Chapter 12

Conclusions

The long term storage and non-destructive interrogation of cryogenic antiprotons have made it possible to measure the antiproton-proton mass ratio 1000 times more accurately than with any previous technique (Fig. 12.1). We have measured the antiproton to proton mass ratio to be

$$\frac{m_{\overline{p}}}{m_p} = 0.999\,999\,977(42). \tag{12.1}$$

This measurement has a fractional uncertainty of 4.2×10^{-8}, making it the most stringent test of CPT invariance using baryons.

In addition, as part of a thorough systematic study using the much lighter electron, we have independently compared the antiproton and proton to the electron inertial mass. We obtain

$$\frac{m_{\overline{p}}}{m_e} = 1836.152\,648(89), \tag{12.2}$$

and the fundamental ratio

$$\frac{m_p}{m_e} = 1836.152\,693(88). \tag{12.3}$$

The standard deviation of the later, representing a fractional uncertainty of 4.8×10^{-8}, is smaller than all previous proton-electron comparisons with the exception of the most recent measurement by VanDyck, et al. (Fig. 12.2) for which a standard deviation 2.4 times smaller is reported [100]. Our ratio agrees with their most recent measurement of 1836.152 701(37) and disagrees with their earlier measurement which had a systematic problem [100]. The technique used to measure the

