30 Years of the Cornell Electron Storage Ring

A survey of the accomplishments of the CLEO and CUSB physics collaborations

Started by Karl Berkelman

Finished by David Cassel

Laboratory for Elementary-Particle Physics

Cornell University

APS, Denver, 3 May 09

Karl Berkelman

1933 -- 2009

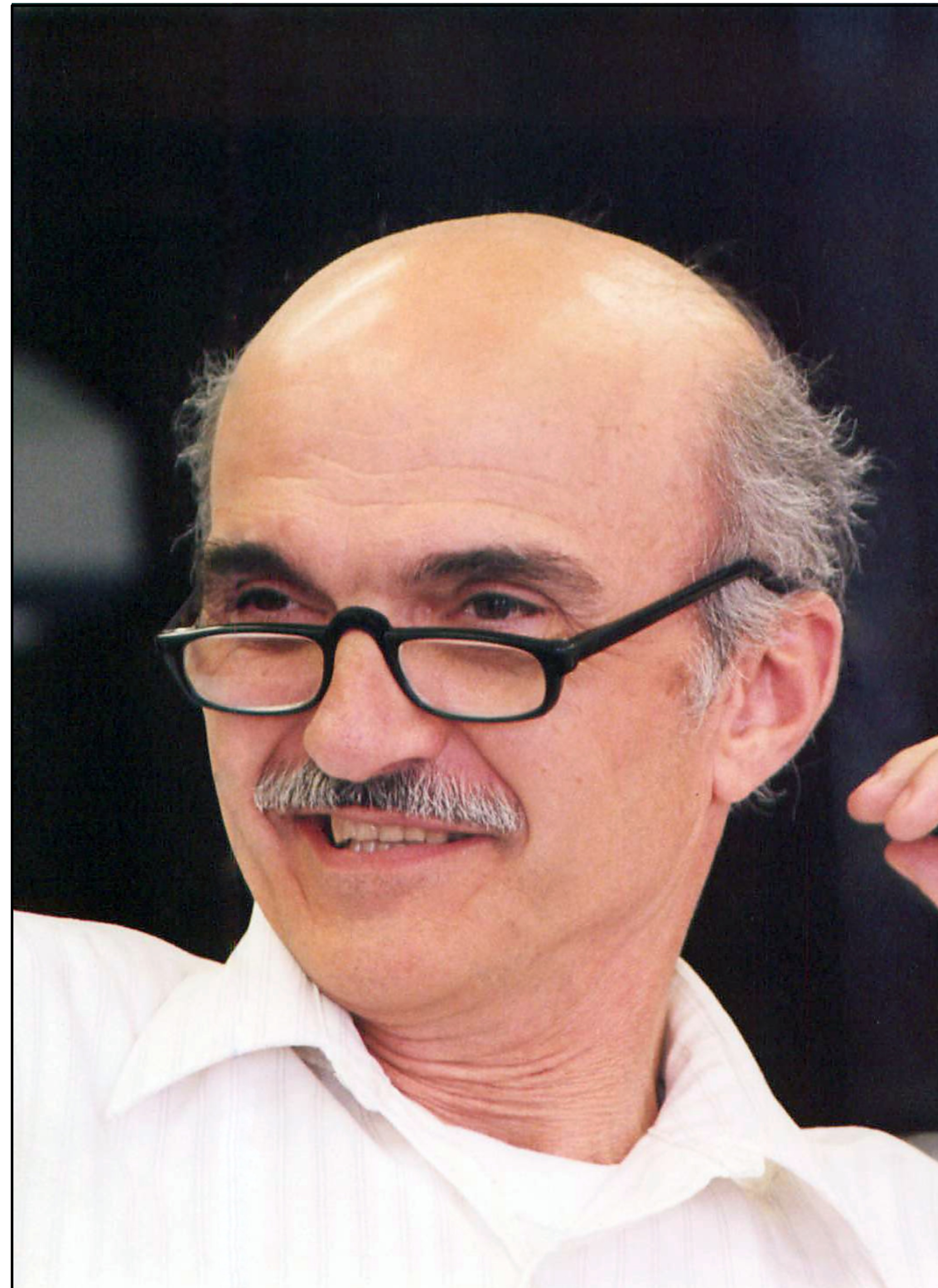
Cornell Career

1955 -- 59 Graduate Student
1960 -- 95 Professor
1995 -- 06 Goldwin Smith Professor
2006 -- 09 Goldwin Smith Professor Emeritus
1985 -- 00 Director Laboratory of Nuclear Studies

Visiting Appointments at Frascati, DESY, and CERN

Member of many laboratory and agency advisory panels

APS Fellow



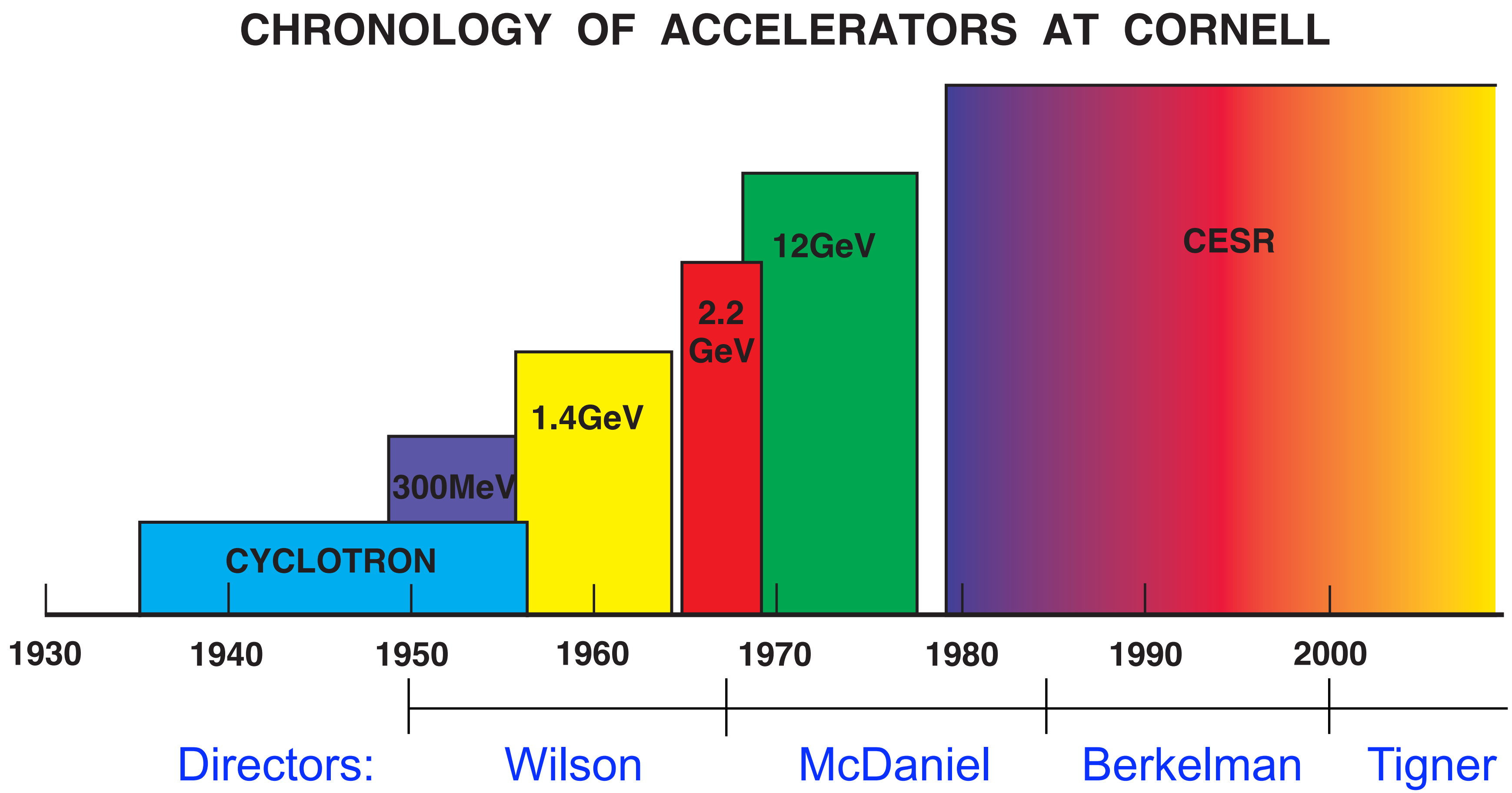
Karl & Mary in the Bavarian Alps

Outline

- Pre-CESR Accelerators at Cornell
- CESR, CLEO, and CUSB
- Upsilon Spectroscopy
- B Mesons
- CESR & CLEO Upgrades
- Moving to Charm
- Some Conclusions

CESR Prehistory

- 1935 -- 1.5 MeV proton cyclotron
- 1949 -- 0.3 GeV electron synchrotron
- 1954 -- 1.2 GeV electron synchrotron
- 1962 -- 2.2 GeV electron synchrotron

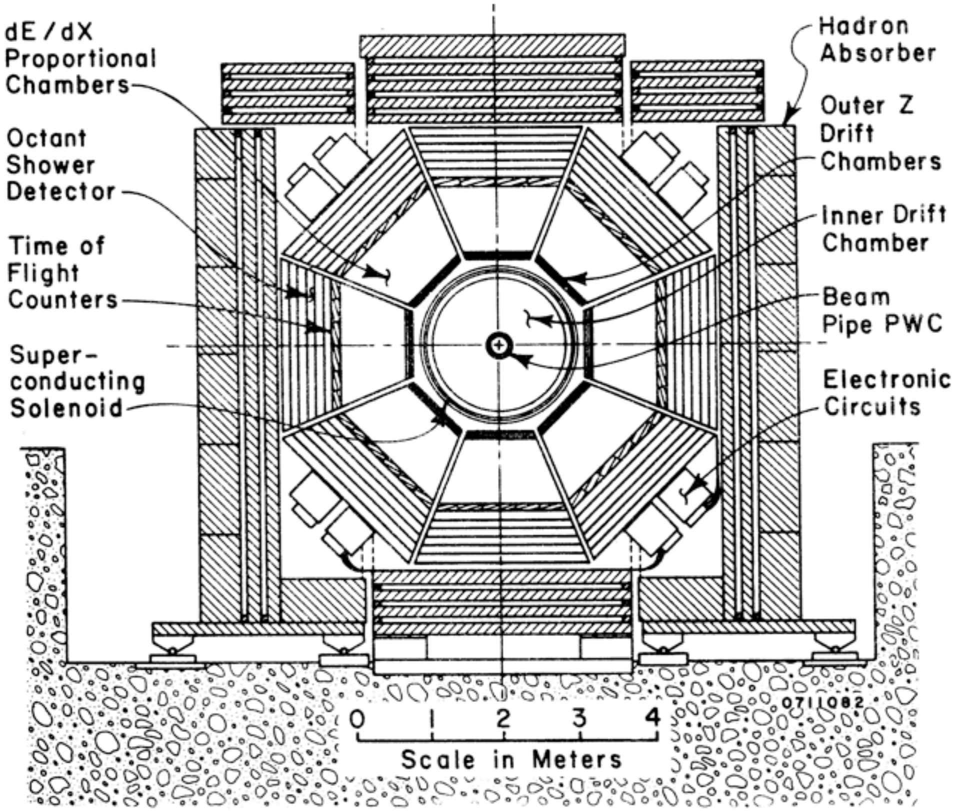


- 1967 – e^- synchrotron
  12 GeV in a 1/2 mile tunnel

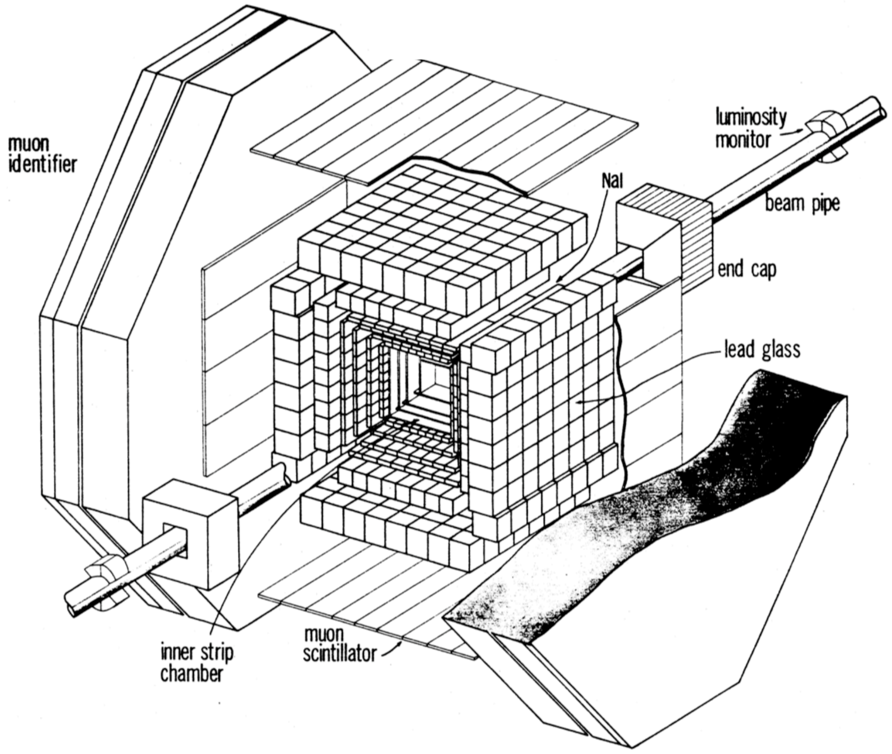
- 1979 – CESR
  Cornell Electron
  Storage Ring
  8+8 GeV e^+e^-

Two Detectors Initially

CLEO (south)



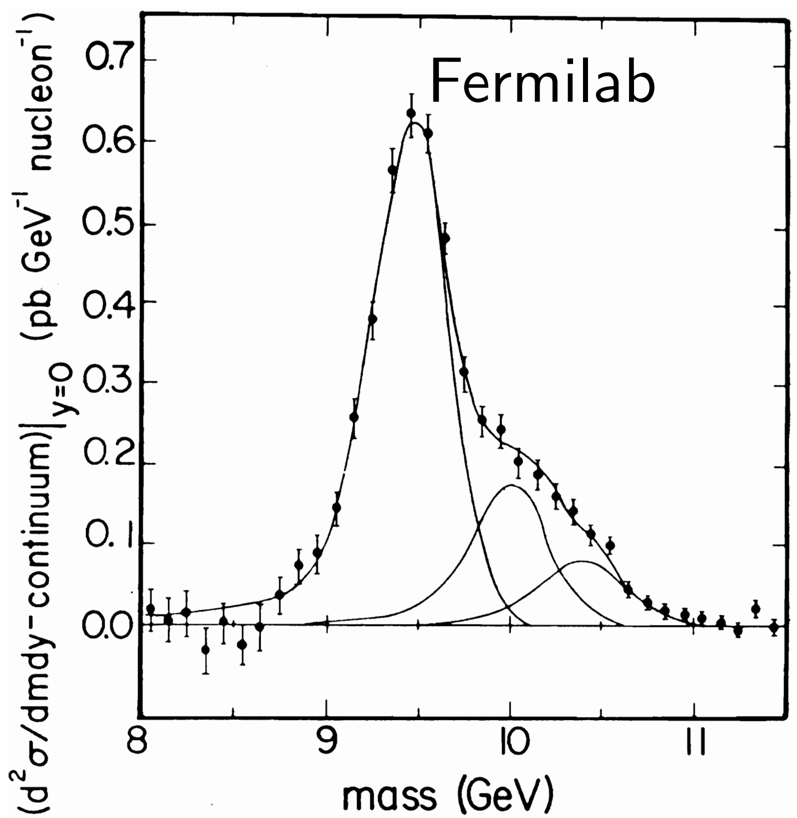
CUSB (north)

