Antiprotonic Helium and CPT Invariance

Eberhard Widmann

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Antiprotonic helium and CPT invariance

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ASACUSA collaboration @ CERN-AD

Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

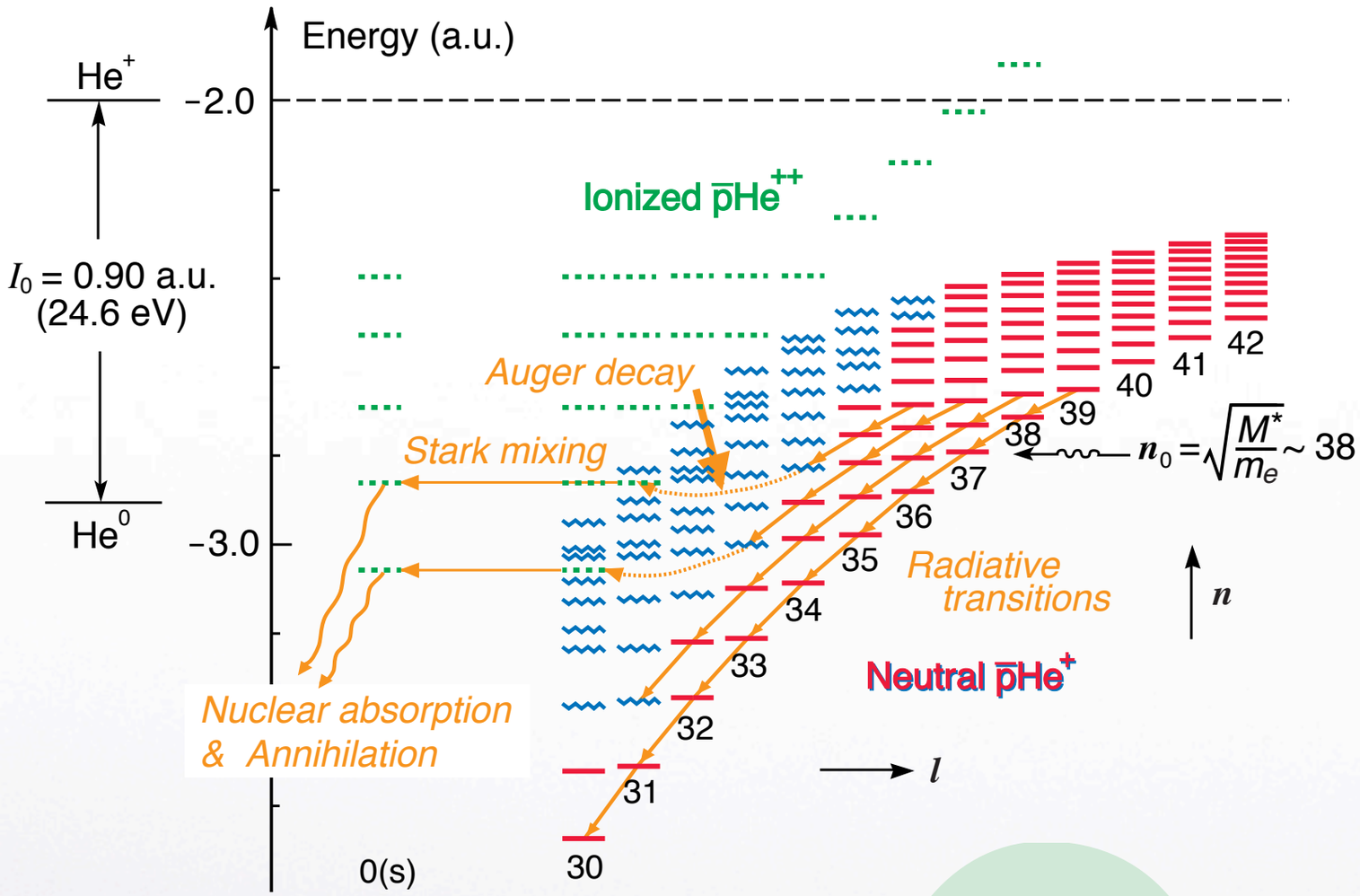
Atomic **S**pectroscopy **A**nd **C**ollisions
Using **S**low **A**ntiprotons

Spokesperson: R.S. Hayano, University of Tokyo

- University of Tokyo, Japan
  - College of Arts and Sciences, Institute of Physics
  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University & ISA, Denmark
- Niels Bohr Institute, Copenhagen, Denmark
- Max-Planck-Institut für Kernphysik, Heidelberg, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- University of Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen's University of Belfast, Ireland

~ 44 members

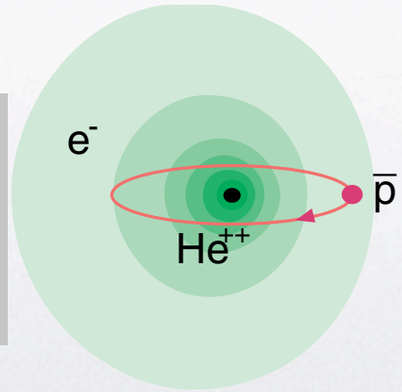
Antiprotonic helium



Metastable states
τ~ μs

short-lived states
(Auger decay)
τ ≤ 10 ns

Atom+molecule: atomcule



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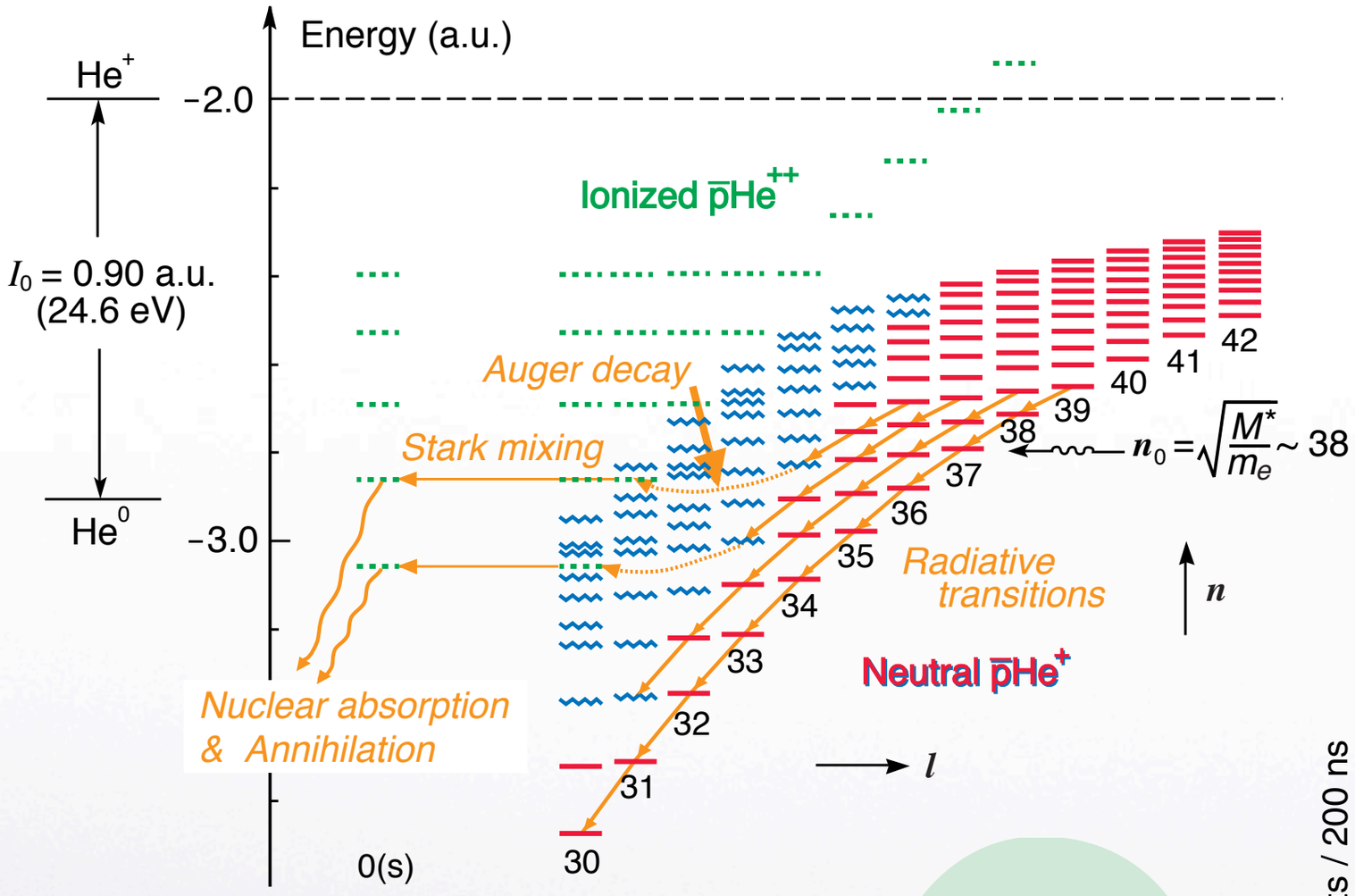

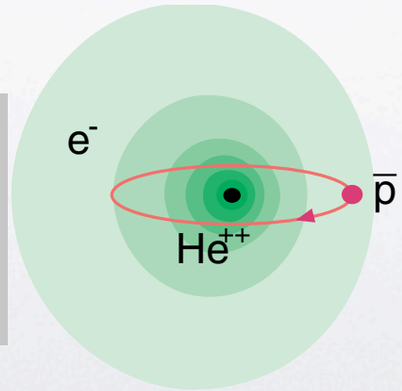

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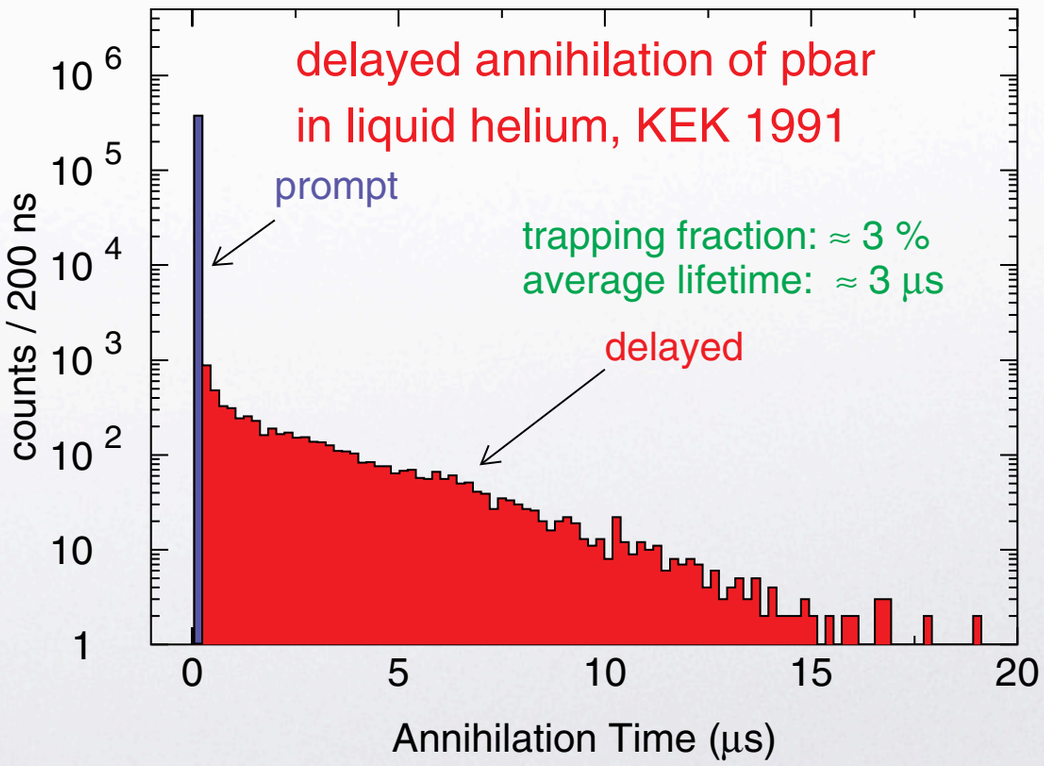
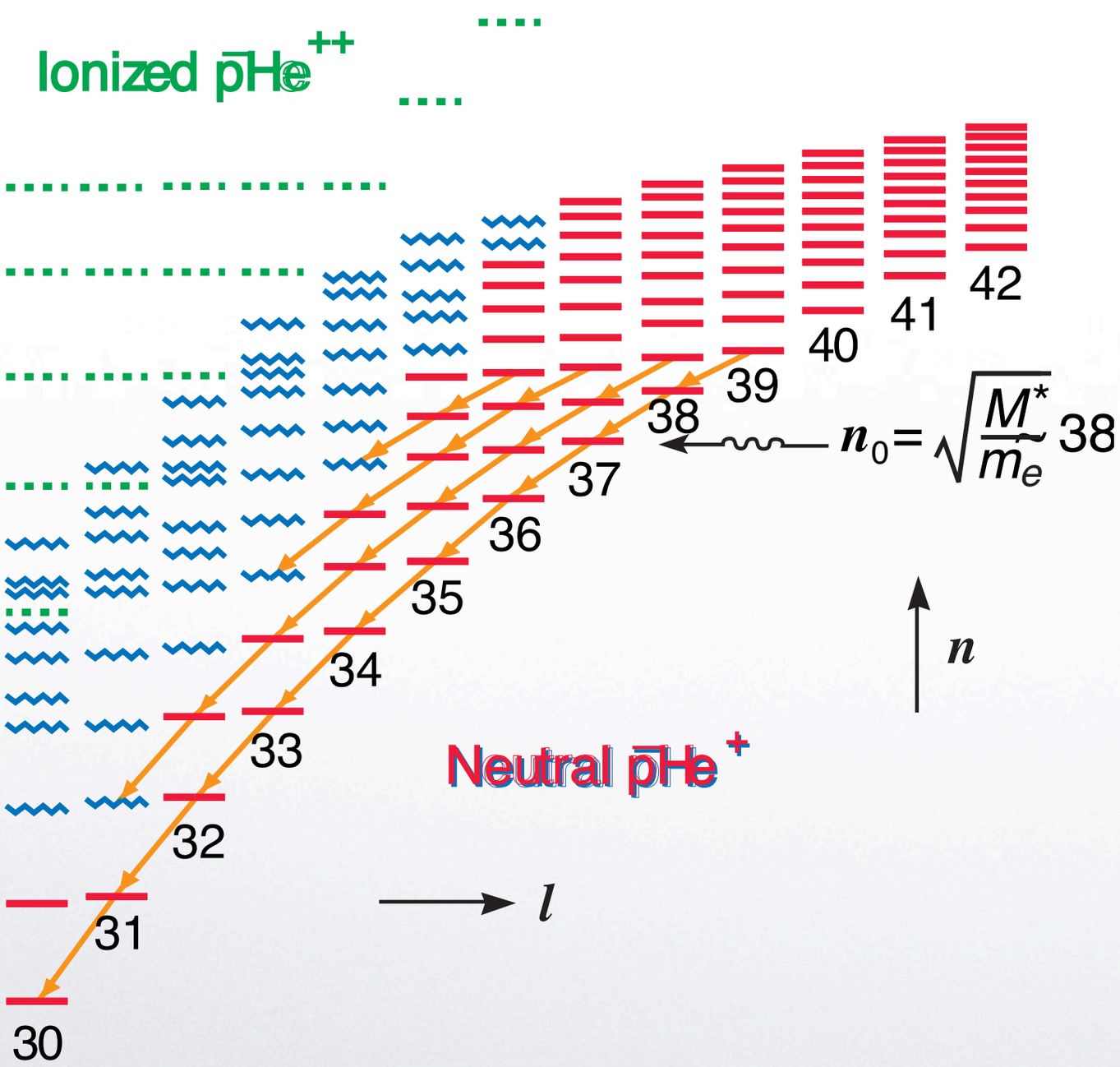


Precision spectroscopy



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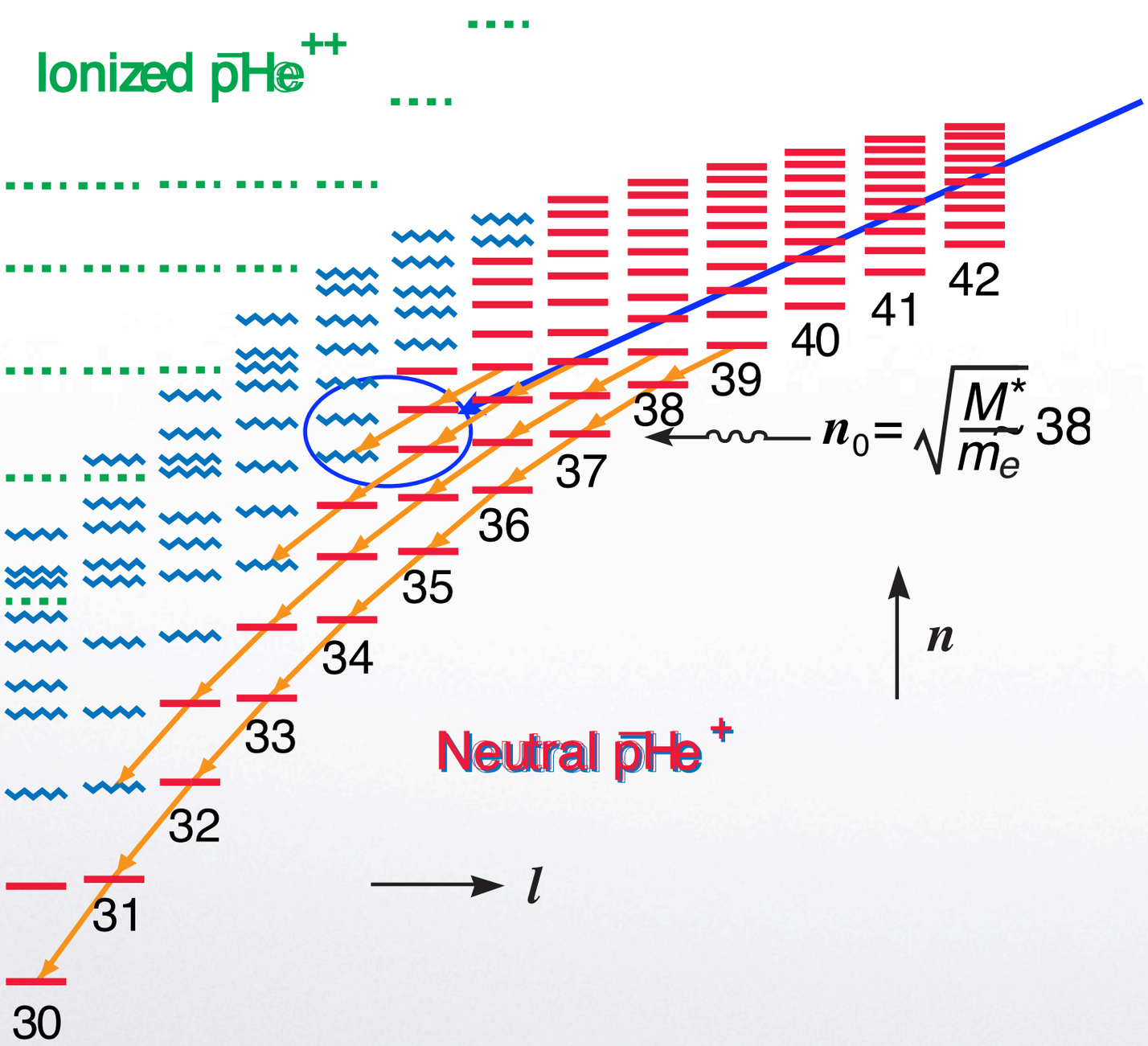

- pairs of metastable - short-lived state
- laser spectroscopy
- antiproton charge and mass

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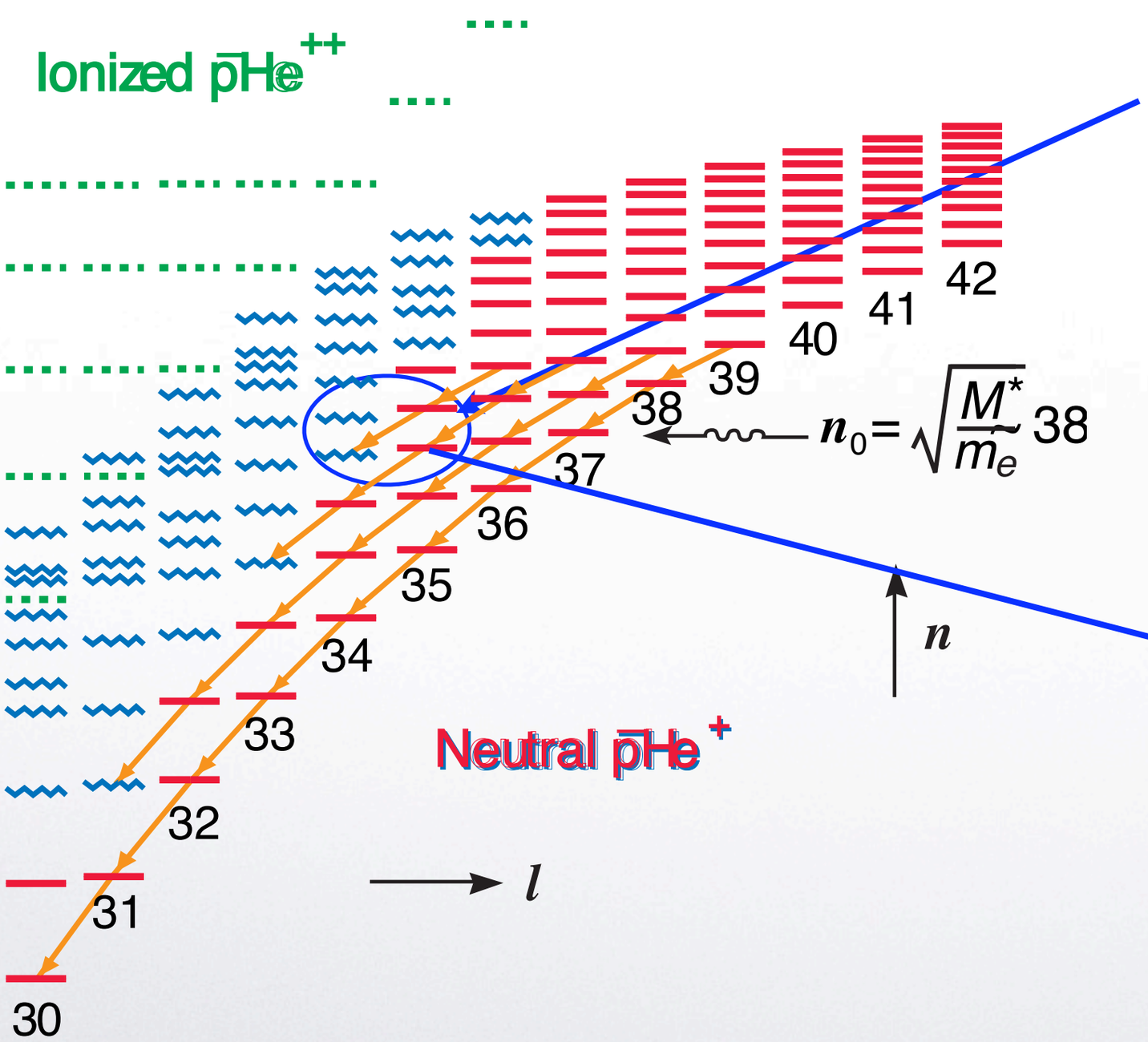

