HHHFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

Measurement of the HYPERFINE STRUCTURE of ANTIHYDROGEN in a beam

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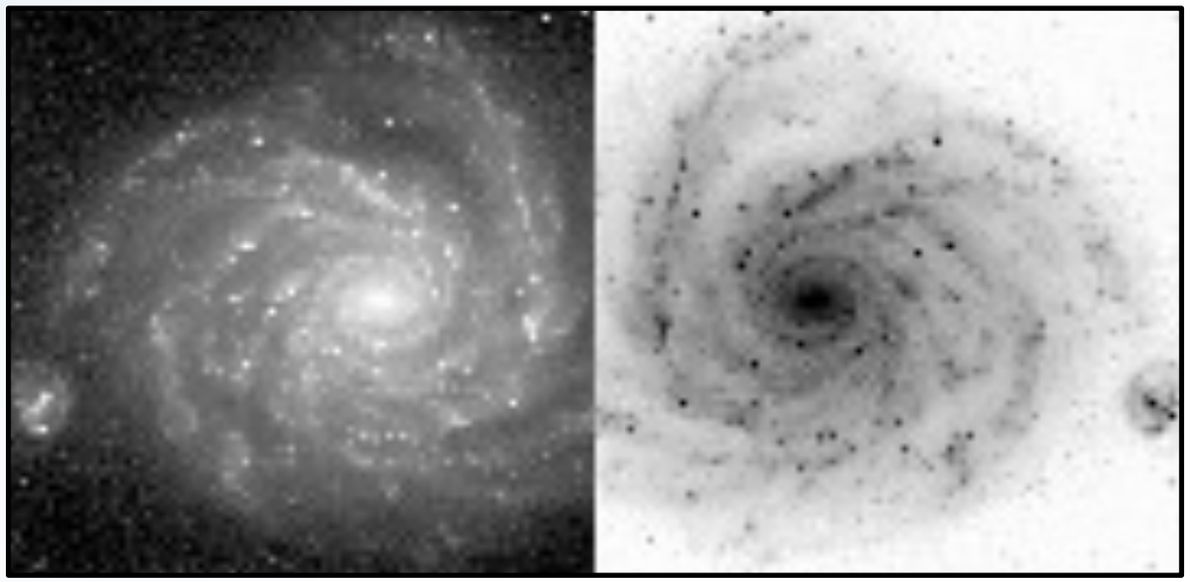
STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS, VIENNA

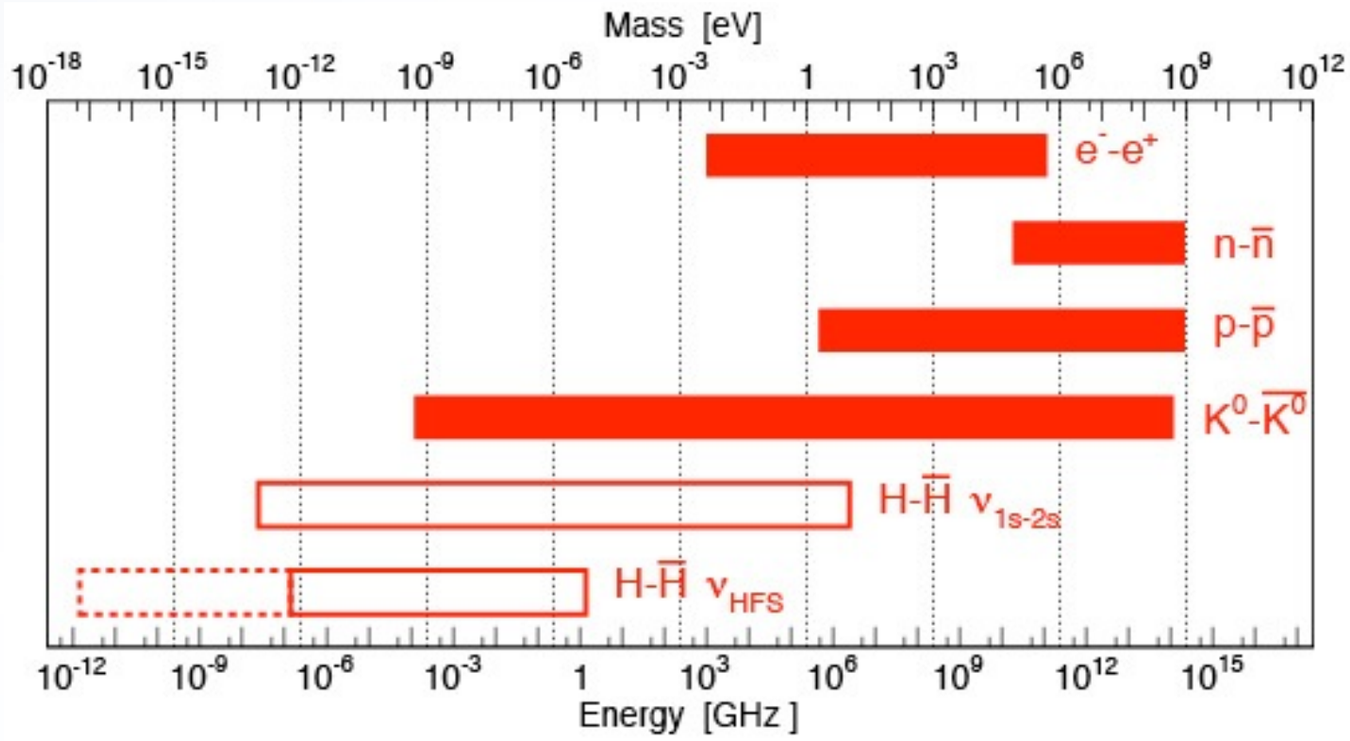
QFFP WORKSHOP CERN

08.05.2014

MATTER-ANTIMATTER SYMMETRY

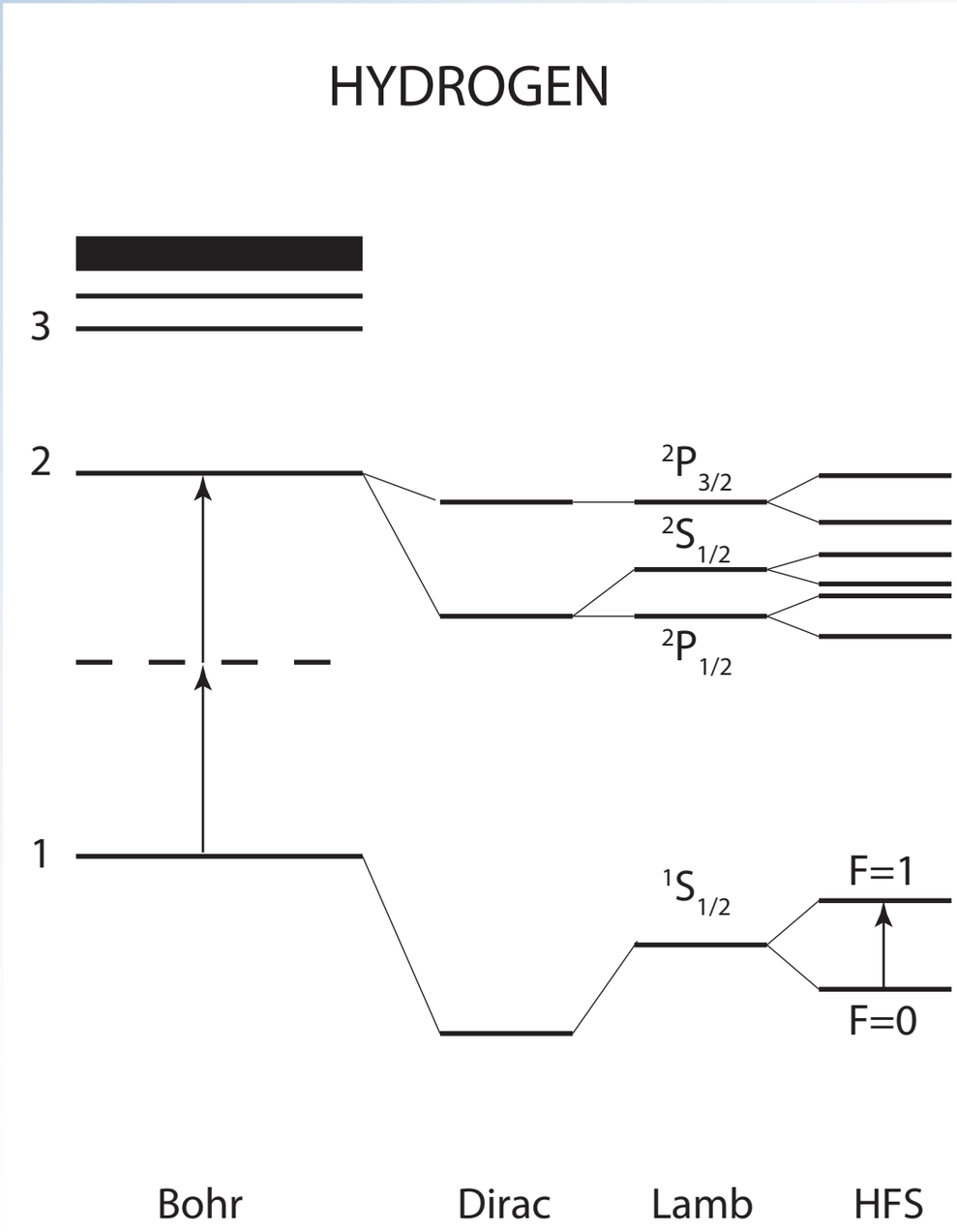
- COSMOLOGICAL SCALE:
  - asymmetry

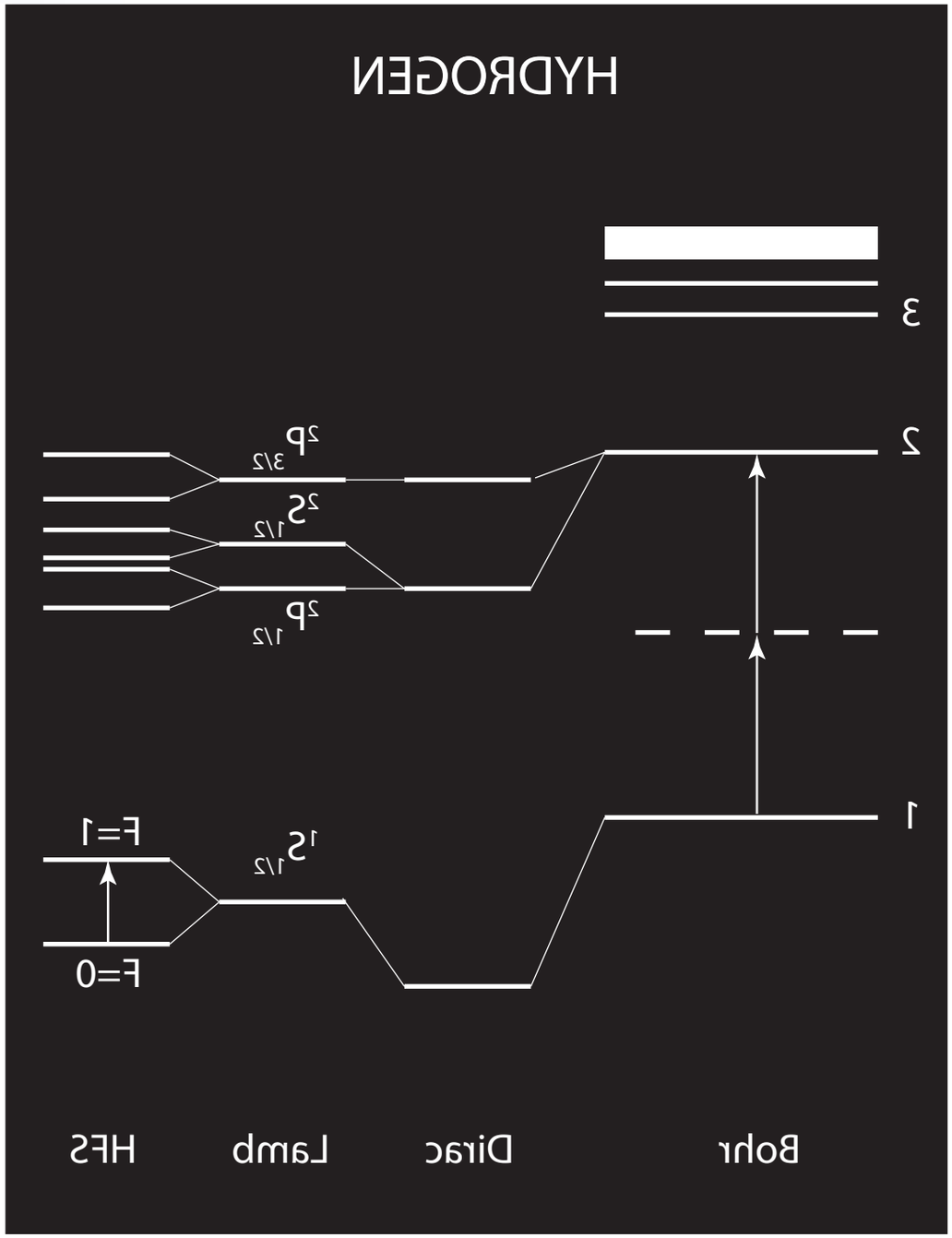




- CPT
  - Microscopic: symmetry?

ANTIHYDROGEN SPECTROSCOPY





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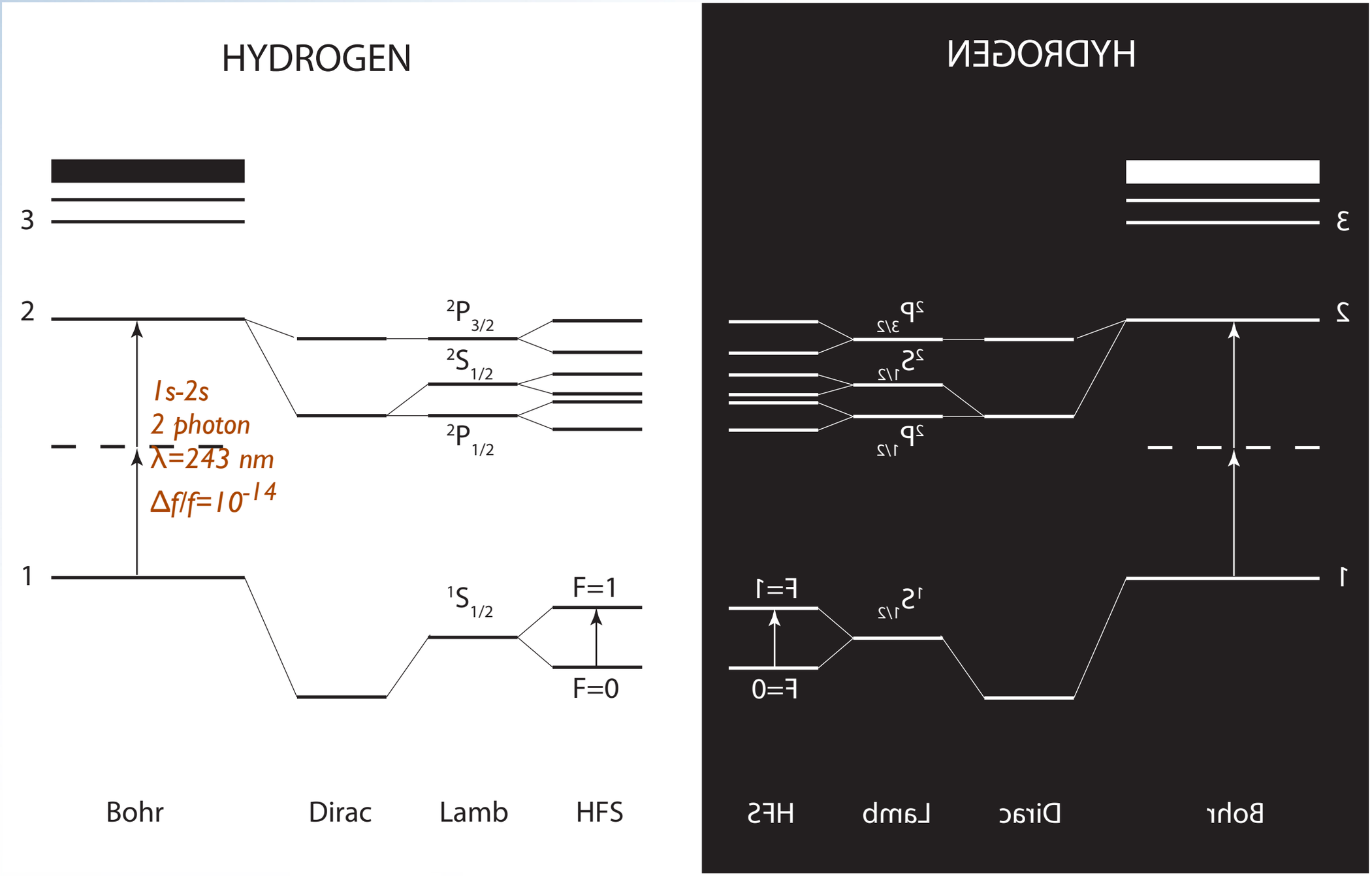

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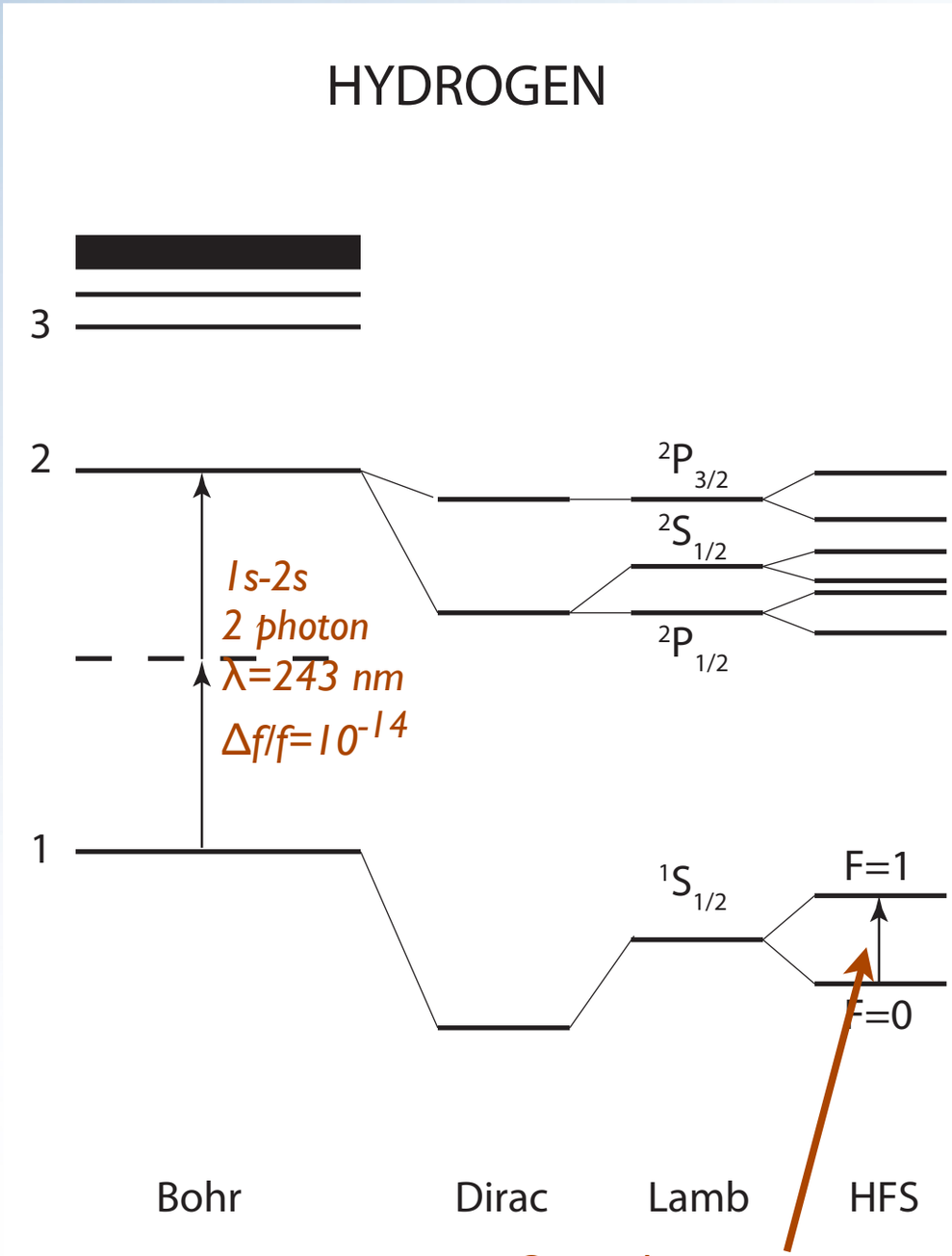
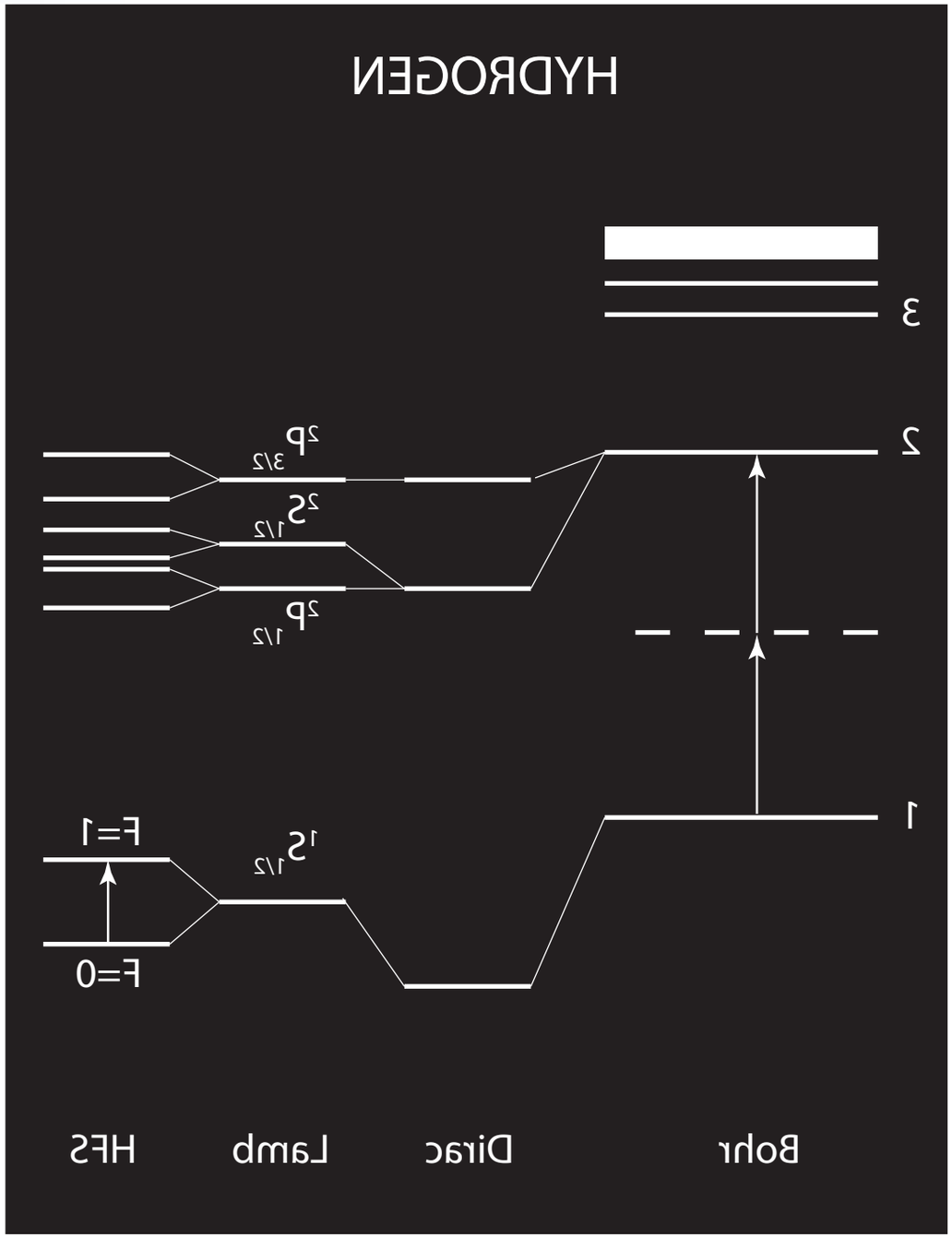
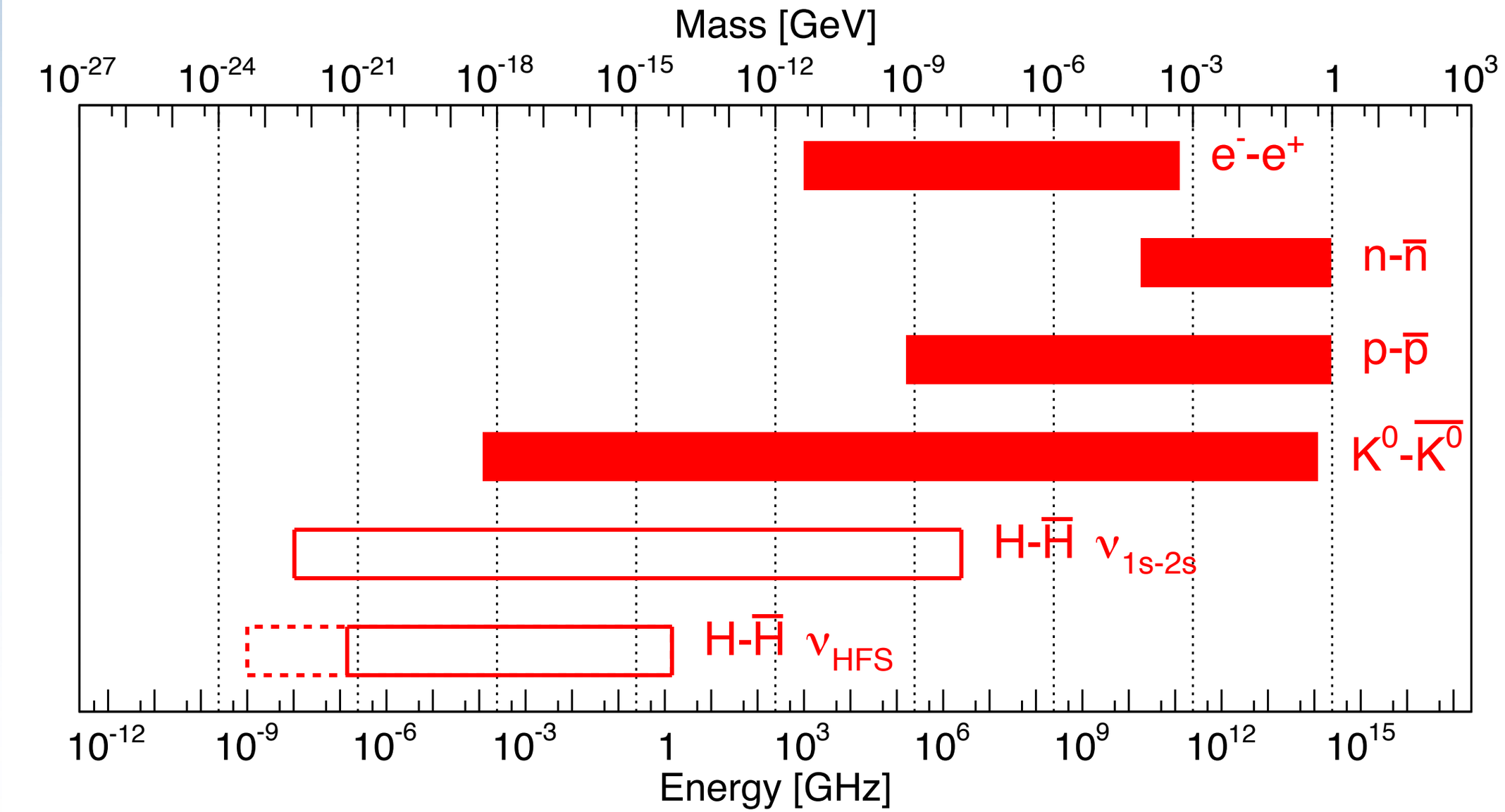




CPT TESTS - RELATIVE & ABSOLUTE PRECISION



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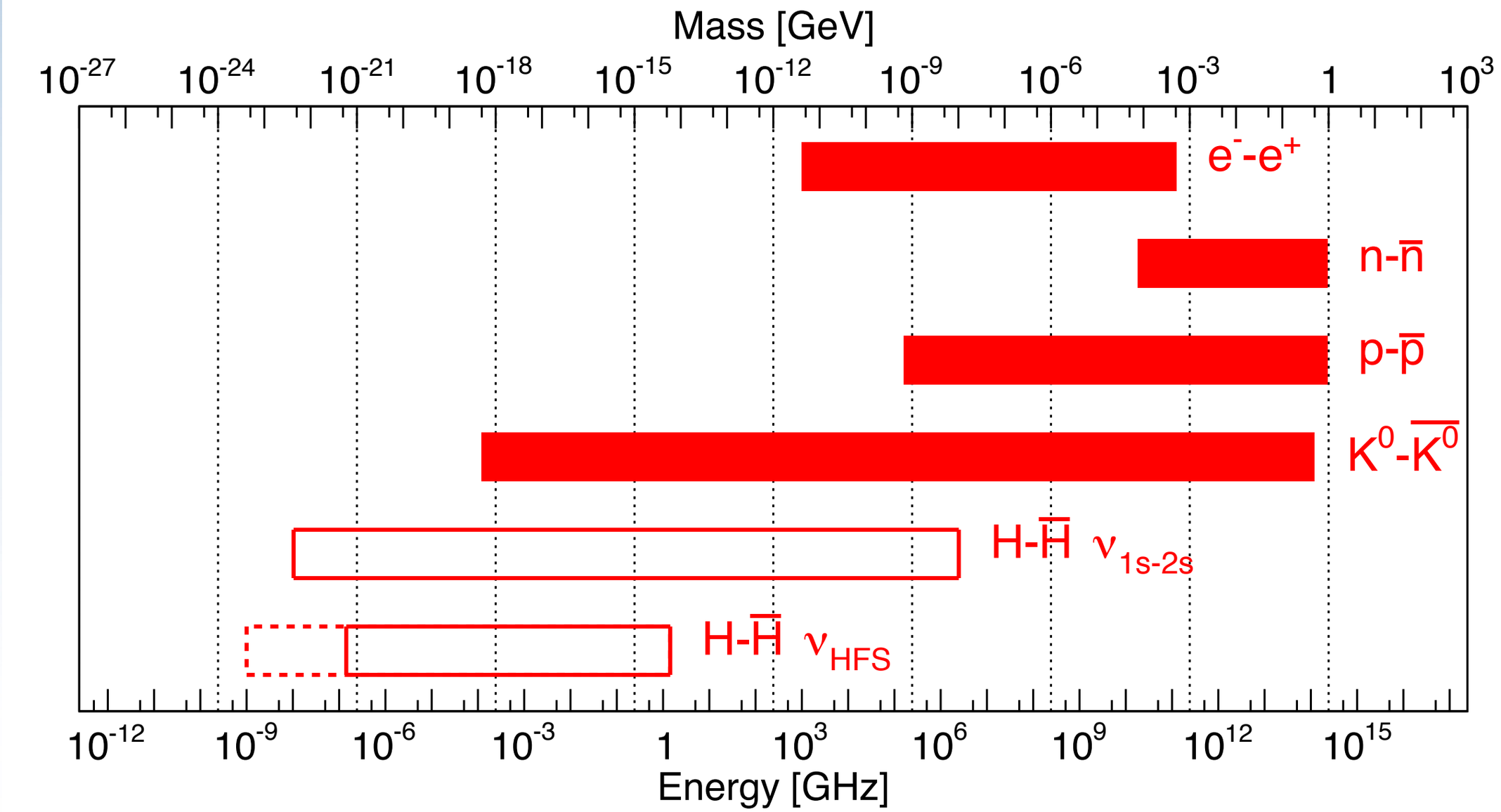