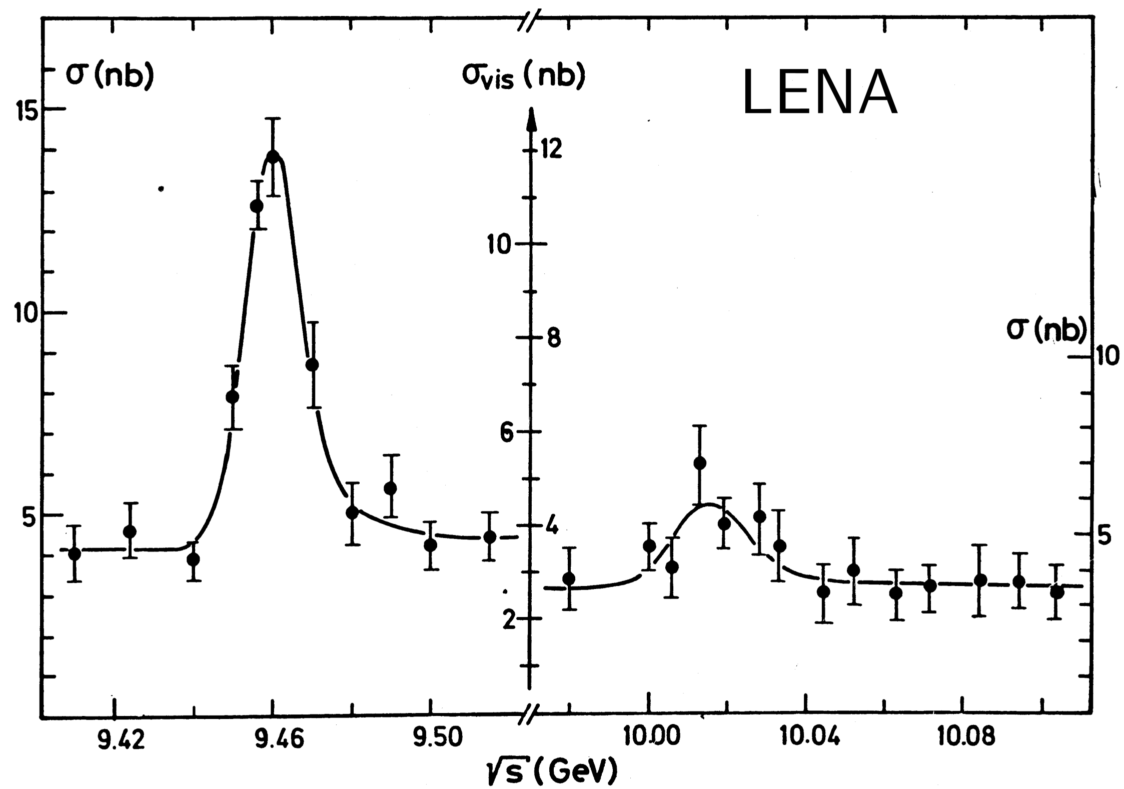


Severely limited space

b Physics Before CLEO

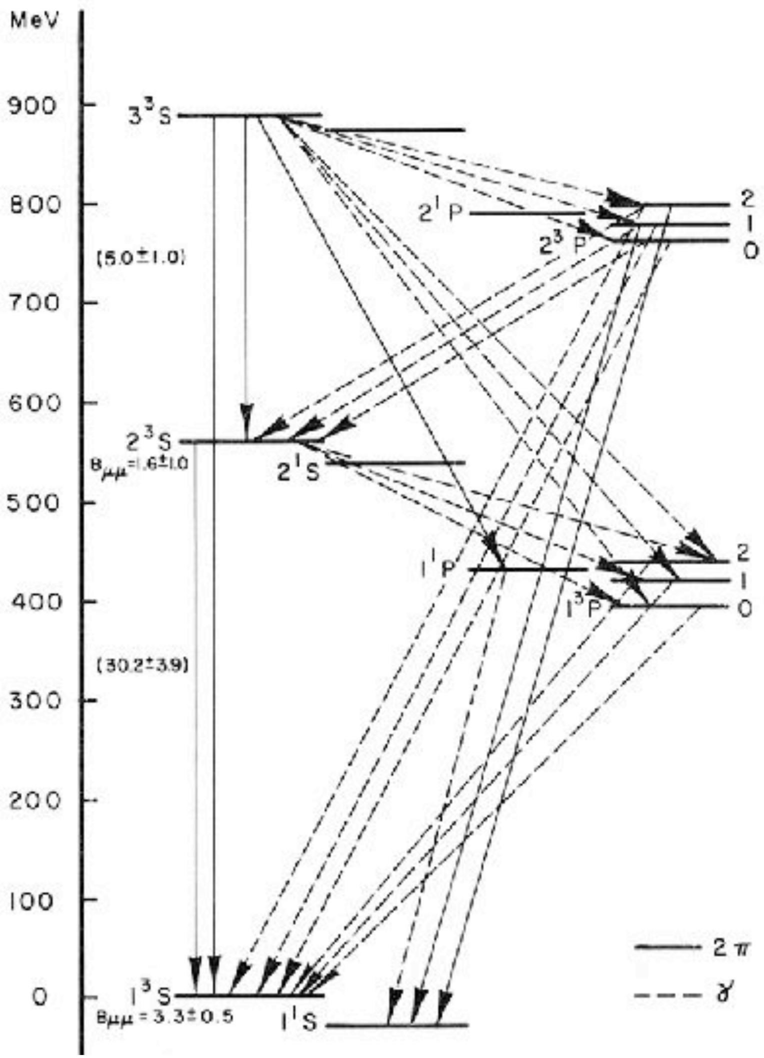
- At Fermilab Lederman *et al*. discovered the Υ states
- DASP and LENA at DESY confirmed $\Upsilon(1S)$ & $\Upsilon(2S)$
  - demonstrated that $\Upsilon(1S)$ & $\Upsilon(2S)$ are narrow resonances
- $\Upsilon(2S)-\Upsilon(1S)$ splitting nearly equal to $\psi(2S)-J/\psi$ splitting
  - $q\bar{q}$ potential $-4\alpha_s/(3r)+br$ works well for $c\bar{c}$ and $b\bar{b}$

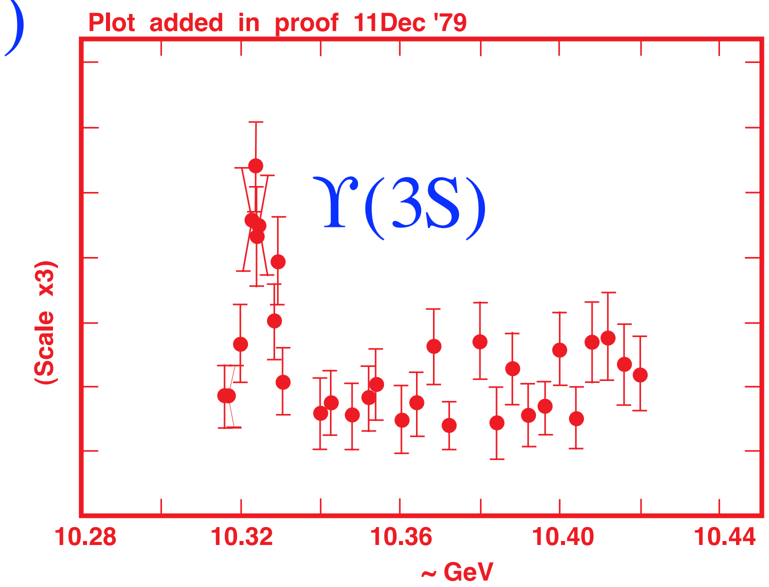


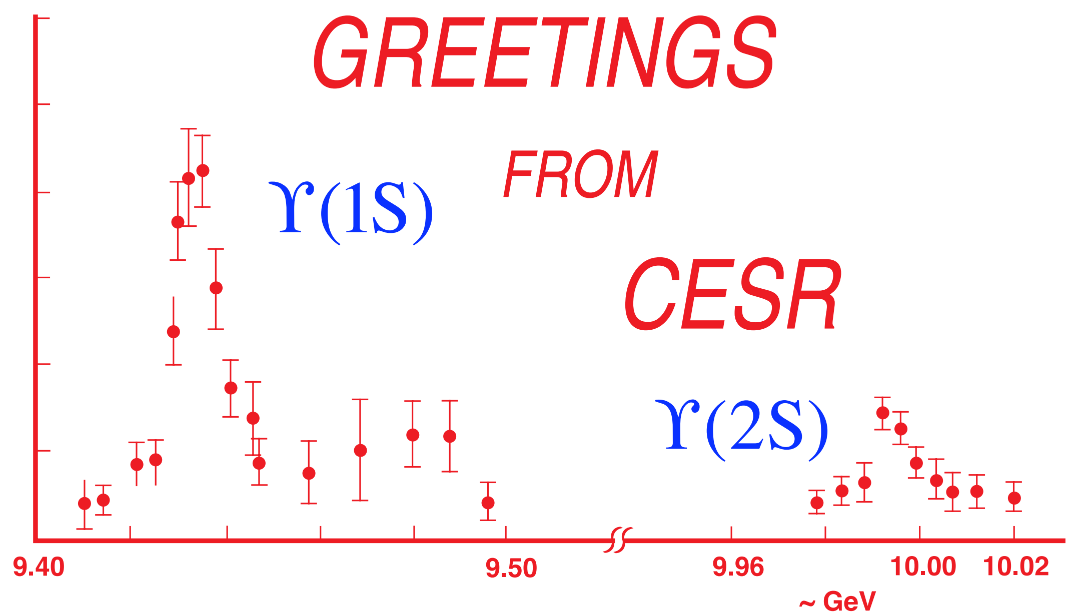


First Data $\Upsilon(1S), \Upsilon(2S)$ & $\Upsilon(3S)$

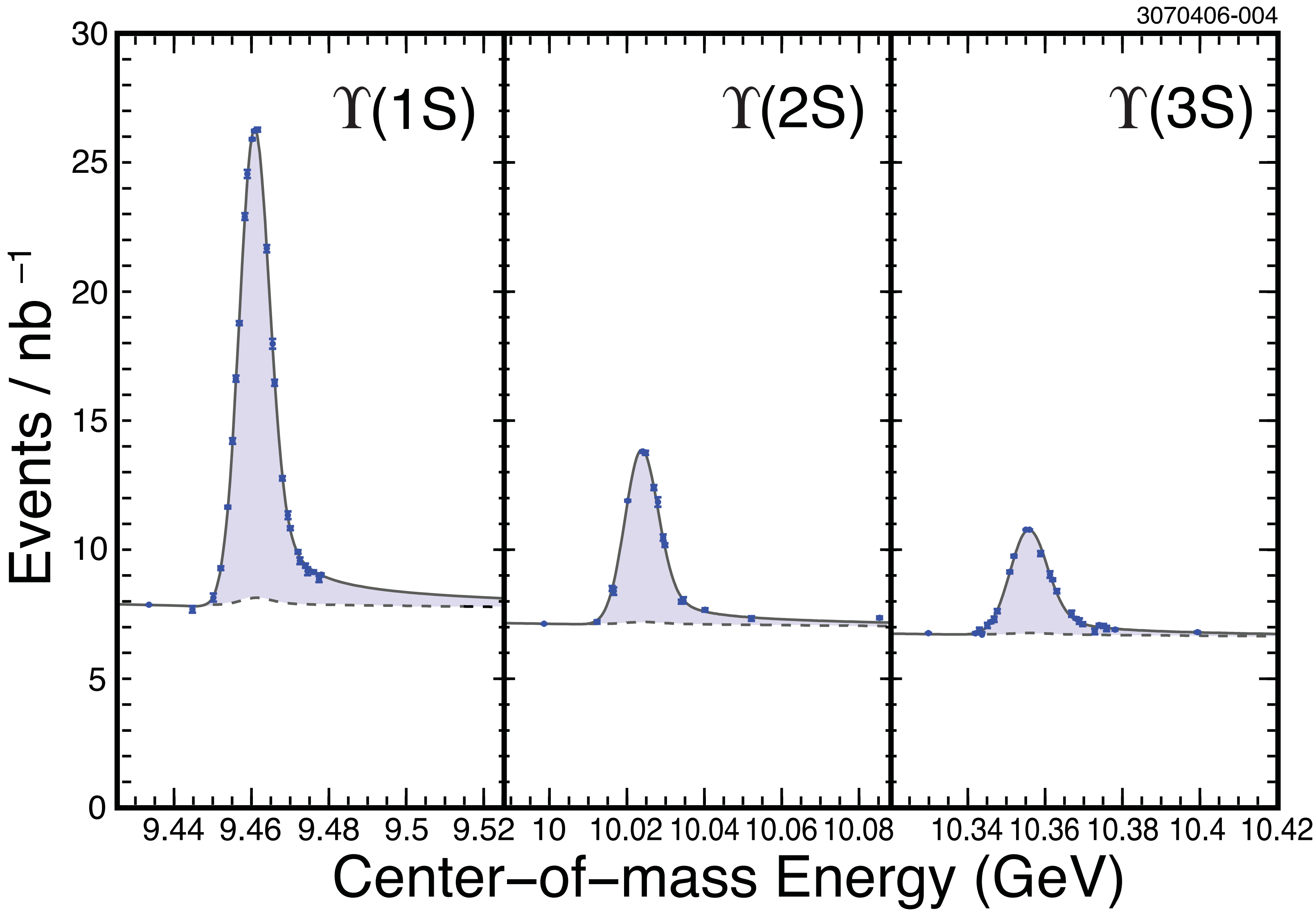
First evidence for narrow $\Upsilon(3S)$
CLEO & CUSB







CLEO's Final $\Upsilon(1S)$, $\Upsilon(2S)$ & $\Upsilon(3S)$ Results

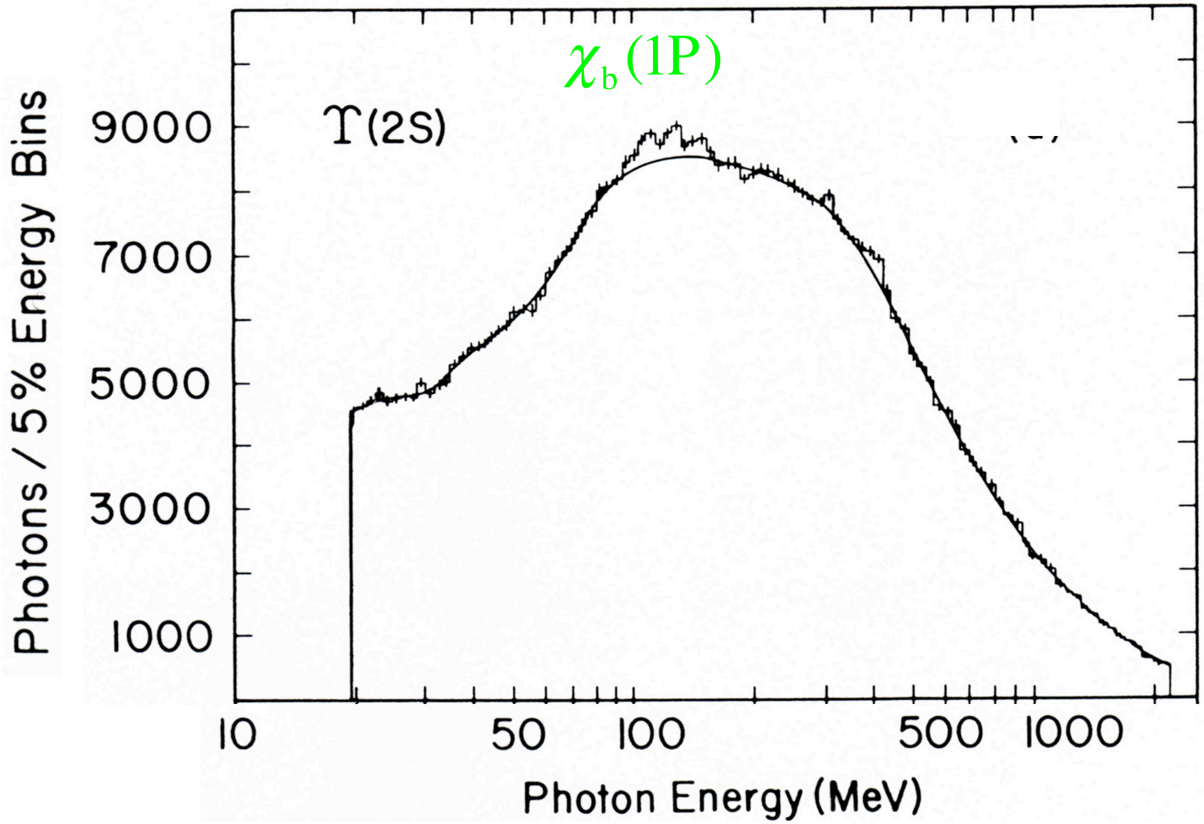


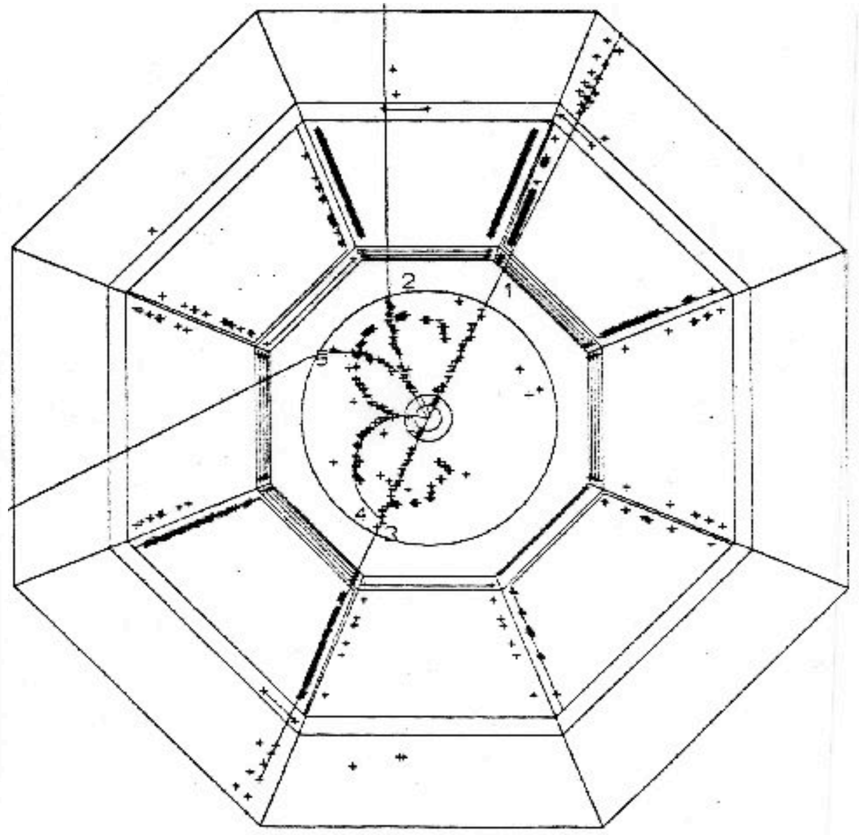
- This was the last CLEO paper with Karl as a principal author (2006). His deep understanding of radiative corrections was essential.