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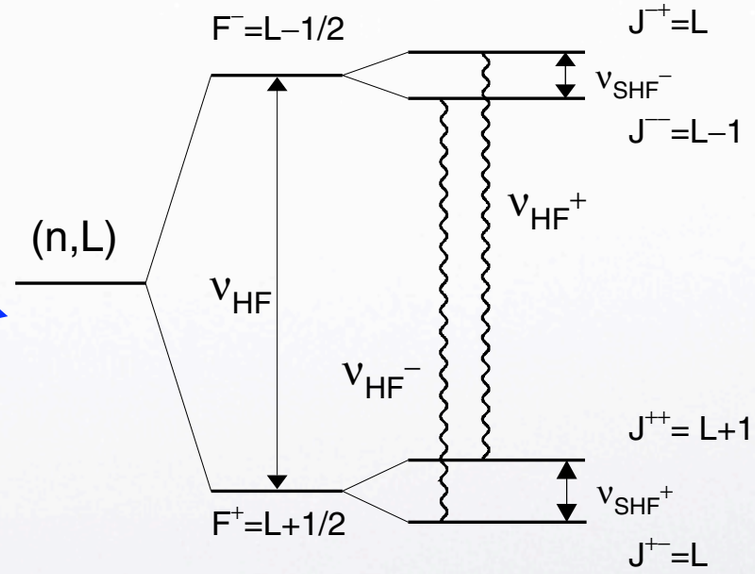
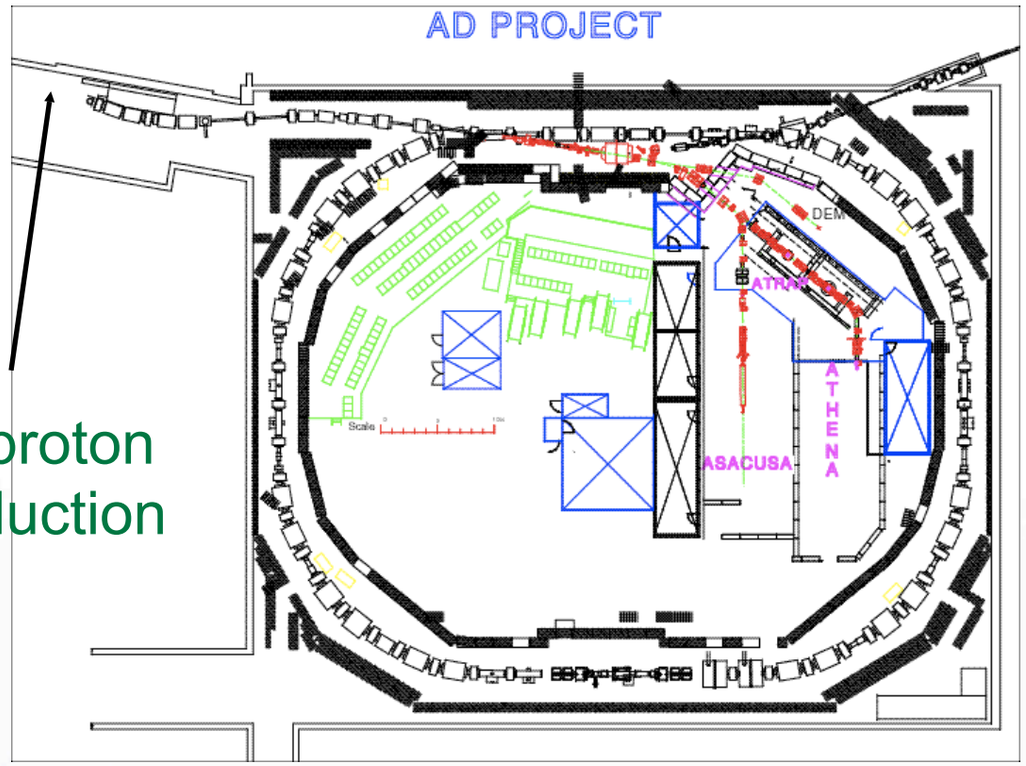


- hyperfine structure
- magnetic moment of antiproton

Experiment at Antiproton Decelerator (AD)



Antiproton production

- ***Pulsed*** extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85 seconds
  - 100 MeV/c (5.3 MeV)

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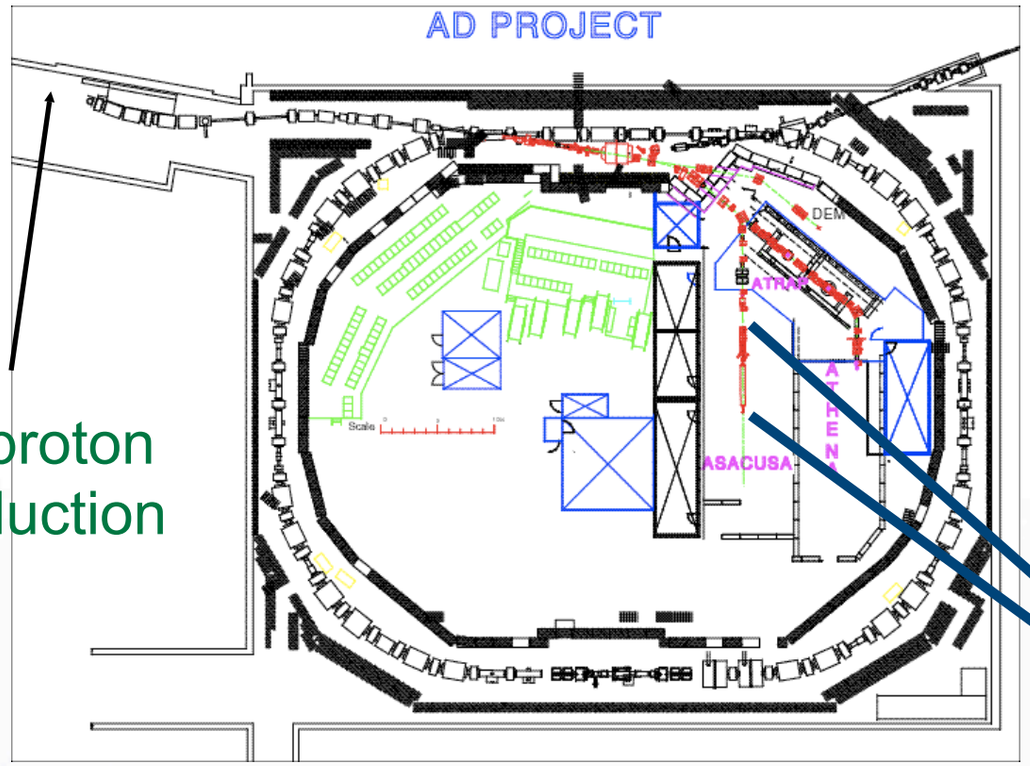

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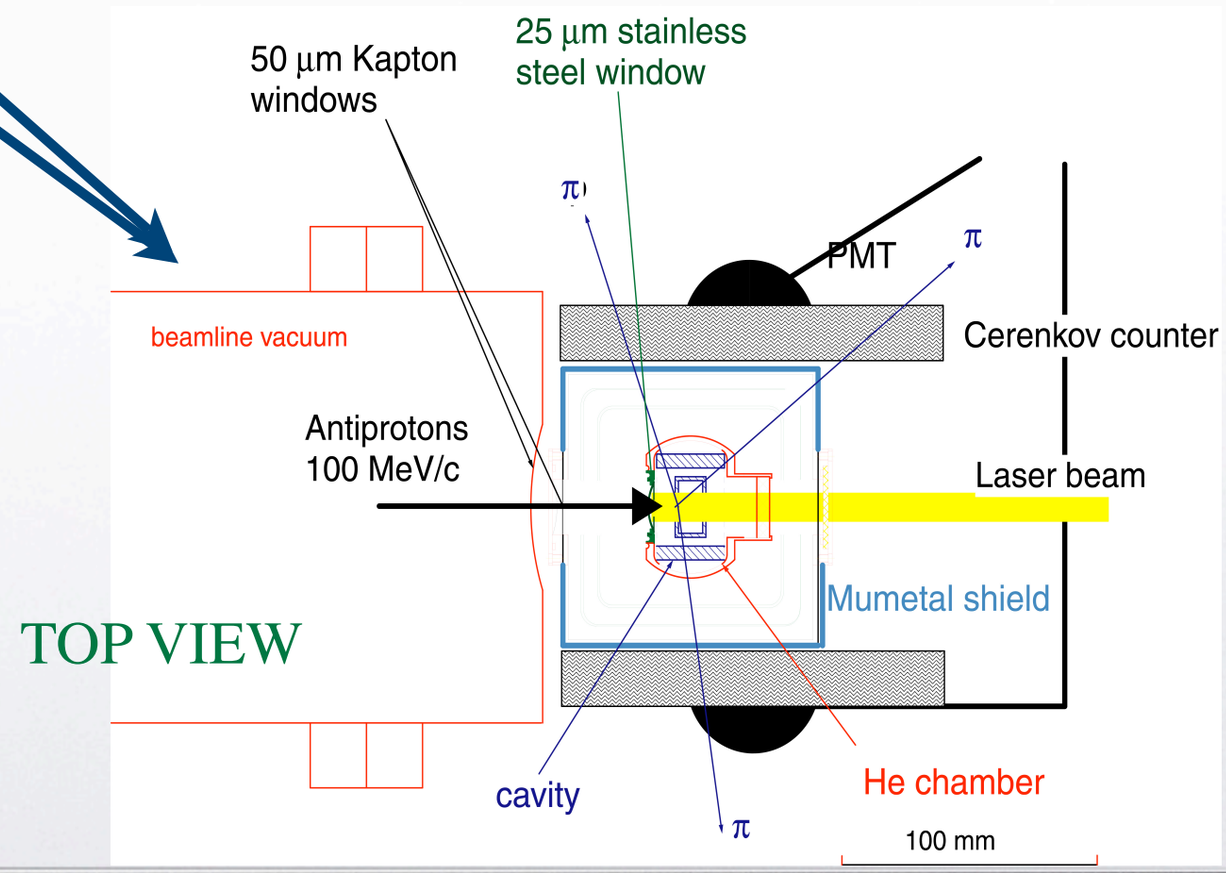

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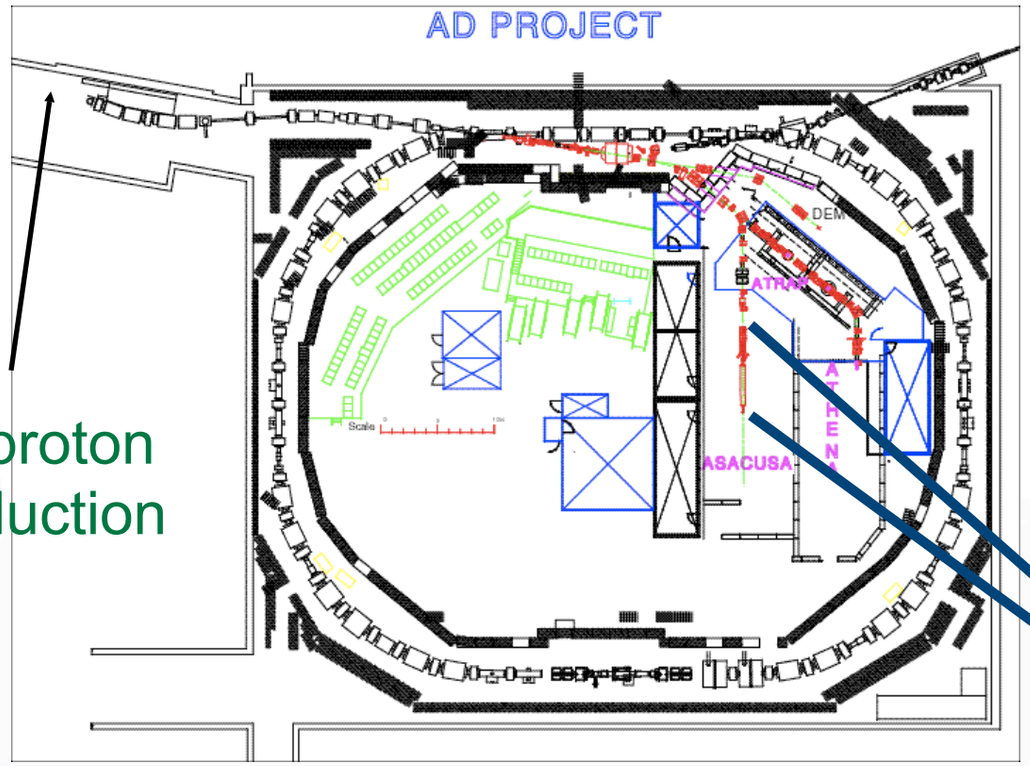

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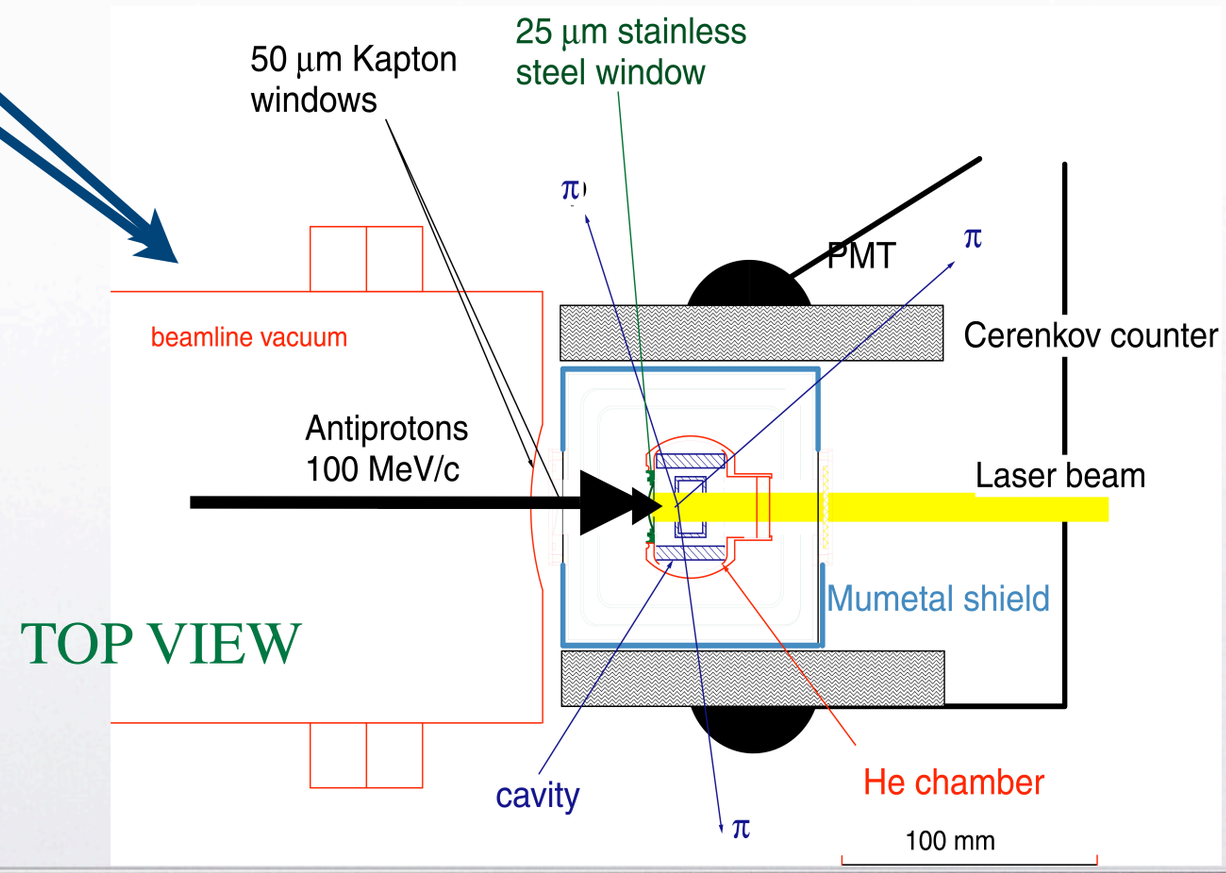

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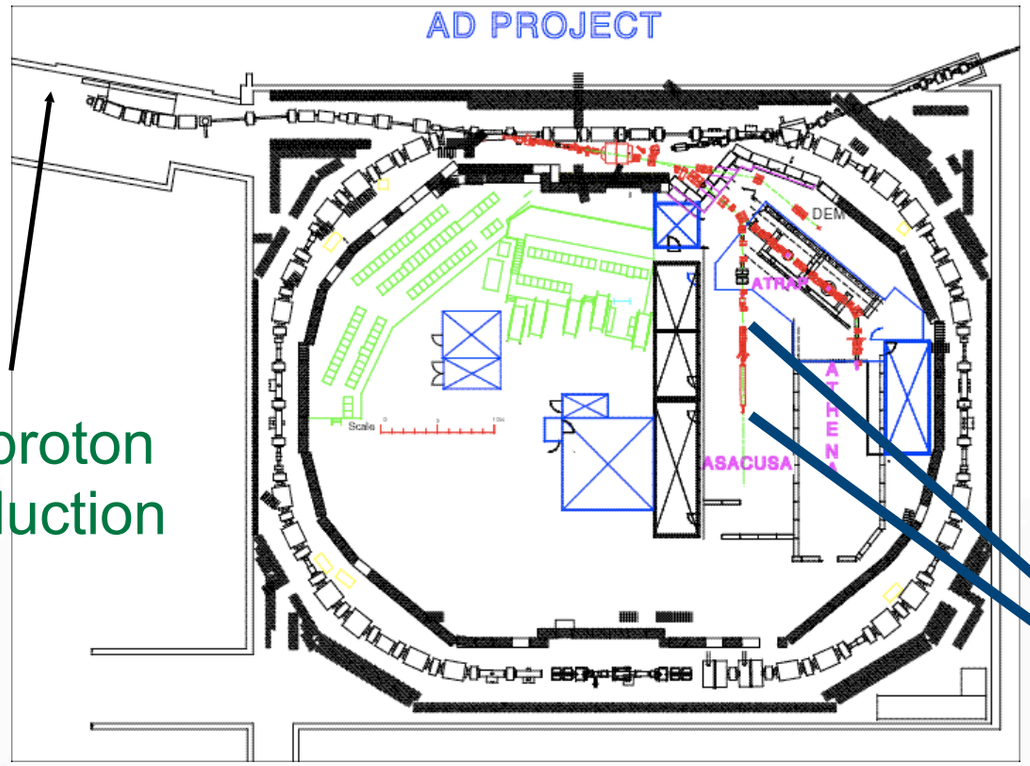

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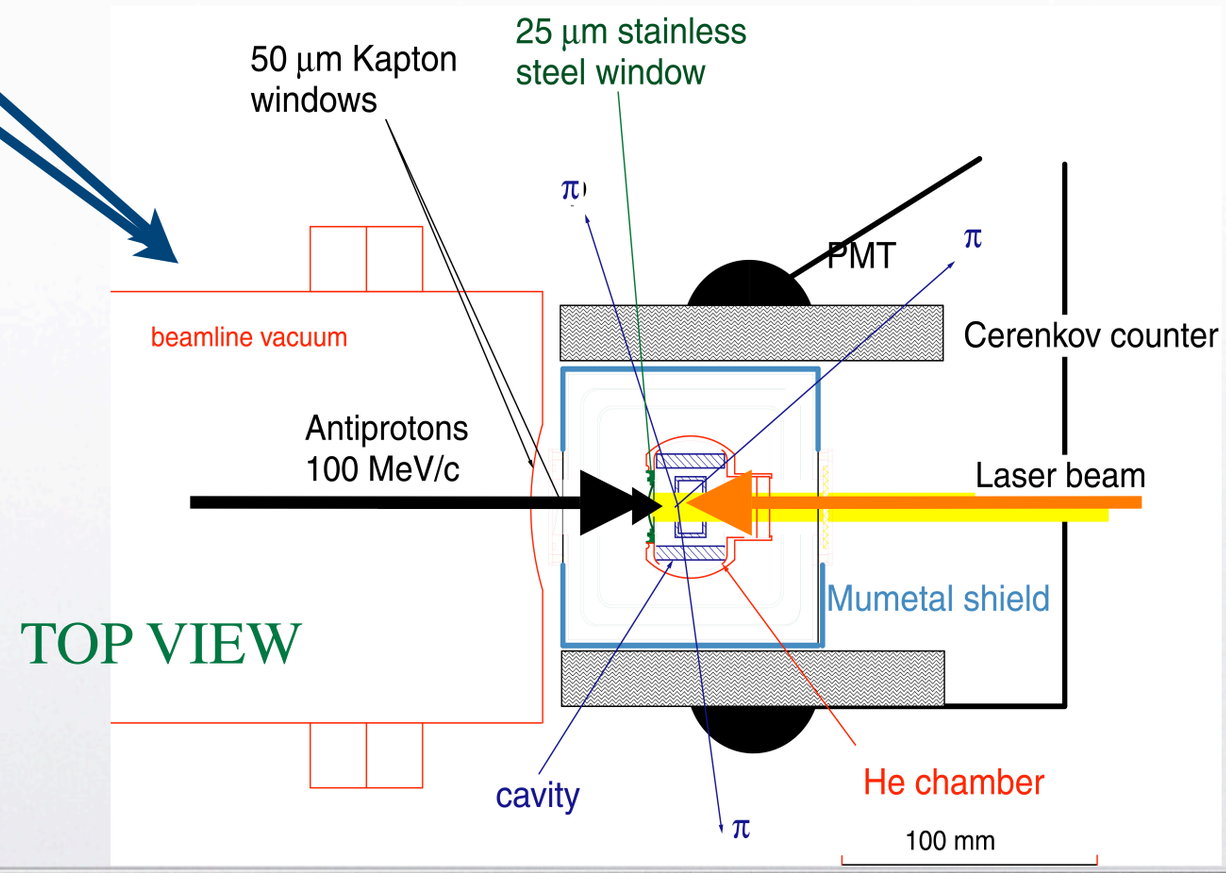

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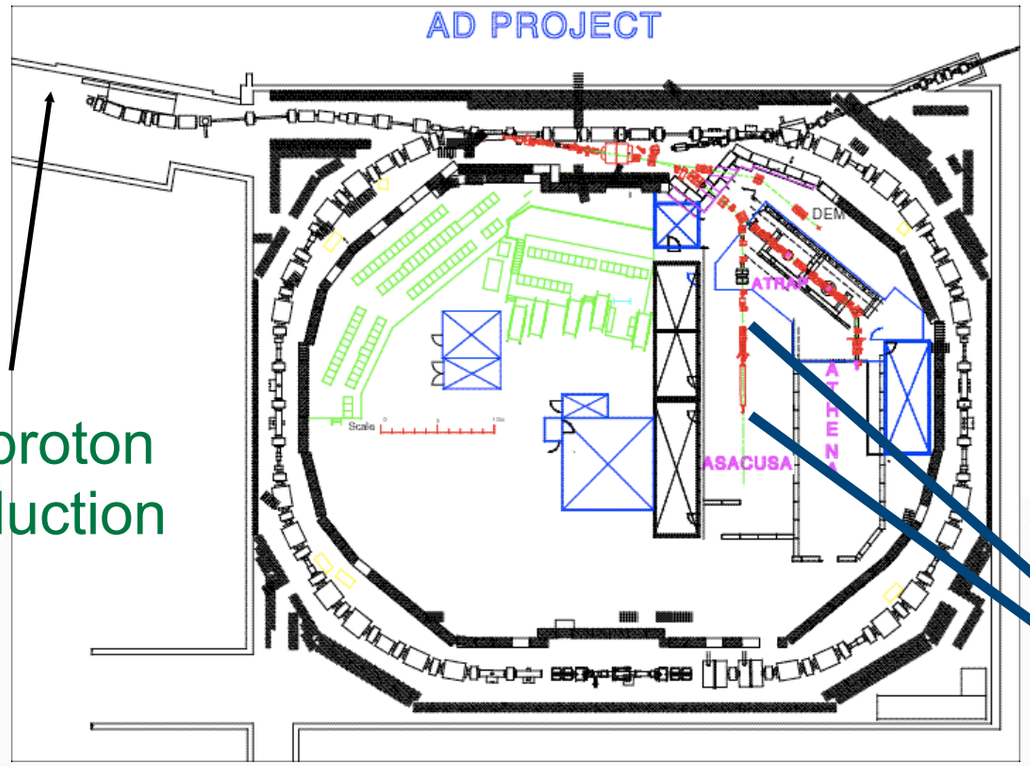

