New High Precision Measurements of the Masses $M(D^0)$ and $M(D^{*0})$ and the Binding Energy of X(3872)

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We have all been fascinated for a long time by hadrons beyond the conventional $|q\bar{q}\rangle$ mesons, and the $|qqq\rangle$ baryons. The literature is full of numerous claims and counterclaims for the discovery of what are called **exotics**.

Most of the earlier claims, which mercifully did not survive, were based on small statistics enhancements arising out of statistical fluctuations. This is no longer true because of observations in large statistics data from the detectors at the B-factories, BaBar and Belle, and the detectors BES at BEPC, and CMS and LHCB at LEP. There has been a unprecedented proliferation of charged and neutral 'exotics', so much so that we are running out of what alphabet with which to designate them, X, Y, Z, …

Through all these developments, the poster-child of exotics has remained the first exotic – **the X(3872)**. It has been unambiguously identified by all who had enough energy to produce it, and enough energy in its decay products to identify it. It is indeed unique among the claimed exotics by having a width < 1 MeV, and its structure remains a mystery.

Over the years many theoretical models for the structure of X(3872) have been proposed, but the most popular remains that it is a **hadronic molecule** made up of two well established mesons, the D^0 and D^{*0} mesons. The undeniable reason for the particular appeal of the $D^0\overline{D^{*0}}$ molecular model is the fact that the mass of X(3872) is very close to the sum of the masses of the D^0 and D^{*0} mesons, as was noted the day it was born.

For any molecule the most important observable is its binding energy, and for several years we have been trying to measure the binding energy of the presumed X(3872) molecule with greater and greater precision. I want to report on the latest two steps we have taken in this pursuit.

A measurement of the binding energy of X(3872) as a $D^0\overline{D^{*0}}$ molecular requires knowledge of three masses:

$M\big(X(3872)\big)$, $M(D^0)$, $M(D^{*0})$, or $\Delta M \equiv M(D^{*0})$- $M(D^0)$

Since the discovery of X(3872) in 2003 the uncertainties in the measurements of two of the three required masses have gradually decreased:

$M\big(X(3872)\big)$: ±800 keV (2003) → ±500 keV (PDG 2006) → ±170 keV (PDG 2014)

$M(D^0)$: ±1000 keV (2003) → ±1000 keV (PDG 2006) → ±180 keV (CLEO 2007)

$M(D^{*0})$ - $M(D^0)$: ±70 keV **(CLEO 1992)**

BE$\big(X(3872)\big)$: -900±2100 keV (2003) → -900±2100 keV (PDG 2006) → +600±600 keV (CLEO 2007)

I am going to tell you about two major improvements in these mass measurements which have taken place since 2007, so that the latest determination of the binding energy of X(3872) has improved from

BE$\big(X(3872)\big) = +600 \pm 600$ keV (2007) to **$+13 \pm 192$ keV (2014)**

I am going to tell you about the two measurements which have led to this impressive development.

A NEW MEASUREMENT OF $M(D^0)$

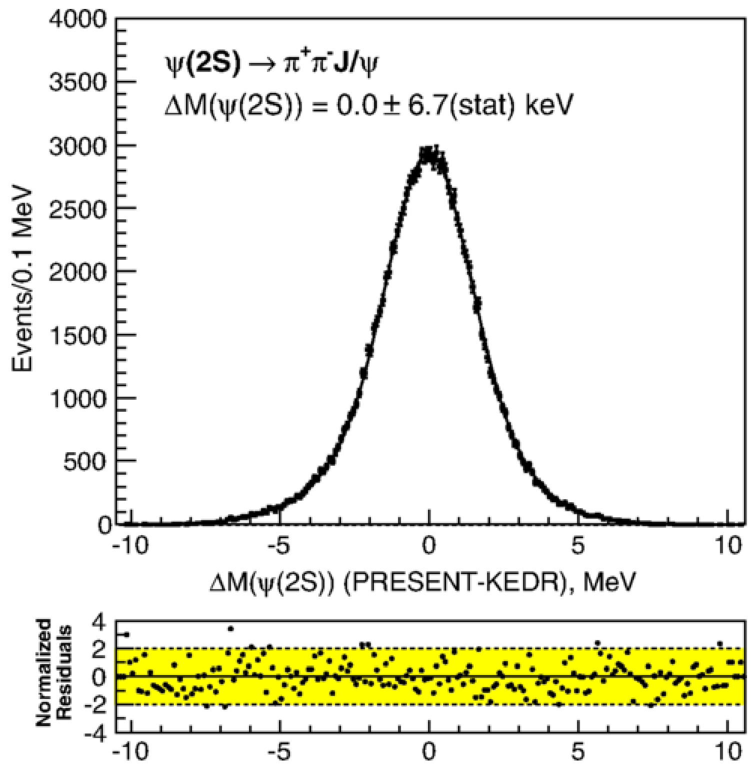
PRD, 031501 (2014)