Other $b\bar{b}$ States χ_b

- CUSB discovered the $\chi_b(1P)$ states in the γ spectrum from radiative $\Upsilon(2S)$ decay
- $\chi_b(2P)$ from $\Upsilon(3S)$ decay

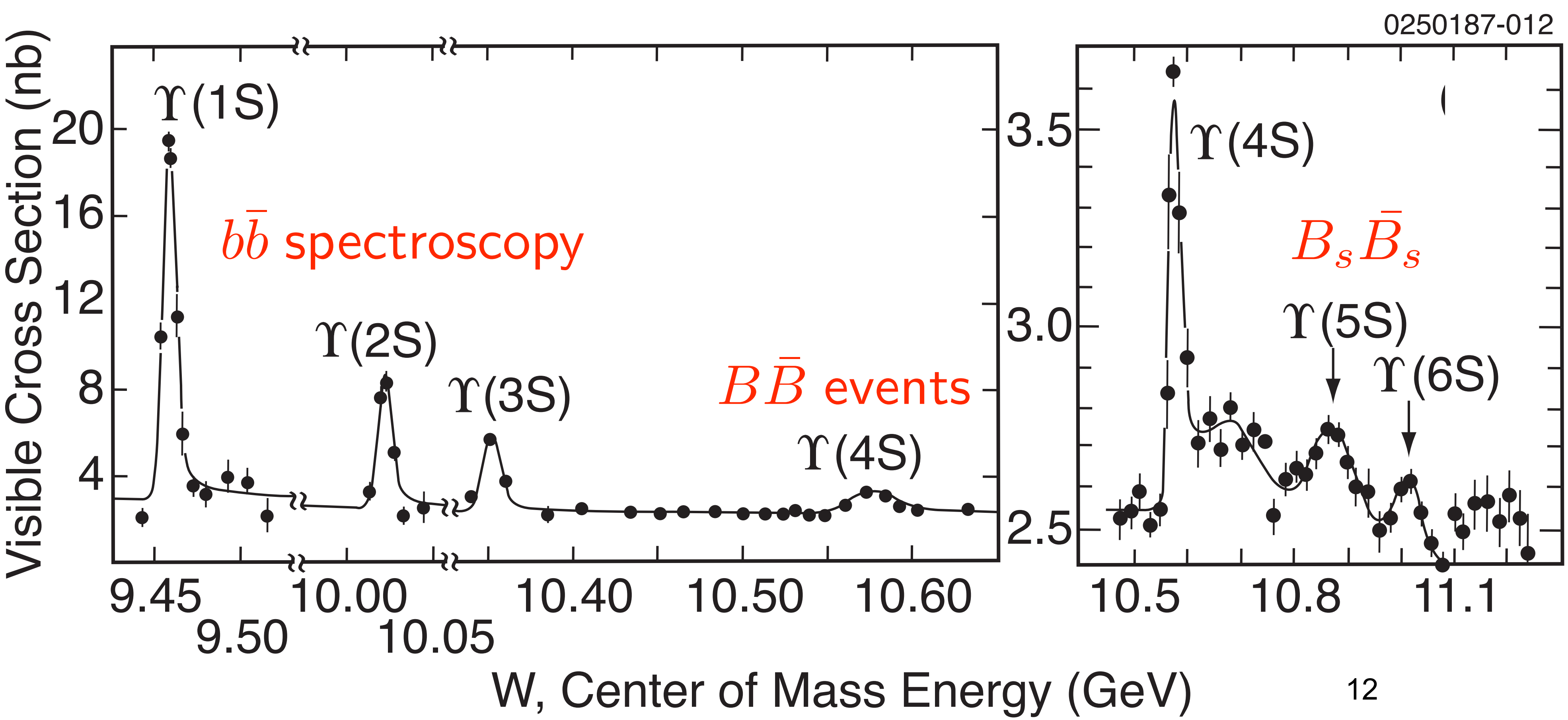
CLEO $\Upsilon(2S) \to \chi_b(1P)\gamma$
$\to \Upsilon(1S)\gamma\gamma$
$\to e^+e^-\gamma\gamma$





The $\Upsilon(4S)$ Resonance

- $\Upsilon(4S) \to B\bar{B}$ 22 MeV above threshold
- $\Upsilon(4S) \to B^0\bar{B}^0$ or B^+B^- without extra particles
- $\Upsilon(4S)$ decay is suppressed by phase space
- $e^+e^- \to \Upsilon(4S)$ 1 nb peak
- Realized our hopes for a B factory like the $\psi(3770)$ D factory

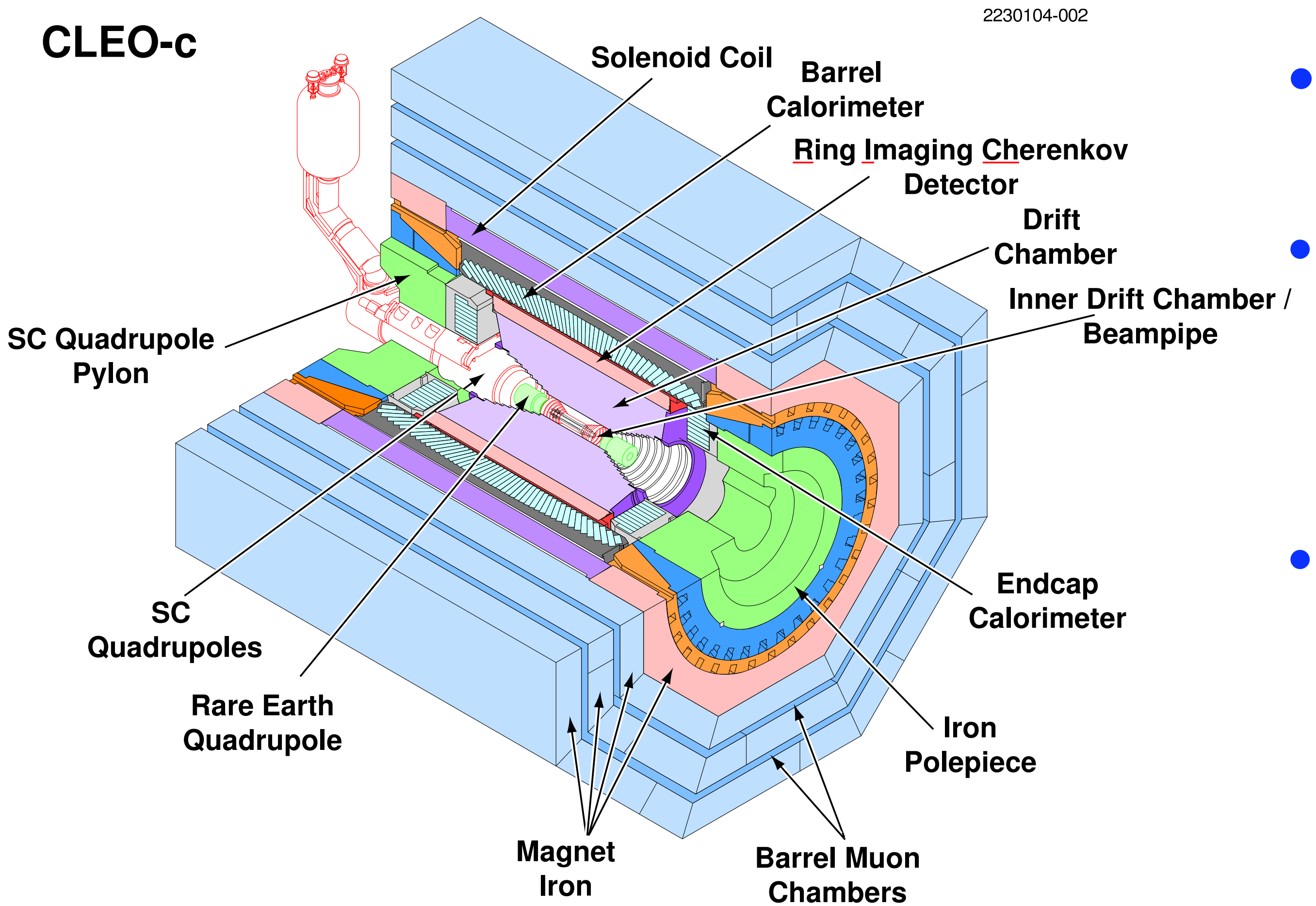


b-Quark Serendipity

- b is the fifth quark with $M(b\bar{b}) < E_{CESR}$
- t is much heavier than b
- The t quark decays without forming bound states, so the $b\bar{b}$ system is the most ideal NR $q\bar{q}$ spectroscopy
- t must decay weakly to u or c
- b is off-diagonal in the CKM matrix so the B lifetime τ_B =1.6 ps, longer than expected due to small $|V_{cb}|$
- Most B decays go to D mesons with $|V_{cb}| = 0.04$
- $B \to X_u \ell \nu$ seen yielding $|V_{ub}| = 0.004$
- $B^0\bar{B}^0$ mixing discovered by ARGUS yielding $|V_{td}|$, and implying a large value of m_t and the possibility of CP violation
- $B^+ = \bar{b}u$ and $B^0 = \bar{b}d$ (KB -- matches K meson quark content)

CLEO Detector Upgrades

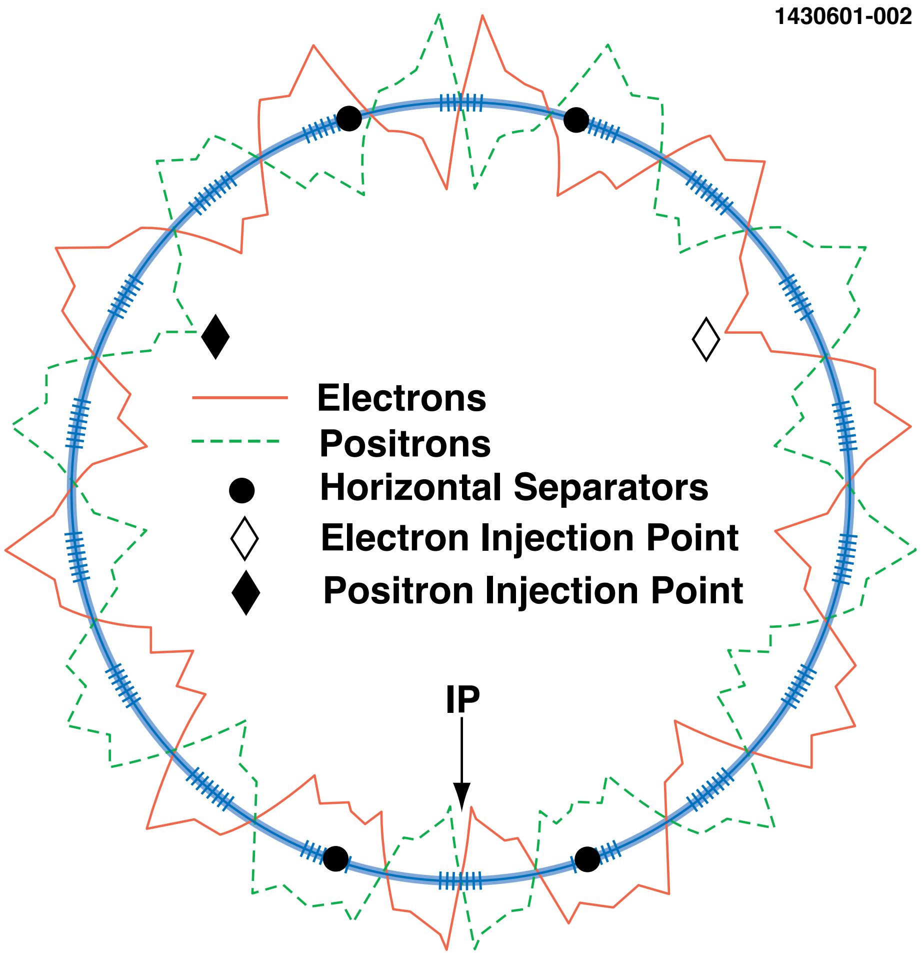
- CLEO-II: CsI EM calorimeter, dense small-cell drift chamber, particle identification with time of flight (ToF) & ionization (dE/dx), and muon chambers

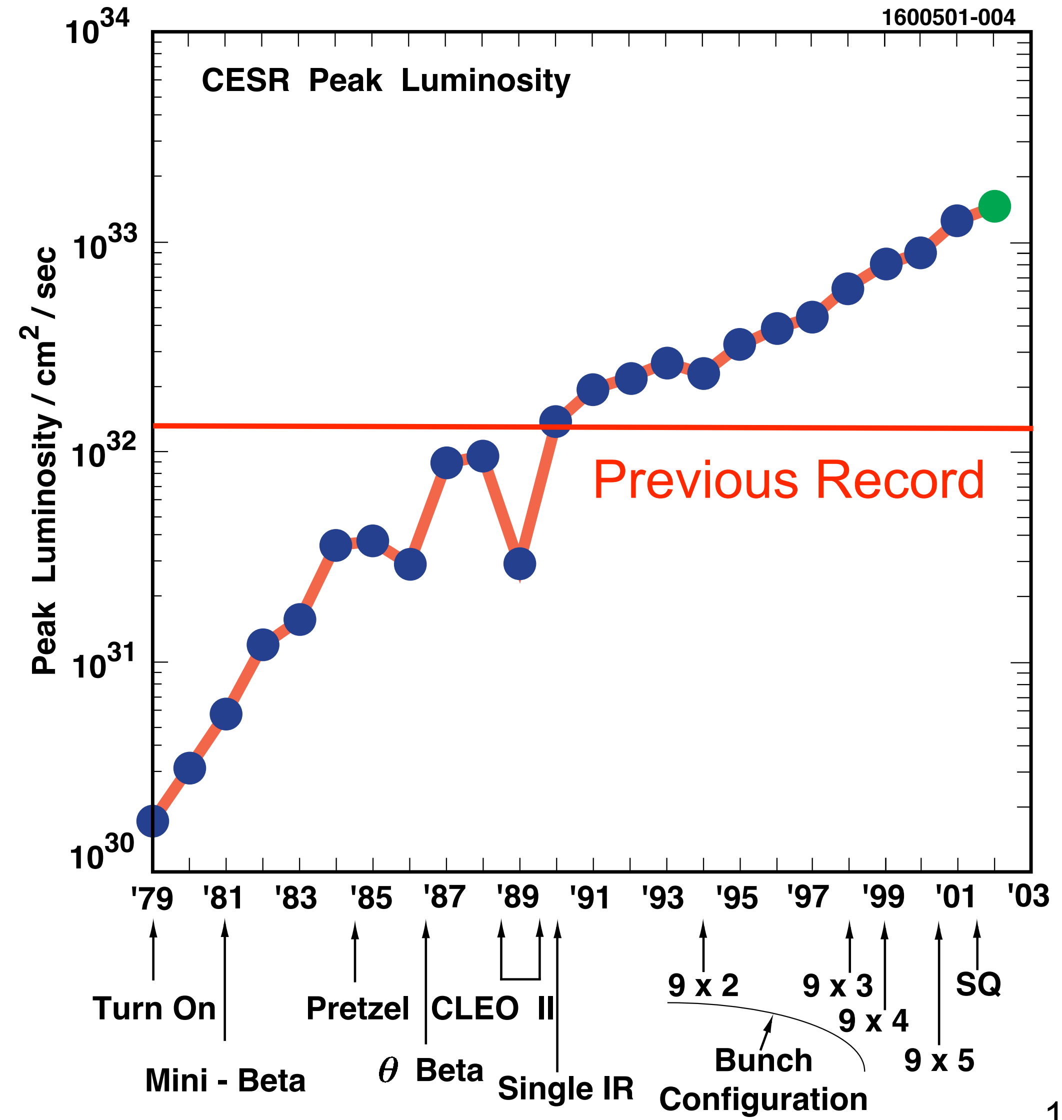


- CLEO-II.V: silicon vertex detector (SVX)
- CLEO III: replaced ToF with a Ring Imaging Cherenkov detector (RICH)
- CLEO-c: replaced SVX with a vertex drift chamber

CESR Luminosity Improvements

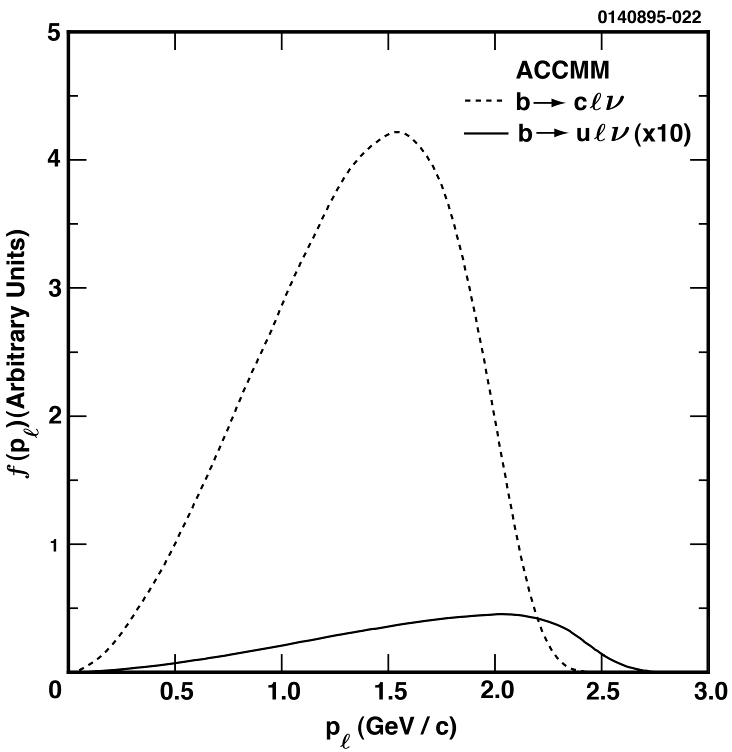
- Multibunch pretzel orbits
- Superconducting RF cavities
- "μβ" IR focusing
- Single IR (no CUSB)