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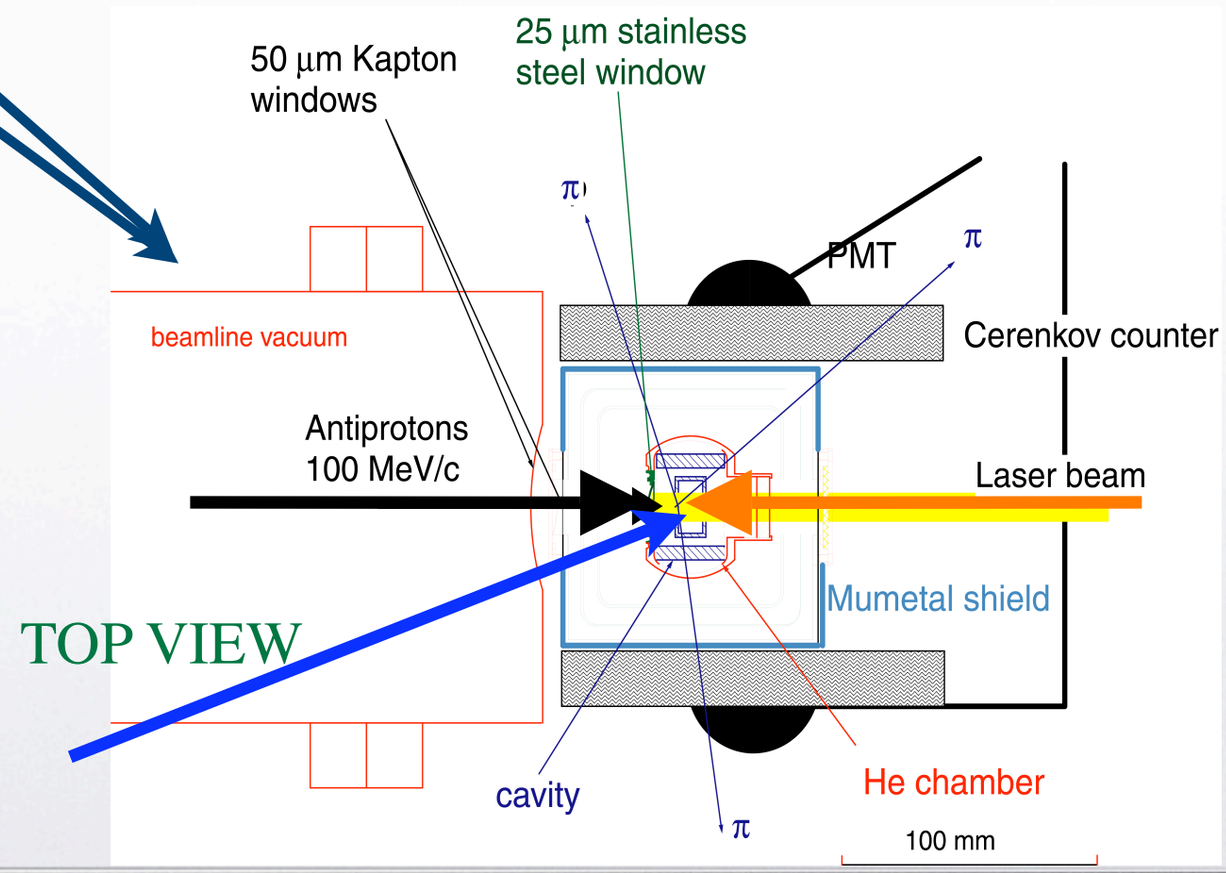

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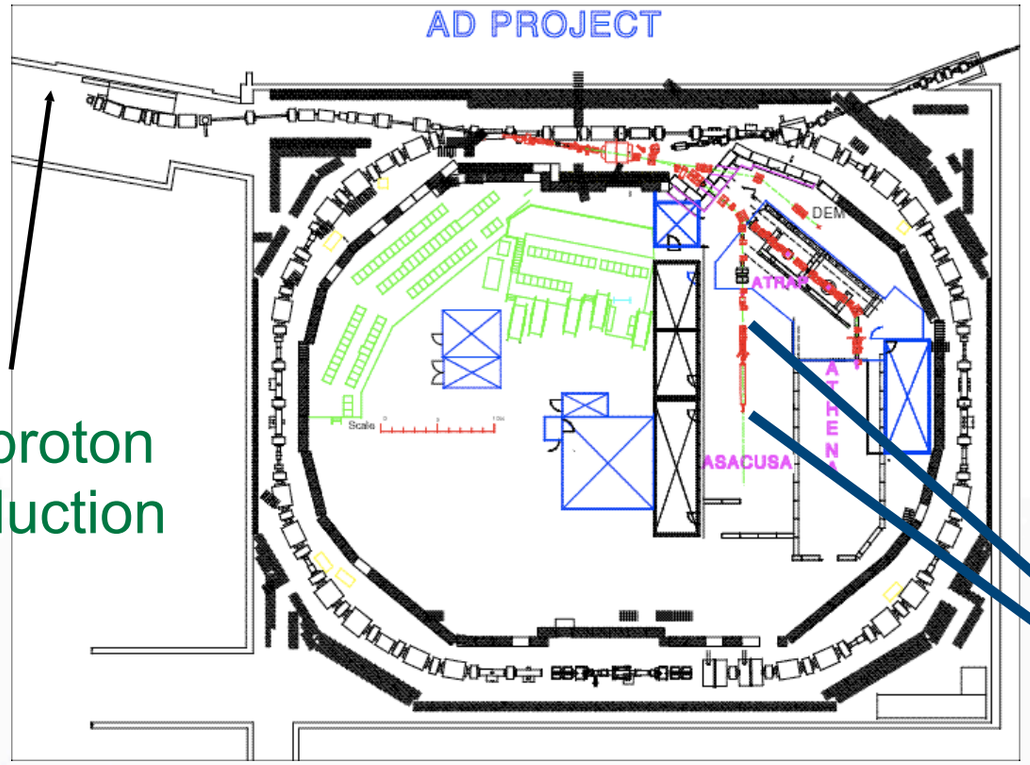

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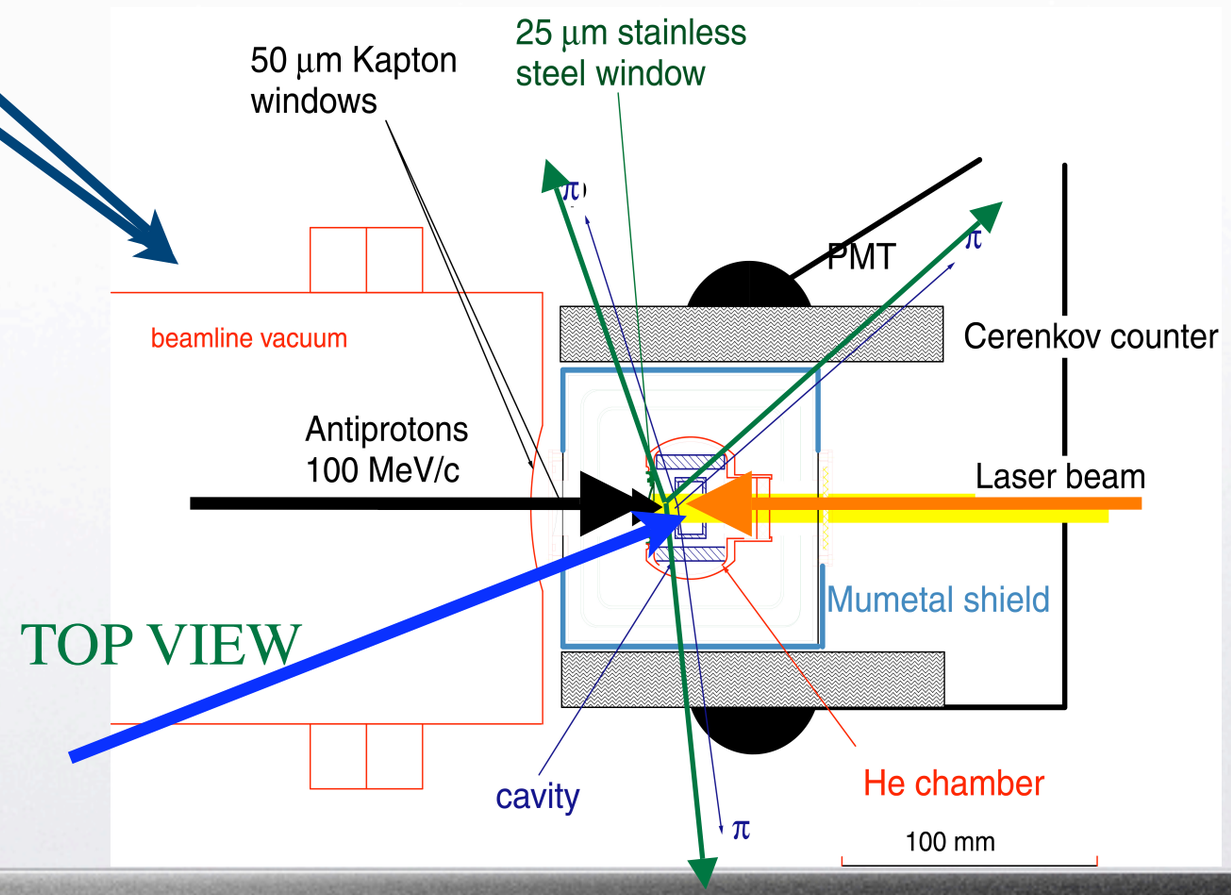

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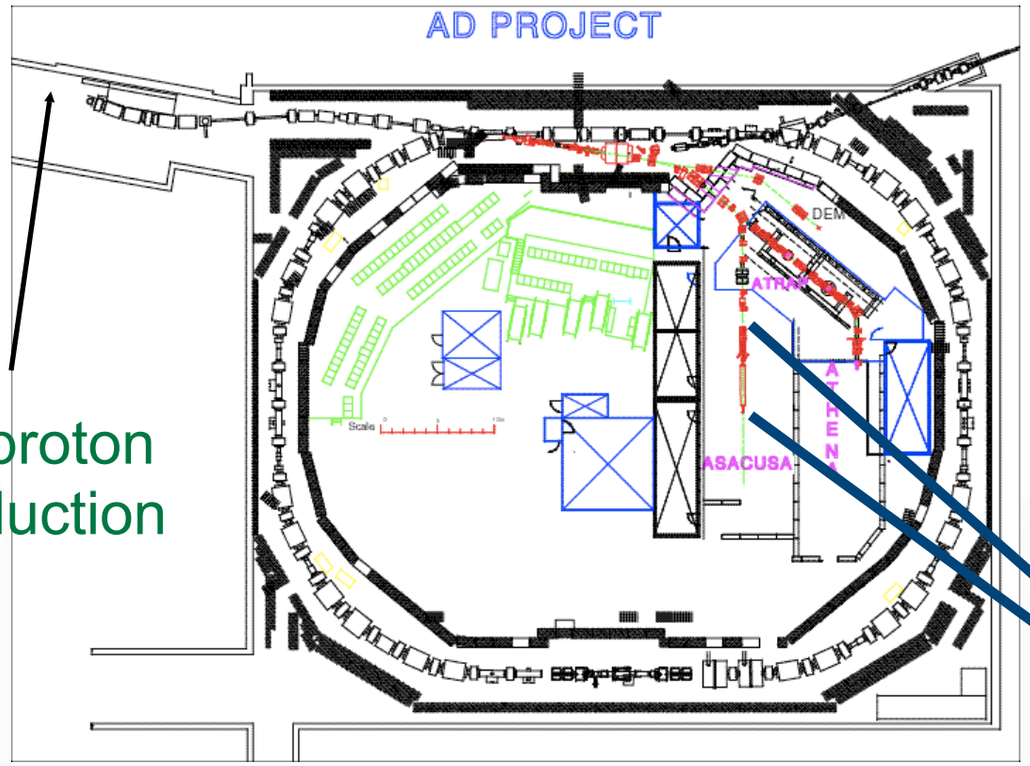
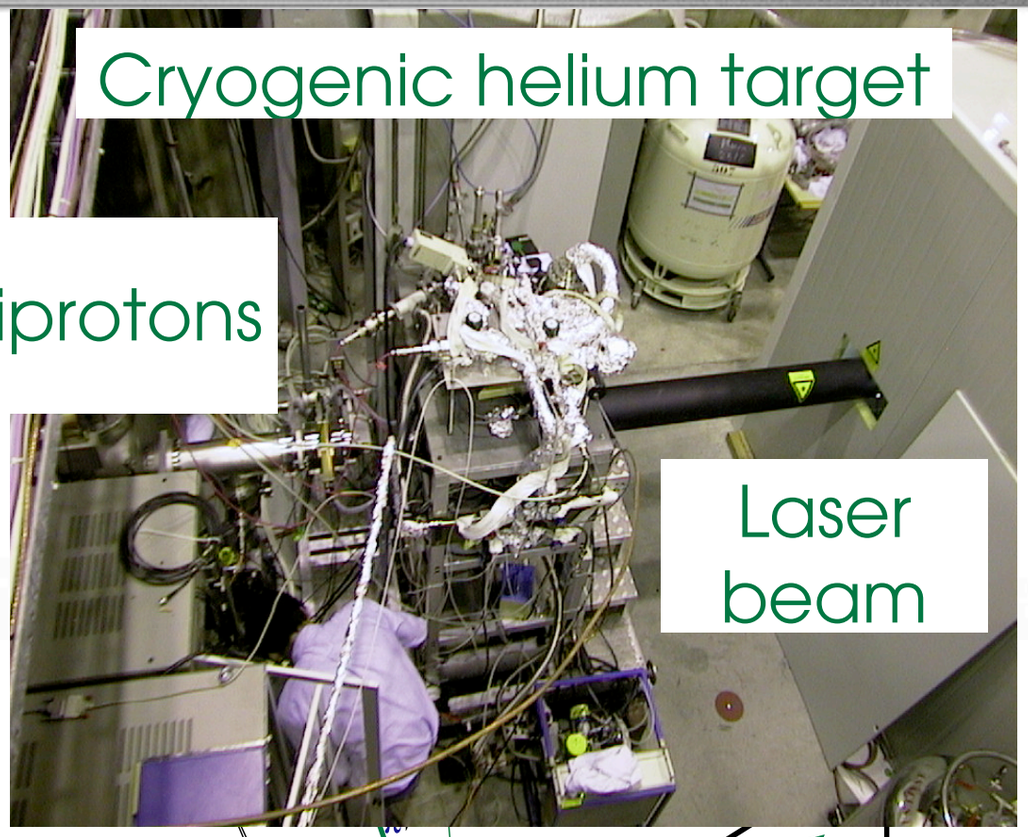


Antiproton production

Antiprotons



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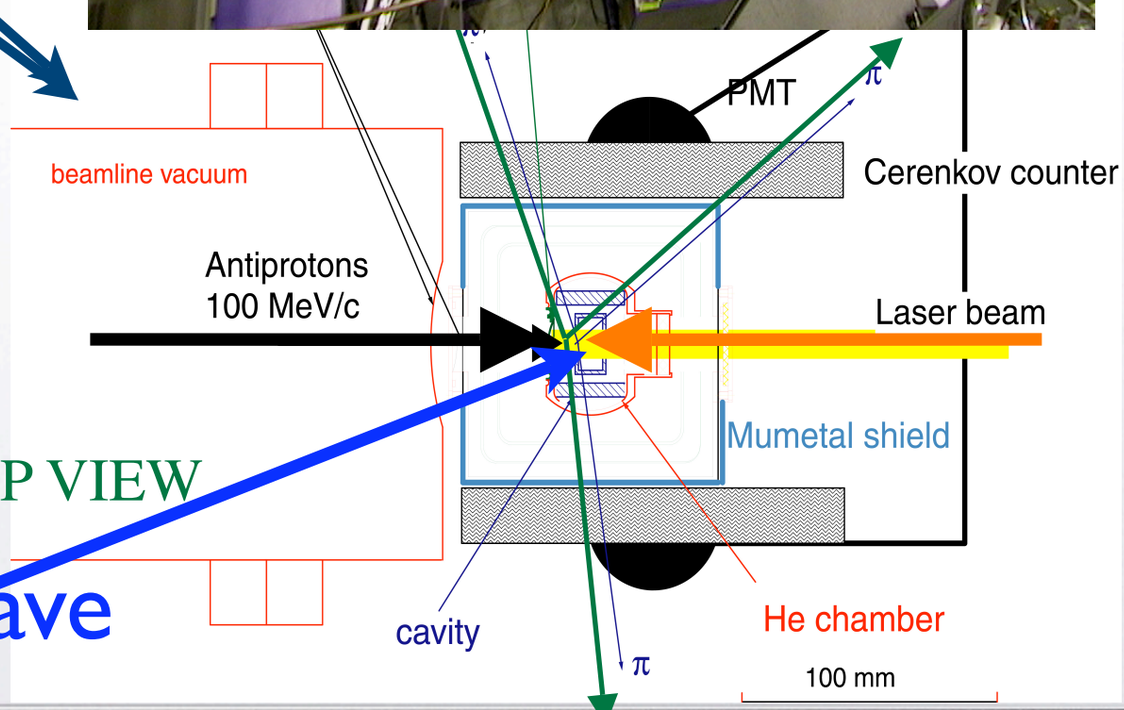
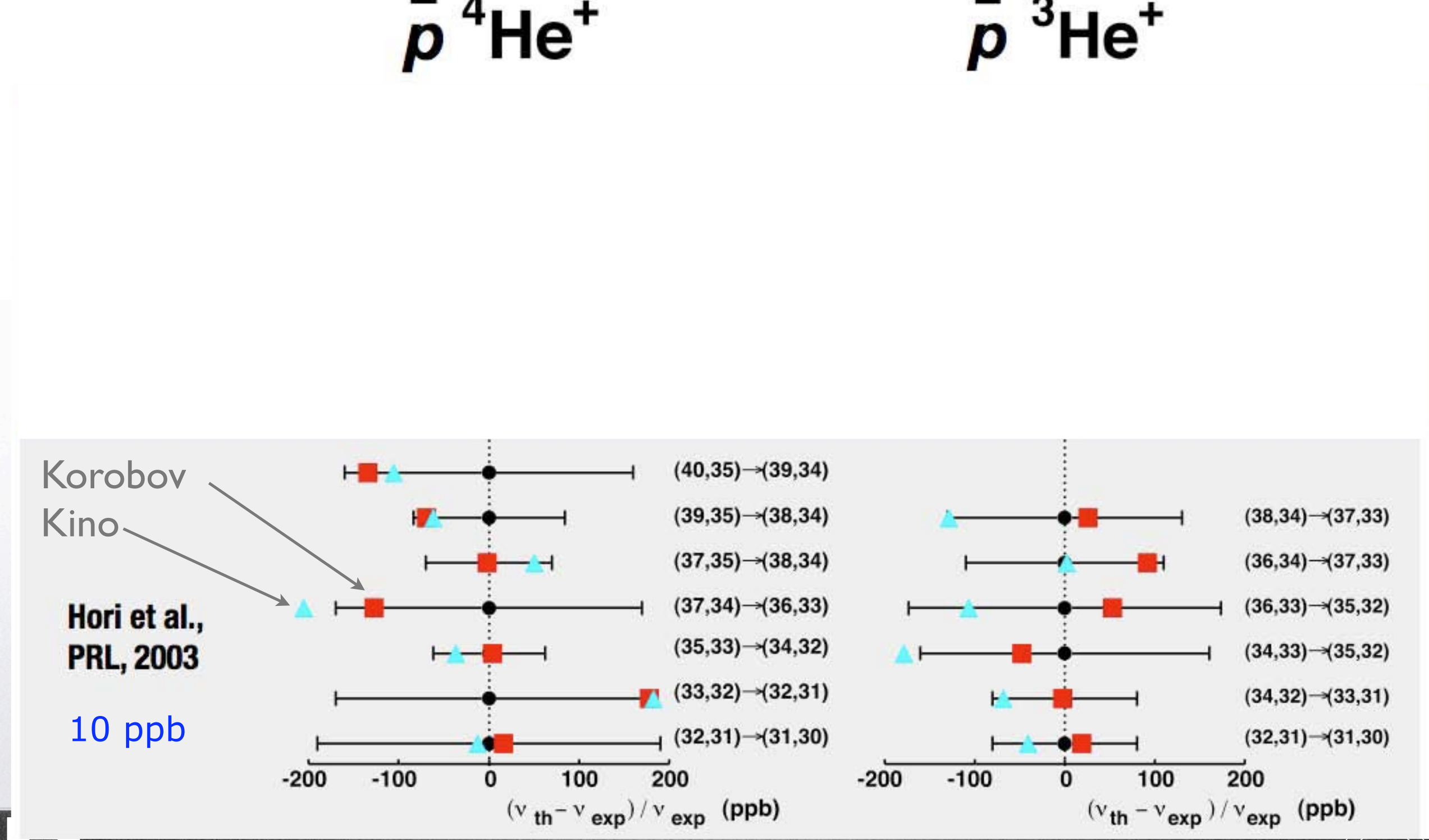
microwave



