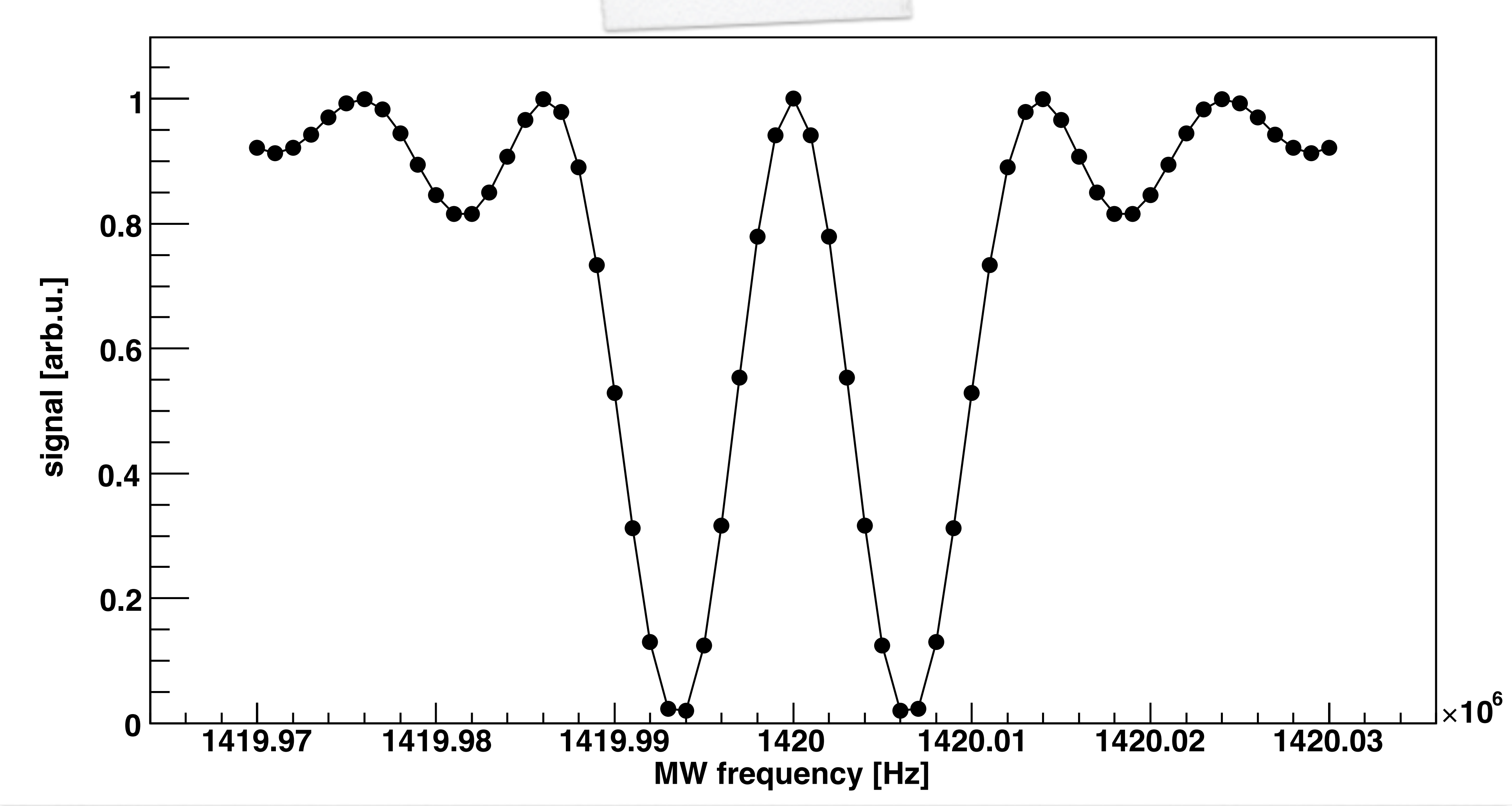
- ☐ Ideal profile with (non-existing) ideal RF field



Resonance profile

- ☐ Ideal profile with (non-existing) ideal RF field
- ☐ Ideal profile with double stripline resonator