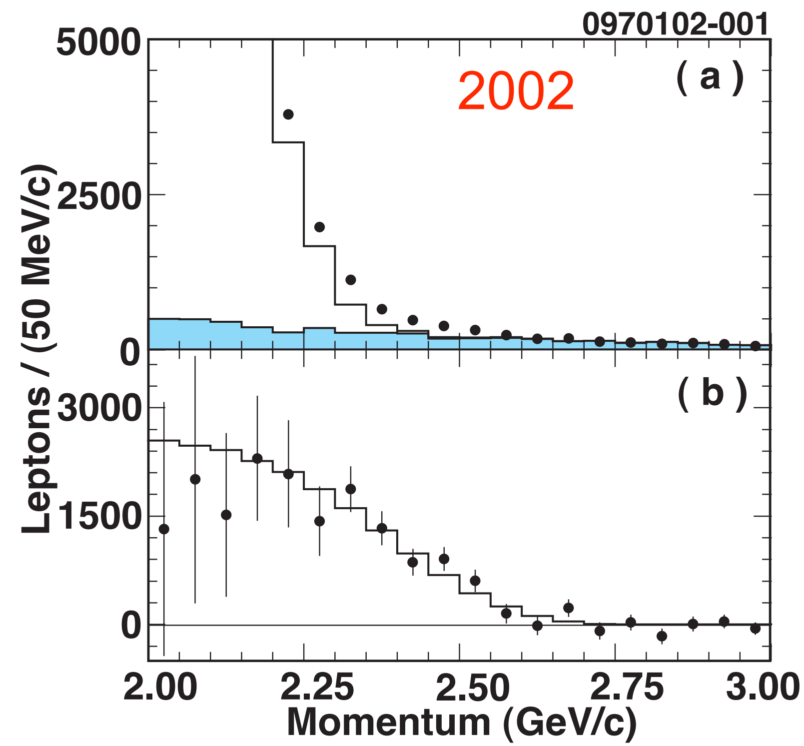


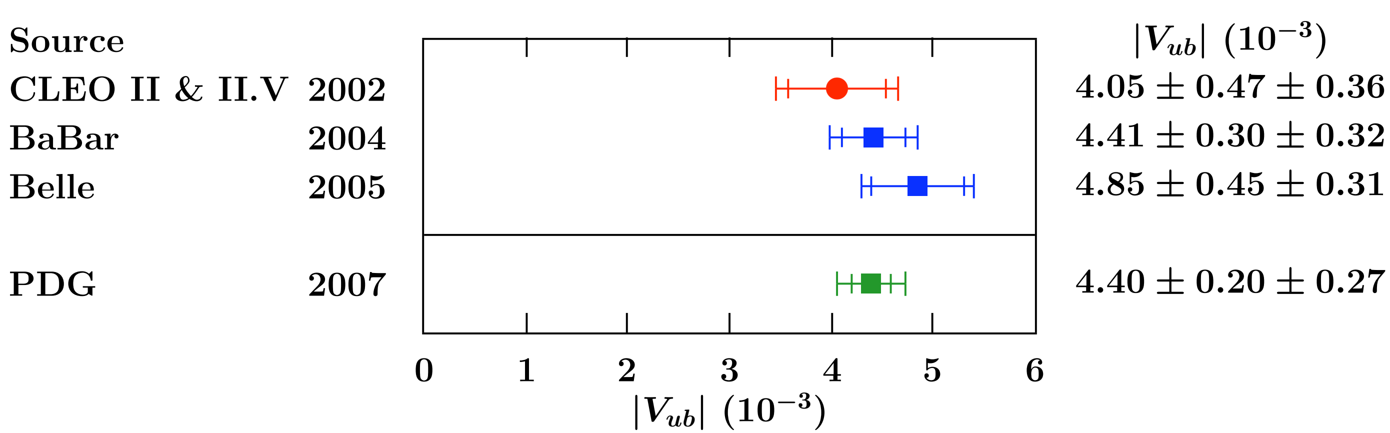


Discovery of $b \rightarrow u\ell\nu$ decays

- Search for $b \rightarrow u\ell\nu$ decays beyond the endpoint of $b \rightarrow c\ell\nu$ decays in the inclusive lepton momentum spectrum.

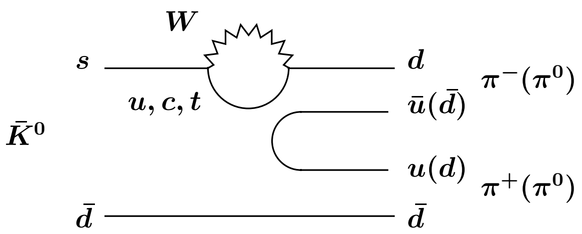


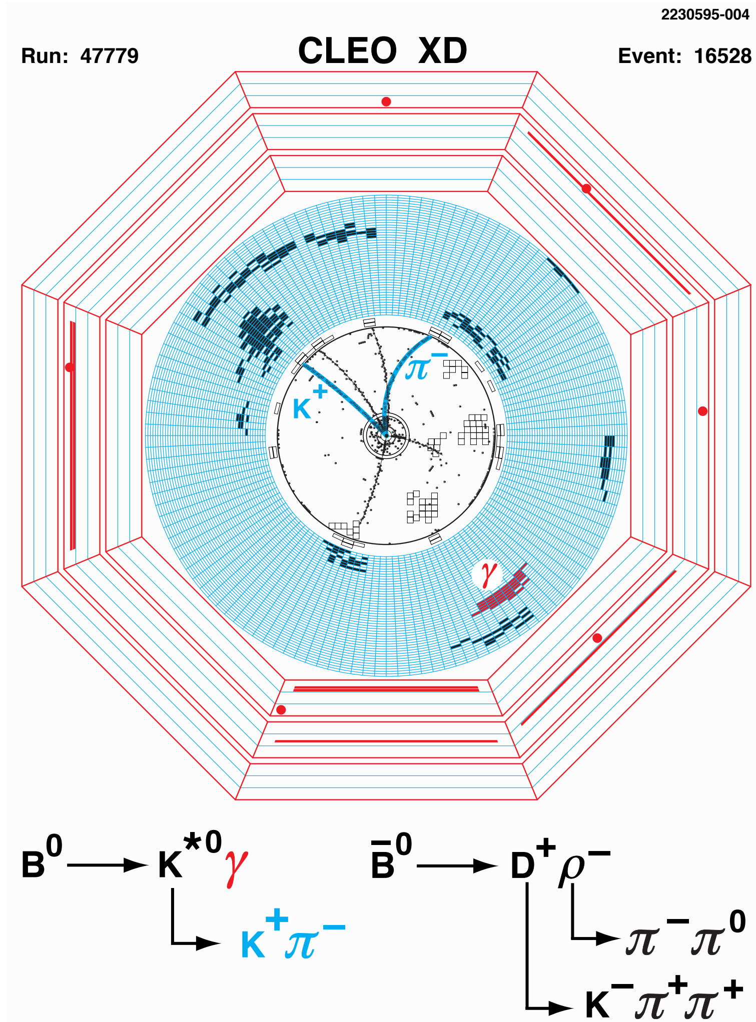




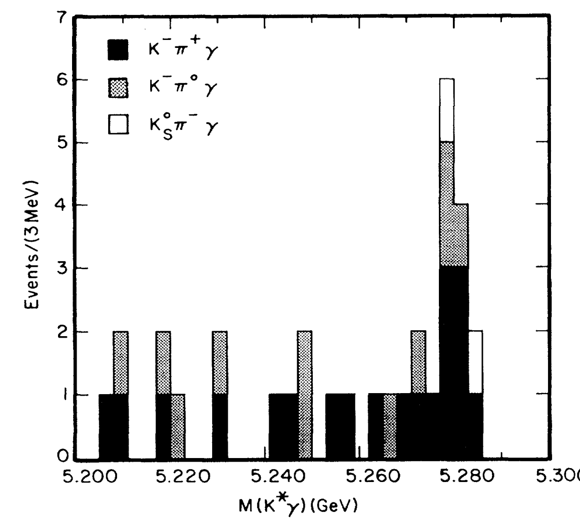
Discovery of Radiative Penguin Decays

Penguin diagrams were proposed to explain the $\Delta I = 1/2$ rule in K decay.



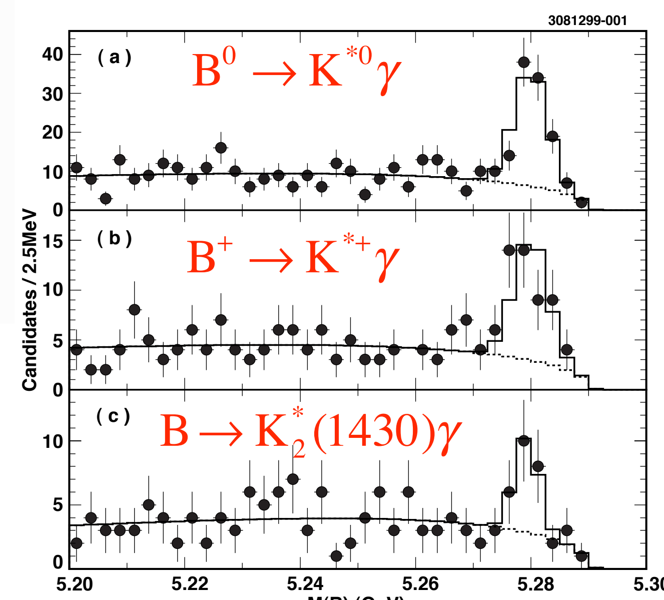


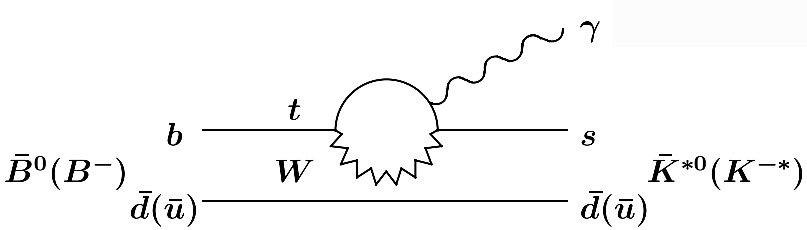
CLEO 1993



No hard experimental evidence for penguin processes was found for nearly 20 years, until CLEO observed $B \to K^*\gamma$ decays.

CLEO 2000

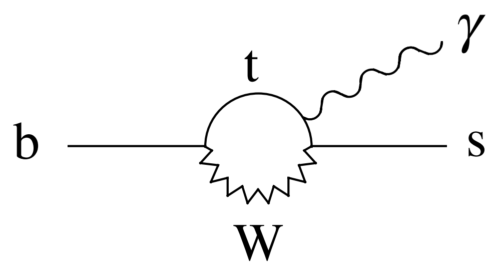


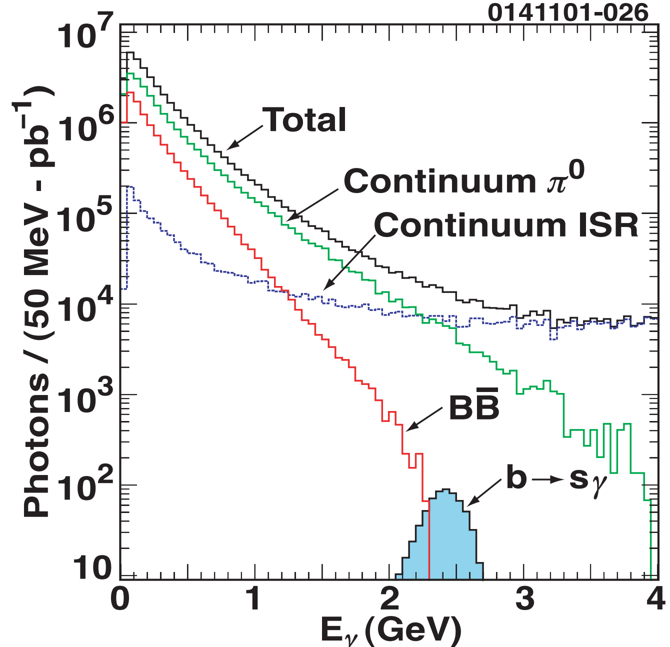


Inclusive $\mathcal{B}(B \to X_s\gamma)$

Inclusive $\mathcal{B}(B \to X_s\gamma)$ is much more important than $\mathcal{B}(B \to K^*\gamma)$

- SM rate can be calculated.
- Rate sensitive to Higgs and Beyond SM effects in the loop.





HFAG Summary

CLEO Phys.Rev.Lett.87,251807(2001)
BR(B→Xsγ) = (3.29± 0.53) 10^{-4} (9.1 fb^{-1})

Belle Semi Phys.Lett.B511:151(2001)
BR(B→Xsγ) = (3.29± 0.53) 10^{-4} (5.8 fb^{-1})

BaBar Semi Phys.Rev.D72:052004(2005)
BR(B→Xsγ) = $(3.29^{+0.62}_{-0.50})$ 10^{-4} (81.5 fb^{-1})

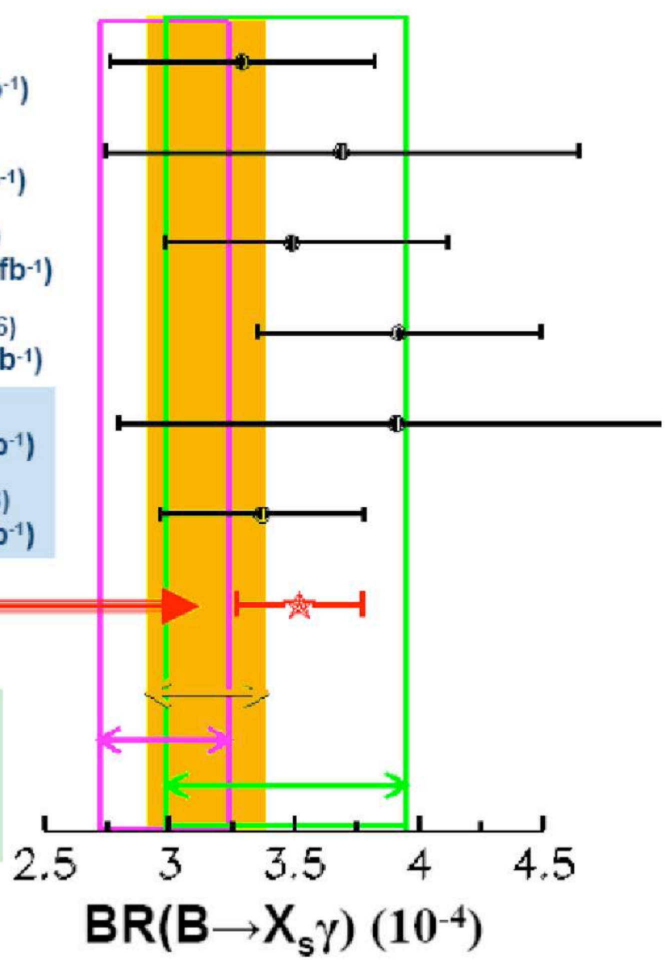
BaBar Incl Phys.Rev.Lett.97:171803(2006)
BR(B→Xsγ) = (3.92± 0.56) 10^{-4} (81.5 fb^{-1})

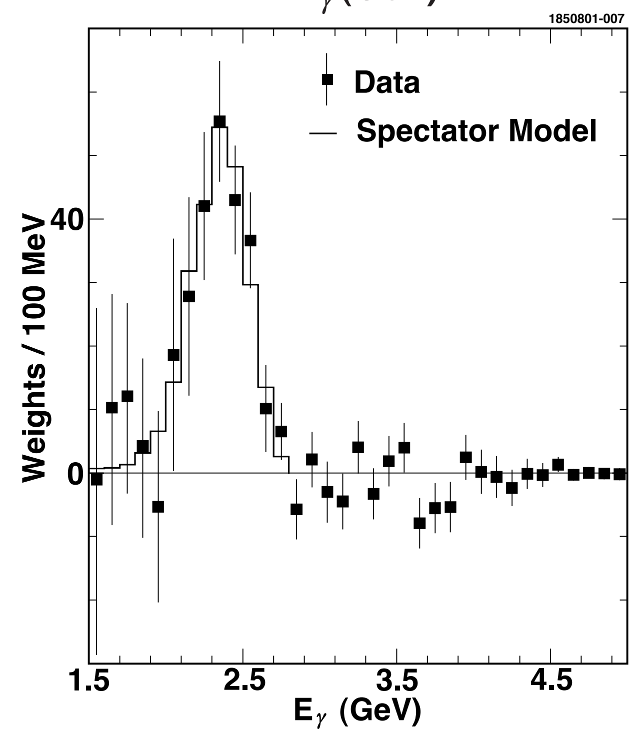
BaBar Full Phys.Rev.D77:051103(2008)
BR(B→Xsγ) = (3.91± 1.11) 10^{-4} (210 fb^{-1})

BELLE Incl (A. Limosani, Moriond EW08)
BR(B→Xsγ) = (3.37± 0.41) 10^{-4} (605 fb^{-1})

HFAG Average 08 (preliminary)
BR(B→Xsγ) = (3.52± 0.25) 10^{-4}

SM predictions:
Misiak et al. (hep-ph/0609232)
Becher et. al. (hep-ph/0610067)
Andersen et al. (hep-ph/0609250)