CPT test: comparison to theory



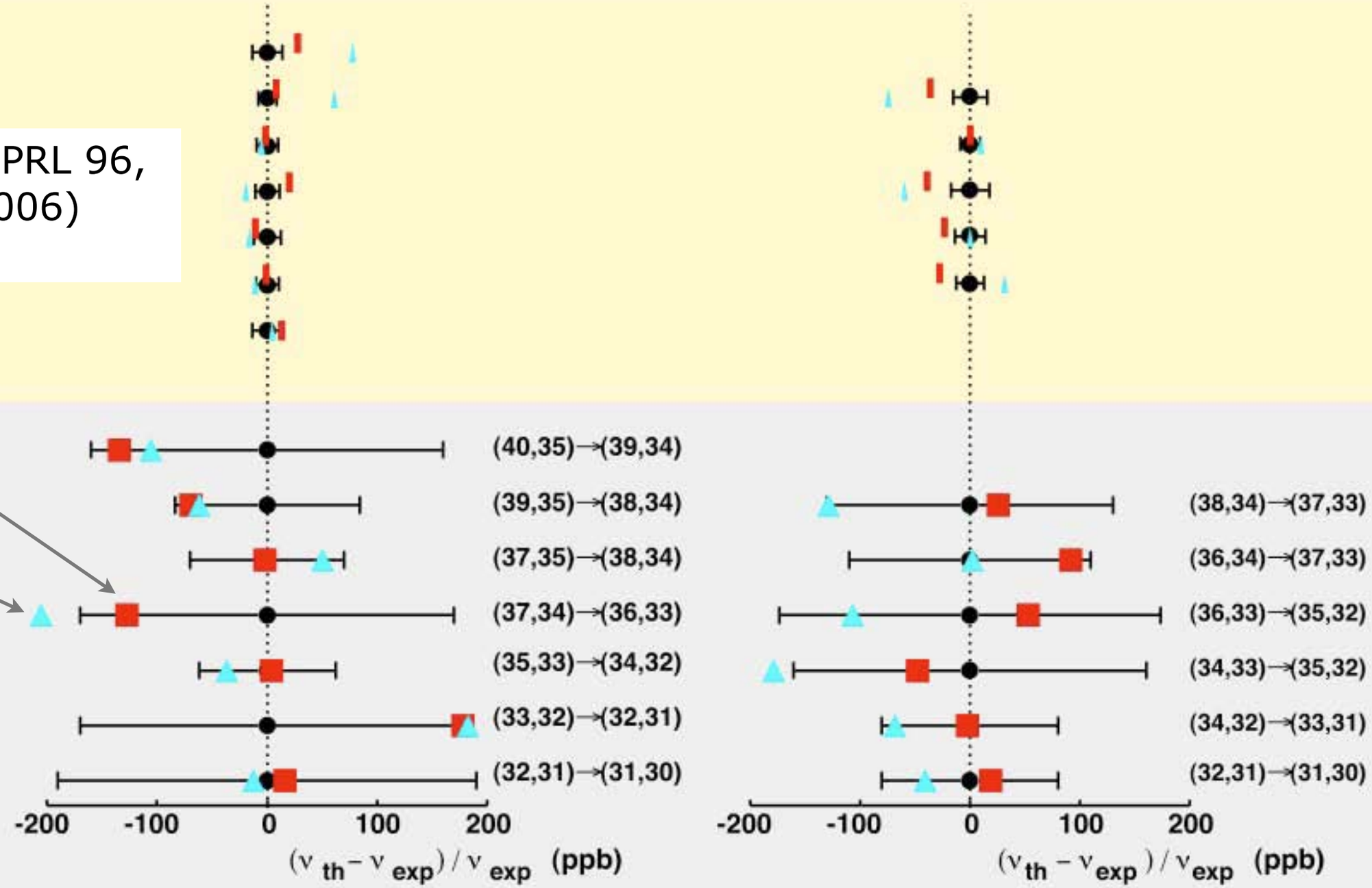
CPT test: comparison to theory

M. Hori et al. PRL 96, 243401(2006)
2 ppb

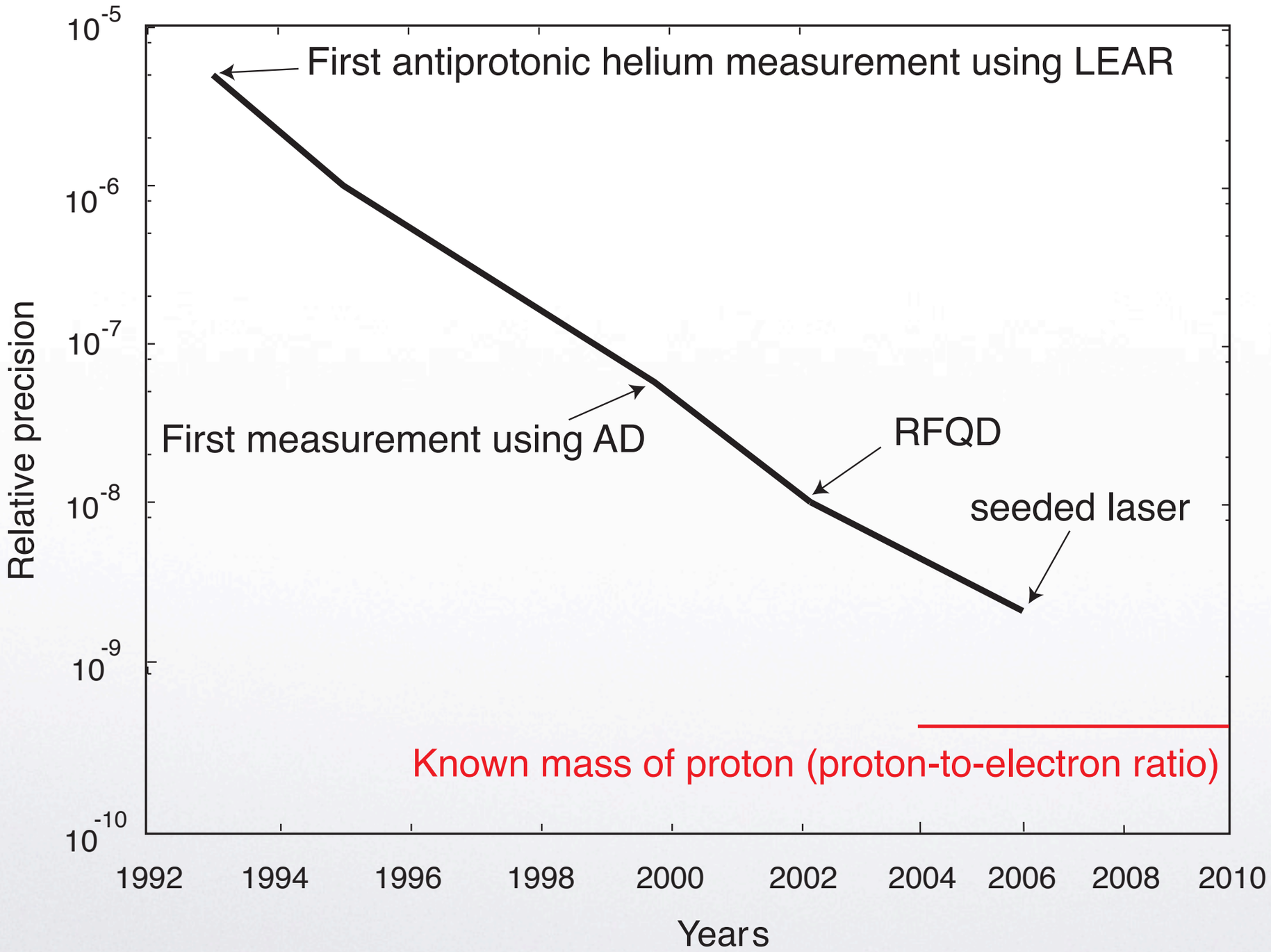
Korobov
Kino

Hori et al., PRL, 2003

10 ppb



Progress in atomcule spectroscopy



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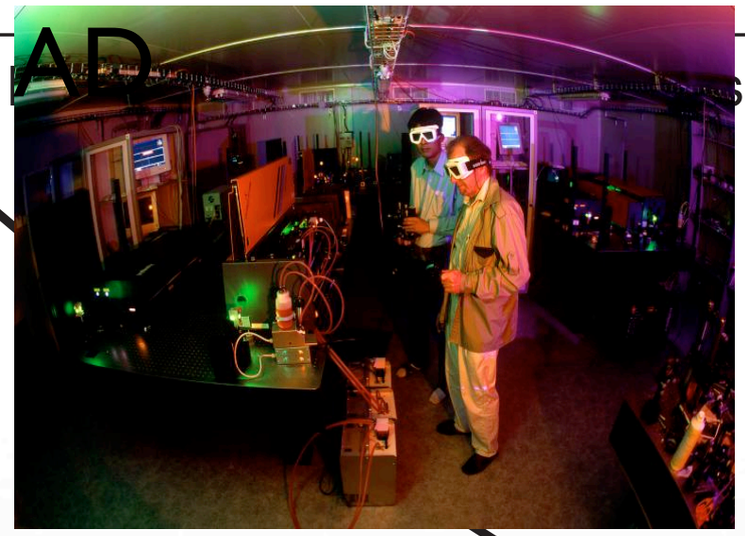

AD 5.3 MeV,
pulsed dye laser
6×10^{-8}

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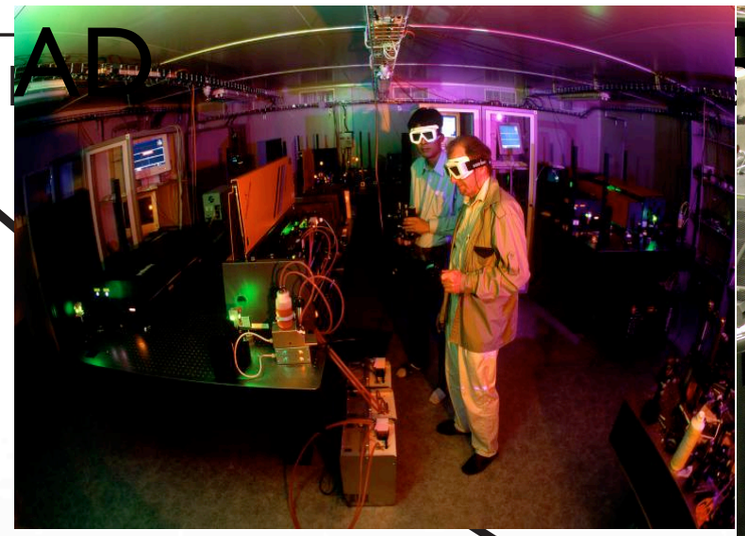

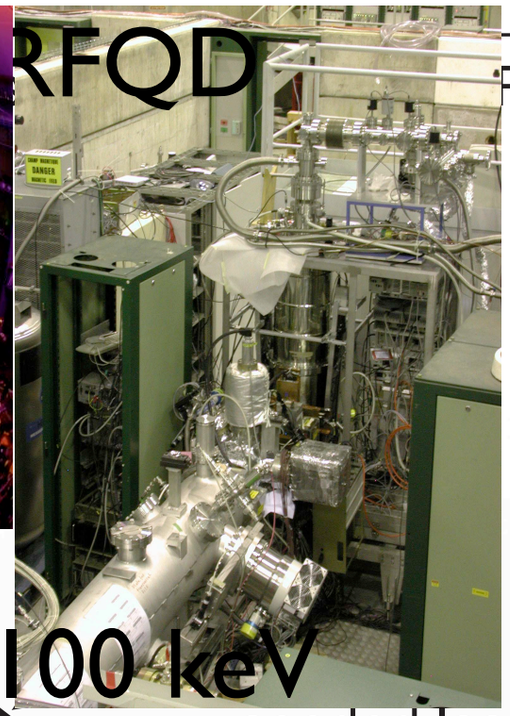

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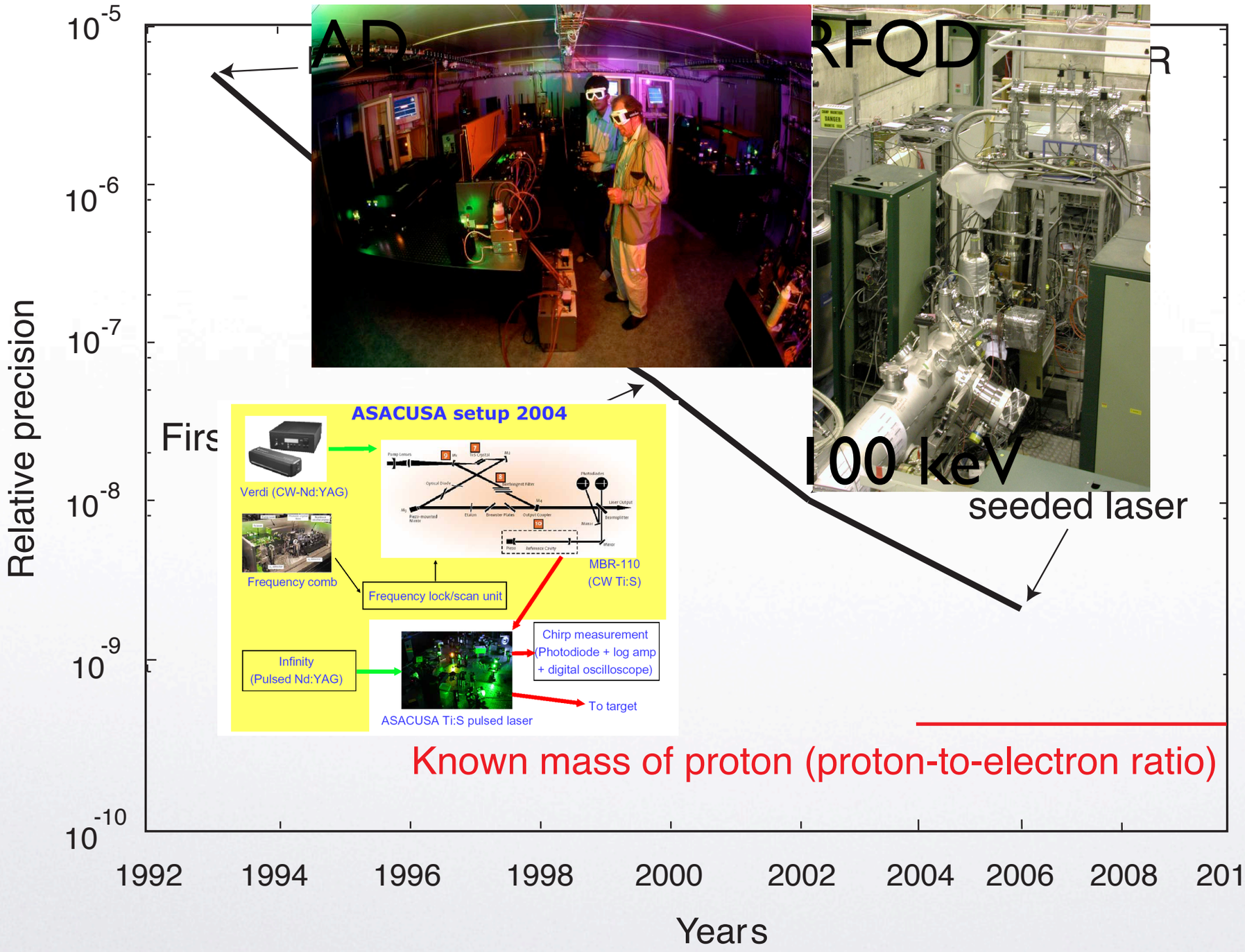

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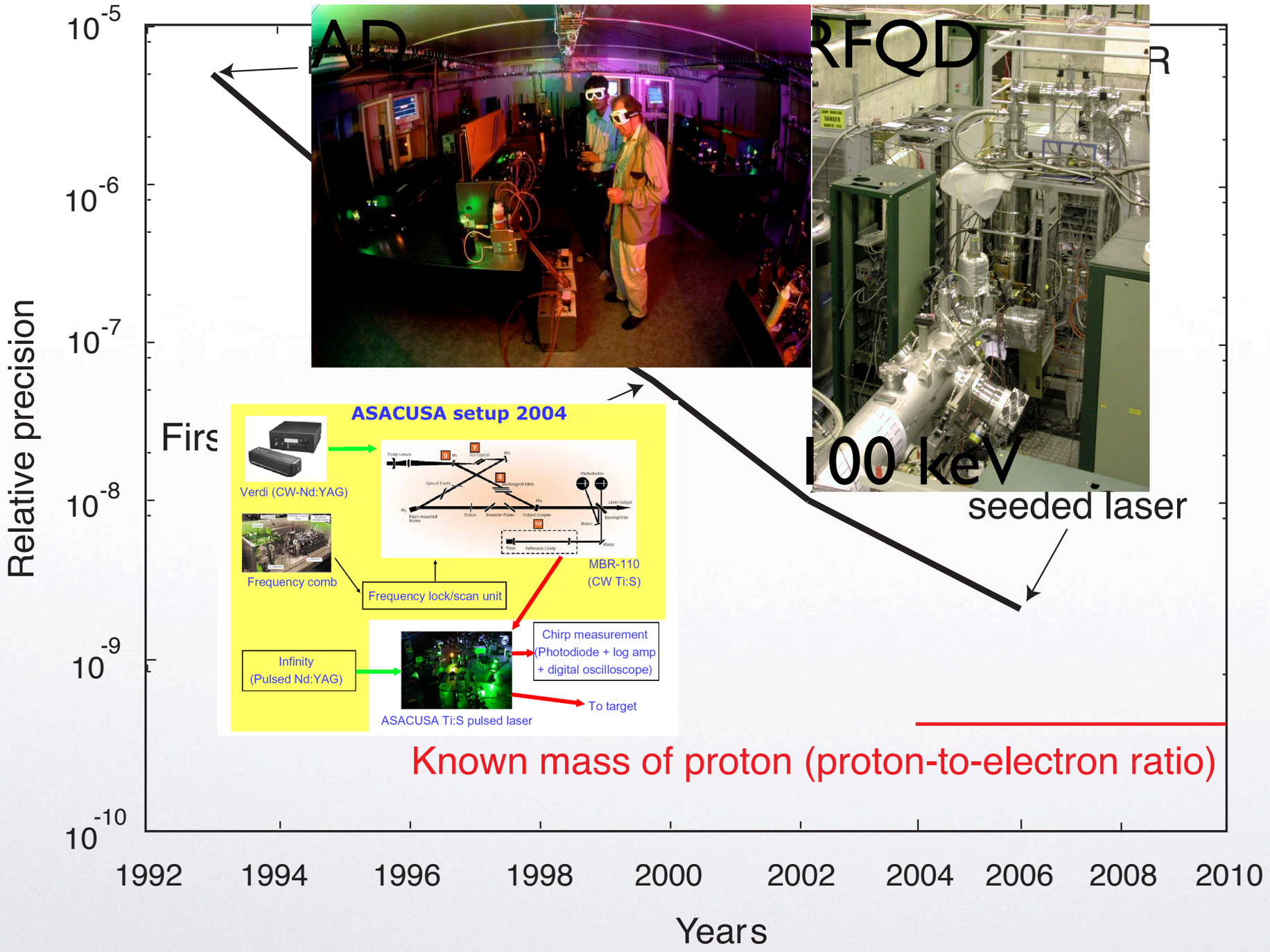

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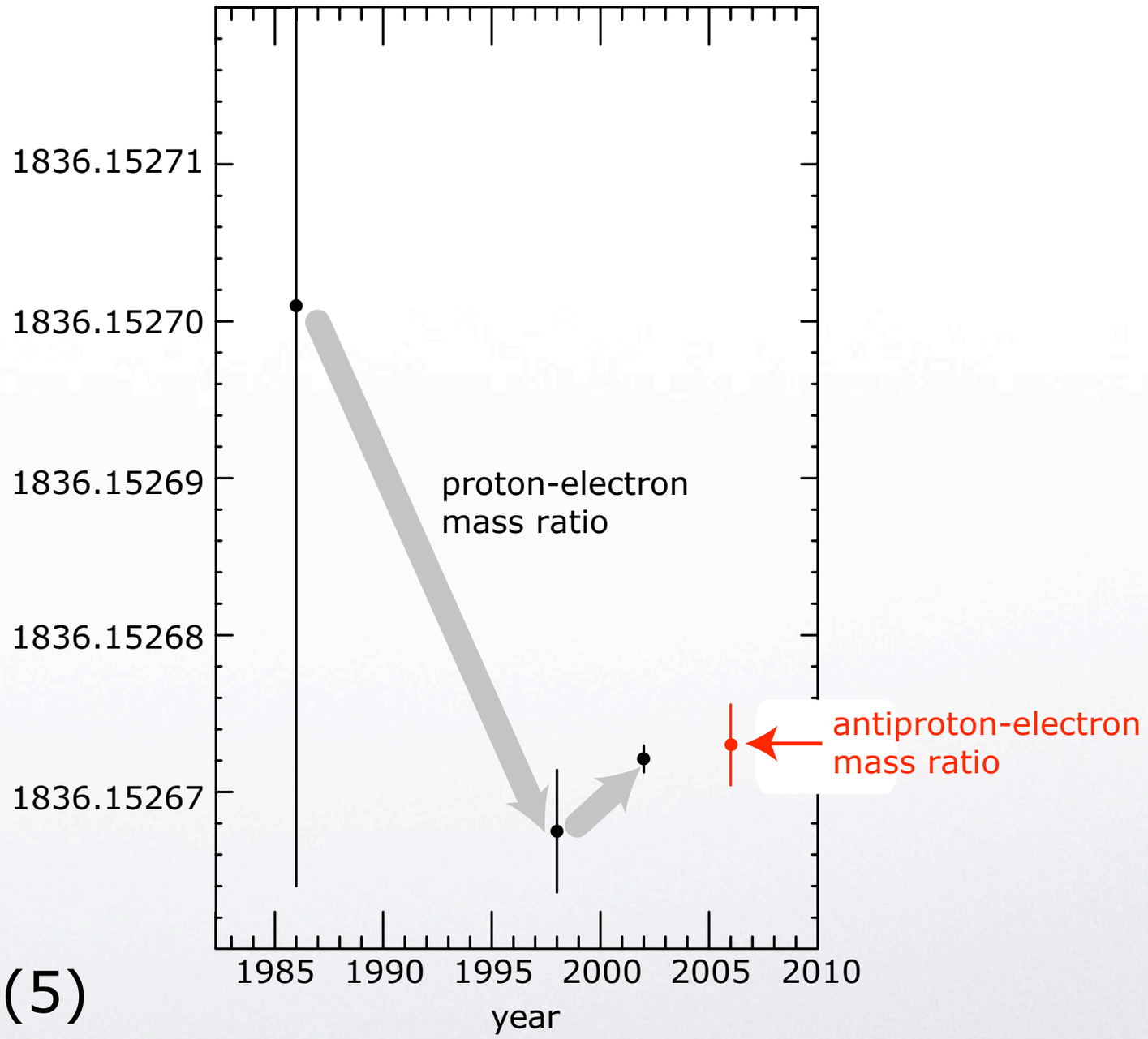
future:
two-photon,
hole bunring
techniques

p(bar)-e mass ratio

- CODATA value m_p/m_e changes over time
- errors comparable
- antiproton mass measurement agrees with latest value for proton (test of CPT)



$m_{\bar{p}}/m_e = 1836.152674(5)$

M. Hori et al. PRL 96 (2006) 243401

CPT test of p/pbar charge and mass

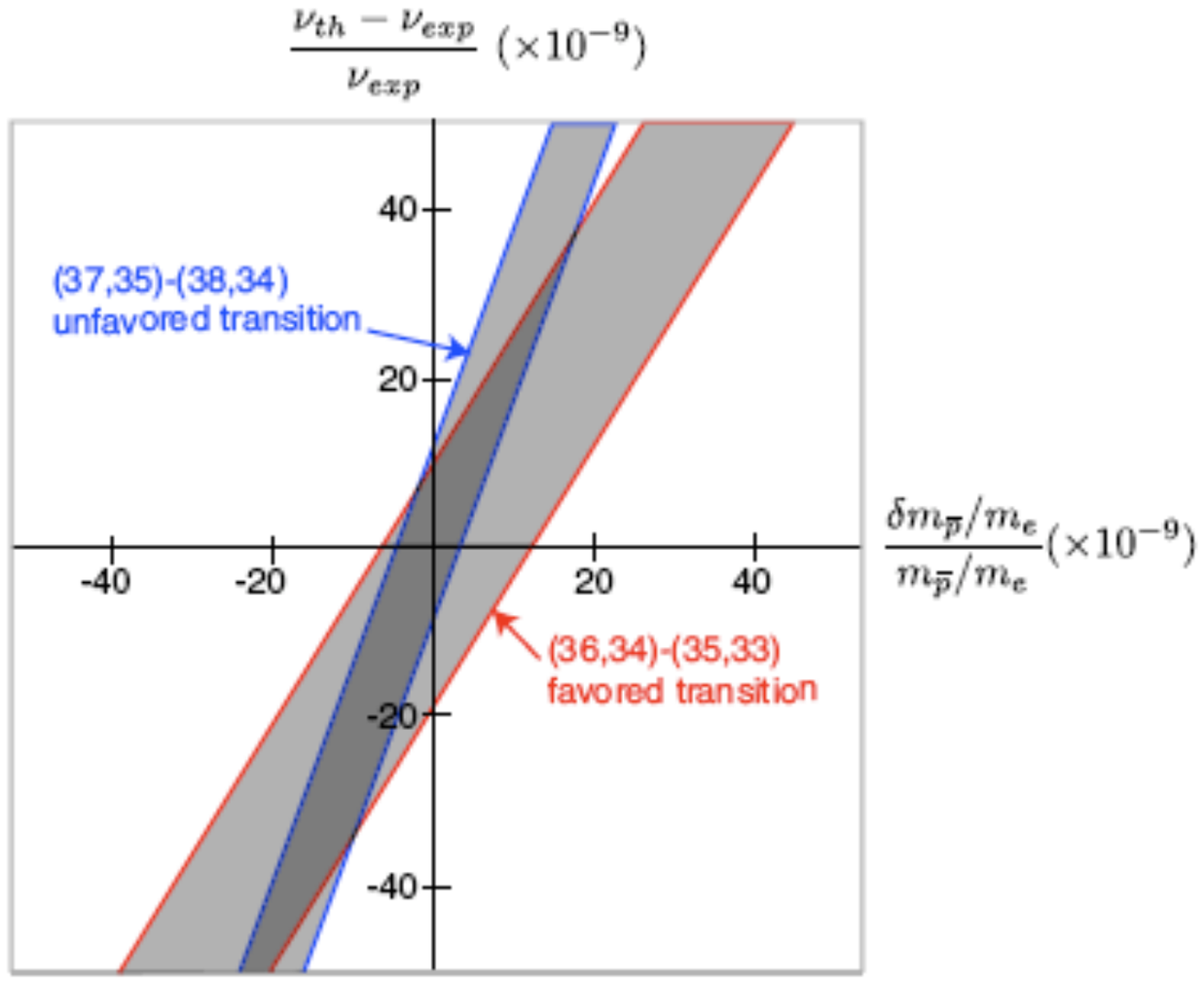
- Theory uses numerical values of proton
- Scaling factor for energy levels

$$Ry_\infty(\bar{p}) \propto M_{\bar{p}} Q_{\bar{p}}^2$$

- Deviation between experiment and theory

$$\frac{\nu_{th} - \nu_{exp}}{\nu_{th}} = f\frac{M_p - M_{\bar{p}}}{M_p} \sim f\frac{Q_p + Q_{\bar{p}}}{Q_p}$$

- f=2.5 – 5 (calculated by Y. Kino)



RS Hayano, M Hori, D Horvath and E Widmann
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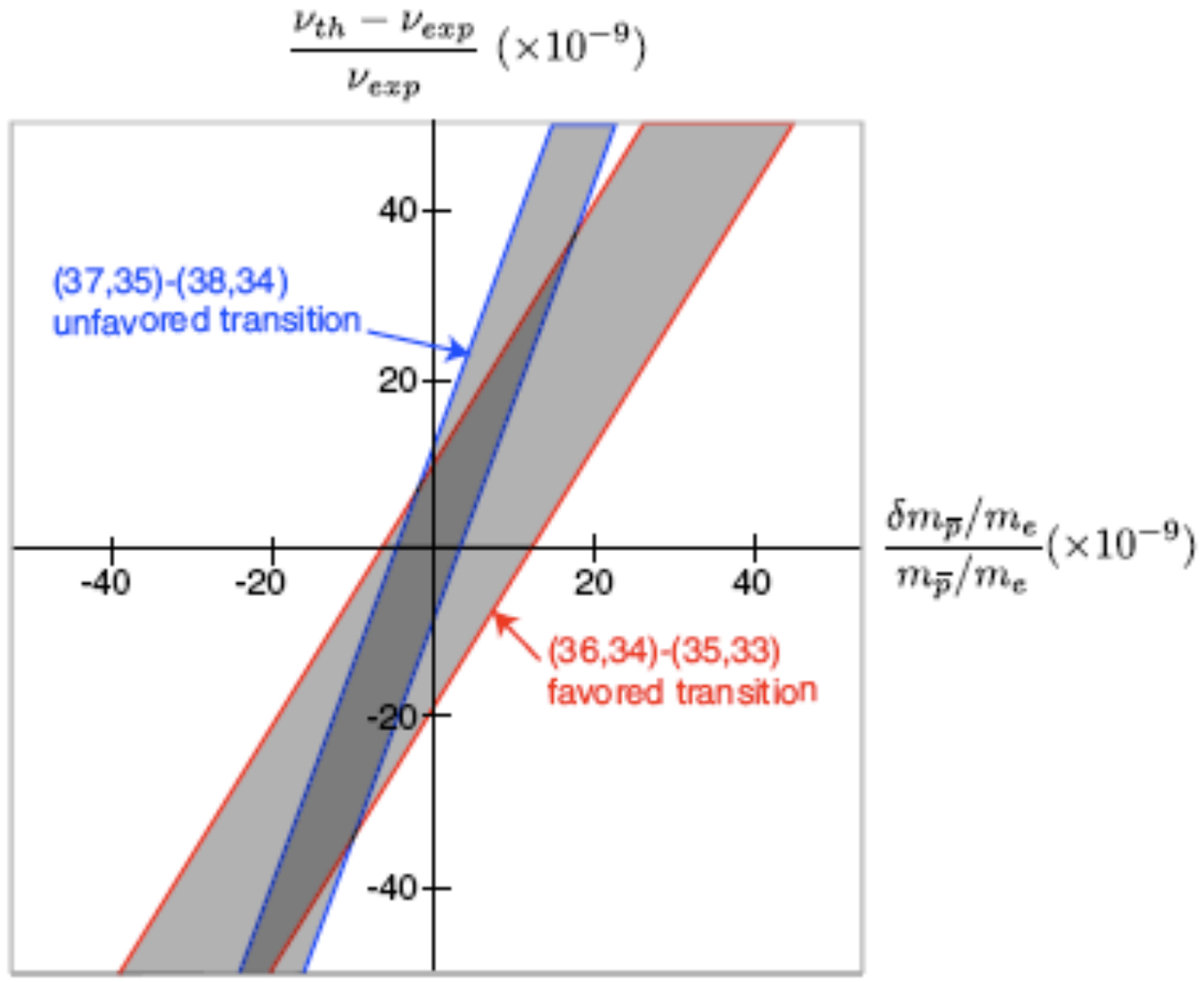