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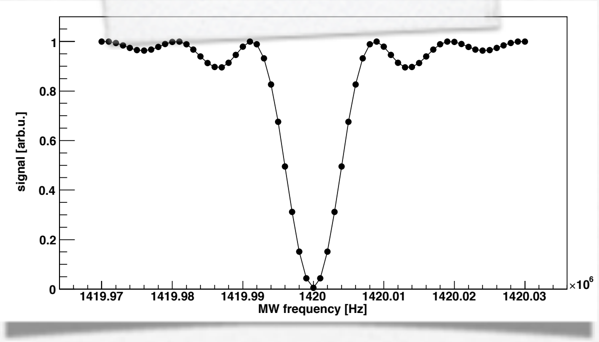
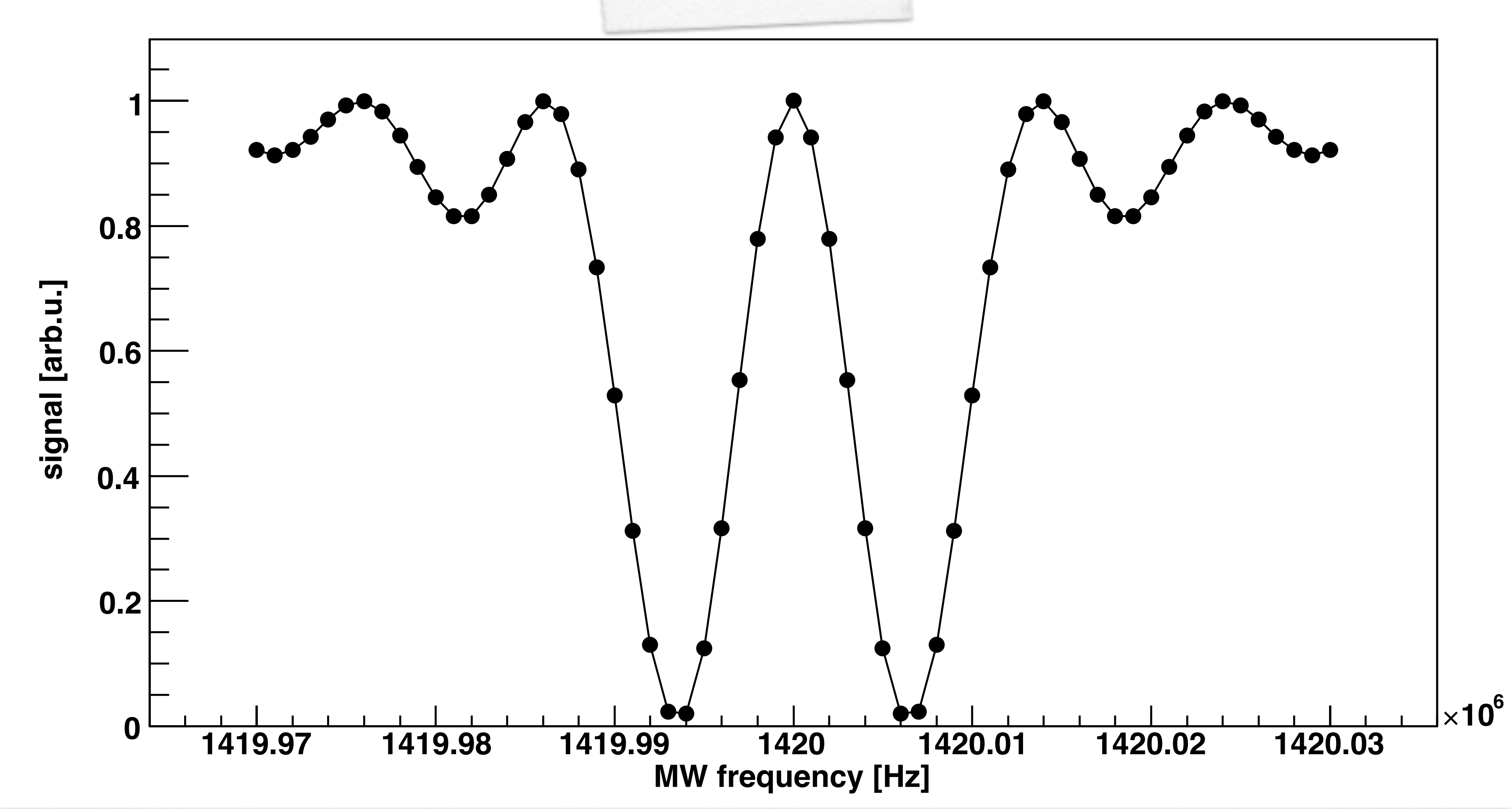
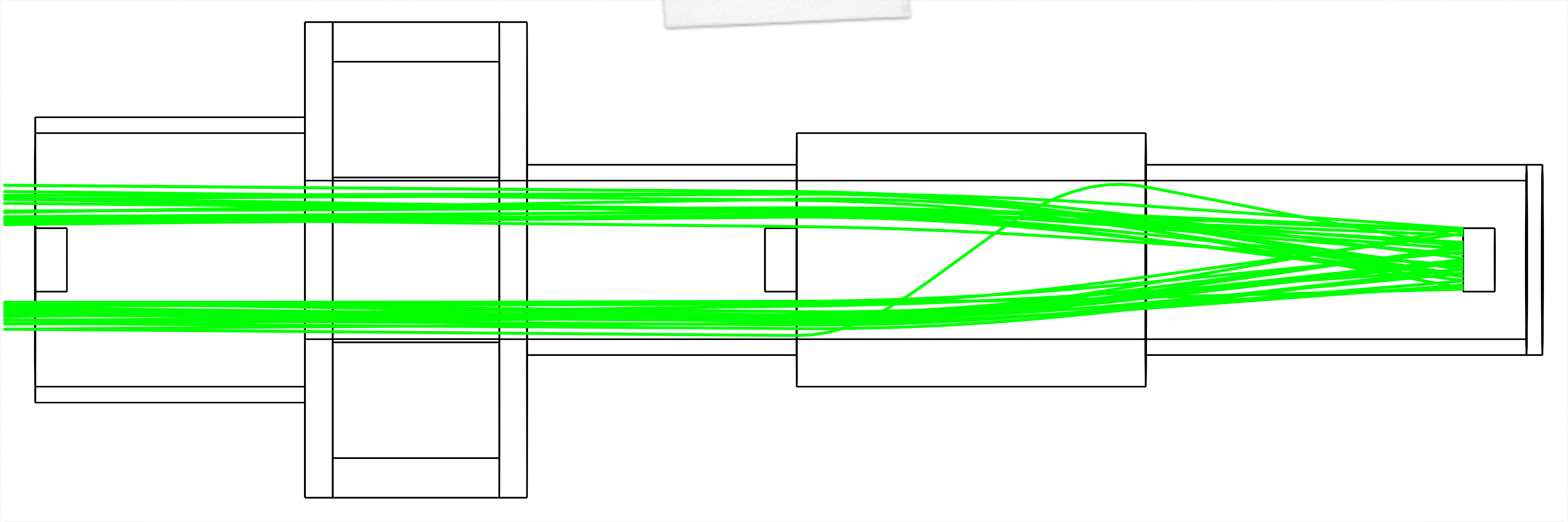