- ATOMIC PHYSICS EXPERIMENTS, ESPECIALLY ANTIHYDROGEN OFFER THE MOST SENSITIVE EXPERIMENTAL VERIFICATIONS OF CPT

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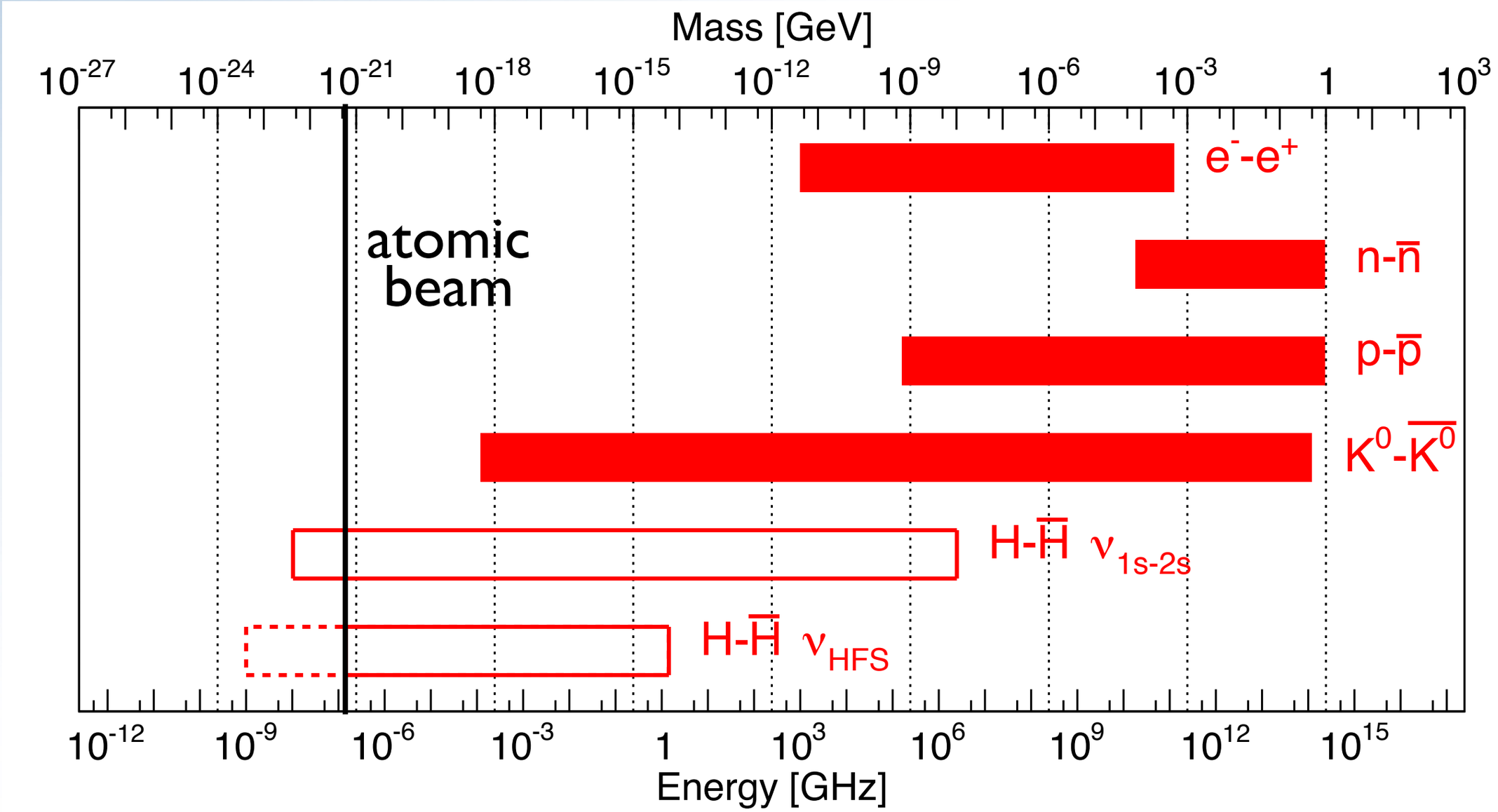

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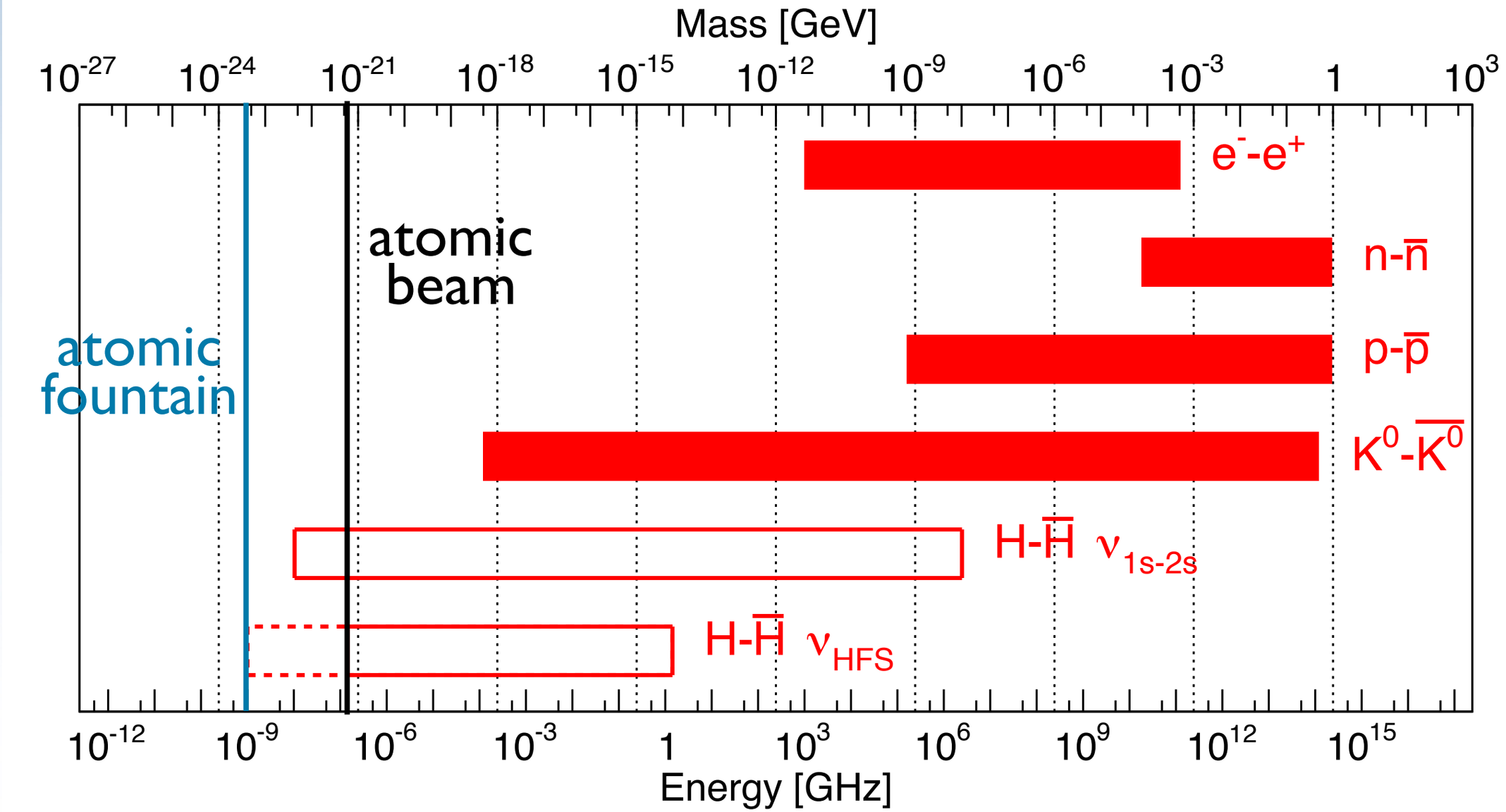

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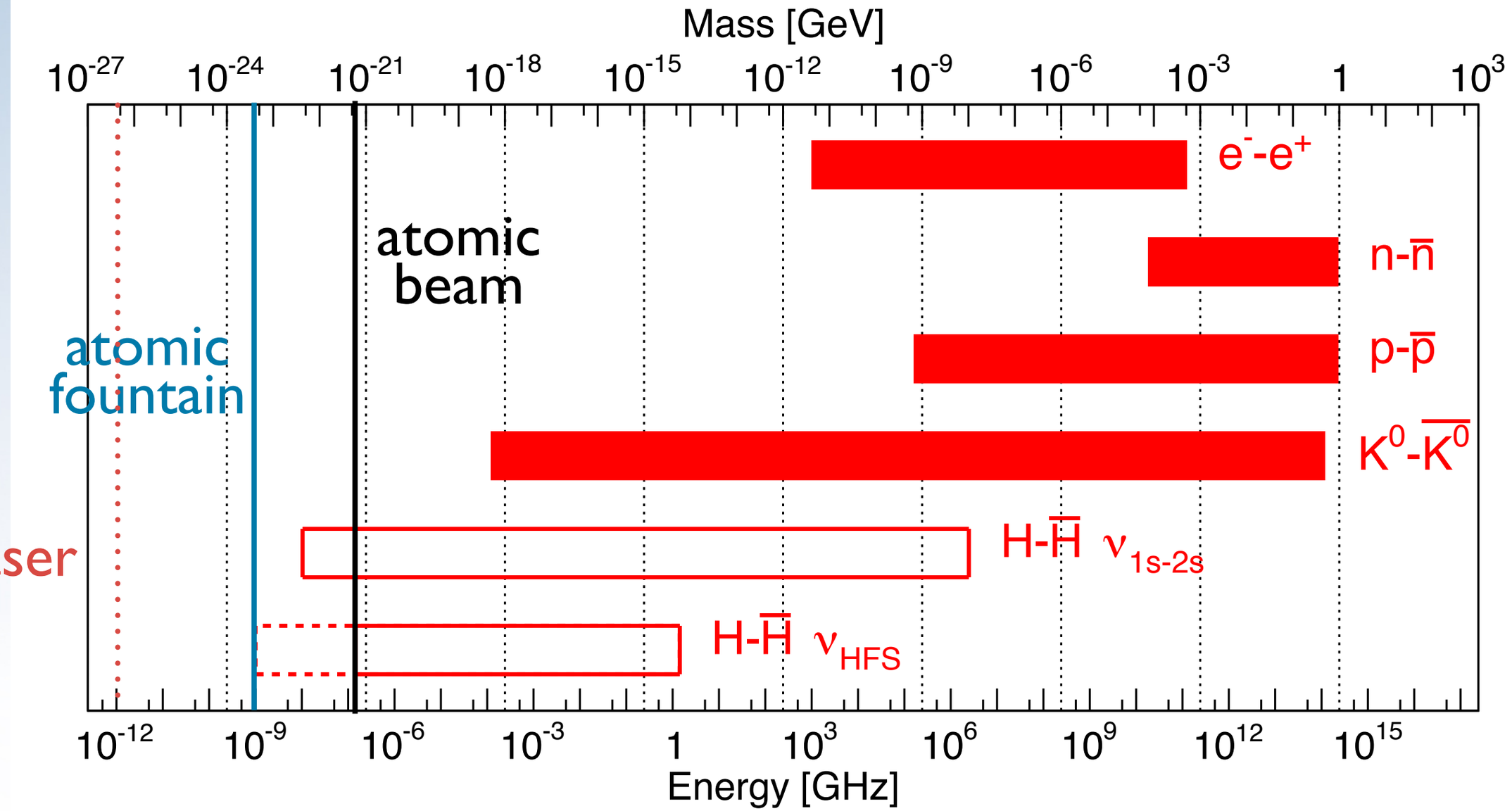

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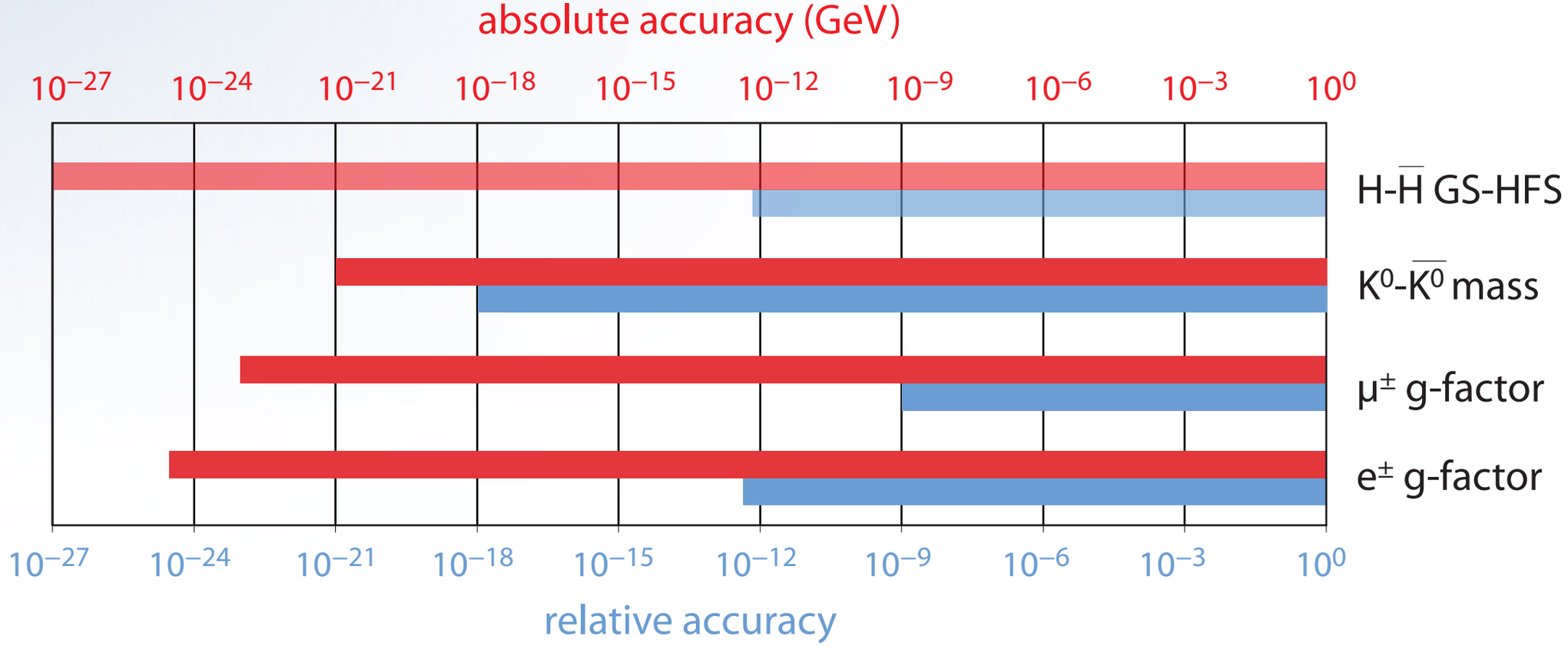
HFS and Standard Model Extension

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

CPT & Lorentz violation

Lorentz violation

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



no CPT effect on 1S-2S transition

allows to compare different quantities in different sectors

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

GROUND-STATE HYPERFINE SPLITTING OF H/$\bar{H}$

- SPIN-SPIN INTERACTION
  POSITRON - ANTIPROTON

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

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

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

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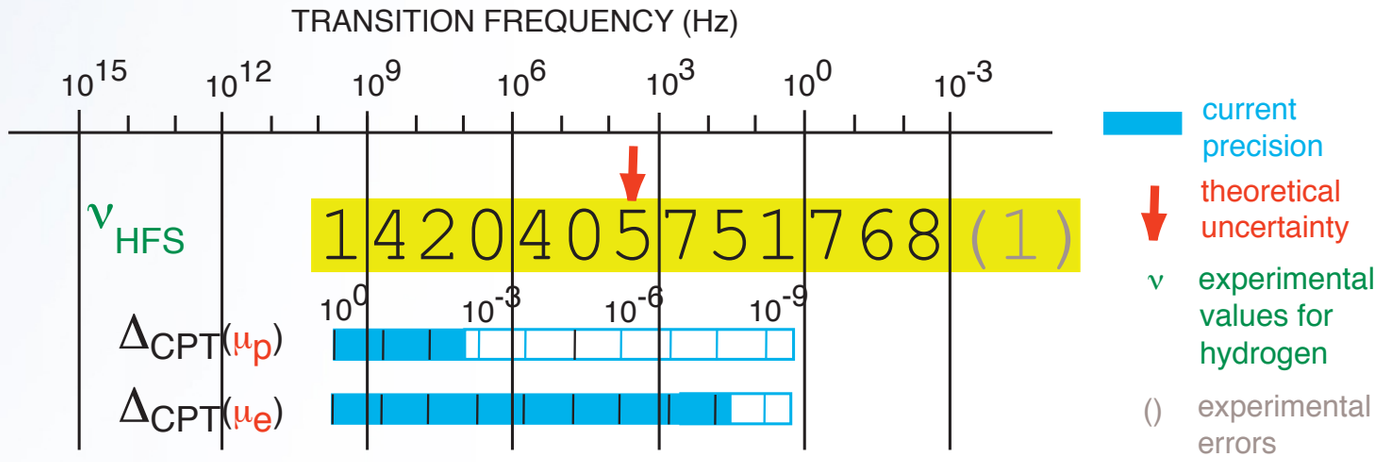

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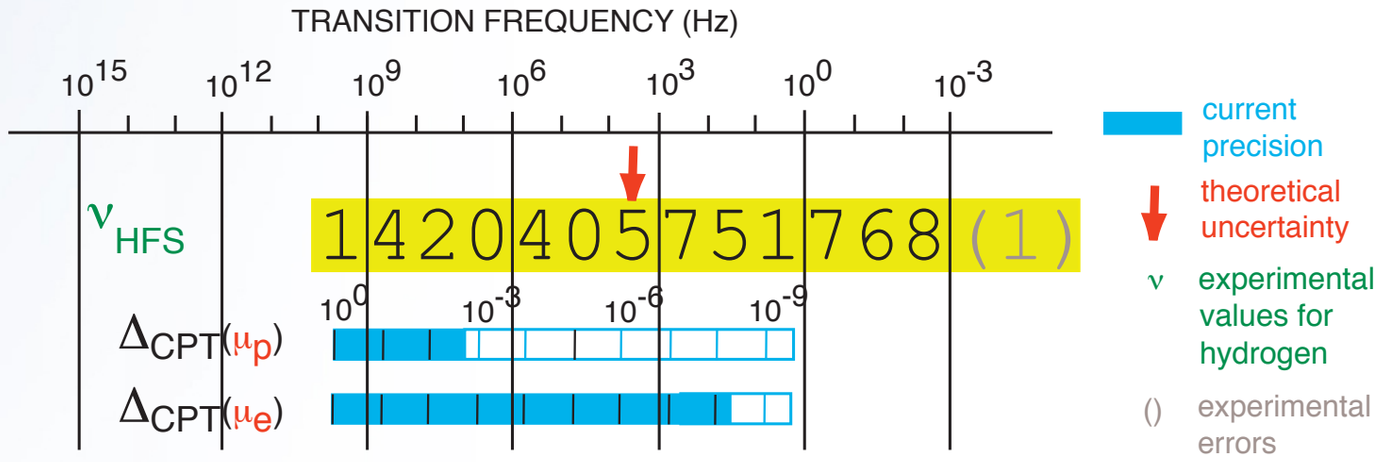

- magnetic moment of $\bar{p}$
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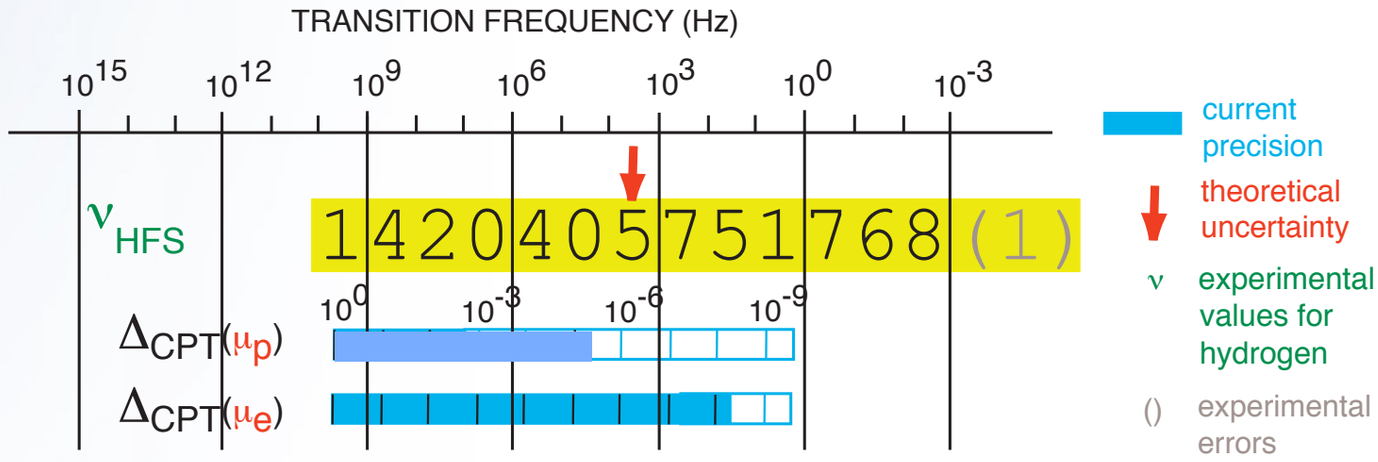

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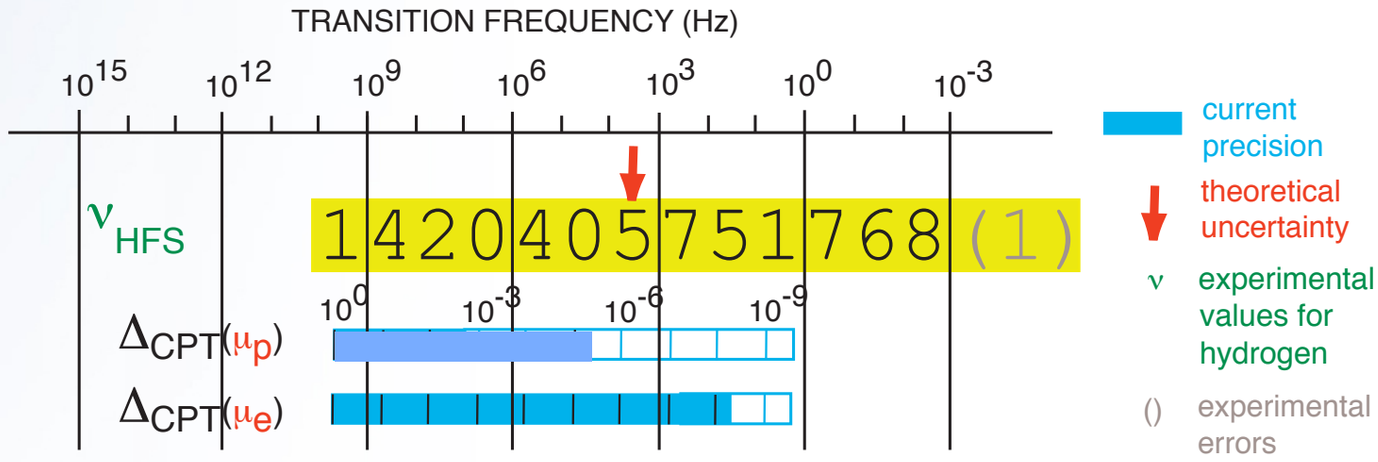


- magnetic moment of $\bar{p}$
  - previously known to 0.3%, 2012 Gabrielse Penning trap 4.4 ppm PRL 110,130801 (2013)
- H: deviation from Fermi contact term: ~ 32 ppm
  - finite electric & magnetic radius (Zemach corrections): 41 ppm
  - polarizability of p/$\bar{p}$: < 4 ppm
  - few ppm theoretical uncertainty remain

$$\Delta\nu(\mathrm{Zemach}) = \nu_\mathrm{F}\frac{2Z\alpha m_\mathrm{e}}{\pi^2}\int\frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

ASACUSA COLLABORATION

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

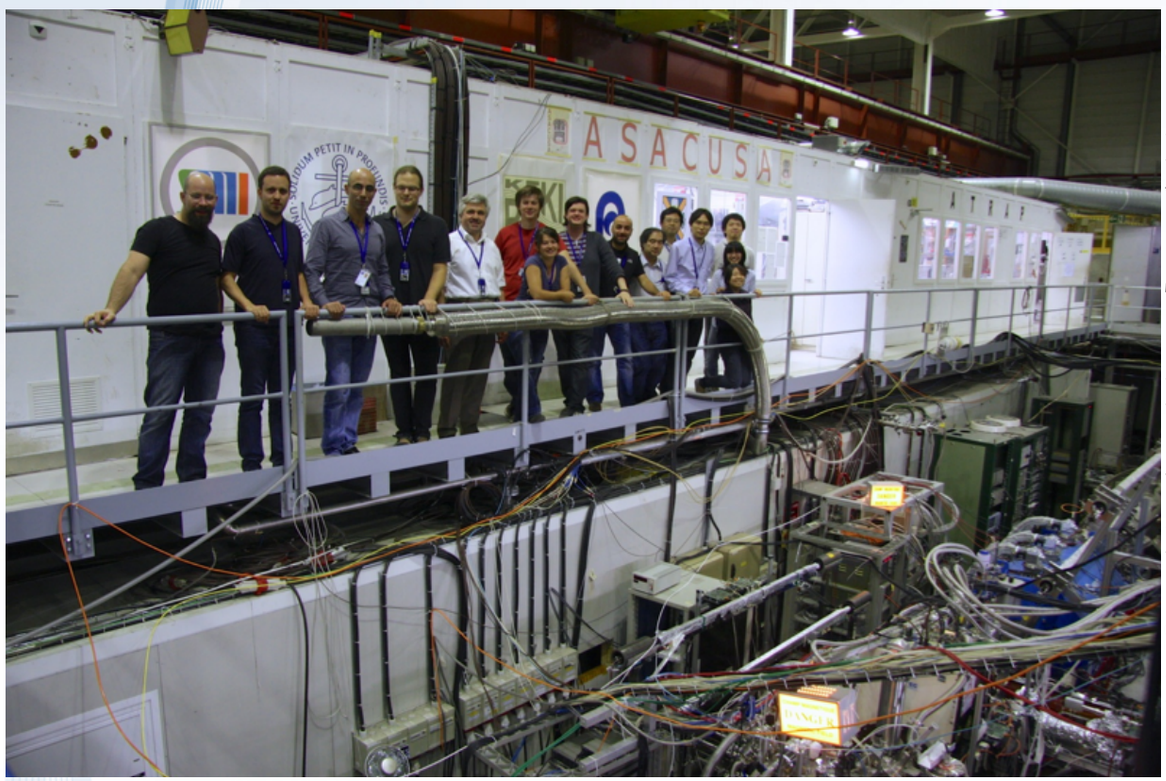
ASACUSA Scientific project

(1) Spectroscopy of p̄He

(2) p̄ annihilation cross-section

(3) H̄ production and spectroscopy

The H̄ 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

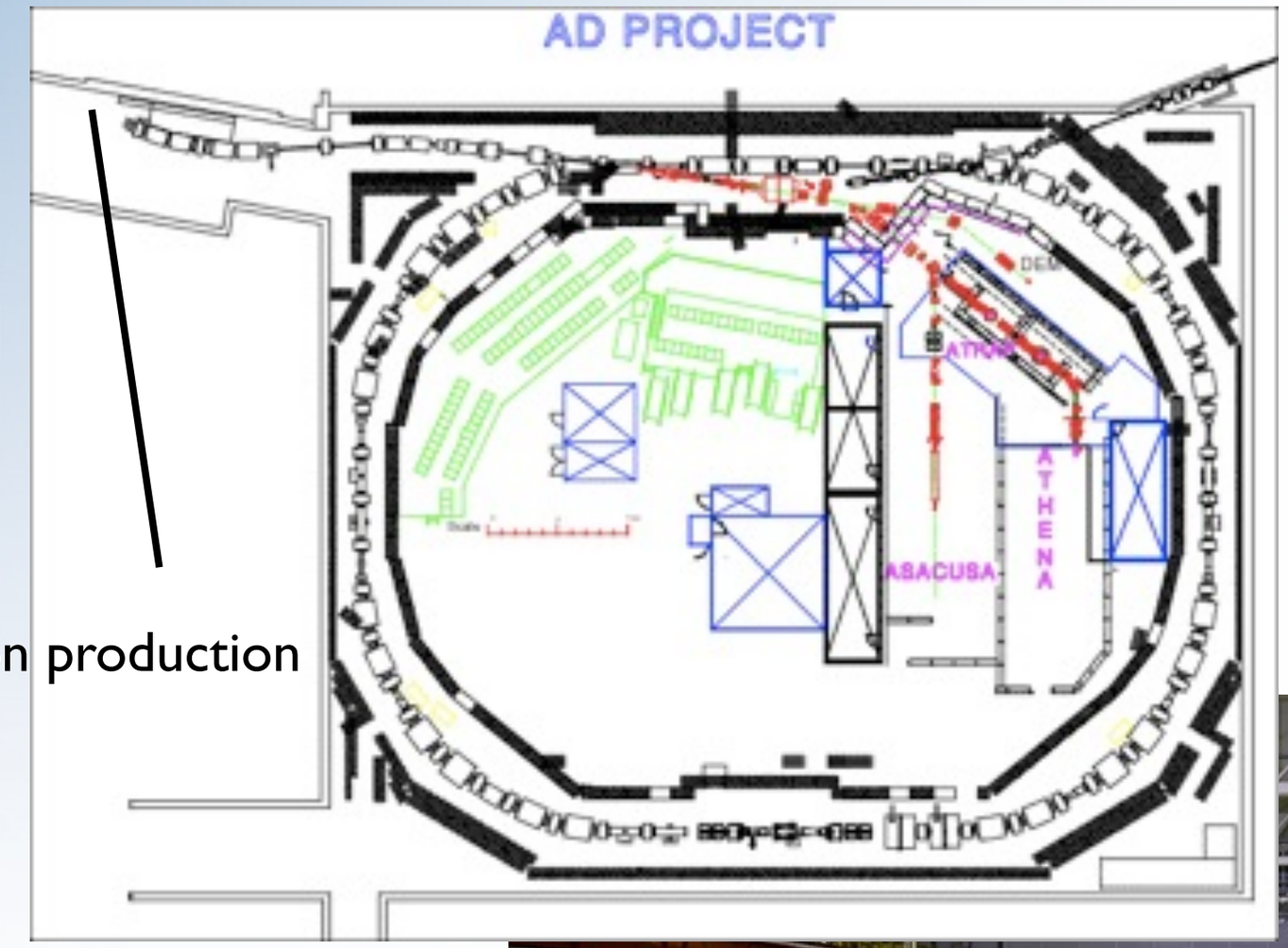
Univerita di Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli, N. Zurlo

