Accomplishments of the CESR/CLEO Program

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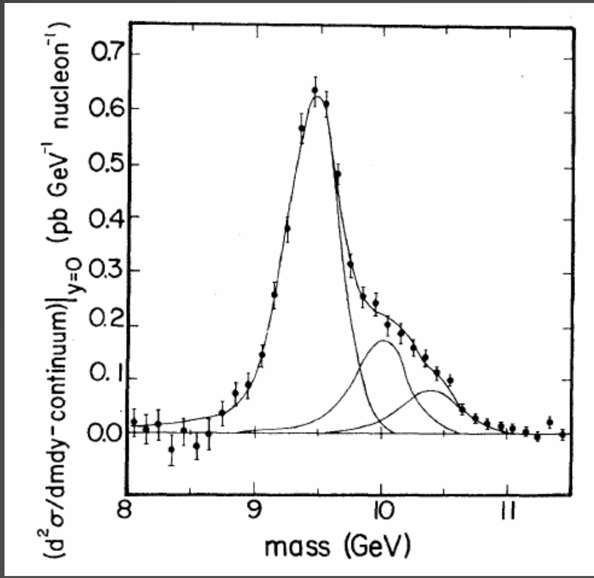
Introduction

- Context: Late 1970's, J/ψ had been discovered in Nov. 1974, we knew about open charm & τ, but not about existence of b, t, W or Z !
- Idea: explore e^+e^- collisions in 8 -16 GeV center-of-mass range, hope for something new
- Competition: PEP/Petra at higher energy (up to 32 GeV) at SLAC & DESY, later ARGUS at DESY
- CESR proposal May 1975 for single ring collider with $\mathcal{L}=10^{32}\ cm^{-1}s^{-1}$
- Surprise – After detector design started discovery of b quark 1977 (Lederman) at FNAL via Υ(1S) & Υ(2S) (hint of Υ(3S)). Could there be a nice state for threshold $B\bar{B}$ production like the ψ(3770) for D's?



Uneno et. al, FNAL $\mu^+\mu^-$, background subtracted (1979)

b Physics Goals

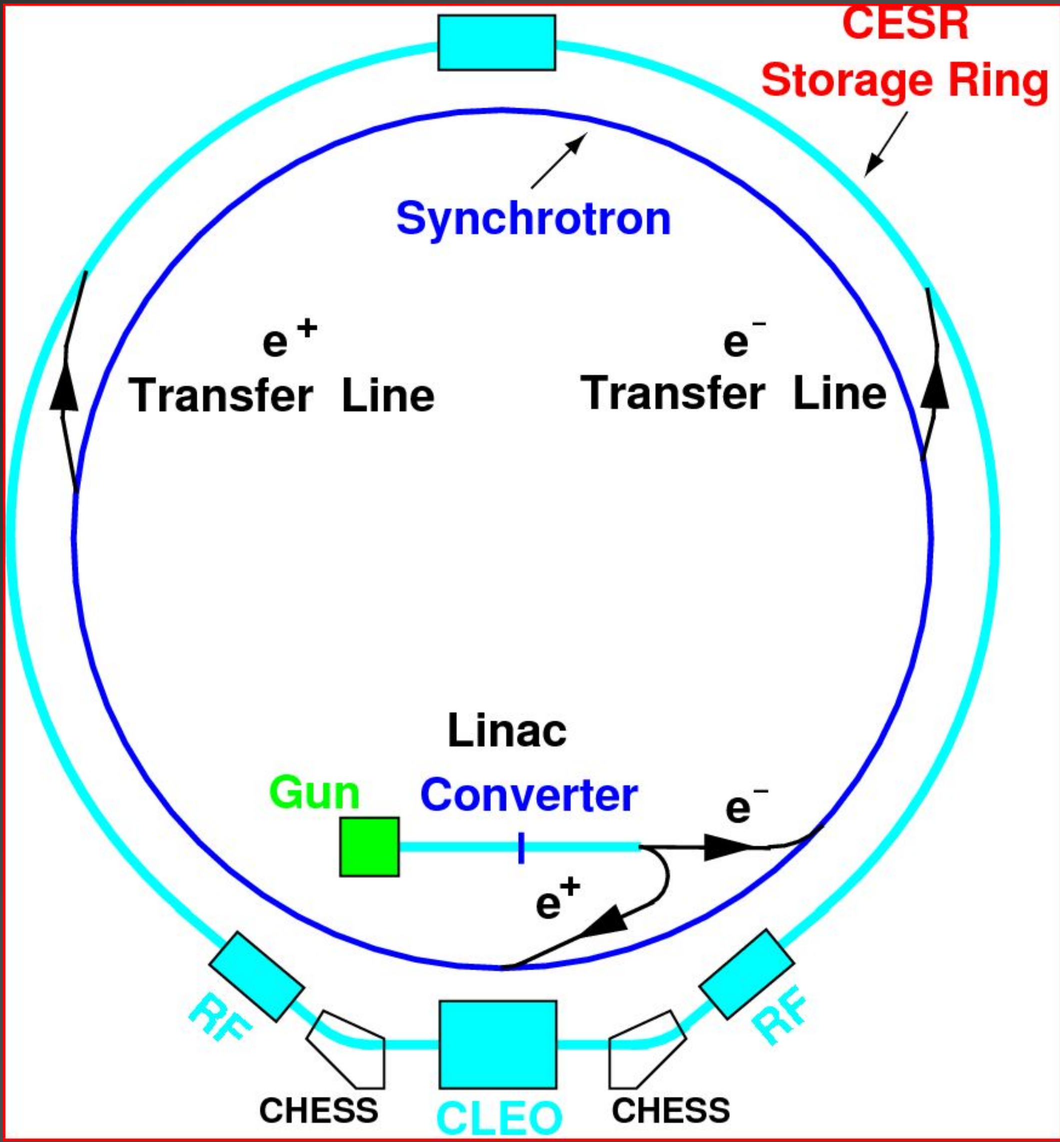
- Would b’s decay as “predicted” or could we see new phenomena?
- Could we learn something seminal about QCD studying Υ transitions & decays?
- Was there anything to learn from charm decays, since $e^+e^- \to c\bar{c}$ is 1 nb, 40% of total?
- Is there anything unexpected?

Machine

- On the Cornell Campus
- Two interaction regions originally
  - CUSB
  - CLEO
- CHESS: Vigorous synchrotron radiation program
- Storage Ring very new & lots to learn

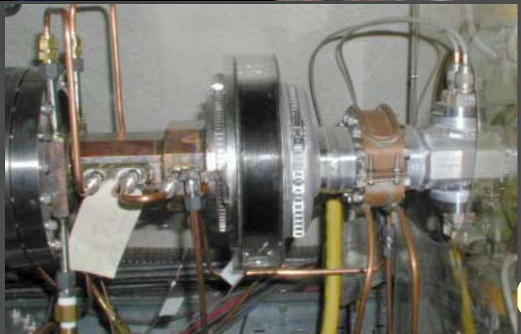
Stacking Scheme

- Use 8 GeV Synchrotron
- Diameter of CESR larger than Synch by exactly two bunch spacings; allows for stacking

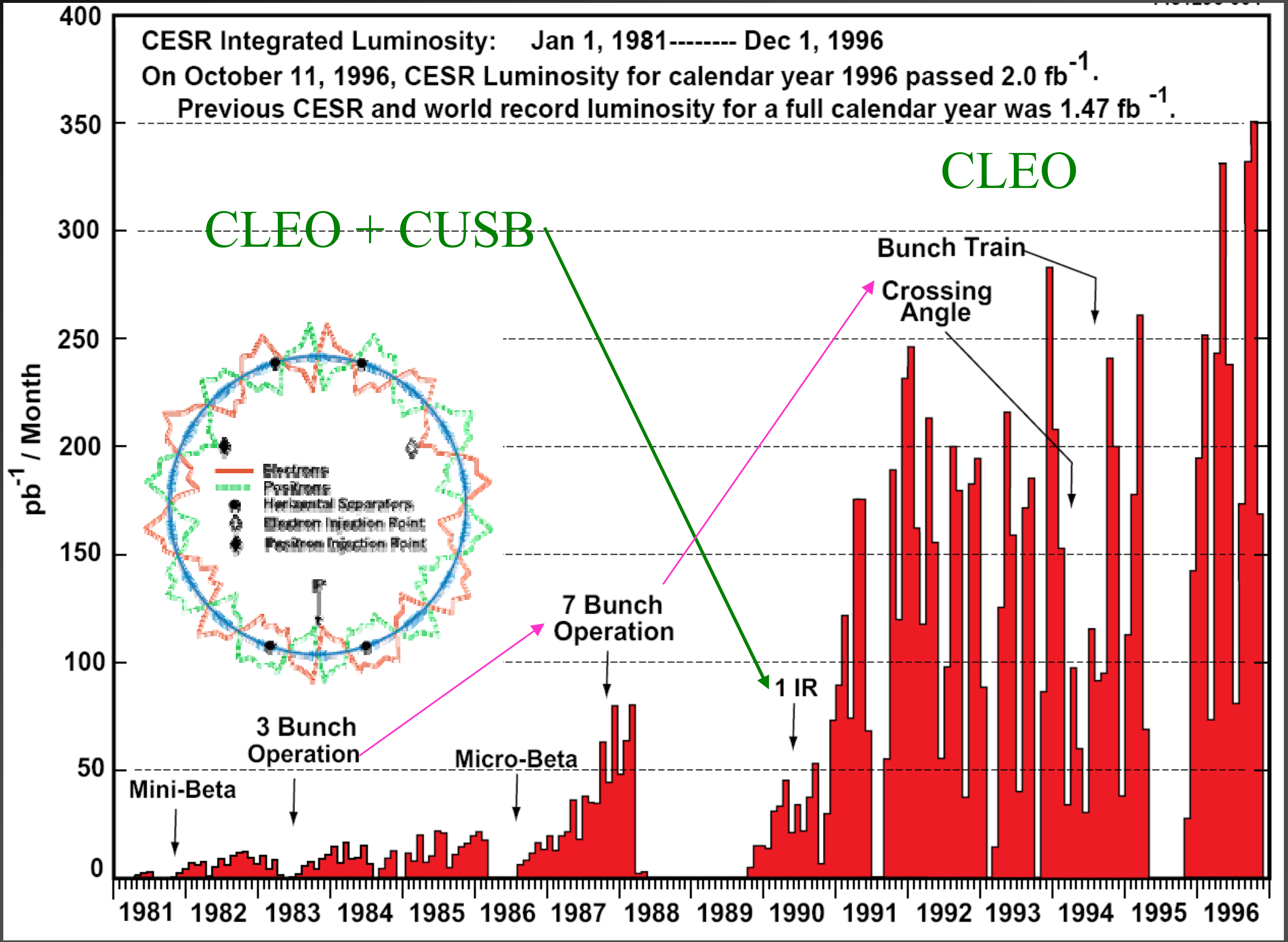


Inside the Tunnel

- First impedance controlled storage ring



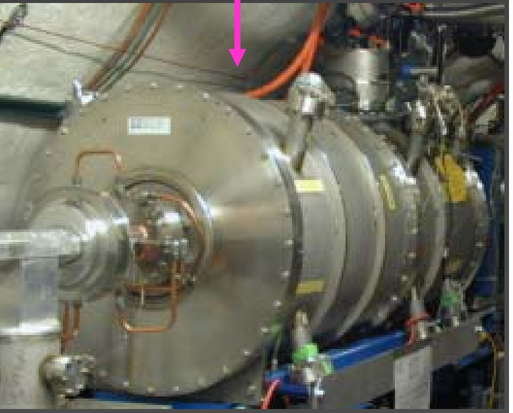
Luminosity Progress: Early Years

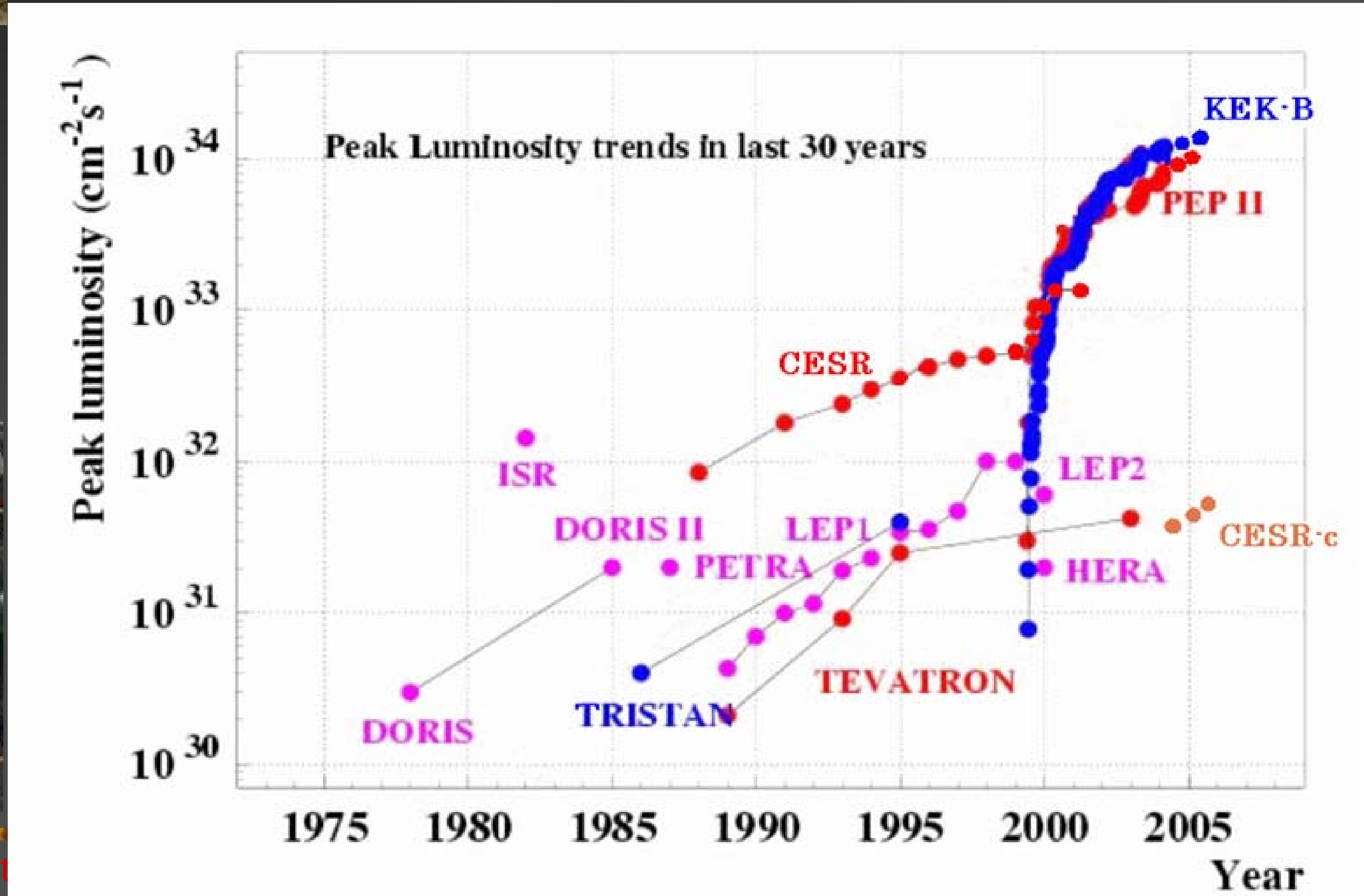


CESR Highlights

- 1986: First “Micro-beta” collision point with permanent magnets
- 1994: 1st crossing angle for bunched beams