Using 580 $\mathrm{pb}^{-1}$of e^+e^- annihilation data taken with the CLEO-c detector at $\psi(3770)$, we have studied the decay chain

$$\psi(3770) \to D^0\overline{D^0}, D^0 \to K^\pm\pi^\mp\pi^+\pi^-, \text{ or } K3\pi$$

to measure $M(D^0)$ with high precision. Our measurement involves three steps:

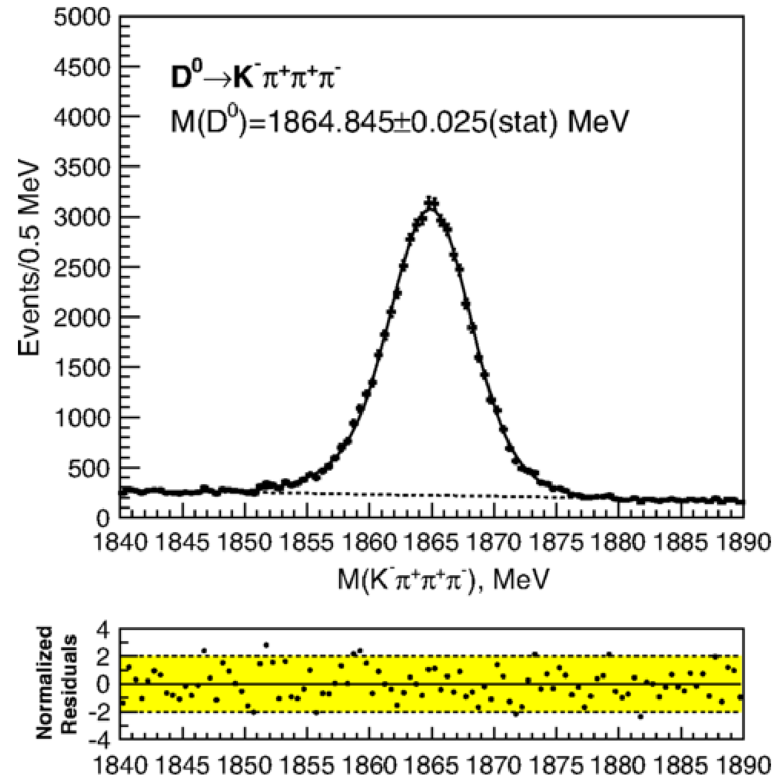
1) Calibration of the CLEO-c magnetic field by requiring that our measurement of $\mathrm{M}(\psi(2S))$ agree with the very high precision KEDR (Novosibirsk) measurement of $\mathrm{M}(\psi(2S)) = 3686.114 \pm 0.012$ MeV.
2) Precision determination of the mass of K_S by analyzing the inclusive decay, $\psi(2S) \to K_S + X, K_S \to \pi^+\pi^-$.
3) Using K_S mass to monitor and correct for the small variations of the magnetic field between sub-runs, and determining $M(D^0)$ in the decay $D^0 \to K3\pi$.



Using the decay $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$ we obtain

$$\boldsymbol{M(D^0) = 1864.845 \pm 0.025(\text{stat}) \pm 0.022(\text{syst}) \pm 0.053(\text{B field})\text{MeV}}$$

This represents a factor four improvement in precision over our 2007 measurement of $M(D^0)$.



This result is in excellent agreement with a recent measurement by BaBar [PRD88, 071104(R) 2013] using the decay $D^*(2010)^+ \to D^0\pi^+, D^0 \to K^-K^-K^+\pi^+$ BaBar obtained

$$\boldsymbol{M(D^0) = 1864.841 \pm 0.048(\text{stat}) \pm 0.063(\text{syst})\ \text{MeV}}$$