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

HH-HFS

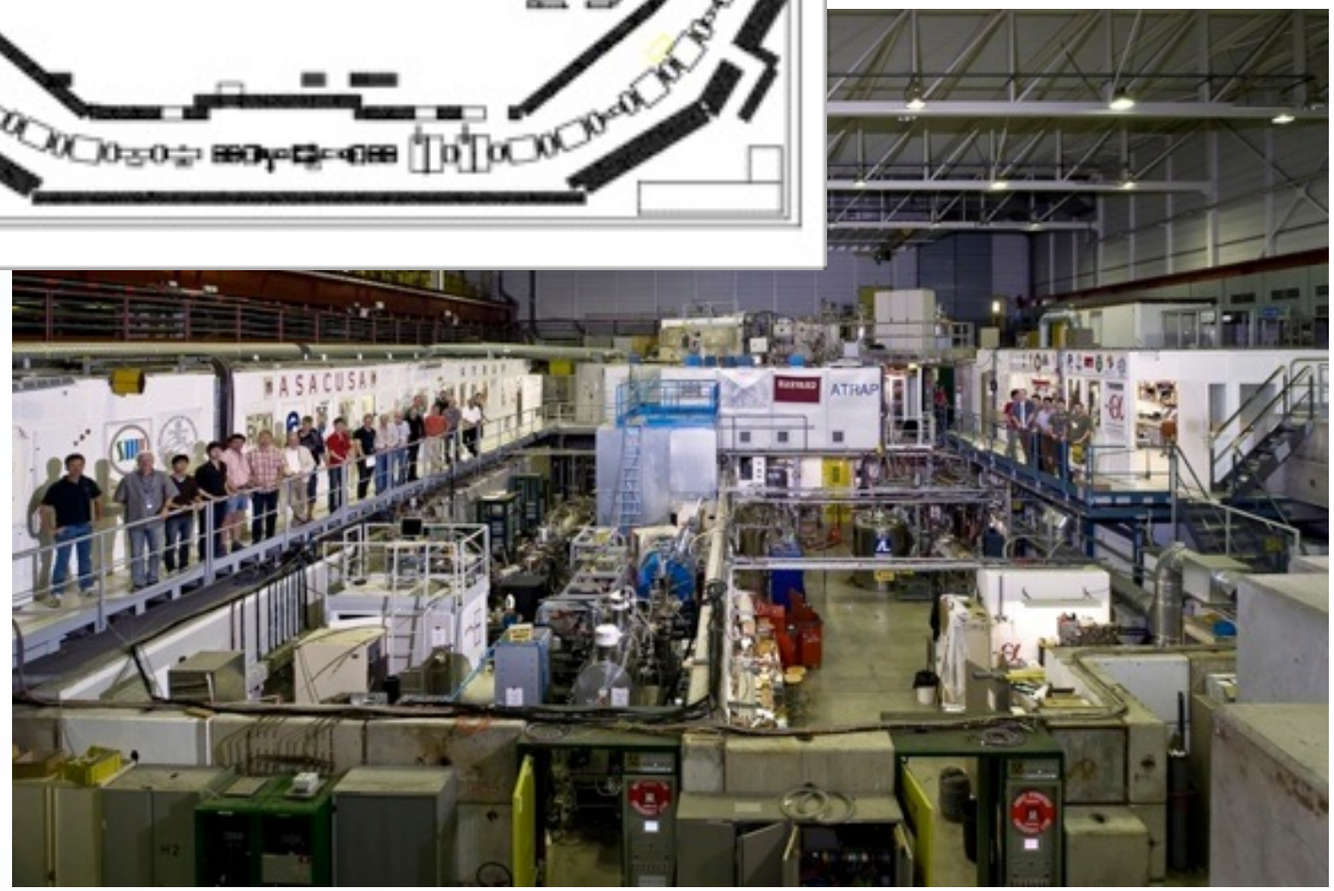
Antiproton decelerator CERN-AD

Antiproton Decelerator @ CERN

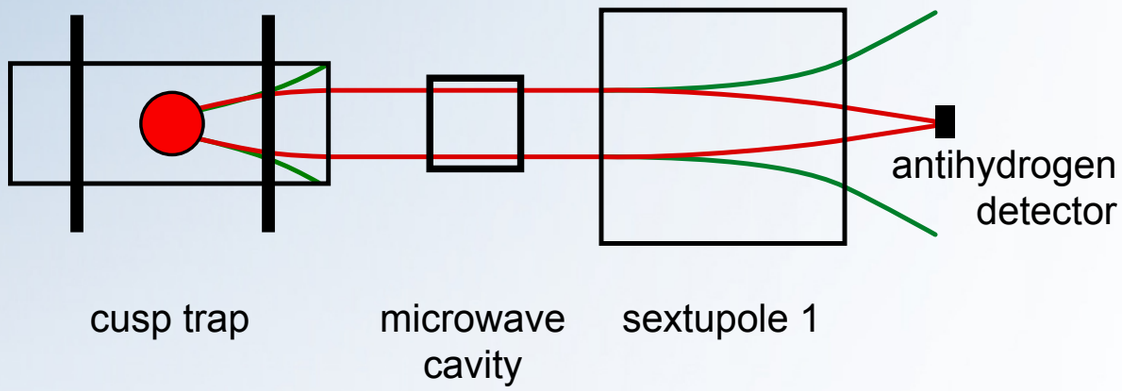


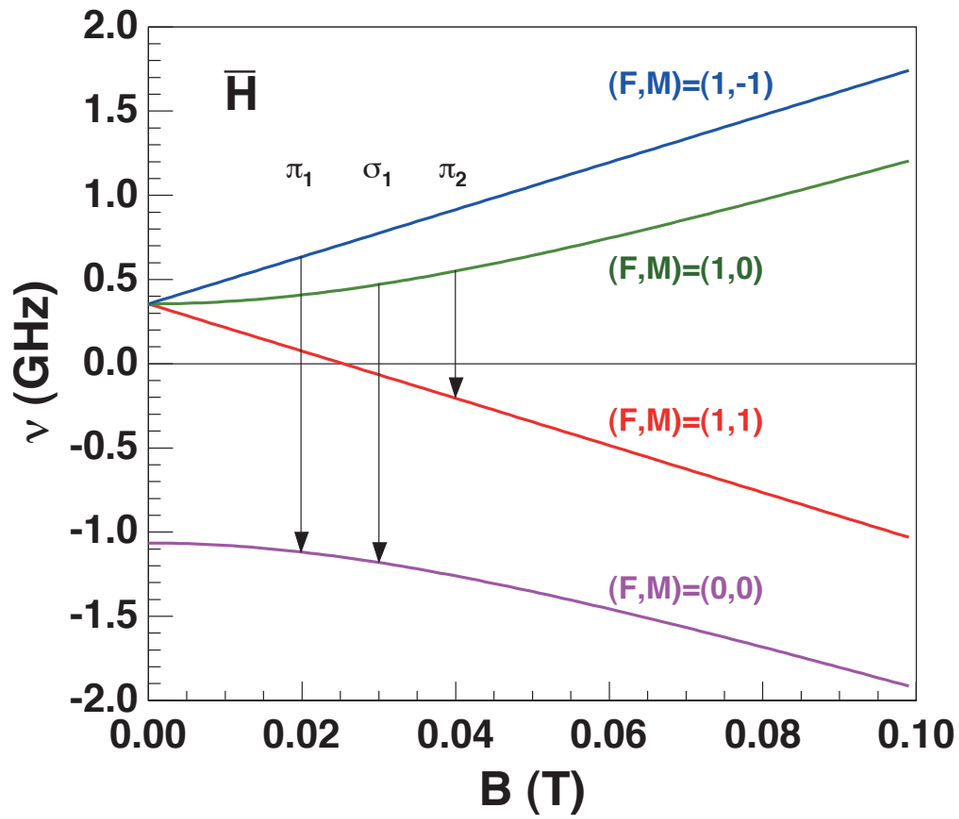
Antiproton production

- All-in-one machine:
- Antiproton capture
- deceleration & cooling
- 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85–120 seconds



HFS MEASUREMENT IN AN ATOMIC BEAM





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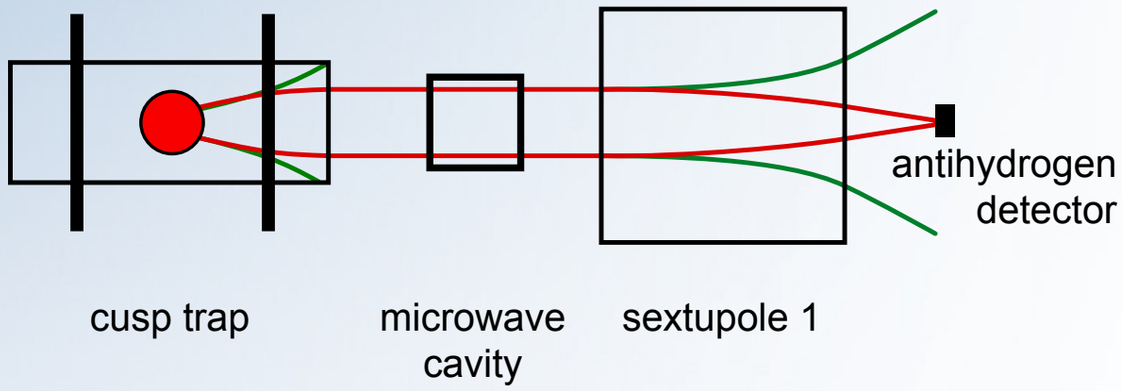

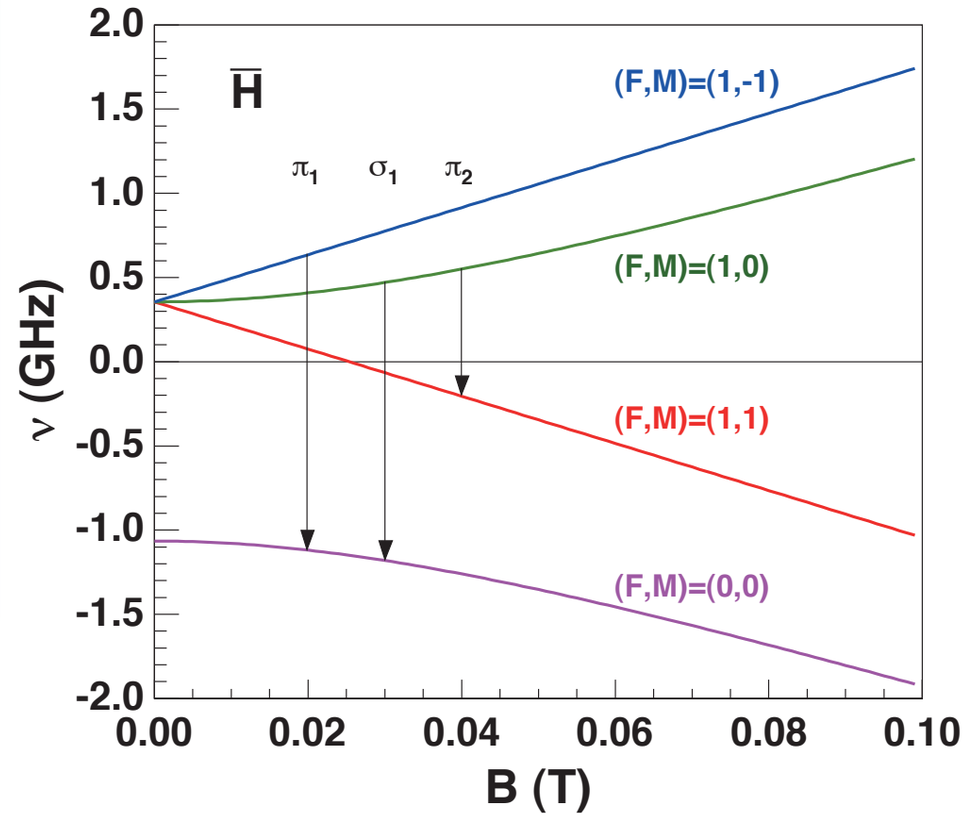

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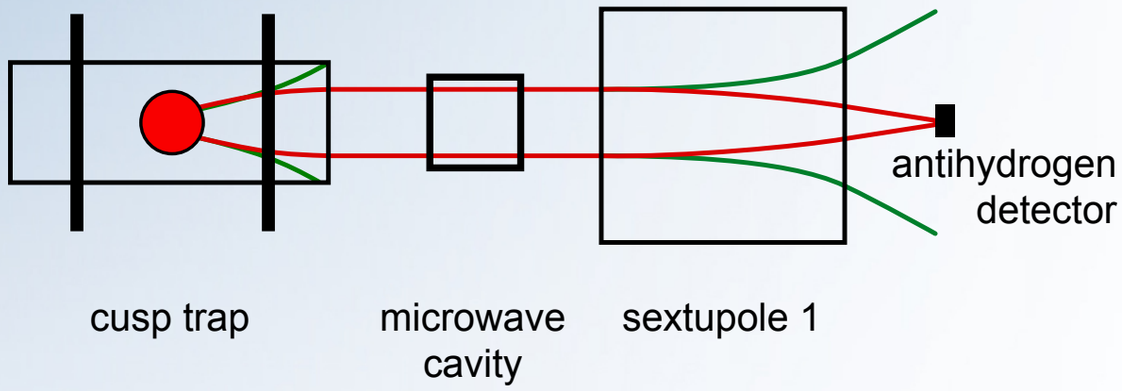

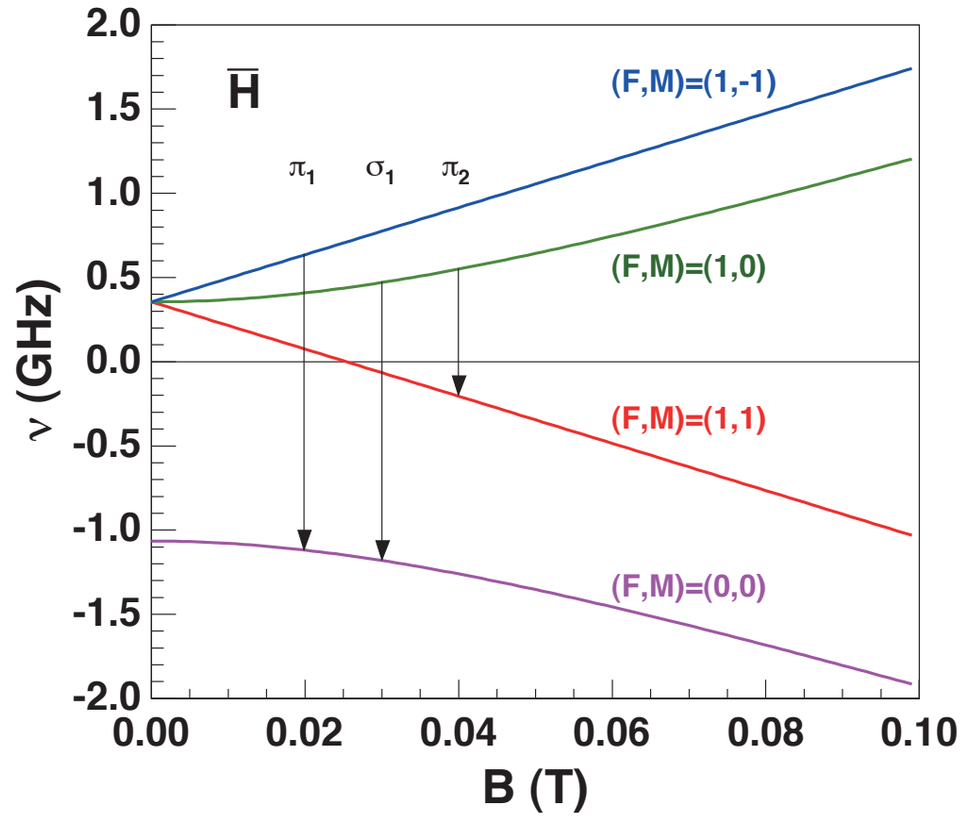

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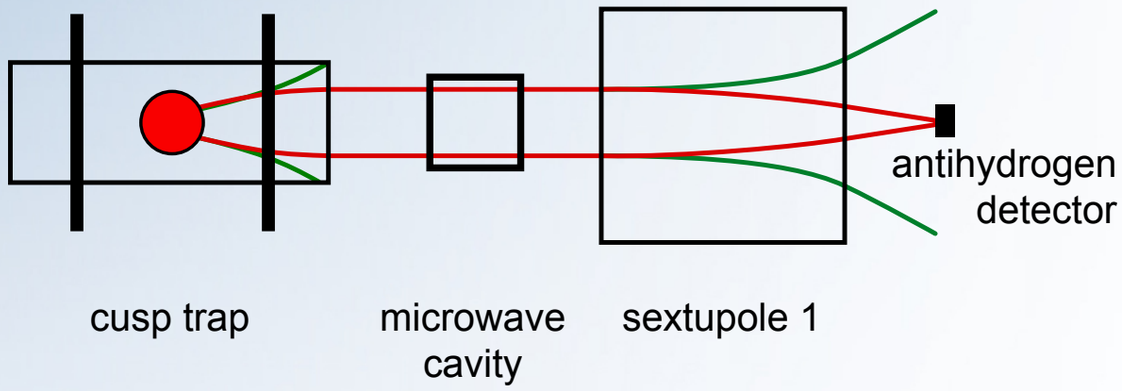

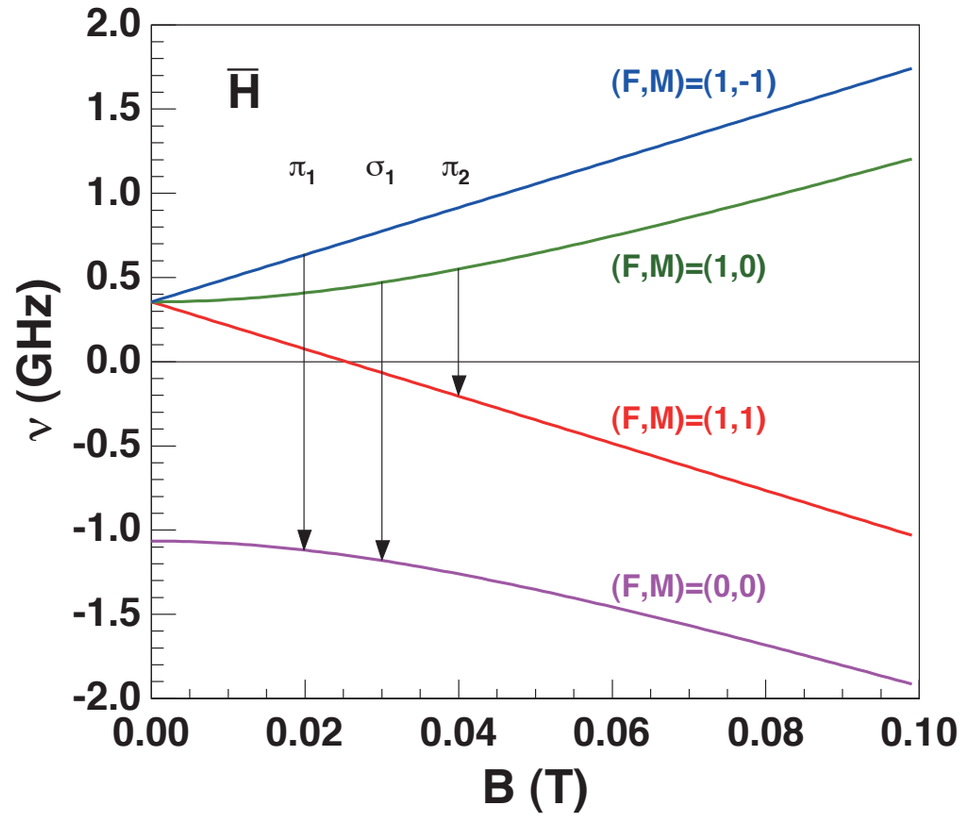

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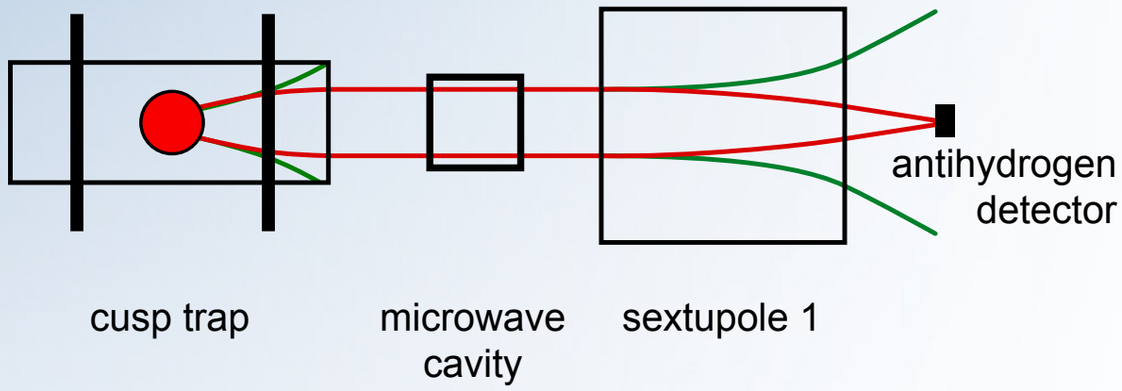

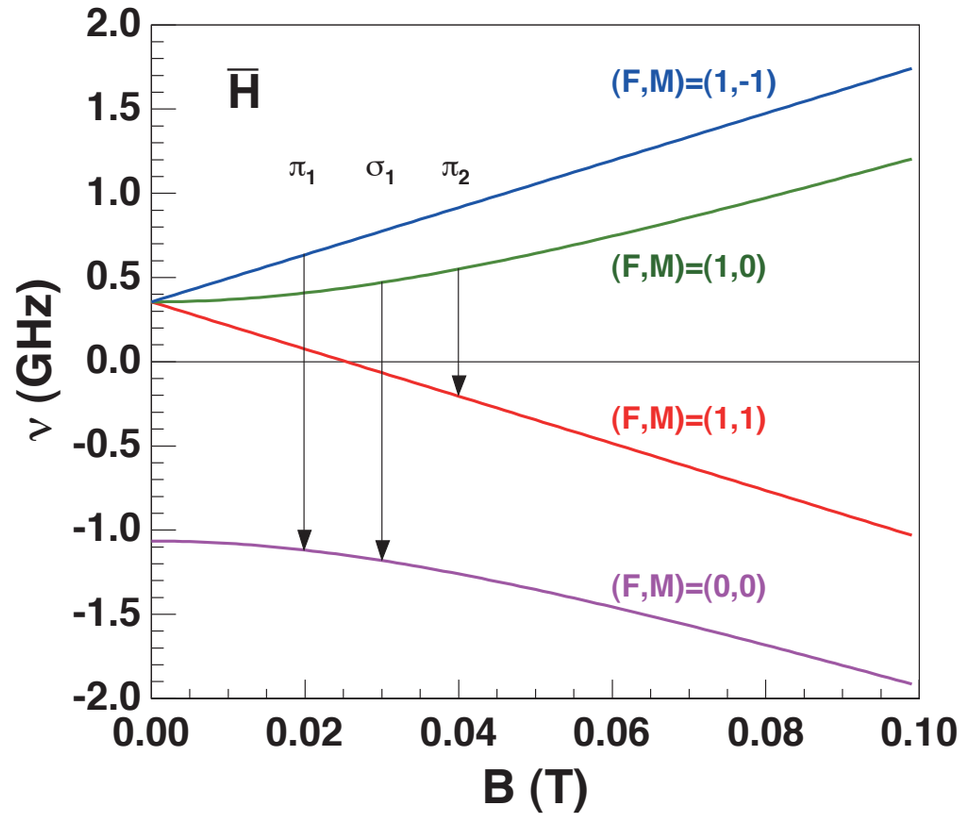

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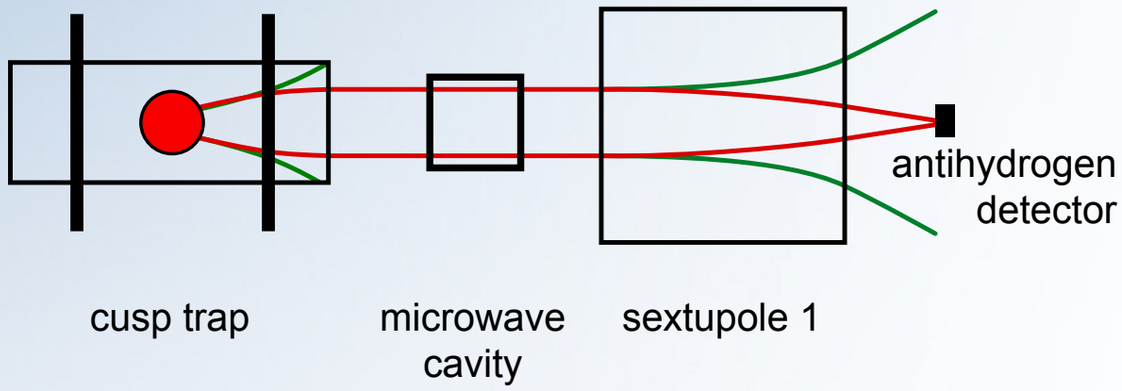

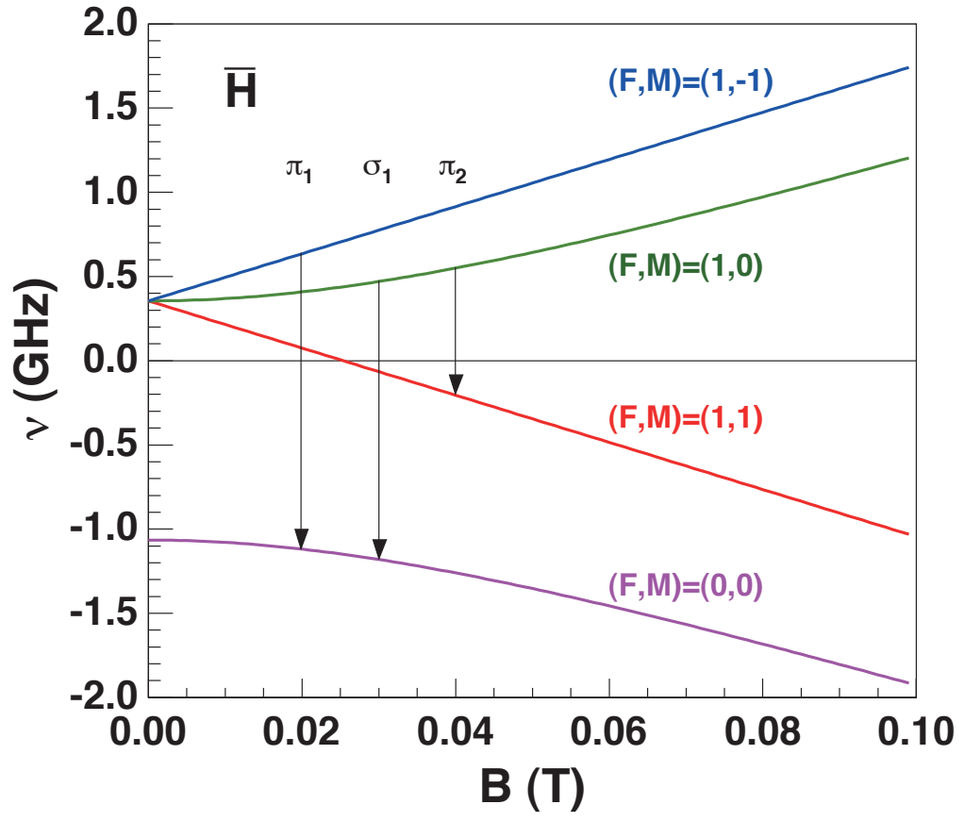

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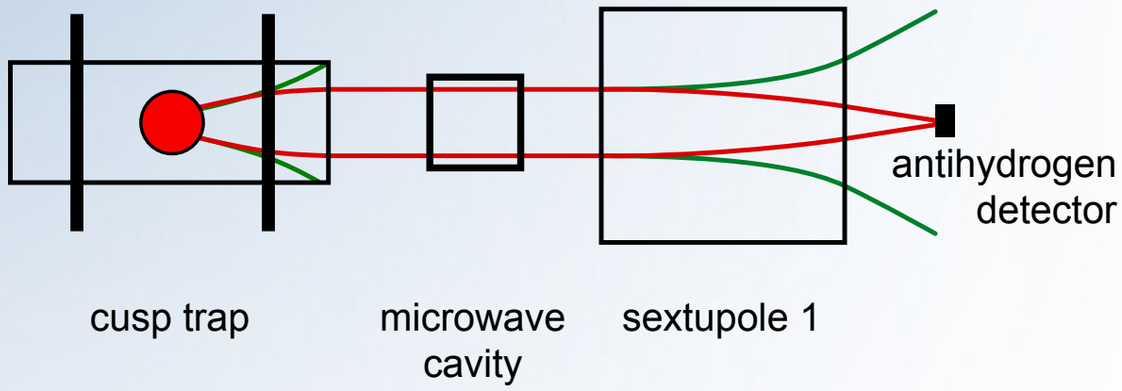

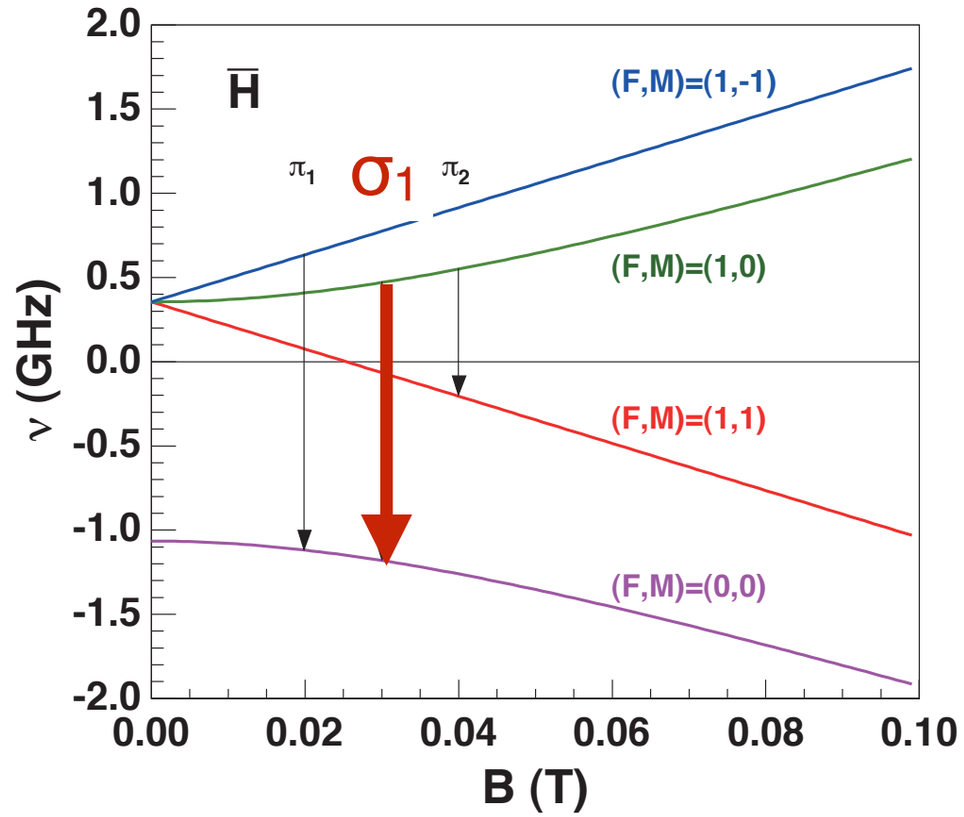

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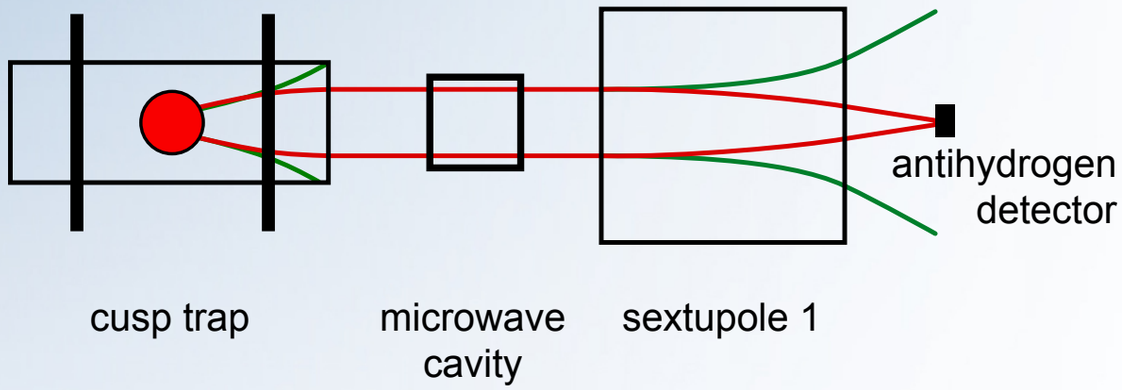