- 1990-2000: Highest L collider
- 2003: First wiggler dominated collider

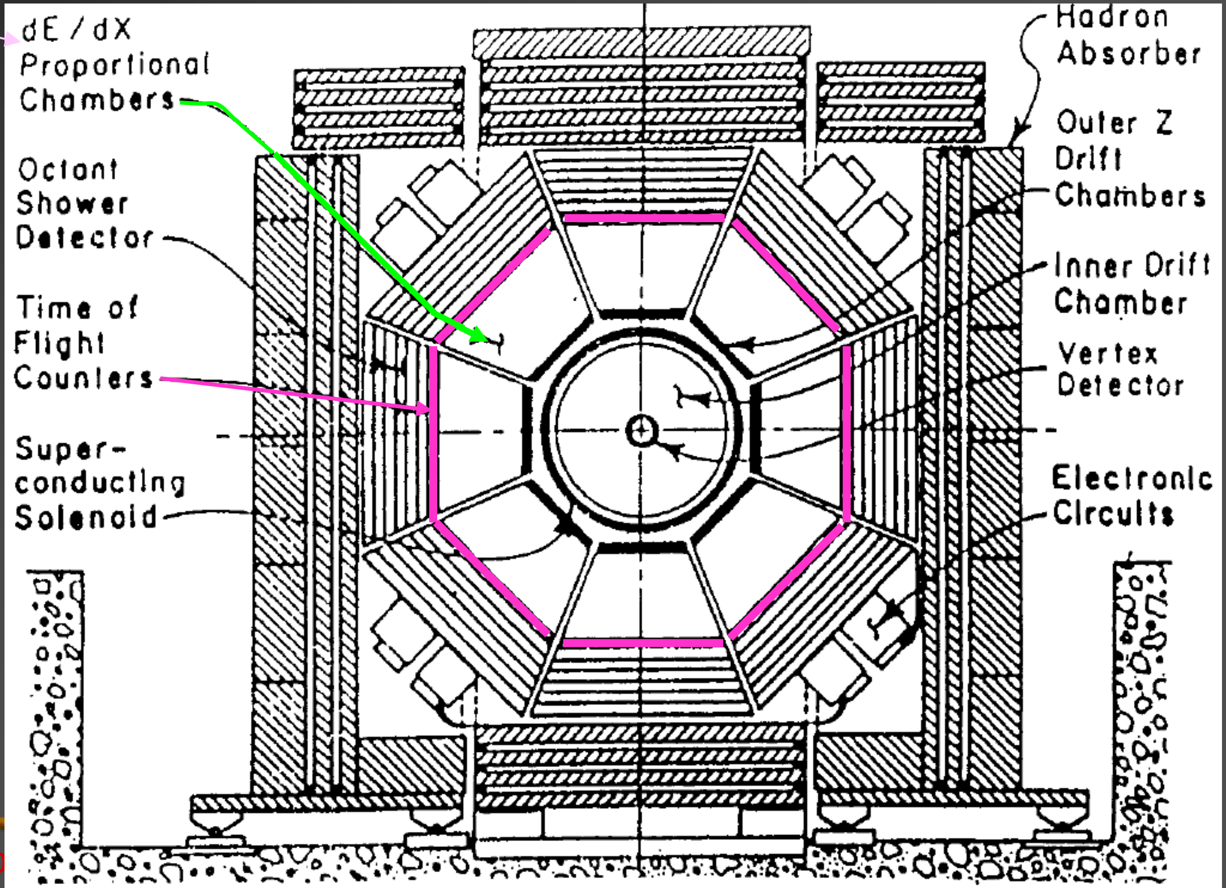




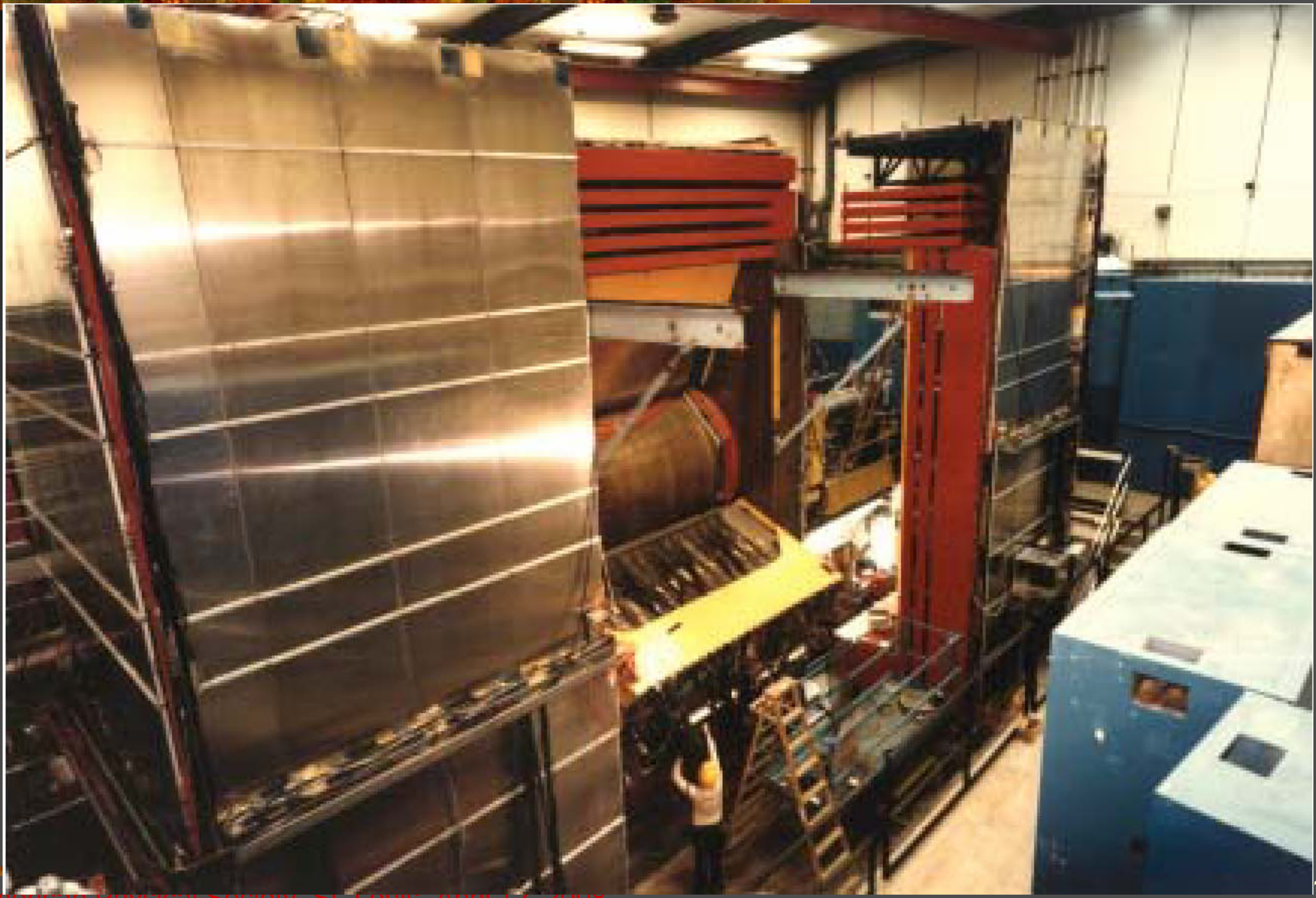
CLEO I Detector

- Built on the cheap ~10M$, lots to learn
  - Components
  - Developing technologies widely adopted applied to upgraded detectors CLEO II, II.V, III
  - Example: PID in outer dE/dx → in DR → RICH

CLEO I Detector (circa 1981)

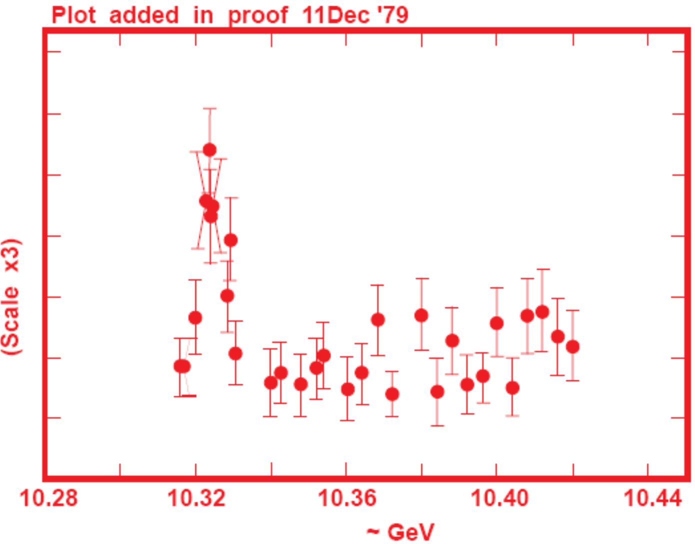


A Photo of CLEO I

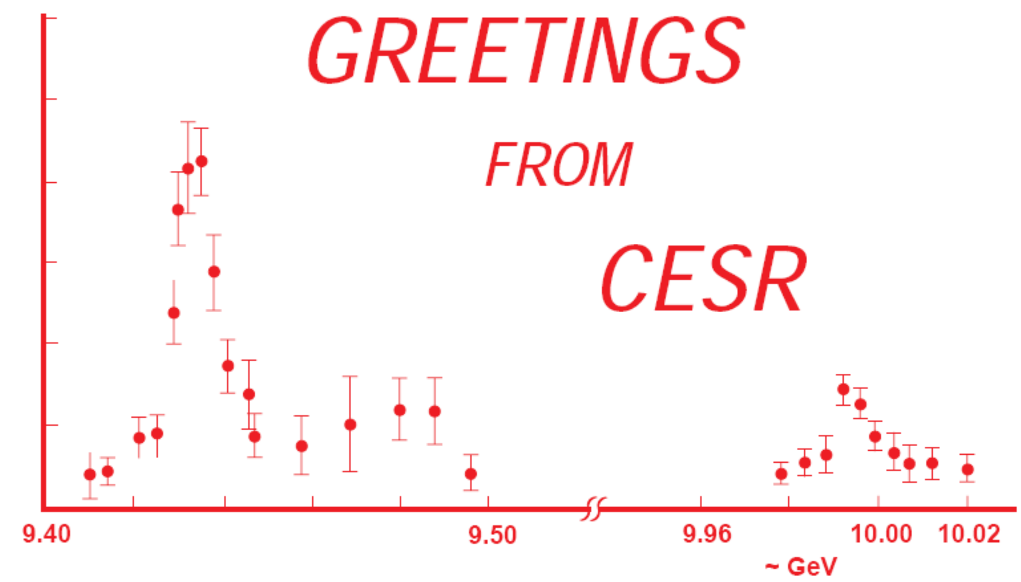


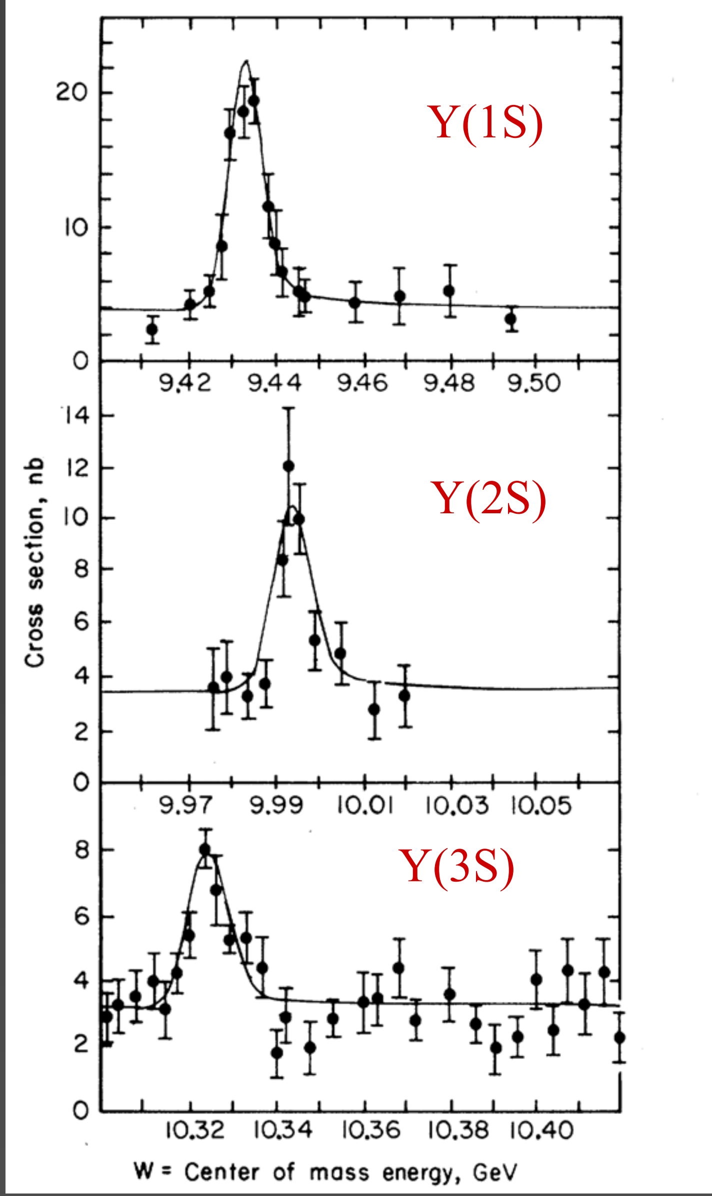
First Results (Narrow Upsilons)

$\mathcal{L}$=0.4 pb^{-1}



Xmas card 1979

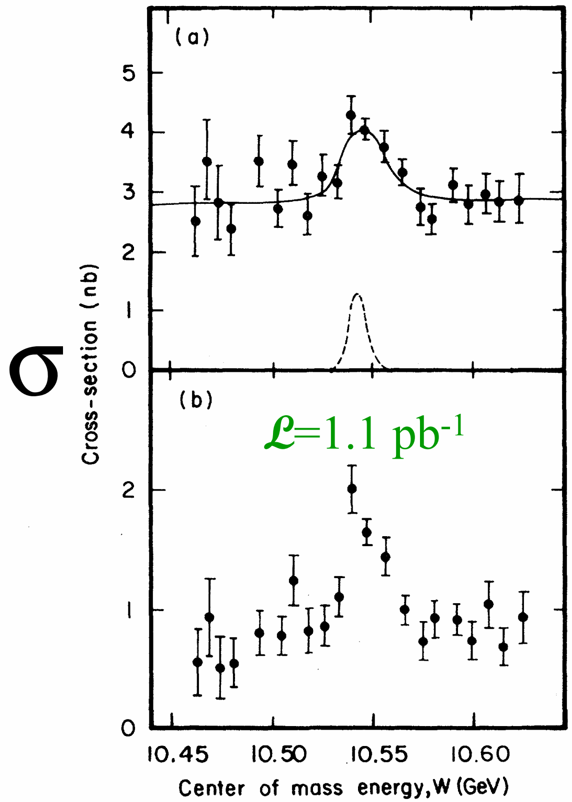




VOLUME 45, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JULY 1980

Observation of a Fourth Upsilon State in e^+e^- Annihilations

■ Discovery of Υ(4S)



$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

■In 1985, Υ(5S), etc..