RS Hayano, M Hori, D Horvath and E Widmann
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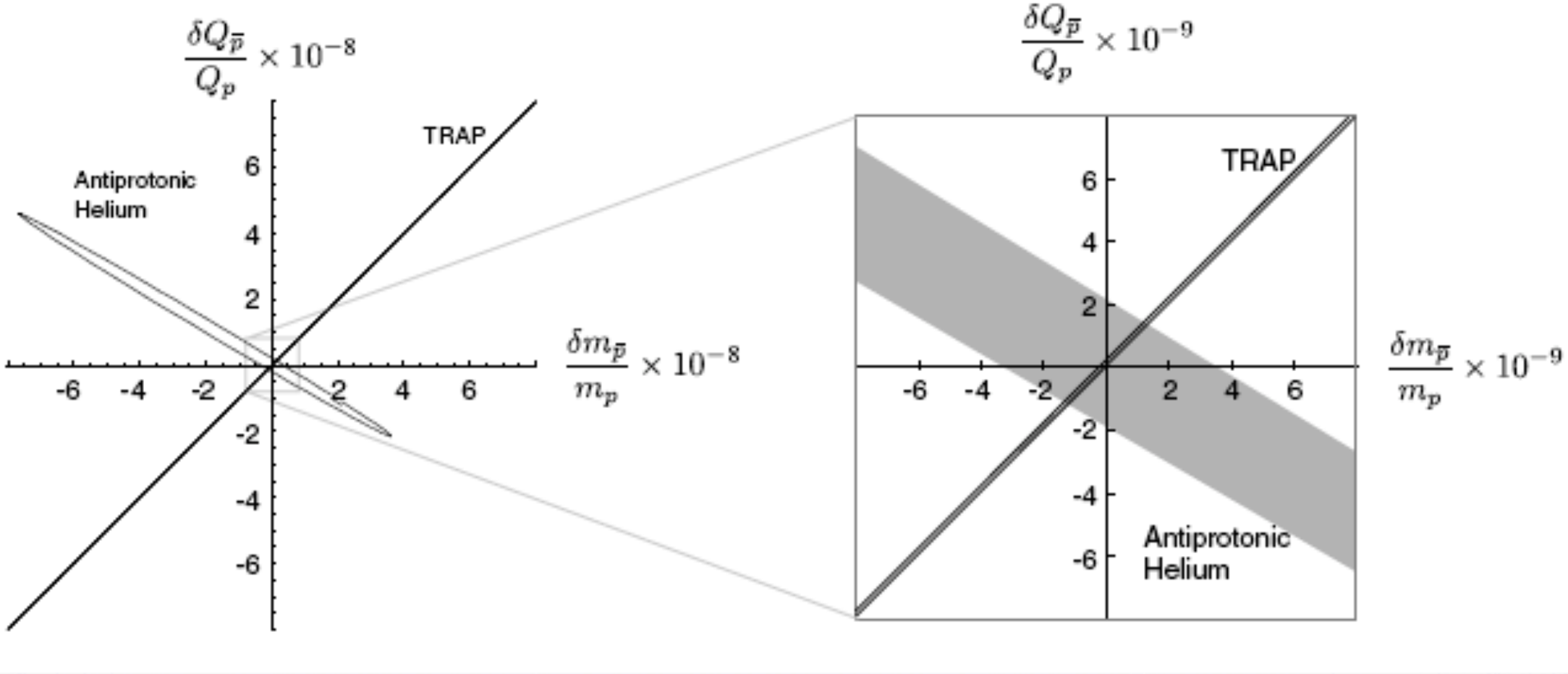
Factor ~150 better than LEAR
~10000 better than X-ray measurements

p/pbar charge and mass: pbHe + TRAP



Q/M of proton/antiproton

$$\frac{\left|Q/M(\bar{p}) - Q/M(p)\right|}{\text{average}} < 9 \times 10^{-11}$$

Gabrielse et al Phys. Rev. Lett. 82 (1999) 3198

2×10^{-9} (2006)

RS Hayano, M Hori, D Horvath and E Widmann
Rep. Prog. Phys. 70 (2007) 1995–2065

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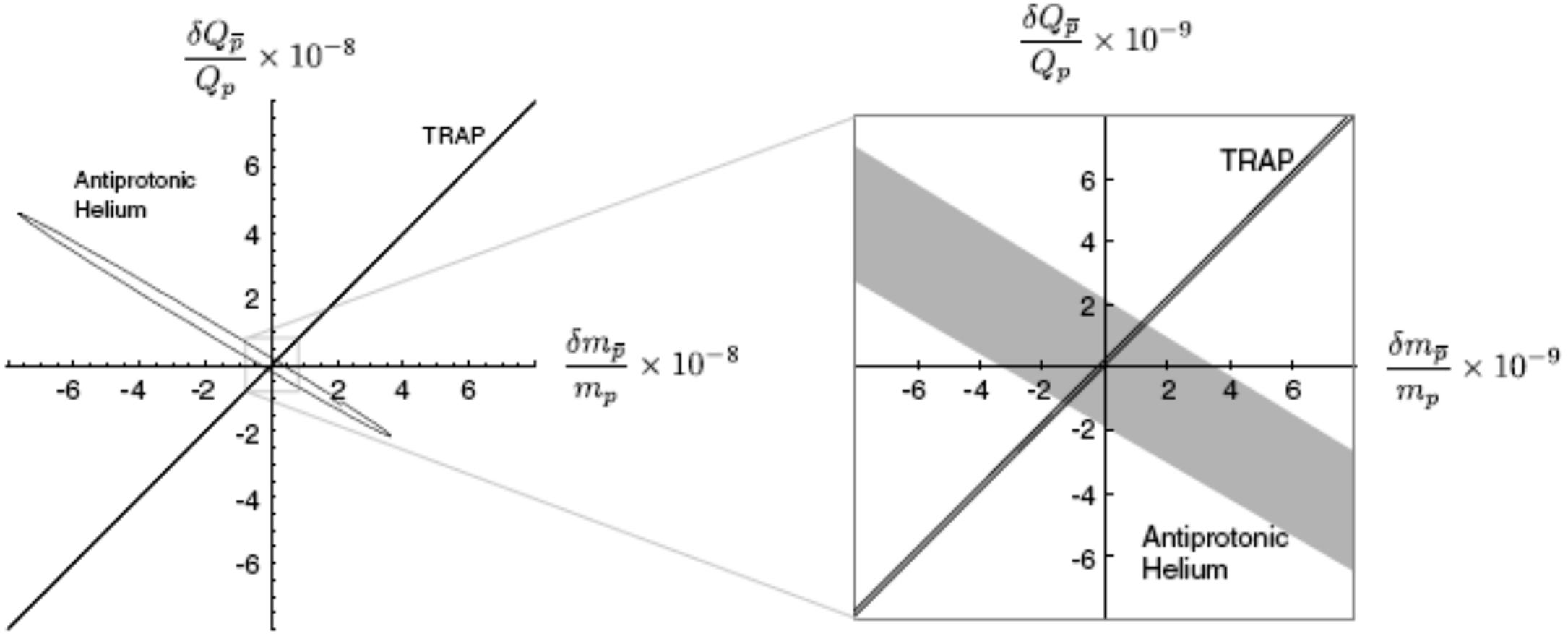

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Gabrielse et al Phys. Rev. Lett. 82 (1999) 3198

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < \begin{cases} 6 \times 10^{-8} & (2000) \\ 1 \times 10^{-8} & (2003) \end{cases}$$

2x10^{-9} (2006)

RS Hayano, M Hori, D Horvath and E Widmann
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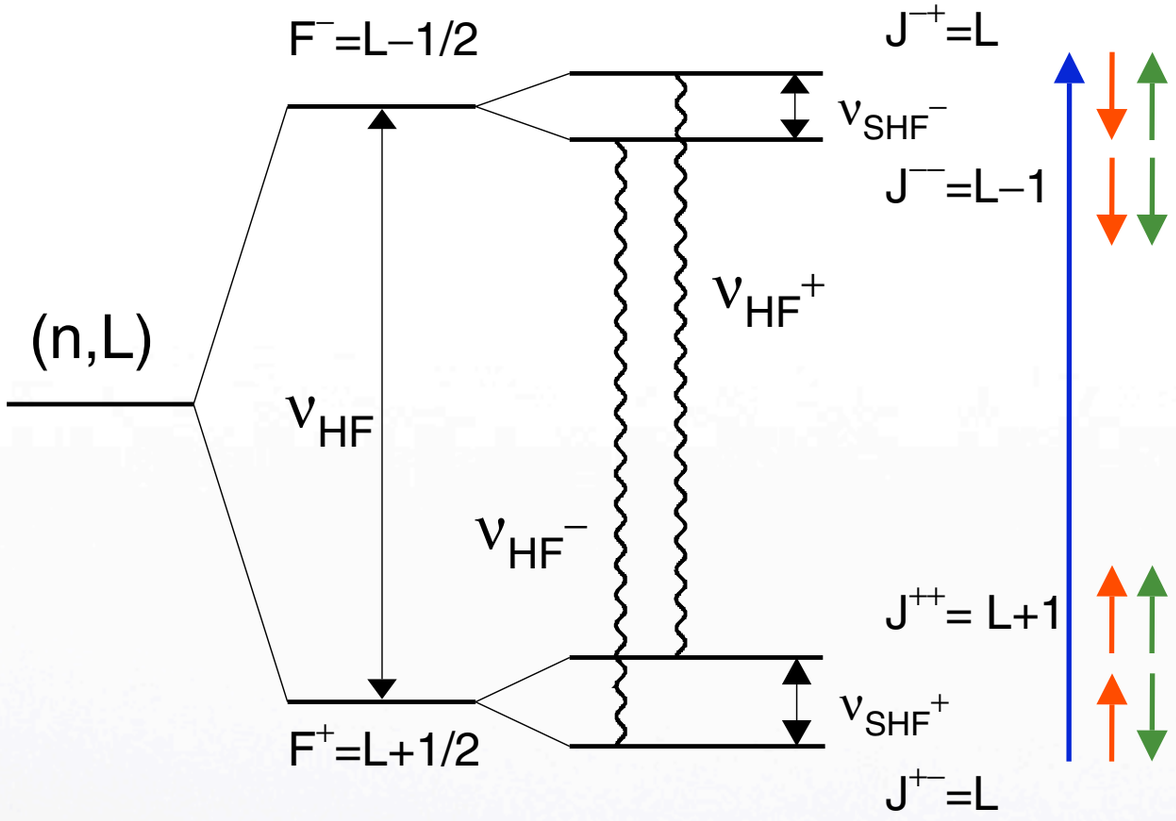
Hyperfine Structure of $\bar{p}^4He^+$



ν_{SHF} sensitive to magnetic moment of pbar

(known to **3×10^{-3}**)

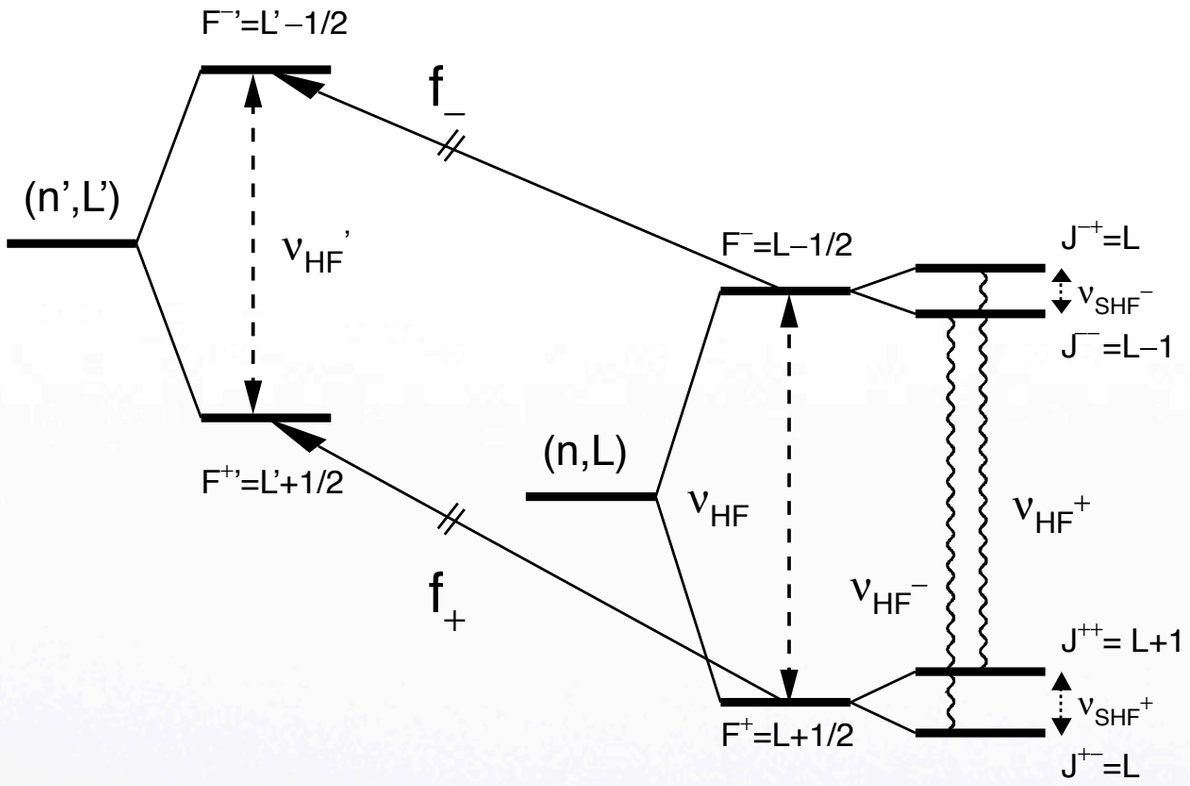
ν_{HF} tests *orbital* angular moment: g_l

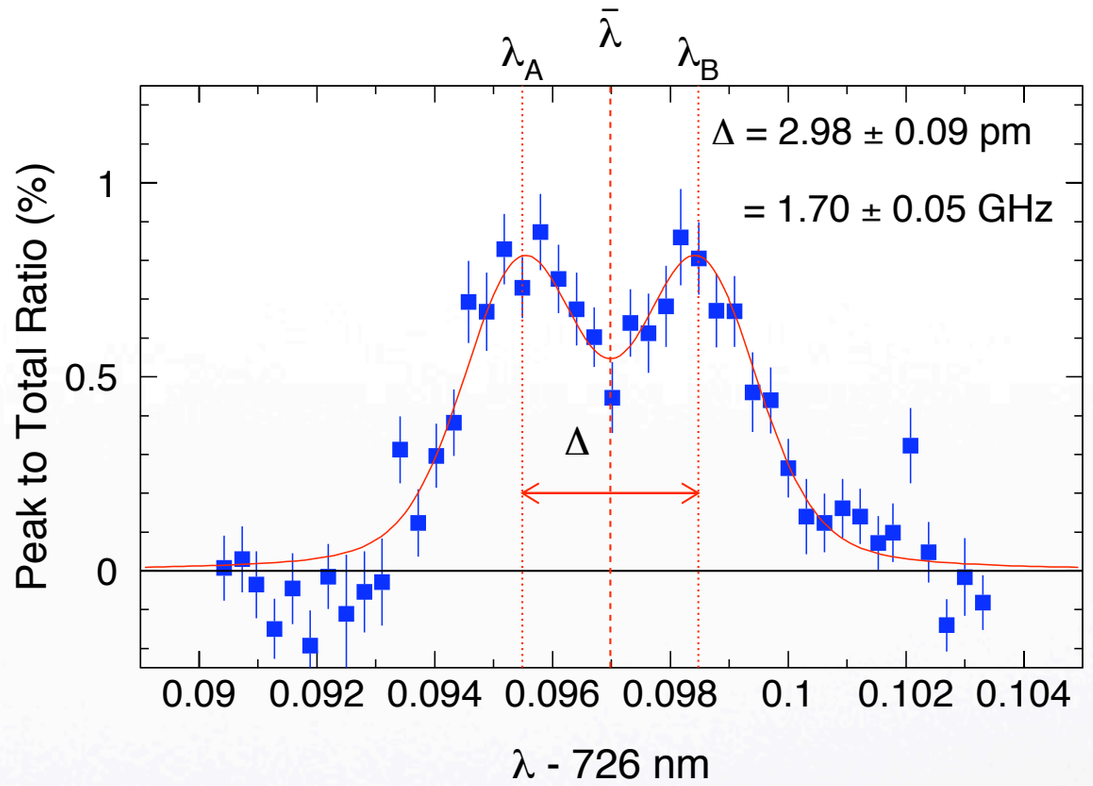
- *interactions of magnetic moments:*
  - electron: $\vec{\mu}_e = g\mu_B \vec{S}_e$
  - pbar: $\vec{\mu}_{\bar{p}} = [g_s(\bar{p})\vec{S}_{\bar{p}} + g_l(\bar{p})\vec{L}_{\bar{p}}]\mu_N$
- *"Hyperfine" splitting HFS:*

  $\vec{L}_{\bar{p}} \cdot \vec{S}_e$
  - dominant because of large L
- *"Superhyperfine" splitting*

  $\vec{S}_{\bar{p}}$
- *HFS: 10 ... 15 GHz*
- *SHFS: 0.1 ... 0.3 GHz*

1st Observation of HFS in a laser transition





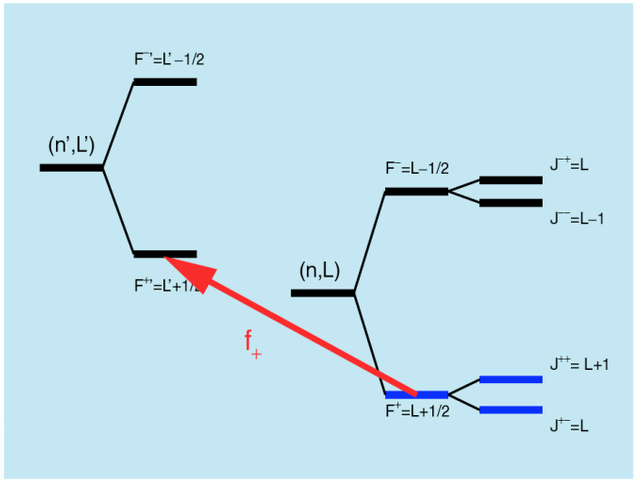
LEAR, E. W. et al. PLB 404 (1997) 15-19

- 1.75 GHz is difference of HF splitting of (37,35) and (38,34) state
- SHFS transitions cannot be observed due to Doppler broadening & laser bandwidth

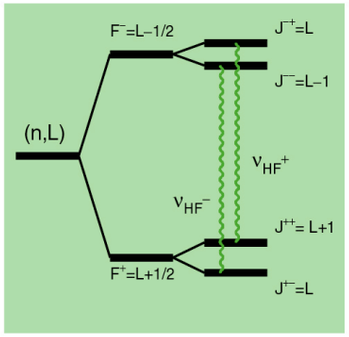
Laser-microwave-laser resonance experiment

Parameters of (37,35) state:

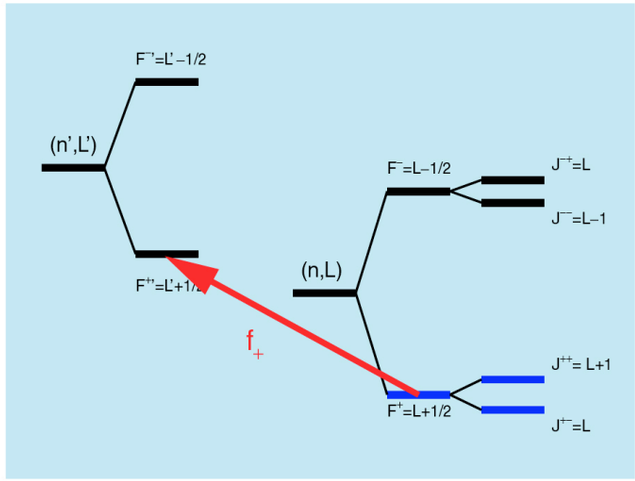
ν_{HF} = 12.91 GHz
ν_{SHF^+} = 161 MHz
ν_{SHF^-} = 133 MHz



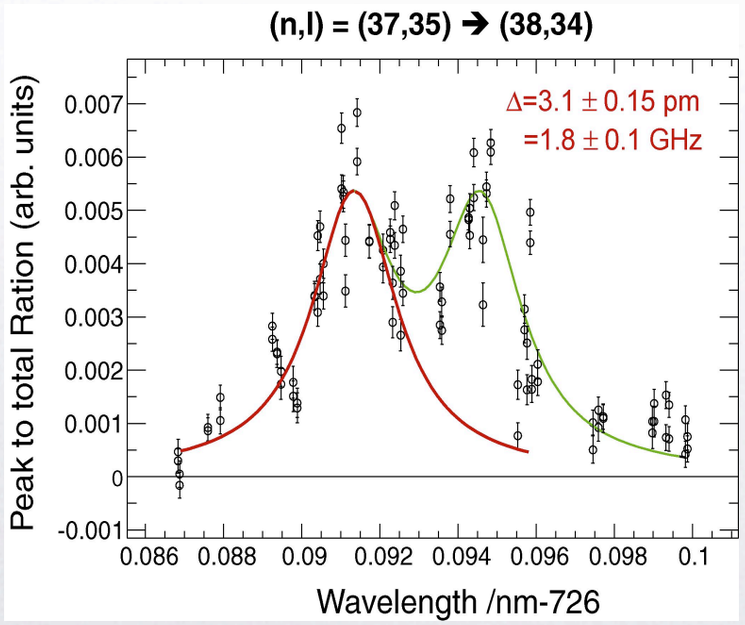
Step 1: depopulation of F^+ doublet with f_+ laser pulse



Step 2: equalization of populations of F^+ and F^- by microwave



Step 3: probing of population of F^+ doublet with 2nd f_+ laser pulse



Laser scan

Time spectrum with 2 laser pulses

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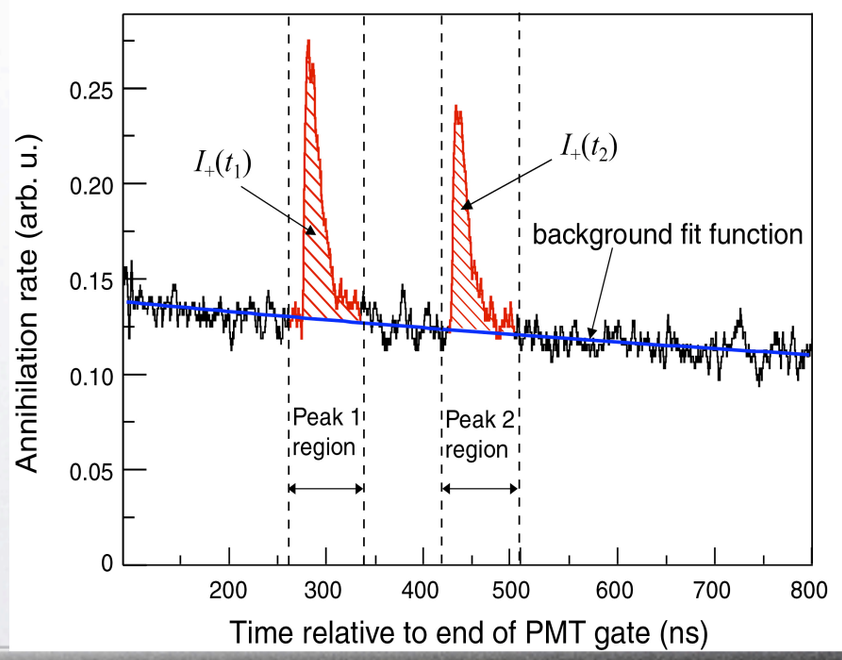