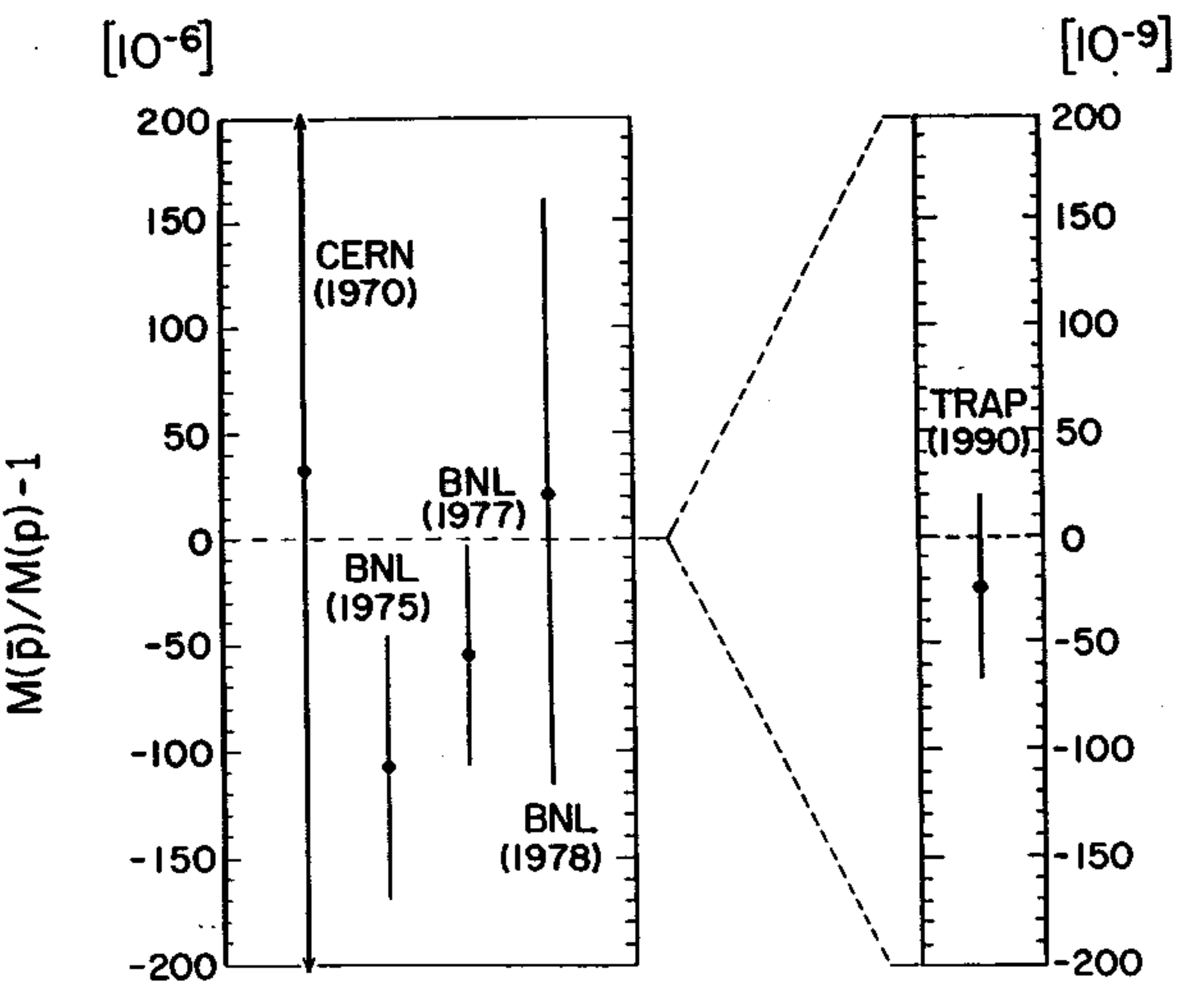

Figure 12.1: Measurements of the ratio of antiproton to proton inertial masses. Our new measurement shown on the right is an increase in accuracy of 1000.