The average of the two high precision measurements of BaBar and ours is:

$$\boldsymbol{M(D^0) = 1864.843 \pm 0.044\ \text{MeV}}$$

MASS OF $M\left(D^{*0}\right)$

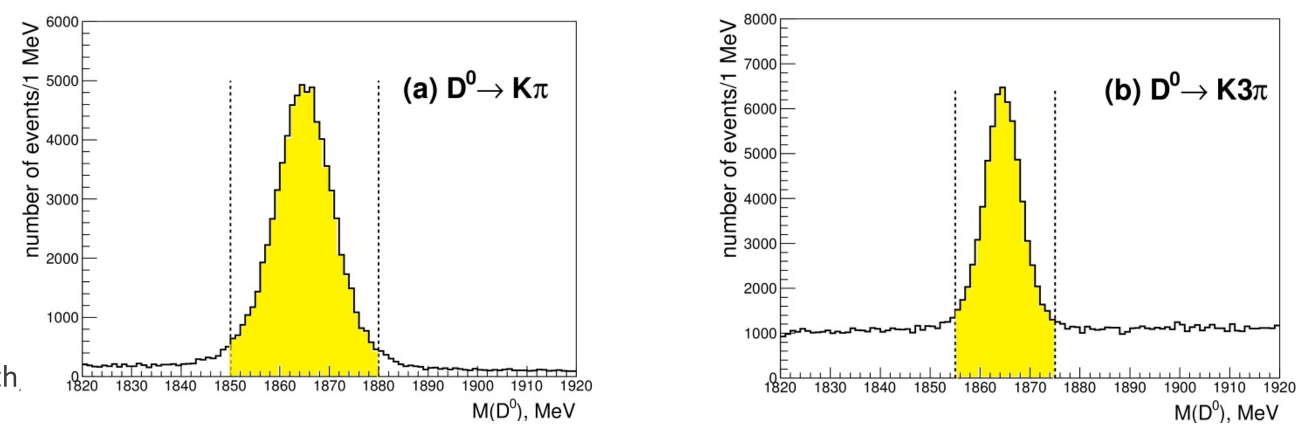
After the above results the one mass that remained to be measured with precision was the mass of the D^{*0} meson, or equivalently the difference in the masses of D^{*0} and D^0. The mass difference has not been revisited since the 1992 measurement by CLEO using data taken at the $\Upsilon(4S)$ resonance [Phys. Lett. 69, 2046 (1992)].

$$\Delta M \equiv M\left(D^{*0}\right) - M\left(D^{0}\right) = 142.120 \pm 0.070 \text{ MeV}$$

We have now made a new, high precision measurement of ΔM using 316 pb^{-1} of e^+e^- annihilation data taken with the CLEO-c detector at $\sqrt{s} = 4170\ \text{MeV}$. We study the decay of $D^{*0} \to D^0\pi^0$ with two different subsequent decays of D^0

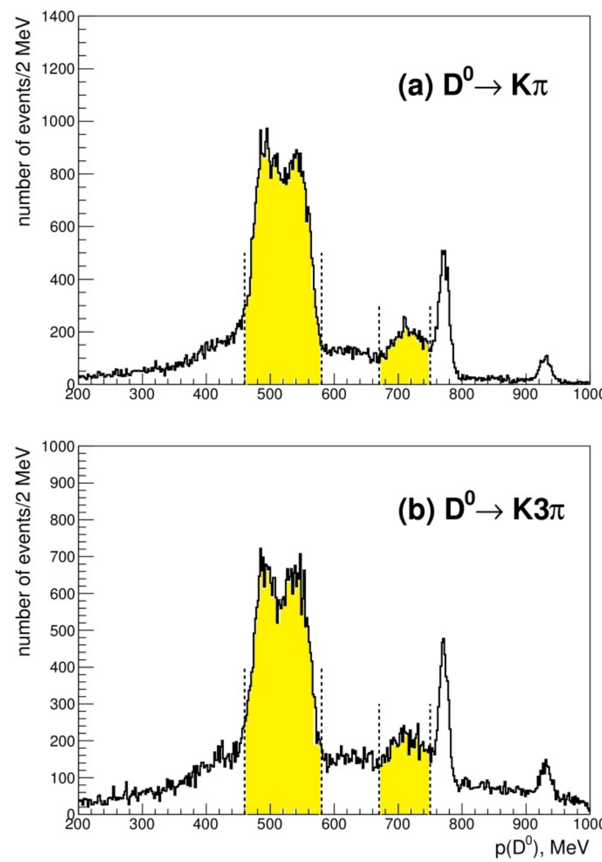
$$D^0 \to K^-\pi^+ \text{ and } D^0 \to K^-\pi^+\pi^-\pi^+.$$