Laser-microwave-laser resonance experiment

Parameters of (37,35) state:

ν_{HF} = 12.91 GHz
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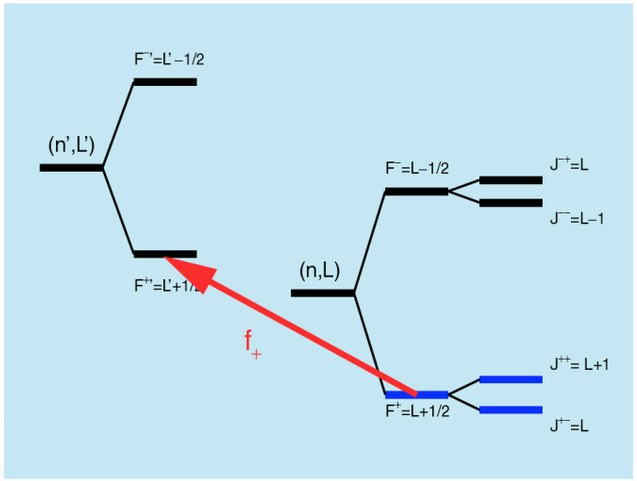

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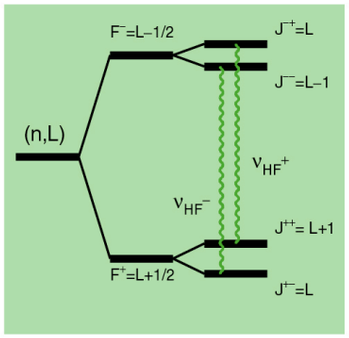

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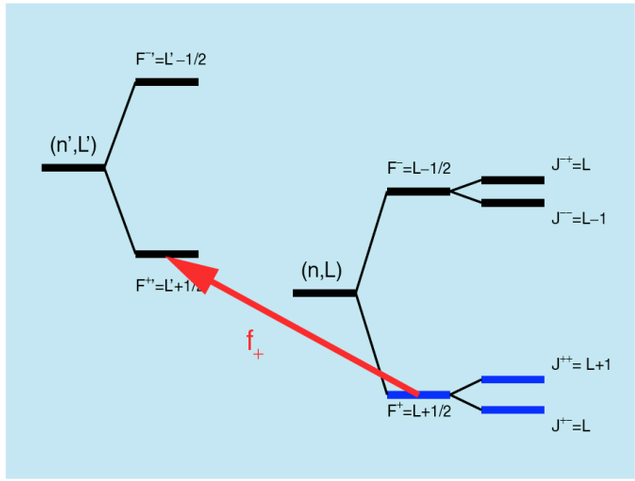

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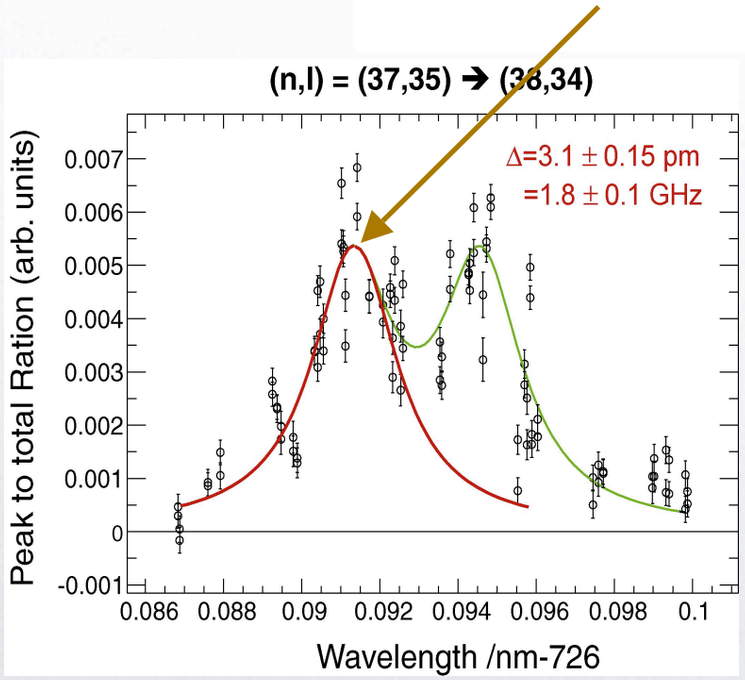

← Laser scan

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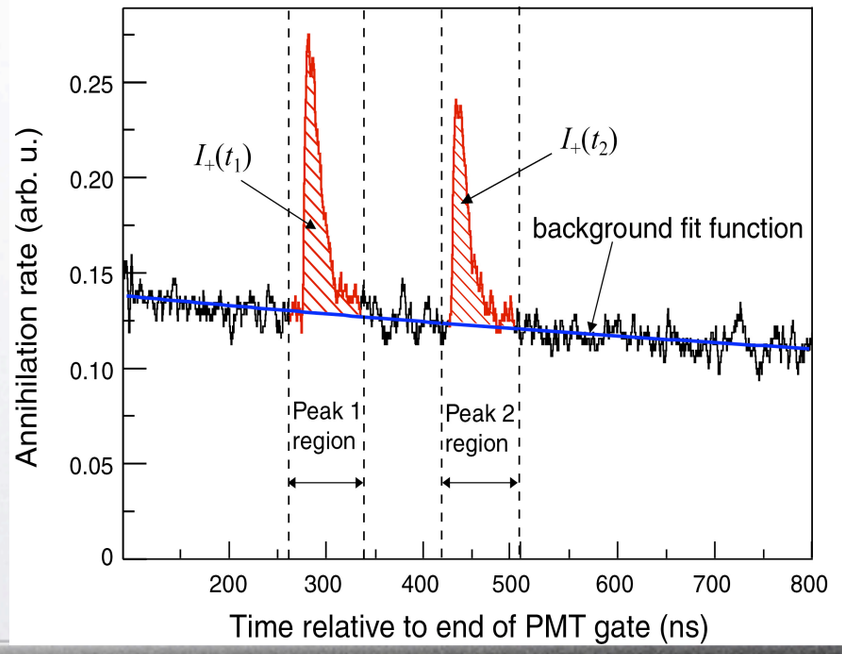

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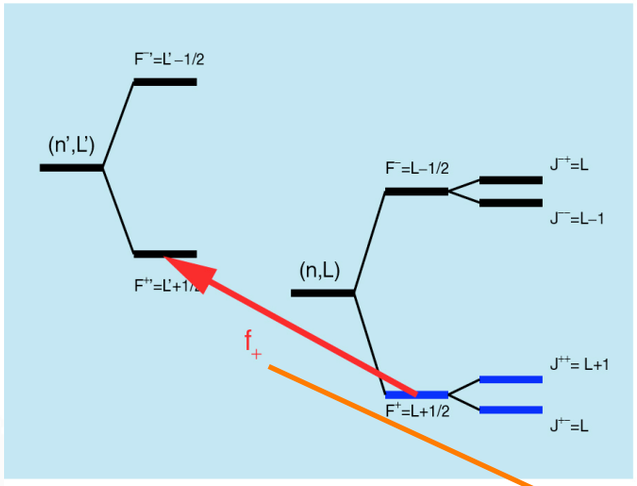

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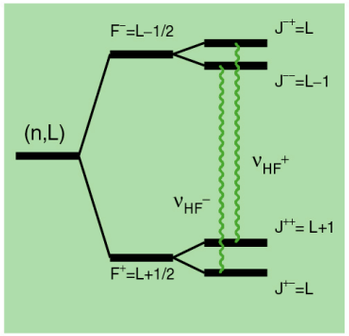

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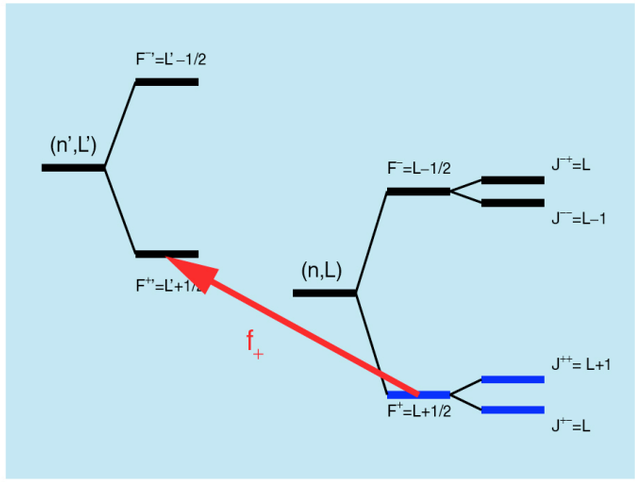

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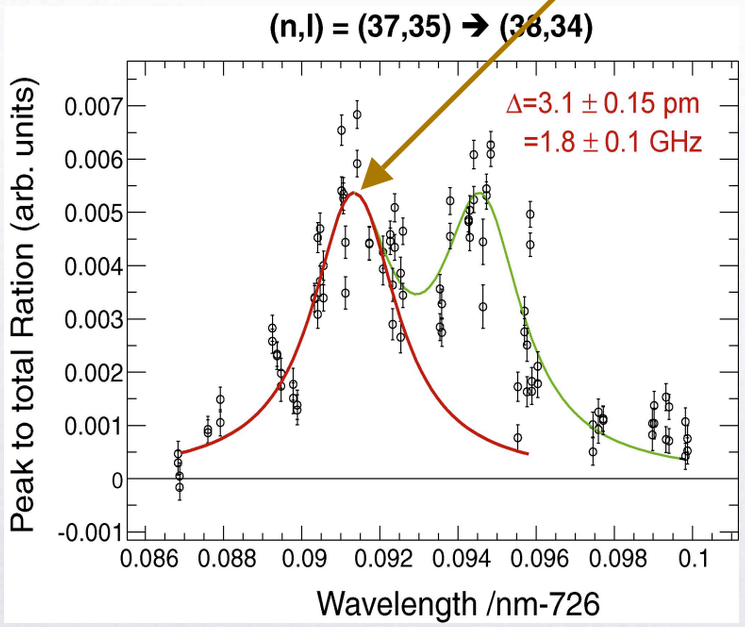

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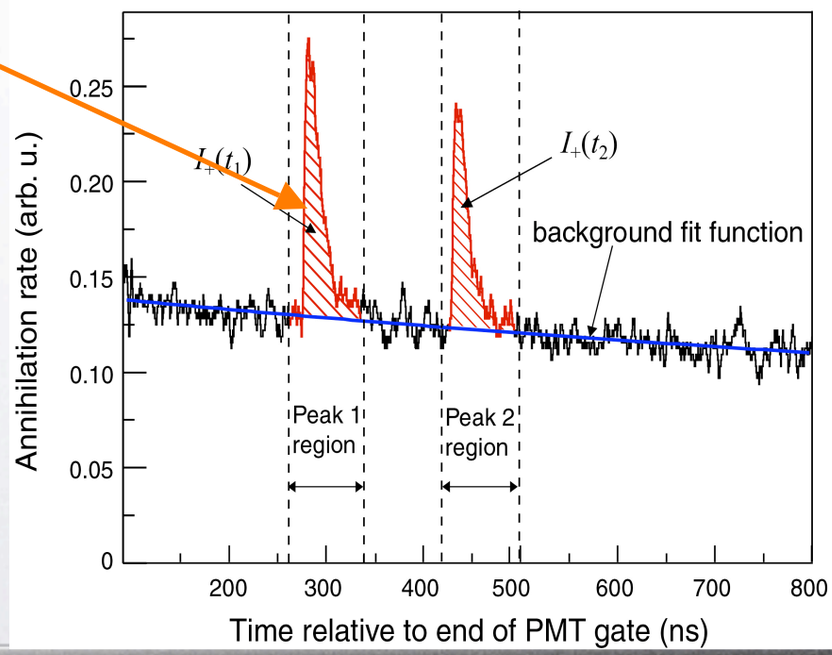

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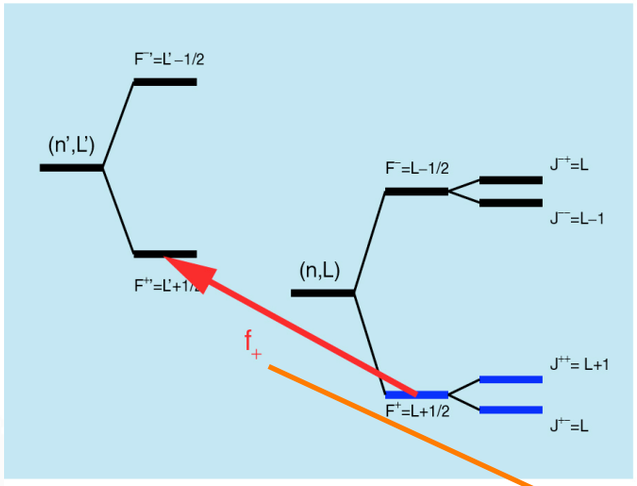

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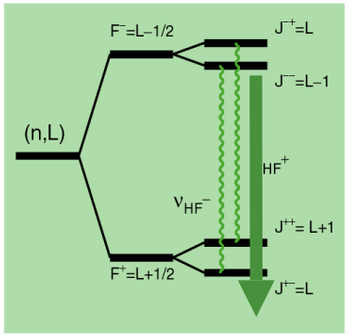

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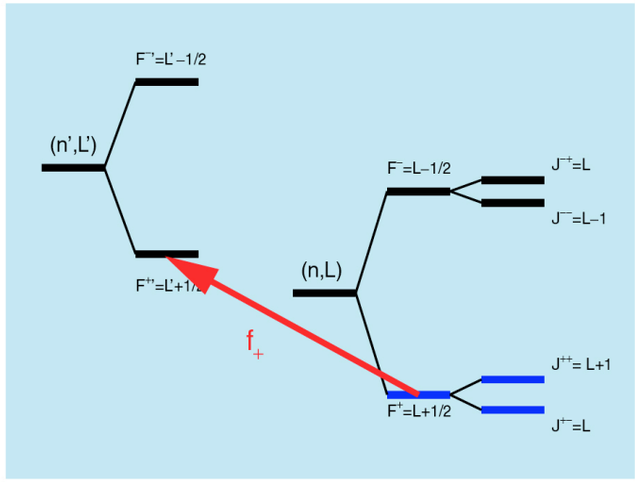

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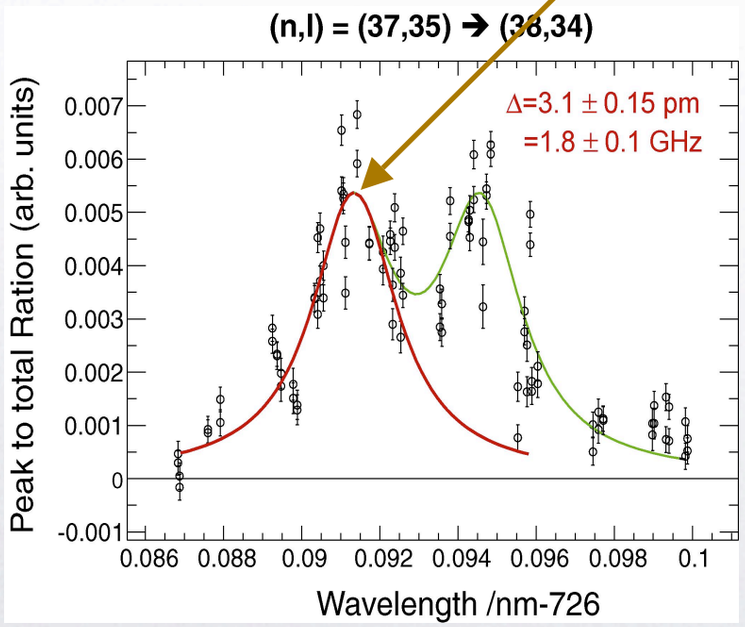

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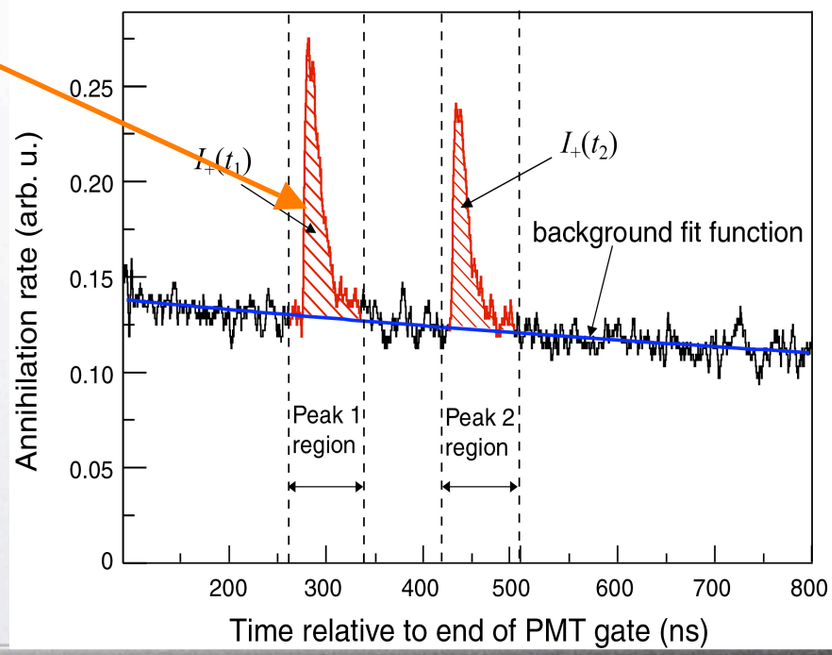

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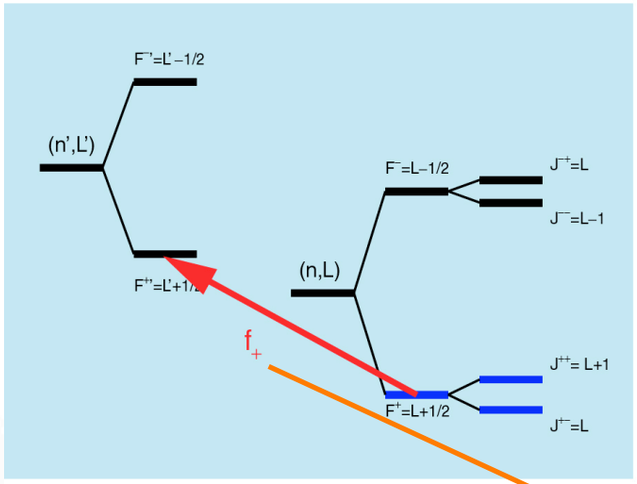

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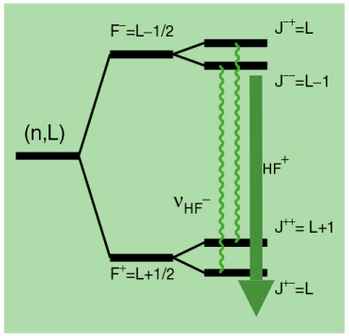

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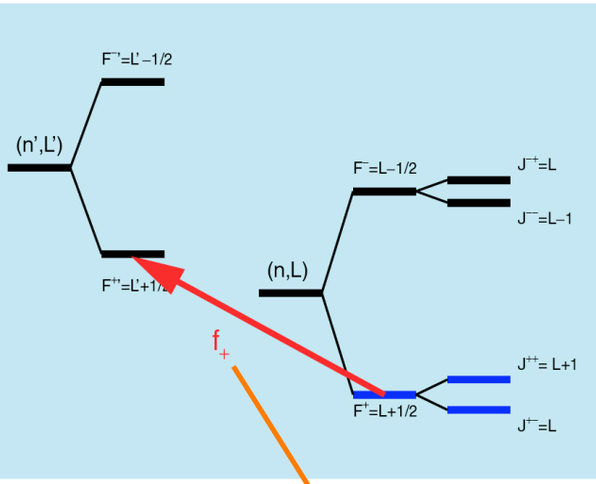

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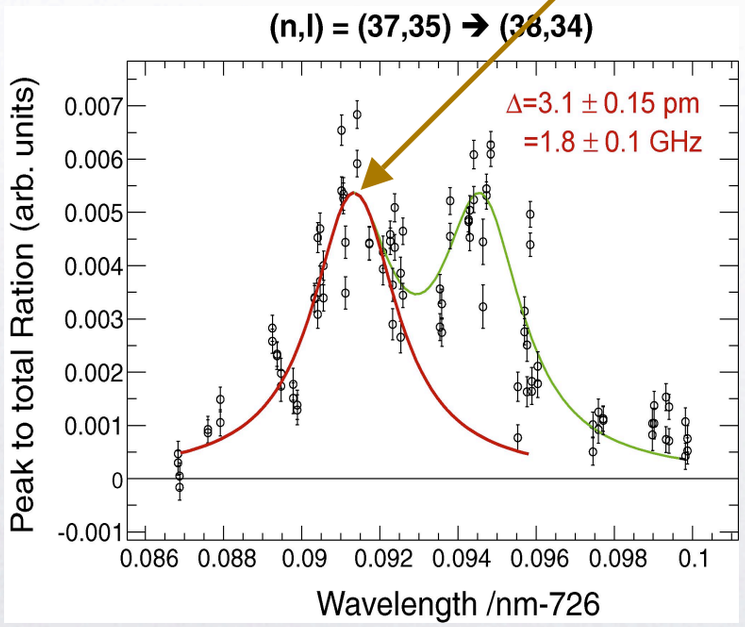