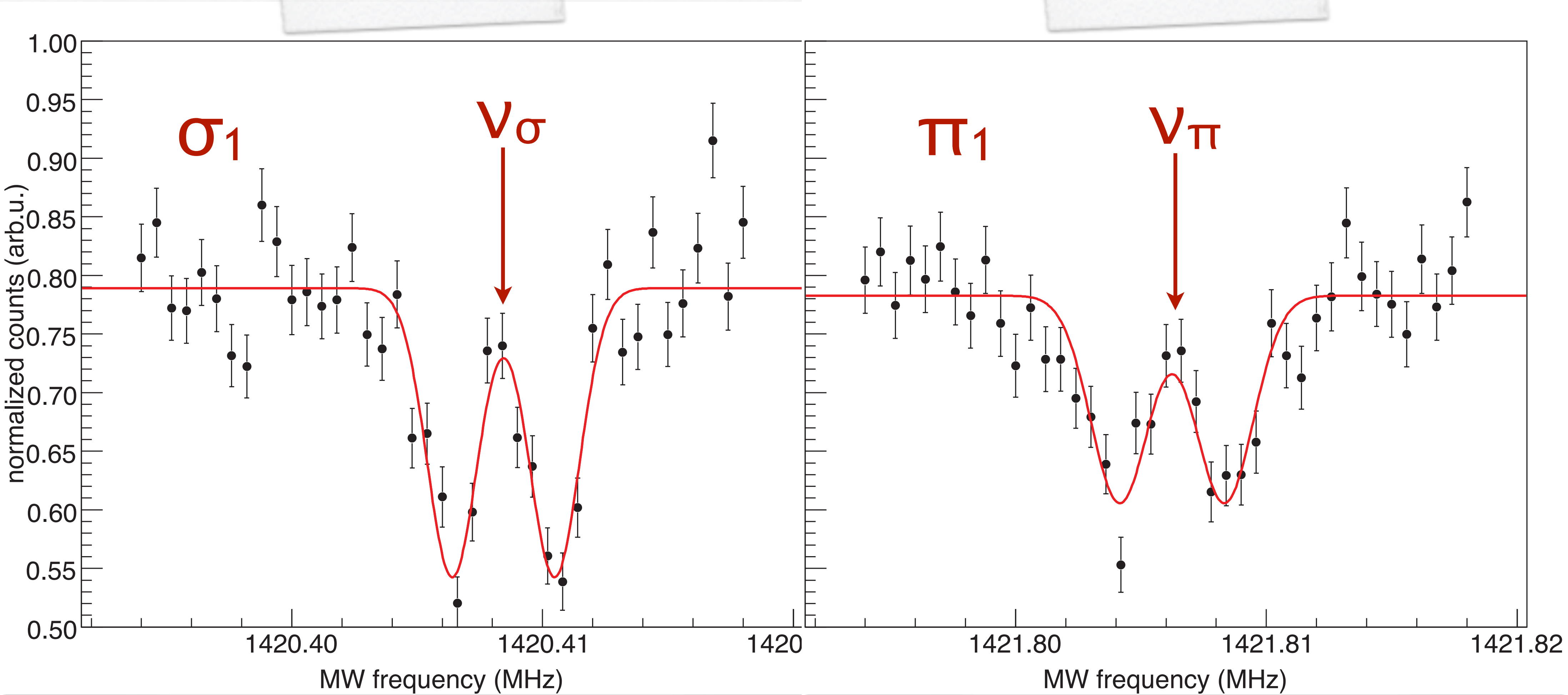
- Splitting is essentially Doppler splitting → proportional to velocity