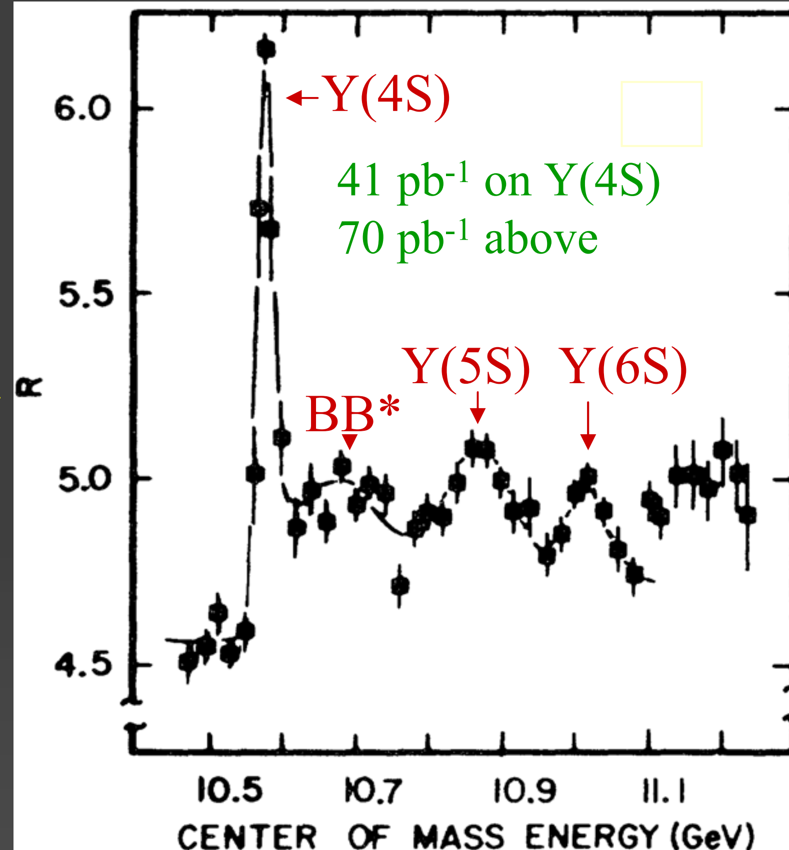
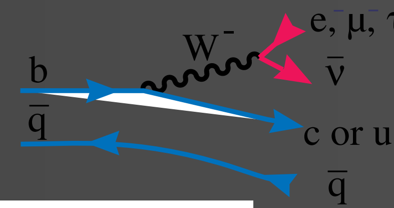


FIG. 1. Hadronic cross sections corrected for acceptance, as a function of center-of-mass energy, W. There is an additional overall systematic error of $\pm 15\%$, arising mainly from the uncertainty in the detector acceptance. (a) Total hadronic cross section. The curve is a radiatively corrected Gaussian fit to the resonance above a smooth continuum varying as W^{-2}. The dashed curve indicates the beam energy resolution. (b) Partial cross section for events with $R_2 < 0.3$. (See text.)

Mystery: mass differences: Υ(5S)-Υ(4S) > Υ(4S)-Υ(3S)

b-quarks Decay As Expected



- First observation of semileptonic decays
- Exotic decays not dominant – We are still looking for non-SM decays. New Physics, must produces these & their pattern will tell us a great deal about the NP.

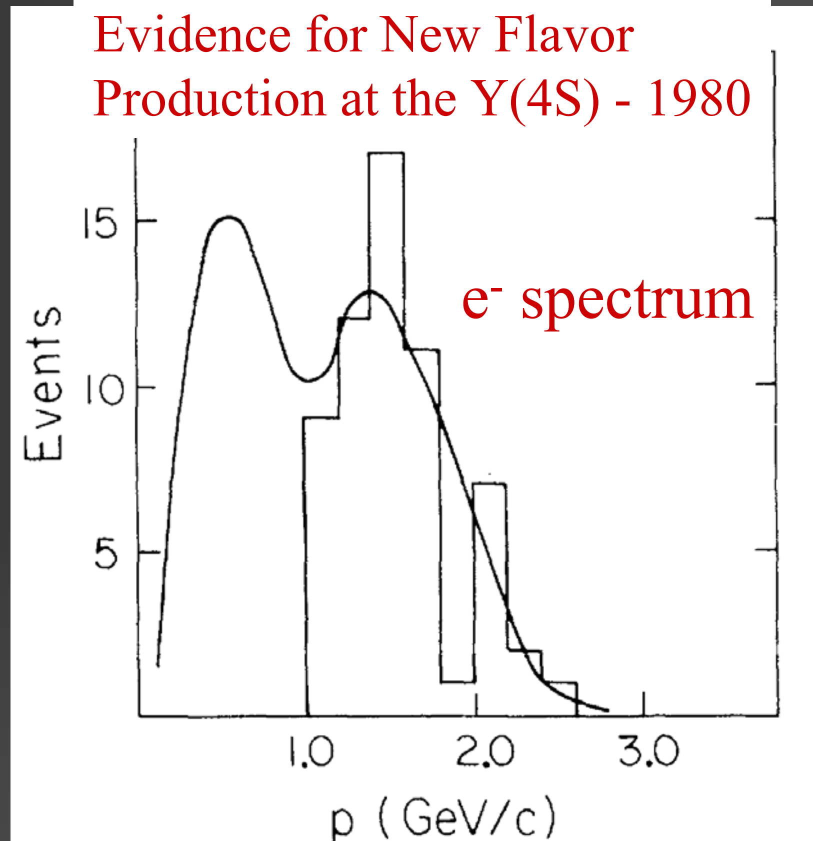
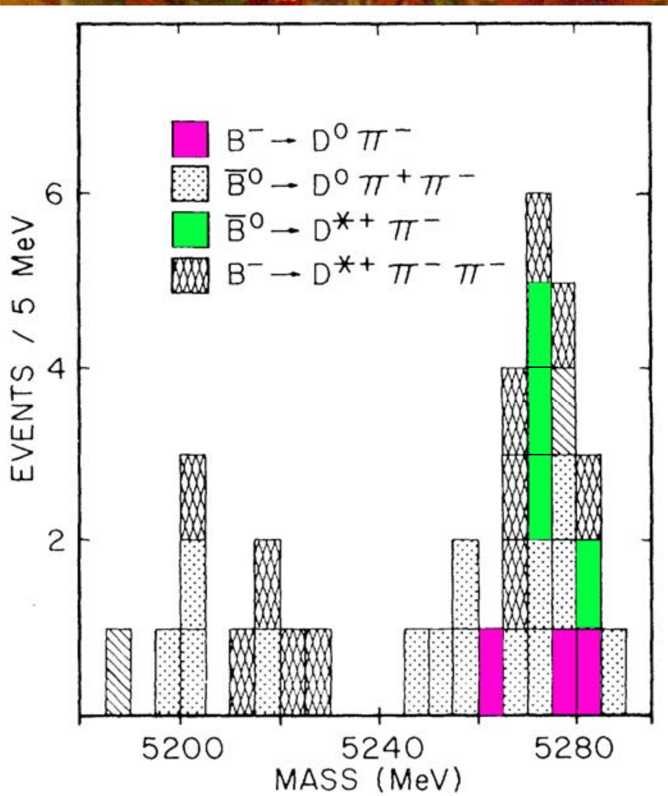


FIG. 3. The histogram is the raw momentum spectrum of the electrons from the $\Upsilon(4S)$ peak. The curve is a Monte Carlo estimate of the combined electron spectrum expected from $B\rightarrow De\nu$, $B\rightarrow D^*(2000)e\nu$, and $D\rightarrow Xe\nu$ decays. The peak at ~1.4 GeV/c is due to B decays; the one at ~0.5 GeV/c to daughter D decays. No events appear below 1 GeV/c due to our cut at that momentum.

Further Expectations (~1983)

- B meson lifetime will be short
- B^o mixing will be small
- CP violation will be small
- B's will decay in very high multiplicities making full reconstruction difficult
- But in 1983, the B meson lifetime was measured as relatively long ~1 ps by PEP experiments

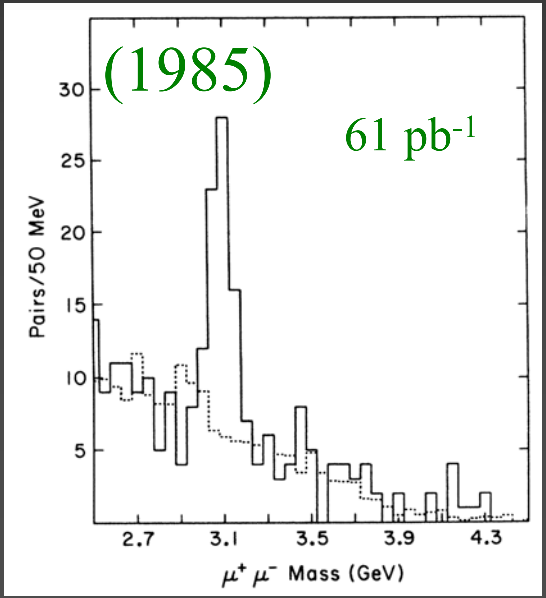
Fully Reconstructed B Mesons (1983)



- Br's too large (partially due to ~x2 wrong D° rate)
- Two-body modes had real events
- 3-body were wrong
- Many new techniques developed – learned better tracking software was in order

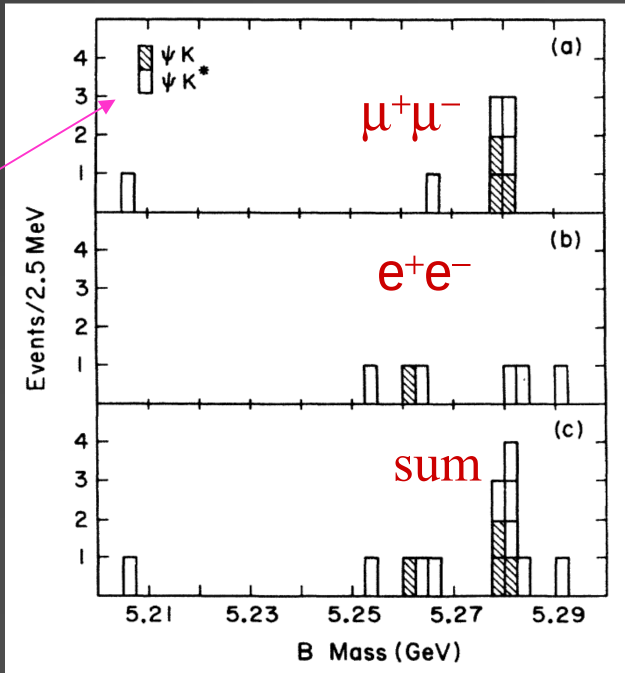
Better $\mathcal{L}$, Competition From ARGUS

- B physics
  - Confirm ARGUS discovery of B^o-$\overline{B}^o$ mixing. ARGUS has better lepton identification (1989)
  - First observation of $B \rightarrow \psi X$, & $B \rightarrow \psi K^{(*)}$, (ARGUS just about simultaneously)

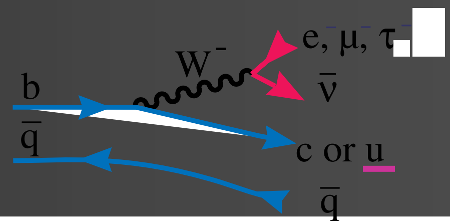


•In 1984: dE/dx in Drift Chamber, new 10 layer Vertex Detector (wires), a total of 119 pb^{-1}

•Later in 1986 new 51 layer DR installed, called "CLEO I.V"



Discovery of the b→u Transition



- Look for semileptonic decays $b \to u \ell \nu$ beyond endpoint of $b \to c \ell \nu$; there must be a D meson ($B \to D \ell \nu$) so the lepton cannot be as energetic
- First measurement of $|V_{ub}/V_{cb}|$~0.1, side of CKM triangle

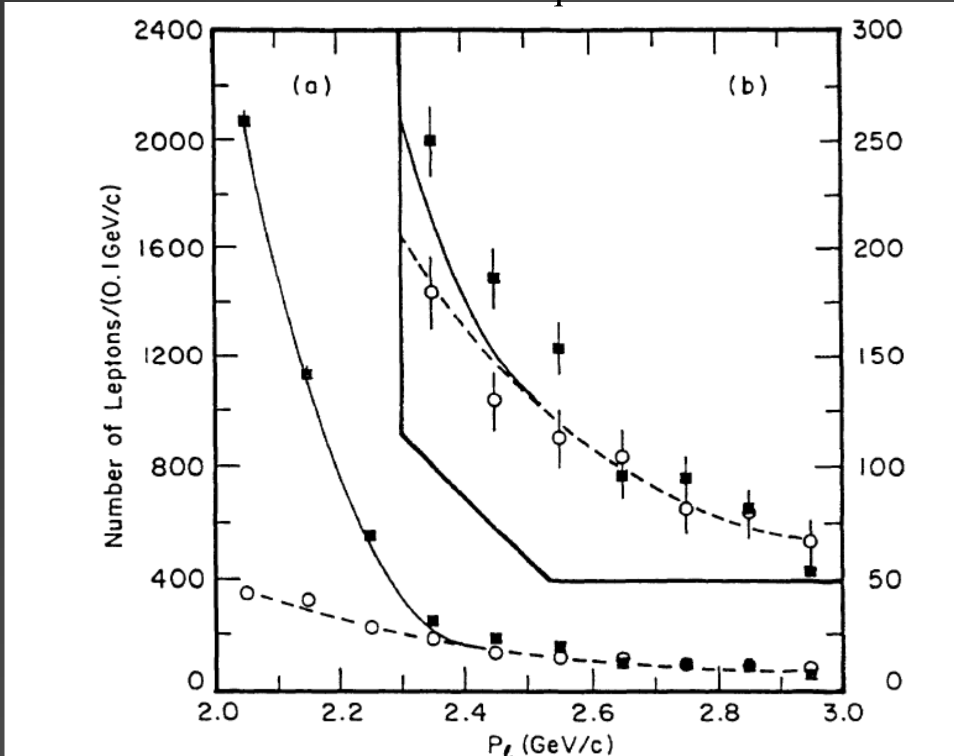
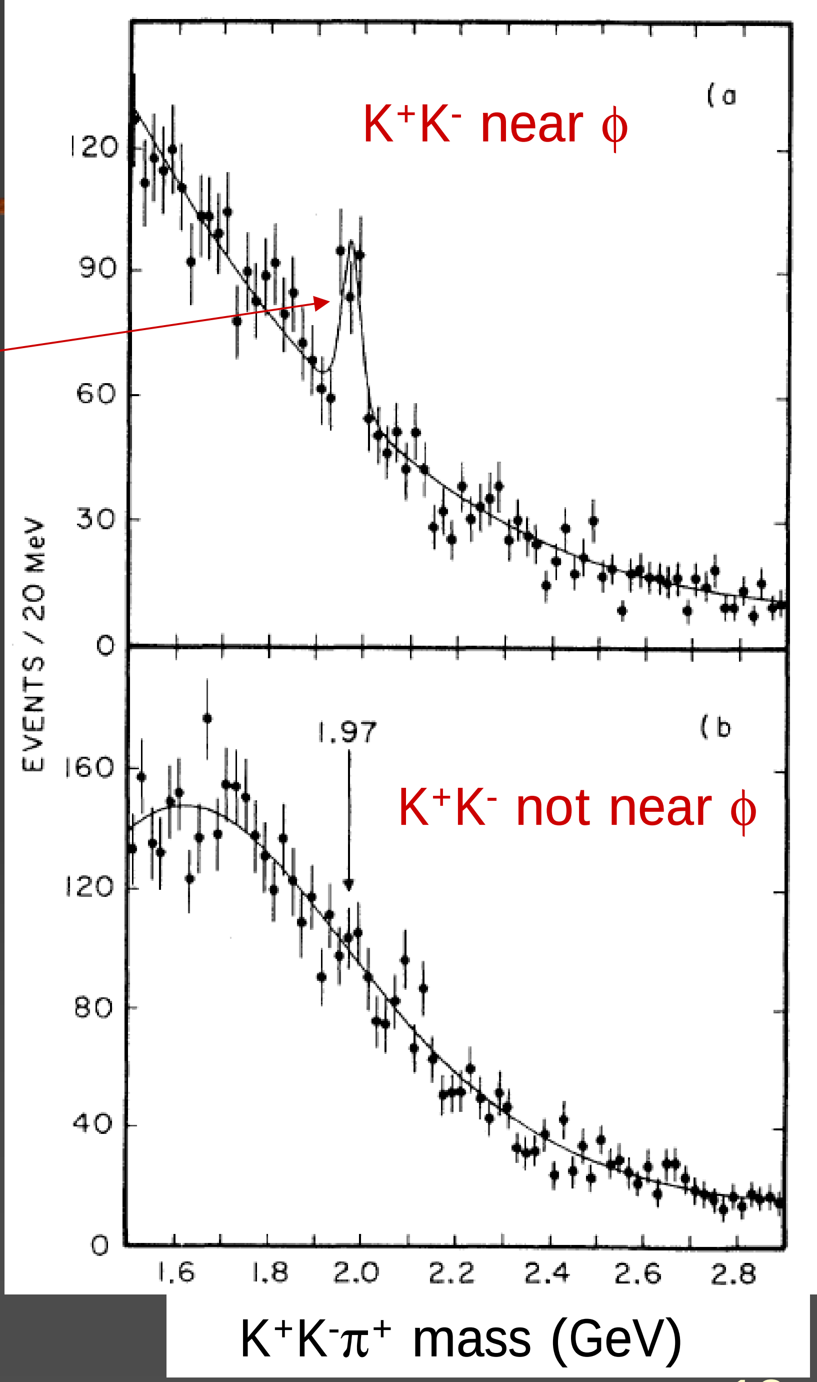


FIG. 1. Sum of the *e* and *μ* momentum spectra for ON data (filled squares), scaled OFF data (open circles), the fit to the OFF data (dashed line), and the fit to the OFF data plus the $b \to c l \nu$ yield (solid line). Note the different vertical scales in (a) and (b).