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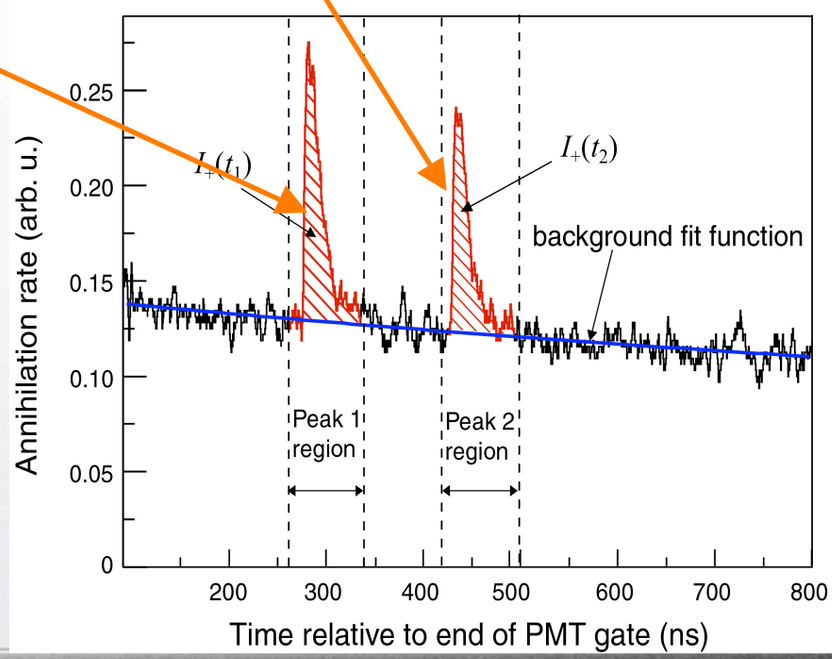
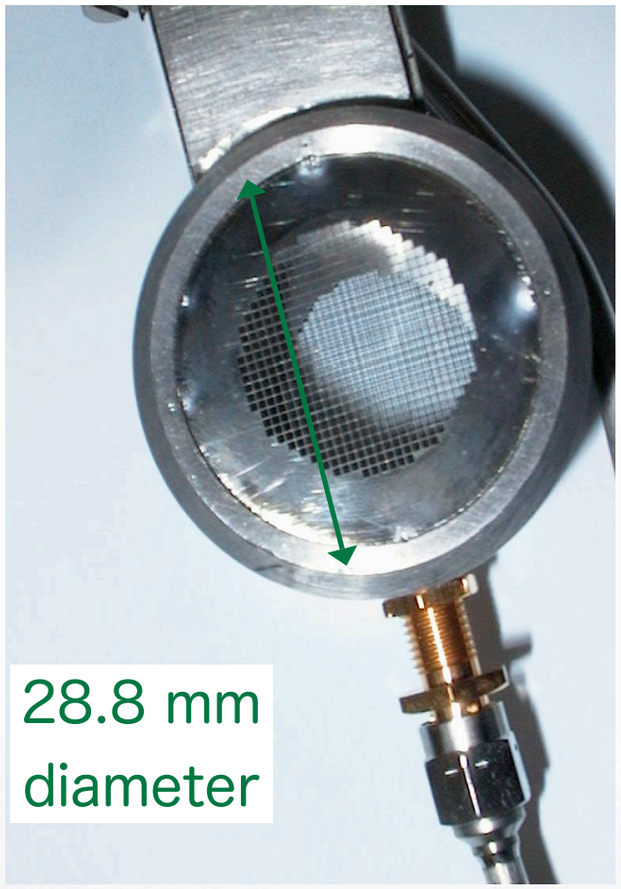
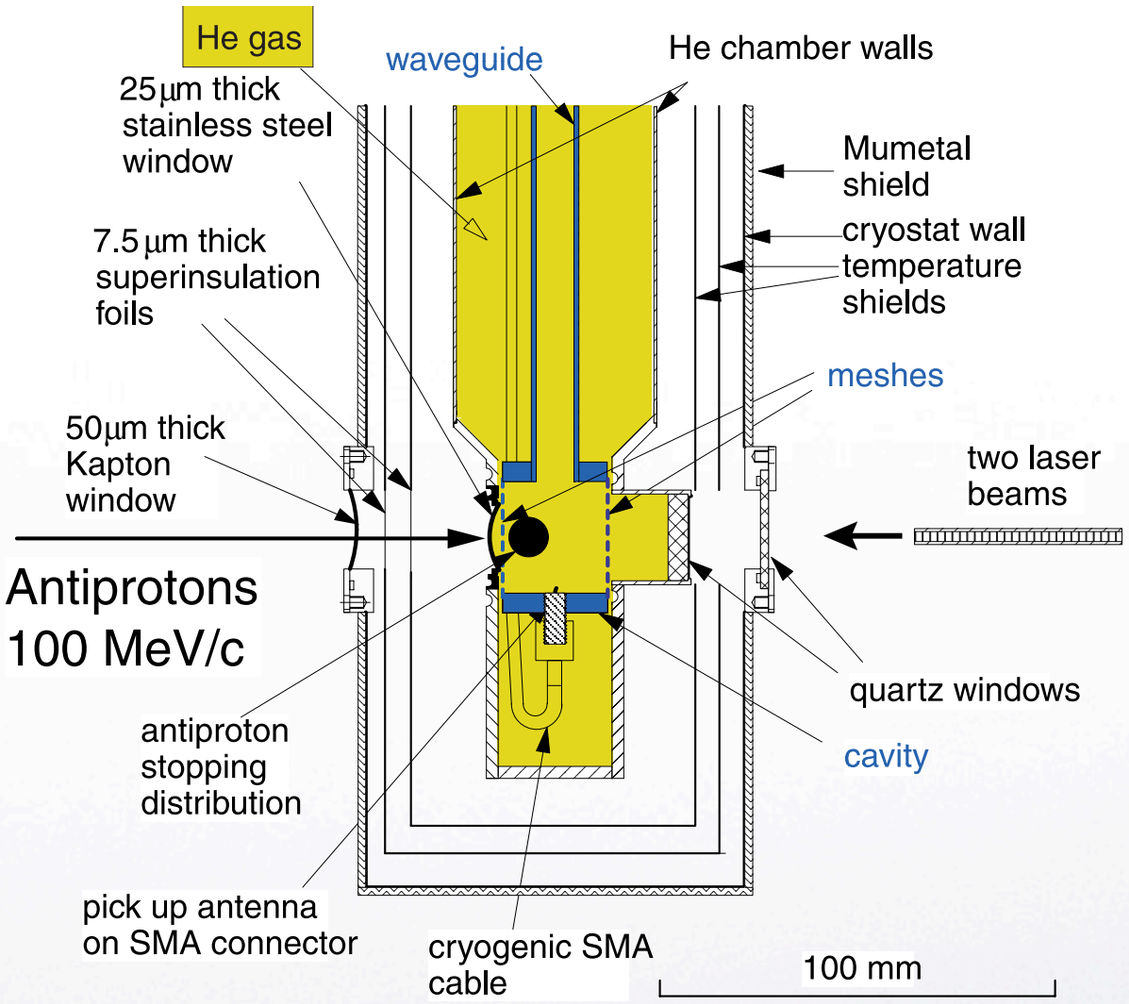


Microwave cavity for HFS measurement

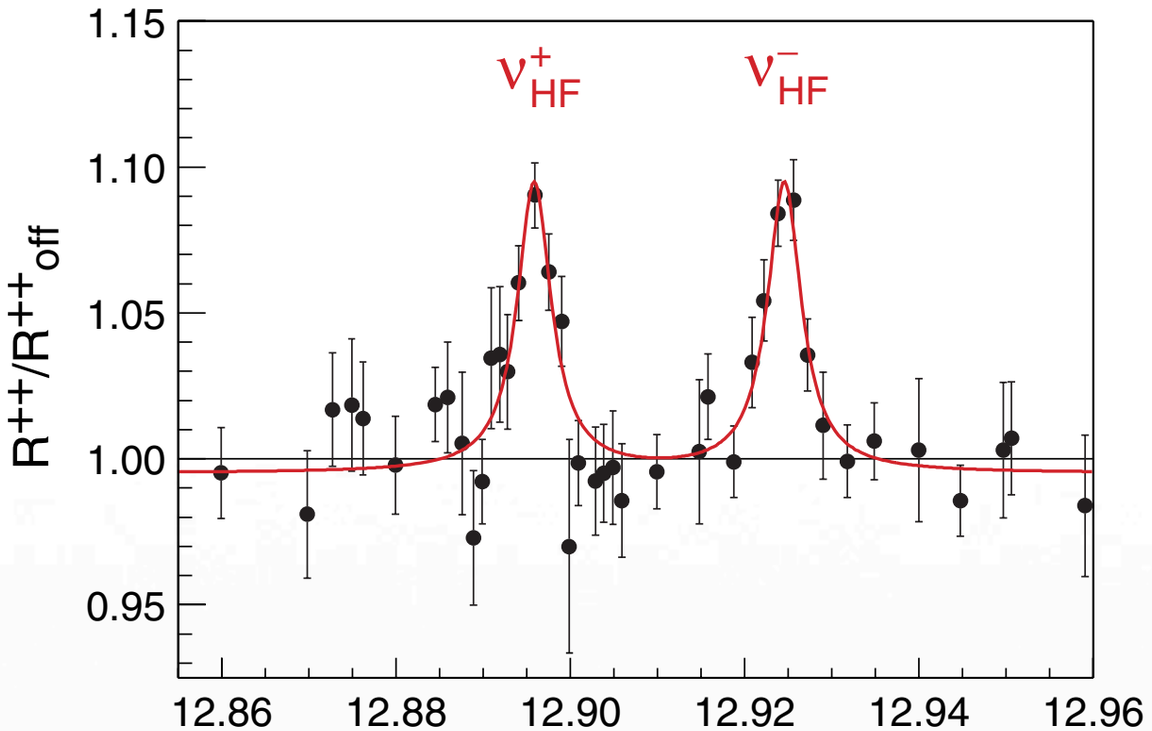




- cavity for 13 GHz at < 10 K to reduce Doppler broadening
- Meshes to allow pbar and laser light to enter

- low Q (~100) to avoid mechanical tuning
- tuning via synthesizer and stub tuner

First observation of HFS transition



- Experimental accuracy: ~ 3 x 10^{-5}

ν_{HF}^{+}	12.895 96(34) GHz	27 ppm
ν_{HF}^{-}	12.924 67(29) GHz	23 ppm

- E.W. et al. PRL 89 (2002) 243402

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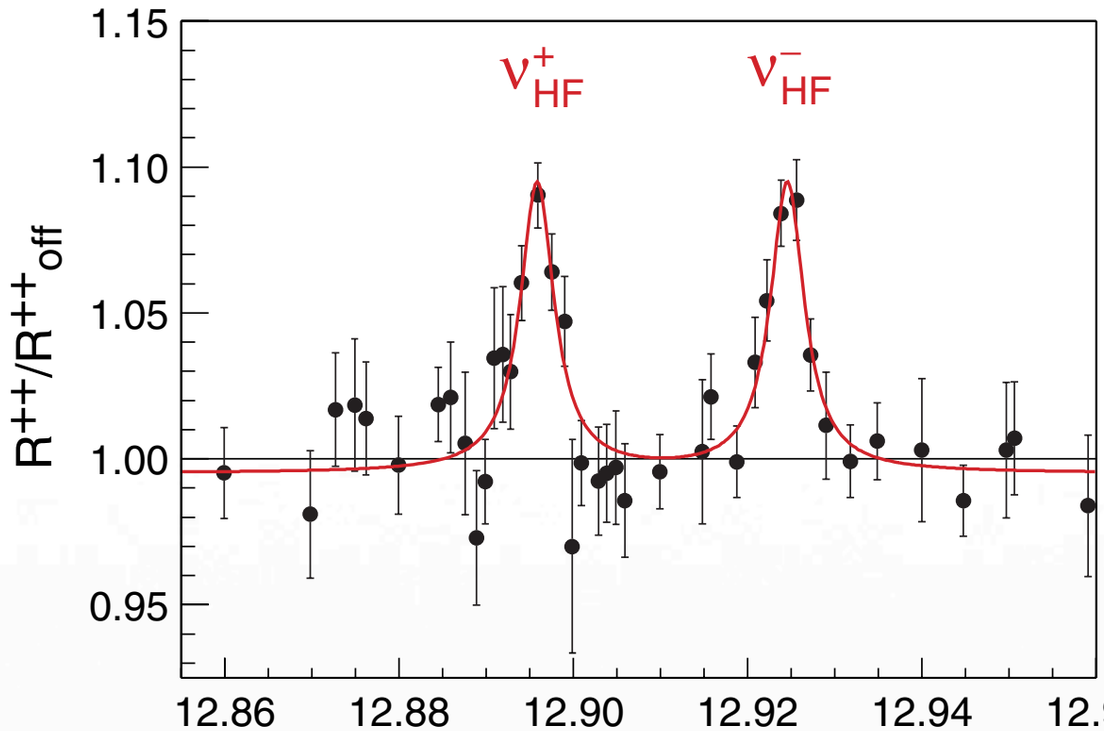

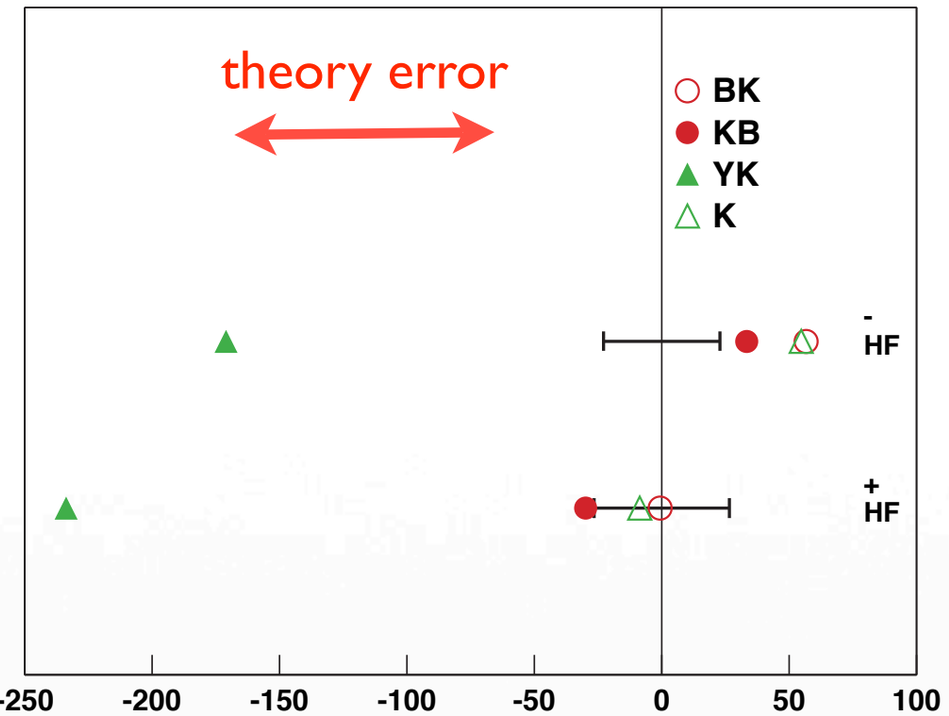

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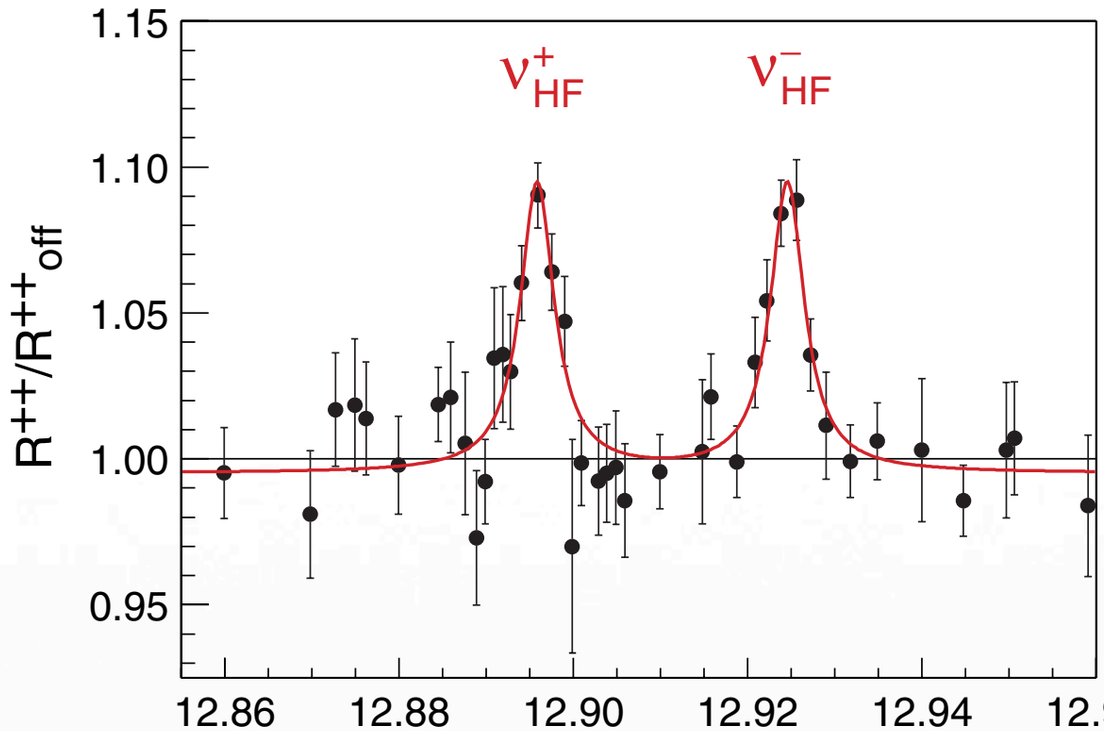

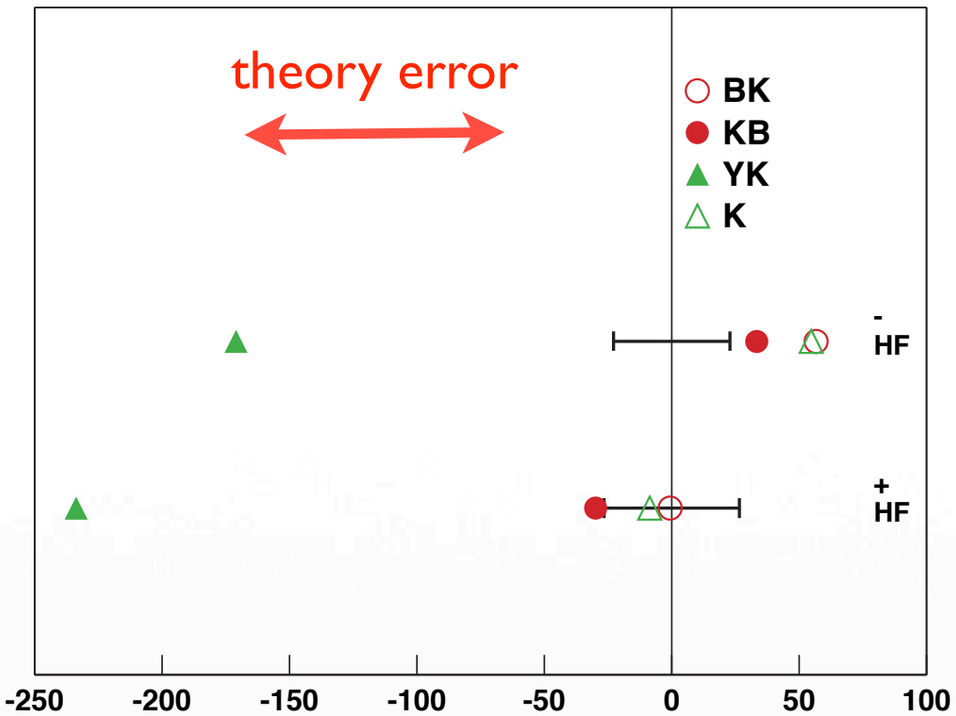

ν_{MW} (GHz)

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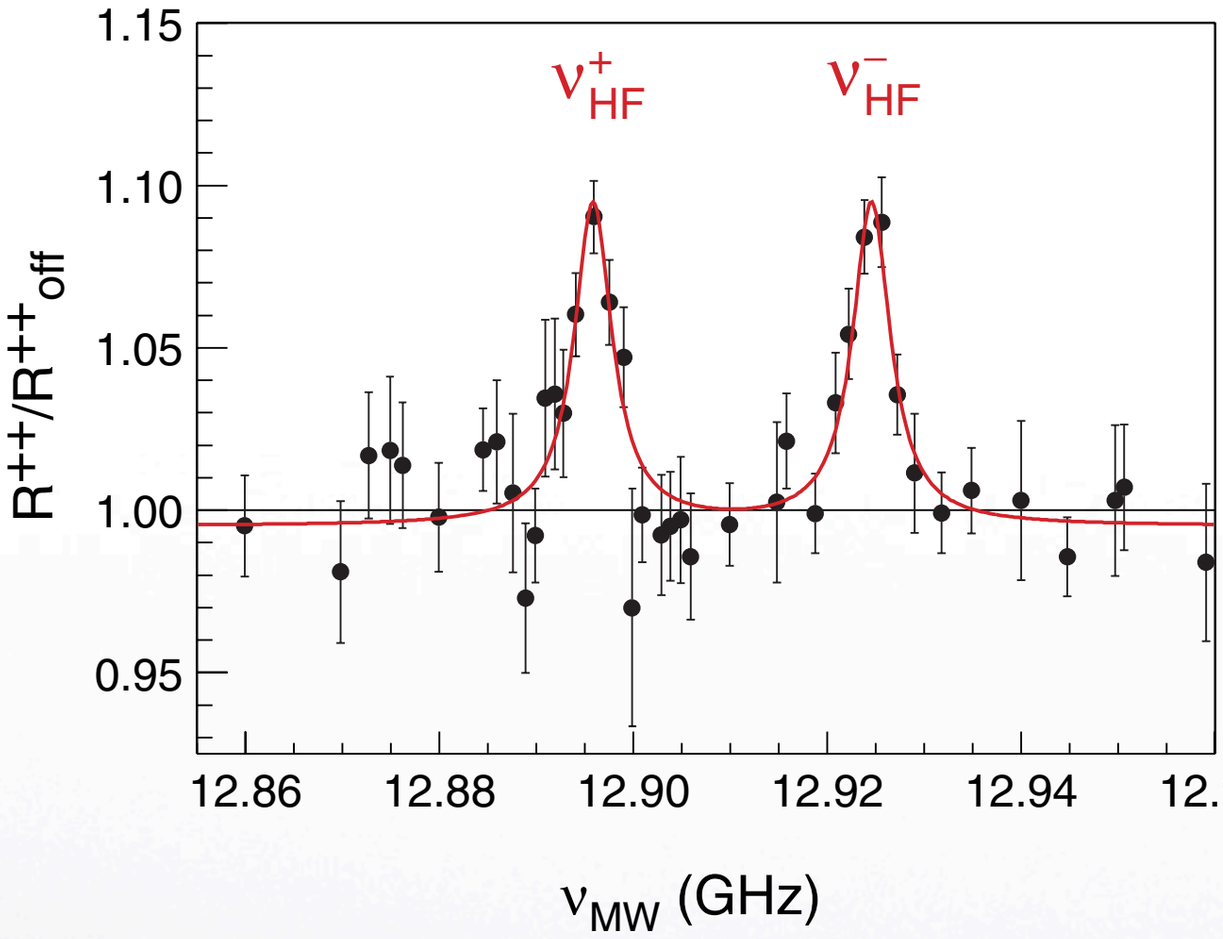
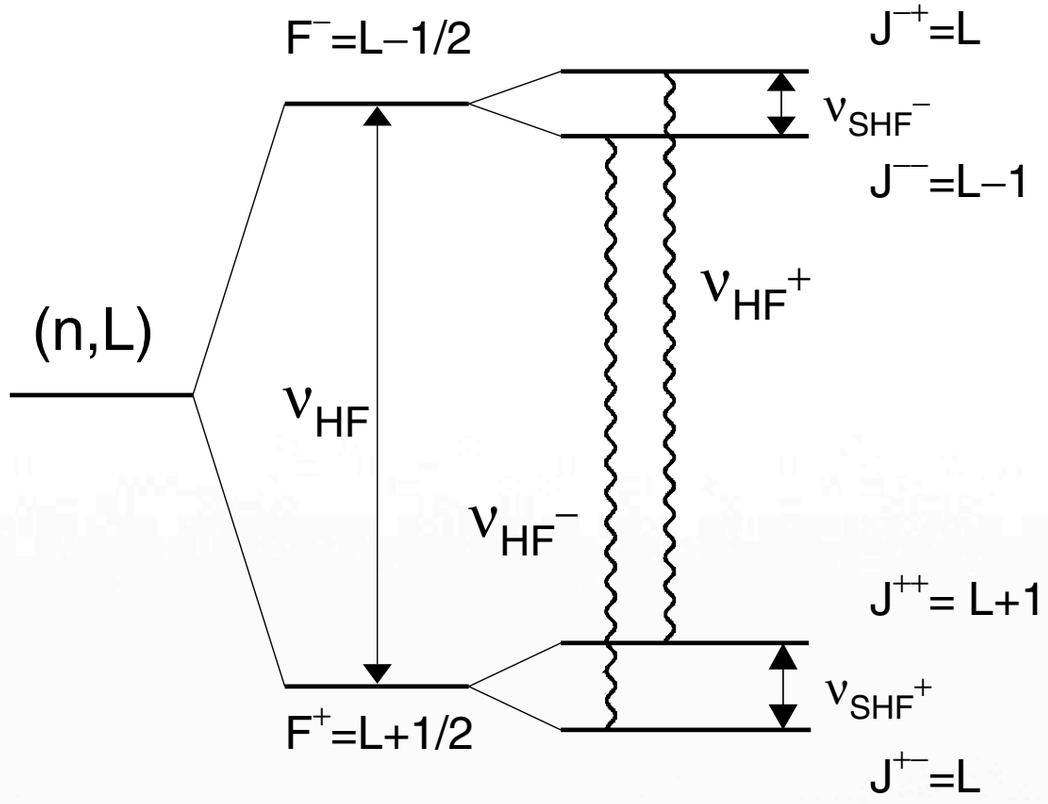
- *Comparison to theory favours most recent results of both groups*
  - *Korobov & Bakalov JPB 34 L519 2001*
  - *Kino et al. Proc. APAC 2001*
- *Difference < 6×10^{-5}*
- *Corresponds to theoretical uncertainty*
  - Omission of terms $O(\alpha^2) \sim 10^{-4}$