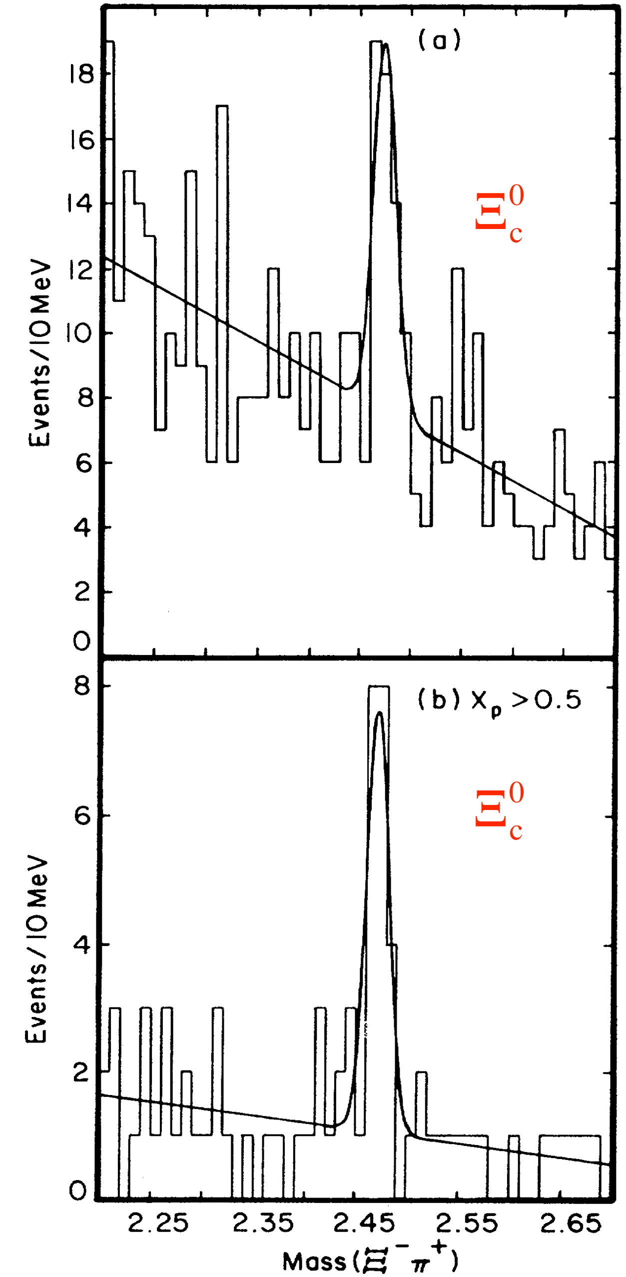




Charmed Baryons

- In 1989 CLEO initiated a charmed baryon program with the discovery of $\Xi_c^0 \to \Xi^- \pi^+$
- CLEO's charmed baryon results:

discovered 15		confirmed 3
Ξ_c^0 $\Xi_c^{0'}$ $\Xi_c^{+'}$		Ξ_c^+
$\Xi_c^0(2645)$	$\Xi_c^+(2645)$	
$\Xi_c^0(2930)$	$\Xi_c^+(2930)$	
$\Xi_c^0(2980)$	$\Xi_c^+(2980)$	
$\Sigma_c^0(2455)$		
$\Sigma_c^0(2520)$	$\Sigma_c^+(2520)$	$\Sigma_c^{++}(2520)$
$\Lambda_c(2593)$		
$\Lambda_c(2765)$	$(\Sigma_c\ ?)$	
$\Lambda_c(2880)$		
		Ω_c^0



Some Early CLEO* and CUSB* Results

1980	*	*	$\Upsilon(3S)$	Potential models
	*	*	$\Upsilon(4S)$	Wide so it is above the $B\overline{B}$ threshold
			$B^0 \& B^+$	Inclusive leptons at the $\Upsilon(4S)$
1982		*	$\chi_b(1P)$	Confirmed Υs are $b\overline{b}$
1983	*		D_s	Found in $D_s^+ \to \varphi\pi^+$ at the right mass
	*		$b \to c\ell\nu$	Measure $\lvert V_{cb} \rvert$ and $b \to c$ dominance
1984	*	*	$\Upsilon(5S) \& \Upsilon(6S)$	Sources of B_s and Λ_b
1985		*	B^*	Found in $B^* \to B\gamma$
1988	*		Ξ_c^0	Initiated charmed baryon program
	*		$B \to \psi K_S^0$	Golden CP violation channel
1989	*		$B \to X_u \ell\nu$	$\lvert V_{ub} \rvert$ determination
1993	*		$B \to K^*\gamma$	Verified existence of penguin processes
1995	*		$b \to s\gamma$	Sensitive to Higgs & SUSY

CLEO & CUSB B Physics Accomplishments

- $b\bar{b}$ spectroscopy fits the same potential as $c\bar{c}$
  - QCD $q\bar{q}$ coupling is flavor independent
    $\alpha_S(s)$ at $s = M_\Upsilon^2$ determined
- B and B* mesons discovered
  - m_b determined
- Many B hadronic and semileptonic decay modes measured
- Discovered $b \to u\ell\nu$ so $|V_{ub}| \neq 0$
- Discovered $B \to K^*\gamma$ and $b \to s\gamma$ penguins
- $|V_{cb}|$, $|V_{ub}|$, $|V_{td}|$ measured & A, ρ, η determined
  - Open CKM triangle implies CP violation

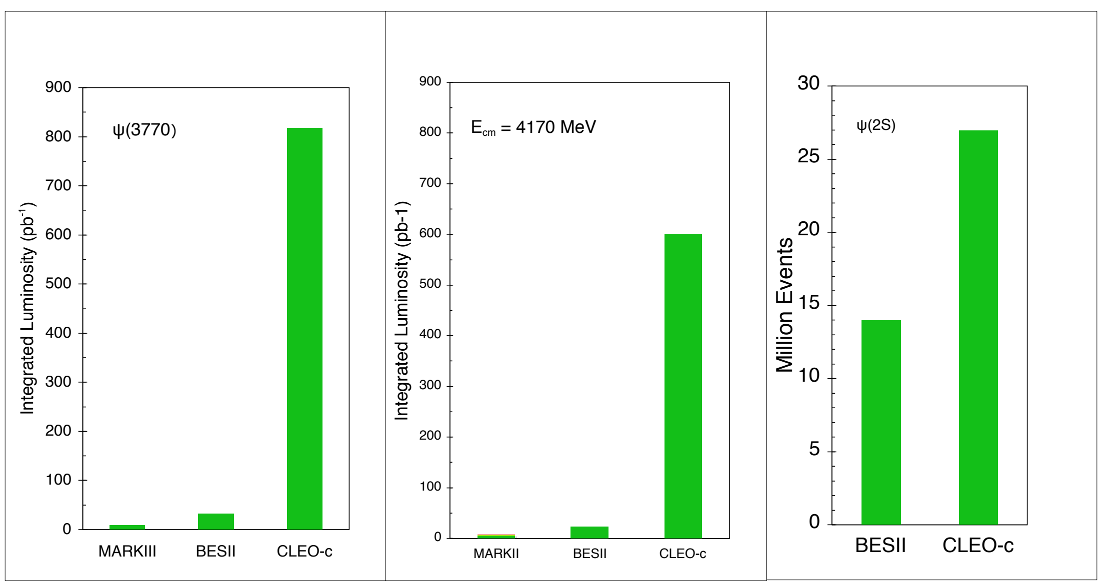
CLEO Moves to the $c\bar{c}$ Threshold Region

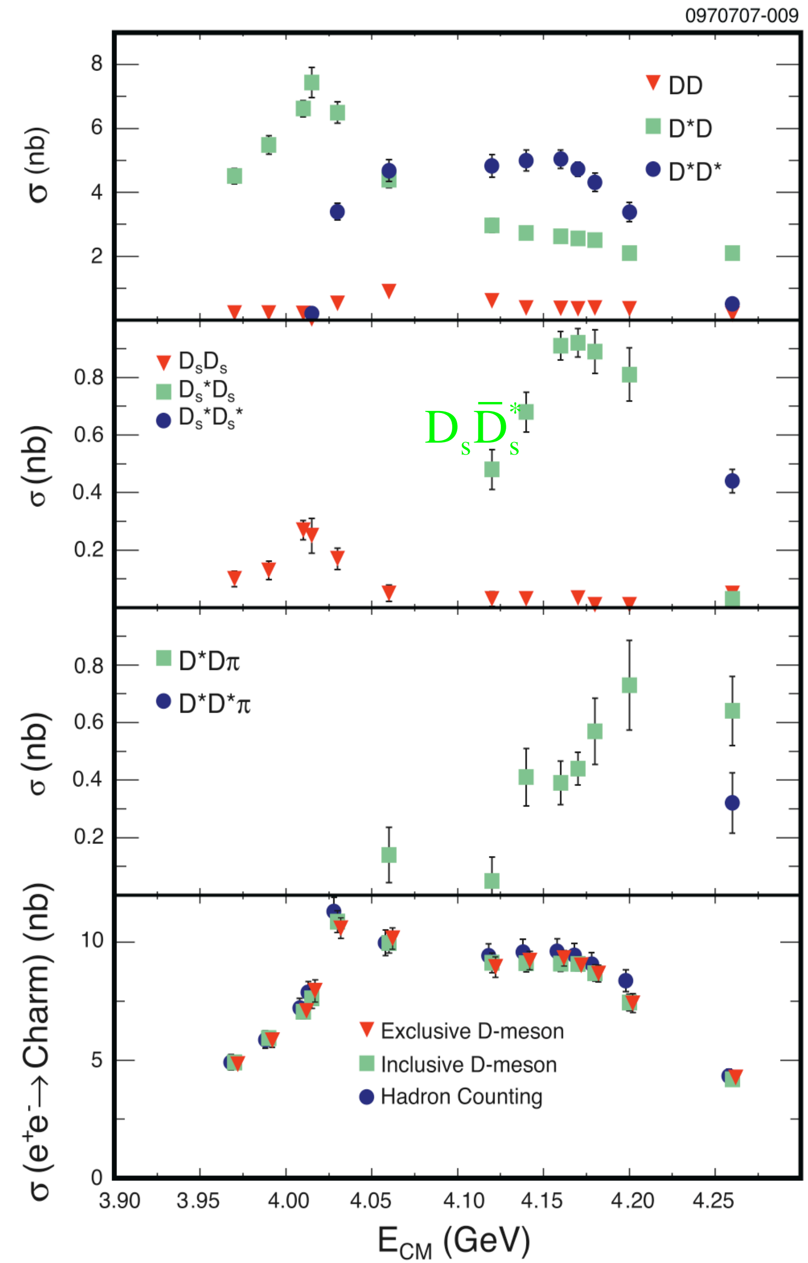
- CLEO eclipsed at $b\bar{b}$ energies by PEP-2 and KEK-B
  - CESR optimized for the charm threshold region
  - Inserted wigglers to increase luminosity
  - Much higher luminosity than previous charm experiments
  - CLEO-c detector superior to previous charm detectors
- Principal motivations for the CLEO-c program include:
  - Precise D and D_s hadronic branching fractions
    They are required for $B \to D_{(s)}X$ branching fractions
  - Validate Lattice QCD where V_{cs} and V_{cd} are known:
    Determine the decay constants $f_{D_{(s)}}$ from $D_{(s)} \to \ell\nu$ decay.
    Determine branching fractions and form factors for exclusive semileptonic D and D_s decays.
  - Obtain strong phases from $D\bar{D}$ quantum correlations to understand $D^0\bar{D}^0$ mixing and measure the CKM angle γ / φ_3
  - Improve understanding of $c\bar{c}$ spectroscopy and decay

Charmonium Physics Opportunities

- Bound state spectroscopy
  - $\eta_c(^1S)$, $\eta_c(^1S)$, $h_c(^1P)$, $\chi_c(^3P)$
  - Many new decay modes
- Resonances above $D\bar{D}$ threshold are sources of $D_{(s)}\bar{D}_{(s)}$ events
  - $\psi(3770) \rightarrow D\bar{D}$ 5.3 M
  - $\psi(4170) \rightarrow D_s\bar{D}_s^* \rightarrow D_s\bar{D}_s\gamma$ 0.57 M

    0.9 nb peak in $\sigma(e^+e^- \rightarrow D_s\bar{D}_s^*)$

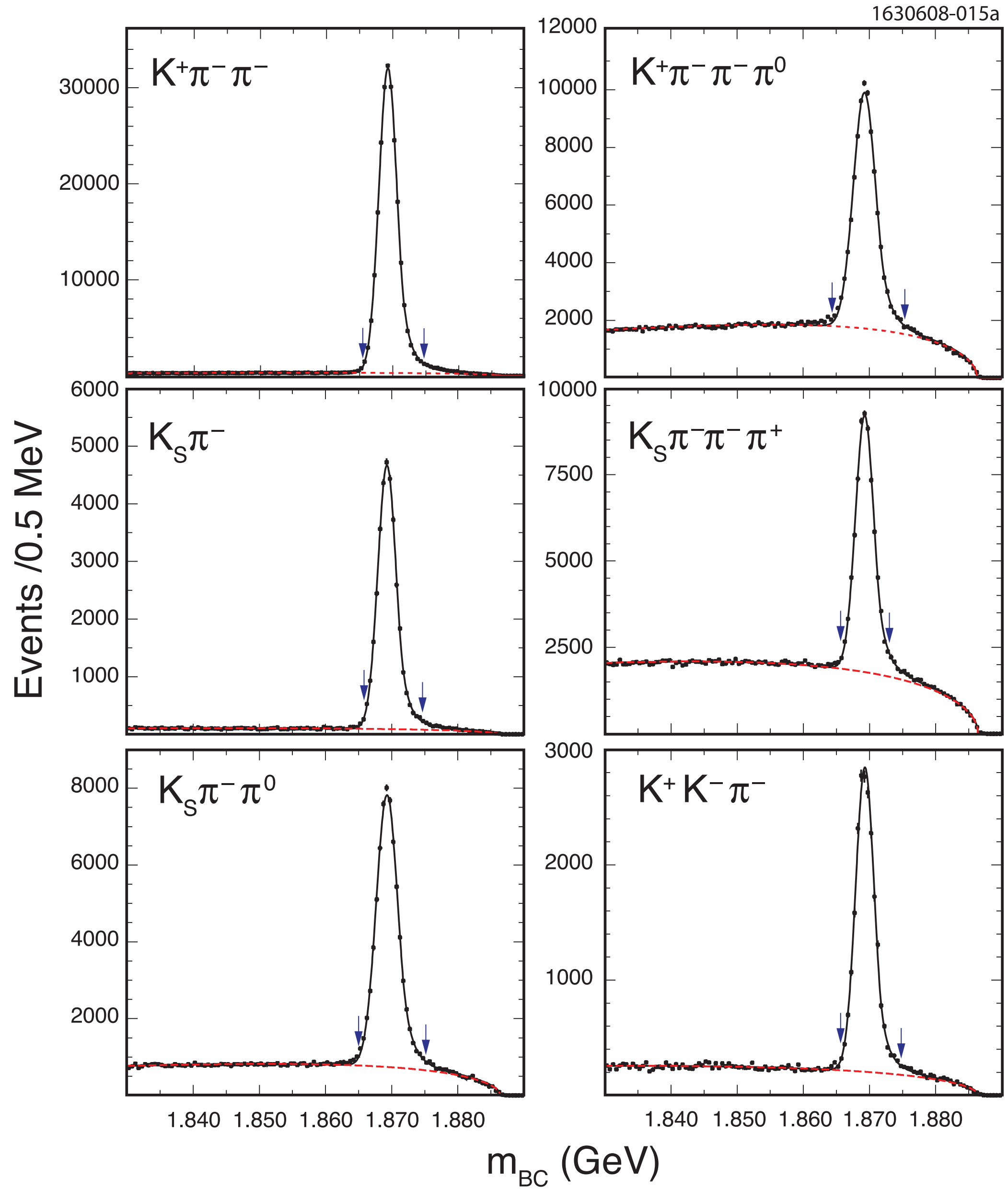




Double Tagging

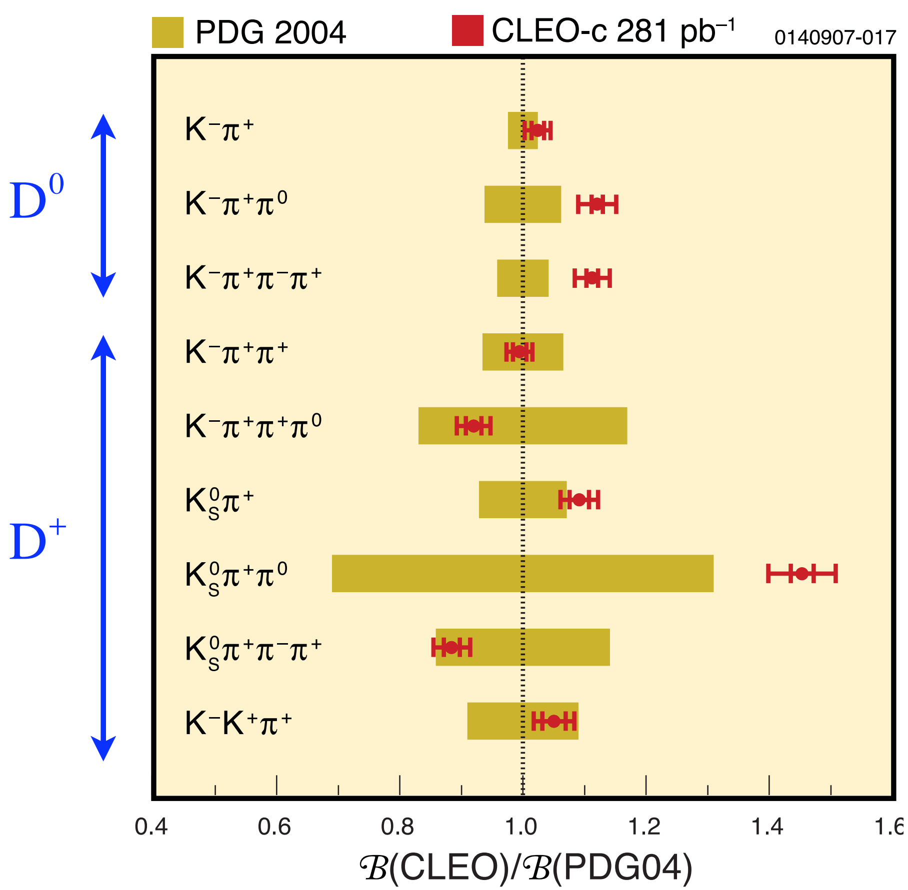
- Reconstruct one $D_{(s)}$ in $\psi(3770) \rightarrow D\bar{D}$ or $\psi(3770) \rightarrow D_s \bar{D}_s \gamma$ to get a clean sample of the partner $D_{(s)}$ decays
- Enables accurate, absolute branching fraction measurements
- Technique pioneered by Mark III