(1989)

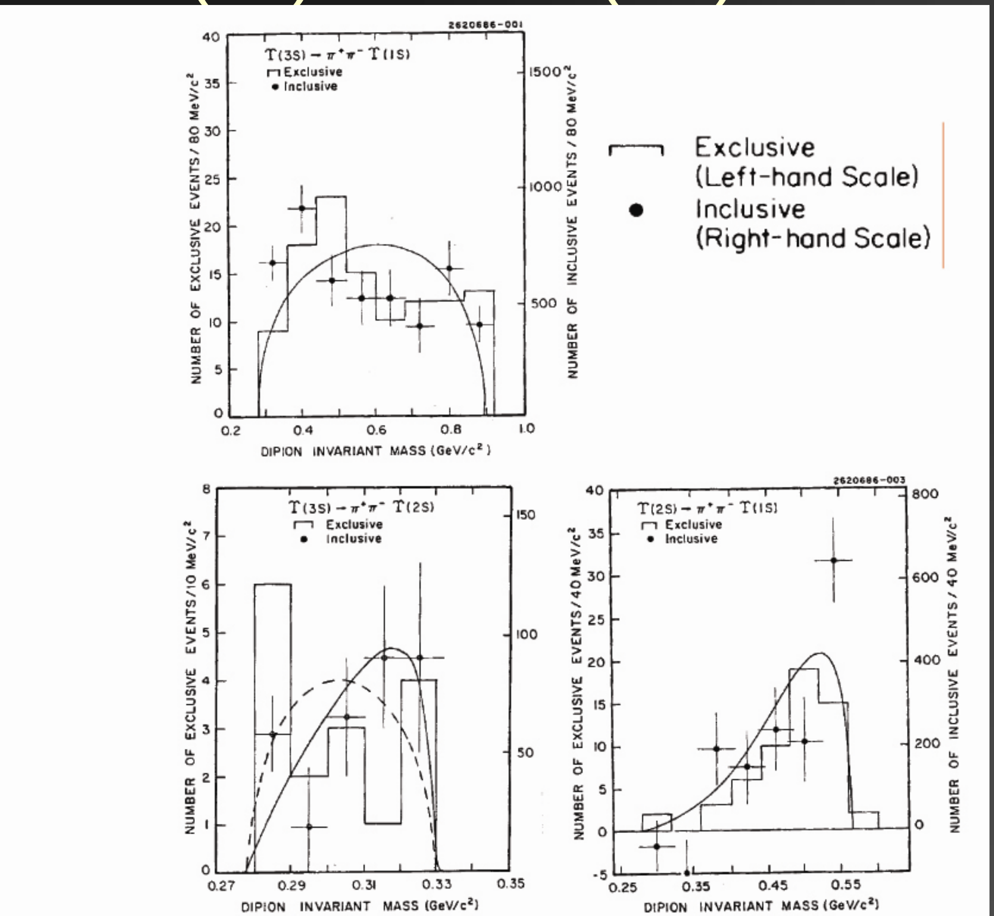
Discovery of the $F \equiv D_S$

- Mass of 1970 MeV (1983)
- Previously thought to be at 2020 MeV (See . arXiv:hep-ph/0010295 for details)
- Much charm physics: continuum production of D's & D*'s
- Much τ physics



Upsilon Spectroscopy

- Y(ns) $\rightarrow \pi^+\pi^-$Y(1S)
- Y(1S)$\rightarrow\gamma$gg



Mysterious differences

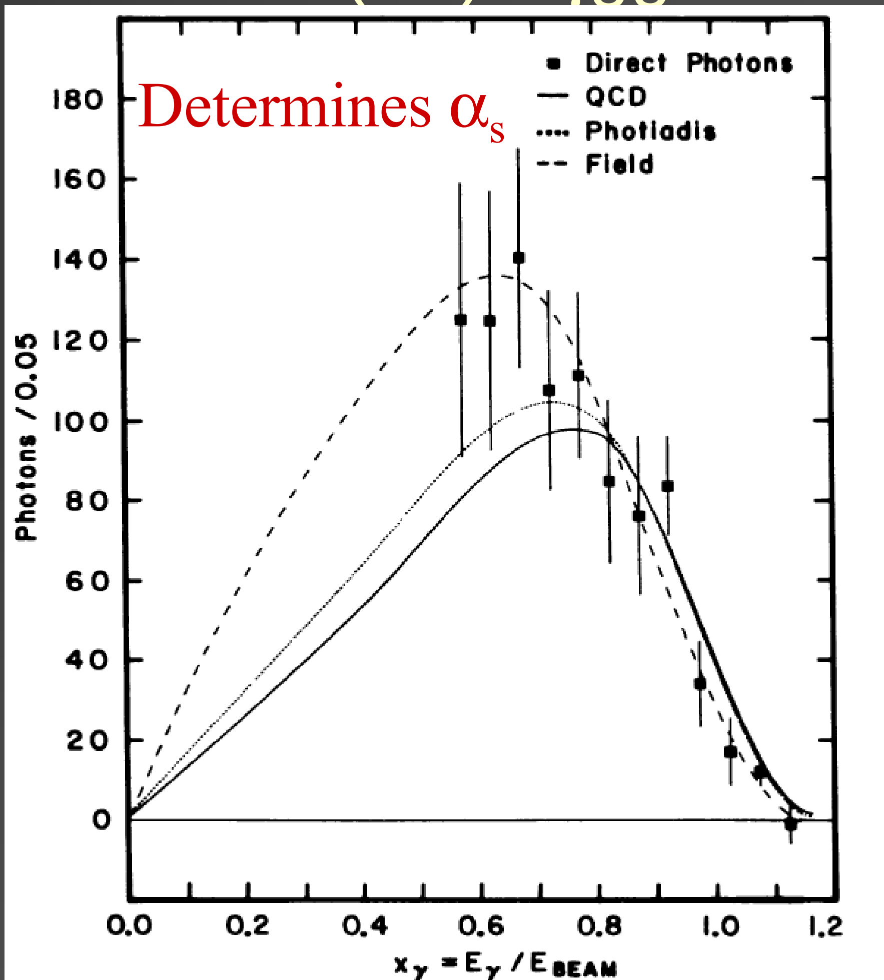
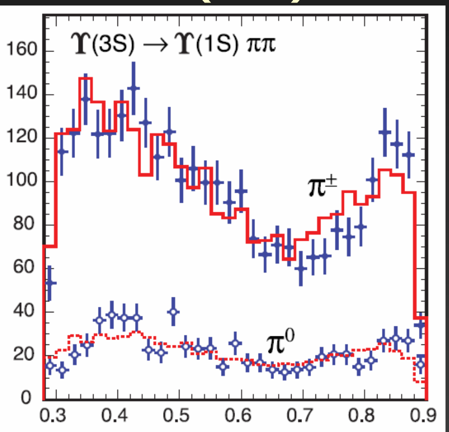


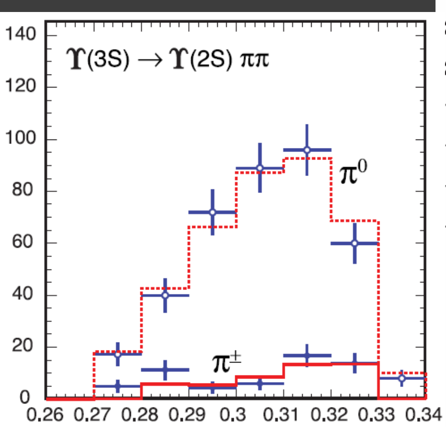
FIG. 3. Background-subtracted photon spectrum and fits to the various theoretical spectra. Errors are statistical only.

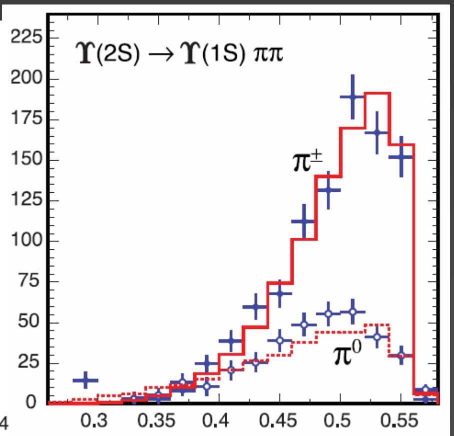
Both Results Improved Immensely

- $\Upsilon(ns) \to \pi\pi\Upsilon(1S)$ (2007)



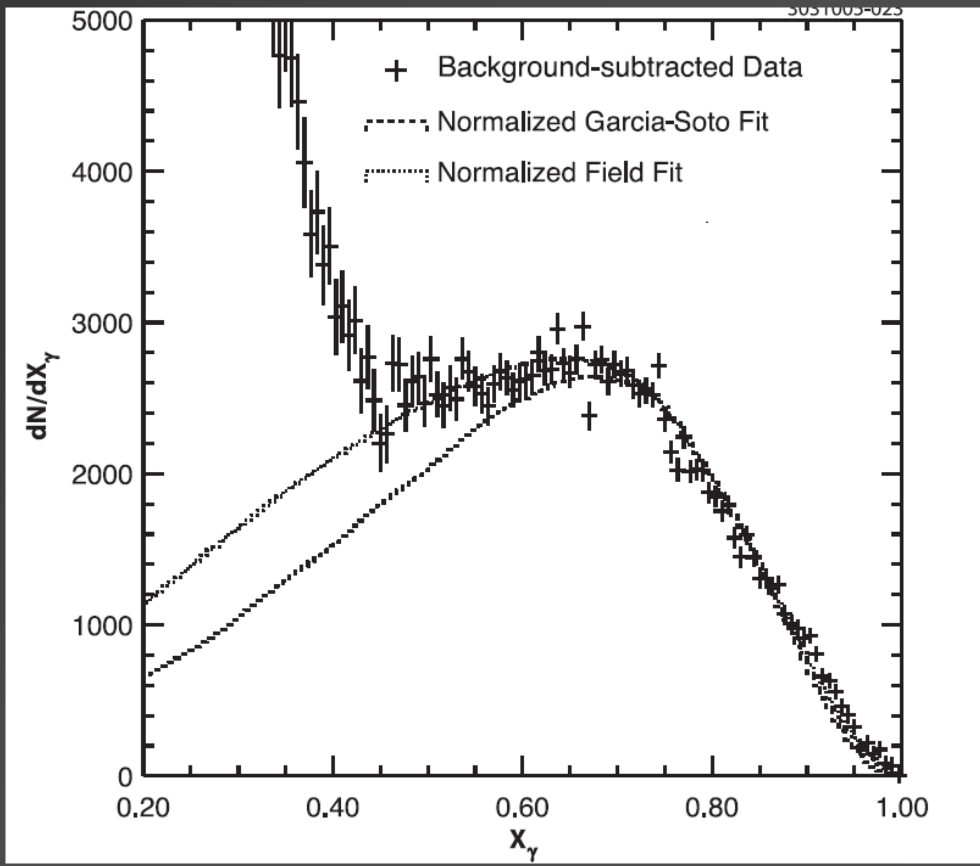
Red curves are full matrix element fits





$M_{\pi\pi}$ (GeV/c)

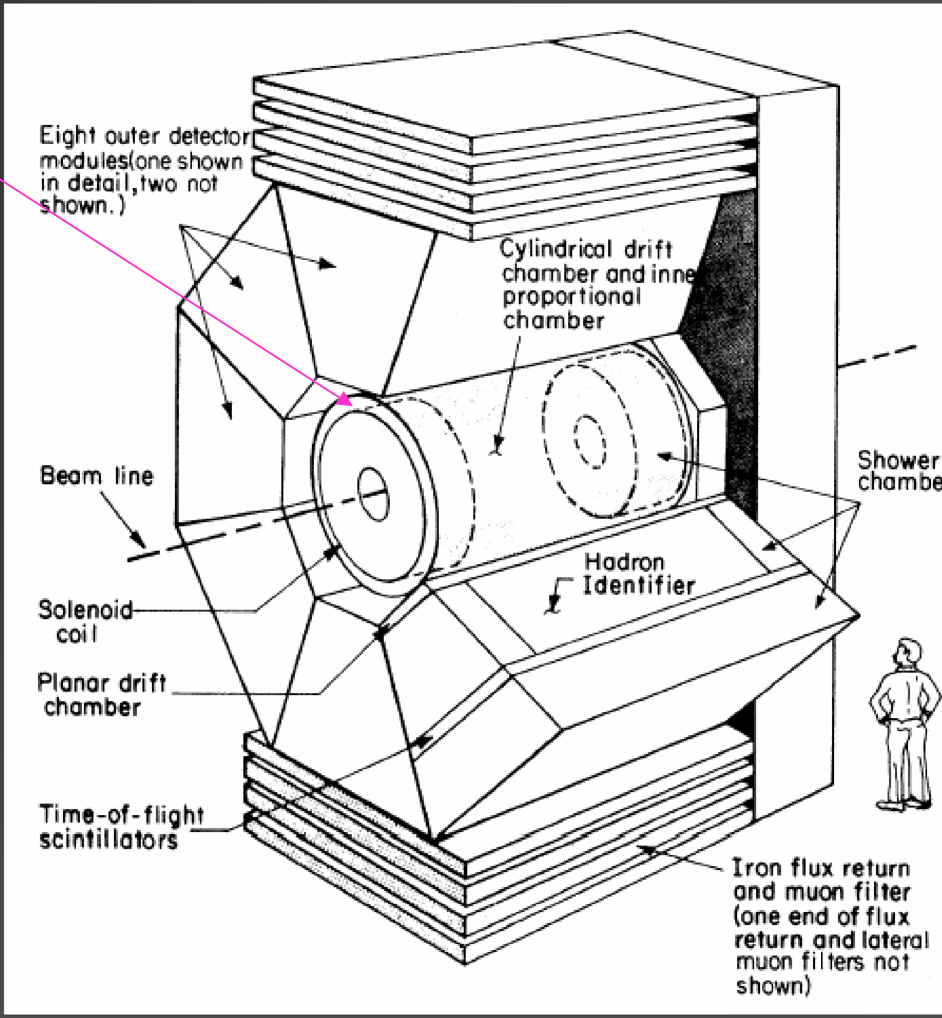
- $\Upsilon(1S) \to \gamma gg$ (2006)



- $\alpha_s(M_Z)=0.1114\pm0.0002\pm0.0029\pm0.0053$

What we learned not to do

- Magnet coil is a thick barrier: put particle ID & EM cal inside
- Muon system is too thick at front, p acceptance full only >1.4 GeV/c
- EM calorimeter has too many cracks, not enough segmentation & poor Energy resolution ~17%/√E
- Too few tracking layers: tracking problems, pid...