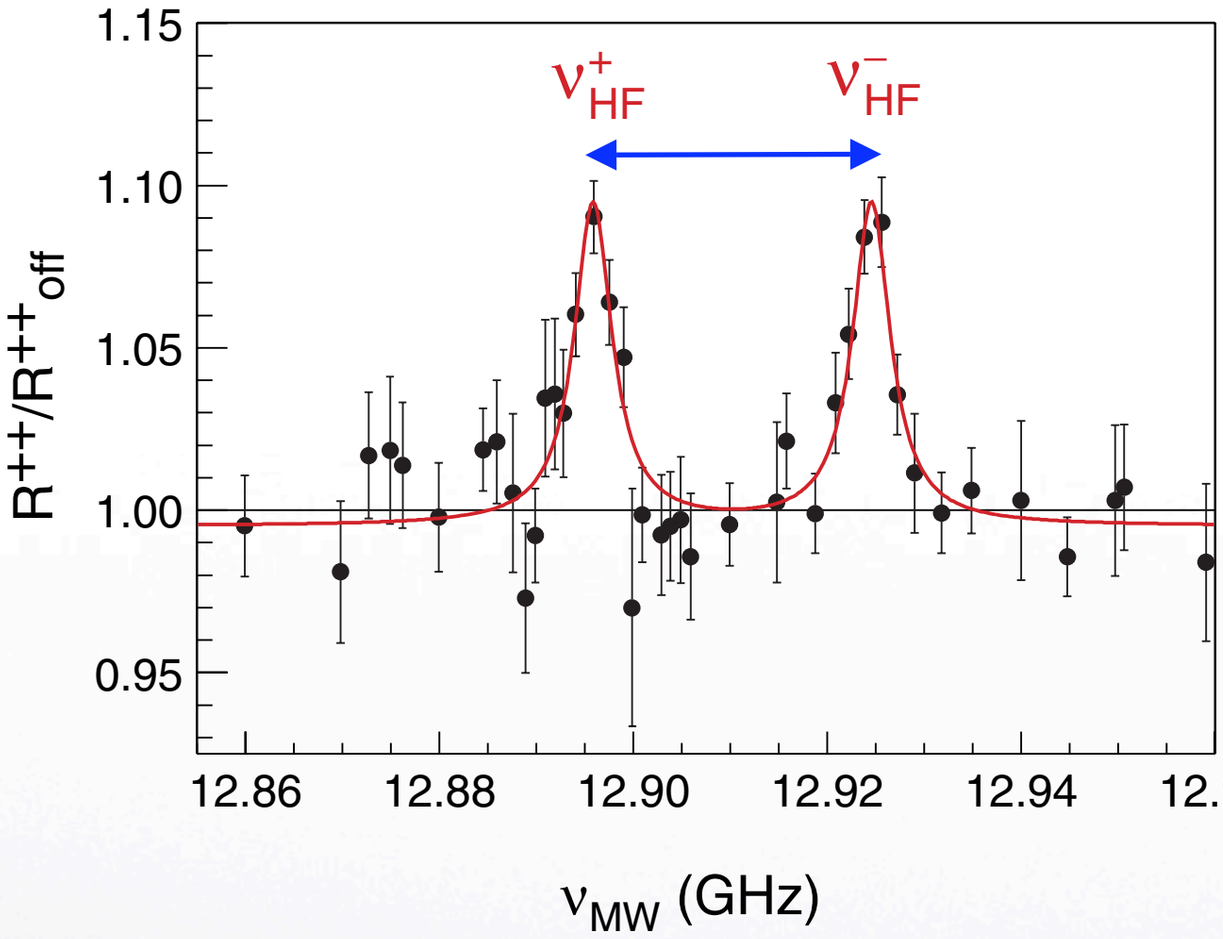
determination of $\mu_{\bar{p}}$

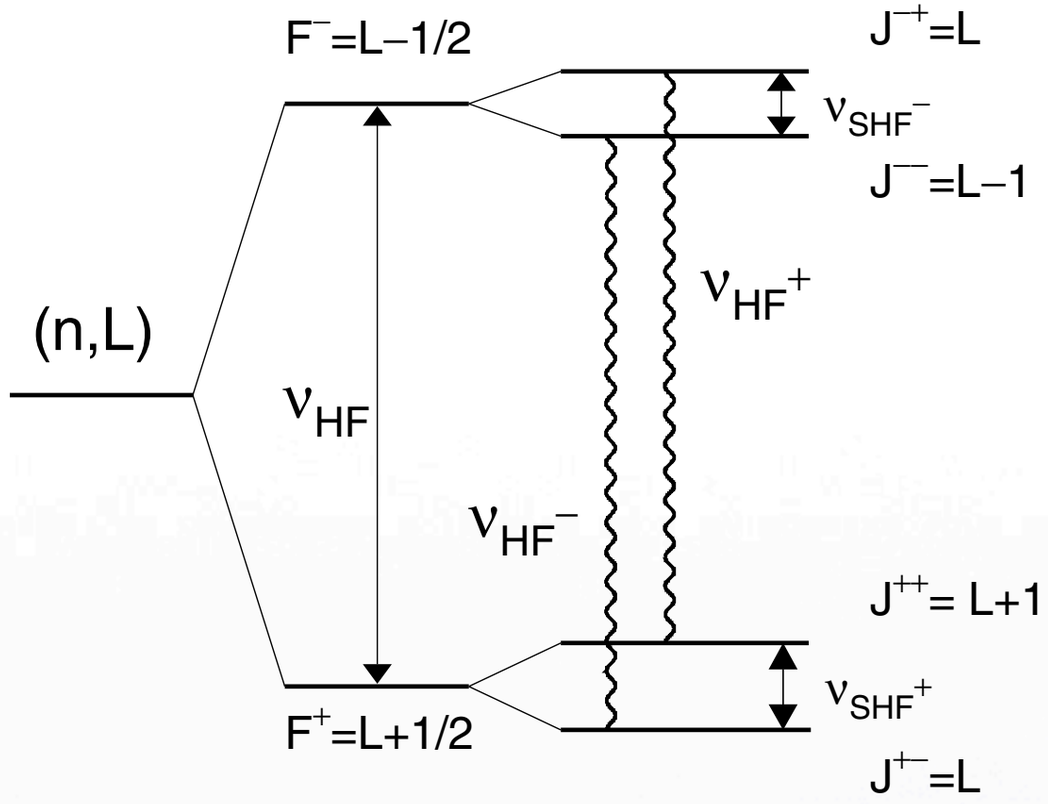




- ν_{SHF}^{+} , ν_{SHF}^{-} most sensitive, but impossible to measure (power requirement)
- $\Delta\nu_{HF} = \nu_{HF}^{-} - \nu_{HF}^{+} = \nu_{SHF}^{+} - \nu_{SHF}^{-}$: sensitive to $\mu_{\bar{p}}$
- sensitivity factors from theory (D. Bakalov and E.W., PRA 76 (2007) 012512)
  - limiting factor: accuracy of theory: 10^{-4} for ν_{HF} , 10^{-3} for $\Delta\nu_{HF}$
  - maximum improvement factor 3-9 (dep. on state) over PDG value

determination of $\mu_{\bar{p}}$





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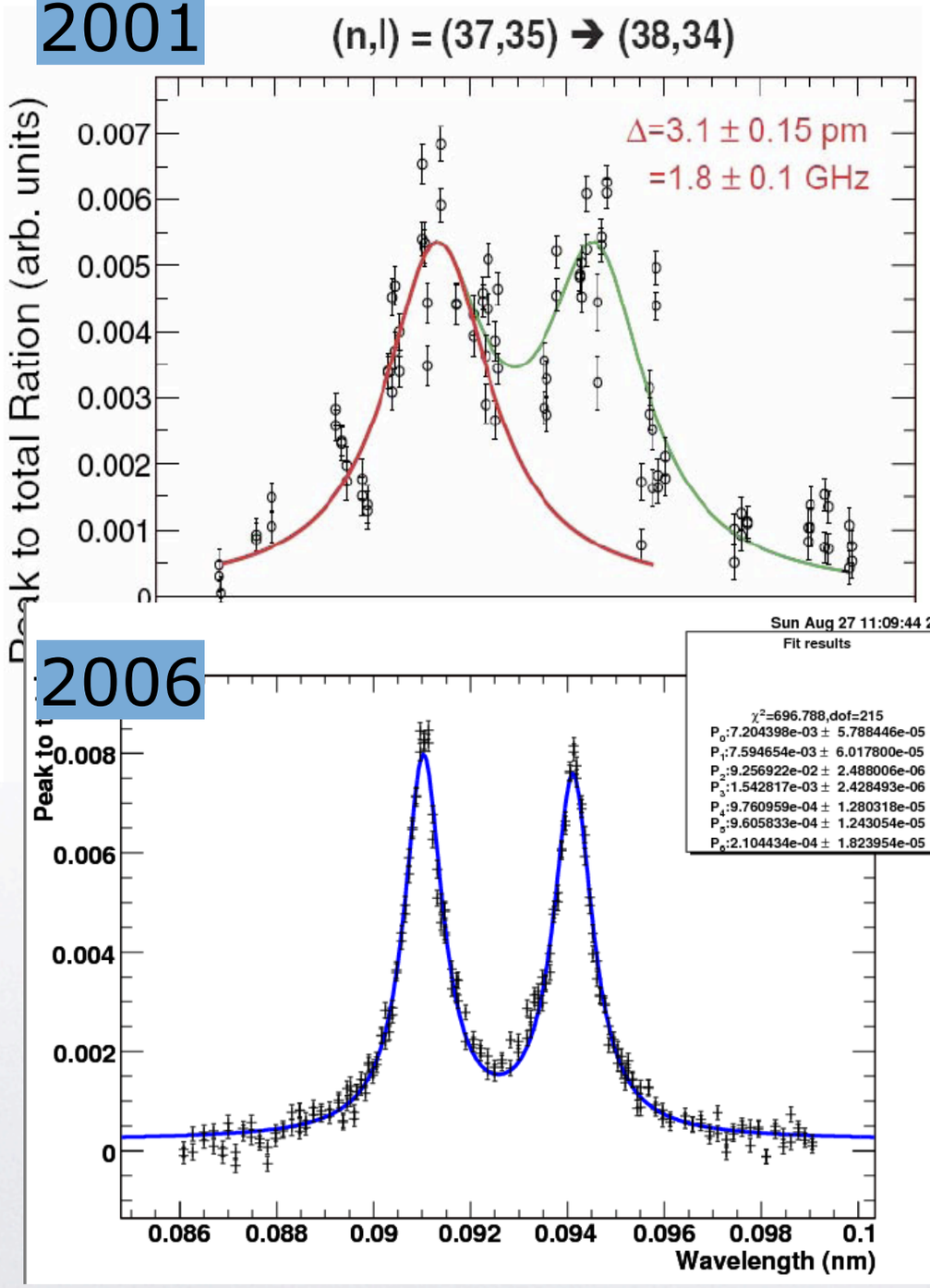
Improved laser & microwave scans

2001



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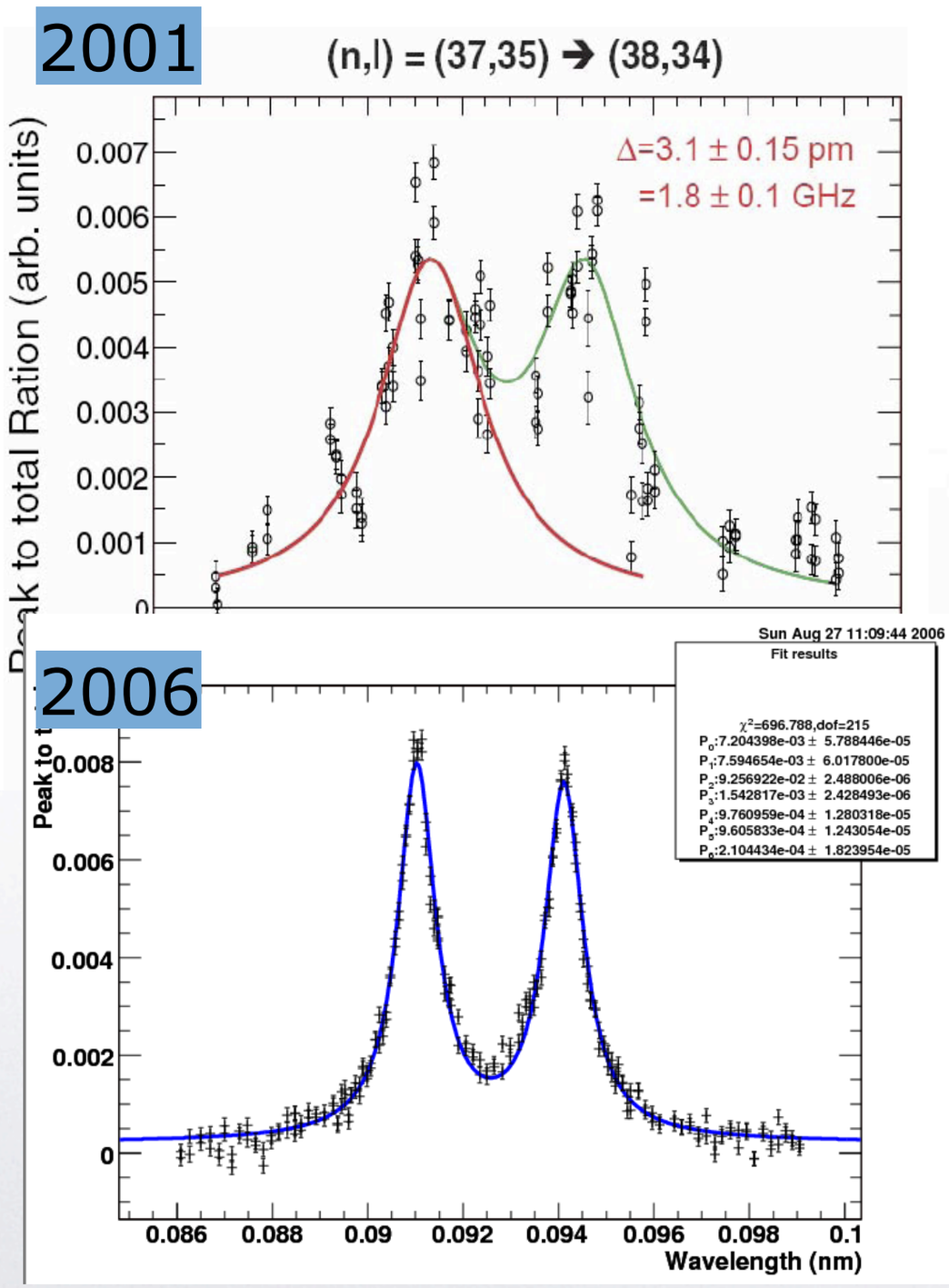
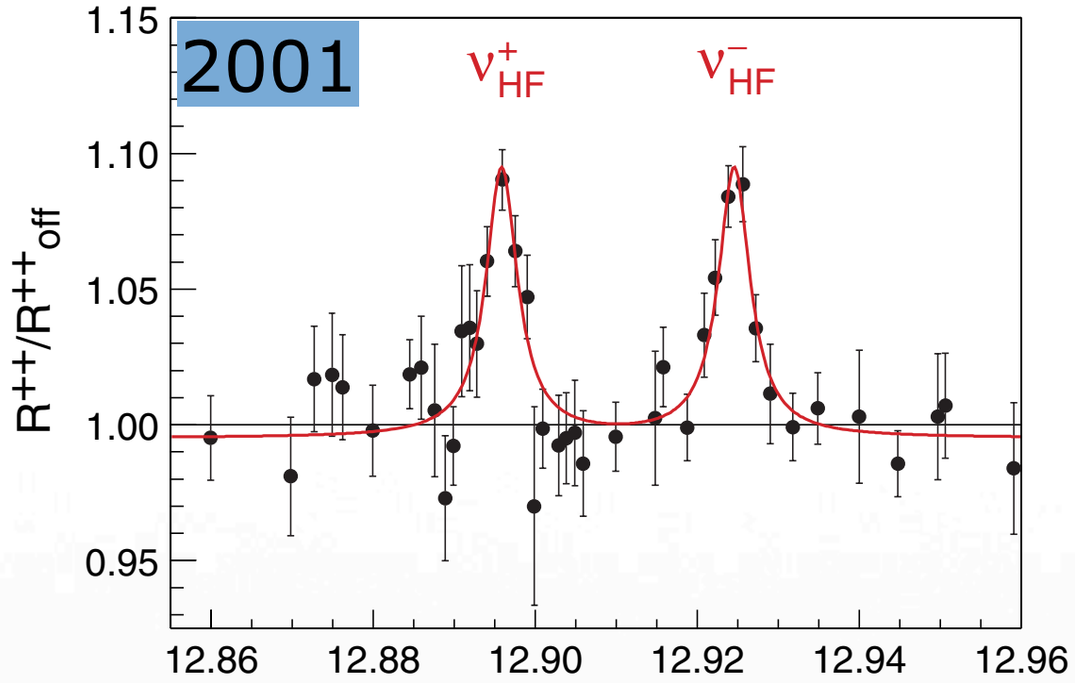
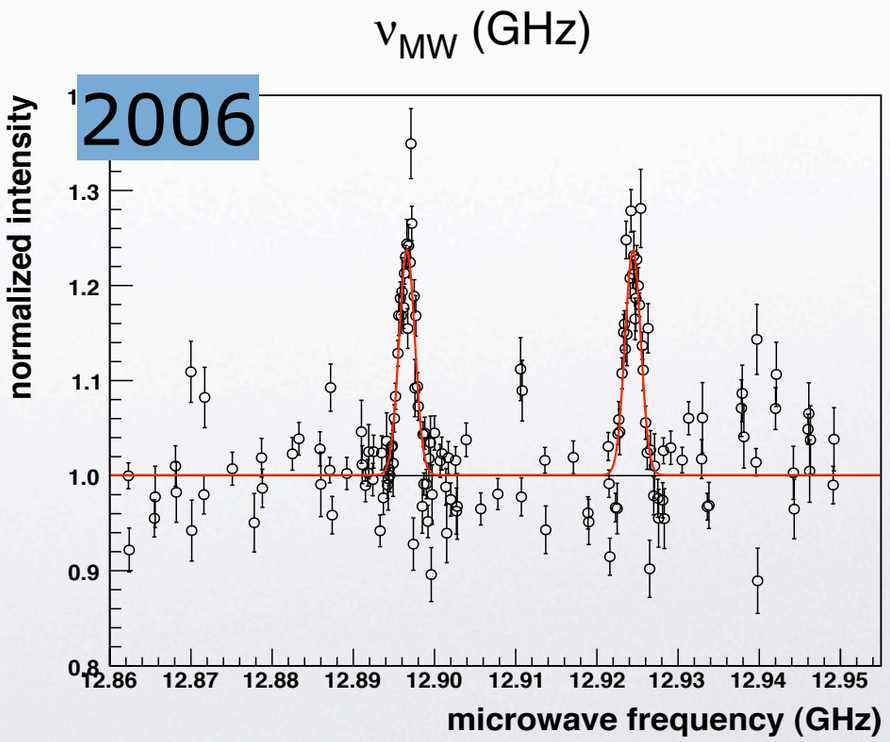
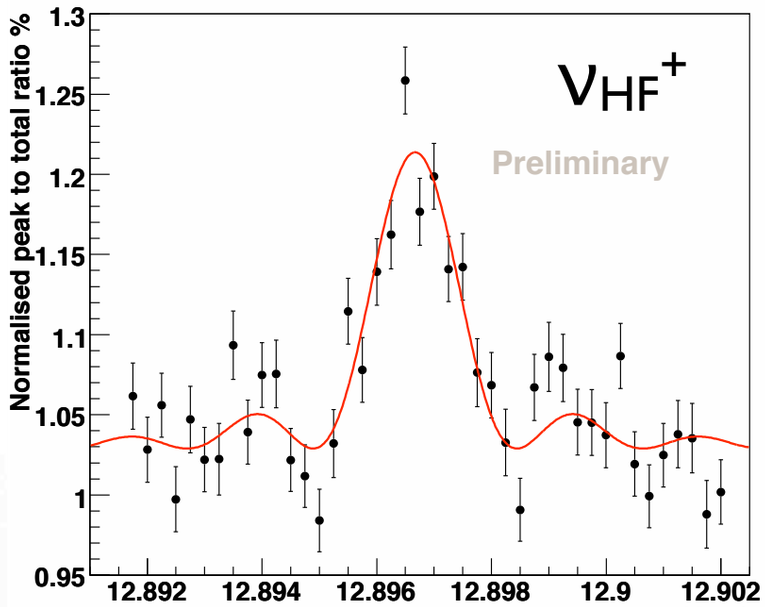


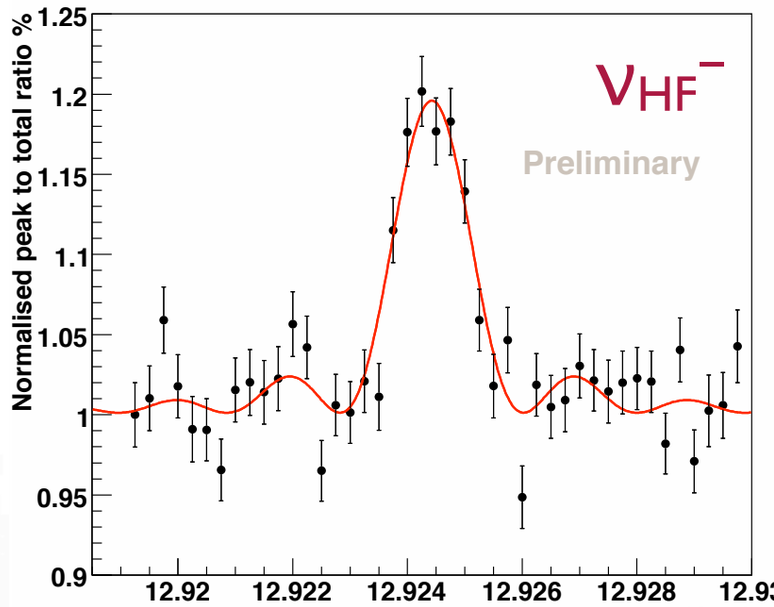


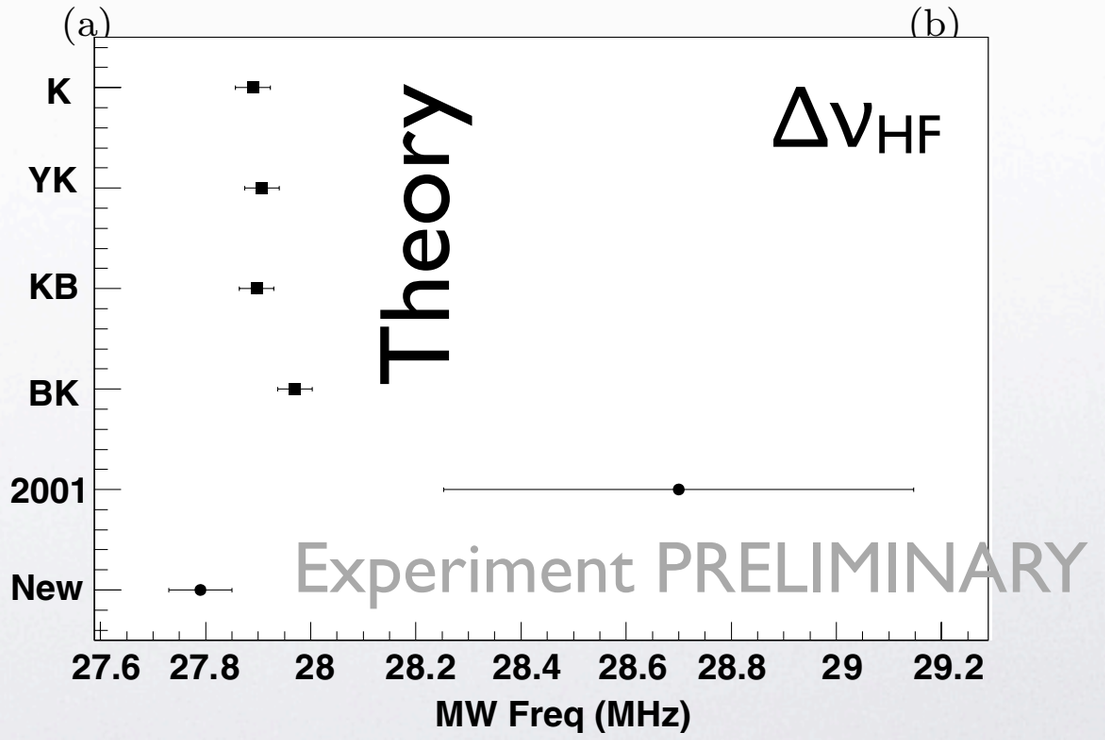


Recent results (8/2008)

- statistical error:
  20 kHz on $\nu_{HF}^{\pm}$:
  $\Delta\nu/\nu = 1.5 \times 10^{-6}$
- 30 kHz on $\Delta\nu_{HF}$:
  $\Delta\nu/\nu = 10^{-3}$
- no density nor power shift observed
- close agreement to theory
- analysis being fnalized







Summary and outlook

- Antiprotonic helium one of best tests of 3-body bound-state QED
- Agreement with theory gives test of CPT symmetry for charge, mass, magn. moment of pbar
- laser spectroscopy: $\Delta_{CPT}(M,Q)\sim 2$ ppb
- microwave spectroscopy: $\Delta_{CPT}(\mu)\sim 10^{-3}$
- future plans:
  - two-photon laser spectroscopy, hole burning
  - HFS of pbar-^{3}He