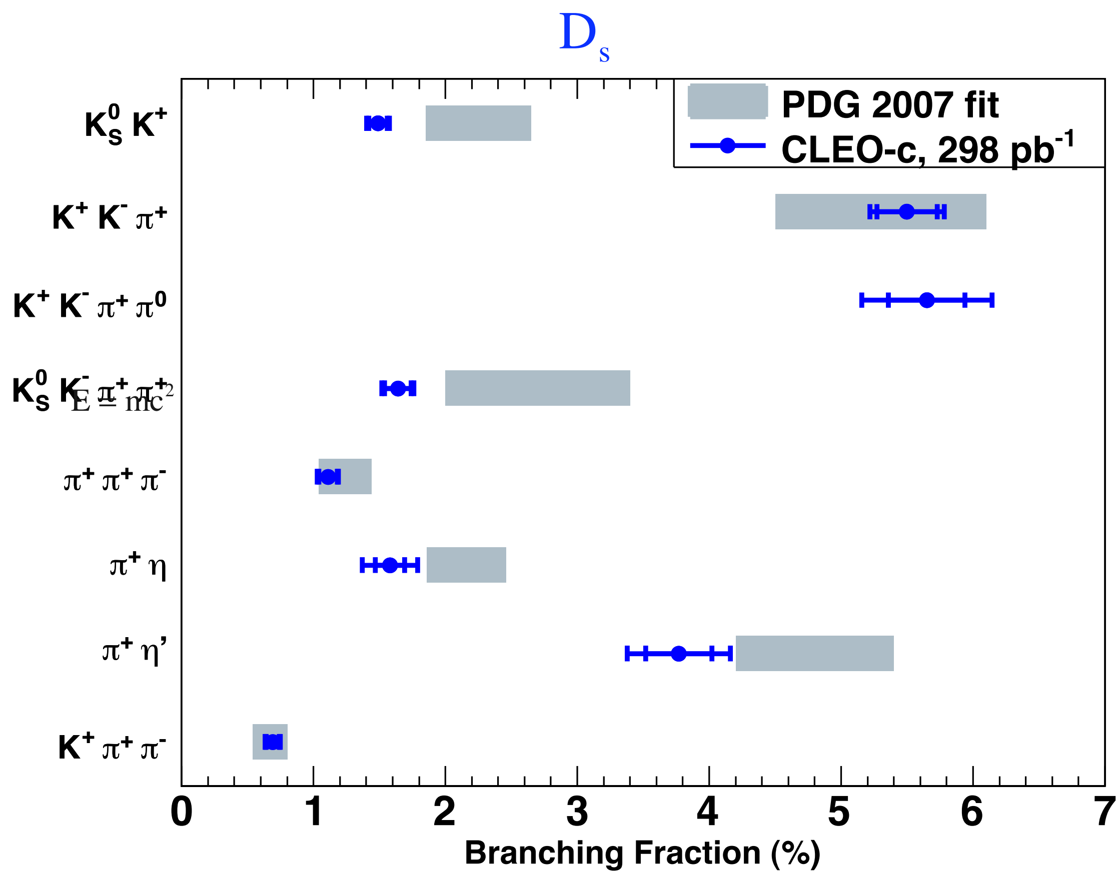
D^- Single Tags for $D^+ \rightarrow \mu^+\nu \ \ (f_{D^+})$



Absolute D Branching Fractions

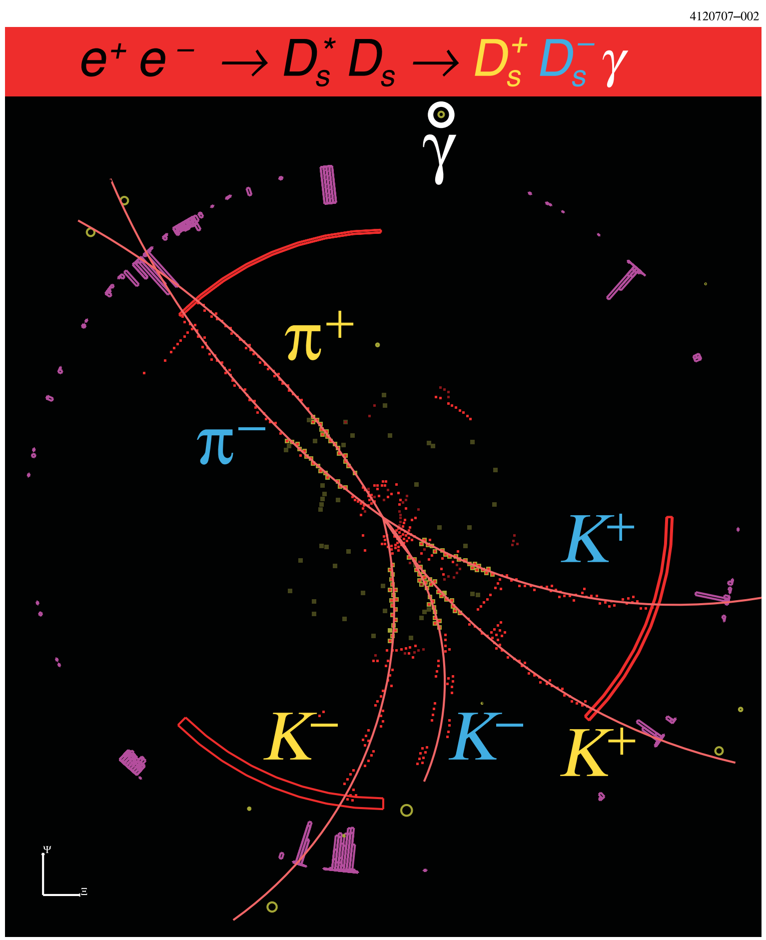
- Using double tags, measured absolute branching fractions for 3 D^0, 6 D^+, and 8 D_s modes

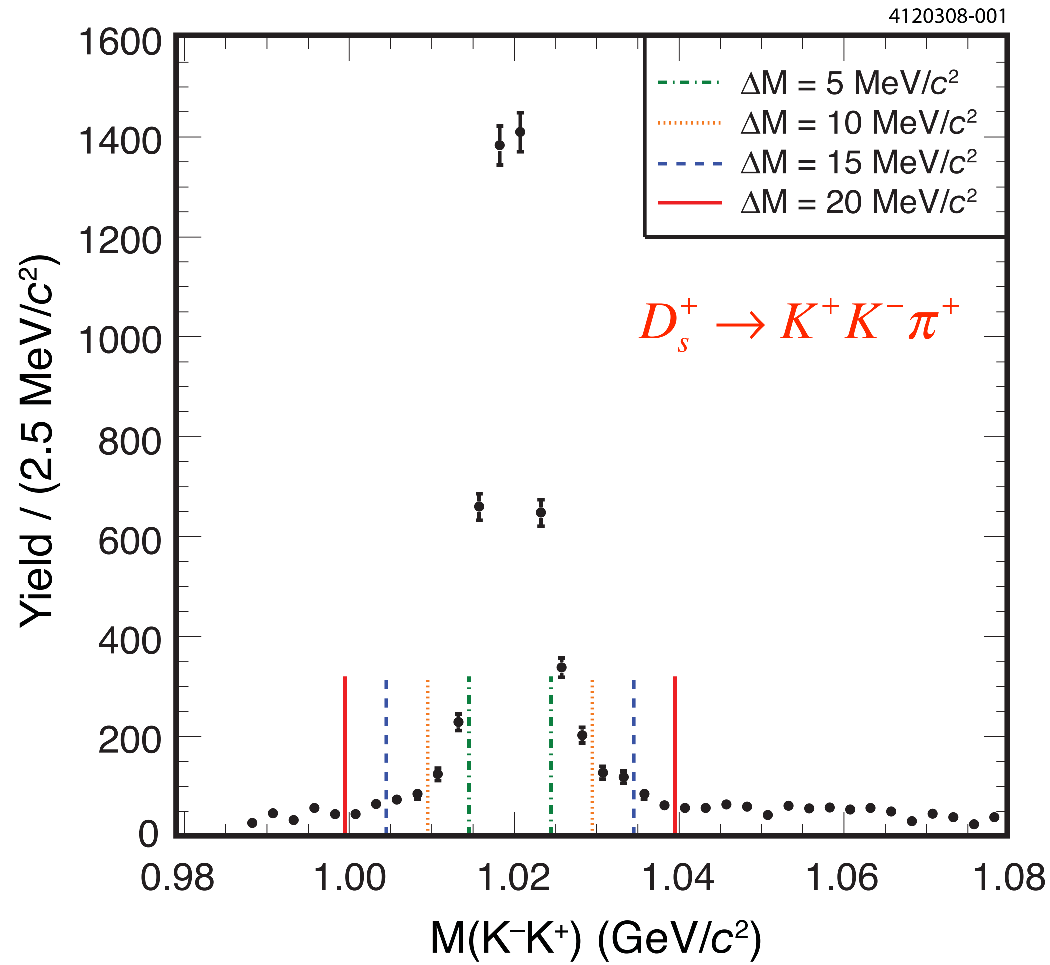




Absolute D_s^+ Branching Fractions

- First measurement of absolute D_s^+ branching fractions
  - $\mathcal{B}(D_s^+ \to \phi\pi^+)$ poorly defined due to interfering scalar contribution
  - Replace with $\mathcal{B}_{\Delta M}(D_s^+ \to K^+K^-\pi^+)$ within a mass window ΔM (MeV)
  - For example, $\mathcal{B}_{10}(D_s^+ \to K^+K^-\pi^+) = (1.99 \pm 0.10 \pm 0.05)\%$



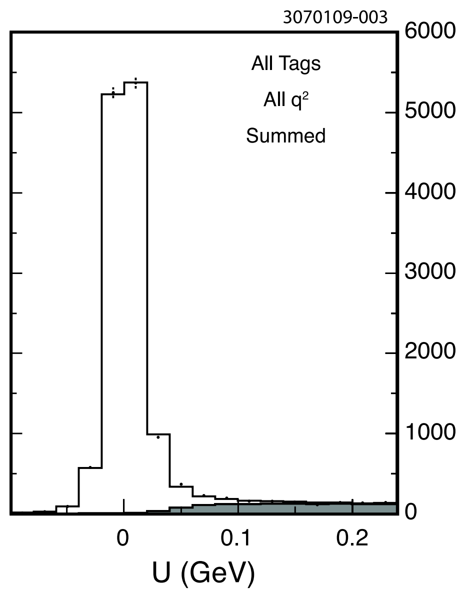


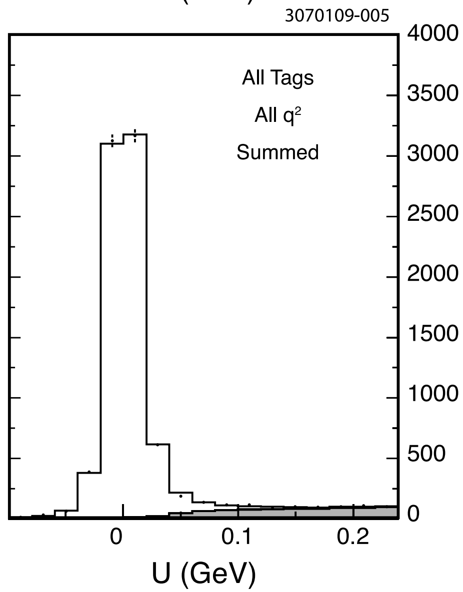
$D \to K e \nu$ Decays

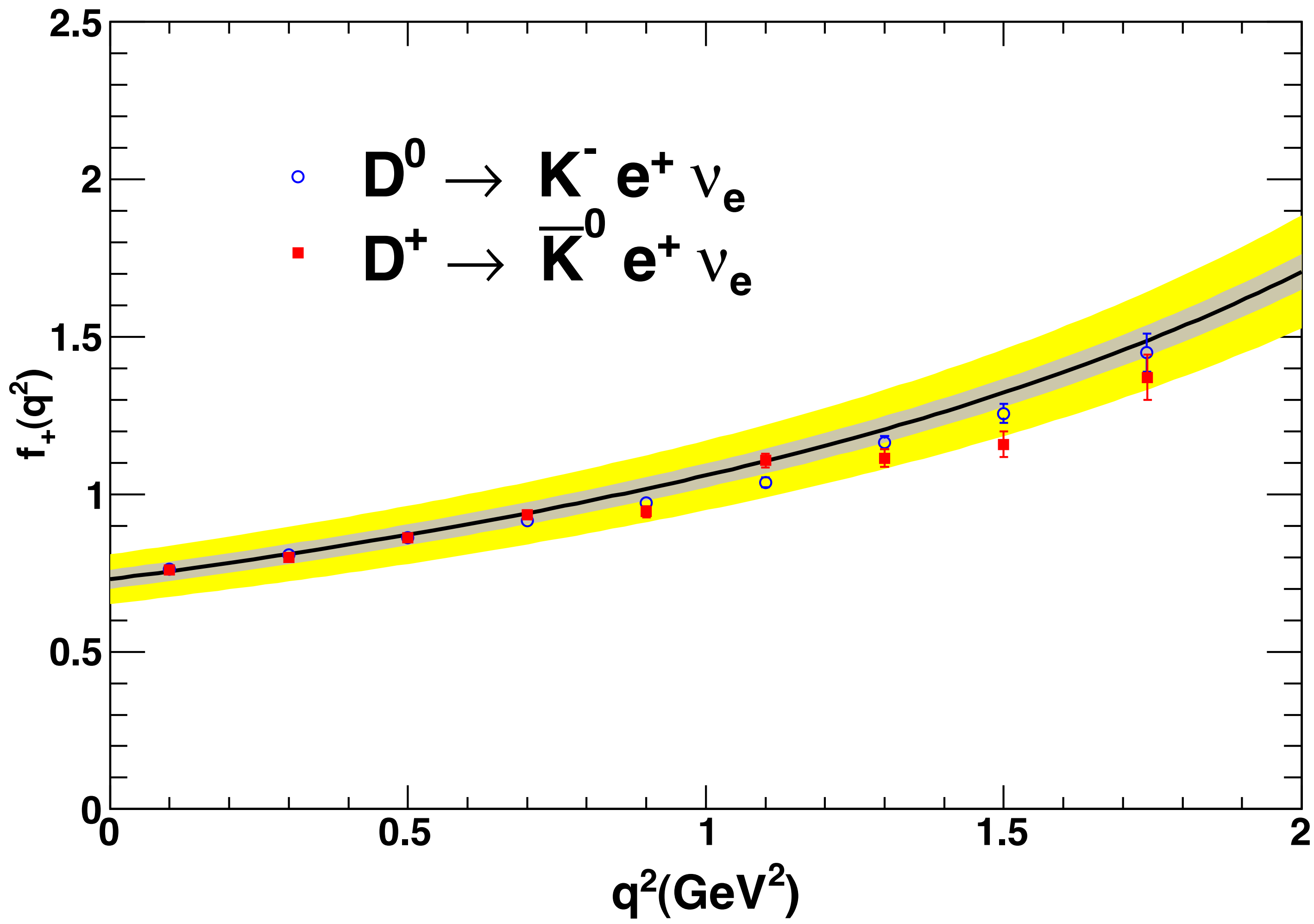
- Measure semileptonic decays to validate LQCD calculations of form factors