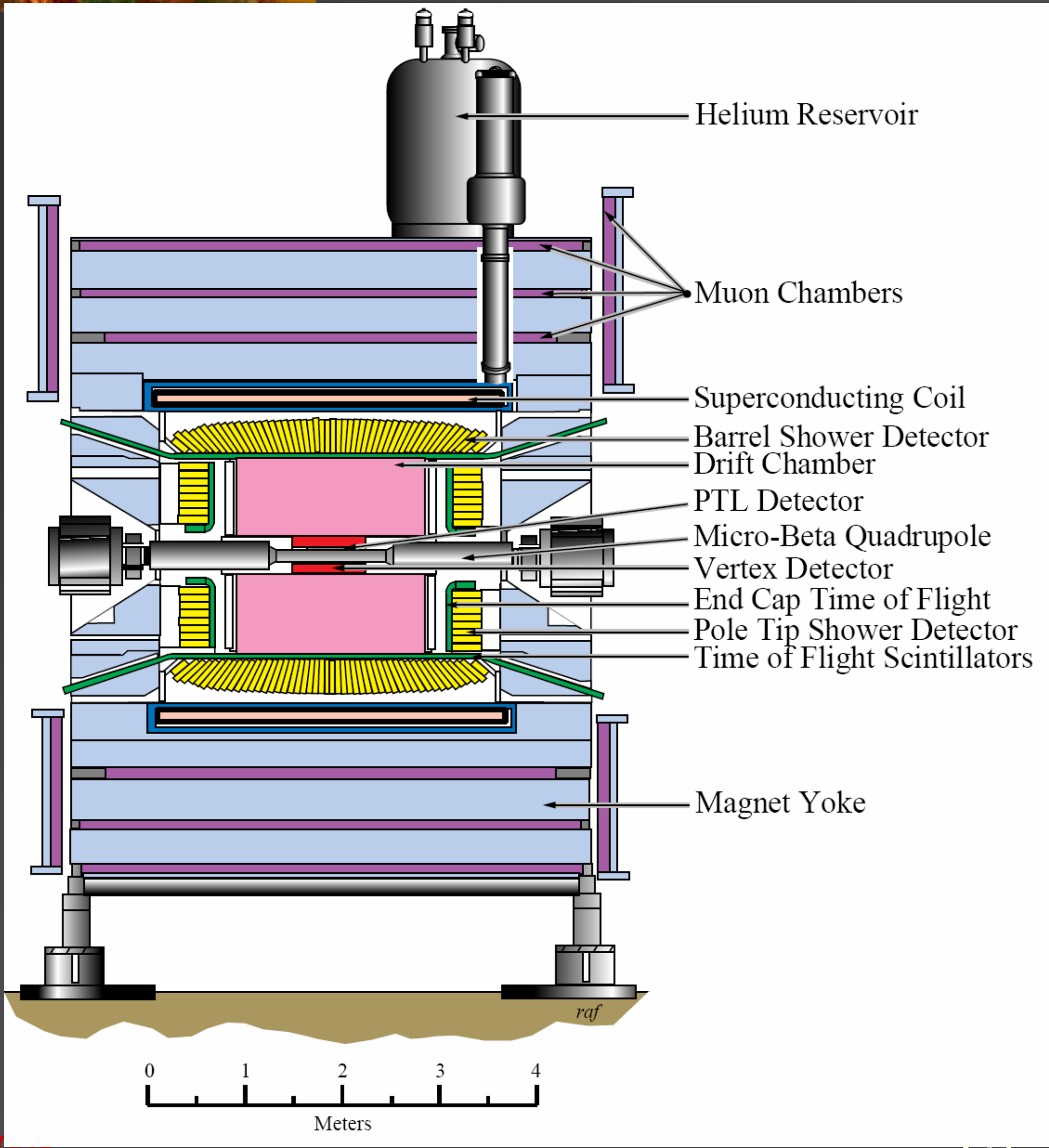


CLEO II Requirements

- Improve B physics capabilities
- Detect photons with ~same ability as charged tracks; identify e^- cleanly
- Improve resolution on charged tracks B goes from 1.0 T to 1.5 T
- Improve dE/dx and tracking flaws by filling up Drift chamber gas with detection layers
- Lower muon id threshold

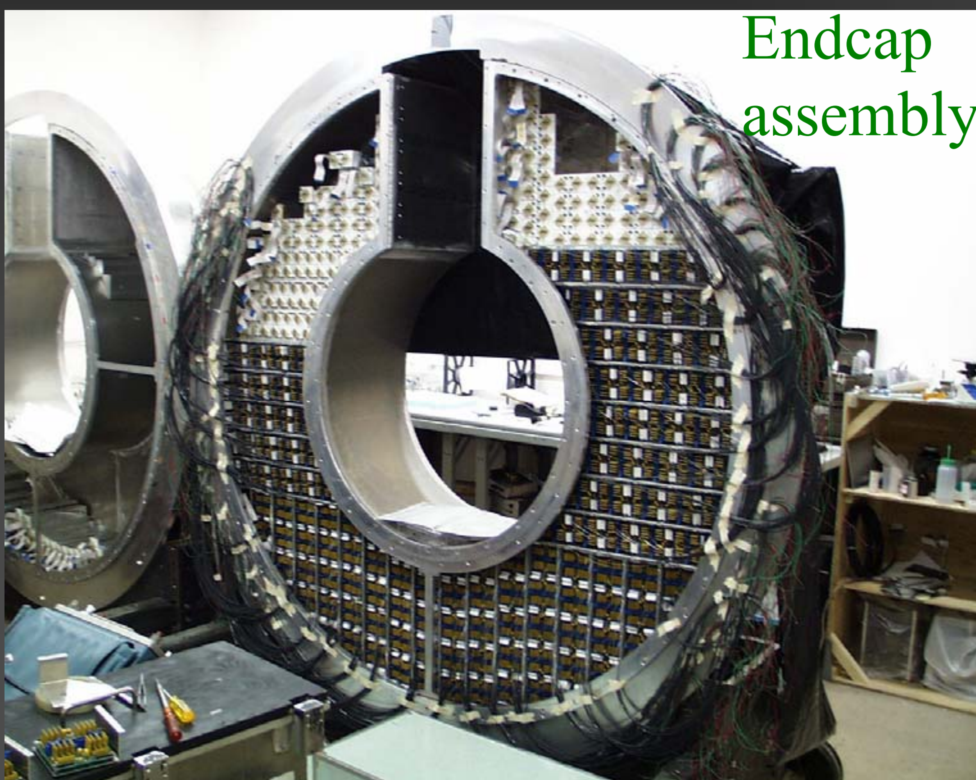
CLEO II

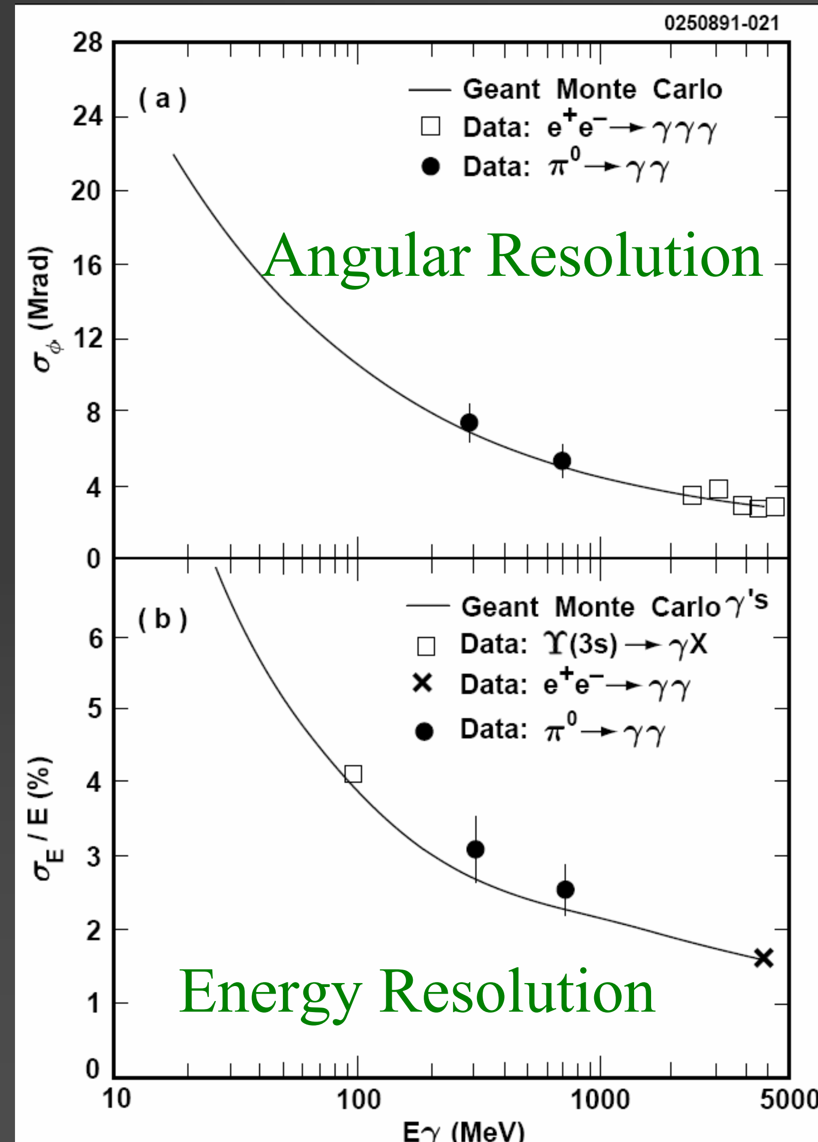
- All particle id: TOF & dE/dx inside coil
- CsI(Tℓ) inside coil
- Lower p threshold on muons to ~ 1 GeV/c
- Problems
  - poor pid > 0.9 GeV/c (some with dE/dx)
  - DR endcaps too thick
  - Vertex Detector not silicon based



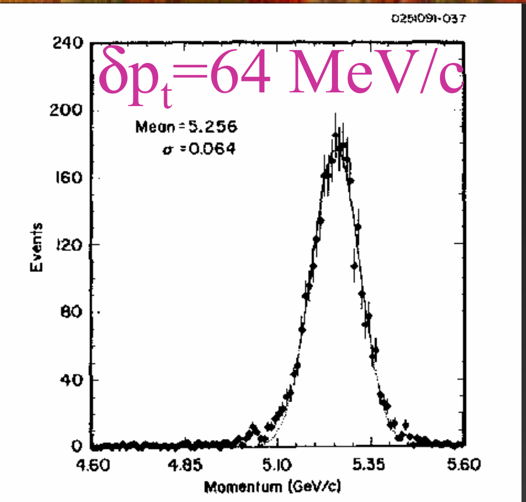
CsI Performance

- CsI angular resolution & energy resolution close to MC prediction

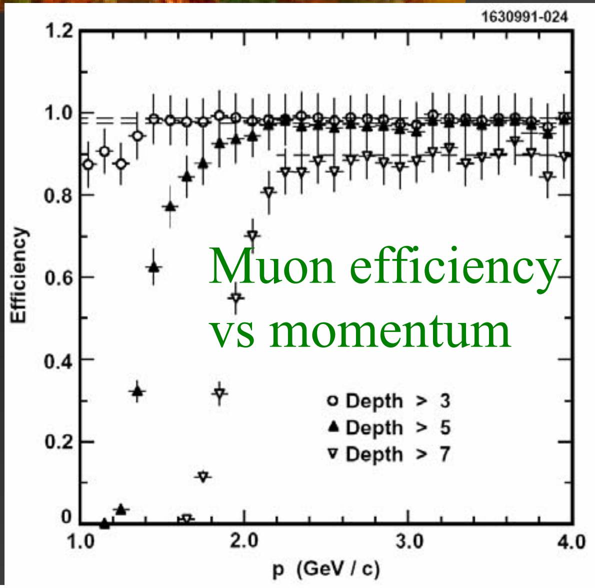




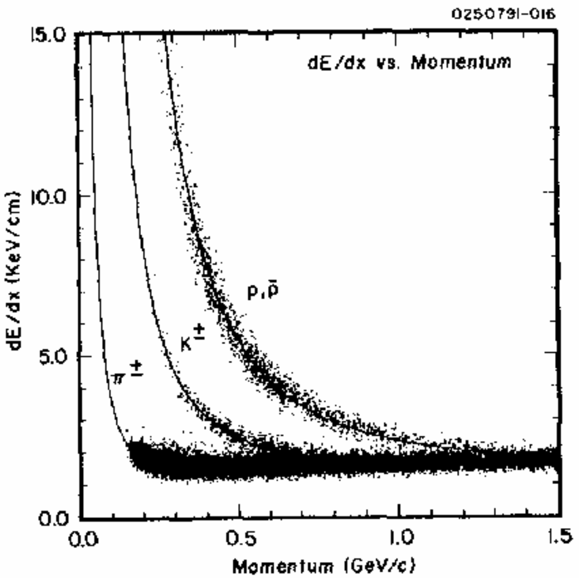
CLEO II Performance Benchmarks



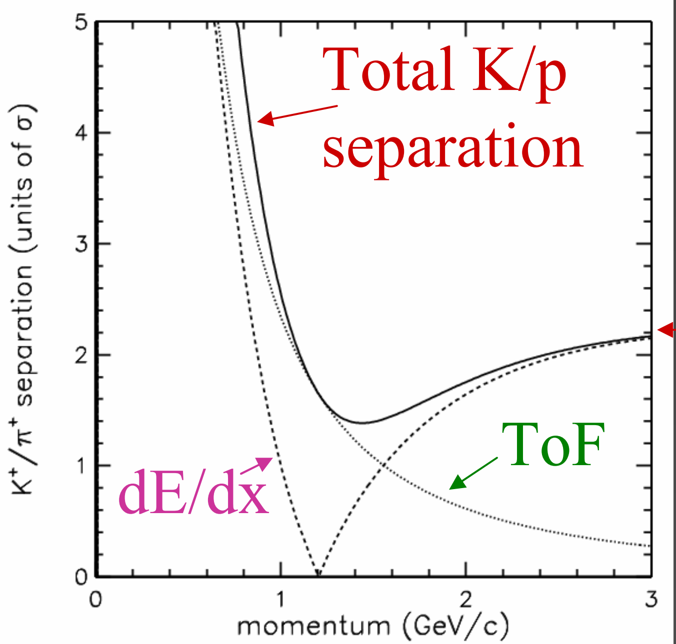
21 Observed momentum of muons from the reaction $e^+e^- \to \mu\mu$ at 5.280 GeV beam energy



- Excellent overall detector performance



23 Specific Ionization vs Track Momentum for Hadrons



Not very good at high momentum

Most Important (& Fun) Results from CLEO II

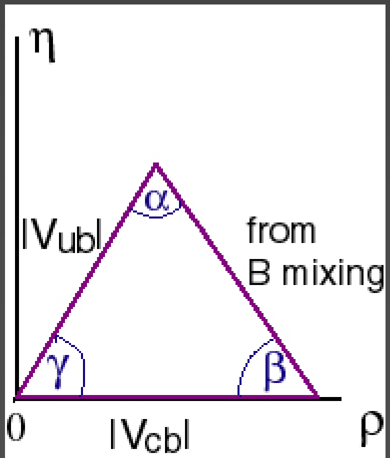
Detector

- CsI was copied by B factory detectors
  - BaBar resolution slightly worse
  - Belle resolution slightly better
  - Acceptances both worse due to asymmetric beams
- Another upgrade: CLEO II.V – replace wire chamber with Silicon strip VD
  - Best upper limits for a long time on D^o mixing
  - Lifetime measurements of charm particles

Some Important B Physics Measurements

Main goals were to

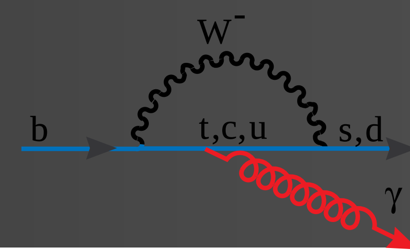
1) Measure rare decays
2) Determine sides of CKM triangle