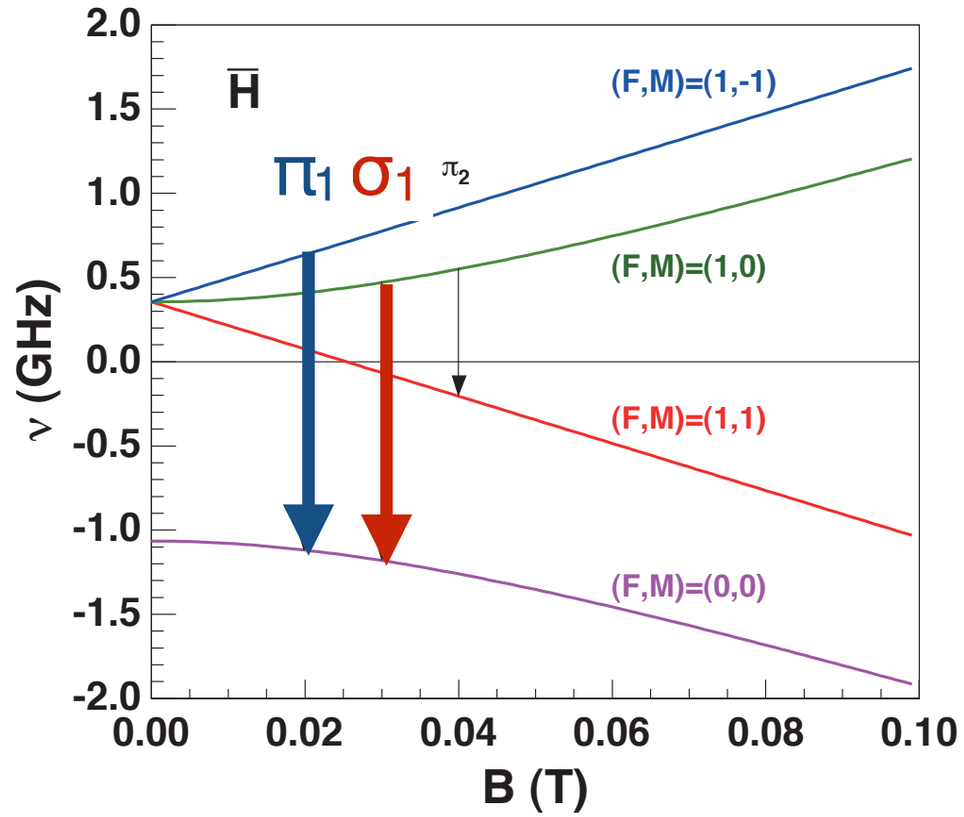

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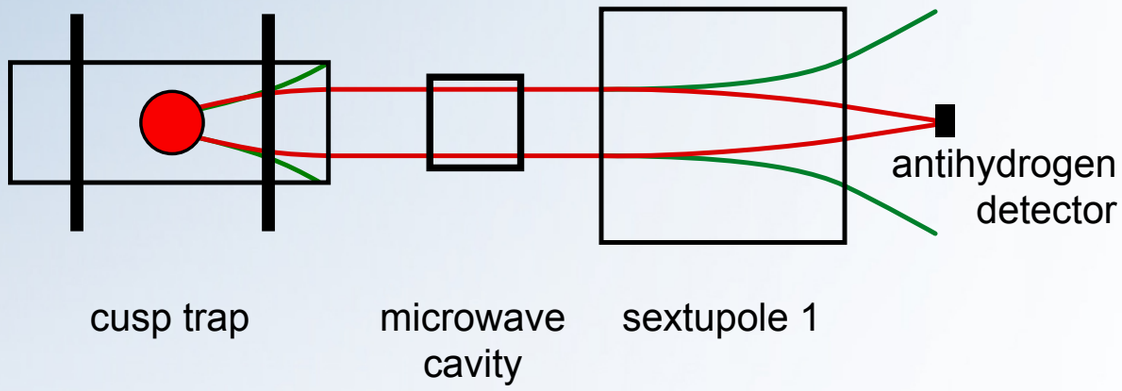

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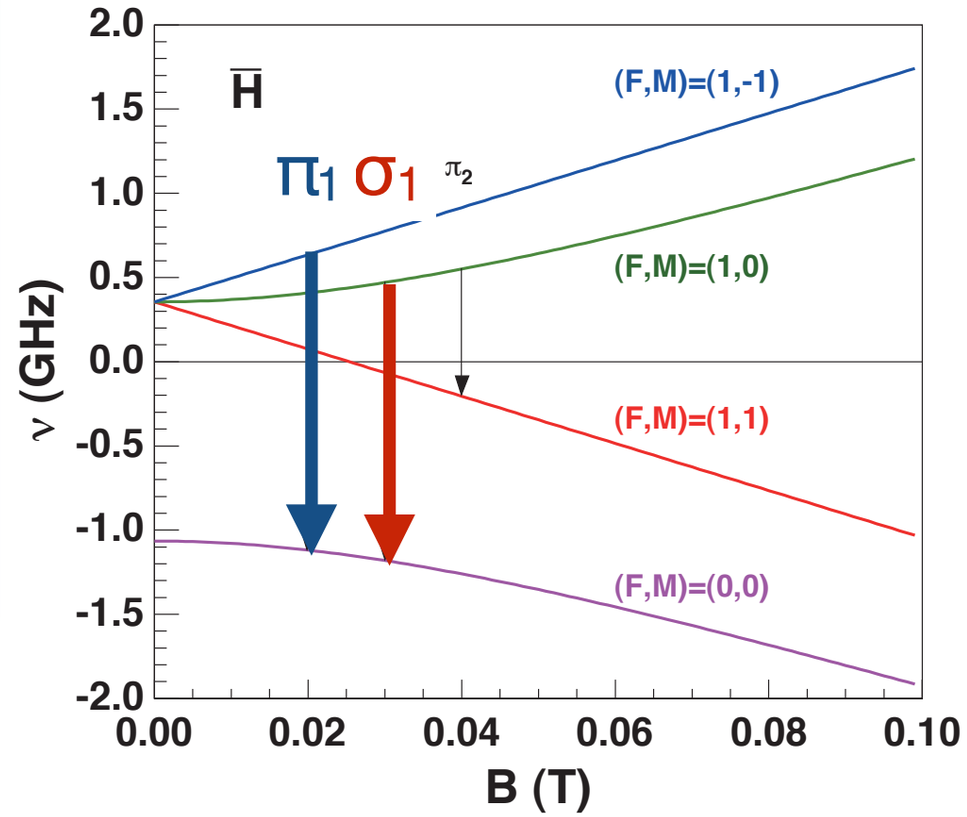
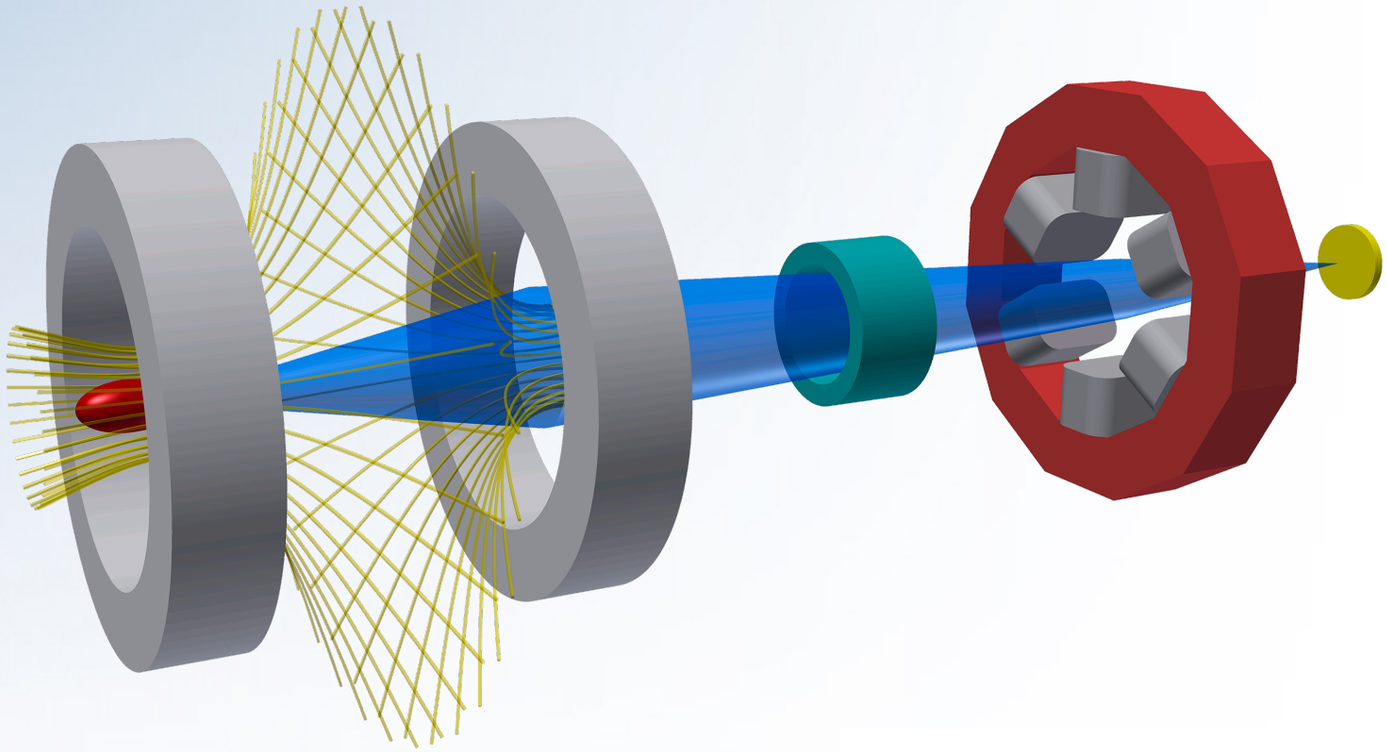


achievable resolution

- 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

Polarized $\bar{H}$ beam from "cusp"

- First antihydrogen production in 2010



A. Mohri & Y. Yamazaki,
Europhysics Letters 63, 207 (2003).

Y. Enomoto et al.
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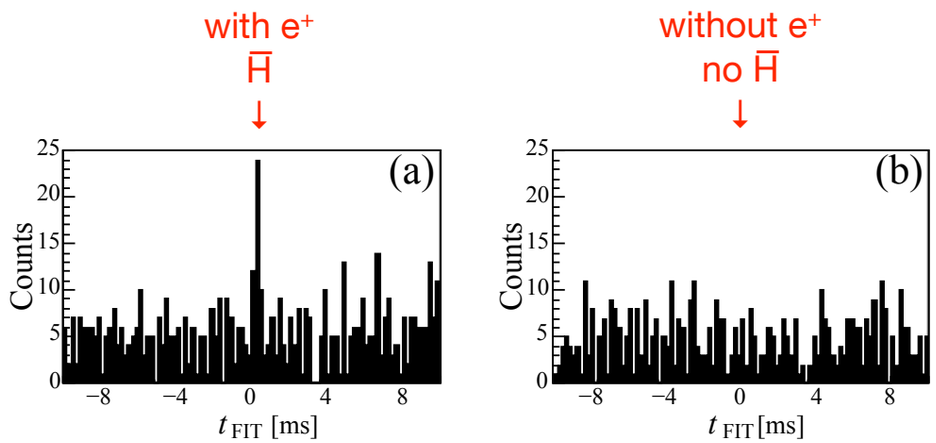

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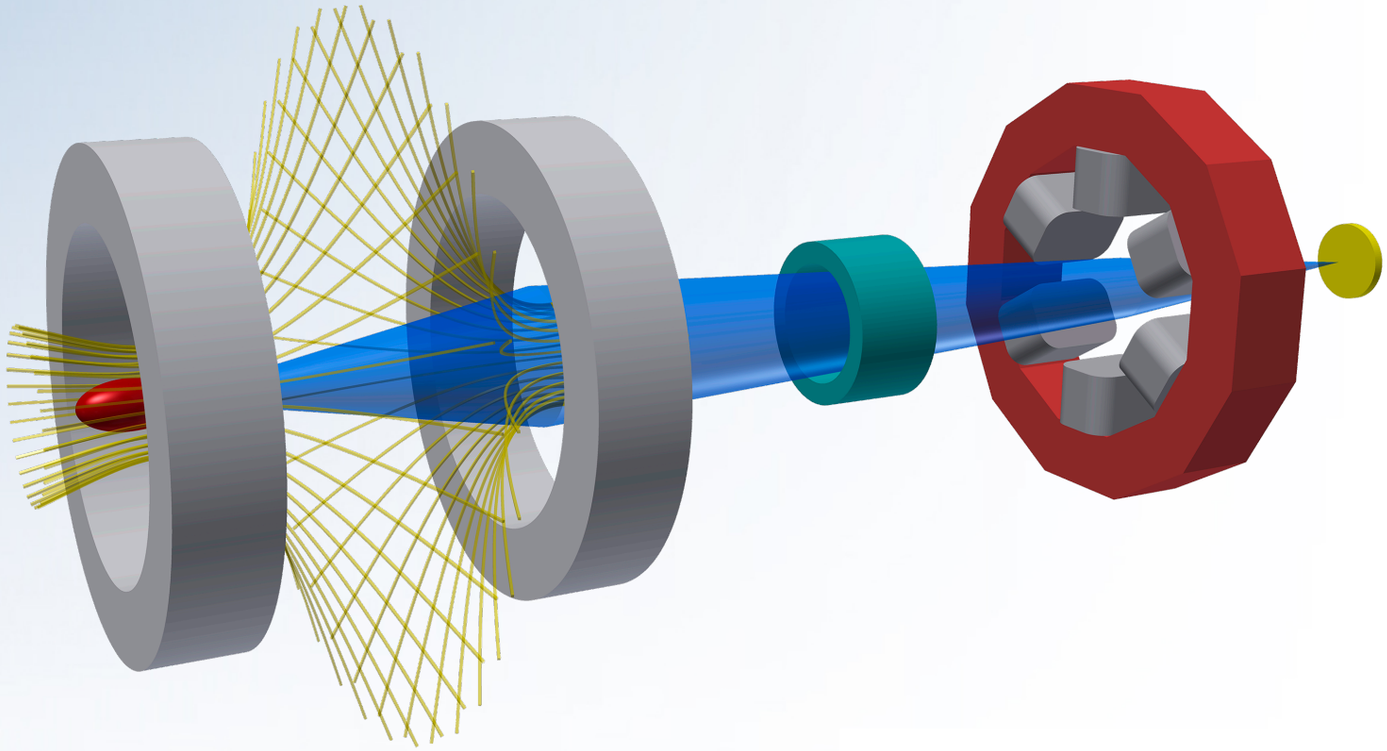

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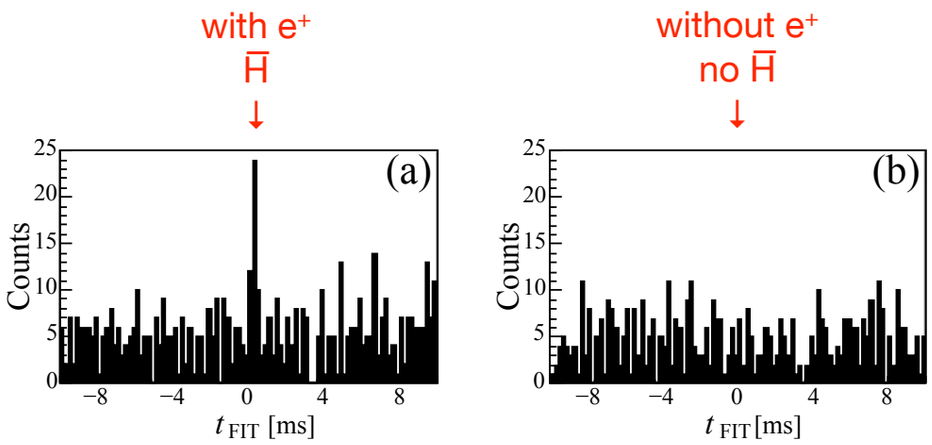
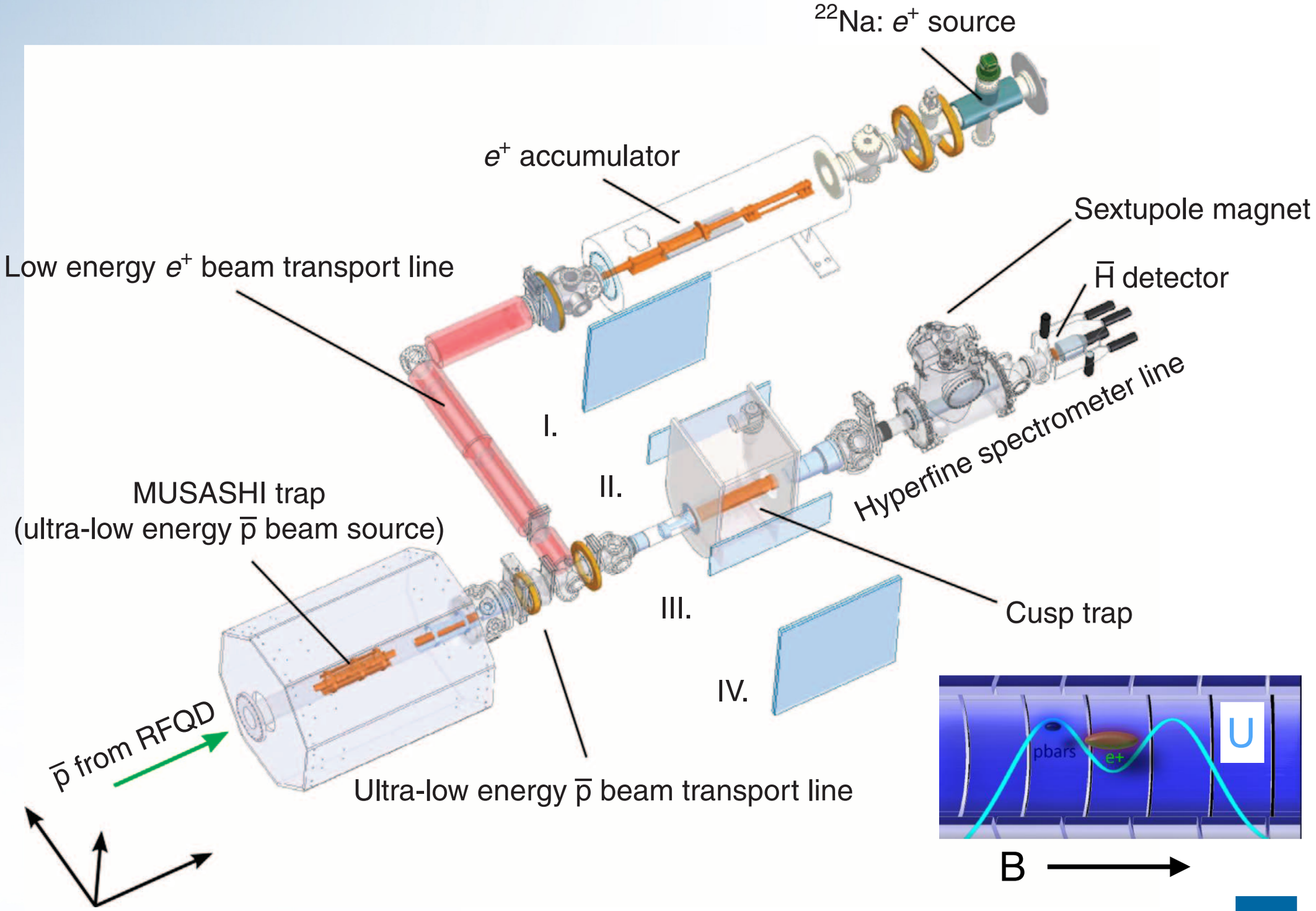


ASACUSA $\bar{H}$ PRODUCTION



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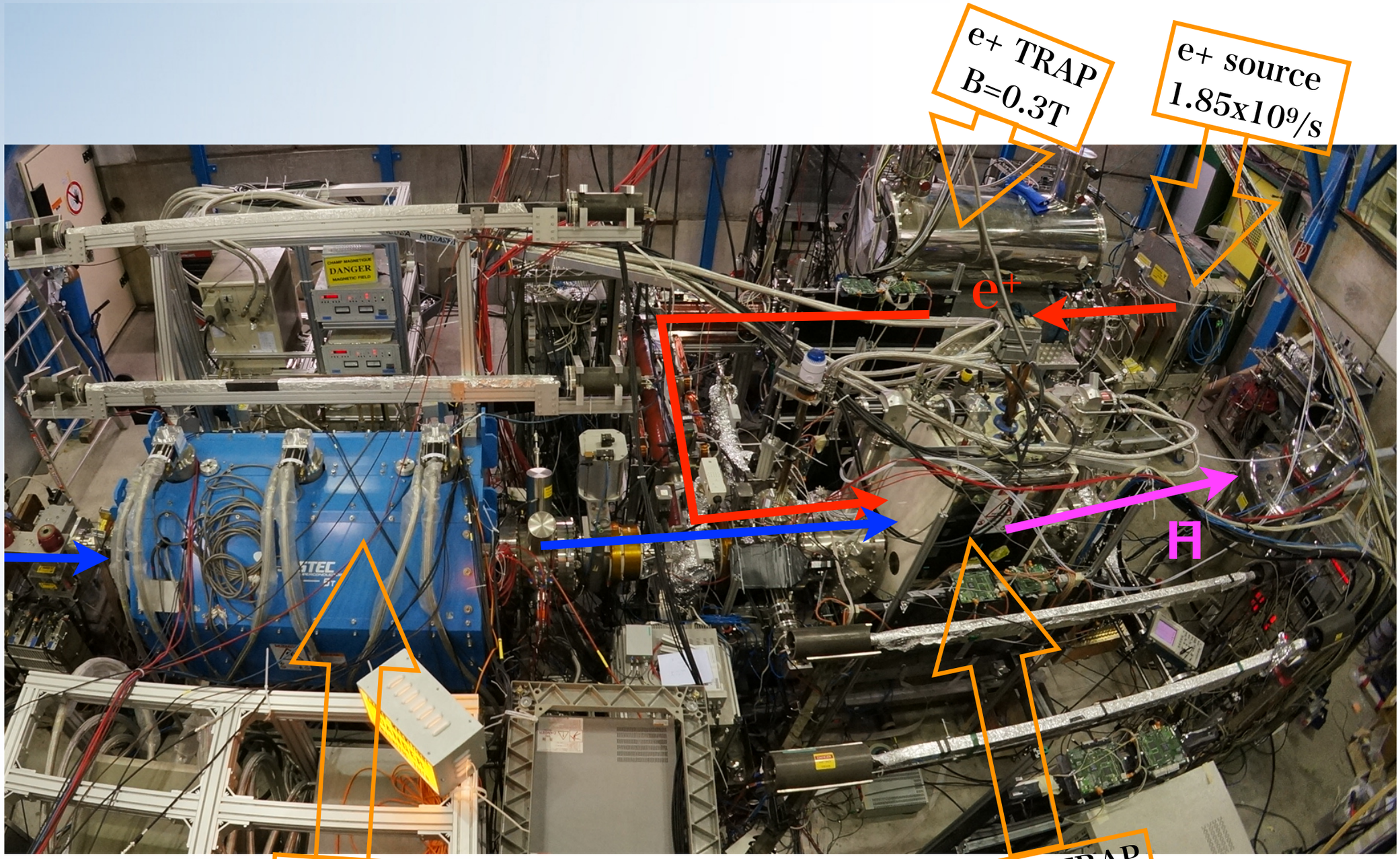
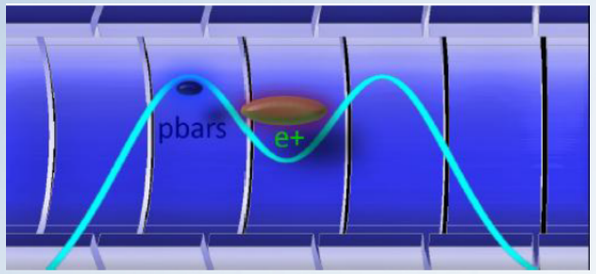
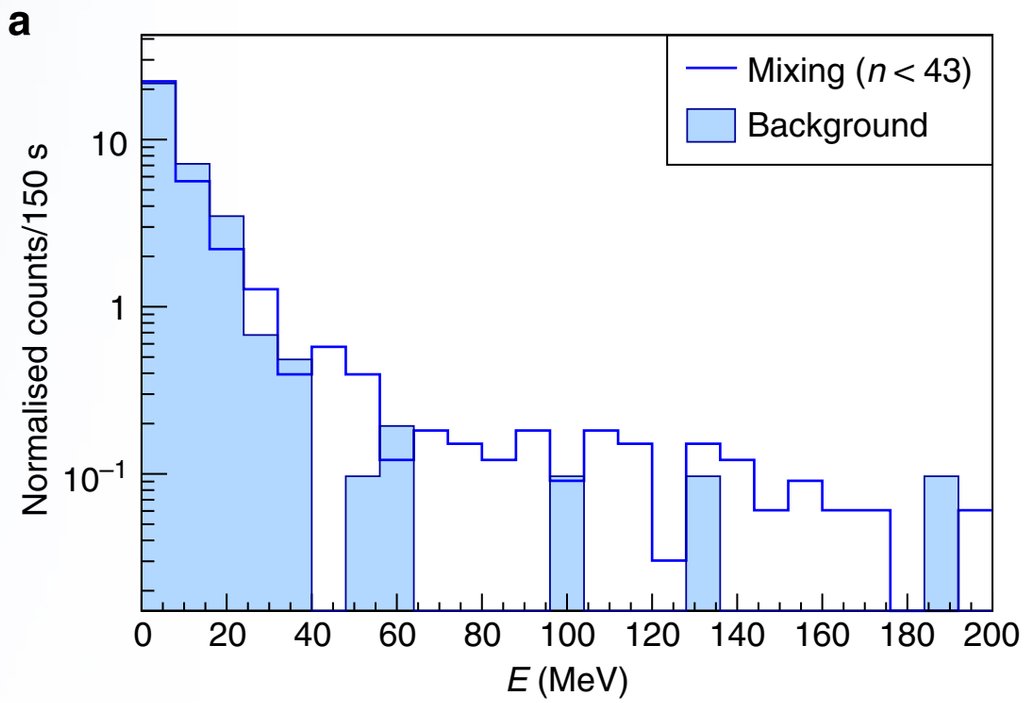


RECENT RESULTS





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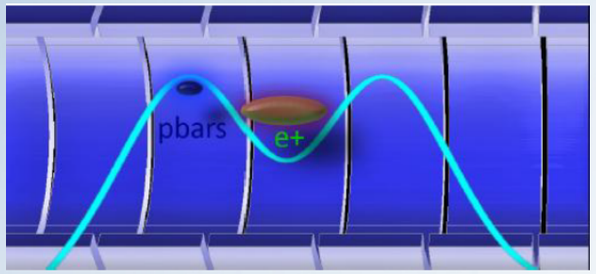
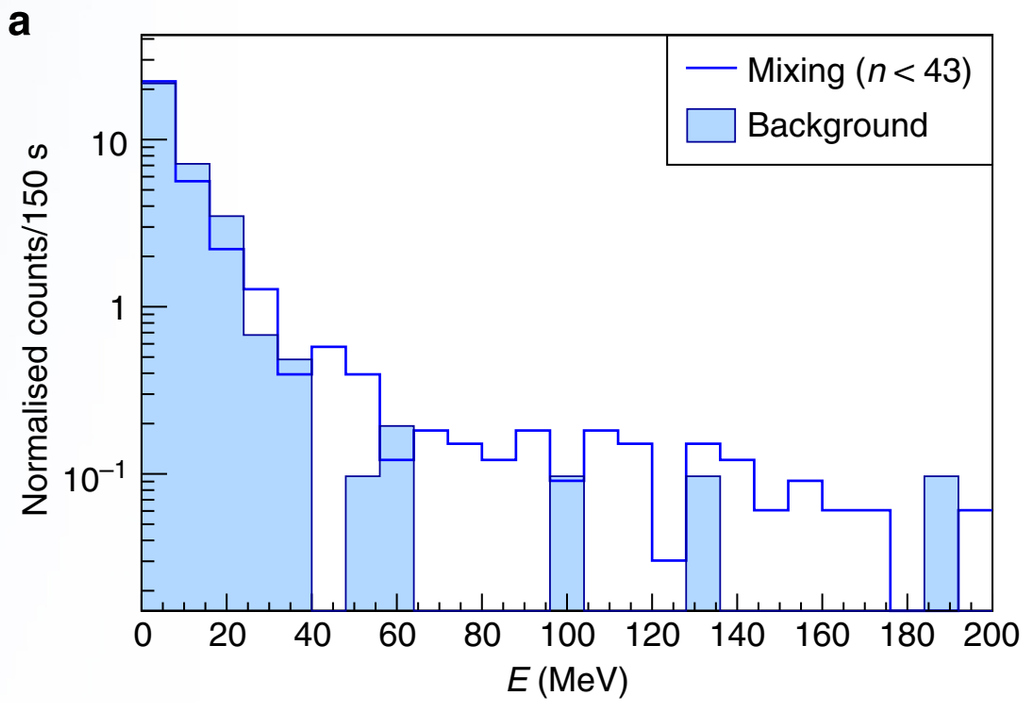
RECENT RESULTS



- BACKGROUND



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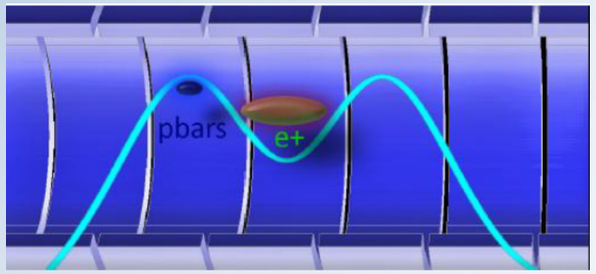
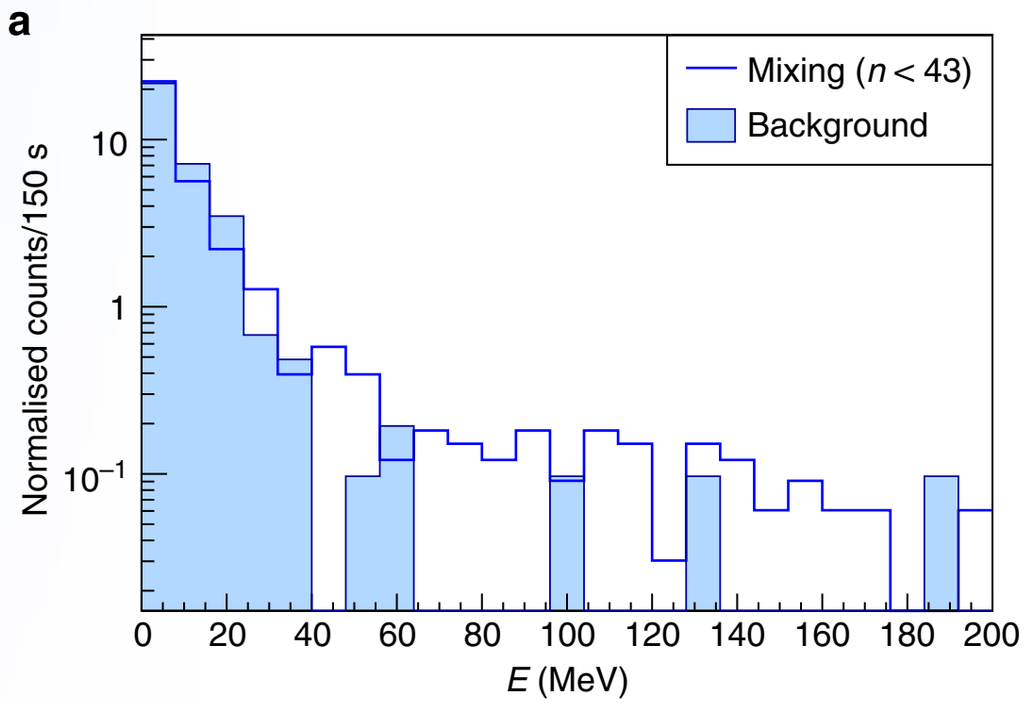