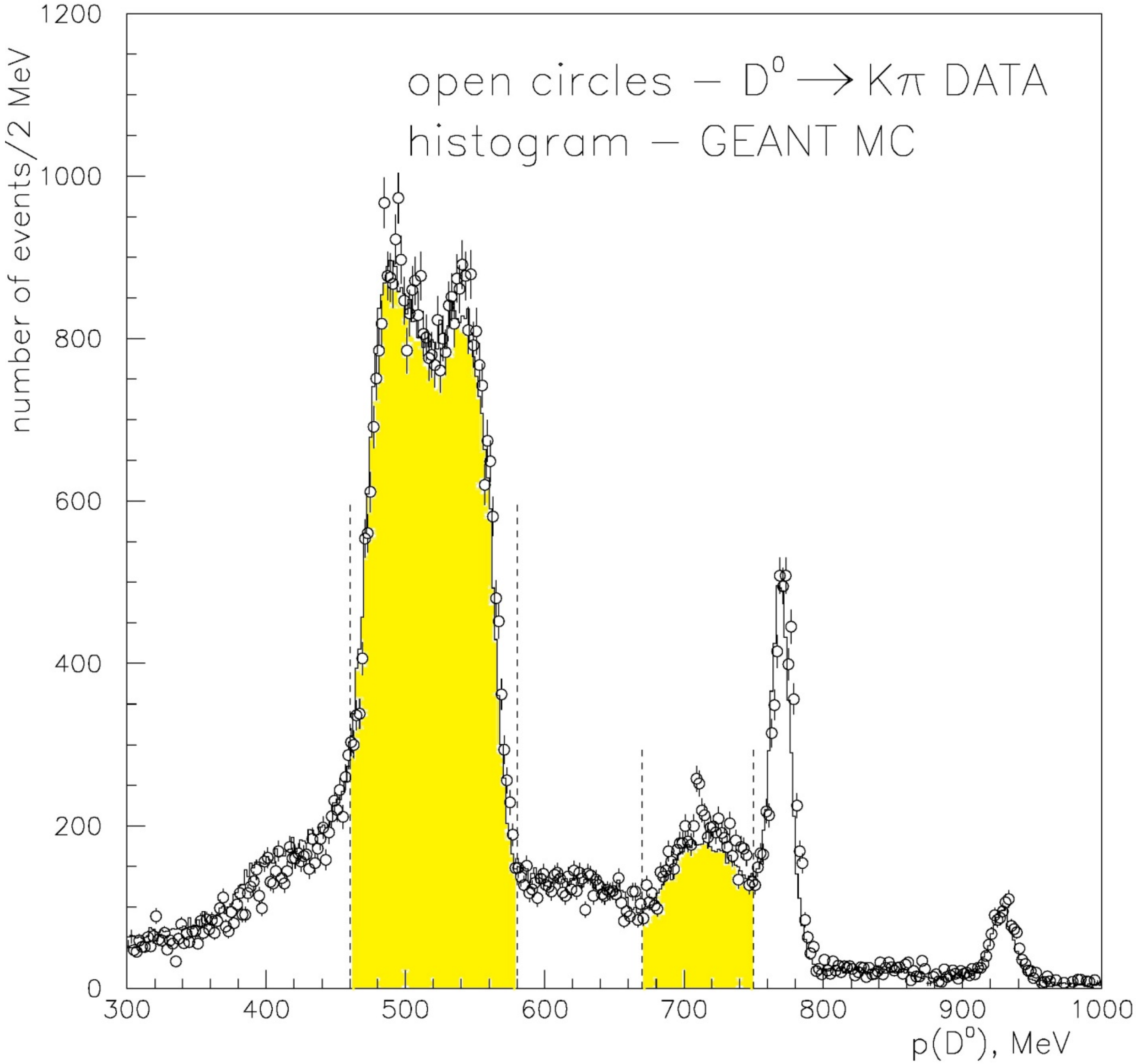
The figure shows mass distributions of D^0 for the two decays.