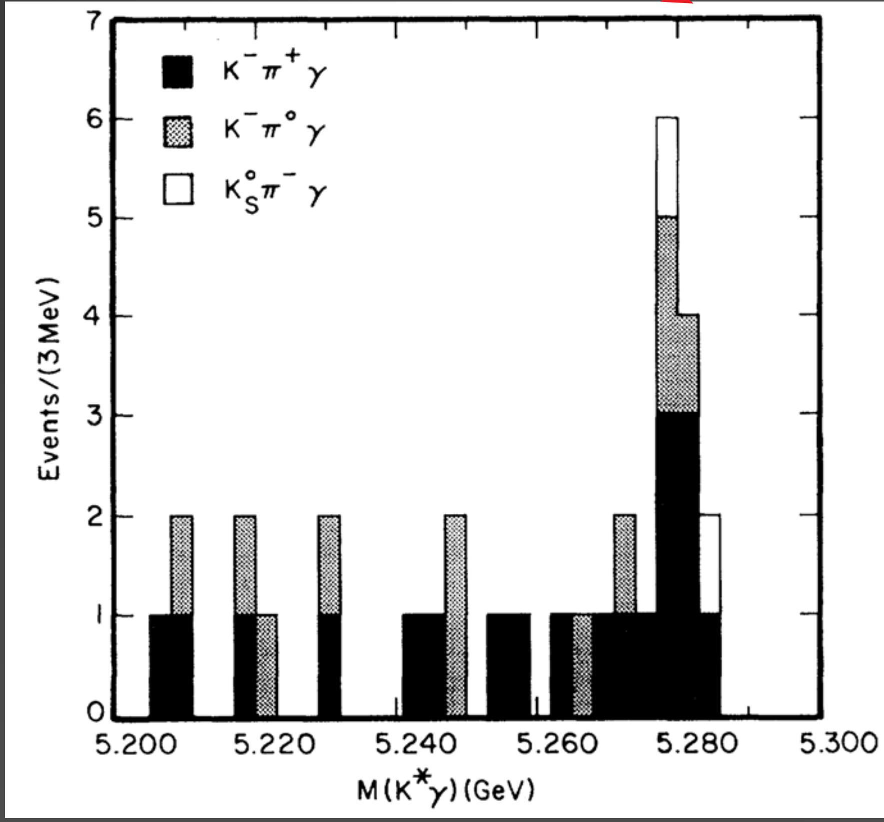


VOLUME 71, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1993

Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$

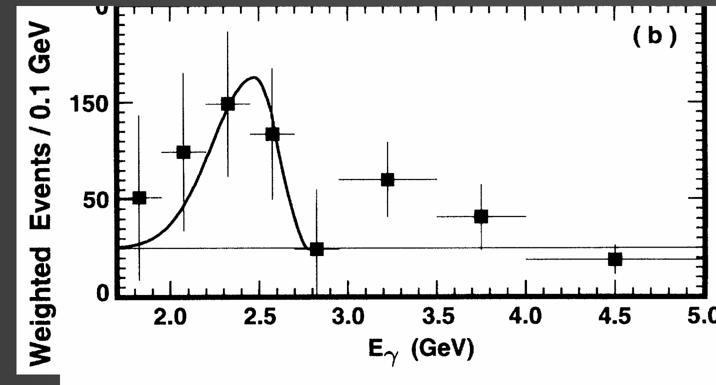
- $\mathcal{B}(B^o \to K^{*o}\gamma)$ $=(4.0\pm1.7\pm0.8)\times10^{-5}$
- $\mathcal{B}(B^- \to K^{*-}\gamma)$ $=(5.7\pm3.1\pm1.1)\times10^{-5}$
- But theory wants inclusive rate $b \to s\gamma$

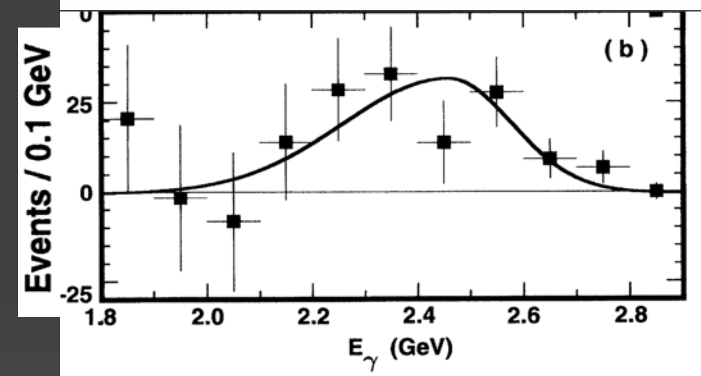




VOLUME 74, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1995

First Measurement of the Rate for the Inclusive Radiative Penguin Decay $b \to s\gamma$

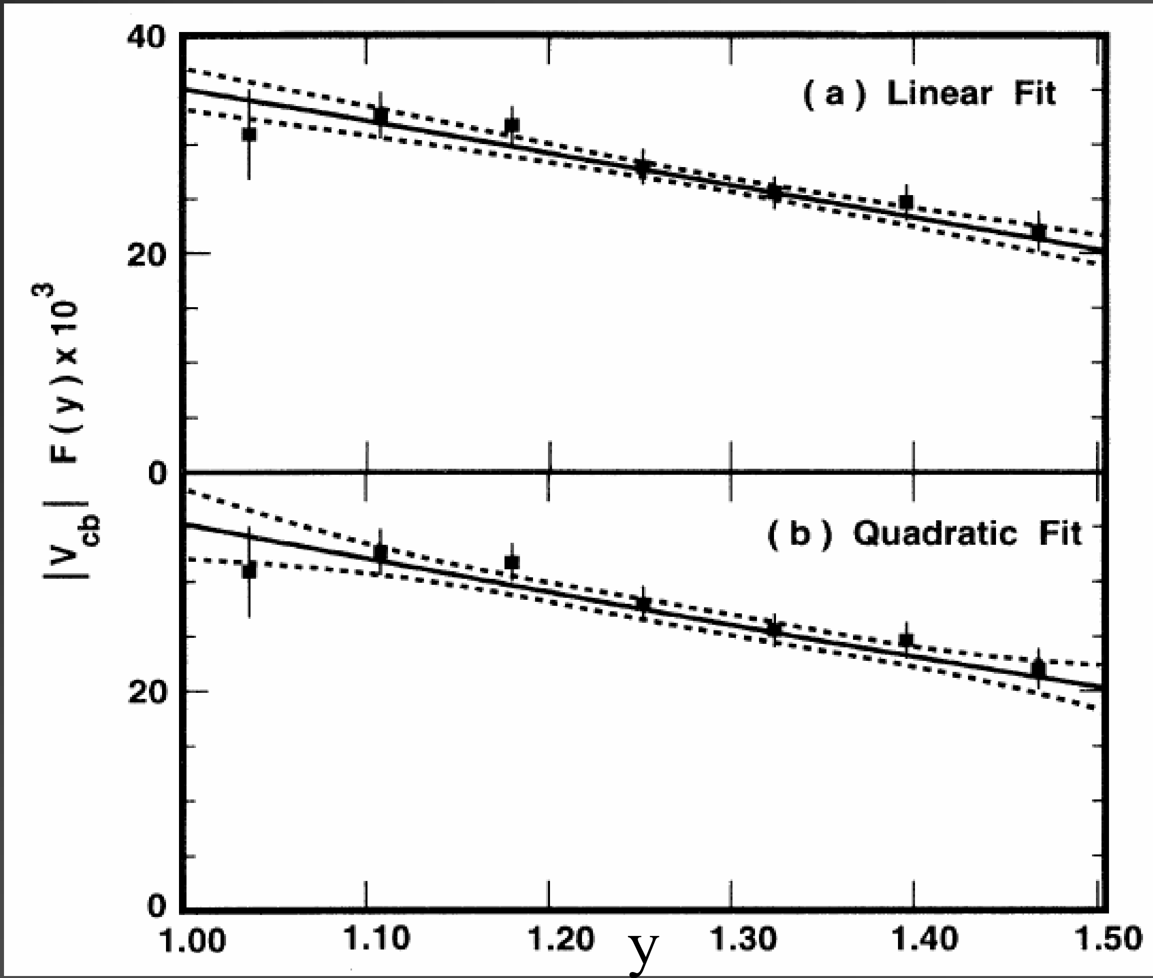




- Two new techniques developed
  - one used event shapes & inclusive distributions
  - the other was based on full B reconstruction for K+nπ+γ
- $\mathcal{B}$=(2.32±0.57±0.35)x10^{-4}
- More recent: CLEO $\mathcal{B}$(b→sγ)=(3.21±0.43±0.30)x10^{-4} +ALEPH, Belle & Babar, =(3.55±0.26)x10^{-4}
- Theory: 3.5±0.5 x10^{-4} ⇒Limits on many non-Standard Models: minimal supergravity, supersymmetry, etc…

V_{cb}: Measure $B \to D^* \ell \nu$

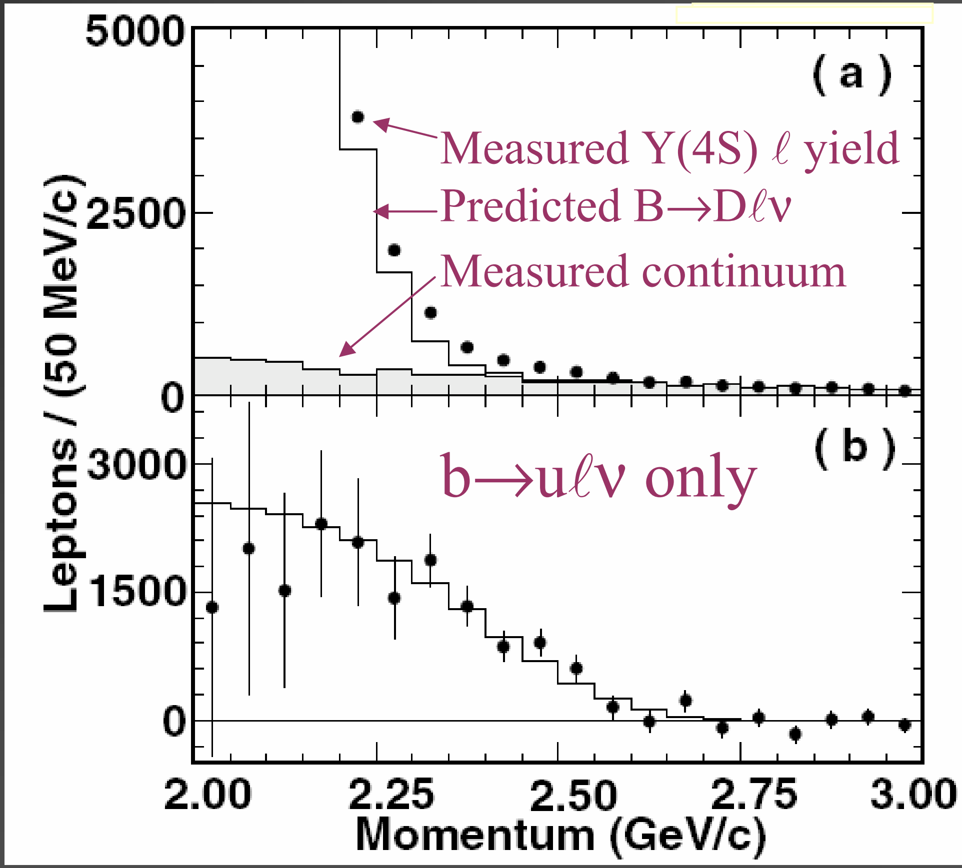
- Measure the decay rate as a function of invariant 4-velocity transfer (Isgur – Wise function) (1995)
- Value of V_{cb} depends on theoretical model of $\mathcal{F}(1)$



Model	$\mathcal{F}(1)$	$\lvert V_{cb}\rvert \times 10^3$
Neubert [39]	0.93 ± 0.03	$37.7 \pm 2.0 \pm 2.1 \pm 1.2$
Shifman *et al.* [58]	0.89 ± 0.03	$39.4 \pm 2.1 \pm 2.2 \pm 1.3$

V_{ub} From Inclusive $b \to u\ell\nu$ Decays

- Inclusive lepton spectrum fit gives:
- $|V_{ub}|= (4.08 \pm 0.63) \times 10^{-3}$
- circa 2002



First Observations of B→π(ρ)(ω)ℓν

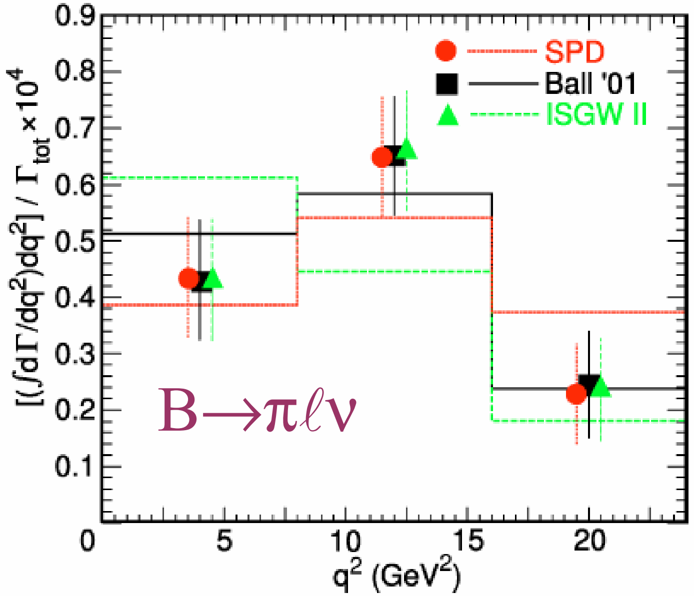


FIG. 12. Measured branching fractions in the restricted q^2 intervals for $B^0 \to \pi^- \ell^+ \nu$ (points) and the best fit to the predicted $d\Gamma/dq^2$ (histograms) for the three models used to extract both rates and $|V_{ub}|$. The data points have small horizontal offsets introduced for clarity. The last bin has been artificially truncated at 24 GeV^2 in the plot—the information out to $q^2_{\max}$ has been included in the work.