MC simulations with the cusp trap



- Same superconducting magnet as for the Paul trap
- Total efficiency: ~10^{-5}
- Expected count rate: ~100 $\bar{H}$/min

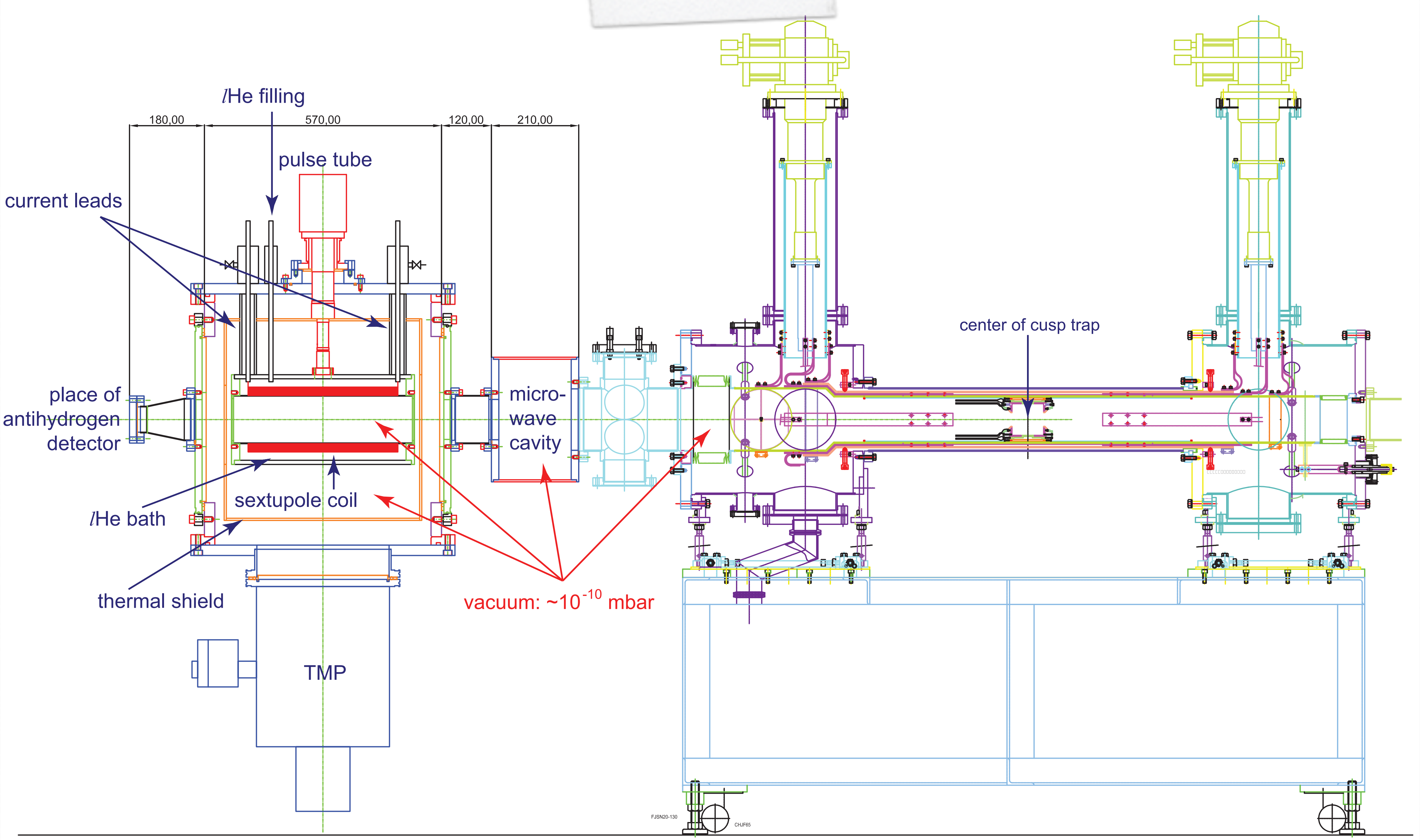
Simulated resonance profiles



- $B_0 = 1$ G ± 0.5 mG, $T = 5$ K
- ν_σ & $\nu_\pi \rightarrow \nu_{HF}$
- $\Delta\nu_{HF} \simeq$ 210 Hz → $\Delta\nu_{HF}/\nu_{HF} \simeq 1.5\times10^{-7}$