The decays of $\psi(4170)$ lead to enhancements at different values of the momenta of D^0, as the figures show. The decay $\psi(4170) \to D^{*0}\overline{D^{*0}}$, with both D^{*0} and $\overline{D^{*0}}$ decaying into $D^0(\overline{D^0})\pi^0$ leads to the double humped enhancement at $p(D^0) \approx 460 - 580\ \mathrm{MeV}$. The decay $\psi(4170) \to D^{*0}\overline{D^0}$, with $\overline{D^{*0}} \to D^0\pi^0$ leads to the broad enhancement at $p(D^0) \approx 670 - 750\ \mathrm{MeV}$, and a narrow peak at $p(D^0) \approx 775\ \mathrm{MeV}$. Other decays of $\psi(4170)$ contribute to the background in the momentum distributions. A GIANT based Monte Carlo simulation faithfully reproduces both the observed enhancements and the background.

We analyze the data including both ~ 520 and 720 MeV enhancements originating in D^{*0} decays, for the two decays of D^0, $D^0 \to K\pi$ and $D^0 \to K3\pi$. We reconstruct $D^{*0} \to D^0\pi^0$ and D^0 and the difference distributions $\Delta M \equiv M(D^0\pi^0) - M(D^0)$. Because the instrumental contributions to mass resolution essentially cancel in the difference ΔM, the spectra for ΔM have very good resolution (FWHM ≈ 2.8 MeV). We make fits to the unbinned ΔM spectra.




open circles – $D^0 \rightarrow K\pi$ DATA
histogram – GEANT MC
number of events/2 MeV
$p(D^0)$, MeV
0
200
400
600
800
1000
1200
300
400
500
600
700
800
900
1000

The results are:

$$\Delta\mathrm{M}(K\pi) = \mathbf{142.007} \pm \mathbf{0.018(stat)} \pm \mathbf{0.016(syst)\ MeV}$$

$$\Delta\mathrm{M}(K3\pi) = \mathbf{142.008} \pm \mathbf{0.027(stat)} \pm \mathbf{0.016(syst)\ MeV}$$

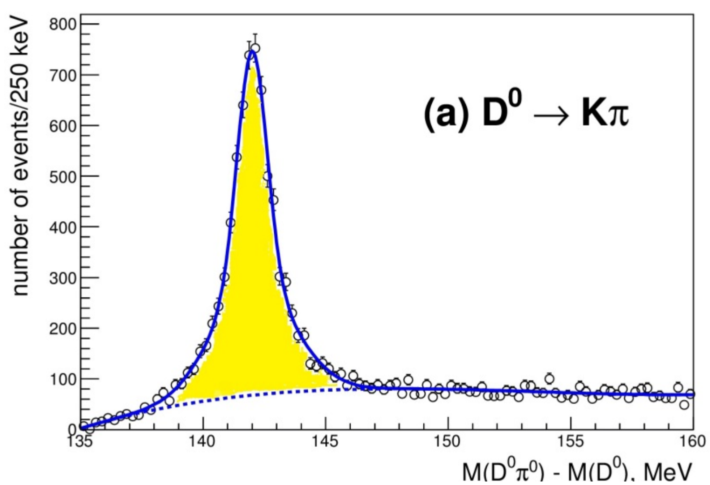
with the average

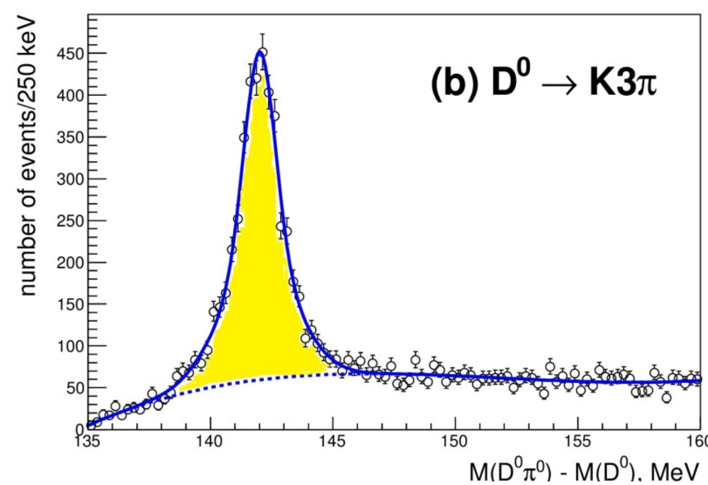
$$\Delta M \equiv M(D^{*0})\text{-}\ M(D^0) = \mathbf{142.007} \pm \mathbf{0.015(stat)} \pm \mathbf{0.014(syst)\ MeV}$$

This result is based on ~ 10,000 counts, has factor ~ four smaller error than the old 1992 measurement, and has a 113 keV smaller value.