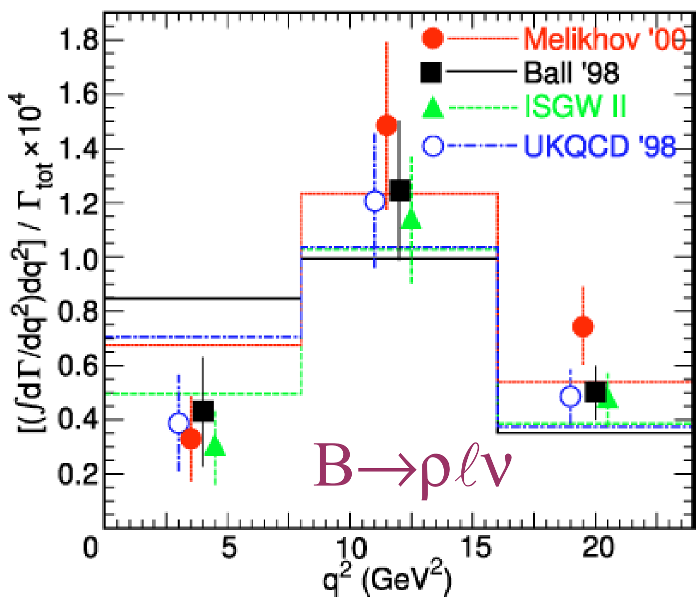
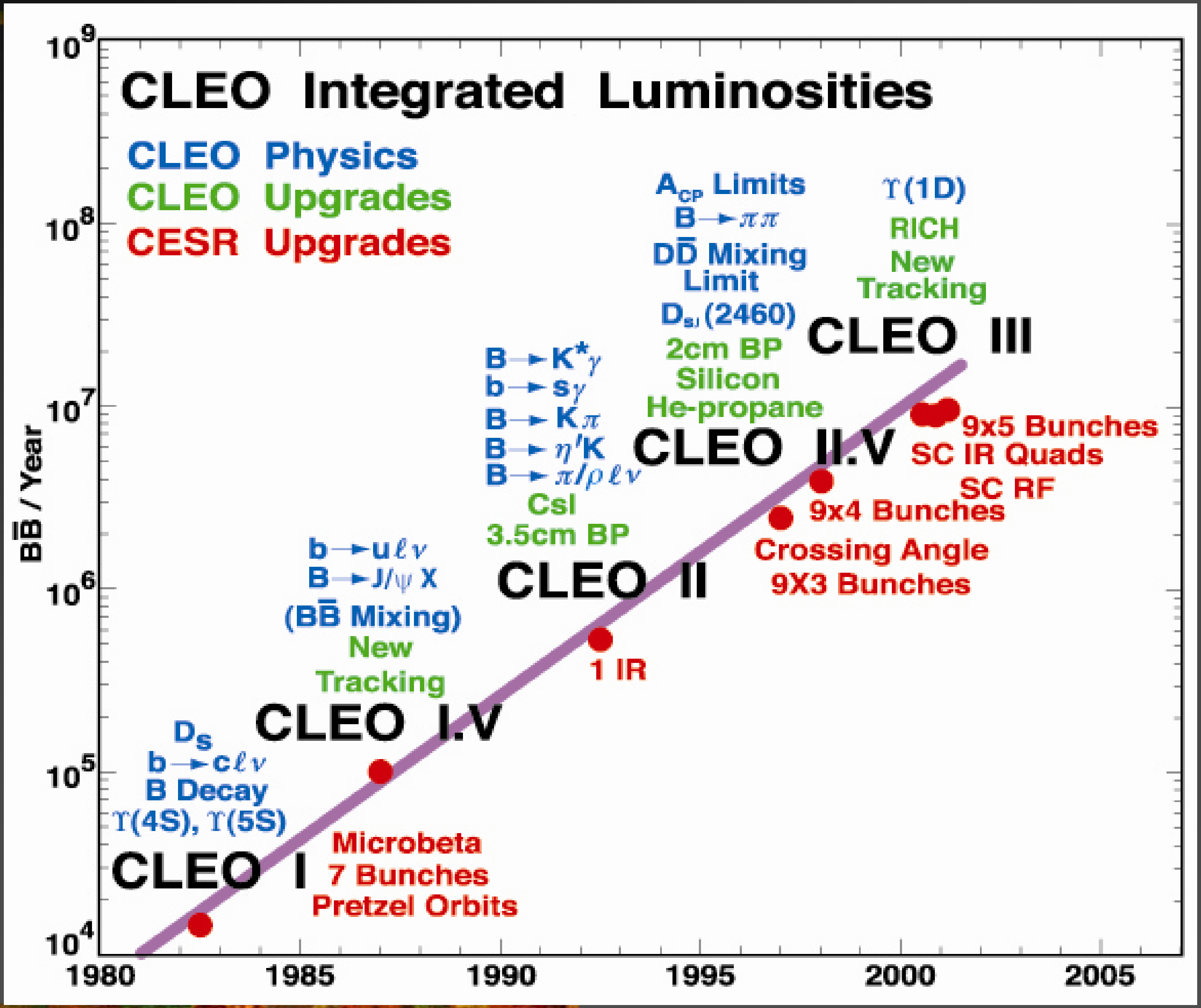


FIG. 14. Measured branching fractions in the restricted q^2 intervals for $B^0 \to \rho^- \ell^+ \nu$ (points) and the best fit to the predicted $d\Gamma/dq^2$ (histograms) for the models used to extract both rates and $|V_{ub}|$. The data points have small horizontal offsets introduced for clarity.

$$|V_{ub}| = (3.17 \pm 0.17 {}^{+0.16}_{-0.17} {}^{+0.53}_{-0.39} \pm 0.03) \times 10^{-3}$$

circa 2003

Some of the More Important CLEO II Results

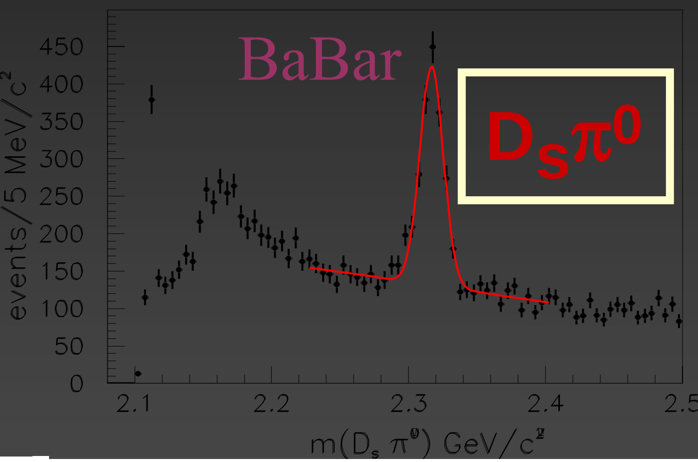


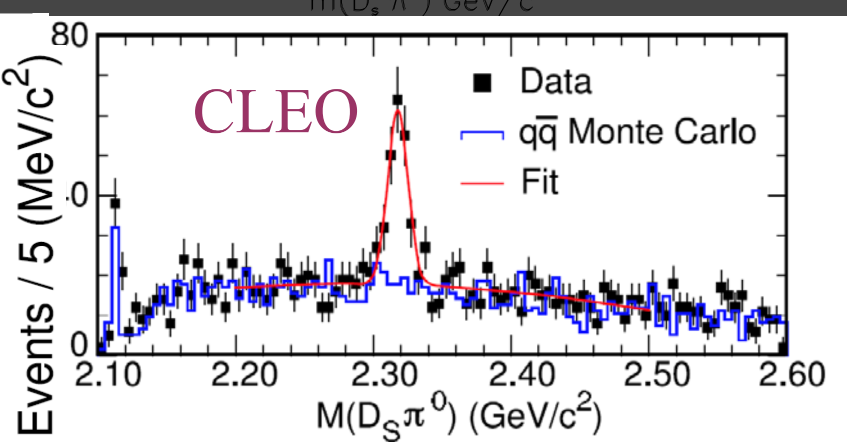
Charm Decay Studies: Most important results

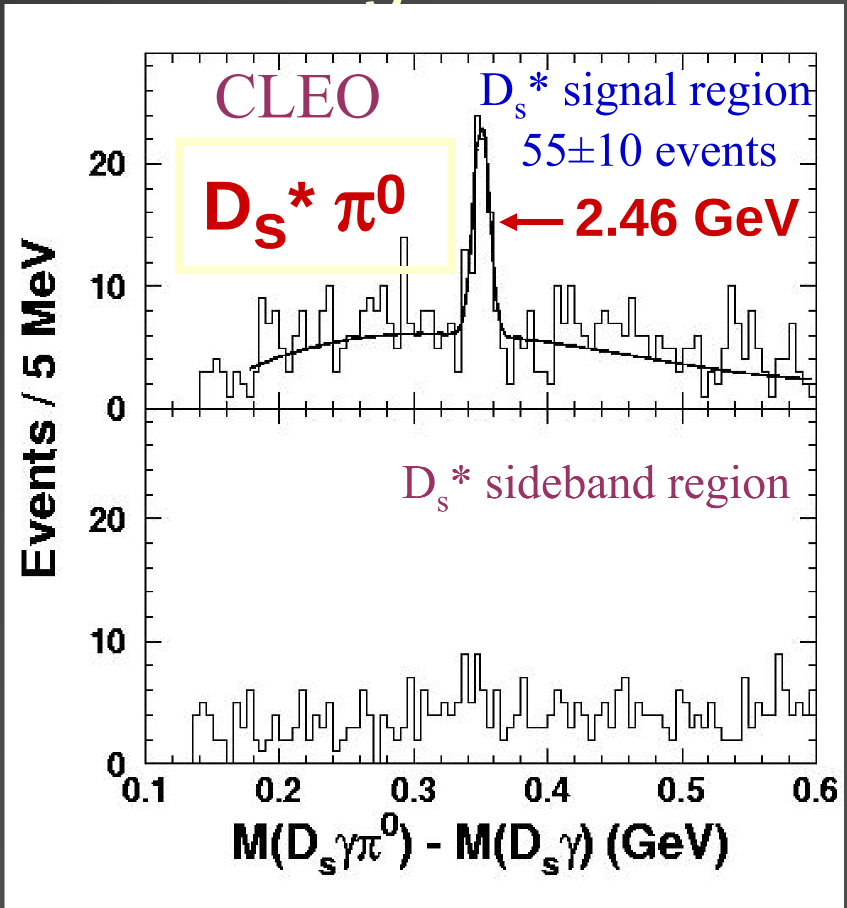
- Best limit in 2005 on D^o-$\overline{D}^o$ mixing using a time dependent Dalitz analysis of $D^o \to K_S\pi^+\pi^-$.
- First precision measurements of the D* BR's and isospin mass splittings (1992)
- First accurate measurement of $\mathcal{B}(D^o \to K^-\pi^+)$
- First measurement of the D_s modes $\eta^{(\prime)}\pi^+$, $\eta^{(\prime)}\rho^+$ (1992), $\phi\pi^+$ (1996), and $\mu^+\nu/\phi\pi^+$ (1994)
- First observations of many charm baryon states including the Σ_c^+, Σ_c^{*+}, Σ_c^{**+}, Σ_c^{*o}, Ξ_c^o, Ξ_c^{*o}, Ξ_c^{*+}
- 1st measurement of $\Gamma(D^{*+}) = 96\pm4\pm22$ MeV (2001)
- Discovery of $D_{sJ}(2460)$

Discovery of the DsJ(2460)

- BaBar sees a new state at 2317 MeV that decays into $\pi^o D_s$ (isospin violating)
- CLEO confirms & also sees analogous state





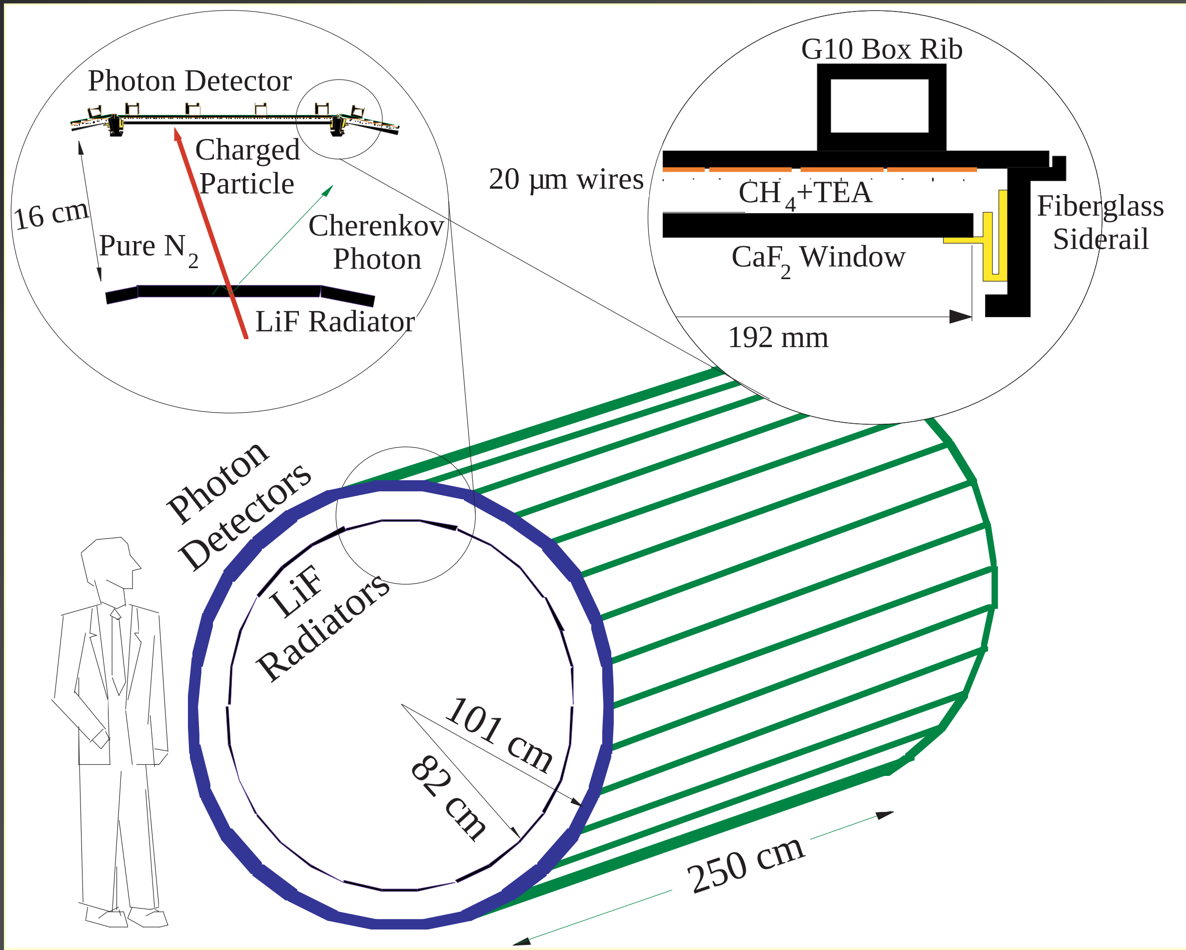


Upsilon & τ decays

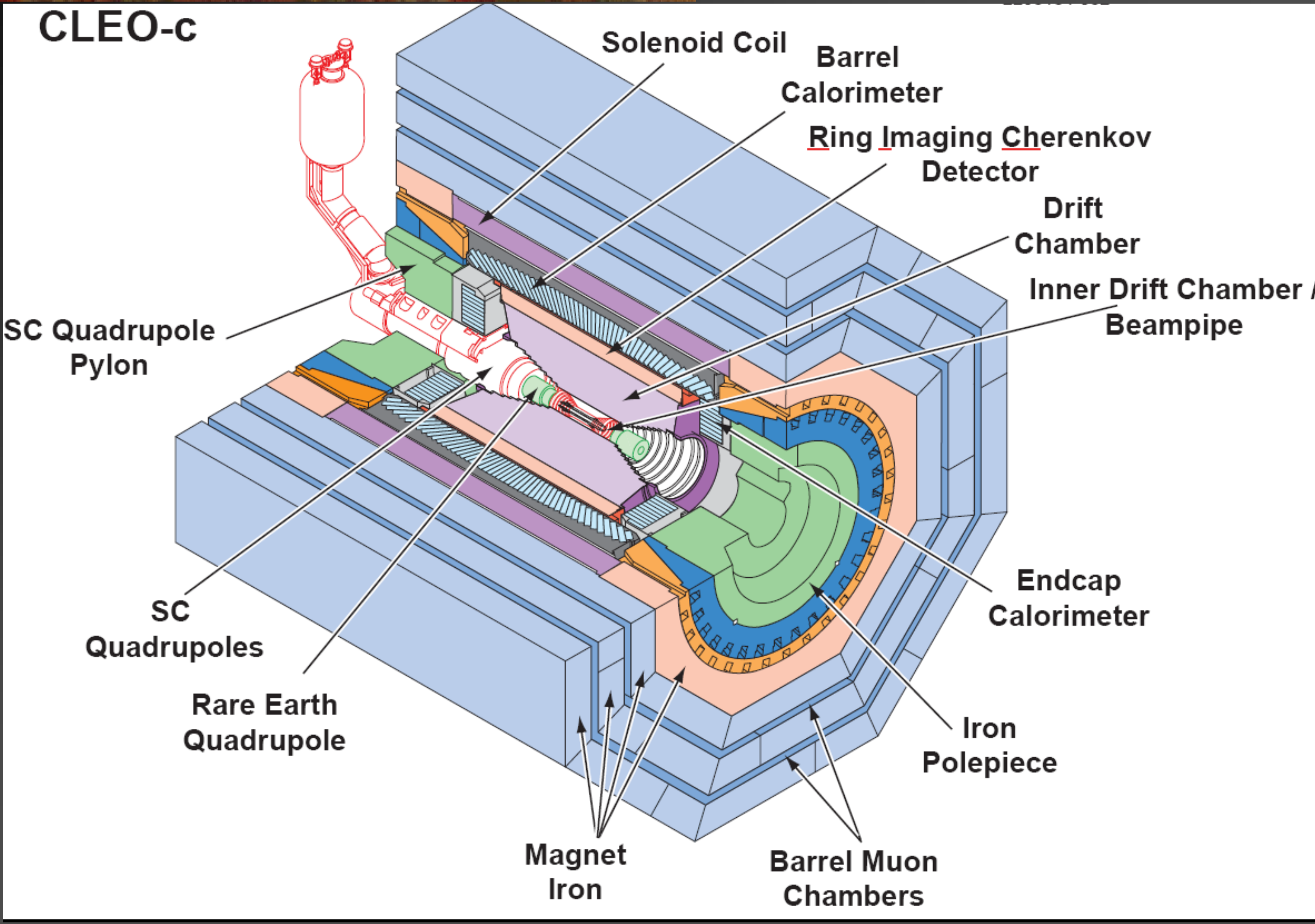
- Much interesting physics, but no time to discuss
- Also $\gamma\gamma$ collisions