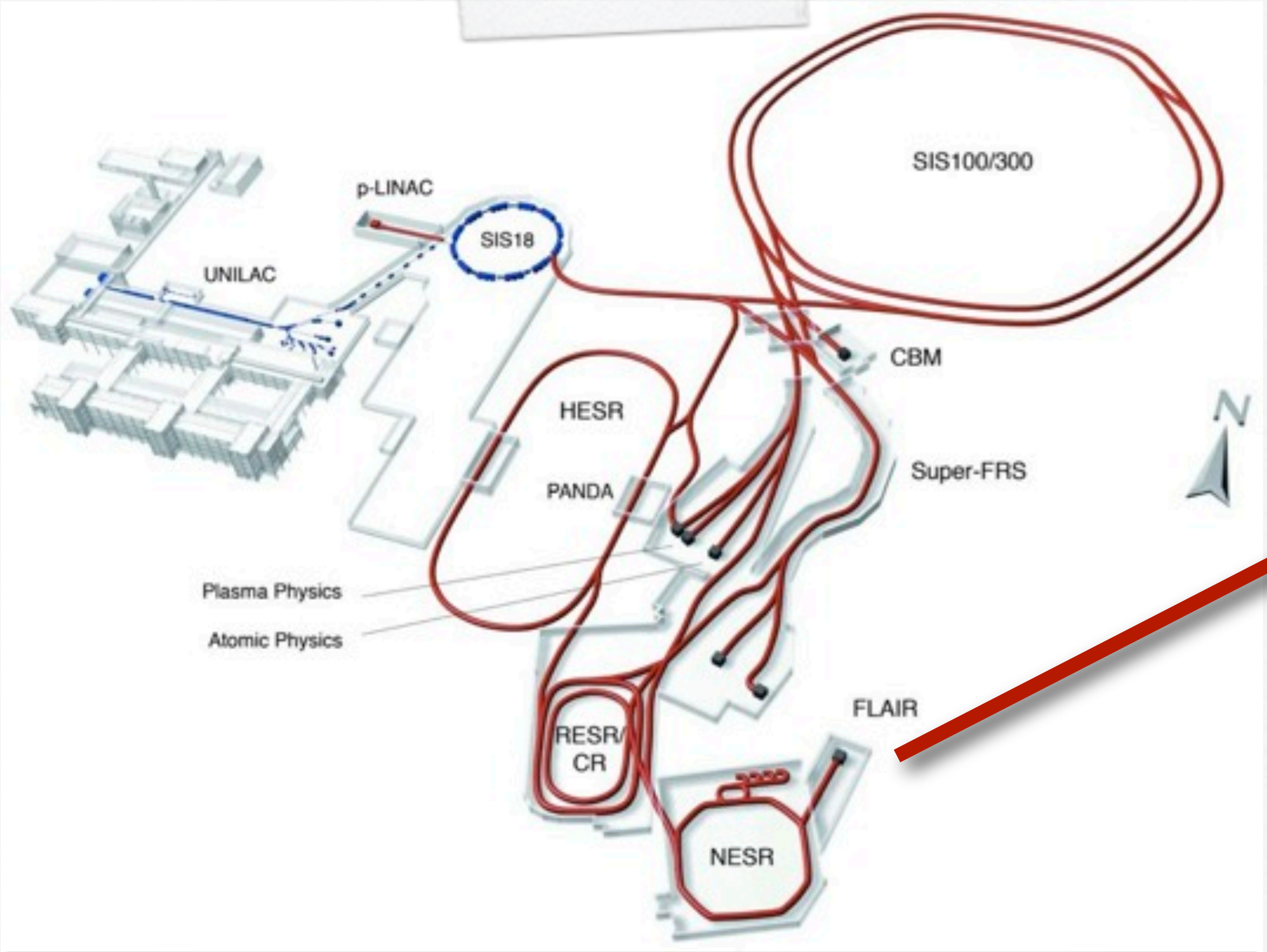
Cusp trap with the sextupole beam line

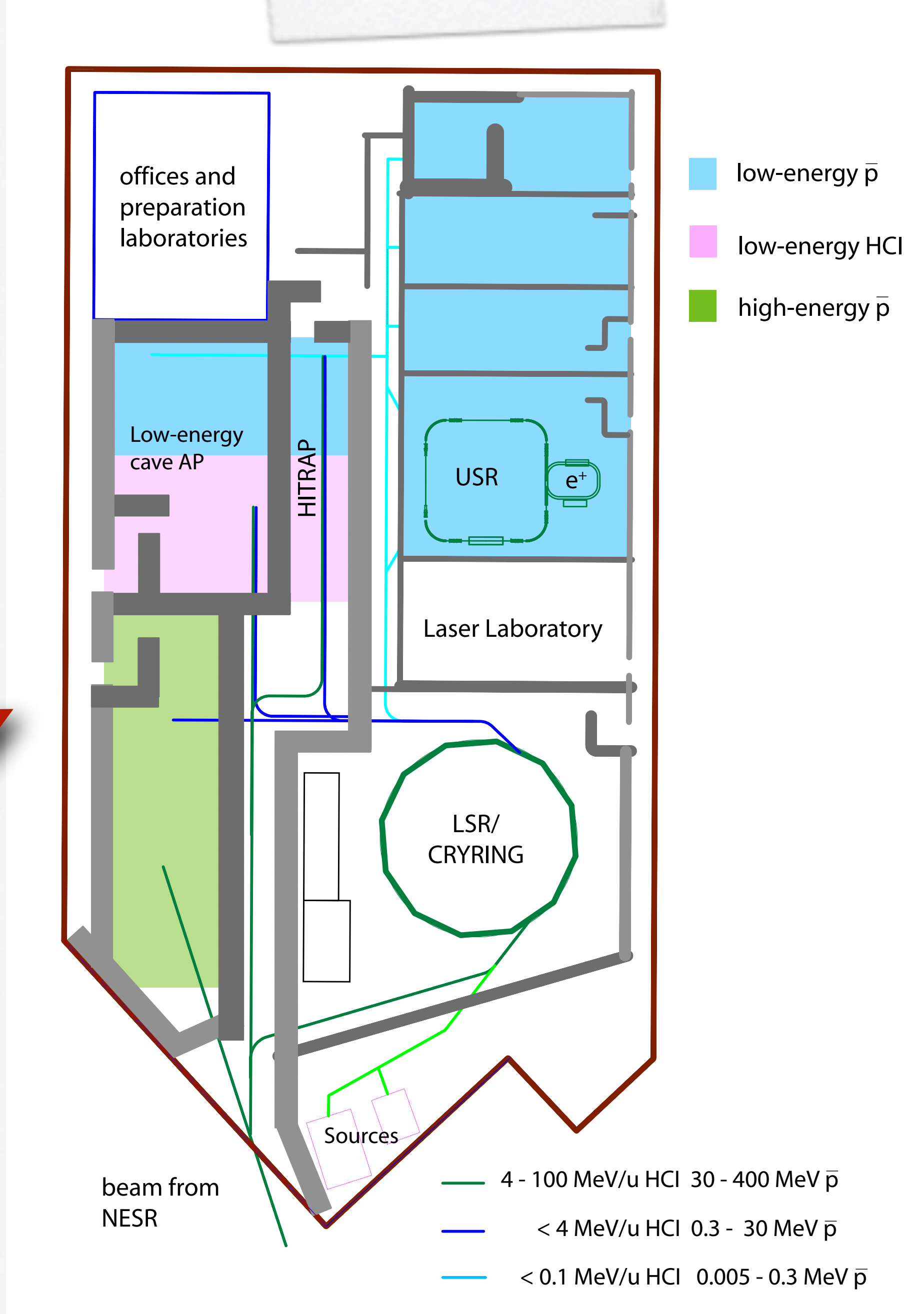
- Preliminary design



Future at FLAIR

Facility for Low-energy Antiproton and Ion Research





Future at FLAIR

- FLAIR is significantly better than AD/ELENA:
  - Higher intensity (factor 10-100)
  - Lower energy (5 keV vs. 100 keV)
  - Slow extraction
- Same GS-HFS measurement can be continued at FLAIR, or
- New measurement methods could be tried:
  - Ramsey's separated oscillatory field (narrower resonance line, less sensitivity to magnetic field inhomogeneities)
  - Circulating antihydrogen beam?

Summary

- Ground-state hyperfine splitting of antihydrogen is a good candidate to test CPT violation effects
- Kostelecký *et al.*: not relative but absolute precision matters
- Measurement: atomic beam method
- $\overline{\mathrm{H}}$ source: cusp trap (soon) & Paul trap (later)
- 1(+1) superconducting sextupole(s), 1 RF resonator
- Expected count rate with cusp trap: ~100 $\overline{\mathrm{H}}$/min
- Expected precision: ~10^{-7}; ~0.2 kHz = ~10^{-12} eV
  3 orders of magnitude better than the K^0-$\overline{K}^0$ mass comparison
- First measurements at the AD @ CERN, later at FLAIR @ FAIR