- BACKGROUND
  - e^- cooling of $\bar{p}$



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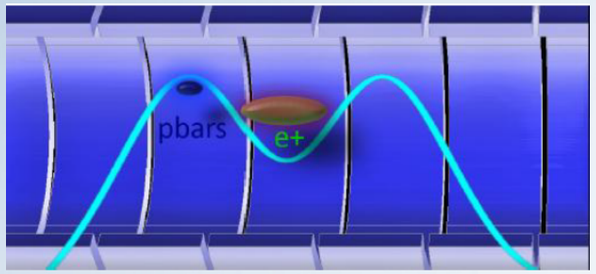

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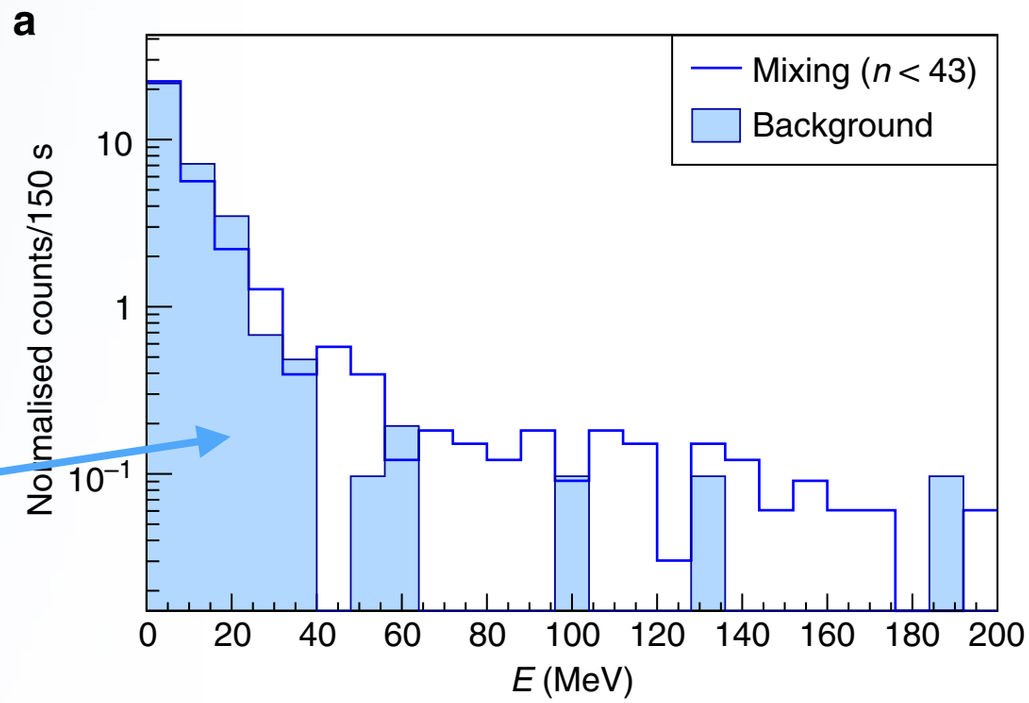
  - mix e^- and $\bar{p}$



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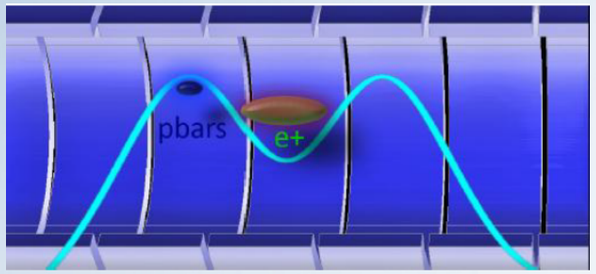
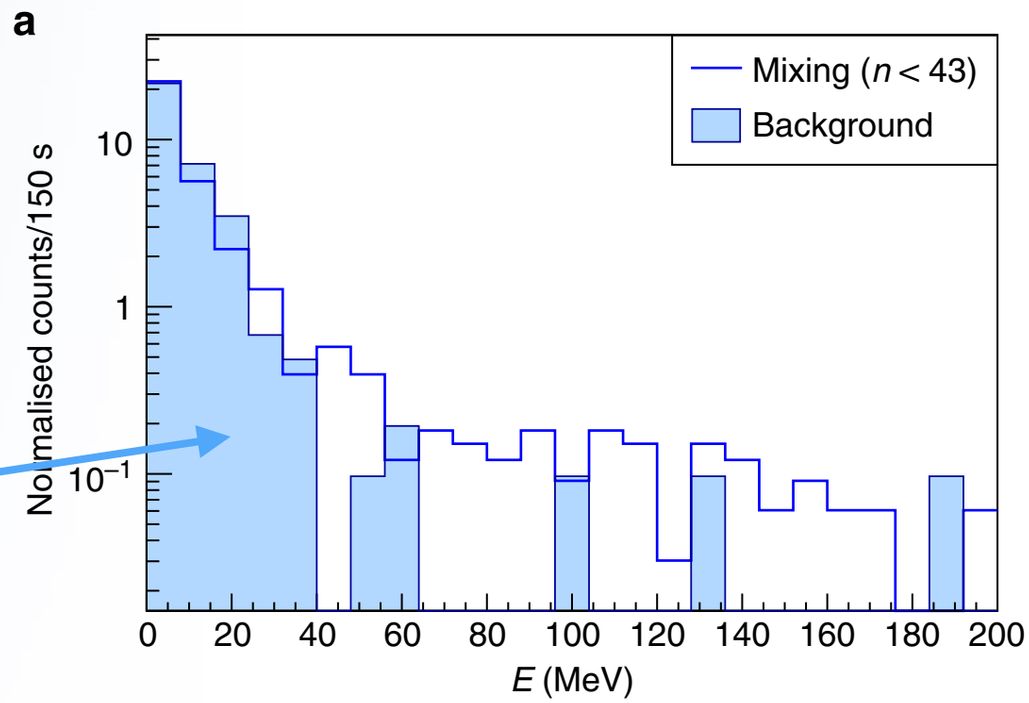


- BACKGROUND
  - e^- cooling of $\bar{p}$
  - mix e^- and $\bar{p}$
- SCHEME 1



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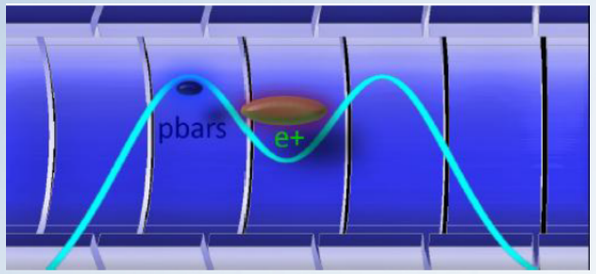

- BACKGROUND
  - e^- cooling of $\bar{p}$
  - mix e^- and $\bar{p}$
- SCHEME 1
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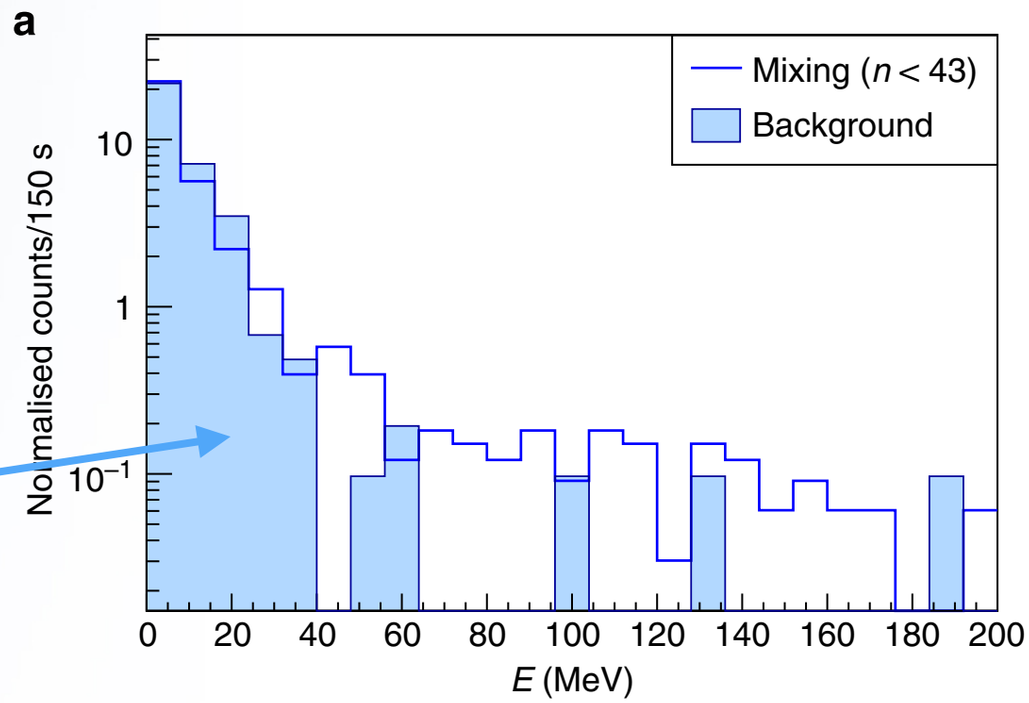

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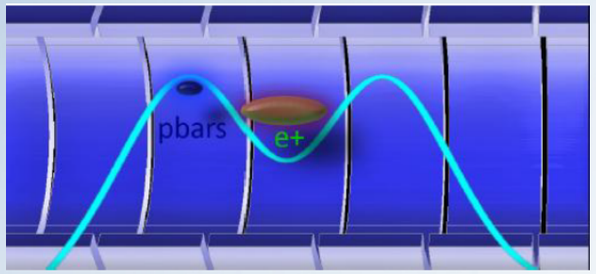

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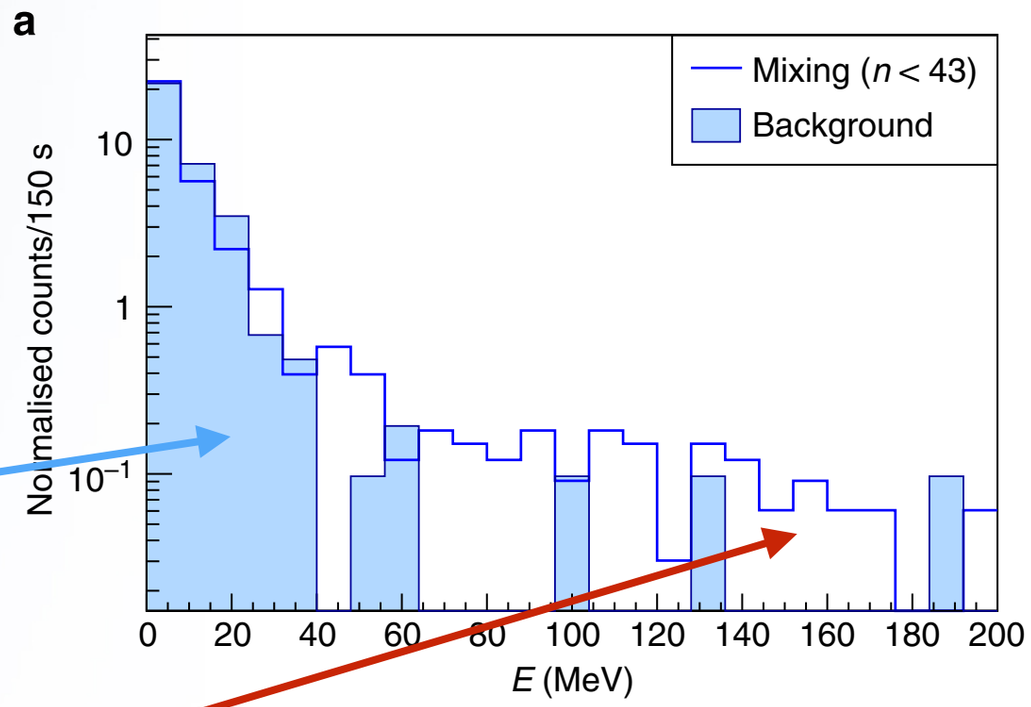

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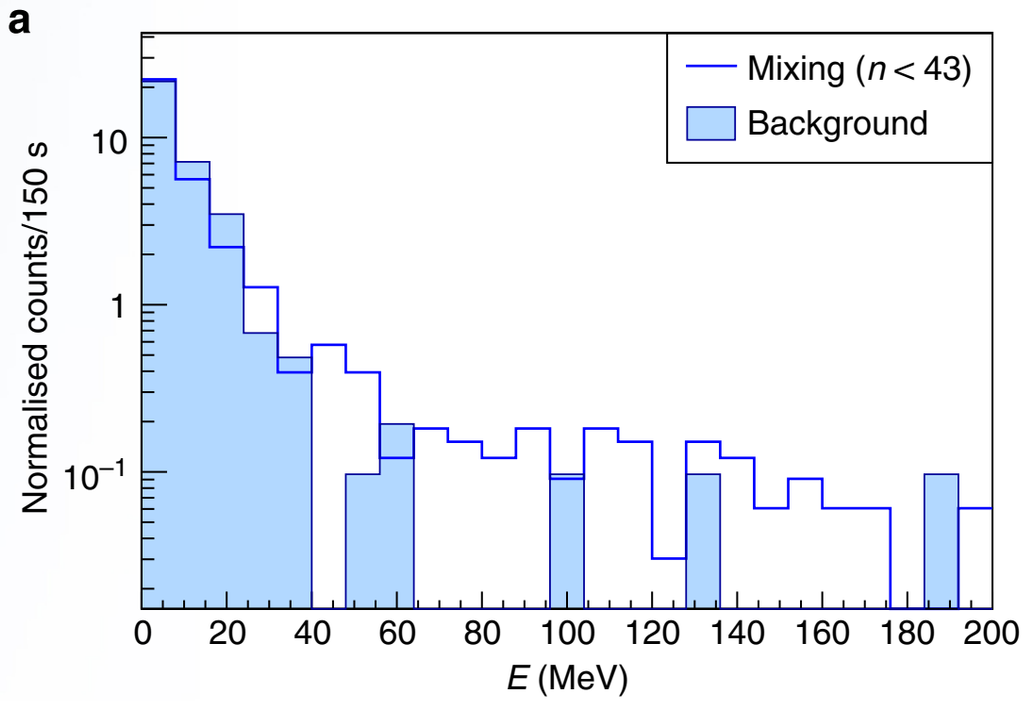

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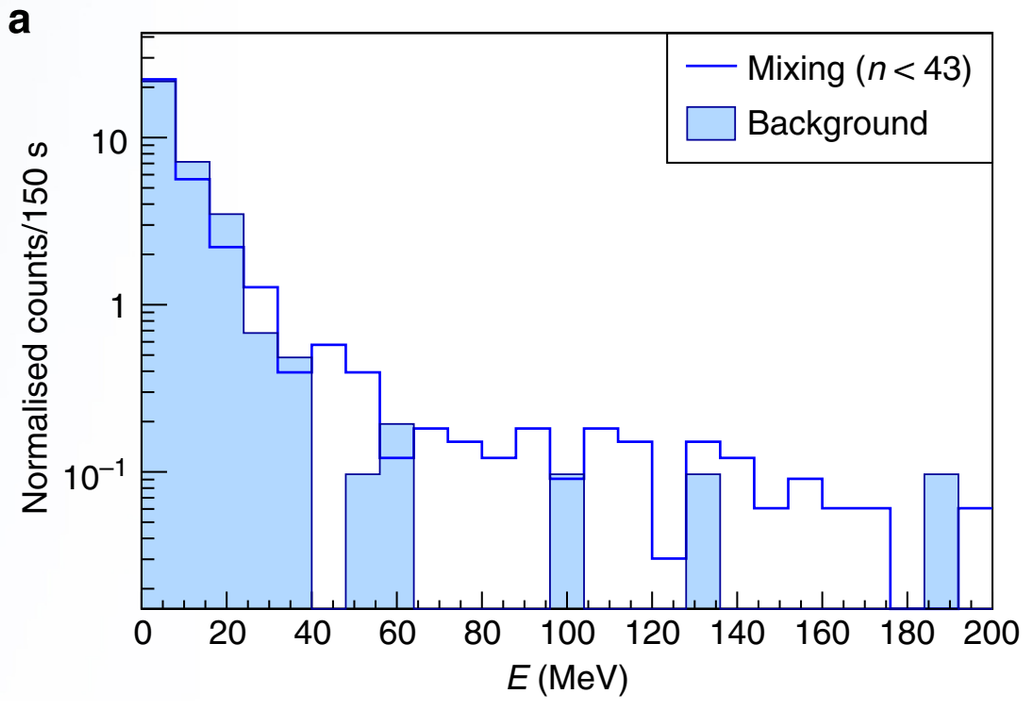
RECENT RESULTS

- $\bar{H}$ BEAM OBSERVED WITH 5σ significance
  - n≲43 (field ionization)
  - 6 events / 15 min



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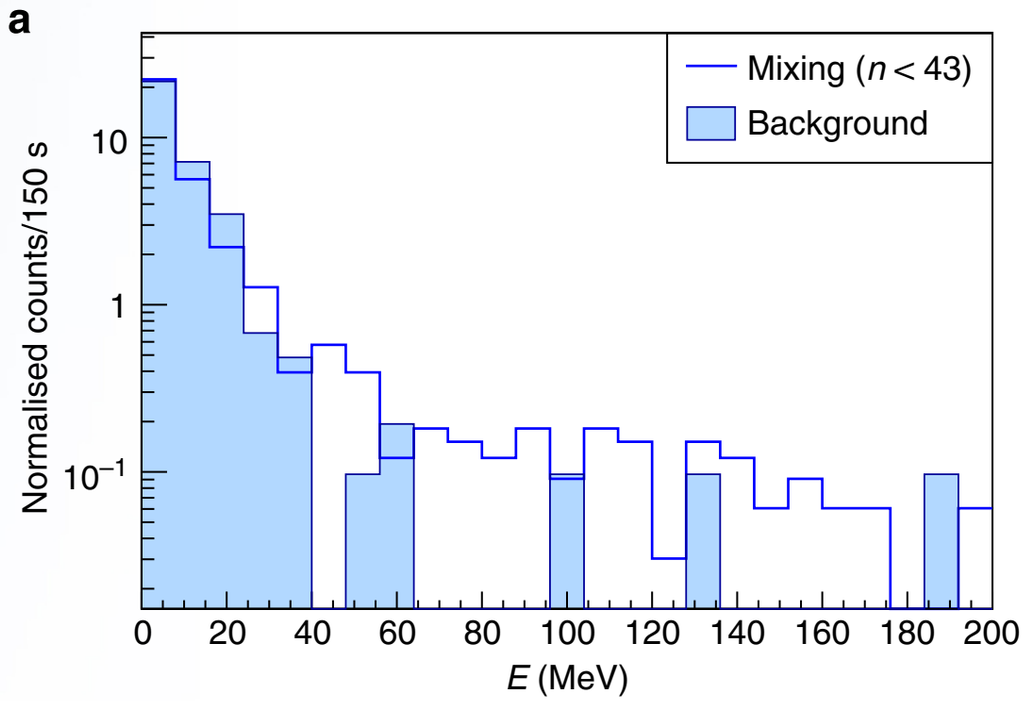
RECENT RESULTS

- $\bar{H}$ BEAM OBSERVED WITH 5σ significance
  - n≲43 (field ionization)
  - 6 events / 15 min
- significant fraction in lower n
  - n≲29: 3σ
  - 4 events / 15 min
  - τ ~ few ms



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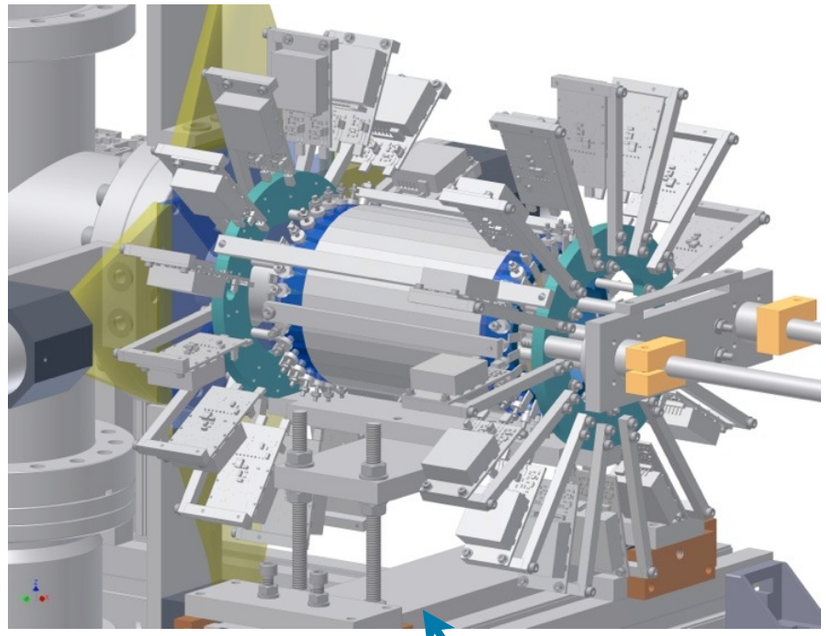
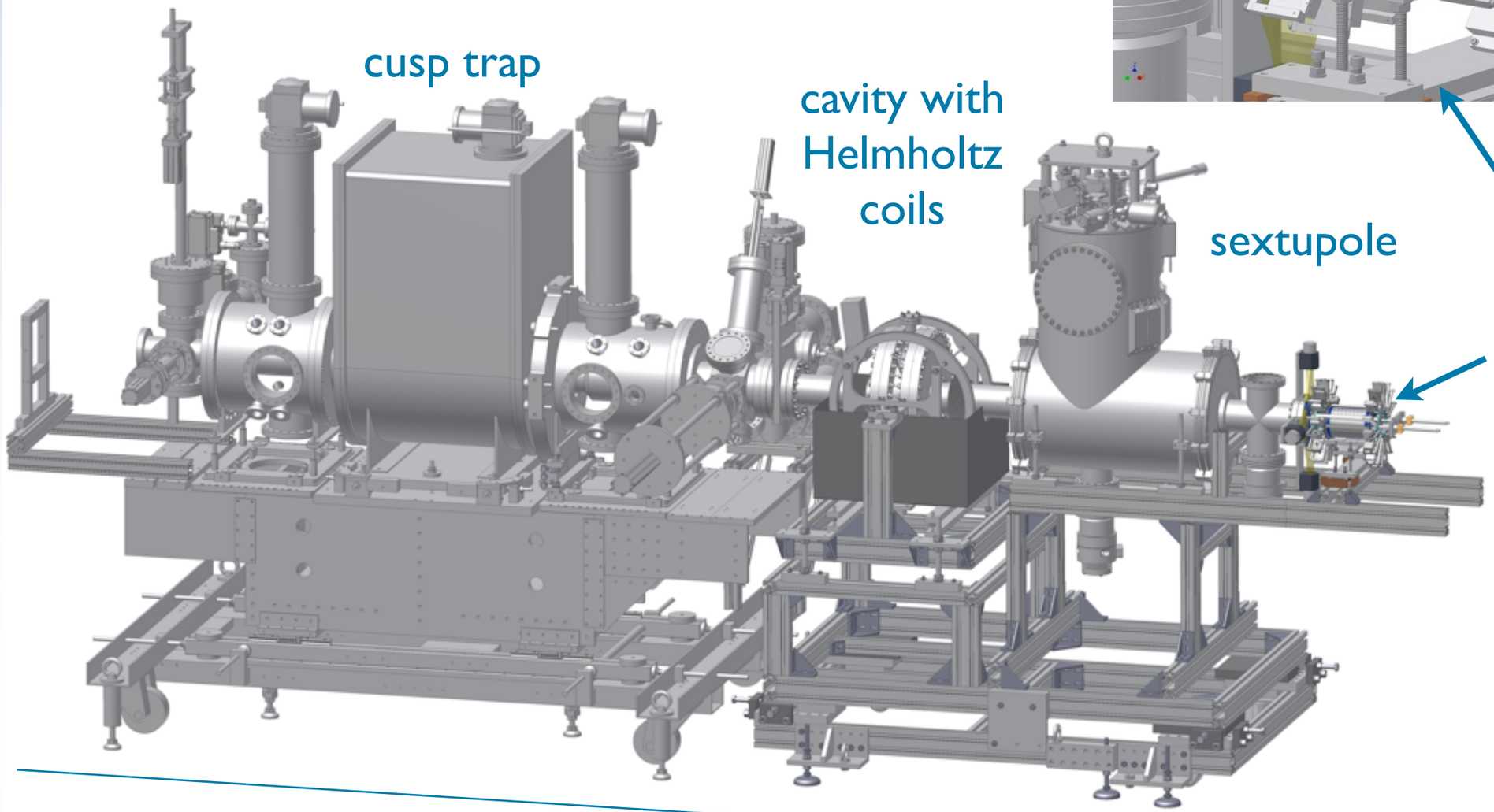
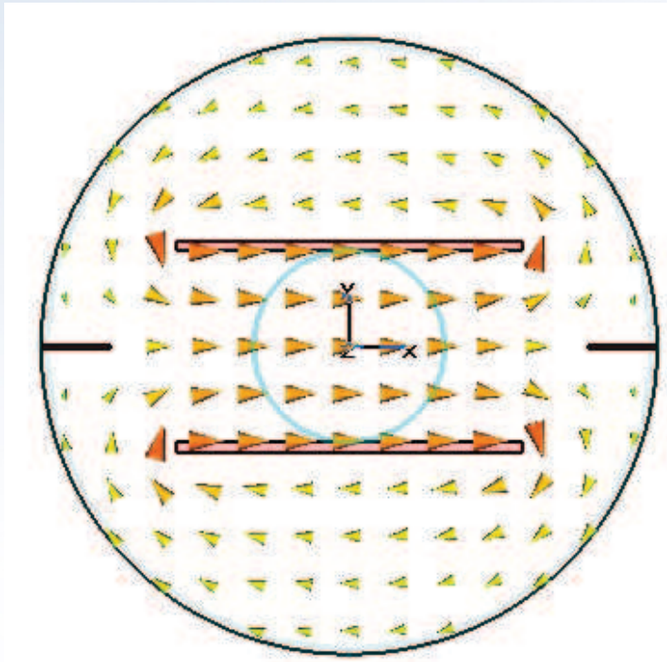
$\bar{H}$ HFS BEAM LINE 2012