  Needed for determining $|V_{ub}|$ from exclusive $B \to X_u \ell \nu$ decay

$$|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103(\text{LQCD})$$

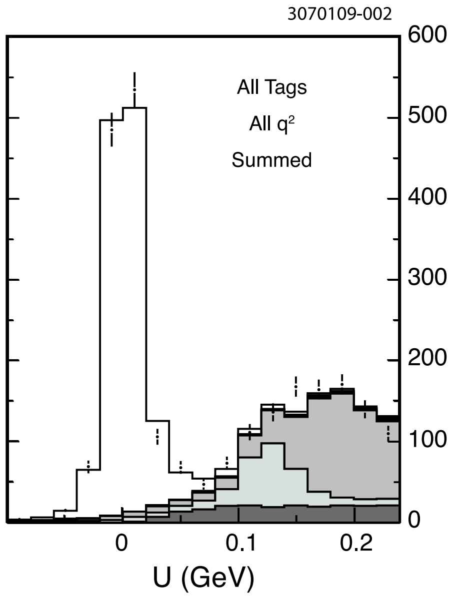


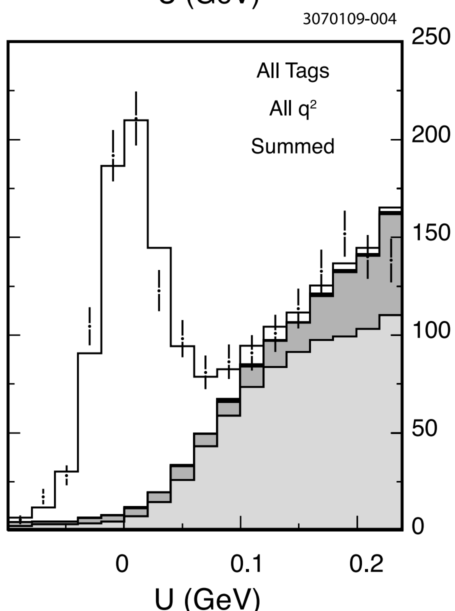




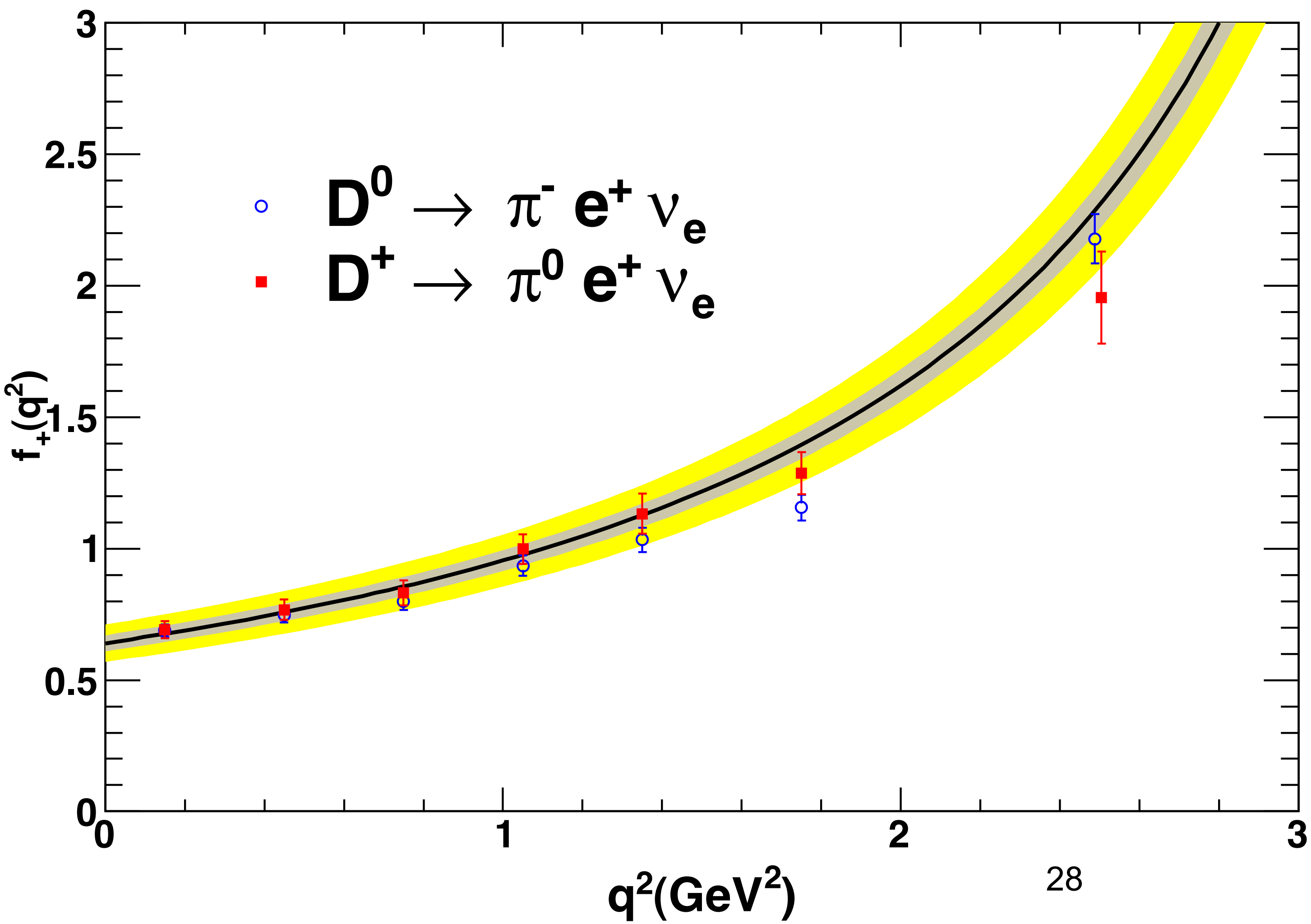
$D \to \pi e \nu$ Decays

- Same motivation as $D \to K e \nu$ decays



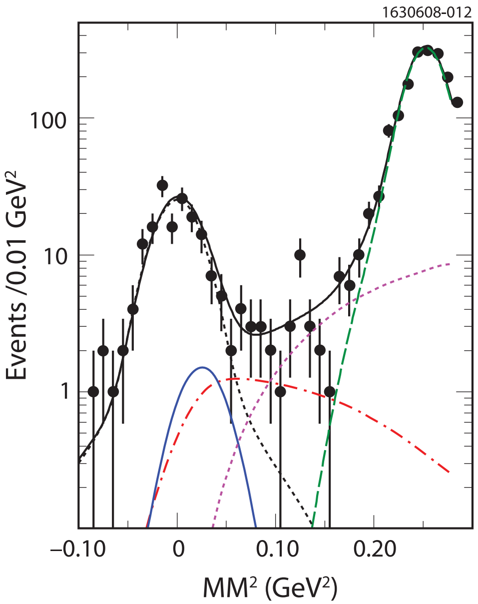


$|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025(\mathrm{LQCD})$

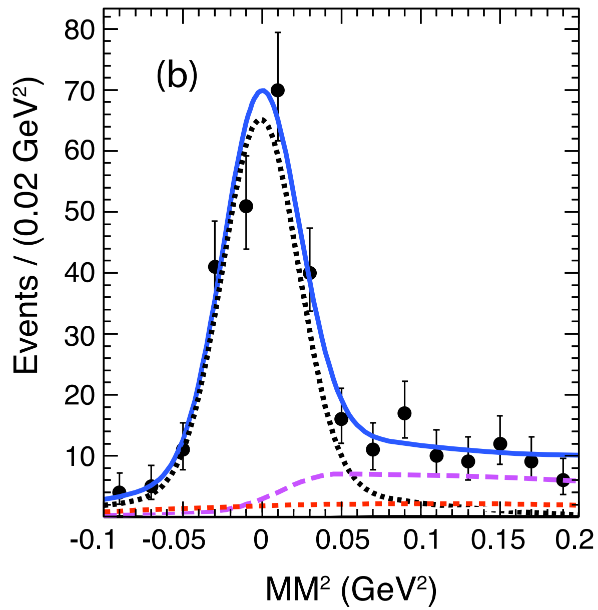


f_{D^+} and f_{D_s}

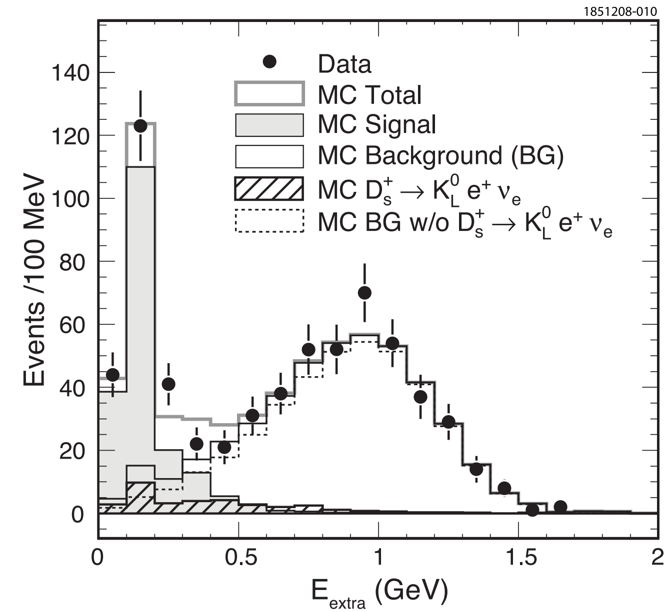
$D^+ \to \mu^+\nu$



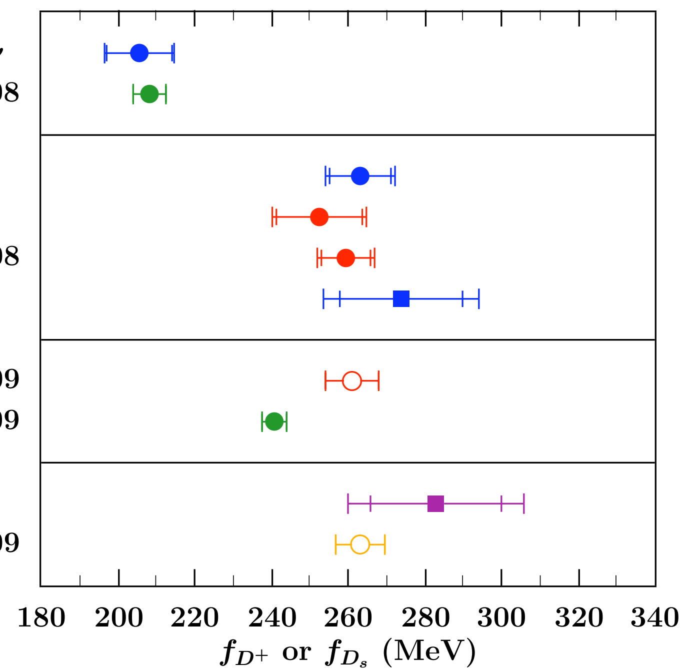
$D_s^+ \to \mu^+\nu(\tau^+\nu), \tau^+ \to \pi^+\nu$



$D_s^+ \to \tau^+\nu, \tau^+ \to e^+\nu\nu$



	f_{D^+} or f_{D_s} (MeV)
CLEO-c $D^+ \to \mu\nu(\tau\nu)$, $\tau \to \pi\nu$	$205.8 \pm 8.5 \pm 2.5$
LQCD Follana *et al.* 2008	208 ± 4
CLEO-c $D_s \to \mu\nu(\tau\nu)$, $\tau \to \pi\nu$	$263.3 \pm 8.2 \pm 3.9$
CLEO-c $D_s \to \tau\nu$, $\tau \to e\nu\nu$	$252.5 \pm 11.1 \pm 5.2$
CLEO-c D_s Average 2008	$259.5 \pm 6.6 \pm 3.1$
Belle $D_s \to \mu\nu$	$274 \pm 16 \pm 12$
CLEO-Belle Average 2009	261.2 ± 6.9
LQCD Follana *et al.* 2009	241 ± 3
BaBar $D_s \to \mu\nu$	$283 \pm 17 \pm 16$
BaBar Included Average 2009	263.0 ± 6.6

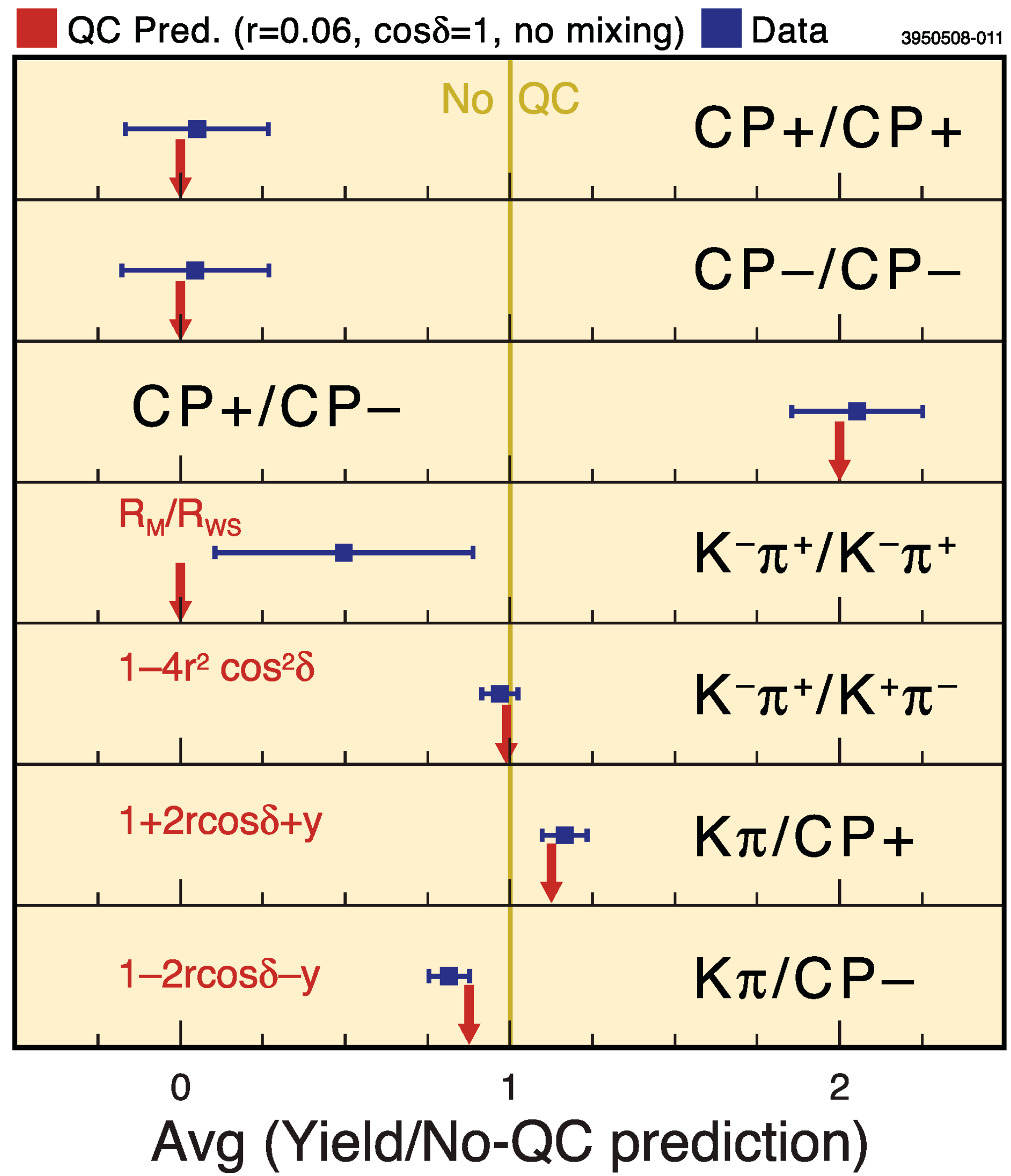


$D\bar{D}$ Quantum Correlations

- A strong phase δ rotates the $D^0\bar{D}^0$ mixing parameters x and y.
- CLEO measures δ by comparing quantum correlated yields with uncorrelated branching fractions
- Using about 35% of the $\psi(3770)$ data, CLEO finds

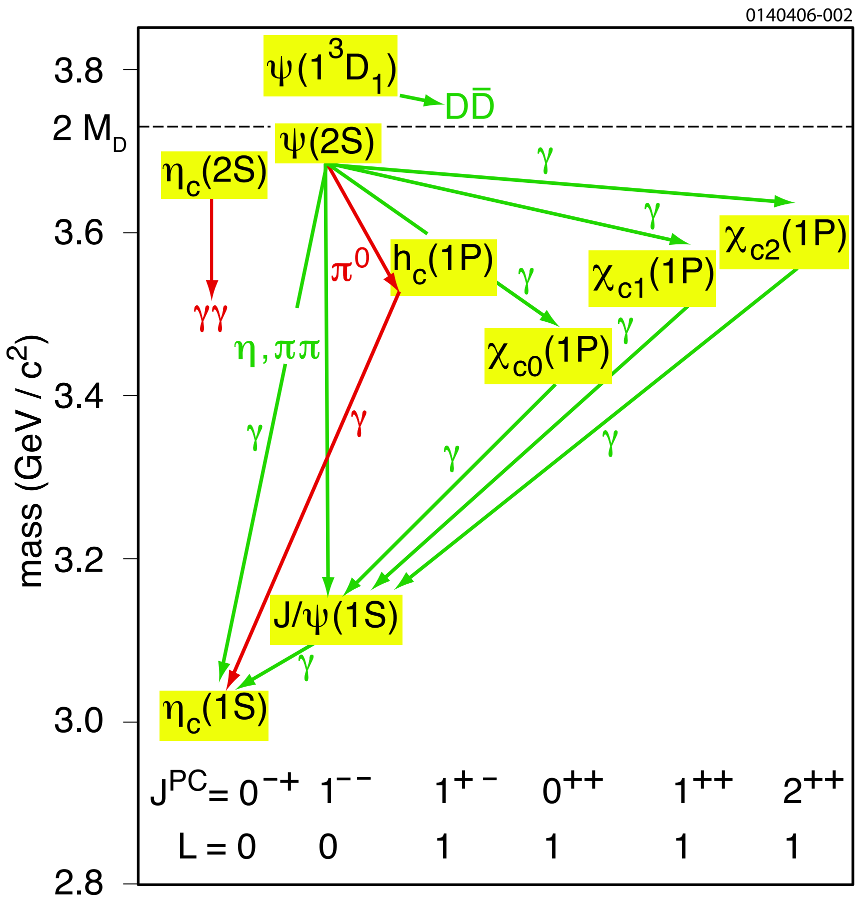
$$\cos\delta = 1.10 \pm 0.35 \pm 0.07$$

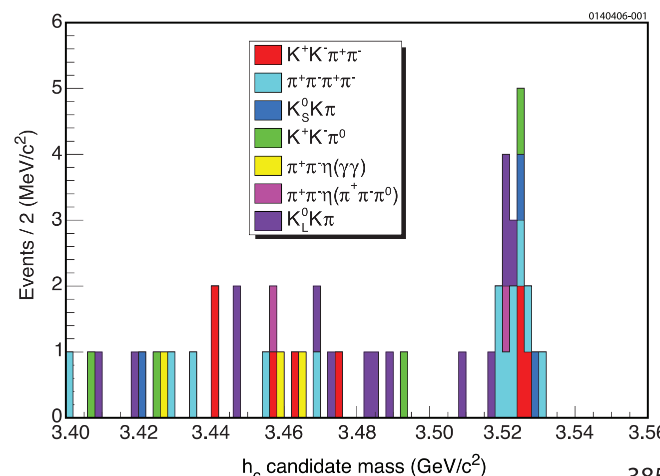
$$x\sin\delta = (4.4^{+2.7}_{-1.8} \pm 2.9)\times 10^{-3}$$