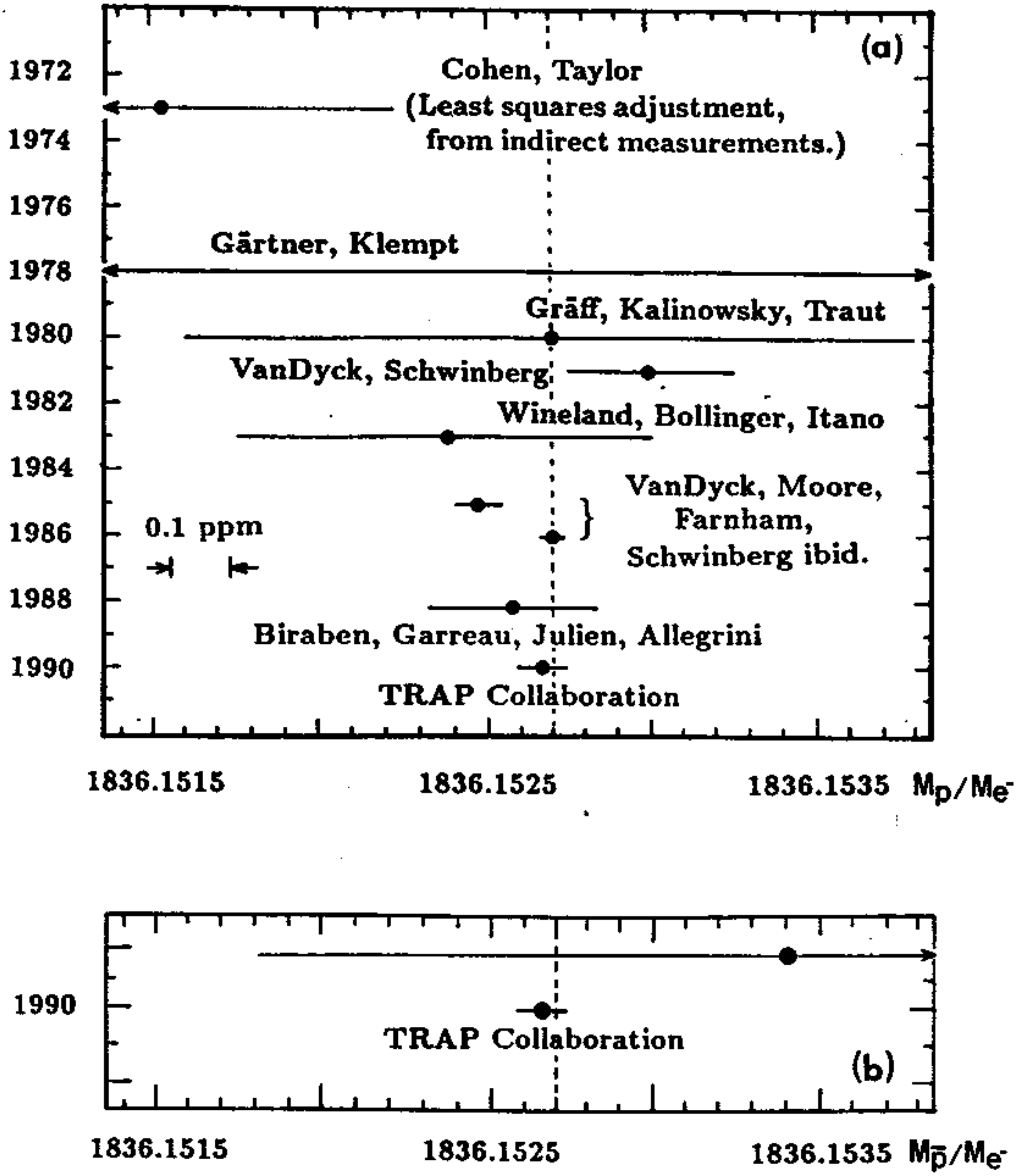

Figure 12.2: (a) Previous Measurements of the proton-electron mass ratio with our new measurement performed in the new open endcap trap. It is in agreement with the most recent, higher precision measurement by VanDyck et. al. . (b) Our new measurement of the antiproton-electron mass ratio.

mass ratio is similar except in our case no magnetic bottle is introduced, cylindrical electrodes are used rather the hyperbolic electrodes, and the effective size of our cylindrical trap is approximately six times larger than the hyperbolic electrodes used for the previous measurements.

Our large trap minimizes many potential systematic perturbations. Measurements are much less sensitive to misalignment of the quadrupole field with respect to the magnetic field and to distortions in the trap electrodes. Measurements are also much less sensitive to perturbations due to particle number or contaminant ions. Distortions to the magnetic field (the magnetic bottle) resulting from the residual paramagnetism and diamagnetism of the trap electrodes are also greatly reduced as is the effect of possible voltage offsets which could displace the physical center of the confined particle(s).

This work demonstrates that the cylindrical Penning trap can produce a sufficiently good quadrupole potential for high precision mass spectroscopy. The cylindrical trap is easier to construct than traditional hyperbolic traps. It is also orthogonalized, making possible deliberate mistuning which is useful for systematic studies or as a coupling mechanism between the various eigenmodes. With the use of compensation coupling in the electron measurements, cyclotron resonances are measured with a resolution of better than one part in 10^8. At the level of the comparisons made in this thesis, no line splitting is required in either the electron, proton, or antiproton measurements.

The use of direct detection of the cyclotron motion for antiprotons and protons, has been used for studying polarity dependence effects and as a means to probe the effect of space charge due to contaminant ions in the trap. This is the first use of such a detection scheme for opposite but similar mass particle-antiparticle pairs (the positron and electron have presently only been measured by indirect detection techniques) For ion measurements, direct detection allows the observation of the lineshape as a function of energy, particle number, and spatial extent. An understanding of the cyclotron lineshape is often difficult to obtain with indirect detection through the axial motion, which is commonly used in Penning mass spectroscopy experiments. The extrapolations of the cyclotron frequency as a function of trap voltage for antiprotons and protons to directly determine the free space cyclotron frequency have also been used as an independent check of measurements determined using the invariance theorem.

Since the inertial mass measurement was performed at the CERN accelerator complex, much attention was paid to the fluctuating magnetic field environment. The self shielding magnet system developed and constructed especially for this project and was shown to be capable of shielding uniform fluctuations in the magnetic field by a factor of 156 [42,46]. This system should have applicability in future mass spectroscopy measurements and in NMR research. With the self shielding, uniform fluctuations in the magnetic field were measured to be reduced at the trap region by a factor of 156.

Even though for the inertial mass comparison we need only a small number of antiprotons our techniques to obtain and cool antiprotons have broader applicability. To date, we have loaded and electron cooled more than 100,000 antiprotons into the high precision region of the trap. Because of the extremely good vacuum with a pressure estimated to be less than 5×10^{-17} Torr (100 atoms/cm^3), we once held approximately 1850 antiprotons for 59 days. This provides a conservative containment lifetime (which subsequently is the longest measured antiproton lifetime limit) of

$$\tau_{\bar{p}} \geq 103 \quad days. \tag{12.4}$$

The availability of a cold antiproton source with a long confinement time should lead to other intriguing experiments.