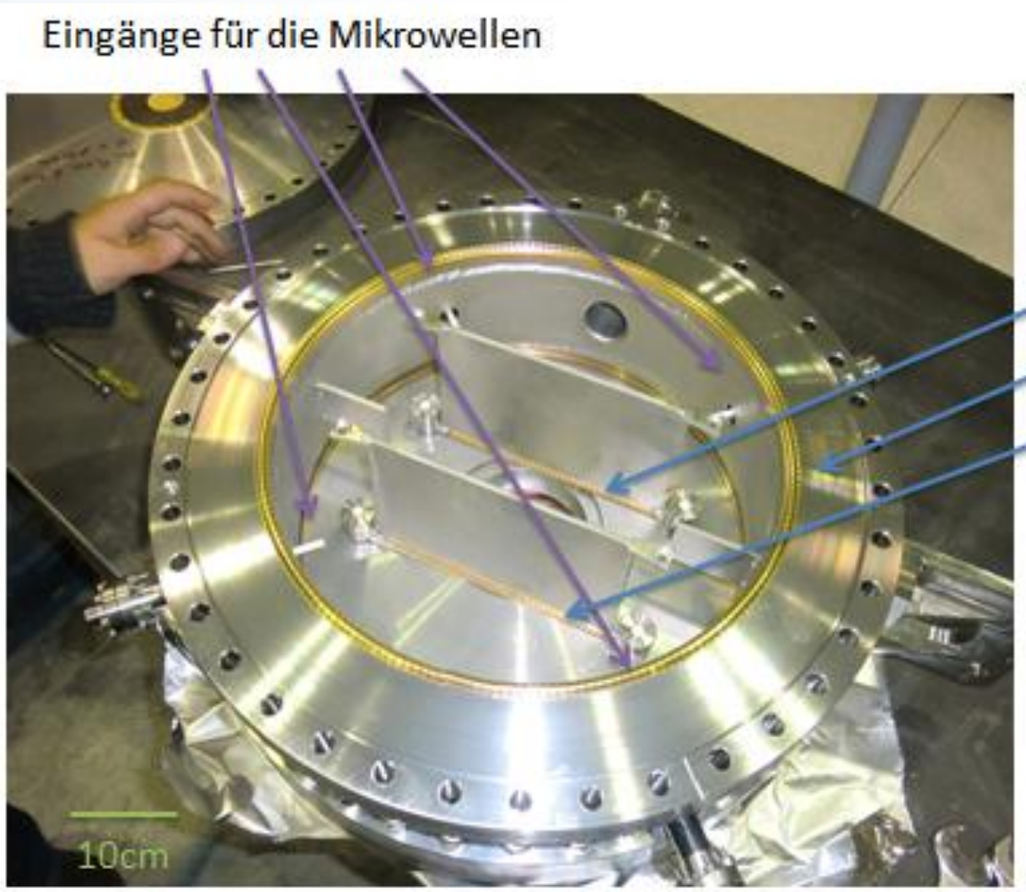


SPIN-FLIP RESONATOR

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



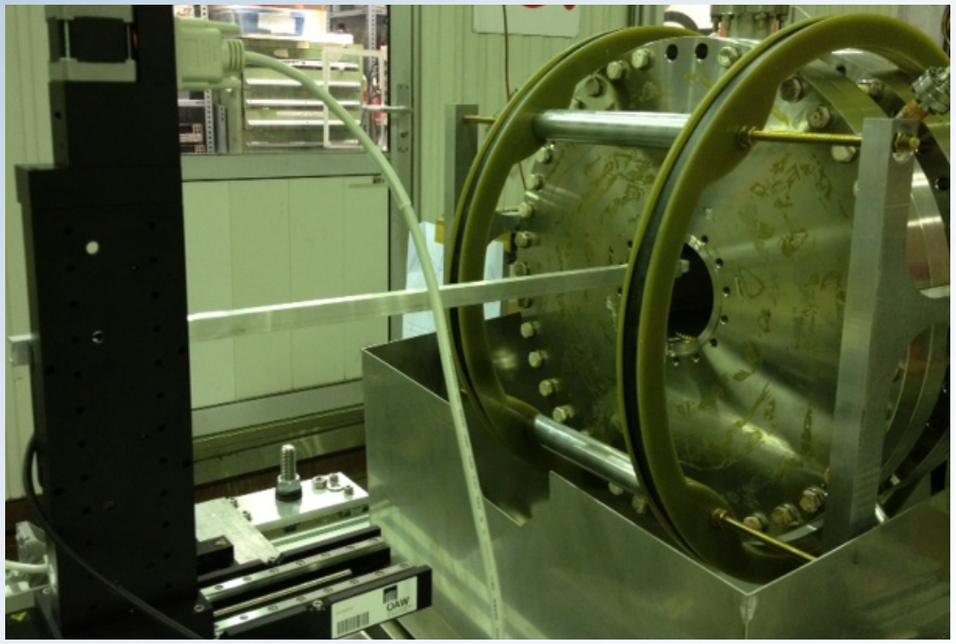
strip line

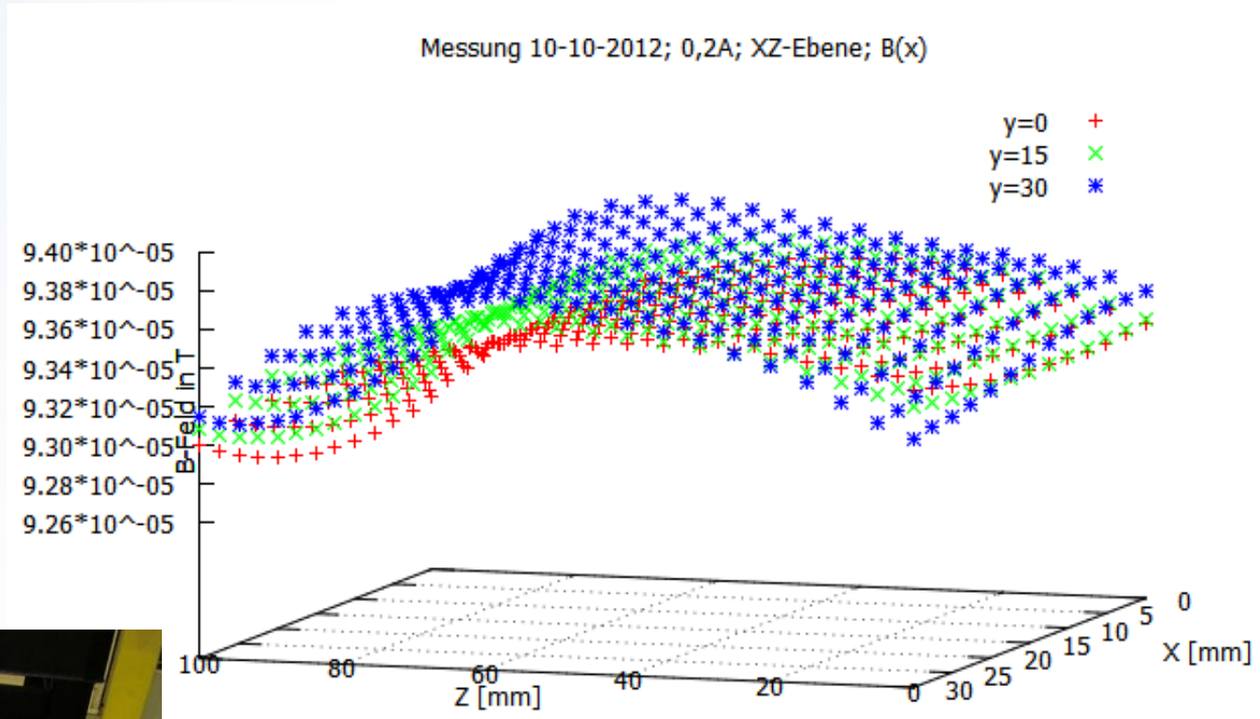


RF cavity

CONSTANT B-FIELD

Helmholtz coils

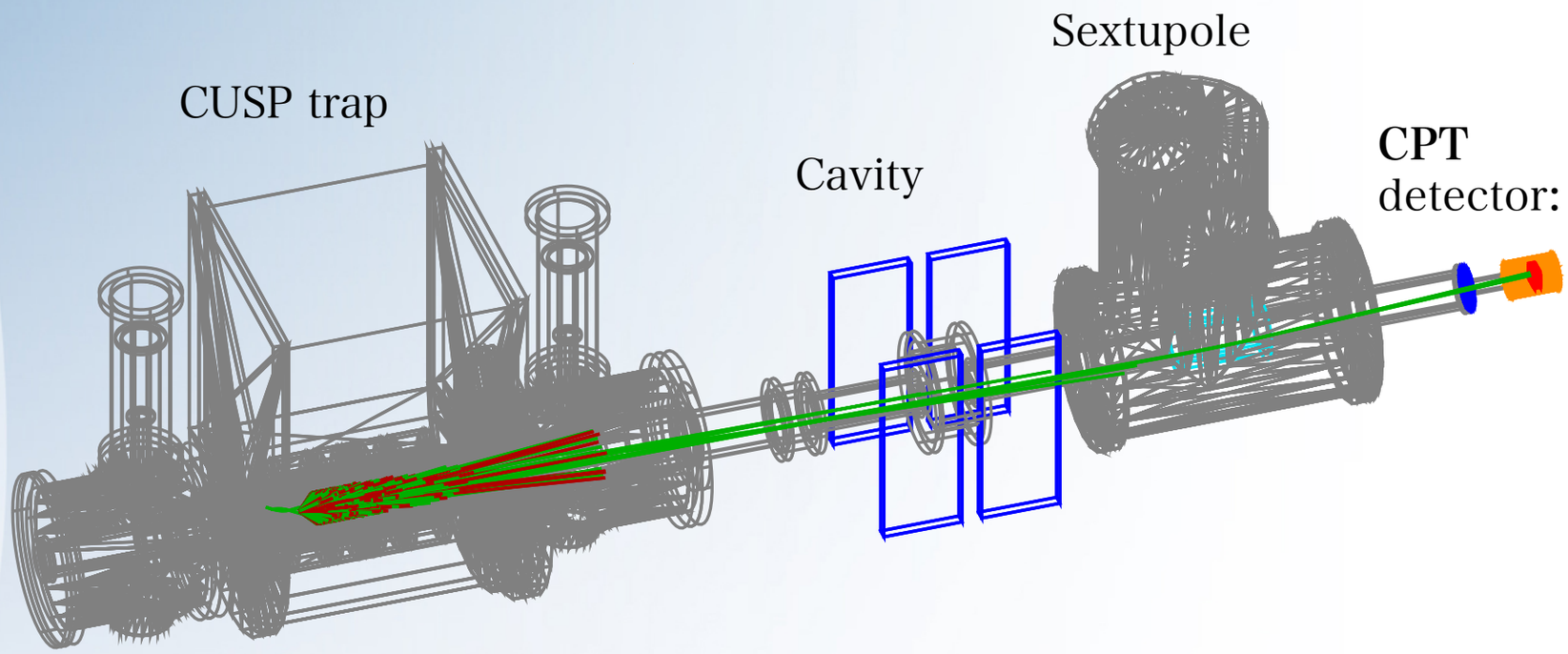




Fluxgate sensors

magnetic shielding

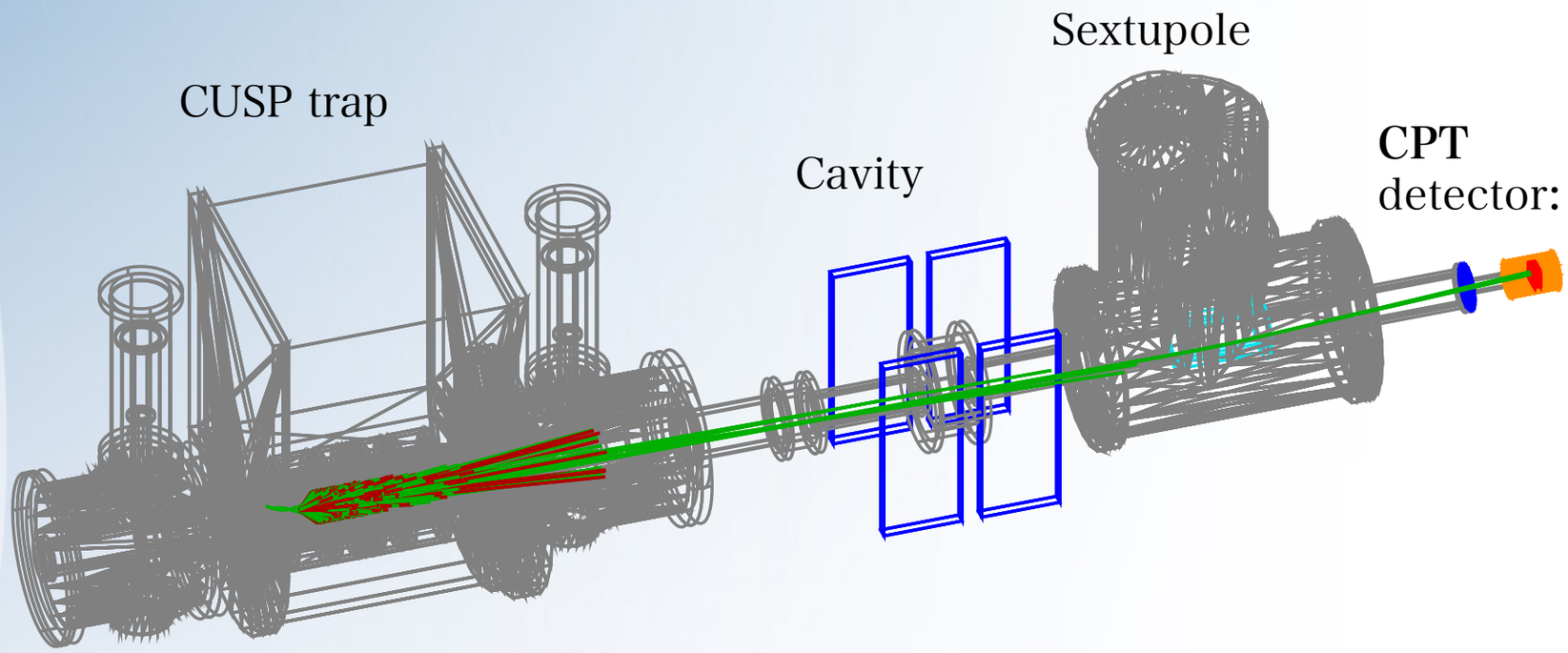
SIMULATION AND DATA



G4 studies:

- simulation of $\bar{H}$ trajectories in field
- background creation
- cosmics
- estimation of transition probabilities
- effect of homogeneities

SIMULATION AND DATA



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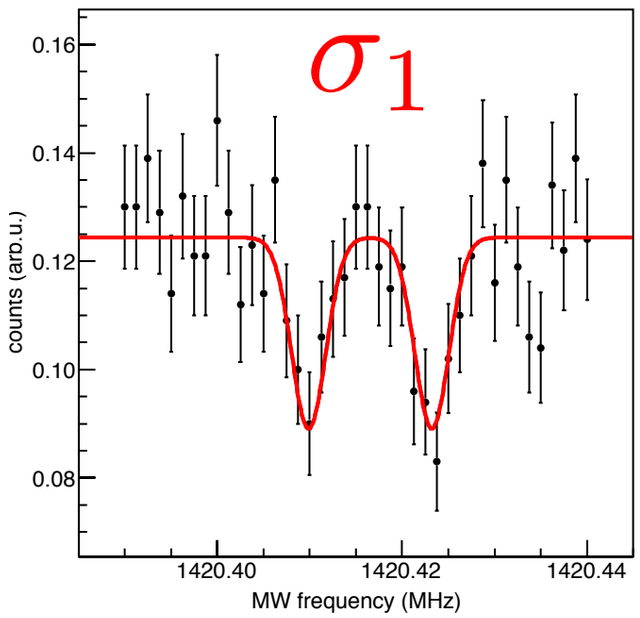
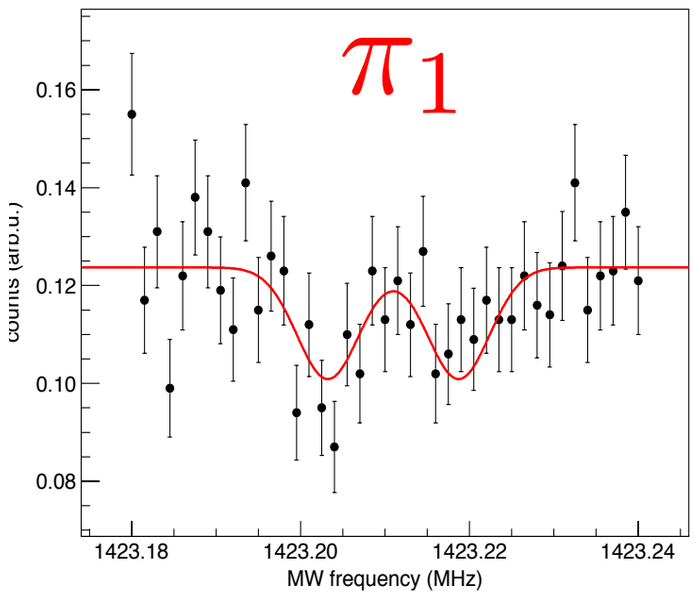
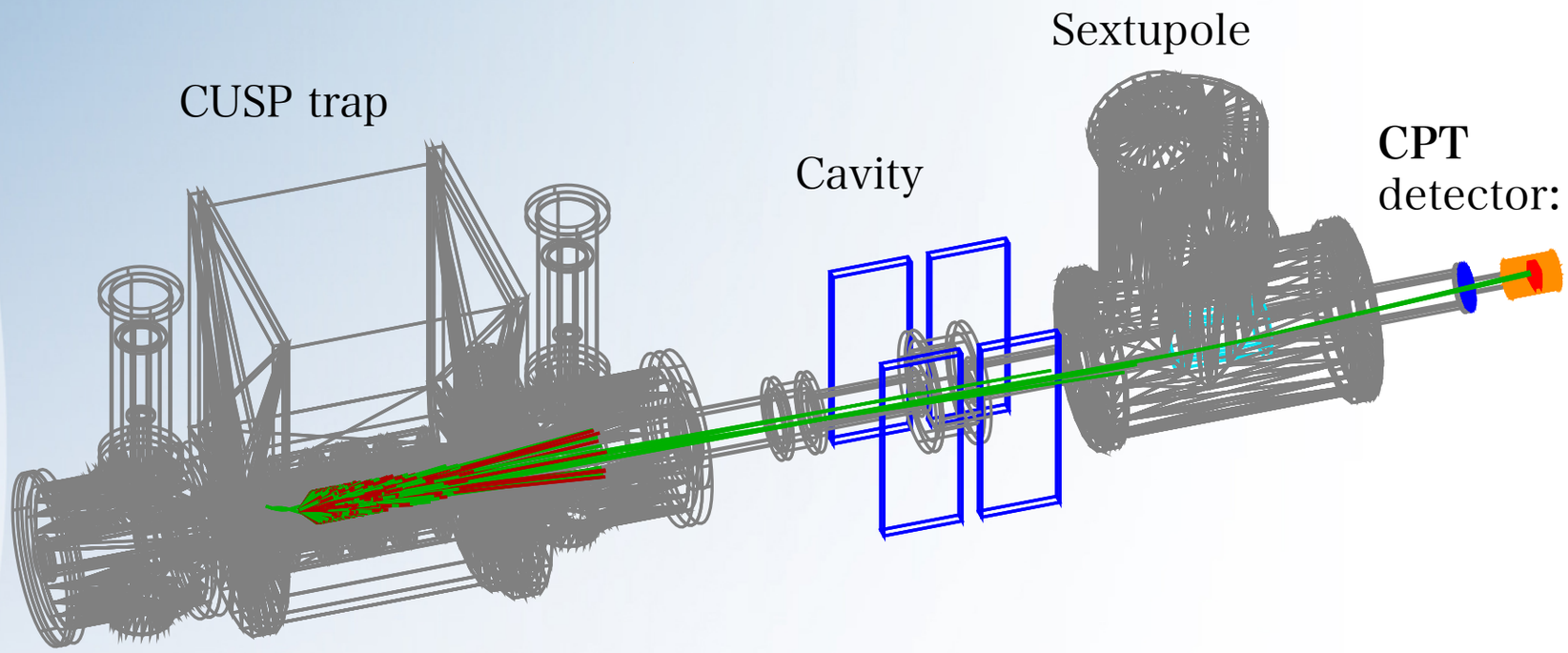




simulation done at 2G, T=50K

SIMULATION AND DATA



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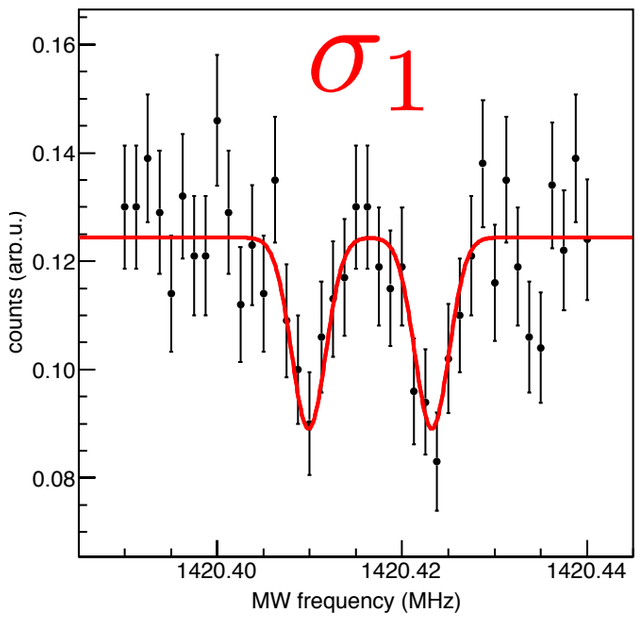

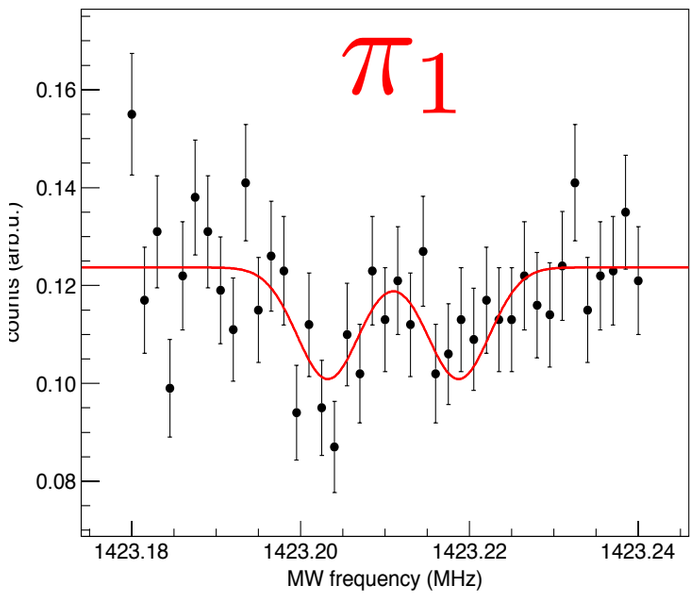

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needed: 2000 evts per scan

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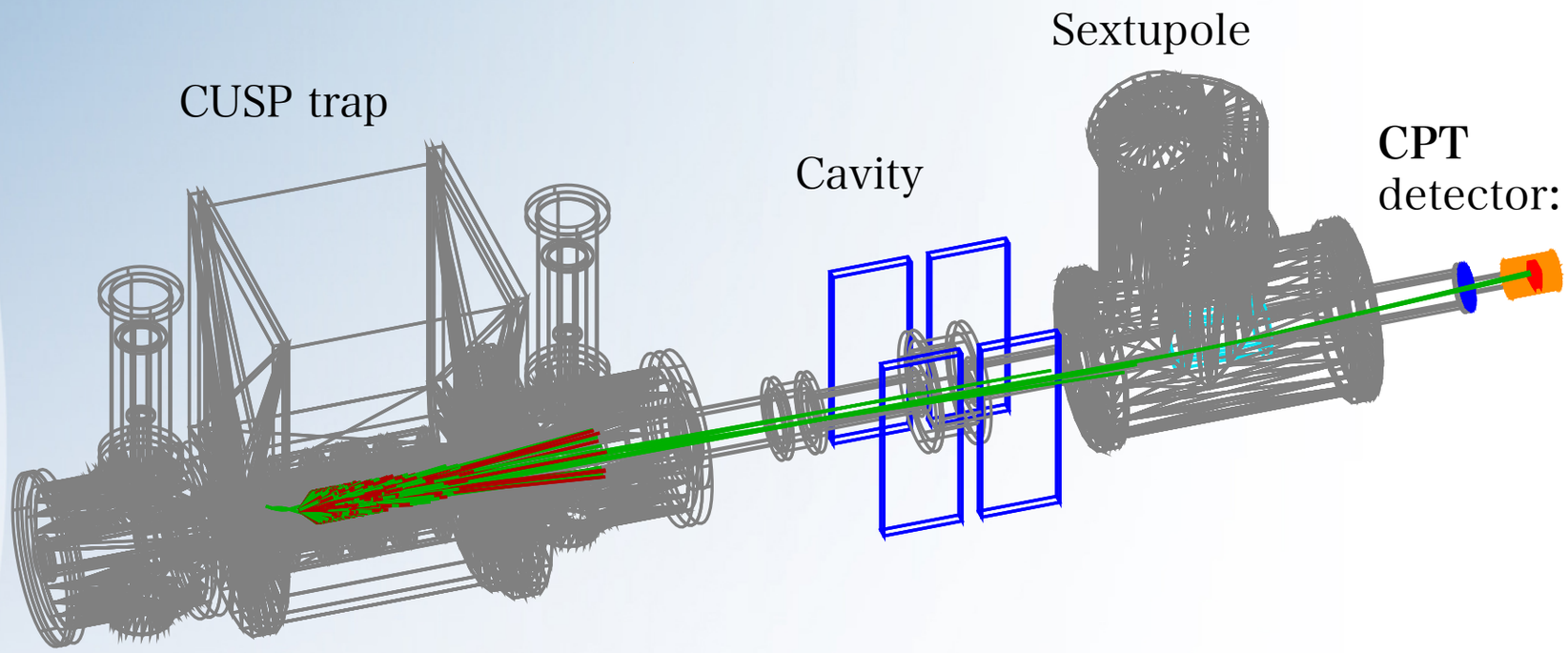

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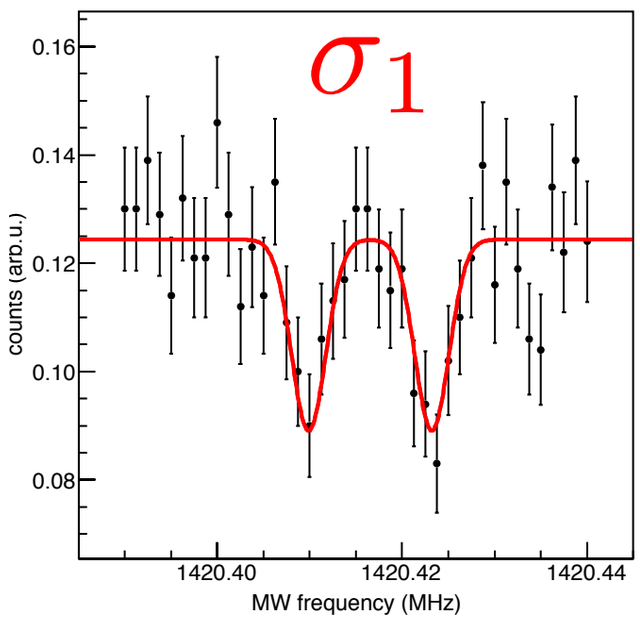
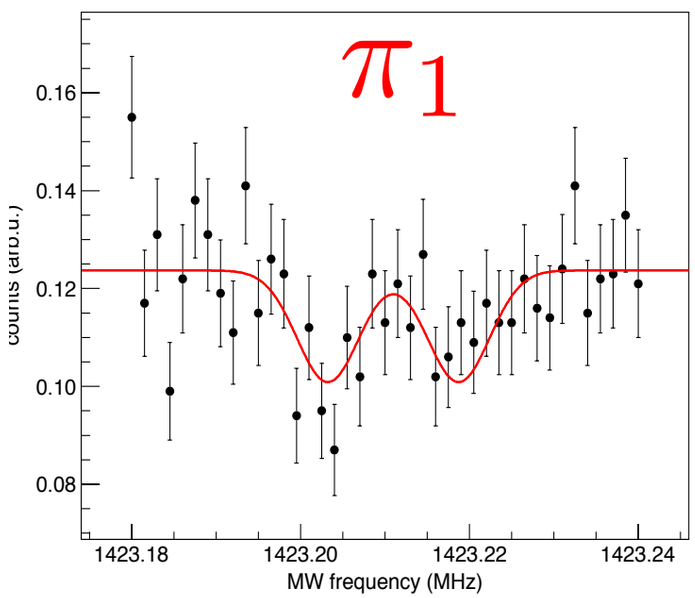
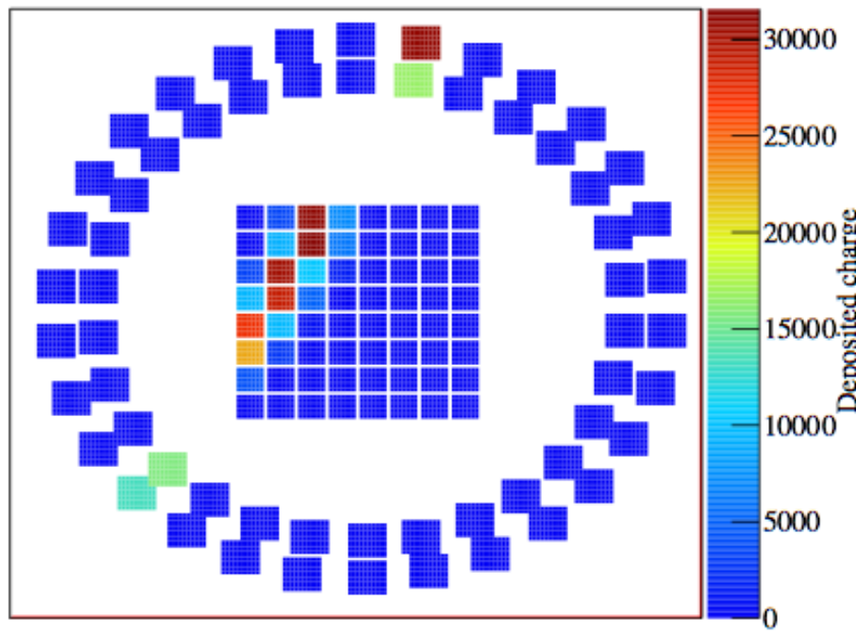






cosmic events in the CPT detector (2012)

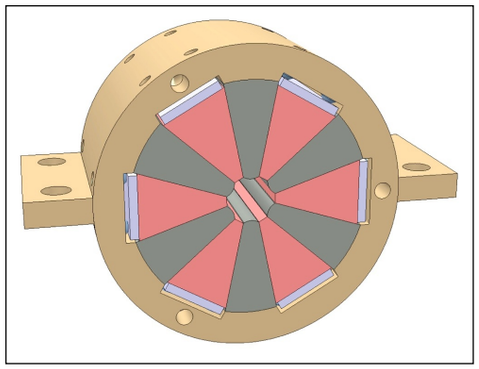
simulation done at 2G, T=50K

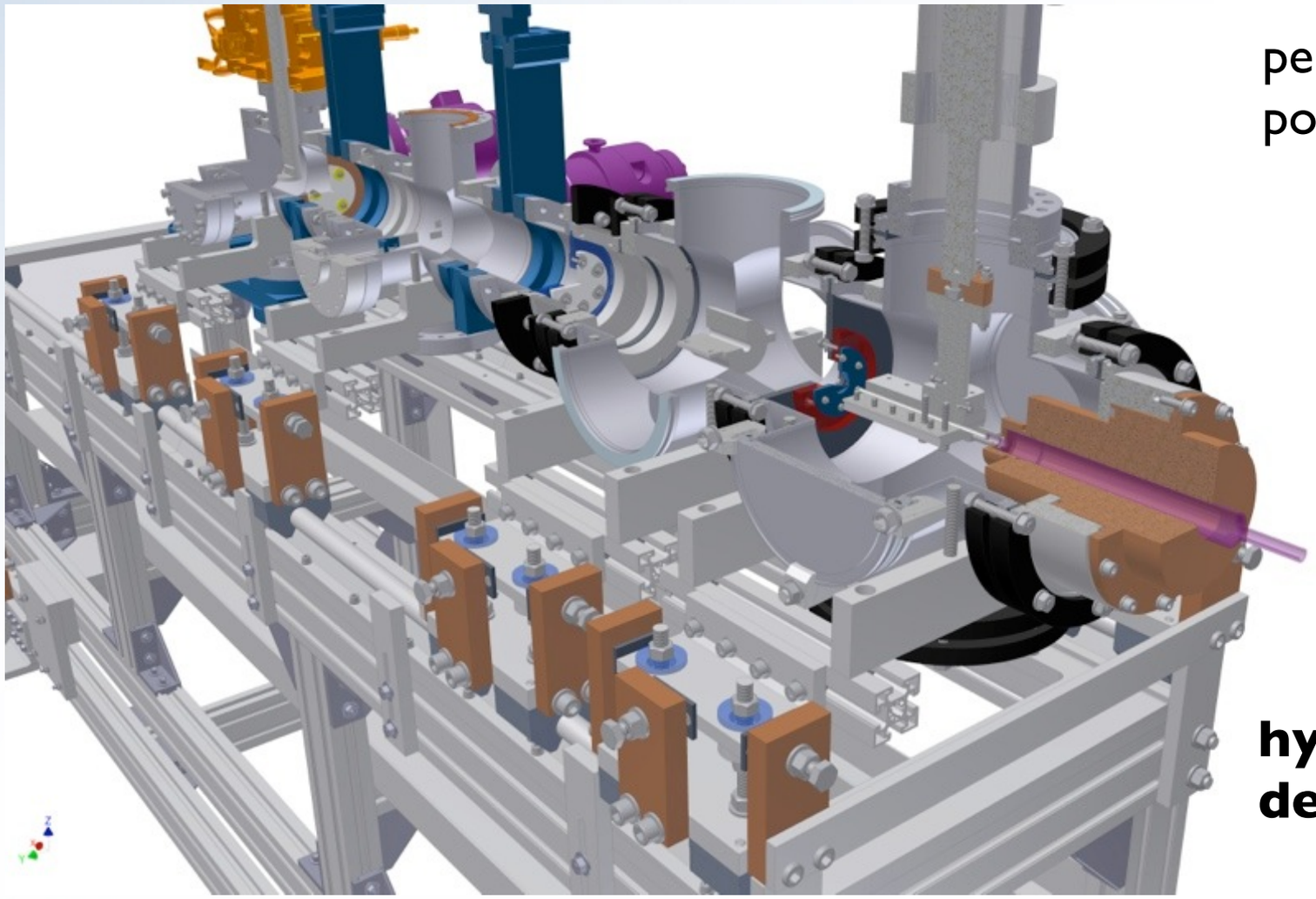
needed: 2000 evts per scan

SETUP TESTING DURING LS1

Polarized cold hydrogen beam:

- Source of atomic hydrogen (microwave discharge)
- Permanent sextupoles create polarized hydrogen beam
- QMS detect GS hydrogen
- Choppers connected to a lock-in amplifier for noise reduction





permanent sextupole for initial polarization developed at CERN

- 1.4 T integrated field
- 10mm inner diameter
- Permendur/permanent magnet

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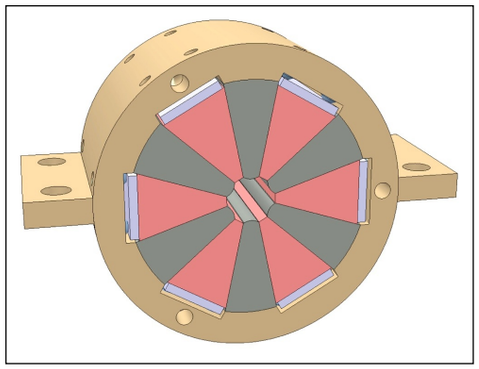