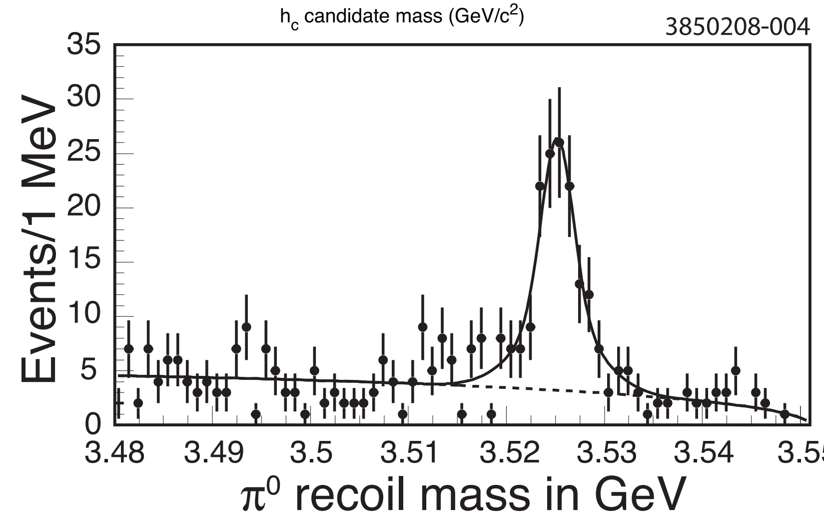
Exclusive hc Events

- The h_c was the last $c\bar{c}$ bound state to be observed
  - Seen by E760 in $p\bar{p} \to J/\psi\ \pi^0$
- CLEO reconstructed $\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\eta_c,\ \eta_c \to hadrons$
- Hyperfine mass splitting $\langle M(\chi_{cJ})\rangle - M(h_c) = +0.02 \pm 0.19 \pm 0.13$ MeV





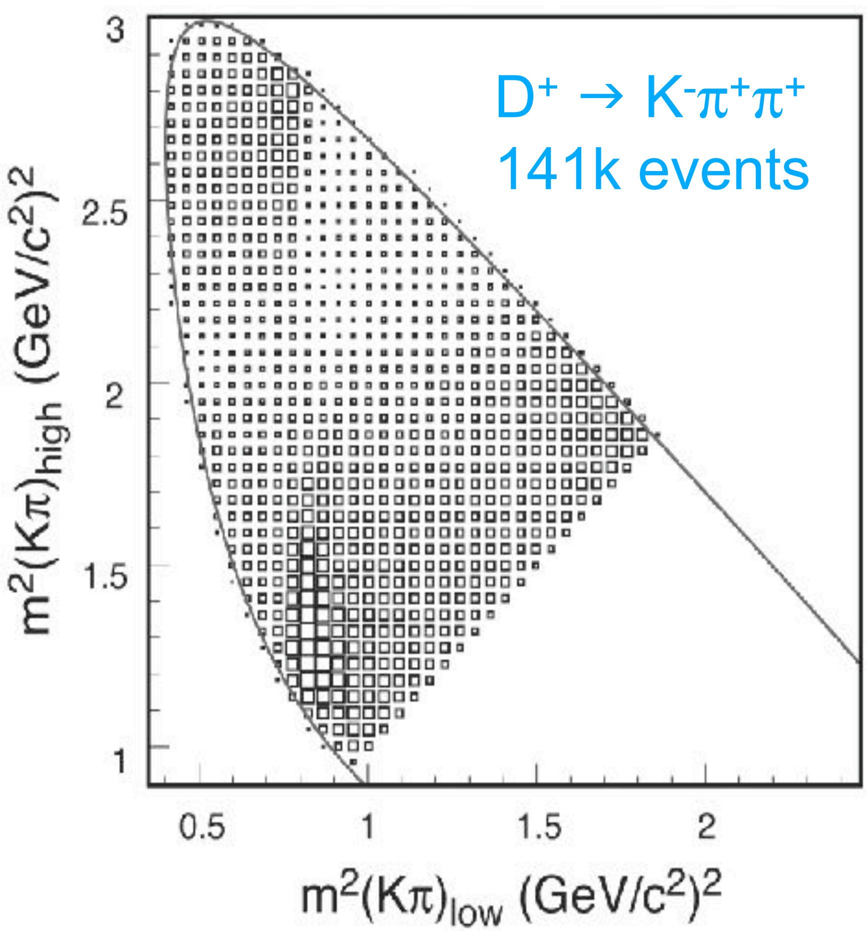
CLEO 2005

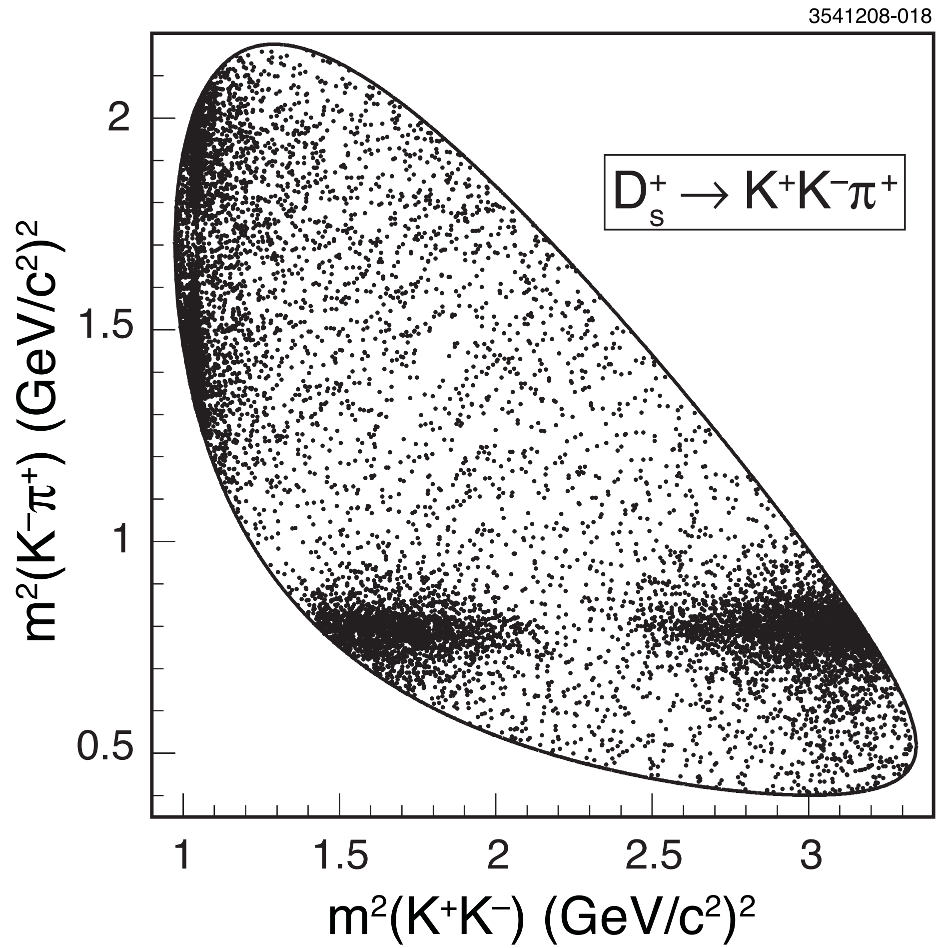


CLEO 2008

Dalitz analyses of 3-body decays

- Interfering 2-body resonances in Dalitz plot analyses of $D_{(s)}$ decays to 3 hadrons.
- Strong phases determined from quantum correlations used in measurements of the CKM angle γ / φ_3





CESR & CLEO Accomplishments

- 498 papers, 225 CLEO & 32 CESR PhD theses
- 6-quark Standard Model works well
  - 3x3 CKM matrix is apparently unitary – A, ρ, η measured
  - Measured $|V_{ij}|$ imply CP violation in B decays
- Gluon exchange works well for $c\bar{c}$ and $b\bar{b}$ binding
  - $\alpha_s(s)$ varies smoothly, as expected
  - Lattice QCD works well
- No evidence for physics beyond the Standard Model
  - Many limits on forbidden processes
- CESR luminosity tricks have benefited other facilities
  - Multibunch pretzel orbits, crossing angle, microbeta focusing,
  - superconducting RF cavities, wigglers

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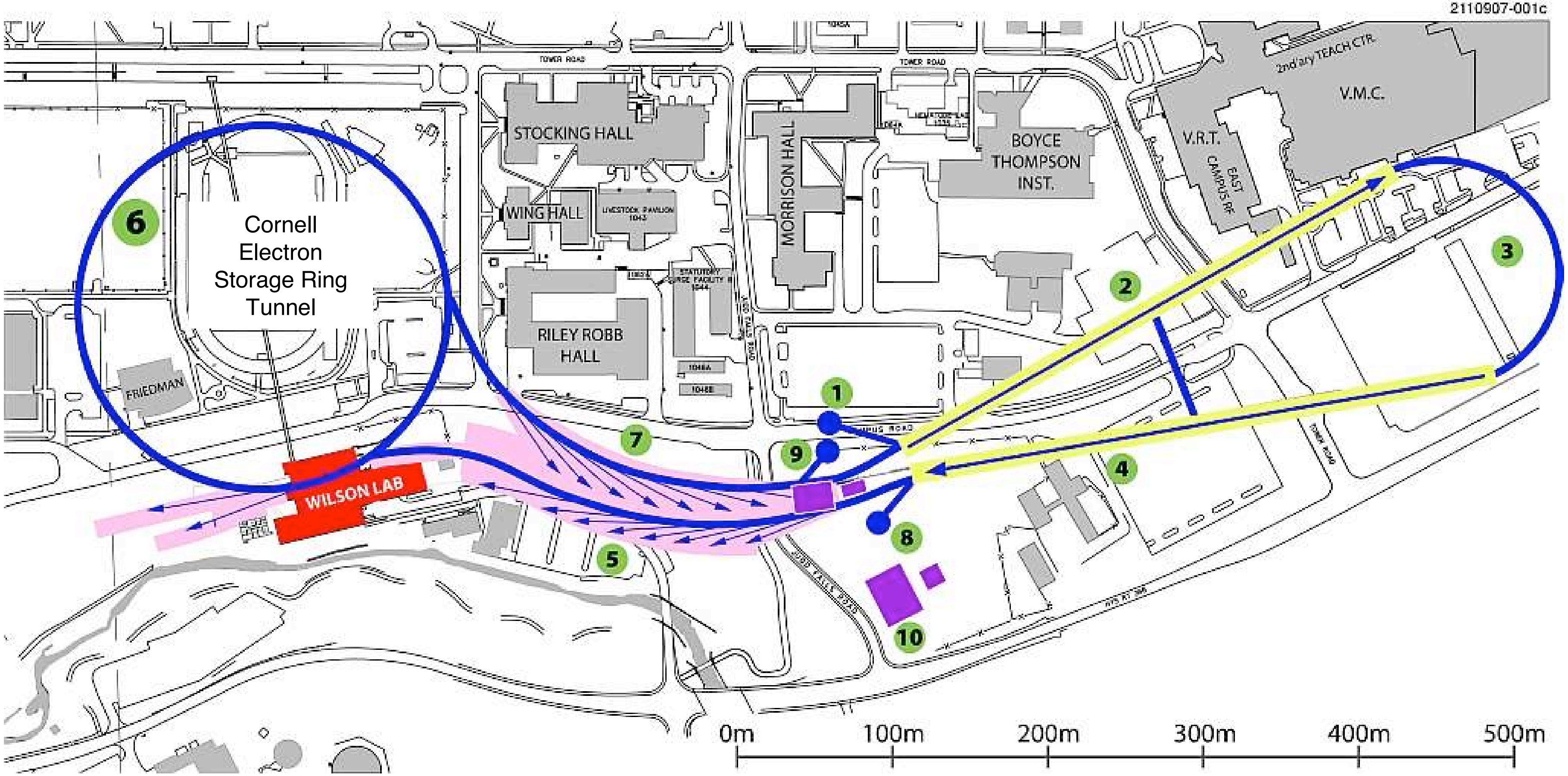
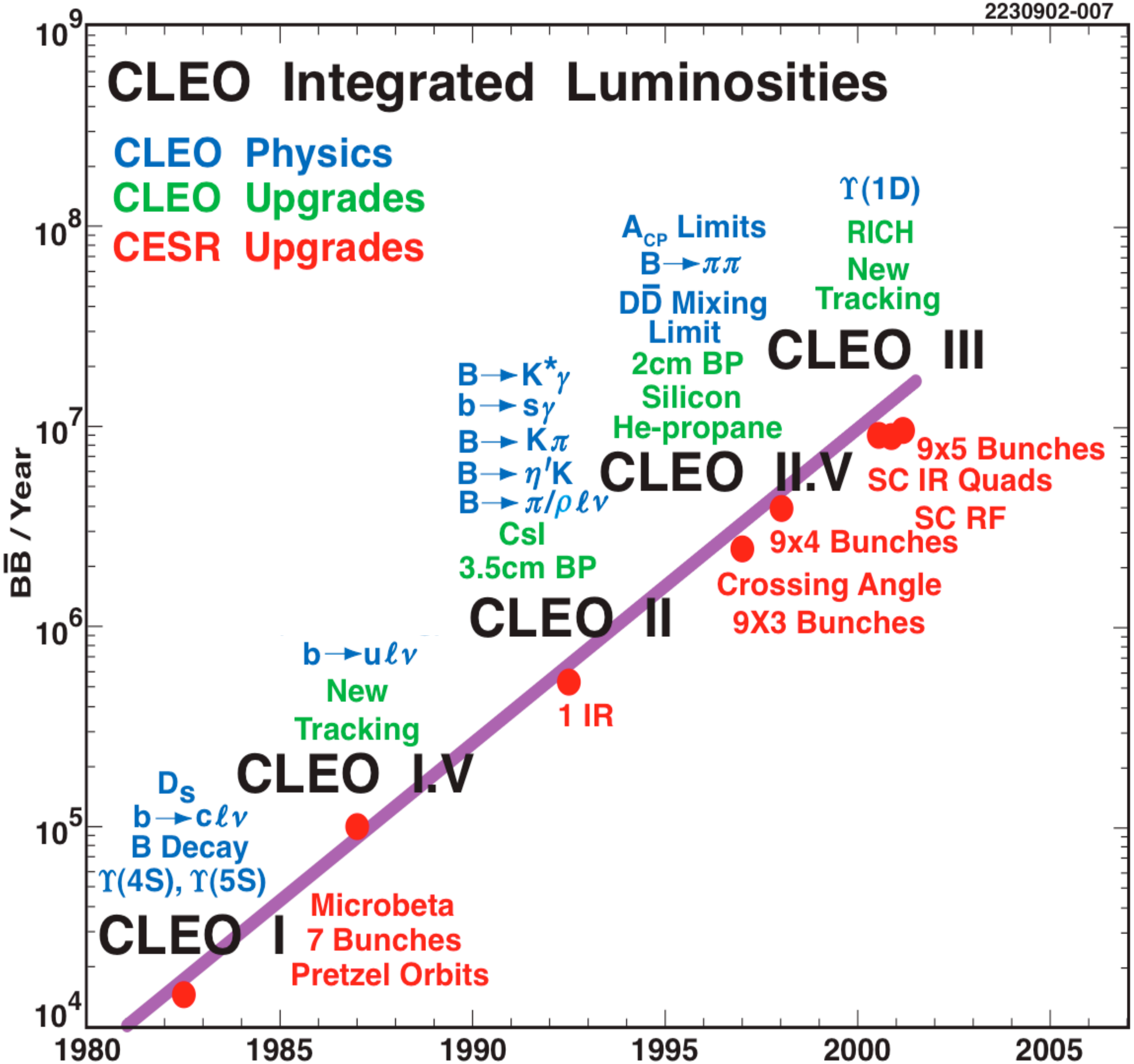
CLASSE

Cornell x-ray ERL



The ERL is an extension of the CESR ring

(1) Injection, (2-4) acceleration, (5-7) x-rays, (2-4) deceleration, (8) beam dump.



CLEO-c Physics

Observations

f_{D^+}

Confirmations

$h_c(1P)$

$\eta_c(2S)$

$\Upsilon(4260)$

Precision

f_{D_s} & f_{D^+}

$M_{D^0}, M_\eta, \& M_{\eta'}$

Absolute $\mathcal{B}$

$\eta \& \eta'$

$J/\psi \to \gamma\gamma\gamma$

Hadronic &

Semileptonic

$D^0, D^+, \& D_s$