This leads to $M(D^{*0}) = \mathbf{2006.850} \pm \mathbf{0.049\ MeV}$

This compares with $M(D^{*0}) = \mathbf{2006.96} \pm \mathbf{0.10\ MeV}$ obtained by the PDG2014 from simutaneous fit of four masses, $M(D^{*+})$, $M(D^{*0})$, $M(D^{+})$, and $M(D^{0})$.





Our measured masses lead to

$$\boldsymbol{M\left(D^{*0}\right) + M\left(D^{0}\right) = 3871.693 \pm 0.17\ \mathrm{MeV}.}$$

Using $M\big(X(3872)\big) = 3871.68 \pm 0.17\ \mathrm{MeV}$ we obtain the binding energy of $X(3872)$ as a proposed $D^0\overline{D^{*0}}$ molecule,

$$\boldsymbol{E_b \equiv (3871.693 \pm 0.090) - (3871.68 \pm 0.17)\ \mathrm{MeV} = 13 \pm 192\ \mathrm{keV}}$$

The largest contribution to the uncertainty in the above result is due to $\pm\,170\ \mathrm{keV}$ uncertainty in the PDG2014 average value of the mass of $X(3872)$.

The negative limiting value of the binding energy E_b implies that $D^0\overline{D^{*0}}$ system is unbound by as much as $179\ \mathrm{keV}$.

The positive limiting value $E_b = 205\ \mathrm{keV}$ implies that the radius of the proposed molecule is larger than $R = 1/\sqrt{2\mu E_b} = 9.9\ \mathrm{fm}$.

Hopefully, our new result for the binding energy will shed light on the continuing saga of the $D^0\overline{D^{*0}}$ molecule and other models of the structure of $X(3872)$.

BACKUP SLIDES

The CLEO-c detector is a cylindrical general purpose detector. The detector components important for the present measurements are the CsI electromagnetic calorimeter, the drift chamber for charged particle detection, and the RICH detector, all of which are located in a 1 Tesla solenoidal magnetic field. The acceptance for photons and charged particles in the central detector is $|\cos\theta| < 0.8$.

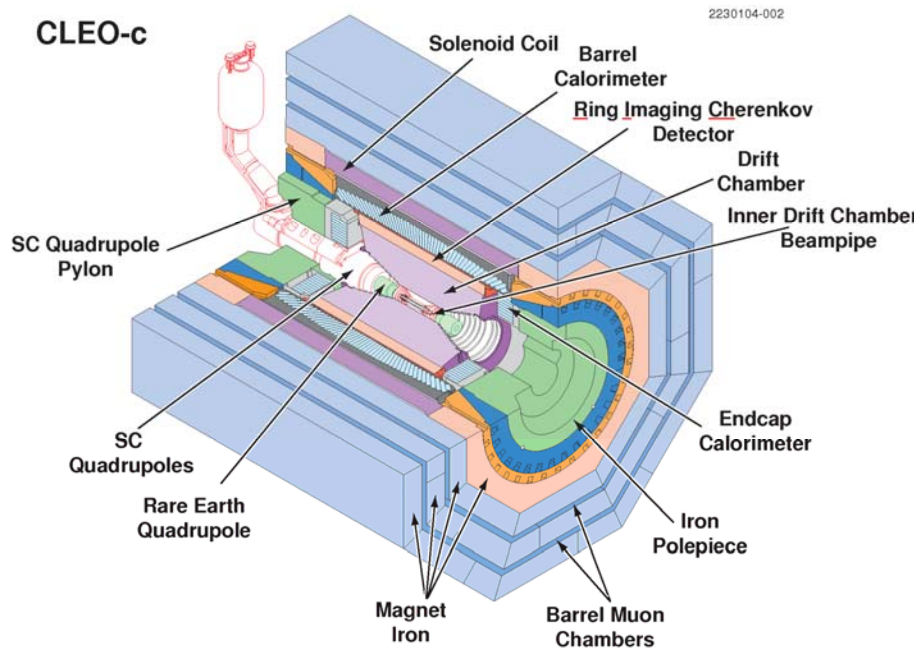
Charged particle resolution is

$\sigma_p/p = 0.6\%$ @ 1 GeV/c.

Photon resolution is

$\sigma_E/E = 2.2\%$ @1 GeV,

and 5% @ 100 MeV.



The data we use consists of

805 pb^{-1} at $\psi(3770)$, $|Q^2| = 14.2$ GeV^2, and

586 pb^{-1} at $\psi(4170)$, $|Q^2| = 17.4$ GeV^2.