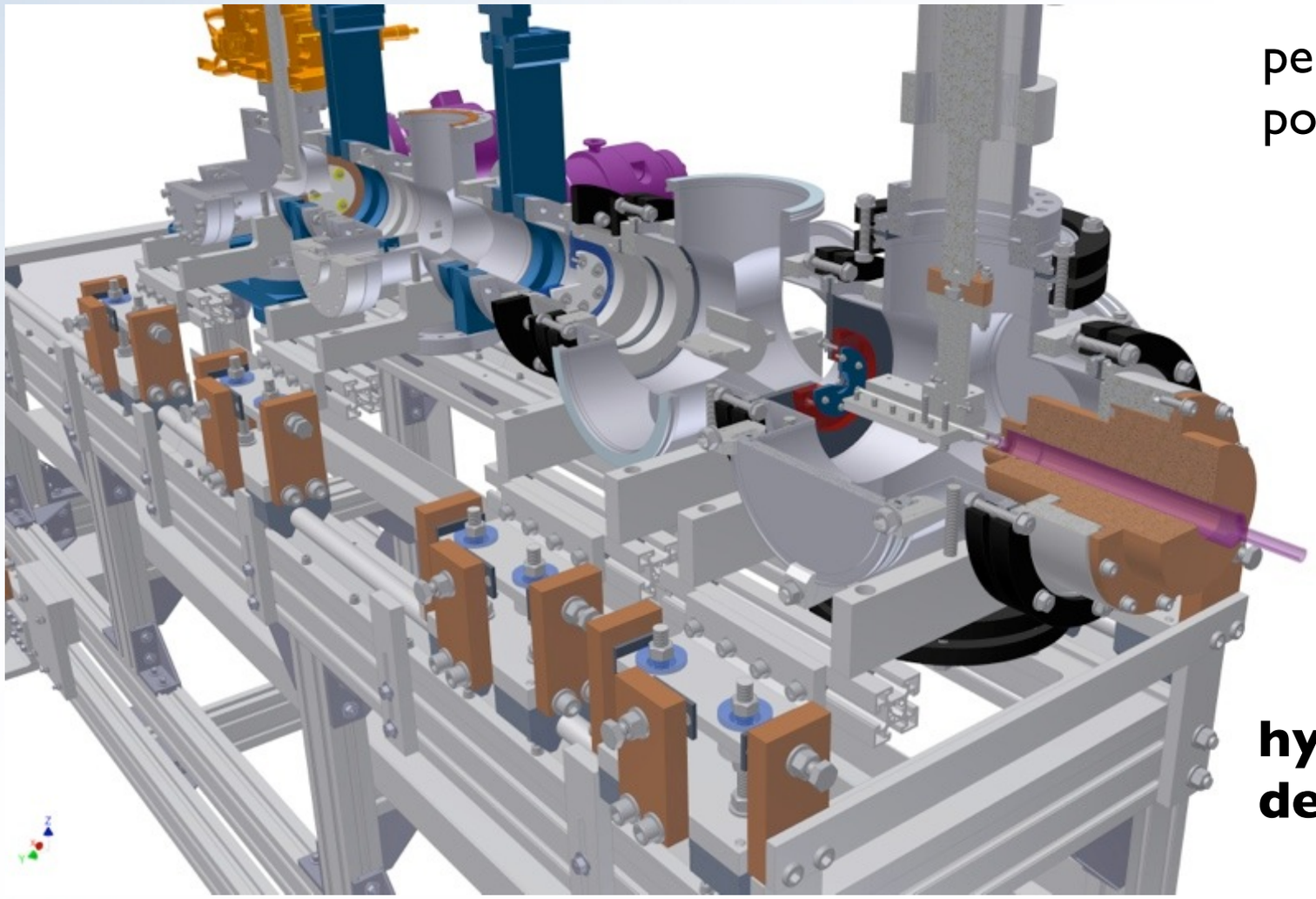

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H BEAM SETUP @ CERN-CRYOLAB

atomic hydrogen source

Cryogenic

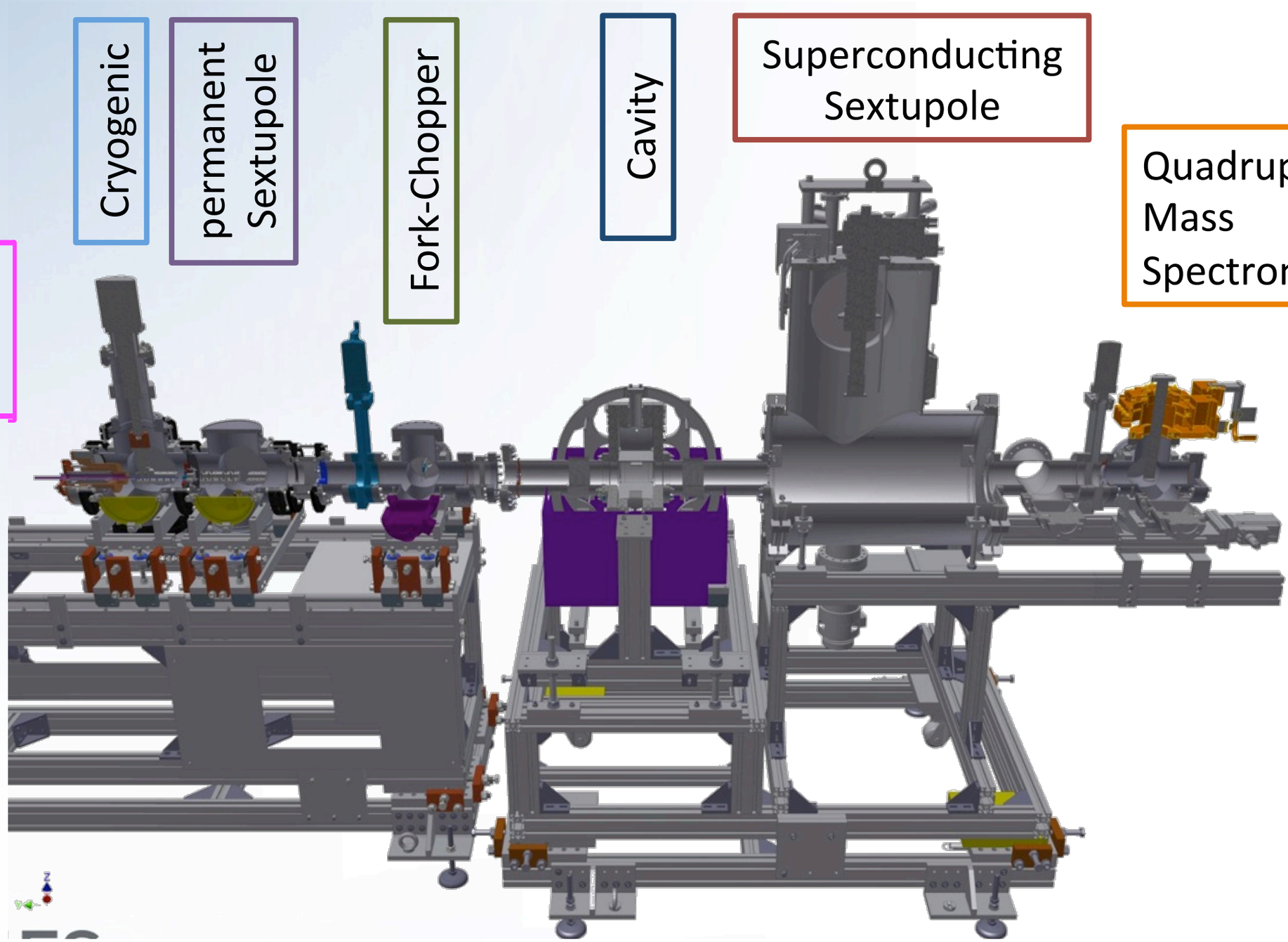
permanent Sextupole

Fork-Chopper

Cavity

Superconducting Sextupole

Quadrupole Mass Spectrometer



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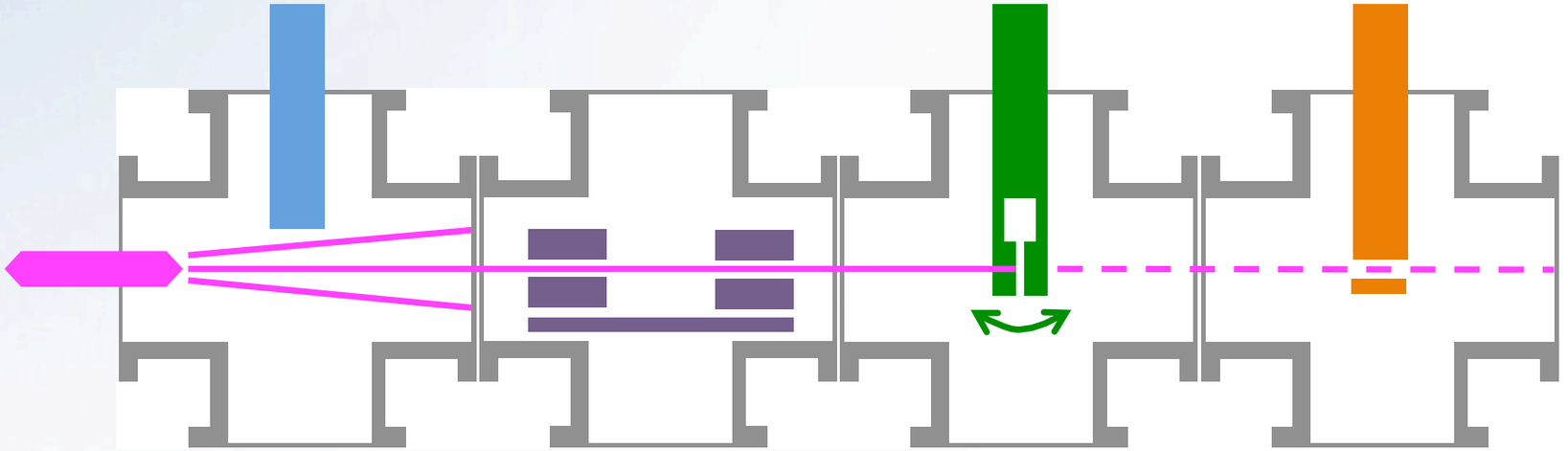
B BEAM SOURCE SCHEMATIC

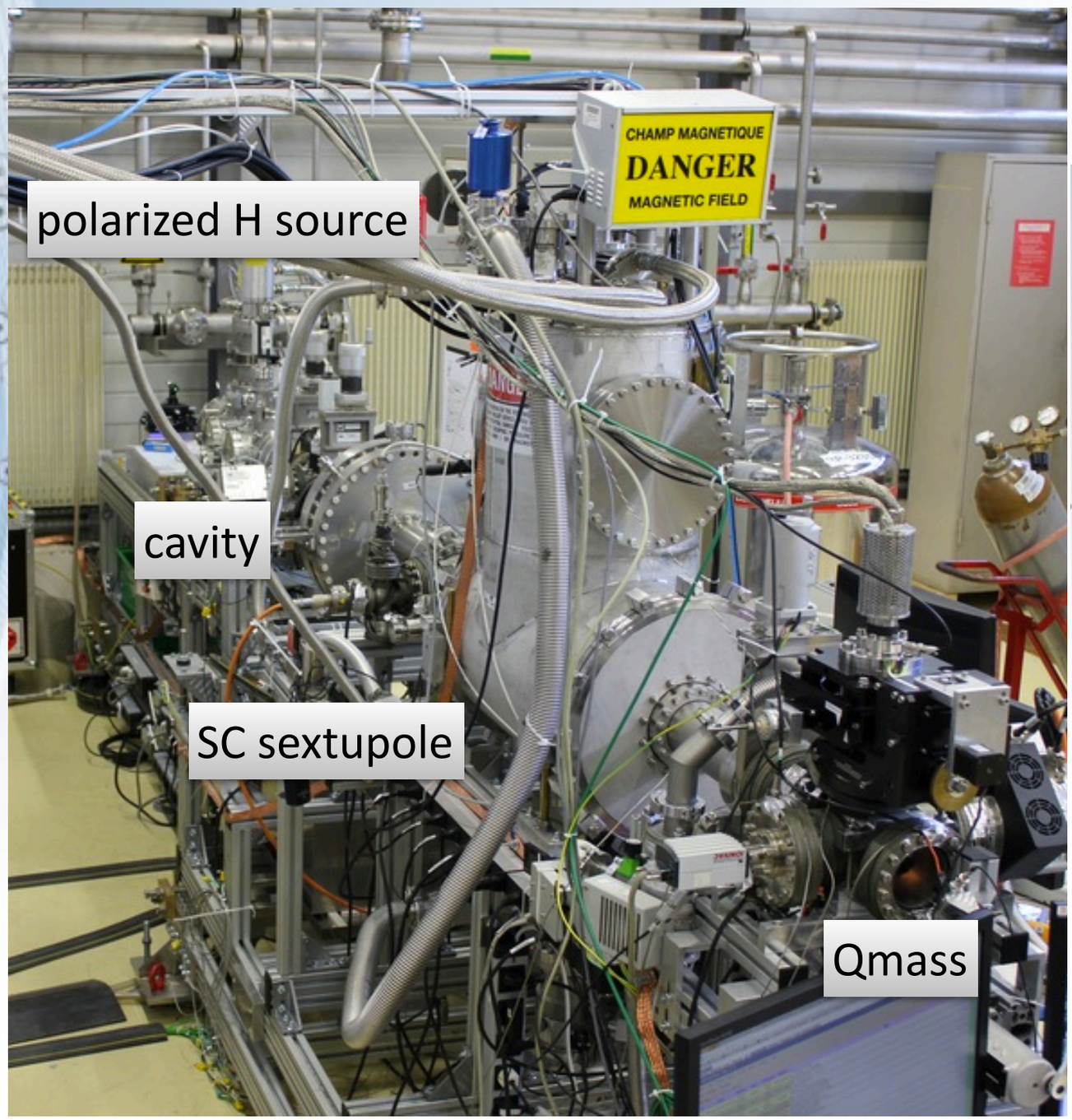
atomic H source	Cryogenic (cold head)	Sextupole	Fork-Chopper	Quadrup. Mass Spec.
ON → H and H_2 OFF → H_2 only	for 50-100K beam	for polarized beam	f ≈ 178 Hz 50% duty cycle	detects mass=1 H_1^+ or mass=2 H_2^+

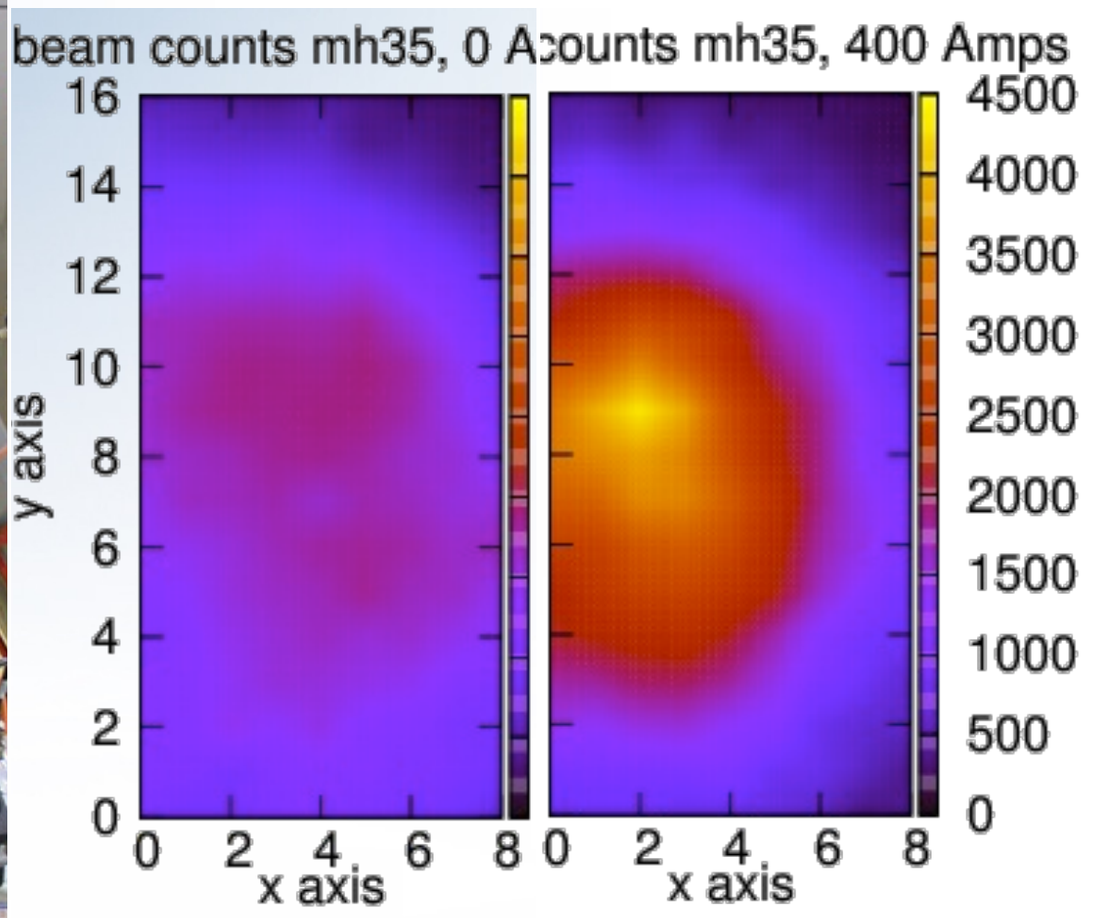


Parameters

Microwave Power & Frequency H_2-flow rate	temperature tube dimensions	velocity selection (distance)	Amplitude	Ionization & Transport (5 Parameters) Mass Scan Line Detector

HYDROEN BEAM LINE TEST SETUP@CERN

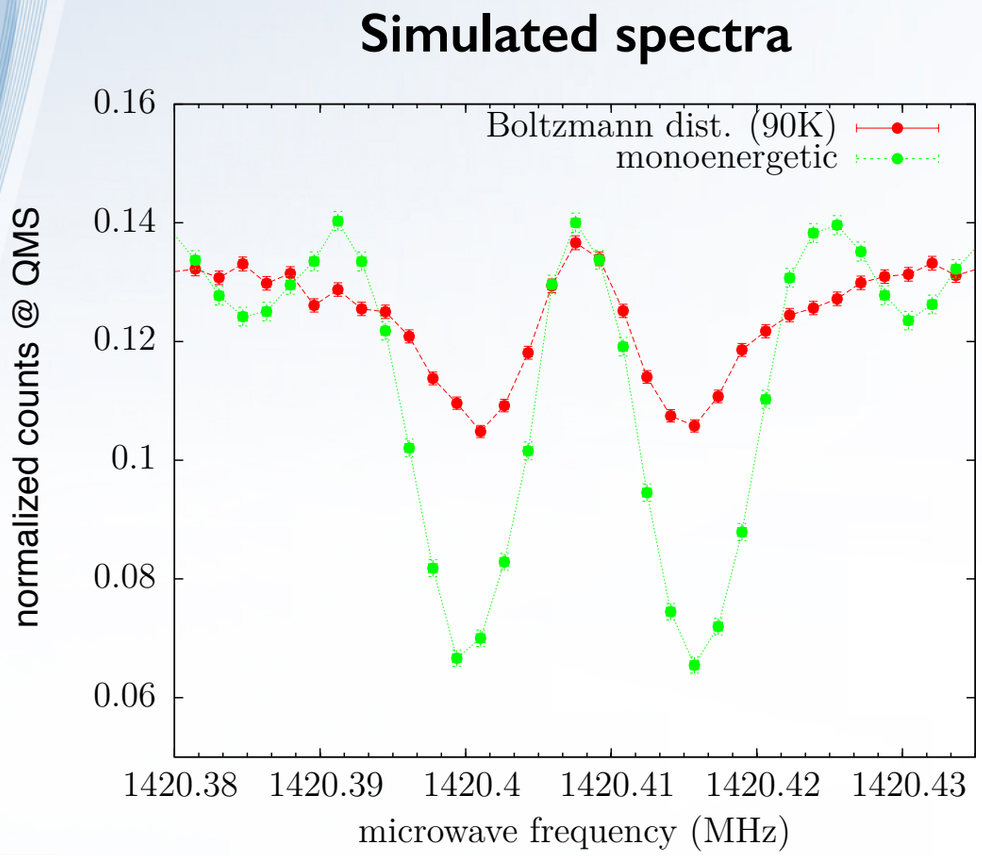




beam focussing by superconducting sextuple observed

1st H RESONANCE SCAN: σ_1

- NO MAGNETIC SHIELDING
- EARTH MAGNETIC FIELD OF 20 µT
- CAVITY L=10 CM



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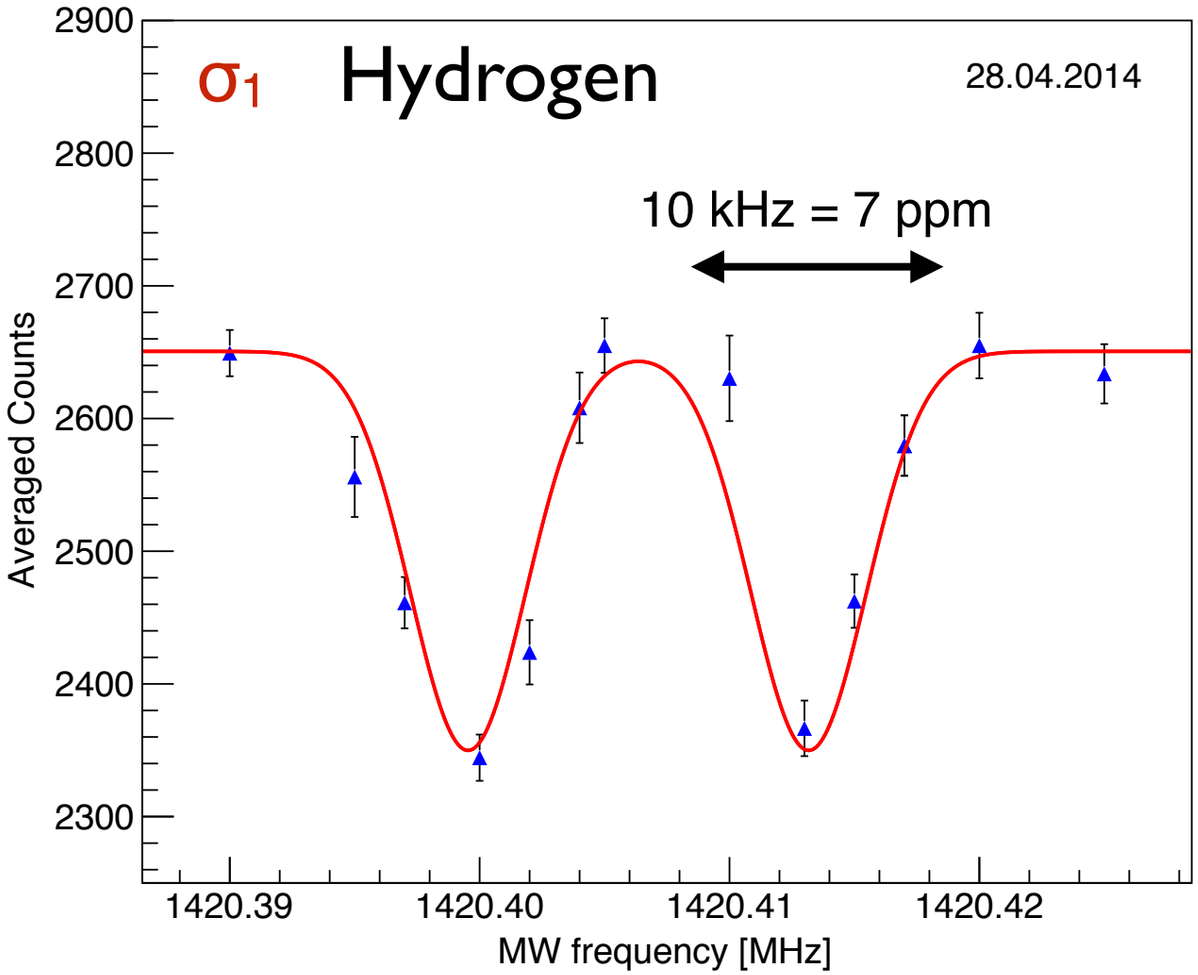
Simulated spectra



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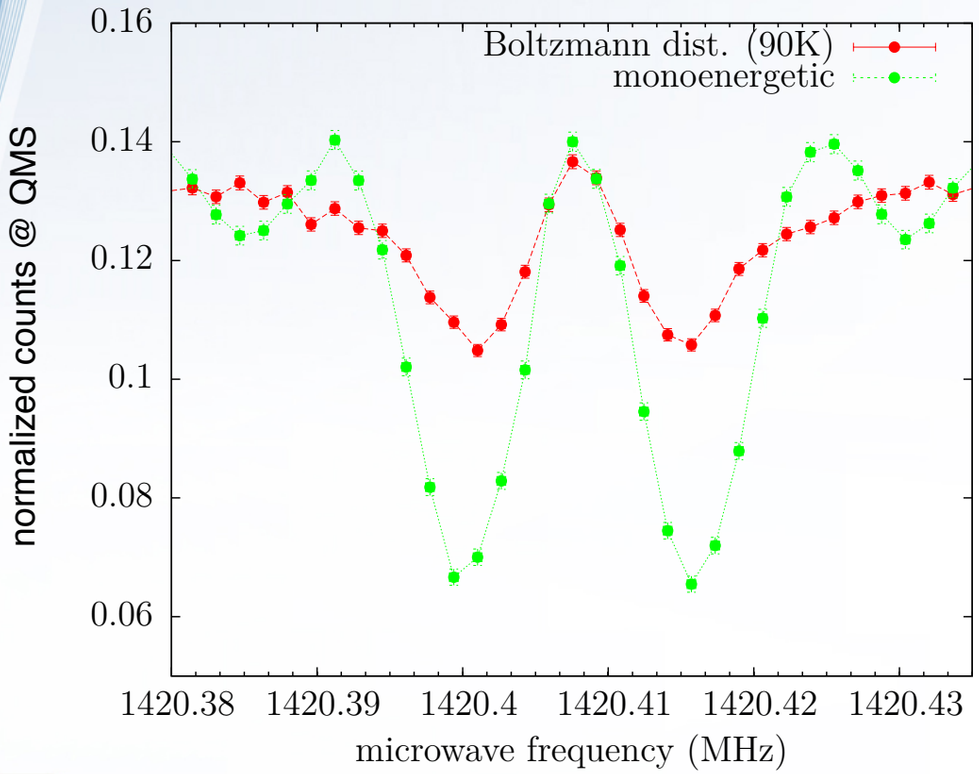

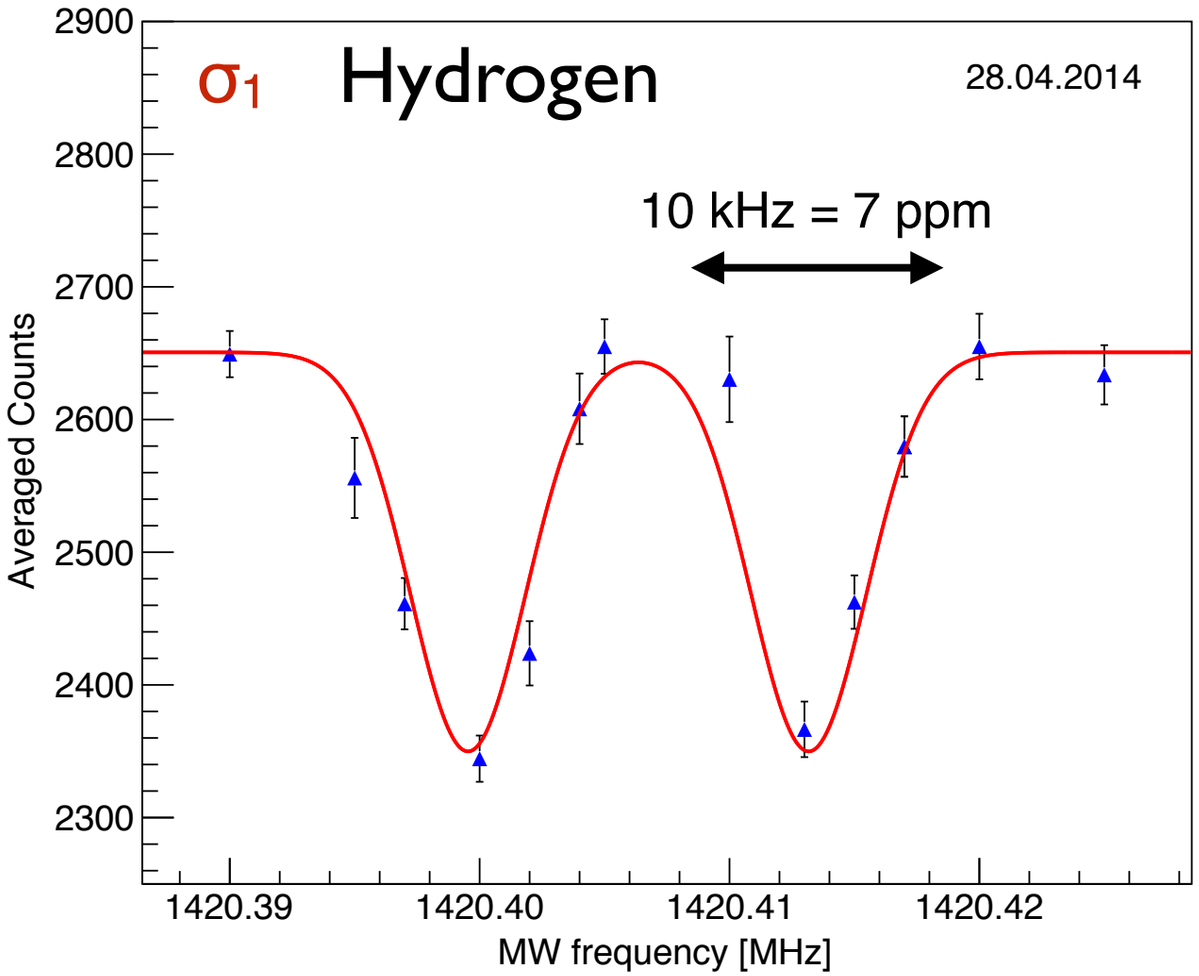

	ν(MHz)	Error (Hz)/ deviation	Rel error/ deviation
Resonance center	1 420.406 354	133	9E-08
ν_{HF}	1 420.405 751 768	603	4E-07

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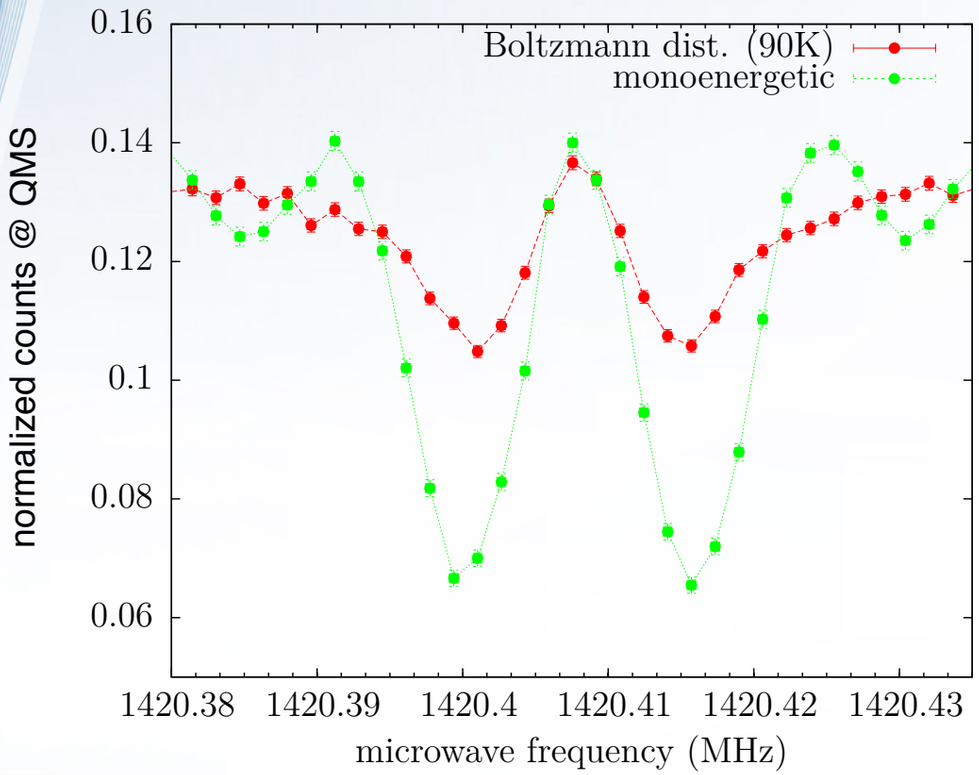