CLEO III & CLEO-c

- CLEO III adds a RICH detector for particle identification
- Replace CLEO III Si VD with a low mass wire chamber for CLEO-c
- Dr gas He-C_3H_8



CLEO-c


CLEO-c
Solenoid Coil
Barrel Calorimeter
Ring Imaging Cherenkov Detector
Drift Chamber
Inner Drift Chamber / Beampipe
SC Quadrupole Pylon
SC Quadrupoles
Rare Earth Quadrupole
Endcap Calorimeter
Iron Polepiece
Magnet Iron
Barrel Muon Chambers

Techniques for D Decays

Most important measurements involve reconstructing a D^- & investigating the D^+, (similarly for D_S)

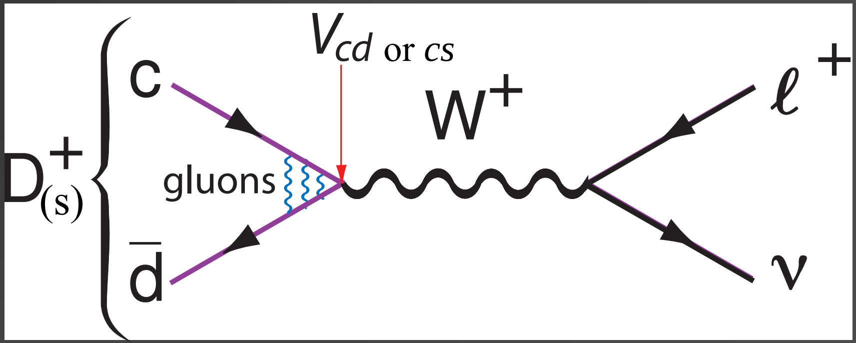
- Absolute branching ratios
- Leptonic Decays
- Semileptonic Decays

Leptonic Decays: $D \to \ell^+ \nu$

Introduction: Pseudoscalar decay constants

c and $\bar{q}$ can annihilate, probability is $\propto$ to wave function overlap

Example :



In general for all pseudoscalars:

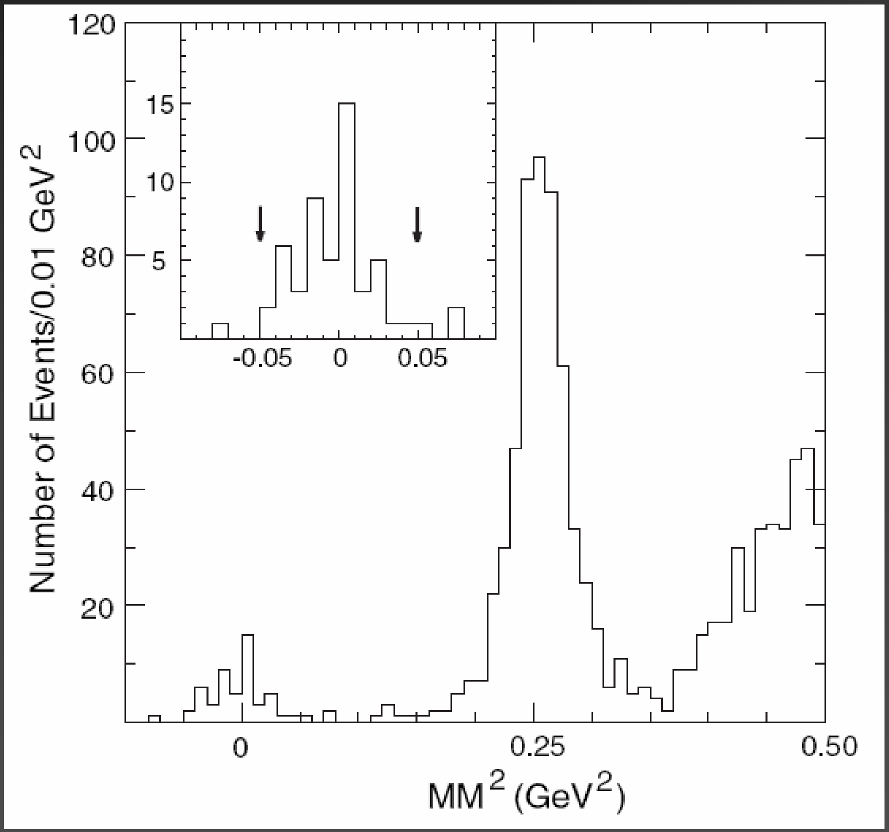
$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known

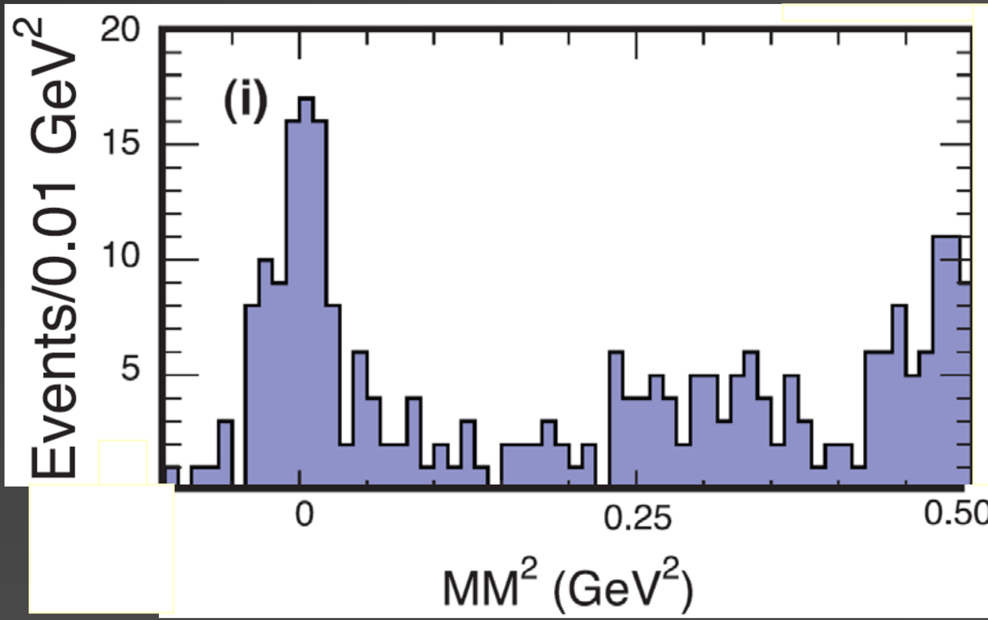
Signals for $D^+ \rightarrow \mu^+\nu$ & $D_S^+ \rightarrow \mu^+\nu$

Fully Reconstruct a D^- or D_S^-, then compute Missing Mass squared

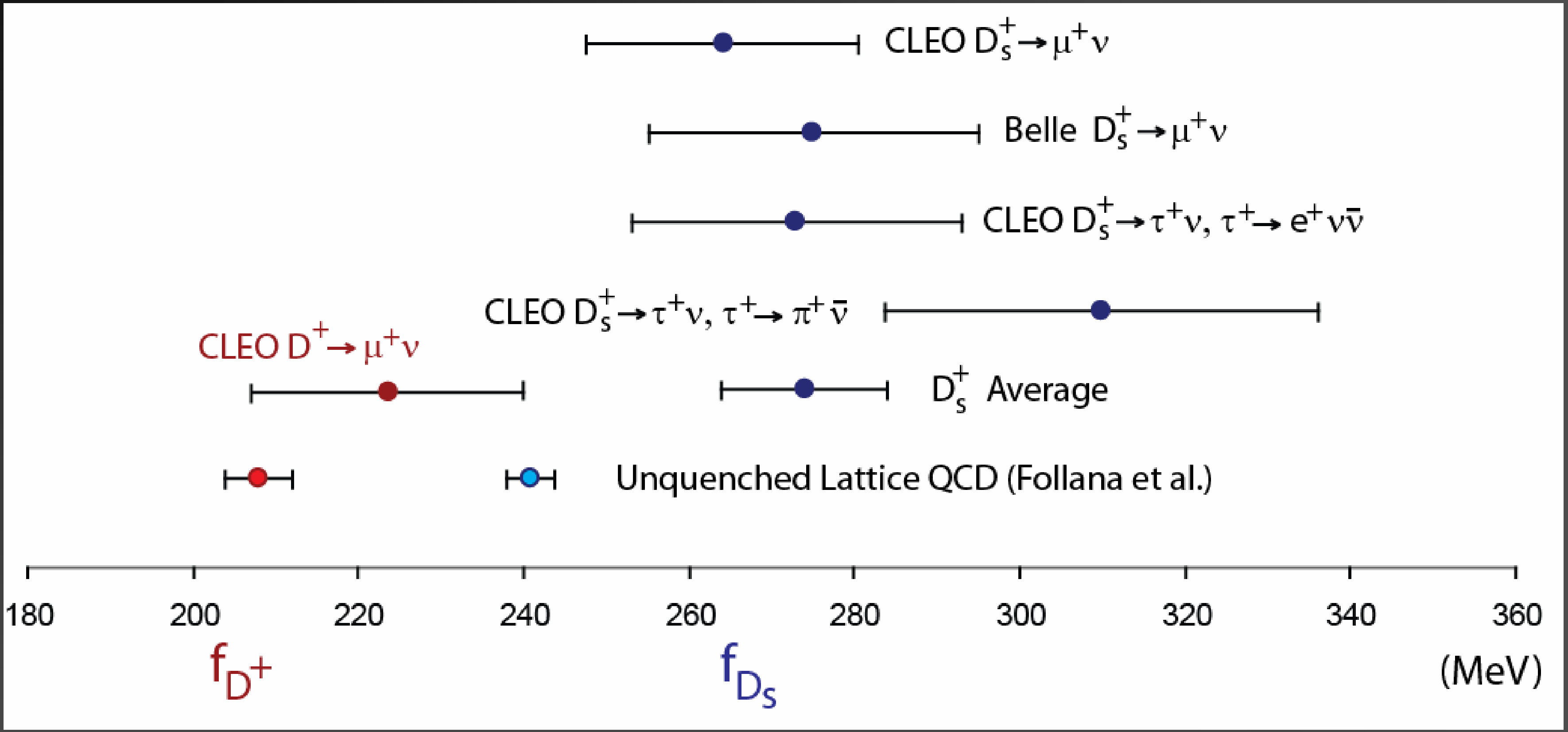
D^+



D_S^+

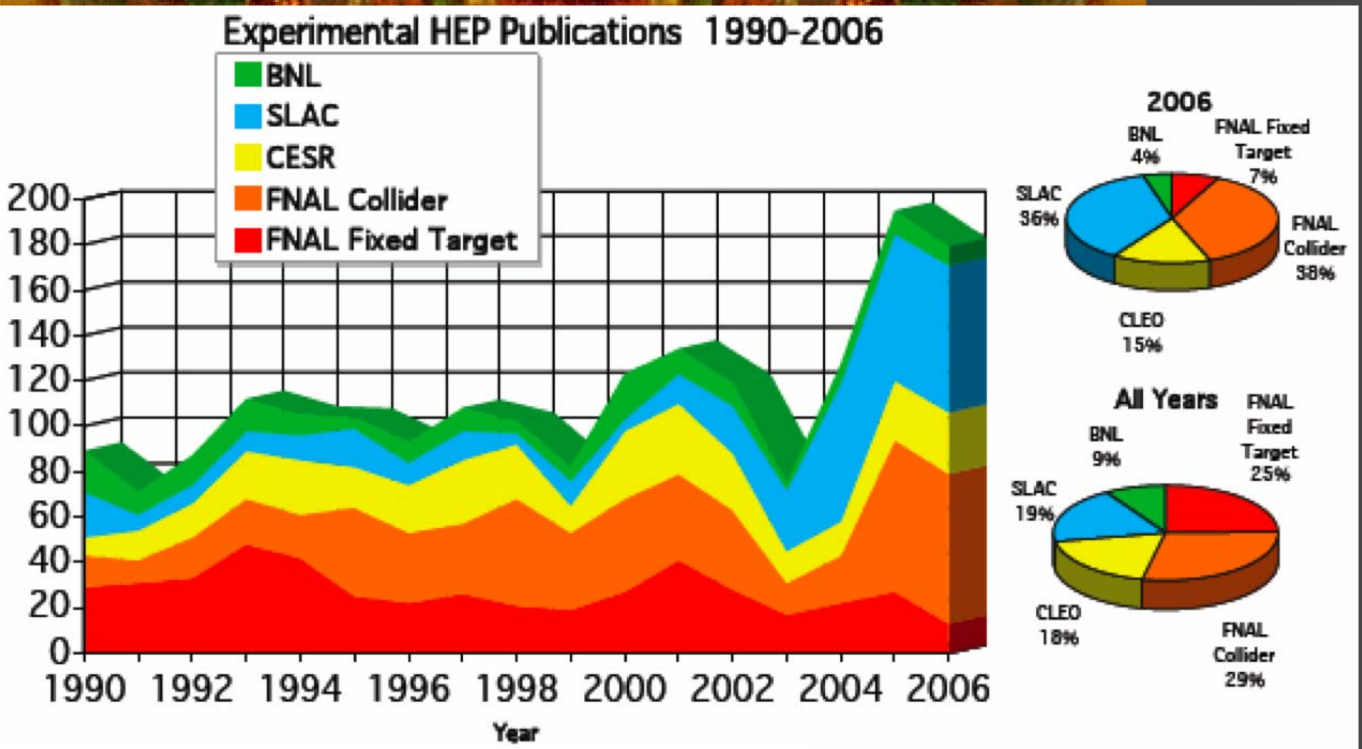


Measurement of f_{D^+} & f_{Ds}

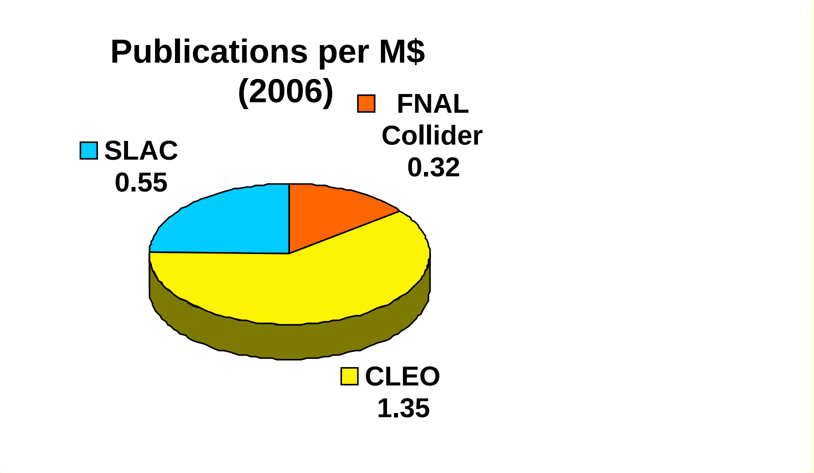


- Is this New Physics? See Dobrescu & Kronfeld arXiv:0803.0512
- CLEO f_{D^+} will improve by x2 next month
- CLEO f_{Ds} wil improve by end of summer

U.S Experimental Publications



Information compiled by Fermilab



Conclusions

- Other CLEO-c physics
  - Charm weak decays: absolute br's, leptonic decays, semileptonic decays
  - Charmonium – discovery of h_c, properties of $\psi(4260)$
- CESR – important path toward higher luminosity colliders
- CLEO – pioneering efforts in heavy quark decay, many discoveries leading to future studies of CP violation and a path toward finding or classifying new physics (unless CLEO-c has found it already in leptonic decays)

The End

Progression in Flavor Physics