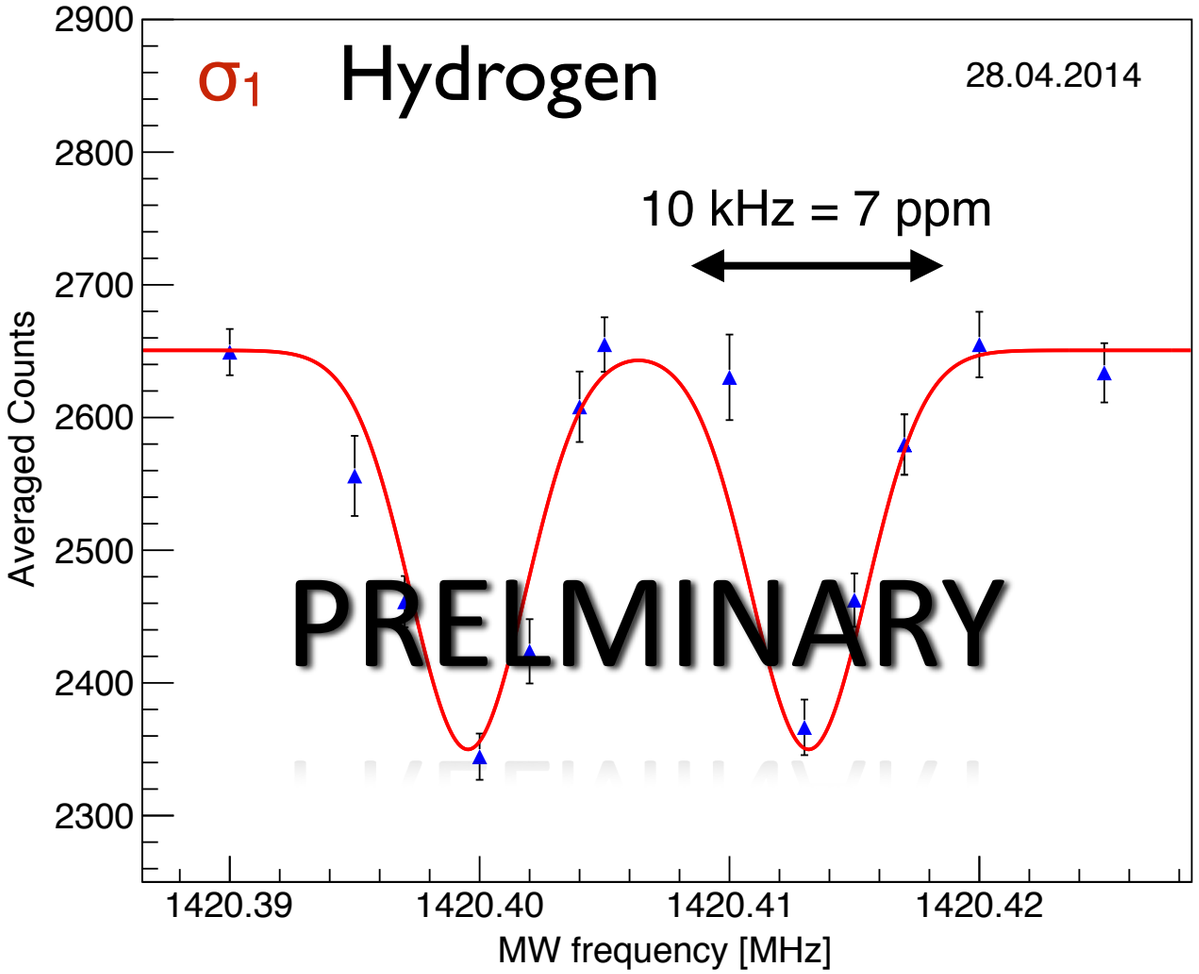

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2nd H RESONANCE SCAN: π_1

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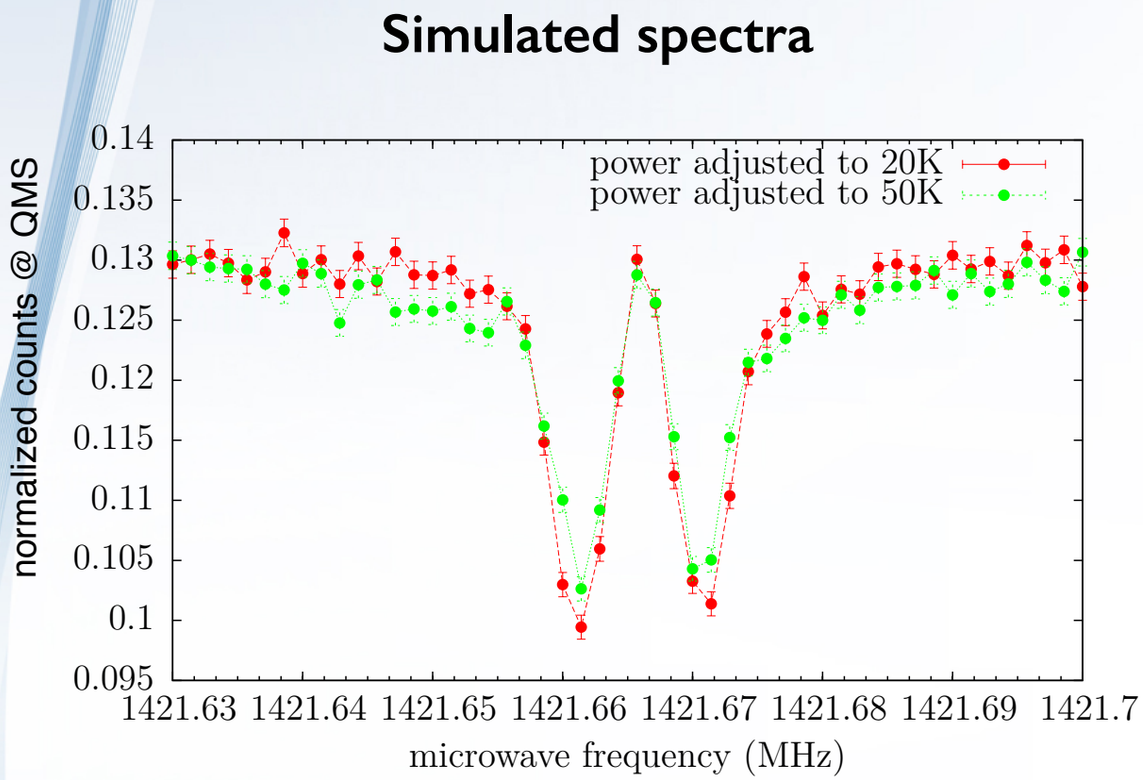

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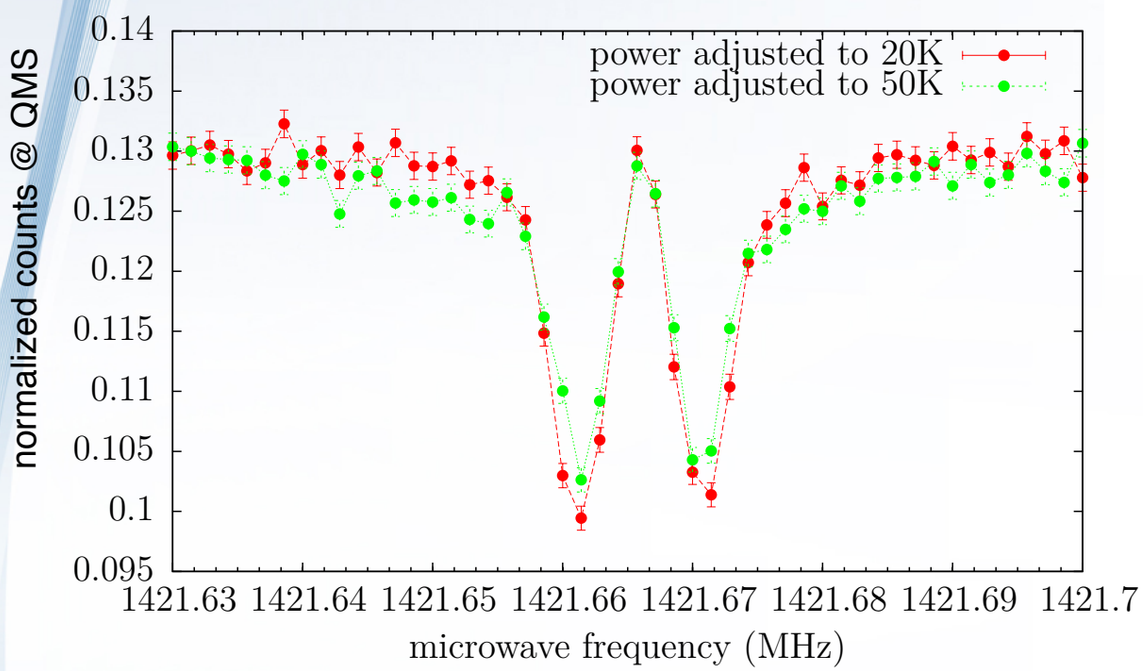

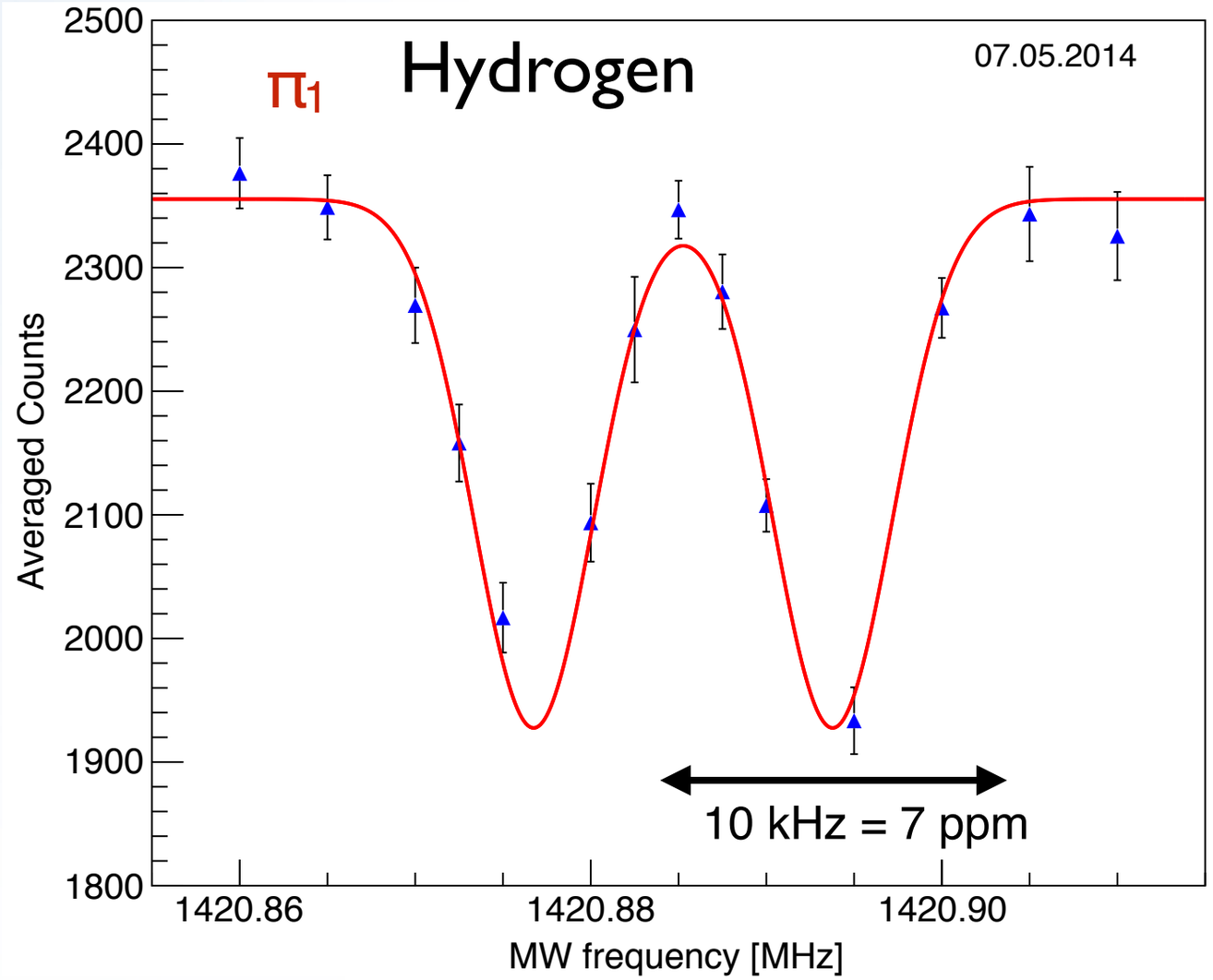

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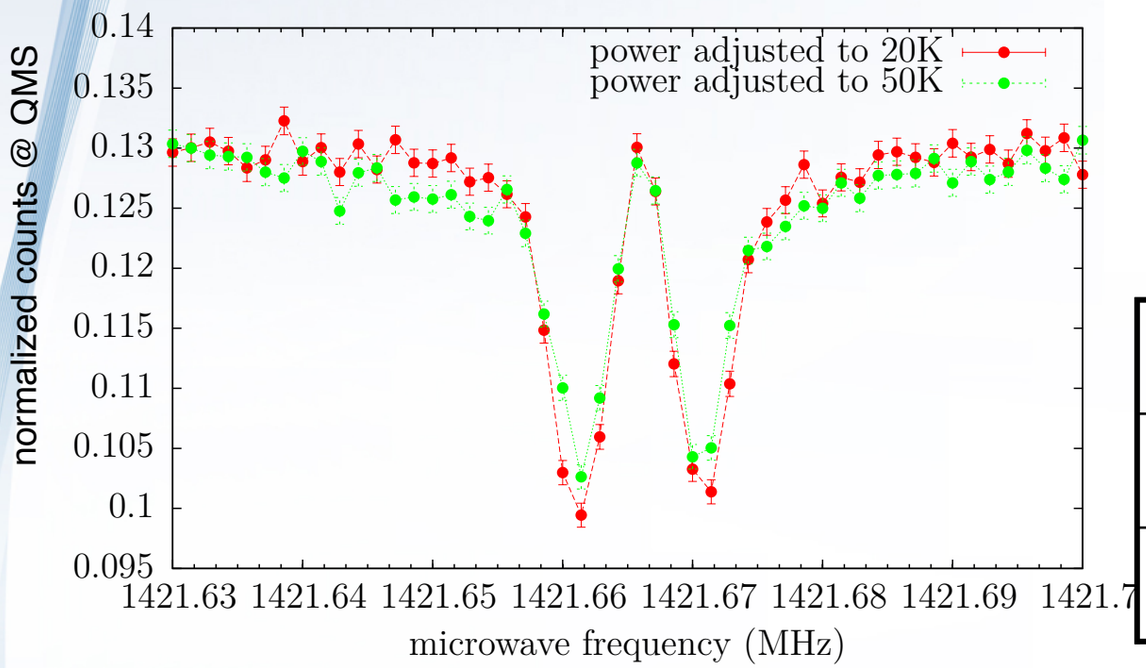

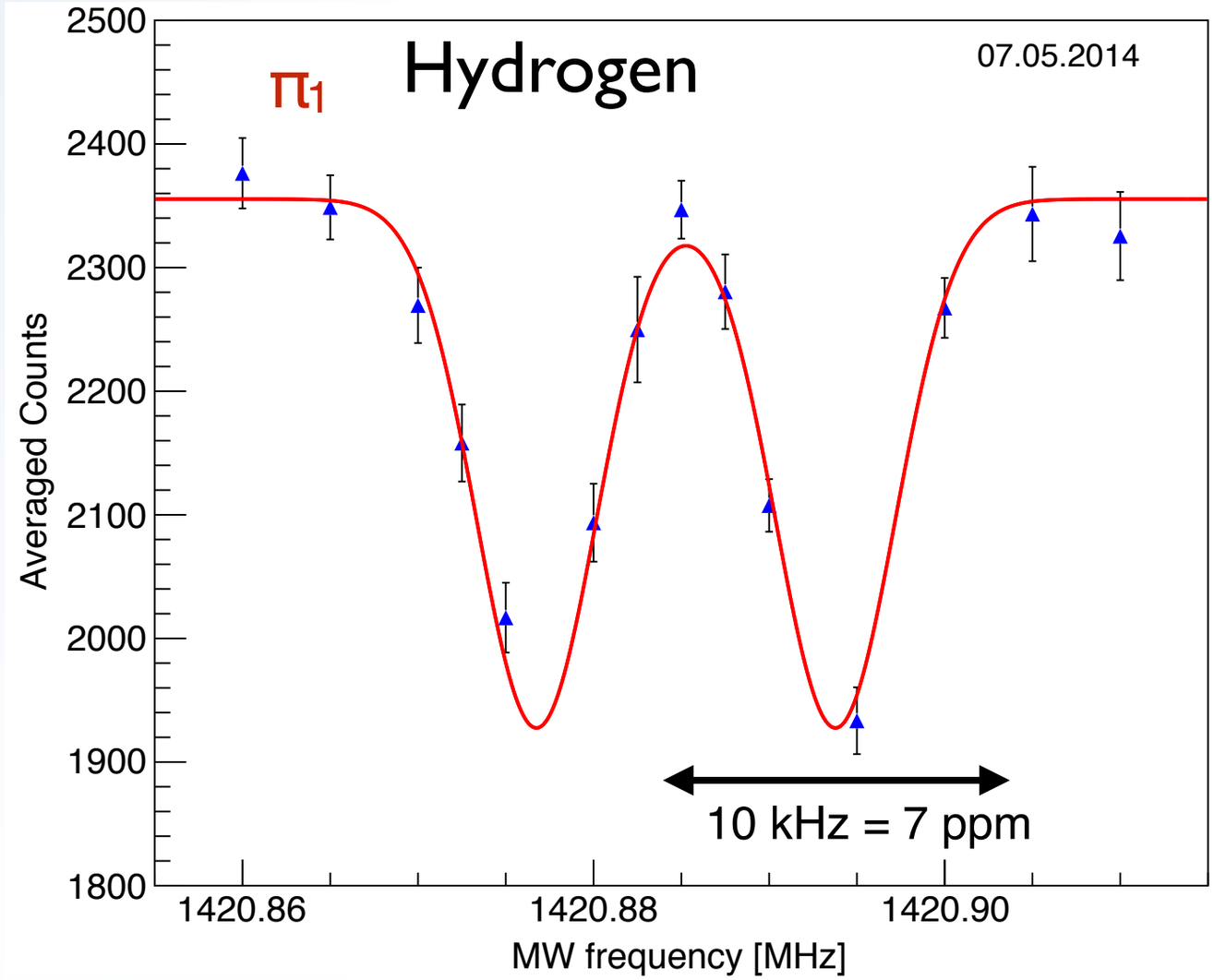

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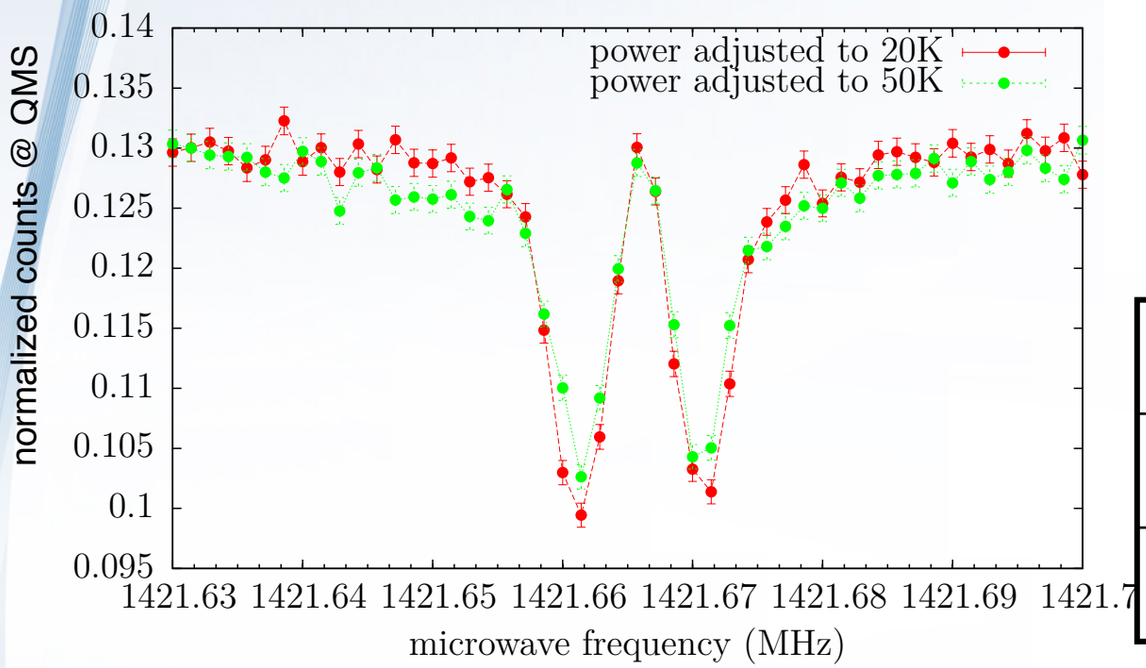

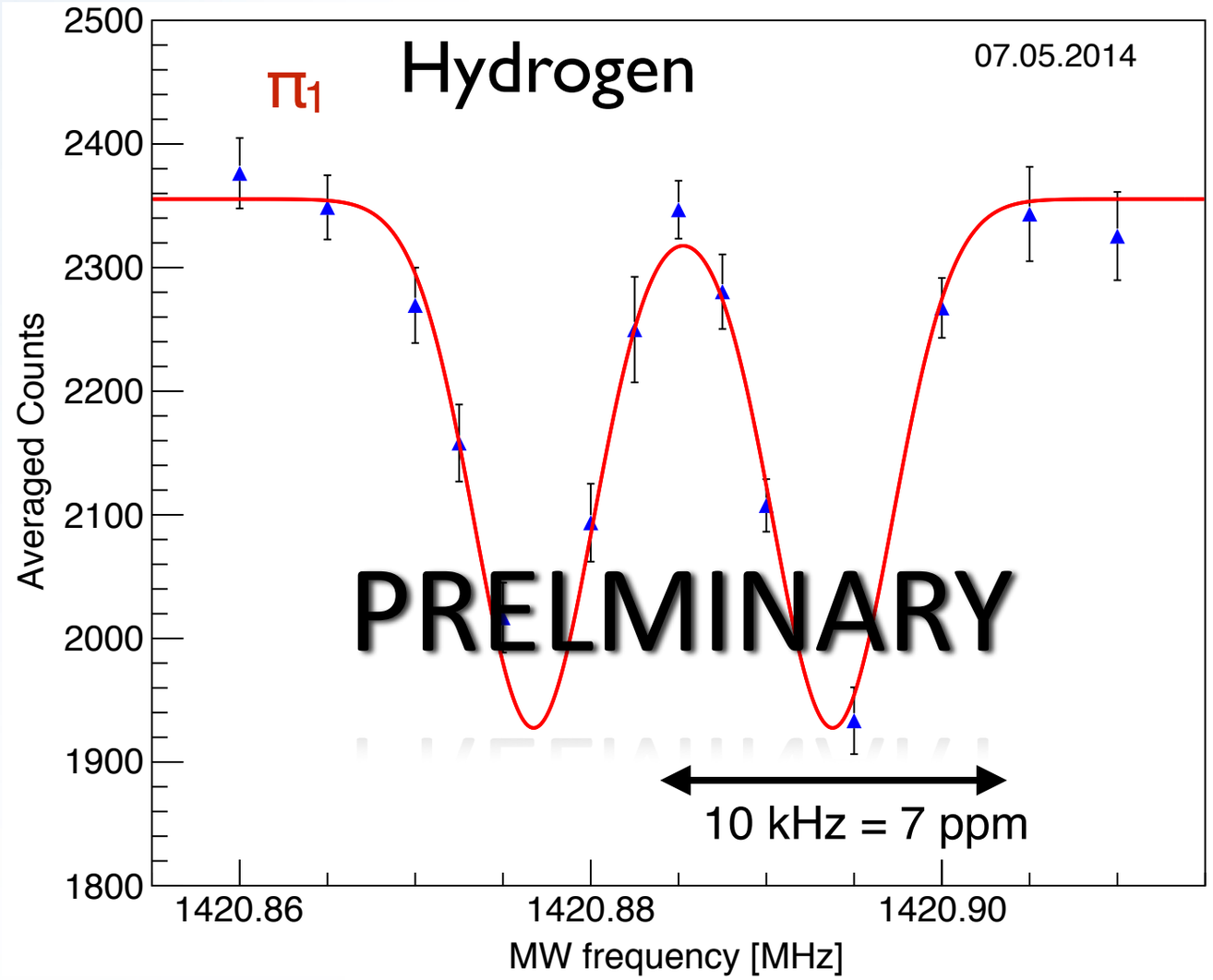

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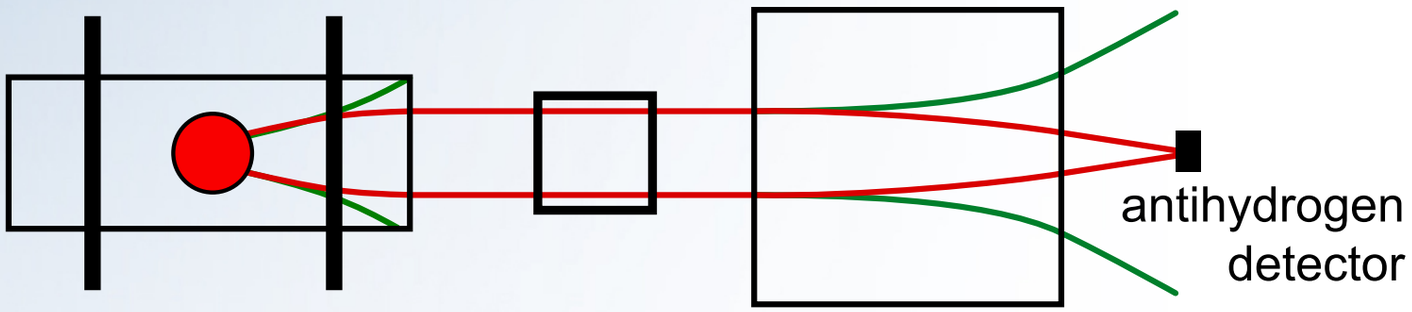
EXPERIMENTS IN AN ATOMIC BEAM

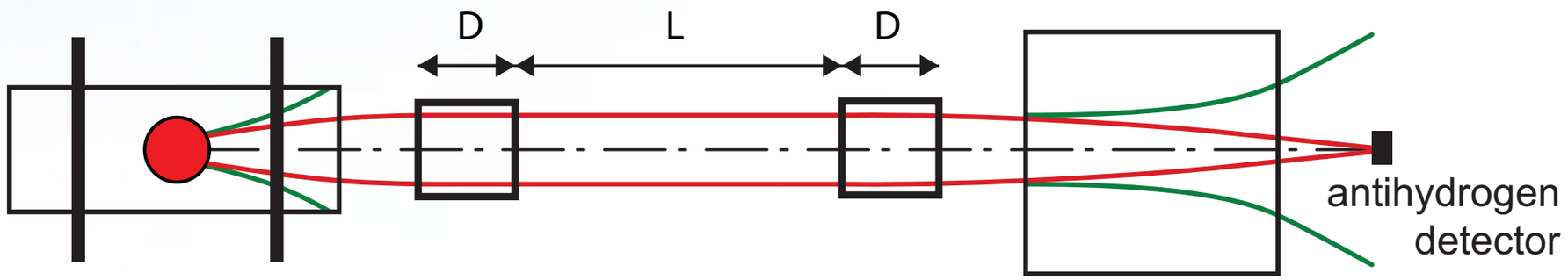
- Phase 1 (ongoing): Rabi method



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

cusp trap microwave cavity sextupole 1

- Phase 2: Ramsey separated oscillatory fields



cusp trap microwave cavity 1 microwave cavity 2 sextupole 2

Linewidth reduced by D/L

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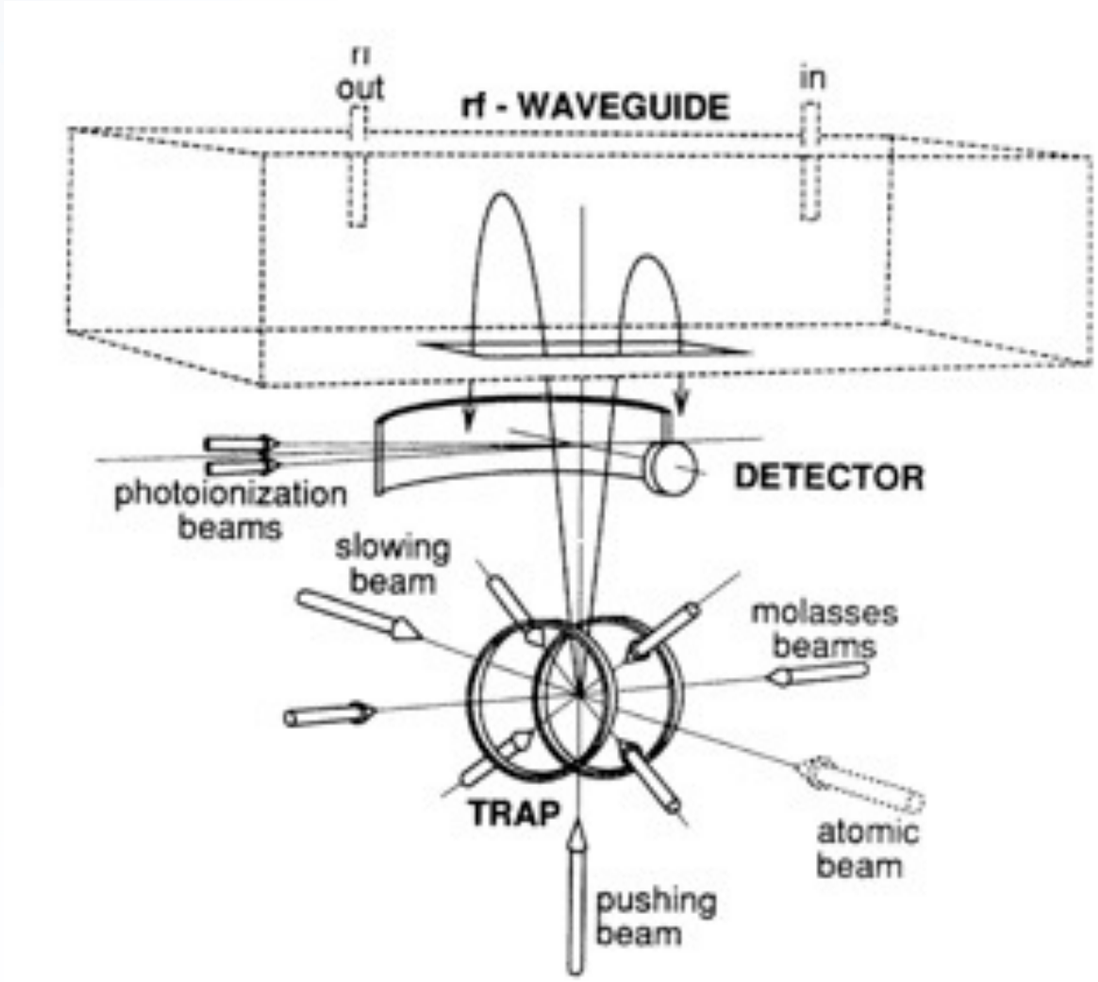
(FAR) FUTURE EXPERIMENTS

- PHASE 3: TRAPPED $\bar{H}$
  - 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
    - $\Delta f \sim 3$ Hz, $\Delta f/f \sim 2 \times 10^{-9}$



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

SUMMARY

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

SUMMARY

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry

Bundesministerium für Wissenschaft, Forschung und Wirtschaft

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- Time scale of precision experiments is 5-10 years

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HHHFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

THANK YOU FOR YOUR ATTENTION

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